1984

An evaluation of methods used to measure groundwater flow and transport characteristics in clayey deposits at two sites in Essex County, Ontario.

Timothy Gordon. Orpwood
University of Windsor

Recommended Citation
Orpwood, Timothy Gordon., "An evaluation of methods used to measure groundwater flow and transport characteristics in clayey deposits at two sites in Essex County, Ontario." (1984). *Electronic Theses and Dissertations.* Paper 1009.

National Library
of Canada

Canadian Theses Service

Ottawa, Canada
K1A 0N4

Bibliothèque nationale
du Canada

Services des thèses canadiennes

CANADIAN THESES

THÈSES CANADIENNES

NOTICE

The quality of this microfiche is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Previously copyrighted materials (journal articles, published tests, etc.) are not filmed.

Reproduction in full or in part of this film is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30. Please read the authorization forms which accompany this thesis.

AVIS

La qualité de cette microfiche dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

Les documents qui font déjà l'objet d'un droit d'auteur (articles de revue, examens publiés, etc.) ne sont pas microfilmés.

La reproduction, même partielle, de ce microfilm est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30. Veuillez prendre connaissance des formules d'autorisation qui accompagnent cette thèse.

THIS DISSERTATION
HAS BEEN MICROFILMED
EXACTLY AS RECEIVED

LA THÈSE A ÉTÉ
MICROFILMÉE TELLE QUE
NOUS L'AVONS REÇUE

NL 339 (r. 86/01)

Canada

AN EVALUATION OF METHODS USED TO MEASURE GROUNDWATER FLOW AND TRANSPORT CHARACTERISTICS IN CLAYEY DEPOSITS AT TWO SITES IN ESSEX COUNTY, ONTARIO

by

Timothy Gordon Orpwood

A Thesis submitted to the
Faculty of Graduate Studies and Research
through the Department of Geology in
Partial Fulfillment of the requirements for
the Degree of Master of Applied Science
at the University of Windsor

Windsor, Ontario, Canada
1984

ABSTRACT

The objective of this study was to use conventional laboratory and field methods to measure a) the hydraulic conductivity of clayey soils and b) a tracer transport rate for comparison with the groundwater flow rate. The distribution of the environmental isotopes, tritium and oxygen-18 was also examined to ascertain if there was consistency with the measured transport rate.

Two locations in Essex County, Ontario, Canada, characterised by differing soil and hydrogeological environments were selected as sites for groundwater monitoring and sampling installations. Boreholes were drilled to determine the soil stratigraphy at each site. A test site located in the western part of the City of Windsor is underlain by a deposit of varved lacustrine silty clay, which overlies an extensive deposit of glaciolacustrine silty clay. A test site located near the town of Woodslee is underlain by silty clay till, fractured to a depth of at least 10 metres.

The water table at both sites is shallow, less than 1.5 metres below grade, and the horizontal component of hydraulic gradient was found to be in the range of 0.002 to 0.004. Horizontal groundwater flow direction is consistent with surface drainage orientation. The vertical components of hydraulic gradient were determined to be in the range 0.05 to 0.07. The West Windsor test site is located in a discharge area and the Woodslee test site is located in a recharge area. The lacustrine silty clay has a horizontal hydraulic conductivity in the range of 4×10^{-8} to 5×10^{-8} cm/sec with a ratio of horizontal to vertical conductivity in the range of 1.6 to 3.3. The hydraulic conductivities of the glaciolacustrine silty clay and silty clay till deposits are isotropic and in the range of 2×10^{-8} to 8×10^{-8} and 1.5×10^{-8} to 15×10^{-8} cm/sec respectively. The bulk hydraulic conductivity of the fractured silty clay till is as much as an order of magnitude greater than the hydraulic conductivity of the intact silty clay till. Laboratory permeameter tests were used to measure accurately the hydraulic conductivity of the glaciolacustrine silty clay. Secondary permeability in the lacustrine silty clay and the silty clay till deposits has resulted in in situ measured hydraulic conductivities an order of magnitude greater than the values obtained in the laboratory.

On the basis of measured porosities, hydraulic gradients and hydraulic conductivity values, the average linear groundwater velocity in the silty clay deposits was determined to be in the range of 0.25 to 3 cm/year. Borehole dilution tests measured the apparent average linear velocity of a transported sodium chloride tracer in the range of 36 to 99 cm/year. Substances transported in the groundwater at the two test sites travel at rates dependent on the advection and diffusion characteristics of the silty clay media. The distribution of tritium and oxygen-18 in the silty clay soils beneath the two sites are discussed with reference to these transport mechanisms.

ACKNOWLEDGEMENTS

I wish to express my gratitude to Professor Michael Sklash for the guidance and insight that he has provided throughout the course of this work. He has been all of advisor, critic and friend. I also wish to thank Professors P.P. Hudec, F. Simpson and C. MacInnis for the time that they have graciously spent for the readings, revisions and grading of this work.

Were it not for the encouragement and co-operation of Mr. Nicholas Sitar, P.Eng. I would never have returned to university. As my employer, he allowed me the time to carry on with this research though in many instances this has greatly affected his own schedules and work load. When the University of Windsor did not have specialized soil laboratory equipment or my access to the University's equipment was restricted for various reasons, Dominion Soil Investigation Inc. has provided laboratory space and the use of such equipment without charge.

Mr Brian Cyr demonstrated the best of his drilling skills for the installation of the observation wells. Miss Yvette Sellars supervised the installation of these wells at both of the sites and diligently carried out the majority of the index property testing on the soil samples obtained. Mr. Mitch Obradovic gave his time to help with the field permeability testing at the West Windsor site and Mr. Tom O'Dwyer helped to prepare some of the figures included in this work.

I want to thank the City of Windsor, Public Works Department and Messrs Lou Romano and Bill Newman of the West Windsor Sewage Treatment Plant, Dome Petroleum Limited and Bob Eccleston, P.Eng., and also Agriculture Canada, Dr. W. Findlay and his staff at the Woodslee Soil Research Centre. Through the co-operation of these organizations and people, test sites were set up.

Words cannot adequately express the value of the contributions of my wife, Pauline, to the completion of this project. She has helped with laboratory equipment, surveying, instrument installations and the preparation of the manuscript. She not only gave of her time and skills but has loaned me the best of her strength and determination when they were most needed and to this end, she has made sacrifices and provided encouragement times uncounted. There is no doubt that without her support this work would neither have started nor been finished.

This study was financed by Supply and Services Canada for Environment Canada through a contract to the Great Lakes Institute of The University of Windsor.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF SYMBOLS

A	cross-sectional area
C	constant of proportionality
C	ion concentration
C_v	coefficient of consolidation
C_o	initial ion concentration
D	diffusion coefficient
F_s	shape factor
F	mass flux
K	hydraulic conductivity
Q	flow
Q_s	flow in well screen
Q_f	flow in formation
T_o	basic time lag
V	volume
a_t	cross-sectional area
a	borehole dilution correction factor
a_v	coefficient of compressibility
e	void ratio
d	characteristic particle size
g	acceleration due to gravity
i	hydraulic gradient
h	hydraulic head
k	intrinsic permeability
l	length
dl	distance
n	porosity
ρ_f	fluid density
p	applied stress
r	radius
t	time

u	fluid viscosity
v	specific discharge
$\underline{v}$	average linear velocity
v_a	apparent average linear velocity
v_d	apparent average linear velocity due to diffusion
v_k	apparent average linear velocity due to density convection
v_m	apparent average linear velocity due to mixing
v_s	apparent average linear velocity due to vertical currents
x	length
dx	distance
γ_w	unit weight of water
δ	delta units
o/o	per cent
o/oo	per mille
SMOW	standard mean ocean water
TU	tritium unit
uS	microsiemens

1.0 INTRODUCTION

As part of a study by the Great Lakes Institute of the University of Windsor, soil samples were obtained and groundwater monitoring equipment installed at two test sites in the Essex County area. The study "A Case Study of Selected Toxic Contaminants in the Essex Region", has the objective of determining the environmental distribution of two trace metals, lead and cadmium, and two organic substances, polychlorinated biphenyls and octachlorostyrene.

There is little detailed hydrogeological information available concerning the silty clay soils that predominate in this area. Water wells penetrate these clayey deposits as far as the bedrock aquifer, generally 20 to 40 metres beneath the ground surface. It is important to understand the extent to which contaminant substances can penetrate deposits which have been considered to be effectively impermeable.

The objective of this study was to obtain detailed hydrogeologic information in the deposits of the clayey soil that underlie the two study sites. This work includes a review of the available information for this area, a detailed investigation of the soil conditions at both of the study sites and monitoring of the groundwater levels to determine the hydraulic gradient and direction of groundwater flow. Conventional laboratory and field methods were used to measure the hydraulic conductivity of the silty clay soils and the results were examined to determine the reproducibility of the tests.

The rate of tracer transport in the silty clay soils was measured and compared to the groundwater flow rate. The validity of the tracer transport rate has been assessed by evaluation of the consistency of this measured rate, with the observed distribution of oxygen-18 and tritium in the soils beneath the test sites.

2.0 STUDY SITES

Essex County is located in Southwestern Ontario and contains the most southerly land in Canada. The county is bounded by Lake St. Clair to the north, the Detroit River to the west, and by Lake Erie to the south. Kent County lies directly to the east of Essex County.

Sites were selected which to allow for representation of an urban and a rural area. It was also the intent that the two sites of study would be representative of differing hydrogeologic environments.

2.1 Site Locations

The locations of the test sites are indicated on the Test Site Location Plan (Figure 2.1). The sites offer differing soil and hydrogeological environments and because it is proposed to use the monitoring installations installed at these sites for further work that will last up to four years, it was necessary to select locations that provided a measure of security and constancy of land ownership.

Test Site No. 1 was located at the Woodslee Soil Research Station, owned and operated by Agriculture Canada. The property of the soil research station is less than 2 kilometres west of the town of Woodslee, south of Essex County Road No. 46 and west of Maidstone Township Concession Road 18-19. The property is rectangular, approximately 600 by 650 metres, in plan area.

Test Site No. 2 was located on two parcels of land within the City of Windsor. One of these parcels is owned by the City of Windsor Department of Public Works and the other by Dome Petroleum Limited. The Dome Petroleum Limited property lies west of Matchette Road, south of Carmichael Road and is bounded by the E.C. Row Expressway

TEST SITE LOCATION PLAN Scale 1:1250

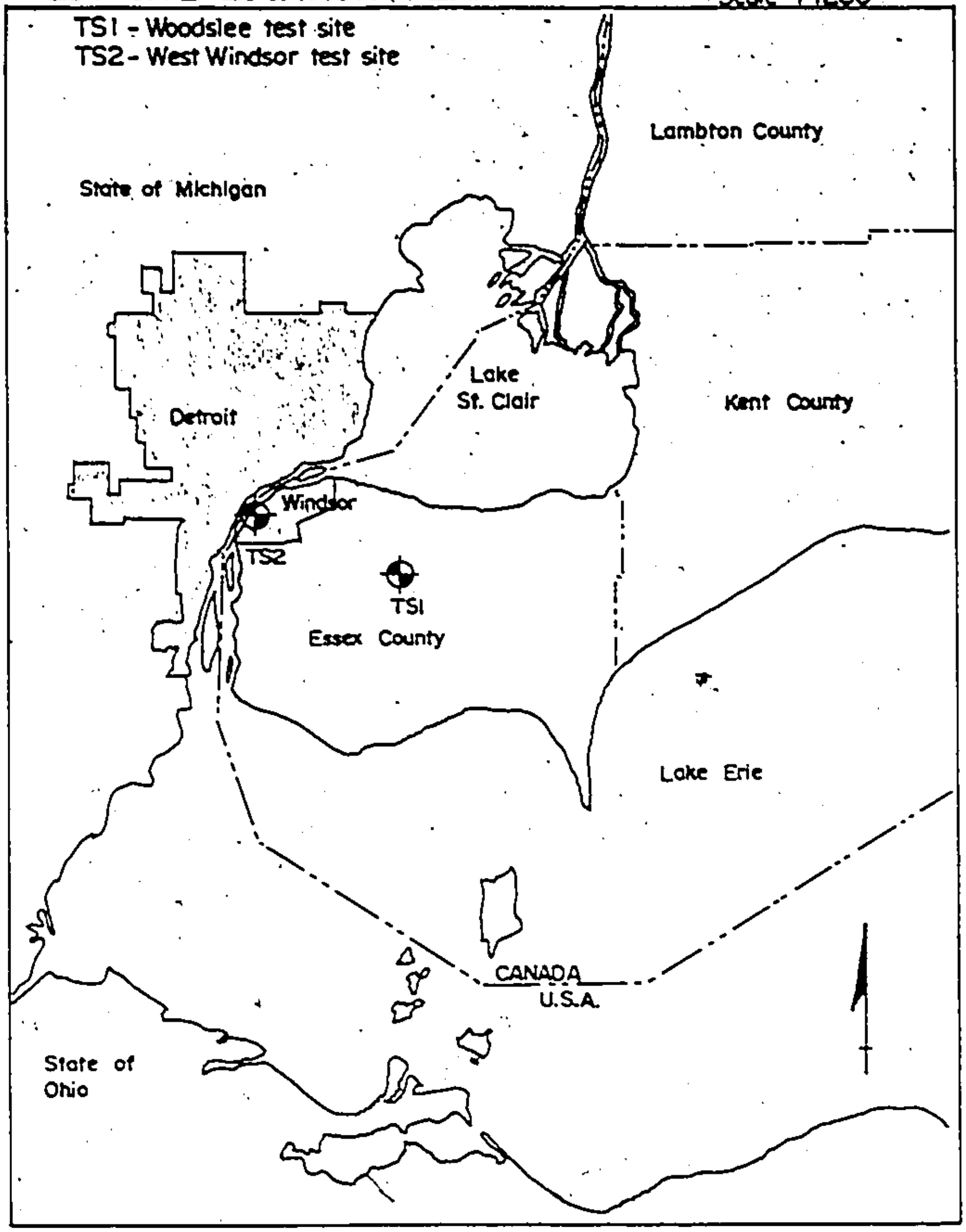


FIGURE - 2.1

and the Essex Terminal Railway R.O.W. (right of way) to the south and west respectively. The West Windsor Pollution Control Plant operated by the City of Windsor Department of Public Works is immediately west of the Essex Terminal Railway R.O.W. and is bounded to the west by the Ojibway Parkway.

2.2 Physiography

The test sites of this study are located in an area generally described as the St. Clair Clay Plain (Chapman and Putnam, 1966) which covers parts of Essex, Kent and Lambton Counties. The area has little relief with the exception of some isolated moraine deposits located in the southern portions of Essex and Kent Counties. The relative levelness of the region provides for very low gradients in the surficial drainage channels and water divides are often indistinct (Chapman and Putnam, 1966). The locations of the Woodslee and West Windsor test sites with reference to the areas of surficial drainage are plotted on the drawing Essex County - Drainage Basins (Figure 2.2) after Allendorf (Ontario Ministry of the Environment 1981).

2.2.1 Woodslee Test Site

The Woodslee test site is typical of the Essex clay plain portion of the St. Clair Clay Plain region as described by Chapman and Putnam. The site occupies a portion of a till plain in the Belle River drainage basin and is separated in an east-west direction by a single drainage ditch with an invert 2 to 3 metres beneath the prevailing level of the ground surface. With the exception of an area approximately 150 metres square located in the southwest corner of the site, the imperfect drainage of the area has been augmented by tile underdrains that empty into the ditch.

ESSEX COUNTY - DRAINAGE BASINS

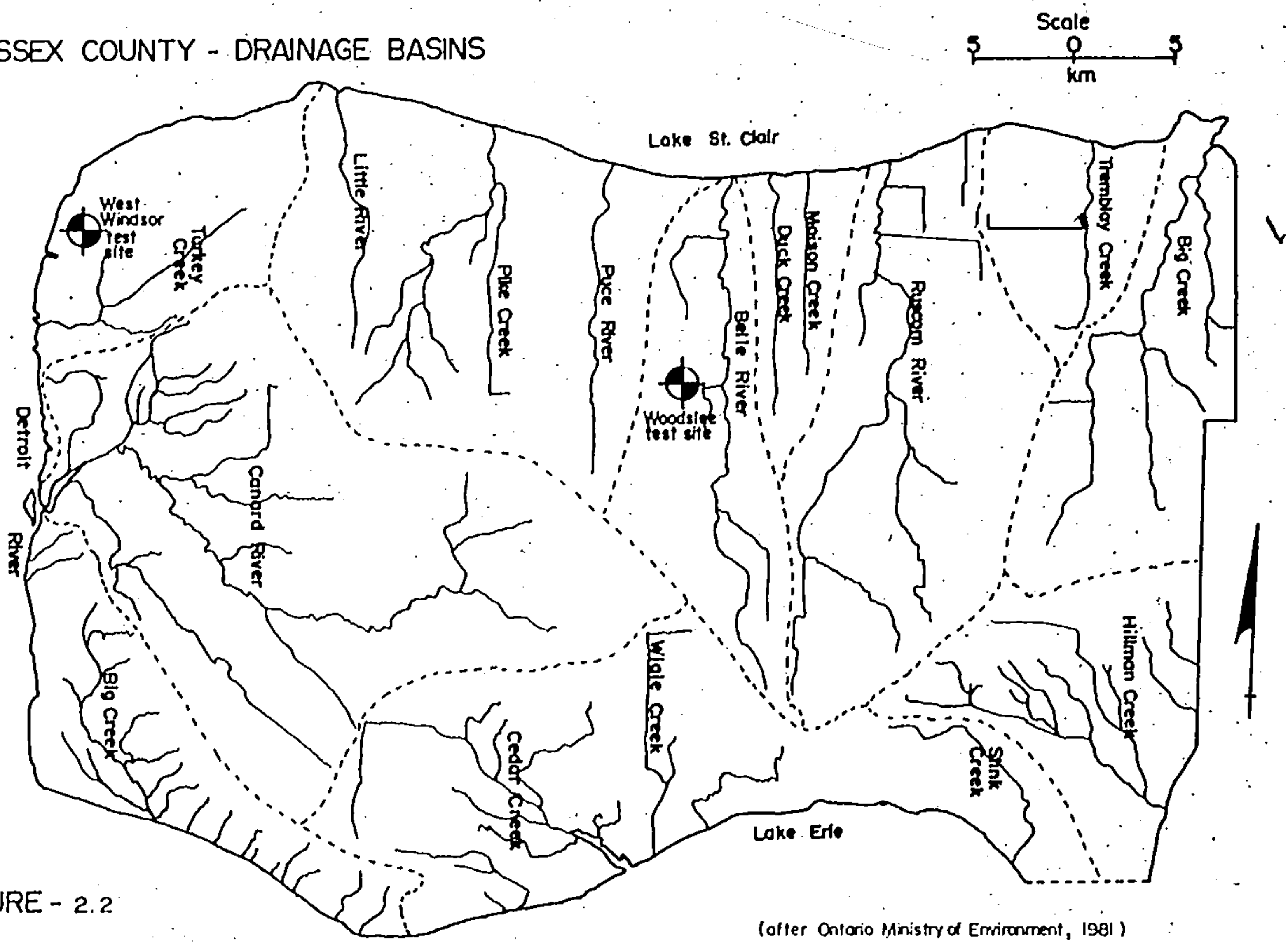


FIGURE - 2.2

(after Ontario Ministry of Environment, 1981)

The site lies within a large agricultural area where crops of corn, soybeans, and winter wheat are commonly grown. In use as an agricultural soil research centre since 1946, the test site is cultivated in distinct plots separated by avenues of sod.

2.2.2 West Windsor Test Site

The West Windsor test site lies in the western fringe of the Essex clay plain and has a gently rolling ground surface. The ground elevation across the site varies by approximately 4 metres. The grade elevation in this area adjacent to the Detroit River is generally at a lower elevation than is common over most of the county area. Typical of the clay plain region, this area is poorly drained and is loosely included in the Turkey Creek drainage basin as plotted by Allendorf (Ontario Ministry of the Environment, 1981). The Dome Petroleum Limited portion of the site is subject to seasonal flooding in some areas. Drainage where provided, is accomplished with shallow ditches that have inverts less than 1 metre below the surrounding grade. The West Windsor Pollution Control Plant site has been levelled by the application of fill but is generally at a lower elevation than the Dome Petroleum Limited site. The construction of catch basins attached to the municipal sewage system essentially controls the surface drainage in this area.

The West Windsor site is located in an urban area in which there is diverse use of the available land. To the north and south of the test site are park land and residential developments. Immediately to the east of the test site on the opposite side of Matchette Road lies the West Windsor Landfill Site. This landfill which is in its final stages of contruction rises approximately 30 metres above the level of the surrounding areas. The test site is a portion of, and is bounded to the west by, land that is used essentially for industrial developments. The Dome Petroleum Limited site is partially occupied by three large brine ponds. This brine is used to displace petroleum products stored in underground salt caverns approximately 300 metres below in the bedrock. There are no active lagoons at the West Windsor Pollution Control Plant. The waste is generally contained and processed in concrete tankage.

2.3 Geology

The Essex County area is generally underlain by limestone, dolostone, and shale deposits of Middle Devonian age, which are mantled by thick deposits of Pleistocene and Recent sediments (Vagners, 1972a and b).

2.3.1 Paleozoic Geology

A deposit consisting of grey brown calcilutite; massive coraline bioclastic limestone; and light brown stromatolitic calcerenite labelled as the Lucas Formation of the Detroit River Group (Telford and Russell, 1981) underlies the southern portion of Essex County and a 1.6 to 3.2 kilometre (1 to 2-mile) wide strip of land along the western edge of the county (Vagners, 1972a and b). The West Windsor test site of this investigation is located above bedrock of the Lucas Formation in this strip of land.

Brown cherty crinoidal limestone of the Dundee Formation overlies the Lucas Formation deposits and constitutes the bedrock for the majority of the northern portion of Essex County (Telford and Russell, 1981). The limestone of the Dundee Formation is mapped as the bedrock underlying the Woodslee test site of this investigation.

2.3.2 Quarternary Geology

The Ontario Division of Mines of the Ministry of Natural Resources has prepared maps of the Windsor-Essex area indicating the thickness of Quarternary 'drift' which covers the bedrock (Vagners <u>et al.</u>, 1973a and b). These maps are based on available water well records, boreholes for petroleum exploration and seismic records. These maps indicate that the

Quarternary deposits at the West Windsor and Woodslee test sites are of the order of 30 and 37 metres thick respectively.

Published water well records (Ontario Ministry of the Environment, 1977) indicate two wells in the area of the West Windsor test site which encountered limestone bedrock at depths of 33 and 35 metres below grade respectively. The records of two wells drilled at the Woodslee Soil Research Centre indicate that limestone bedrock was encountered at a depth of 37 to 37.5 metres below the ground surface.

2.3.2.1 Woodslee Test Site

Vagners (1972b) indicates that the drift in the area of the Woodslee test site is a clayey silt till of Wisconsinan age that is the most common Quarternary sediment in the region. The Wisconsinan till material is also the oldest of the 'drift' deposits that have been mapped in the Essex County area. Vagners notes that this material, "exhibits structures, lithologies that may indicate a waterlaid origin," and some portions of the deposits which have a till-like appearance may have been formed in a series of glacial lakes which inundated the Essex region after the retreat of the Wisconsinan glaciation, in which case these sediments would be described as glaciolacustrine.

The agricultural soil survey of Essex County (Experimental Farms Service, 1947) indicates the Woodslee test site is within an area mapped as underlain by "Brookston Clay". The Brookston Clay soil profile is described as having poor natural drainage and a fairly high organic matter content in the surface soil. A detailed soil map of the Woodslee test site (Experimental Farm Service, 1946) confirms that the site is predominantly underlain by a Brookston Clay profile however it does contain local areas covered by thin deposits of sand and sandy loam, 150 to 450 mm thick. A typical Brookston Clay profile consists of 150 to 200 mm of dark grey brown silty clay, 150 mm of grey drab silty clay with yellow brown mottlings, and 450 to 600 mm of grey silty clay with yellow brown mottlings underlain by heavy calcareous brown silty clay till (grey to light grey) containing shale and limestone fragments. Water well records (Ontario Ministry of the Environment, 1977) indicate the brown silty clay till (yellow clay) extends to depths of 4.5 to 9.0 metres below grade at the Woodslee test site. Beneath this level the silty clay till becomes grey (blue clay) and extends to depths of 34.5 to 36 metres below grade. The silty clay till is separated from the limestone bedrock by 1 to 2 metres of coarse sand and gravel at the Woodslee site.

2.3.2.2 West Windsor Test Site

Following the last of the glacial lakes and prior to the time of Early Lake St. Clair, the Lake St. Clair basin was occupied for a short period by Lake Rouge (Vagners, 1972a). Lake Rouge deposited gravel, gravelly sand and medium sand found in the area of the West Windsor test site.

Agricultural soil mapping in the West Windsor site area (Experimental Research Farms, 1947) designates the surface of the Lake Rouge deposits as the Granby and Berrien Sands. The surface of these sand deposits typically consist of 100 to 150 mm of brown to grey brown sandy loam, poorly drained and high in organic material. This surface layer is underlain by approximately 750 mm of yellow brown or grey sand overlying grey calcareous sand. Silty clay till is encountered beneath the sand at a depth of 1 to 2 metres. Water well records (Ontario Ministry of the Environment, 1977) from this area indicate that the clayey material extends to the bedrock surface, at 33 to 35 metres below grade.

2.4 Hydrogeology

Published information concerning the hydrogeology of a region is generally available in the form of water well records. In the Essex County area about eighty per cent of the recorded wells are terminated in the bedrock (Ontario Water Resources Commission, 1971). Since the majority of the sediments above the bedrock are fine-grained silty clay till and glaciolacustrine material it is not surprising that water supplies are generally derived from the bedrock and information concerning the shallow hydrogeology is sparse.

Some domestic water supplies are obtained from storage in large diameter wells in the silty clay deposits but the yield is generally low. The available information concerning the hydrogeology of the surficial Quarternary age deposits is described by Allendorf (Ontario Ministry of the Environment, 1981) as follows:

> "Groundwater movement through the surficial materials in the study area is slow due to the hydraulic gradient imposed on the ground water by the relatively flat topography. Areas . . . associated with permeable glaciofluvial/glaciolacustrine deposits increase the groundwater gradient locally. Most of the area is underlain by poorly permeable materials (till/silt/clay) and in conjunction with the low hydraulic gradient, the water table is generally found close to the land surface."

Desaulniers et al. (1981), studied the hydrogeology at four sites in Southwestern Ontario underlain by thick deposits of clayey till and glaciolacustrine clay. One of these sites was near Woodslee. It was concluded from this study that the rate of groundwater movement in the clayey deposits was very slow (0.13 to 0.26 cm/year) as substantiated by the assessment of an age of at least 8000 years for the groundwater sampled in the deeper portions of the deposits.

3.0 THEORETICAL CONSIDERATIONS

In order to plan a hydrogeological investigation project, to select the optimum monitoring locations, and design instrumentation that will provide the most information at the least possible cost, it is necessary to consider the theoretical aspects of groundwater flow. The characteristics of soil moisture movement, the limitations of conventional testing procedures, an the parameters affecting the transport of material dissolved in the groundwater are important to the objectives of this study.

3.1 Soil Moisture Migration

The moisture that fills the voids in a saturated soil migrates from areas of high energy potential to areas of low energy potential and energy is lost during this migration owing to viscous resistance on the surfaces of the individual solid soil particles. With the exception of soils containing large openings or fractures, moisture movement is very slow and has laminar flow characteristics.

3.1.1 Hydraulic Gradient

The rate of energy dissipation in the soil by the migrating moisture per unit weight of water, per unit of distance travelled is the 'hydraulic gradient' designated 'i' and it can be demonstrated that the hydraulic gradient of a flow system is equal to the variation in the 'hydraulic head' designated 'h' over a distance 'dl' such that:

$$i = dh/dl \qquad (1)$$

and is dimensionless.

3.1.2 Specific Discharge

In a homogeneous isotropic soil of cross-sectional area, 'A', perpendicular to the direction of moisture migration, subject to a uniform flow, 'Q', the 'specific discharge' designated 'v' is the flow per unit area:

$$v = Q/A \tag{2}$$

The specific discharge has the units of velocity but it is actually a macroscopic property of a soil flow system.

Darcy demonstrated in 1856 that the specific discharge of a flow system is proportional to the hydraulic gradient intrinsic to the system. Darcy's law was formulated on this basis as:

$$Q = -KAdh/dl \tag{3}$$

A constant of proportionality, designated 'K', and known as the 'hydraulic conductivity' of the soil is included and a negative sign adopted to signify the flow takes place from an area of high potential to an area of low potential.

3.1.3 Hydraulic Conductivity

The hydraulic conductivity is a specific property of a soil flow system that is proportional to the characteristic size of the soil particles 'd' and the density of the fluid ' ρ ' and inversely proportional to the viscosity of the fluid 'u', such that:

$$K = Cd^2 \rho g/u \tag{4}$$

where 'C' is a constant of proportionality and 'g' is the acceleration due to gravity. Whereas the factors ' ρ ' and 'u' are functions of the fluid in the system the factor 'Cd^2' is a function of the soil medium that is designated 'k', the permeability of the medium. Thus:

$$K = k \rho g/u \qquad (5)$$

It can be seen from these equations that the permeability of a medium 'k' will have the dimensions of area while hydraulic conductivity 'K' will have the dimensions of velocity.

In most natural groundwater flow systems the fluid involved is usually water which will vary only slightly in density and viscosity because of temperature or dissolved minerals. Therefore in the flow systems of this study the principal variation in measured hydraulic conductivity is a function of the intrinsic permeability of the soil medium.

3.2 Evaluating Hydraulic Conductivity

Several procedures and a number of different pieces of apparatus have been developed to assess the intrinsic permeability of soil samples and the hydraulic conductivity of related flow systems. Similarly there is a variety of approaches for the assessment of the hydraulic conductivity of in situ flow systems.

3.2.1 Empiric Estimation of Hydraulic Conductivity

The intrinsic permeability of a soil medium (k) as represented in the form Cd^2 has long been used to relate grain size to permeability and subsequently hydraulic conductivity. A long-standing relationship attributed to Hazen sets 'd' equal to the mean or effective grain diameter of the soil. Effective grain diameter is often noted as 'd_{10}' where d_{10} is that diameter where 90% of the soil sample is coarser by weight. 'C' is a dimensionless parameter dependent on the units of measure, the grain-size distribution, grain shape and packing arrangement. The Hazen approximation was originally developed for uniformly graded sands but the approximation can be extended to soil ranging in grain size from fine sand to gravel (Freeze and Cherry, 1979).

Refinements of the relationship between grain size and intrinsic permeability have been suggested by several authors. The Kozeny-Carmen equation (Bear, 1972) replaces the parameter 'C' of the Hazen approximation with a porosity relationship based on the premise that the porosity of a soil is an inherent measure of the grain size, grain shape, and packing arrangement. The Fair-Hatch equation (Todd, 1959) introduces separate packing and shape factors in addition to the porosity relationship of the Kozeny-Carmen function.

These relationships are useful to provide rough estimates of the permeability of non-cohesive soils and can also estimate the hydraulic conductivity of soil/fluid systems when terms for the fluid properties, density and viscosity are incorporated in the equations. These relationships break down when applied to soils in which the predominant soil components are cohesive silt and clay. The essence of this breakdown is the inherent porosity relationships associated with cohesive and non-cohesive soil types. The majority of the porosity of a granular soil is 'interconnected' porosity. The nature of non-cohesive soil grains is such that they do not nest in a way that will entirely contain and close a pore space. Conversely plate-like clay particles and their associated envelopes of bound water, form a soil with a substantial amount of unconnected pore space. Relationships which relate decreases in pore space with decreases in permeability are not applicable to cohesive soils. The increase in porosity of a cohesive soil is related to an increase in clay mineral content and an increase in clay mineral content decreases the interconnected porosity. Interconnected porosity is the only component of porosity that influences soil permeability.

3.2.2 Constant Head Permeameters

In a constant head permeameter one end of a saturated soil sample of fixed length (l) and cross-sectional area (A) is exposed to a head of fluid controlled at a constant level relative to the sample. Seepage through the sample takes place at a steady rate under the influence of the gradient established in the sample if the level of fluid leaving the sample is controlled at a constant and lower level relative to the sample. The flow of fluid (Q) through the sample is determined by the direct measure of the volume of fluid passed through the sample in a fixed period of time.

A direct application of Darcy's Law indicates that the hydraulic conductivity of the system (K) is equal to the measured flow divided by the fixed fluid head differential (h), adjusted by the ratio of the sample length to cross-sectional area, such that:

$$K = Ql/Ah \qquad (6)$$

Where the test specimen consists of a fine-grained soil, a substantial period of time would be associated with collecting a significant measurable volume of fluid through the sample with all practical reservoir arrangements that maintain a constant head differential. The constant head permeameter is therfore impractical as a tool for evaluating the hydraulic conductivity of fine-grained soil in this simple form.

3.2.3 Variable Head Permeameters

In a variable head permeameter the sample of soil is similarly constrained with a fixed length (l) and cross-sectional area (A). Fluid is introduced to the sample from a standpipe of significantly smaller cross-sectional area (a_t). Whereas the fluid level at the end of the sample opposite the standpipe is controlled at a constant level, the fluid level in the standpipe is allowed to fall. The rate of the fluid level decrease in the standpipe is measured to determine the time difference between the start of the test ($t_o = 0$) and some stage of the test, time (t_1), where the head differential on the sample has altered from h_o to h_1. As a result of decreasing head differential, the flow through the sample also decreases. The flow in the standpipe is given by:

$$dQ = -a_t \, dh \tag{7}$$

and the equal flow through the soil sample is given by:

$$dQ = KAh \, dt/l \tag{8}$$

equating these expressions and separating variables:

$$KA \, dt/l = -a_t \, dh/h \tag{9}$$

integration of this expression for 't' from 0 to t_1 and 'h' from h_o to h_1 and rearranging terms:

$$K = a_t l/At_1 \times \ln(h_o/h_1) \tag{10}$$

A variation of the variable head permeameter apparatus, the pressure permeameter was used to test samples for this study. A schematic diagram of this device is presented in Appendix E. In a pressure permeameter the fluid head difference on the sample is increased by pressurizing the fluid entering the end of the sample opposite the standpipe such that the hydraulic gradient through the sample is substantially increased and a significant flow is measured in the standpipe by the determination a_t/t_1 in a relatively short period of time. The difference in total applied head differential ($h_o - h_1$) is very small compared to the applied head differential. In this case the average head differential during the time t_o to t_1 can be substituted for ln (h_o/h_1) with no significant error and the test approximates a constant head flow system such that:

$$K = a_t/t_1 \times 1/A \times (h_o - h_1)/2 \qquad (11)$$

3.2.4 One Dimensional Consolidation

The behaviour of a soil mass subjected to an increase in loading is variable with time. The water in the pore spaces of the soil is essentially incompressible and this water initially supports the load increase in total. There is an increase in the pressure on the water in the pores of the soil of a magnitude equal to the applied increase in pressure. This "excess pore water pressure" provides for a hydraulic gradient between the loaded volume of soil and an unaffected volume of soil at some distance. With the passage of time pore water will migrate under the influence of this hydraulic gradient and there will be dissipation of the excess pore water pressure. As the excess pore water pressure dissipates, the solid particles of the soil support the loading transferred from the pore water. This process is known as "consolidation".

Under a given incremental load increase, pore water will migrate from the loaded soil volume until the entire excess load increment is supported by the solid skeleton of the soil particles and equilibrium of pore water pressure with the surrounding unloaded soil is re-established. The equilibrium state coincides with the total dissipation of the excess pore water pressure. The rate of consolidation in a soil is directly related to the hydraulic conductivity of the soil because the hydraulic conductivity governs the rate that excess pore water pressure can be dissipated in the soil.

The one-dimensional consolidation characteristics of a soil are measured in an odeometer apparatus. The soil sample is placed in a cell where the sample is laterally confined by a ring. The unconfined ends of the sample are drained by porous stones and provision is made to axially (one-dimensionally) apply load increments to the sample. These load increments are conventionally applied by a system of weights and levers. For this study an odeometer that employs an air piston to load the samples was used. A schematic diagram of this apparatus is presented in Appendix E.

Following the application of a load increment to the laterally confined sample, the thickness of the sample decreases and the rate of change of the sample thickness is measured. Assuming the soil sample is saturated prior to loading, this change in the sample thickness represents the total void change and therefore the total volume change of the sample under loading.

As noted previously each increment of load applied to the soil sample has a distinct period of consolidation associated with the dissipation of excess pore water pressures induced by the load increment. By measuring the rate of change of sample thickness the consolidation period for a particular load increment can be assessed. A factor designated the "coefficient of consolidation" (C_v) relating the volume change of the sample to time is computed after the methods described by Lambe (1951).

When a sample is subjected to a series of incremental load increases there is a sample void ratio associated with the end of consolidation at each load increment. The relationship between this void ratio and the loading on the sample is non-linear and is described by the "coefficient of compressibility" (a_v) such that:

$$a_v = -de/dp \qquad (12)$$

where 'e' is the void ratio of the soil sample and 'p' is the stress on the sample.

The factors 'C_v' and 'a_v' derived from the consolidation testing of a sample, describe the consolidation characteristics of the sample. These characteristics are dependent on the effective porosity of the soil, the grain size, the grain shape, and the packing arrangement. In effect, the consolidation factors are governed by the same intrinsic soil properties as the hydraulic conductivity of the soil such that the hydraulic conductivity (K) can be derived from these factors by:

$$K = C_v \, a_v \, \gamma_w / 1 + e \qquad (13)$$

where γ_w is the unit weight of the water in the soil.

The compressibility of the soil is dependent on the state of stress in the soil and the coefficient of consolidation is dependent on the stress history of the soil. The hydraulic conductivity value derived from these coefficients is therefore variable with the state and history of stress in the sample tested. The extrapolation of hydraulic conductivity values obtained in the laboratory to field conditions must therefore account for the *in situ* stress conditions.

3.2.5 Three-Dimensional Consolidation

A sample of soil can be consolidated three-dimensionally in a triaxial test cell where the increase in pressure on the membrane covered test sample is applied by a pressurized fluid. Since there is no single direction of shrinkage associated with the volume change of the sample due to consolidation, it is necessary to collect and measure the pore water leaving the sample to determine the consolidation parameters. The relationships established between hydraulic conductivity and the coefficients of consolidation and compressibility are equally applicable to three dimensional consolidation. The conditions of a three-dimensional consolidation test have to be established in such a way that the drainage avenues of the pore water are distinctly defined if the coefficient of consolidation is to be correctly evaluated.

As is the case for the use of one dimensional consolidation tests to evaluate hydraulic conductivity, it is necessary to evaluate the state and history of stress in the test sample if the laboratory hydraulic conductivity determination is to be used to assess in situ conditions.

3.2.6 Single Well Response Testing

Hvorslev notes in the introduction to his paper 'Time Lag and Soil Permeability in Ground-Water Observations' (Hvorslev, 1951), that the hydrostatic pressure in a borehole or a pressure measuring instrument such as a piezometer, is seldom equal to the in situ pore water pressure at the time of augering or the installation of the device. It is after the hole or the device is in place that a flow of water takes place to equalize the pressure in the instrument with the in situ hydrostatic pressure. Hvorslev designated the period required for the elimination of this pressure differential as the "time lag". The magnitude of the time lag for a particular borehole, piezometer or other pressure measuring device is dependent on the geometry of the installation and the hydraulic conductivity of the soil surrounding the instrument.

Since it is possible to alter the level of the water in a standpipe or piezometer after it has initially achieved equalization with the hydrostatic level of the surrounding soil, and the geometry of the instrument is known, then a mechanism is available for the in situ assessment of the hydraulic conductivity of the soil surrounding the device. This type of in situ hydraulic conductivity testing is known as single well response testing.

Increasing or decreasing the hydrostatic pressure inside a piezometer can be accomplished by adding or removing fluid respectively. Alternatively a solid cylinder introduced to the piezometer will raise the fluid level in the piezometer and the pressure in the instrument. If this solid 'slug' is left in the piezometer, the hydrostatic pressure in and around the instrument will again equalize. At this time the withdrawal of the 'slug' will have the same effect as the bailing of water from the instrument. These two variations of the single well response test are consquently described as 'slug' and 'bail' tests respectively.

Hvorslev assumed a homogeneous isotropic medium in which soil and water are incompressible. For the relatively small pressure differentials generated during a single well response test the compressibility characteristics of the soil and pore water are negligible.

If 'H' is the static piezometric head measured in an observation well and this head is 'instantaneously' lowered to a piezometric head of 'h', then Hvorslev noted that the flow 'Q' into the well screen at time 't' is proportional to the hydraulic conductivity 'K' of the soil surrounding the screen and the unrecovered head difference 'H - h' such that:

$$Q(t) = \pi r^2 \, dh/dt = F_s K \ (H-h) \qquad (14)$$

where 'r' is the diameter of the observation well and 'F_s' is a shape factor associated with the geometry of the observation inlet. Equation (14) similarly applies when a static piezometric head measured in the observation well, 'h' is raised 'instantaneously' to piezometric head 'H'.

In both instances it is apparent that Q(t) will decrease at a decreasing rate with increasing time, since the head differential that drives the system decreases in magnitude with increasing time. Hvorslev defined the "basic time lag" (T_o) as:

$$T_o = \pi r^2 / F_s K \qquad (15)$$

where 'T_o' is the time that would be required for the equalization of the initial head difference if the initial rate of flow to the well was constant and:

$$T_o = V/Q_o \tag{16}$$

where 'V' is the volume of water initially removed or added to the well. Freeze and Cherry (1979) describe in detail a simple method to determine 'T_o' from the piezometer recovery data. Hvorslev (1951) evaluated the shape factor 'F' for a variety of piezometer arrangements and the arrangement applicable to the work carried out in this study is that of a piezometer of given length (L) and radius (R) such that L/R is greater than 8. In terms of 'T_o', the hydraulic conductivity of the soil surrounding the well screen is computed by:

$$K = r^2 \ln(L/R)/2LT_o \tag{17}$$

3.3 Evaluation of Groundwater Flow Velocity by Tracer Transport

As previously discussed groundwater migrates from areas of high hydraulic energy potential to areas of lower hydraulic energy potential. Under this energy gradient there is a specific discharge (v) of the flow system as defined in equation (2). Specific discharge has the dimensions of velocity but is a macroscopic property of the flow system, differing substantially from the actual velocity of the water molecules travelling between the solid soil particles. Since the soil is actually comprised of solid particles and void spaces, only that portion of a soil cross section occupied by the void spaces actually supports the flow of moisture through the soil.

3.3.1 Average Linear Velocity

The soil porosity (n) is a convenient measure of that portion of the cross sectional area occupied by void spaces. Combining this concept with equation (2) defines the "average linear velocity" ($\underline{v}$) of the moisture in the soil mass such that:

$$\underline{v} = v/n = Q/nA \tag{18}$$

or from equation (3):

$$\underline{v} = -K\, dh/n\, dl \tag{19}$$

Average linear velocity can be characterised as that velocity at which an average molecule of water would move in a straight line path through a soil mass. Like specific discharge, average linear velocity is a macroscopic property of a soil flow system. Water molecules migrating through a soil mass take a tortuous path between the individual soil grains. Since a water molecule migrating through the soil pore spaces will generally travel a greater distance than a straight line path to travel between two points, the majority of the water molecules in the soil will have actual intergranular velocities in excess of the average linear velocity of the flow system.

It would be effectively impractical to attempt to determine actual molecular velocities in the soil flow system, but the average linear velocity is an effective concept to quantify the transport velocity of substances dissolved in groundwater flow.

3.3.2 Tracers

A tracer is a substance that is either added to, or occurs naturally in a flow system so that the detectable movement of this substance in the flow system can be studied to determine the characteristics of the flow system. A tracer can also be used to determine the characteristics of the flow of a substance dissolved in the groundwater flow system.

An ideal tracer is easily detectable in small quantity, and transported in the groundwater flow system in the same way as the natural groundwater, if the purpose of the tracer testing is the quantification of the groundwater flow parameters. Some substances dissolved in groundwater will substantially alter the density and viscosity of the affected water and subsequently the hydraulic properties of the flow system. A substance introduced as a tracer could also alter the properties of the soil medium or precipitate in the pore spaces of the medium which would also alter the intrinsic permeability of the medium.

A soluble non-reactive substance such as a tracer is transported with the flow of groundwater and this process is called 'advection'. If the tracer does not substantially alter the density and viscosity of the water or the intrinsic permeability of the soil, then the tracer is carried at a rate equal to the average linear velocity of the groundwater. In addition to this simple transport in the direction of groundwater flow, the tracer will spread out in directions essentially perpendicular to the flow direction. The spreading of the tracer substance in the groundwater, 'dispersion', reduces the concentration of the tracer substance with increasing distance from the tracer source.

The dilution effects of dispersion are the result of two processes. A portion of the tracer dilution is the result of mechanical mixing of the tracer molecules with increasing numbers of water molecules in the tortuous flow paths between the solid soil particles. This process is termed 'hydrodynamic dispersion' and is dependent on advection driven by the hydraulic potential energy of the system. The decrease in the concentration of a tracer substance in a soil flow system is also the result of a process called 'diffusion'. Diffusion is independent of advective transport and takes place as a result of the kinetic energy of the tracer molecules.

The diffusion of a dissolved substance takes place at a rate governed by the concentration gradient of that substance 'dC/dt'. Even if there were no hydraulic gradient in the soil (i.e. no flow condition) and therefore no advective transport of a tracer substance, the tracer would disperse in the groundwater until a concentration gradient no longer existed. This concept is aptly described by Fick's first law such that:

$$F = -D\, dC/dx \tag{20}$$

where 'F' is the mass flux, the mass of solute per unit area per unit time, and has the dimensions of mass divided by time and the square of length. 'D' is defined as the coefficient of diffusion and has the dimensions of the square of length divided by time. Diffusion is also a time dependent process as expressed in Fick's second law such that:

$$dC/dt = D\, d^2C/d^2x \tag{21}$$

The electrical conductivity is the measure of a substance's ability to transmit an electrical current. Specific electrical conductance is an indication of the total-dissolved solids (TDS) in groundwater. The greater number of dissolved ions in the groundwater, the greater the conductance. Generally electrical conductance is related to TDS by the expression:

$$TDS = CF \tag{30}$$

where 'TDS' is expressed in mg/l, 'C' is the electrical conductance in microsiemens (uS), and 'F' is a conversion factor that generally has a range of 0.55 to 0.75 (Freeze and Cherry, 1979).

3.3.3 Two-Well Tracer Test Method

The simplest application of a tracer to quantify the characteristics of a flow system is the two-well test method. A tracer substance is injected into the groundwater flow system at one location and the time and concentration of the tracer arriving at another downgradient location is measured. This testing can take two forms, a single finite 'slug' of tracer can be injected at the source point or the tracer can be continuously supplied at controlled concentration. In either case if the direction of groundwater flow is not known then an array of receptor wells is necessary to intercept the tracer contaminated groundwater.

Average linear groundwater flow velocity is determined from the distance of the source to detection location and the measured time of tracer arrival. A typical molecule of the tracer will arrive at a time dictated by the average linear velocity of the soil flow system, but some molecules will arrive sooner and later than the typical molecule, dependent on the particular individual flow path each molecule takes through the soil mass.

For tests where a single finite slug of tracer is injected into the system in can be expected that the concentration of tracer molecules passing through the downstream cross section will be normally distributed with respect to time about that time dictated by the average linear velocity of the flow system.

Where a constant concentration tracer source is used the downstream cross section of the flow system will record increasing tracer concentration after first detection, up to that point where the tracer concentration at the detection point fails to further increase. Since that time corresponds to the arrival at the detection cross section of virtually all of the tracer molecules initially leaving the injection point, the average linear velocity should therefore be determined from some time before the tracer concentration stabilizes. Slichter (1905) suggested the inflection point of the time concentration curve as an indication of that time where a typical tracer molecule has travelled the distance between source and detector.

Whereas tracer curves can be good indicators of average linear velocity irrespective of the magnitude of the concentration peak at arrival, the two-well test is not generally sufficient to quantify the dispersion characteristics of the flow system unless it can be demonstrated that there are no chemical interactions taking place in the soil or groundwater. In general it is necessary to have a considerably more complex testing arrangement to quantify dispersion parameters because few soils are actually homogeneous or isotropic.

3.3.4 Borehole Dilution Test Method

The borehole dilution test method relates the measured rate of dilution of a tracer in a constant volume portion of an observation well to the undisturbed average linear velocity ($\underline{v}$) of the groundwater in the soil surrounding the well screen. The apparent velocity (v_a) of the groundwater flowing through the well screen is described by:

$$dC/dt = -Av_aC/V \qquad (22)$$

where 'C' is the tracer concentration, 't' is time, 'A' is the cross sectional area of flow, and 'V' is the volume of water in which dilution is occurring. If a single 'slug' of tracer is injected into the well at time (t = 0) and concentration 'C_o' and 'C' is the concentration of that tracer at some later time (t) then:

$$v_a = -V/At \times \ln(C/C_o) \qquad (23)$$

The dilution rate of the tracer is the result of several component processes (Drost et al., 1968) and the apparent velocity (v_a) observed, is derived from:

$$v_a = a\underline{v} + v_k + v_s + v_m + v_d \qquad (24)$$

where the coefficient 'a' is a correction factor that takes into account the distortion of the natural groundwater flow path caused by the presence of the observation well. The terms 'v_k', 'v_s', and 'v_m' represent the apparent flow rate caused by density convection, vertical currents, and mixing in the well screen respectively. The term 'v_d' is the apparent flow rate caused by diffusion of the tracer.

The terms 'v_k', 'v_s', and 'v_m' can be eliminated from a borehole dilution test by control of the well geometry and test procedures so that:

$$v_a = a\underline{v} + v_d \quad . \tag{25}$$

Grisak et al. (1977) define the correction factor 'a' as:

$$a = Q_s/Q_f \tag{26}$$

where 'Q_s' is the flow inside the well screen and 'Q_f' is the flow in an equivalent cross sectional area of the undisturbed soil. Drost et al. (1968) provides analytical solutions for the evaluation of 'a'. The expressions are dependent on the permeability of the well screen, sand pack, and the undisturbed formation, as well as the geometry of the well installation. It is noted that some of these parameters are difficult to quantify. Sensitivity analysis of the factor 'a' with respect to these parameters indicates that within certain bounds the analytical expressions for 'a' are relatively insensitive. It is therefore possible to design the observation wells used for this testing in such a way as to control the sensitivity of 'a' so that evaluation is relatively accurate.

The effect of molecular diffusion, associated with the apparent flow rate (v_d) can be disregarded as insignificant if the actual average linear velocity of the groundwater in the soil is greater than 3.5×10^{-4} cm/sec. (Drost et al., 1968). Where '$\underline{v}$' is less than this value, the apparent flow rate due to diffusion must be included in equation 3.3.4.4 such that:

$$\underline{v} = (v_a - v_d)/a \tag{27}$$

3.4 Environmental Isotope Distribution

Most elements exist predominantly in one isotope with only trace amounts of the alternative isotopic configurations. Some of these isotopes are stable, others are radioactive. The abundance of certain isotopes varies in natural groundwater depending on the history of the water and these isotopes can be used to identify different waters and the isotopic signature can sometimes be used to trace water movement. These useful isotopes, naturally occurring in the water cycle are called 'environmental isotopes'.

For the purpose of this work it was decided that measurements would be made of the concentrations of two different environmental isotopes, radiogenic tritium and stable oxygen-18. Tritium was used as an indicator of recent water in the groundwater and oxygen-18 was used for the detection of long term trends in the flow system.

3.4.1 Tritium

Tritium occurs naturally in the atmosphere as the result of the atomic bombardment of nitrogen by cosmic rays. Tritium is a radioactive isotope with a relatively short half life of 12.3 years, but it is not significantly affected by reactions in the water cycle other than radioactive decay.

The tritium content of groundwater is expressed in tritium units 'TU' where 1 TU is equivalent to one atom of tritium in 10^{18} hydrogen atoms.

Prior to 1952 when the first atmospheric testing of thermonuclear bombs occurred, it is estimated that the natural tritium content of rainfall was in the range of 5 to 20 TU (Payne, 1972). During the 1950s and 1960s substantial quantities of tritium were released into the atmosphere. A peak tritium concentration of the order of 5000 TU was measured from rainfall in Ottawa in 1963. The relatively short half life of the tritium has lead to the rapid decrease in tritium concentration since suspension of atmospheric testing. Present tritium concentrations in precipitation are generally in the 50 to 100 TU range.

Tritium is useful in hydrogeological studies as a tracer of 'young' water. If a water sample contains less than 10 TU of tritium then there is assurance that this water entered the groundwater before 1953. However, if the water contains tritium in concentrations of hundreds or thousands of tritium units, then this water is relatively recent.

3.4.2 Oxygen-18

The isotope of oxygen that contains eighteen neutrons, designated '^{18}O', is a stable isotope that constitutes approximately 0.2% of seawater. By comparison ^{16}O constitutes 99.76% of seawater (Perry and Montgomery, 1982).

The variation in ^{18}O content (δ^{18}O) in water is expressed as enrichment or depletion of this isotope with respect to ^{16}O. This variation is measured as parts per thousand (^{o}/oo) difference from the standard ^{18}O to ^{16}O concentration ratio designated SMOW (Standard Mean Ocean Water) such that:

$$\delta^{18}O = \left(\frac{(^{18}O/^{16}O)\text{sample}}{(^{18}O/^{16}O)\text{SMOW}} - 1\right) \times 1000\,^{o}/oo \qquad (28)$$

Oxygen is fractionated by evaporation and precipitation in the water cycle, such that the evaporation and condensation of ocean water as precipitation results in the depletion of the water in the heavier ^{18}O atoms and δ^{18}O is negative.

The quantity $\delta^{18}O$ is affected by the temperature of condensation. Individual precipitation events at any location will have significant variations in $\delta^{18}O$ dependent on the prevailing temperature conditions, but the groundwater recharged by combined yearly precipitation will tend to have a $\delta^{18}O$ value consistent with the average temperature (t_a) of the area such that the mean $\delta^{18}O$ ($\delta^{18}O_m$) is related to the mean annual air temperature in degrees Celcius (t_a) by the expression:

$$\delta^{18}O_m = 0.695t_a - 13.6 \qquad (29)$$

(Dansgaard, 1964).

If there is a consistent trend toward enrichment or depletion of oxygen-18 in the porewater of a soil profile then this change in $\delta^{18}O$ is indicative of a variation in mean annual air temperature affecting the precipitation entering the ground. Since significant variations of mean annual air temperature only occur over geologic time periods the detection of a variation of $\delta^{18}O$ in a soil profile is dependent on a very thick profile or a relatively slow rate of oxygen-18 transport.

4.0 PROCEDURES

The documentation of site conditions, collection of samples, monitoring installations and the measurements and testing using this instrumentation constitute the fieldwork portion of this project. The laboratory testing of the soil and ground water samples is discussed separately.

4.1 Fieldwork

4.1.1 Soil Sampling

Drilling at the Woodslee test site was carried out in two phases because the positioning of some of the monitoring installations was dependent on the preliminary results obtained at the phase one sites. The first phase of the operation took place during the period February 9, 10 and 11, 1983 and the second phase of the work was completed on April 11 and 12, 1983.

Drilling operations at the West Windsor test site were carried out on March 10 and 11 as well as March 16, 17 and 18, 1983. The interruption of the site work was caused by delays in obtaining necessary equipment for the installation of instrumentation.

The drilling unit and skilled operators were obtained from Dominion Soil Investigation Inc. The unit used was a CME 750, four wheel drive power auger machine manufactured by Central Mining Equipment Limited, and equipped with two sizes of hollow-stem augers, 82 and 108 mm inside diameter. Sampling was carried out using either a standard split spoon sampler or thin-walled tube samplers (Shelby tubes) of 51 and 73 mm sizes. The drilling unit was equipped with a standard 62 kilogram (140 pound) hammer with a 760 mm (30 inch) fall to perform Standard Penetration tests or to advance the samplers in hard or dense soils.

In the sampled boreholes (at least one hole per monitoring installation site) samples were taken continuously in 450 mm increments. Where samples were taken with the split spoon sampler the material recovered was carefully removed from the split tube and sealed in air tight containers. Shelby tube samples were trimmed and sealed in the tubes at the drilling site with molten sealing wax. After the wax had solidified these tubes were further sealed with plastic capping and PVC adhesive tape. All of the samples were stored in a heated enclosure to prevent freezing and were transported to the laboratory with as little disturbance as possible.

4.1.2 Observation Well Installations

Four groundwater monitoring sites were constructed at the Woodslee and West Windsor test sites to determine the hydrogeologic conditions. In order to determine the groundwater flow direction and horizontal gradient, three monitoring sites were established in a triangular array and as great a distance from each other as the limits of the Woodslee and West Windsor study site areas would permit. Of these three monitoring sites two sites were equipped with two-level observation well instrumentation and at the third site a six-level observation well installation was constructed.

A schematic diagram of a two-level observation well instrumentation installation is presented in Figure 4.1. This installation consists of a 6.1 metre deep water table well with a 4.6 metre long slotted section and a 10.6 metre standpipe piezometer with a 1.5 metre slotted section. The wells and piezometers are constructed of 38 mm (1-1/2 inch) inside diameter A.B.S. plastic piping which was slotted with a saw at 250 mm intervals and wrapped in a fibreglass filter cloth.

TWO-LEVEL MONITORING SITE

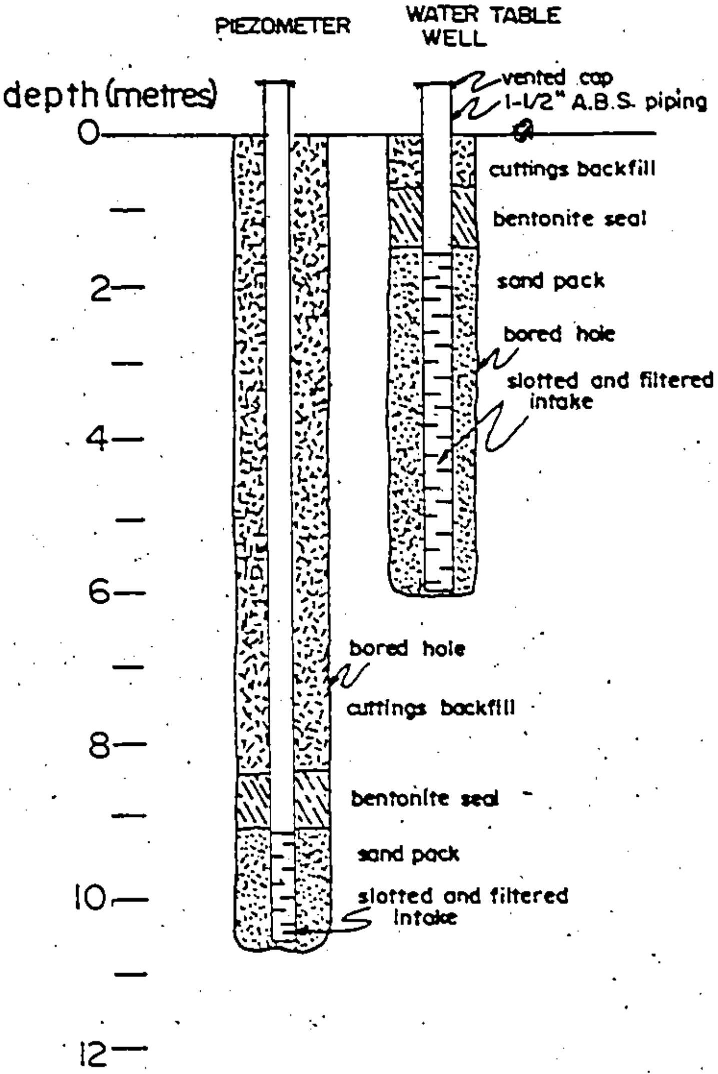


FIGURE - 4.1

A schematic diagram of a six-level observation well instrumentation cluster is presented in Figure 4.2. This installation consists of six standpipe piezometers installed at depths of 3.0, 4.6, 6.1, 7.6, 9.1 and 10.6 metres. These piezometers are comprised of 1.5 metre long continuous slot wound stainless steel Johnson well screens and 38 mm (1-1/2 inch) I.D. stainless steel piping.

Piezometers with isolated screen sections were installed at the fourth and remaining monitoring site locations at Woodslee and West Windsor in order to facilitate <u>in situ</u> point dilution and tracer testing of the soil surrounding the wells. These piezometers were constructed of A.B.S. plastic piping with a 51 mm (2 inch) inside diameter. The base of each of the pipes was fitted with 600 mm long Johnson P.V.C. plastic continuous slotted well screen.

Each of the observation wells was installed in a drilled borehole 165 or 190 mm in diameter through the interior of the hollow-stem augers. The augers were then withdrawn and a filter of fine 'masonry sand' was placed around the slotted pipe sections and screens. Above the filtered and screened pipe lengths a seal of bentonite clay 300 to 600 mm long was placed in the holes to isolate the screened well length and prevent preferential surface infiltration of the borehole. The remaining length of borehole above the bentonite seal was backfilled with the auger cuttings to the ground surface. Where A.B.S. piping was used, a cast iron casing with a screw cap was placed over the exposed portion of the pipe and concreted into place to prevent tampering.

Field conditions were such that precise construction of the observation wells in accordance with the intended design was not always possible. Difficulties in plumbing of the holes lead to inaccurate measurements, and caving of the augered soil and flowing ground water can make placing of the filter and seals difficult. Details of the actual field installations of each of the observation wells are presented in Appendix A.

SIX-LEVEL MONITORING SITE

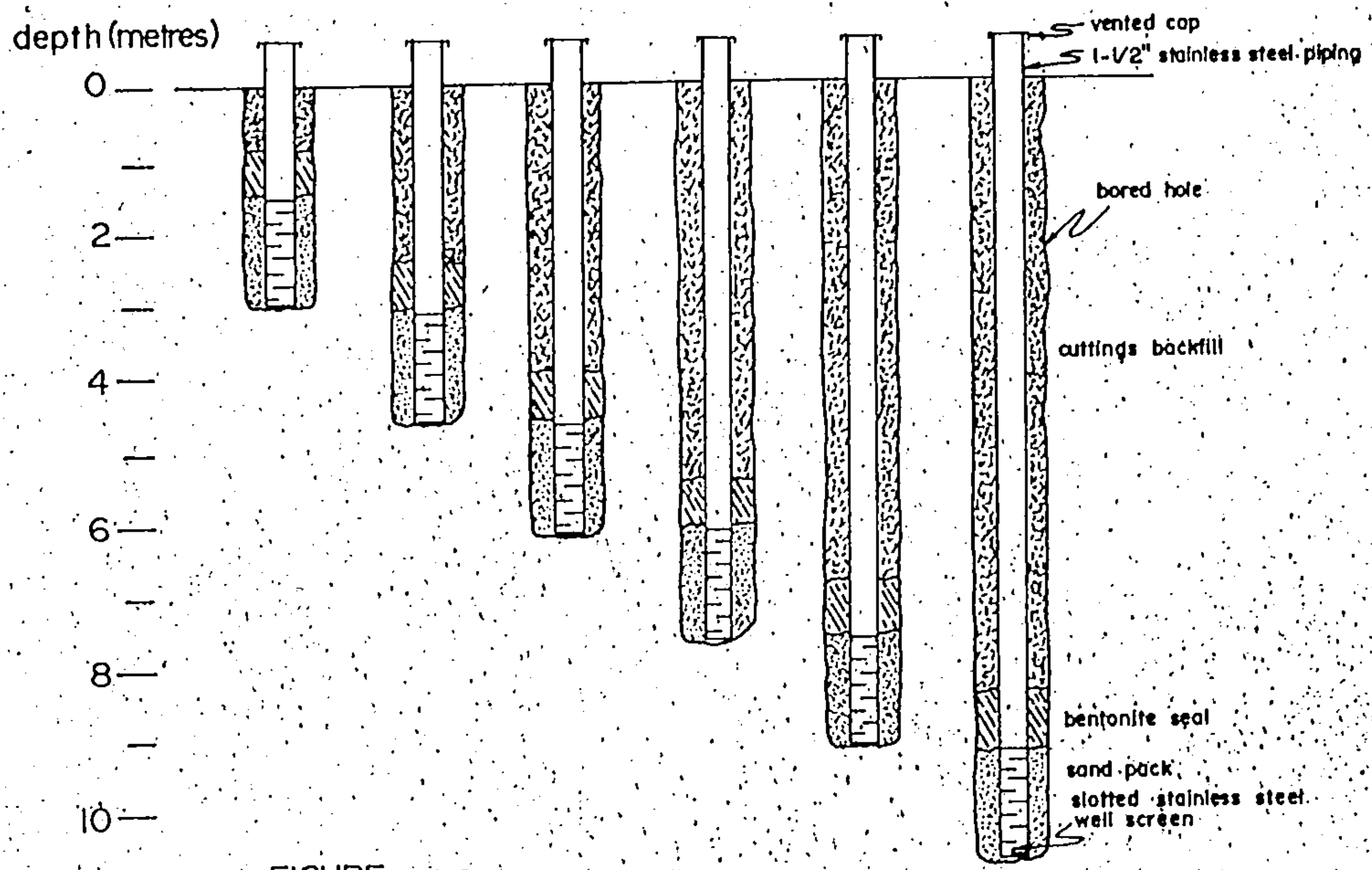


FIGURE - 4.2

4.1.3 Water Level Measurements

After completion of the observation well installations, a surveyor's level was used to measure the ground surface and the top elevation of each of the well casings relative to the geodetic datum. It was then possible to measure the distance from the top of the installed well casing to the surface of the water in the well with an electric tape to an accuracy of approximately 10 mm and to calculate the geodetic elevation of the water in each of the observation wells. Water level readings were taken at approximately two-week intervals throughout the study until a static level was achieved.

4.1.4 Electrical Conductivity Measurements

Measurement of the in situ electrical conductivity of the water in the observation wells was carried out using a portable battery-operated solution conductivity meter. This meter, pHOX Sytems Limited Model 52, measures electrical conductivity in microseimens through an epoxy resin and carbon electrode. The instrument used has a range of 0 to 100,000 microseimens in five scales and fully automatic temperature compensation standardized to 25°C. The conductivity meter specifications are included as Appendix B.

Ten different probes were used during the course of this investigation. These probes were calibrated using a standard 0.0100M solution of potassium chloride which has a specific conductance of 1413 microseimens.

Care was taken in the field that conductivity readings were always taken after measurement of groundwater levels so that the volume of the probe or water removed from the well by the probe would not influence the water level readings obtained. In accordance with the pHOX Systems Ltd. instructions which accompanied the conductivity meter, the probe was always allowed to sit in the observation well for at least a minute prior to obtaining readings so that the temperature sensitive probe could attain thermal equilibrium with the water in the well.

4.1.5 Single Well Response Testing

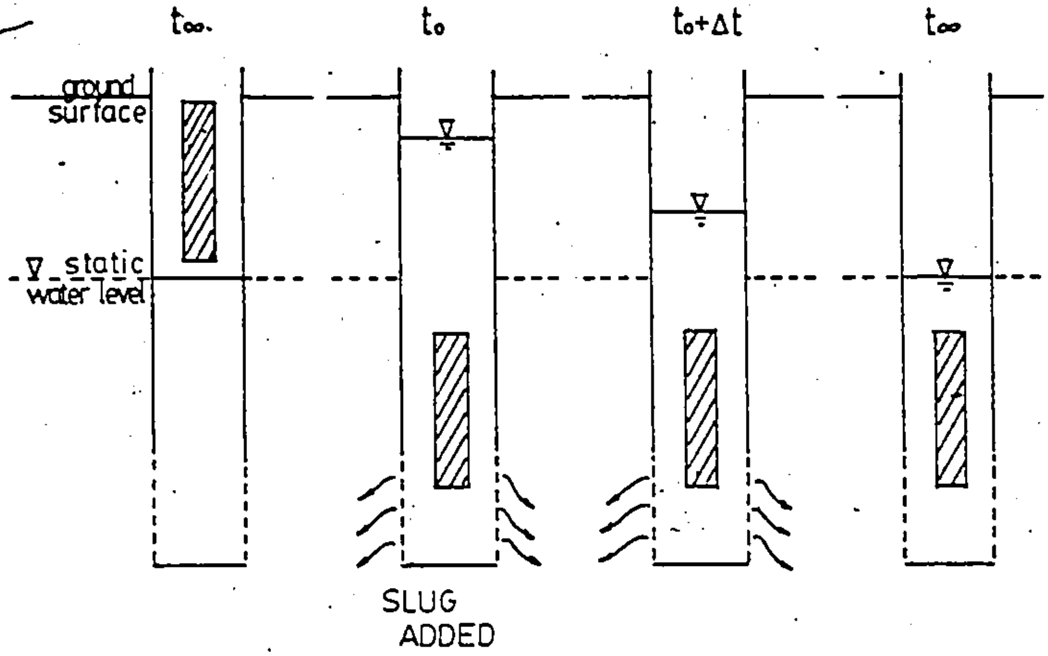
A schematic diagram indicating the two variations of single well response tests which were performed for this study is presented in Figure 4.3.

For the work at the Woodslee and West Windsor test sites a 'slug', consisting of a 25 mm diameter aluminum rod, one metre long attached to a cord, was lowered into the wells to instantaneously raise the water level. This type of testing is therefore described as a slug test. The time and water level were recorded after the introduction of the slug to the well to determine the rate at which the water level in the well returned to the level measured prior to introduction of the 'slug'. The time for the water to again reach equilibrium with the head of the ground water surrounding the well is related to the hydraulic conductivity of the soil as discussed in Section 3.2.6.

Once a steady state water level was again recorded in the wells the 'slug' was removed causing an instantaneous lowering of the water level in the well. The times and water level readings necessary to establish the rate of the rise of the water level in the well to the previously recorded static level were then recorded. At a few of the well locations, the rate of flow of water into the observation wells was sufficiently great as to prevent sufficiently accurate readings to establish the rate of the water level rise in the wells. In these cases a portable sampling pump was used to lower the water in the wells to a greater depth allowing a larger time period for time and water level measurements. Regardless of the method employed, this type of testing where the water level in the observation well is lowered is described as a bail test.

SINGLE WELL RESPONSE TESTS

SLUG TEST



BAIL TEST

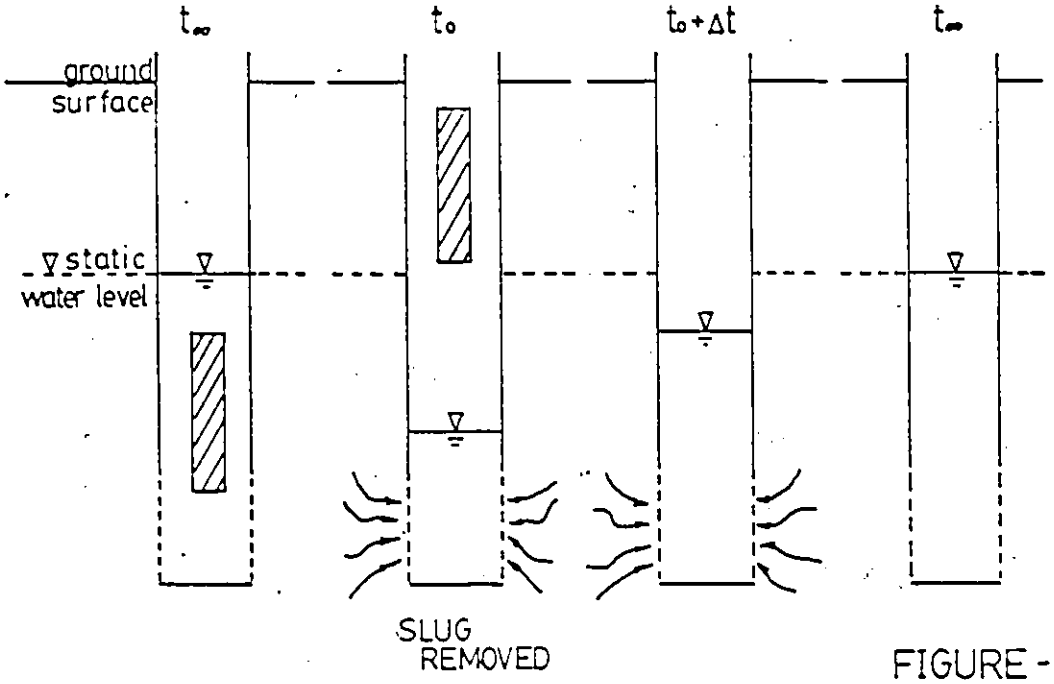


FIGURE - 4.3

From the time an observation well is drilled until it first establishes equilibrium with the piezometric head in the soil surrounding the well screen, there is a time lag similar to that which is introduced artificially in the procedure of a single well response test. If a sufficiently detailed hydrograph of the well is recorded during the time lag period then the results of this hydrograph can be interpreted like the results obtained from a bail test. The water level readings at the test site were not taken continuously and the intervals between measurements were relatively large, therefore it was only possible to analyze the hydrographs of the wells with relatively long time lags in this way.

4.1.6 Point Dilution and Tracer Testing

A substance can be injected into a groundwater flow system at one point and its arrival at another point detected. The average linear velocity of the groundwater flow system is assessed directly and a tracer test has been performed. If the concentration of the substance introduced at the injection point is measured so as to determine the dilution of the injected substance at this point then the velocity of the groundwater can be related to the rate of dilution of the tracer substance. This measuring of rate of dilution in a single location as an indirect measure of groundwater velocity is a point dilution test.

A point dilution apparatus, common in European use, is isolated in a segment of the well screen by packers. A tracer substance is introduced to the isolated screen segment and a mixing unit employed to ensure homogeneity as the groundwater flow passes through the well screen diluting the tracer substance.

The point dilution apparatus developed for tests at the Woodslee and West Windsor sites eliminates the requirement and subsequently the cost of a down-hole mixing device. Standpipe piezometers installed for use in point dilutions tests were equipped with relatively short (600 mm) screened sections isolated from the remainder of the standpipe by a seal formed on the inside of the standpipe. The tracer concentration in the screen volume was measured by an electrical conductivity probe inserted to form an integral part of the seal. It was reasoned that a relatively short length of screen could be inserted into the groundwater flow system and the screen would effectively operate as a point source of tracer. Flow through the screen would be effectively uniform and linear such that segregation of the tracer solution in the small volume of water contained in the screen would be minimal. If the groundwater flow velocity were relatively swift as could occur in a coarse-grained deposit then it would be expected that considerable dilution of the tracer would take place before the detection apparatus could be installed and the well sealed. There would also be difficulty in determining the starting point of the test associated with the equalization of pore water pressure in the soil and isolated screen volume. The soils at the subject study sites were, however, expected to have relatively low flow velocities and these considerations therefore did not apply.

A direct two-well tracer test was carried out only at the Woodslee test site because of the limited resources available for this work and the substantial cost associated with the installation of an injection well and an array of receptor wells to detect the passage of the tracer substance. In anticipation of a relatively low groundwater velocity the wells were placed in a tight array around the injection well in a down gradient direction as indicated by preliminary analysis of the water level readings in the wells at the other Woodslee monitoring sites. The injection well of the tracer test arrangement was installed in an identical manner to the point dilution test wells and consituted an additional point dilution test location. The receptor wells of the tracer test were of the isolated screen type with integrated sheathed conductivity probe. By isolating the screened portion of the receptor wells it was possible to limit the volume of water monitored for the tracer arrival and subsequently eliminate the effects of dilution and segregation within the receptor wells.

The tracer substance selected for use at the subject study sites was sodium chloride (NaCl) which is easily obtainable. A sodium chloride solution is also relatively easy to detect if an electrical conductivity meter is used to indicate variation in the total dissolved solids in a solution.

The seal constructed in the point dilution standpipes consisted of a ring of Flexane, a rubber-like material, formed on the inside surface of the standpipe wall. Through the port in this ring it was possible to introduce the sodium chloride tracer and then close the ring by the installation of an electrical conductivity probe cased in a pipe that mated with the port in the sealing ring. A schematic diagram of a typical observation well with interior seal and the companion sheathed conductivity probe installation is presented in Figure 4.4. A detailed description of the procedure for the construction of the interior well seals and sheathed conductivity probes is included in Appendix C.

The point dilution and tracer injection wells were charged with a saturated sodium chloride solution on June 30, 1983 at the Woodslee test site. The point dilution equipped well at the West Windsor test site was charged with tracer on August 10, 1983. Initially electrical conductivity readings were taken in the wells at daily intervals, however once the rate of dilution of the tracer had been established the electrical conductivity reading intervals were extended to weekly and then bi-monthly periods.

ELECTRICAL CONDUCTIVITY PROBE
for point dilution and tracer test studies

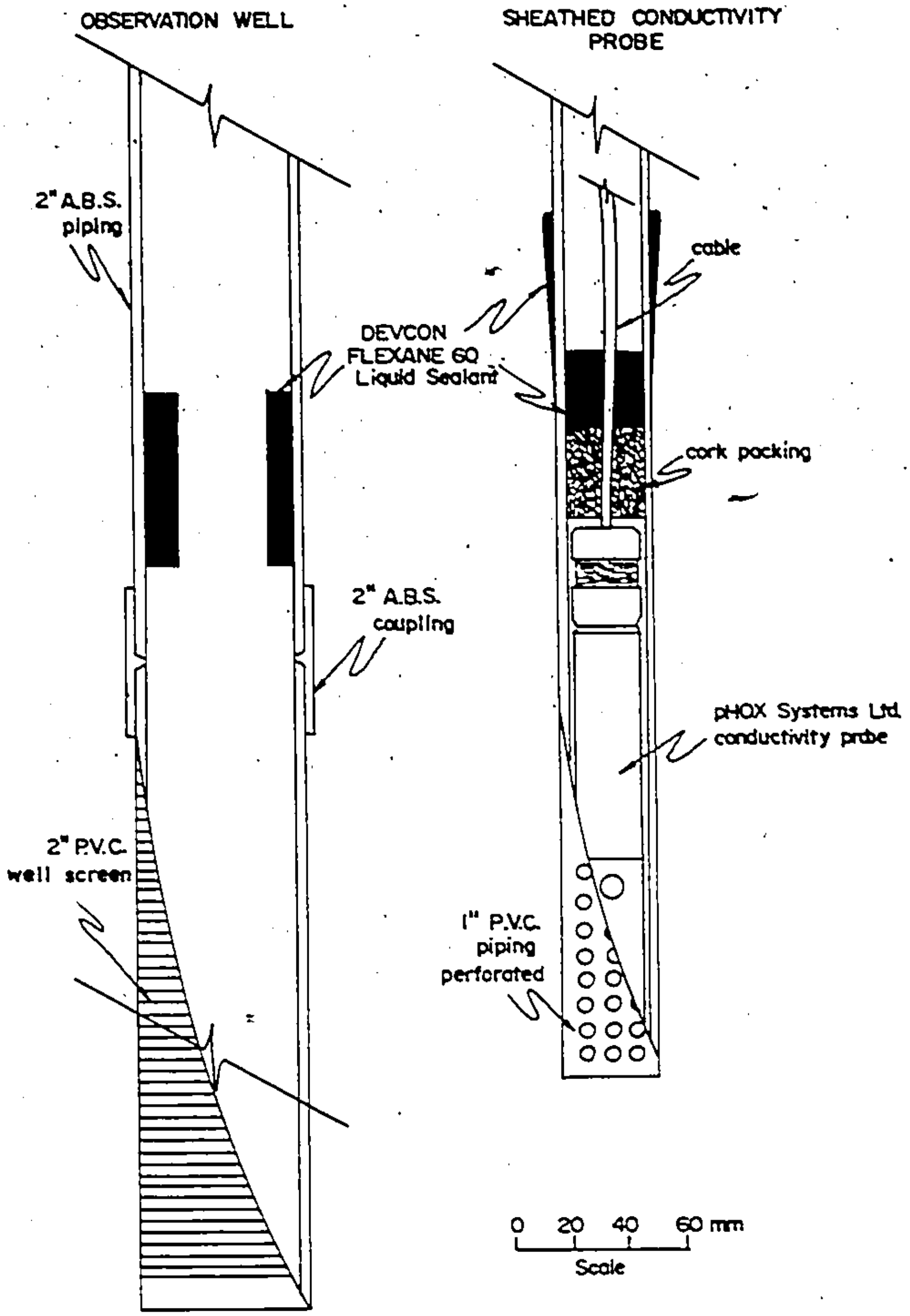


FIGURE - 4.4

4.2 Laboratory Testing

As mentioned in Section 4.1.1, Soil Sampling, split spoon samples sealed in air tight containers and sealed thin walled tube samples were transported to the laboratory from the two test sites. The laboratory testing program included soil indentification tests, environmental isotope analysis, and hydraulic conductivity testing.

4.2.1 Soil Identification

Soil samples were tested for natural moisture content as they were received in the laboratory. The description of the soil samples as recorded on the borehole logs completed in the field were then verified by a visual and tactile examination of each of the samples. Representative samples were subsequently selected and prepared for the grain-size analyses and Atterberg limit tests. Natural moisture content and Atterberg limit determinations, as well as sieve and hydrometer tests, were carried out using the methods detailed by Lambe (1951). These results together with the visual and tactile identification of the soil samples were used to classify each of the samples in accordance with the Unified Soil Classification System of Casagrande (1948). A summary of this classification system is presented in Figure 4.5.

4.2.2 Environmental Isotope Analysis

4.2.2.1 Pore Water Extraction

For this study it was decided to attempt to develop isotope profiles at the Woodslee and West Windsor sites for tritium and ^{18}O. Rather than sampling from the observation wells which would affect the period of time before the wells could be used for in situ testing of hydraulic

UNIFIED SOIL CLASSIFICATION SYSTEM

(after Casagrande 1948)

Description			Group symbols	Laboratory criteria			
				Fines (%)	Grading	Plasticity	Notes
Coarse grained (More than 50% larger than No 200 BS sieve size)	Gravels (More than 50% of coarse fraction of gravel size)	Well-graded gravels, sandy gravels, with little or no fines	GW	0-5	$C_U > 4$ $1 < C_C < 3$		Dual symbols if 5-12% fines. Dual symbols if above 'A' line and $4 < PI < 7$
		Poorly-graded gravels, sandy gravels, with little or no fines	GP	0-5	Not satisfying GW requirements		
		Silty gravels, silty sandy gravels	GM	> 12		Below 'A' line or $PI < 4$	
		Clayey gravels, clayey sandy gravels	GC	> 12		Above 'A' line and $PI > 7$	
	Sands (More than 50% of coarse fraction of sand size)	Well-graded sands, gravelly sands, with little or no fines	SW	0-5	$C_U > 6$ $1 < C_C < 3$		
		Poorly-graded sands, gravelly sands, with little or no fines	SP	0-5	Not satisfying SW requirements		
		Silty sands	SM	> 12		Below 'A' line or $PI < 4$	
		Clayey sands	SC	> 12		Above 'A' line and $PI > 7$	
Fine grained (More than 50% smaller than No 200 BS sieve size)	Silts and clays (Liquid limit less than 50)	Inorganic silts, silty or clayey fine sands, with slight plasticity	ML				
		Inorganic clays, silty clays, sandy clays of low plasticity	CL				
		Organic silts and organic silty clays of low plasticity	OL				
	Silts and clays (Liquid limit greater than 50)	Inorganic silts of high plasticity	MH				
		Inorganic clays of high plasticity	CH				
		Organic clays of high plasticity	OH				
Highly organic soils		Peat and other highly organic soils	Pt				

Plasticity Chart

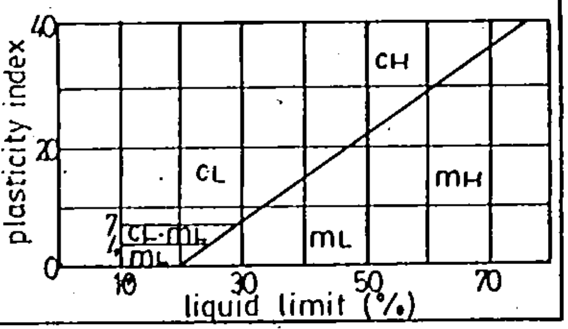


FIGURE - 4.5

conductivity, samples of the pore water were extracted directly from a selection of the soil samples obtained. This direct extraction of pore water allowed for a precise vertical location of the sample source that could not be accomplished with well samples.

In order to extract the pore water from the soil samples, it was necessary to construct a hydraulic squeezing device that would extrude the liquid from the soil. A device of the type described by Patterson et al. (1978) was constructed of stainless steel (Figure 4.6). This squeezing cell together with a hydraulic jack were fitted to a reaction frame (Figure 4.7) through which the required force was applied to extrude the pore water from the samples. Patterson et al. note that Manheim (1966) recorded variations of the concentrations of dissolved components in the pore water at high squeezing pressures. Patterson et al. subsequently limited the pressure applied in the squeezer to less than 4900 kPa (50 kg/cm^2). The pressure applied in the squeezer apparatus extruding the Woodslee and West Windsor samples was limited to 5000 kPa.

Samples for pore water extraction were taken from 73 mm diameter shelby tube samplers and wrapped in two layers of filter paper before being placed in the squeezing apparatus. Water squeezed from the soil samples was placed in clean sample bottles displacing the air prior to sealing with a cap and molten wax.

4.2.2.2 Sample Analysis

The sealed pore water samples were sent to the isotope laboratory of the Department of Earth Science, Faculty of Science, University of Waterloo, Waterloo, Ontario for analysis. Oxygen-18 was measured using a standard mass spectrometric method and the direct counting method was used to determine tritium concentration.

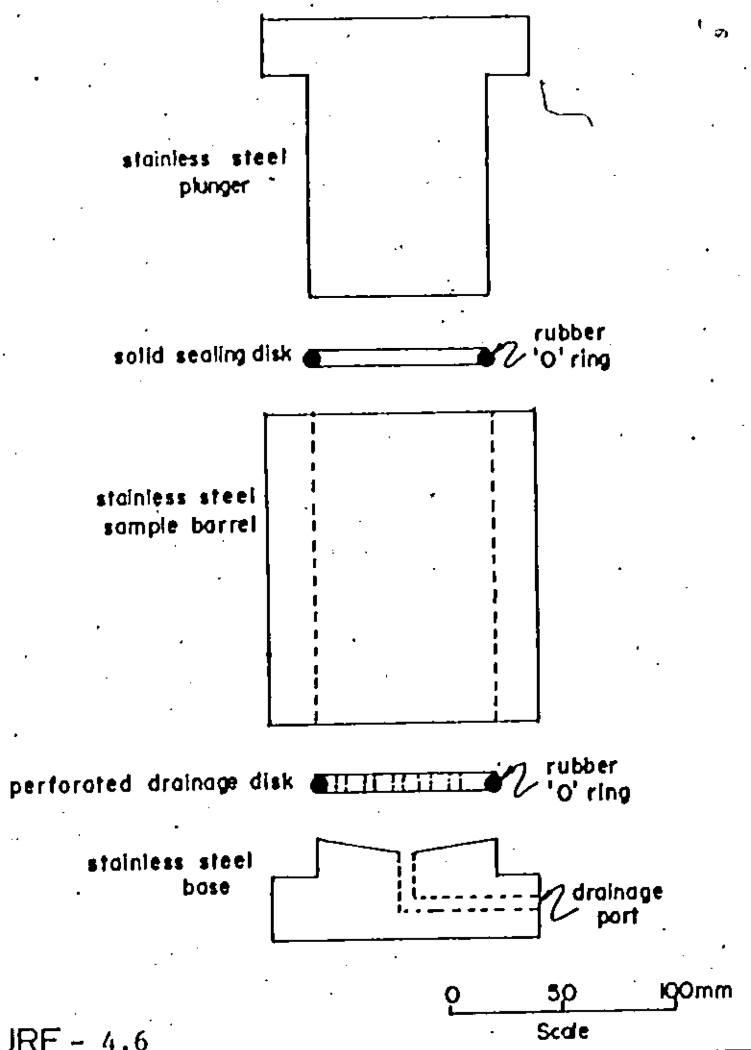


FIGURE - 4.6

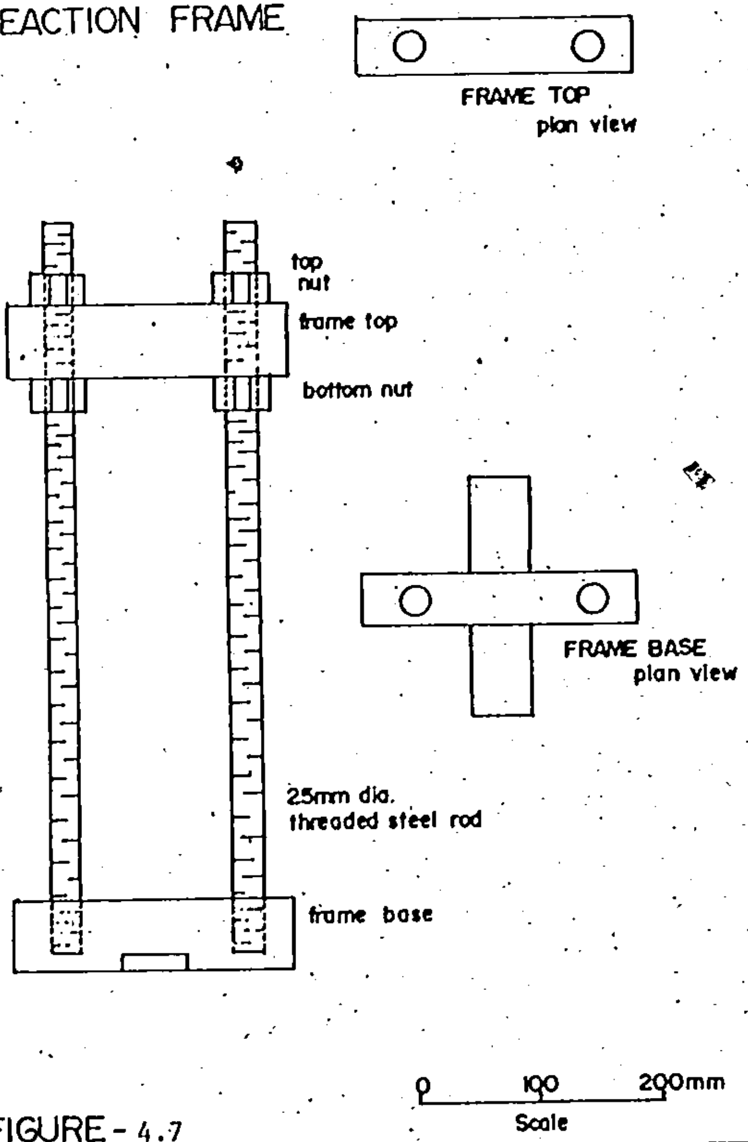


FIGURE - 4.7

4.2.3 Hydraulic Conductivity Testing

Three different laboratory testing procedures to determine the hydraulic conductivity of soil samples obtained from the Woodslee test site were carried out. The testing included falling head pressure permeameter tests, one dimensional consolidation tests and triaxial consolidation tests. Samples from the West Windsor test site were tested using the falling head pressure permeameter and one dimensional consolidation apparatus.

All of the tests were performed on undisturbed samples which were carefully trimmed to fit the apparatus used. All of the samples were also tested for moisture content and unit weight at the time of sample preparation.

4.2.3.1 Pressure Permeameter Testing

In a conventional variable head permeameter as described by Lambe (1951) the hydraulic gradient to induce liquid movement through the test sample is generated by a column of liquid above the sample. A pressure permeameter effectively duplicates the function of this column of liquid by introducing liquid to the sample from a pressurized reservoir. In this way a substantially higher gradient can be achieved than is practically possible in the standpipe of a conventional variable head permeameter. Testing on fine grained samples can therefore be considerably accelerated.

The pressure permeameter used to test samples from the Woodslee and West Windsor test sites is similar to the Soiltest Inc. Model K-670 but the unit used was constructed by the author. A schematic diagram of this unit is presented in Figure E-1 in Appendix E.

Samples for testing in the unit were trimmed to fit the diameter of the sample container which consisted of a piece of 32 mm I.D. copper piping.

The sample was allowed to protrude from either end of the sample container and a sharp needle was used to open an annulus approximately 5 mm deep and 1 mm wide between the sample and the container at both ends. To ensure a seal between sample and container the samples were then dipped in molten wax to fill the inscribed annulus and the samples were carefully trimmed to finished length. Both ends of the soil samples were covered by filter papers and at the liquid source end of the sample a piece of filter fabric with a permeability of 10^{-2}cm/sec was also placed on the end of the sample. The prepared sample was clamped between the base and clamping plates and sealing gaskets of asbestoes-rubber.

At the start of each test the permeant pressure-tank was filled and pressurized to approximately 400 kPa. The standpipe at the top of the sample was opened and the shutoff valve at the base of the sample released to allow permeant to saturate the sample from the bottom to the top. After the permeant had risen in the standpipe above the sample a starting point for the test was marked on the standpipe and the rate of rise of water in the standpipe was recorded. Knowing the pressure of the permeant entering the sample, the static level of the reservoir, the pressure of permeant on the exiting side of the sample, and the volume of the standpipe it is then possible to compute the hydraulic conductivity of the sample in accordance with equation (11). The height of liquid in the standpipe was measured to the nearest millimeter and the rate of liquid rise was evaluated up to eight times per test sample to reduce measurement error.

The permeameter was used to test 20 separate samples from the Woodslee test site and 23 separate samples from the West Windsor test site. As many as 7 discrete samples were obtained from a single shelby tube of material. Samples were tested in both horizontal and vertical orientations. The permeant generally used for the testing was groundwater obtained from the wells at the test sites. Several samples were tested with permeants which varied in NaCl concentration to assess the effect on the soil of the tracer which was used for the field testing.

4.2.3.2 One-Dimensional Consolidation Testing

Conventionally odeometers have employed lever and weight mechanisms to load samples of soil. Recently odeometers have been constructed which apply load by means of an air piston controlled by a regulating valve. It is this pneumatic type of odeometer that was used to test the samples obtained for this study. A schematic diagram of a typical pneumatic odeometer is presented in Figure E-2 of Appendix E.

Four samples from the Woodslee test site and two samples from the West Windsor test site were tested in the odeometer for comparison of hydraulic conductivity assessment with the results of the pressure permeameter testing. For this reason some of the samples tested were taken from the same sample tubes as samples tested in the permeameter. Samples for odeometer testing were oriented horizontally and vertically as were the permeameter test samples.

4.2.3.3 Three-Dimensional Consolidation

A schematic diagram of a typical triaxial consolidation cell is presented in Figure E-3 of Appendix E. Testing of the samples for this study was carried out in the Toronto laboratories of Dominion Soil Investigation Inc. in a commercial version of this cell, manufactured by the Wykeham Farence Company.

The cost and time associated with the use of a triaxial test cell for the assessment of hydraulic conductivity allowed for only limited testing. Two samples were selected from the Woodslee test site.

5.0 OBSERVATIONS AND RESULTS

The observations made during the fieldwork and the subsequent period of monitoring at the two test sites are detailed in the sections which follow. Details of the soil and groundwater conditions at both sites were assessed and the results of testing to measure hydraulic conductivity and groundwater velocity are presented. The subsurface conditions determined, and the test results obtained at the two study sites are substantially different and the two sites will therefore be discussed separately.

5.1 Woodslee Test Site

5.1.1 Monitoring Site Locations

Monitoring Site 1 was located at the extreme north west corner of the Woodslee test site on a slight rise of land that constitutes the area of highest elevation on the test site. In order to achieve maximum separation of the monitoring sites the second of these installations, Monitoring Site 2, was placed on the eastern site boundary near one of the internal roads of the Soil Research Centre. Since the land at the Woodslee test site generally slopes from west to east, Monitoring Site 2 is at a location representative of the lowest ground surface elevation on the test site. It had been intended that the third monitoring site be placed in the extreme southwest corner of the test site but an Ontario Hydro electrical transmission line runs across the south boundary of the Soil Research Centre property and it would have been dangerous to drill beneath the high voltage power lines. Monitoring Site 3 was therefore located on the west test site boundary approximately 100 metres north of the south boundary. Monitoring Site 4 which was designed for borehole dilution and tracer testing, was located in the only unused open space on the test site

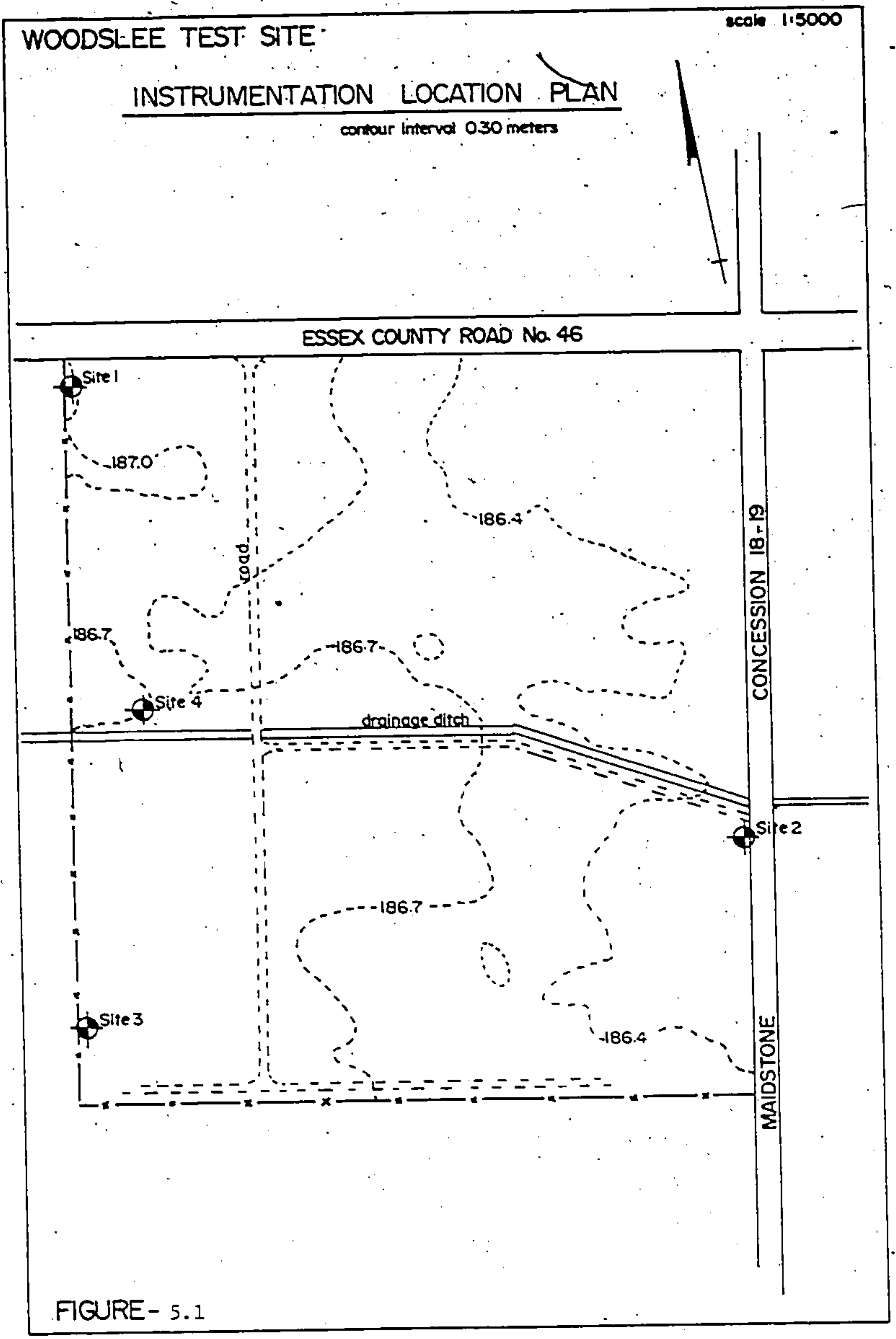

WOODSLEE TEST SITE
INSTRUMENTATION LOCATION PLAN
contour interval 0.30 meters
scale 1:5000
ESSEX COUNTY ROAD No. 46
CONCESSION 18-19
MAIDSTONE
Site 1
Site 2
Site 3
Site 4
road
drainage ditch
187.0
186.4
186.7
186.7
186.7
186.4

FIGURE- 5.1

with sufficient area to contain all of the instrumentation that was to be installed.

The locations of each of the monitoring sites are plotted on a plan of the Woodslee test site. This 'Instrumentation Location Plan' is presented in Figure 5.1. Each of the monitoring sites was installed on relatively flat, grass covered ground. At the location of Monitoring Site 3, there are some large oak and maple trees located immediately north and west of the observation well locations. The nearest of the trees is approximately 3 metres north of observation well 3-1.

5.1.2 Soil Conditions

A detailed description of the soils at each of the monitoring site locations is presented on the Borehole Logs, Figures 5.2 to 5.5, and the following is a summary of the subsurface conditions encountered.

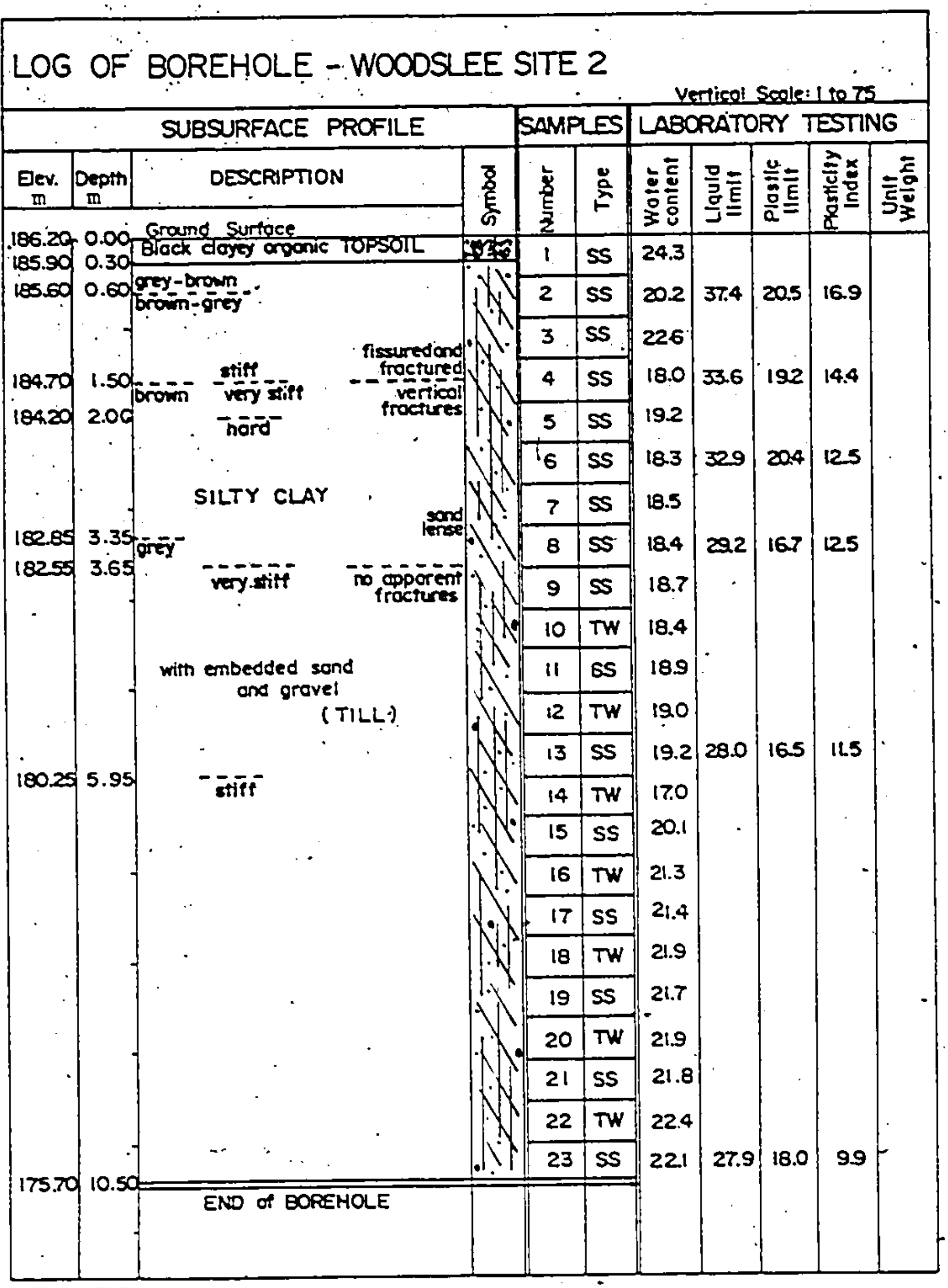
The boreholes penetrated a major deposit of silty clay containing embedded sand and gravel. It was noted that the larger sand and gravel particles are generally worn and have a round to subround shape. Grain-size analysis of selected samples of the silty clay indicate the material is well graded. The results of these analyses are presented as grain-size distribution curves in Appendix 'D'. The silty clay has a glacial origin and constitutes a portion of the Wisconsinan till deposits described by Vagners (1972b). The grain-size distribution test results are summarized in the form of a soil classification chart presented in Figure 5.6. Atterberg Limit determinations were carried out on a number of samples from each of the boreholes and the results of these tests are presented on the borehole logs at the corresponding depths. These results are summarized in the form of a plasticity chart presented in Figure 5.7. Based on these test results the silty clay till has a low to intermediate plasticity.

LOG OF BOREHOLE - WOODSLEE SITE I

Vertical Scale: 1 to 75

SUBSURFACE PROFILE				SAMPLES		LABORATORY TESTING				
Elev. m	Depth m	DESCRIPTION	Symbol	Number	Type	Water content	Liquid limit	Plastic limit	Plasticity Index	Unit Weight
187.00	0.0	Ground Surface								
186.70	0.30	Black organic clayey TOPSOIL		1	SS	26.1				
		fissured and fractured		2	SS	23.4				
186.10	0.90	stiff very stiff vertical fractures		3	SS	19.7	30.6	18.2	12.4	
				4	SS	19.3				
185.15	1.85	brown-grey brown hard		5	SS	18.2	23.8	14.5	9.3	
				6	SS	18.1				
		SILTY CLAY		7	SS	17.8	18.1	12.2	5.9	
				8	SS	17.7				
183.05	3.95	grey		9	SS	19.1				
				10	SS	18.7				
182.45	4.55	very stiff no apparent fractures		11	SS	18.9				
				12	SS	18.7				
181.50	5.50	stiff		13	SS	20.2				
				14	SS	20.8	30.9	18.2	12.7	
		with embedded sand		15	SS	21.4				
		and gravel		16	SS	21.5				
		(TILL)		17	SS	21.3				
				18	SS	21.1	31.2	18.2	13.0	
				19	SS	21.5				
				20	SS	21.8				
				21	SS	22.6				
				22	SS	23.0				
				23	SS	21.9				
176.50	10.50	END of BOREHOLE								

FIGURE - 5.2



LOG OF BOREHOLE - WOODSLEE SITE 2

Vertical Scale: 1 to 75

SUBSURFACE PROFILE			SAMPLES		LABORATORY TESTING				
Elev. m	Depth m	DESCRIPTION	Number	Type	Water content	Liquid limit	Plastic limit	Plasticity Index	Unit Weight
186.20	0.00	Ground Surface							
185.90	0.30	Black clayey organic TOPSOIL	1	SS	24.3				
185.60	0.60	grey-brown brown-grey	2	SS	20.2	37.4	20.5	16.9	
			3	SS	22.6				
184.70	1.50	brown stiff very stiff fissured and fractured vertical fractures	4	SS	18.0	33.6	19.2	14.4	
184.20	2.00	hard	5	SS	19.2				
			6	SS	18.3	32.9	20.4	12.5	
		SILTY CLAY	7	SS	18.5				
182.85	3.35	grey sand lense	8	SS	18.4	29.2	16.7	12.5	
182.55	3.65	very stiff no apparent fractures	9	SS	18.7				
			10	TW	18.4				
		with embedded sand	11	SS	18.9				
		and gravel (TILL)	12	TW	19.0				
			13	SS	19.2	28.0	16.5	11.5	
180.25	5.95	stiff	14	TW	17.0				
			15	SS	20.1				
			16	TW	21.3				
			17	SS	21.4				
			18	TW	21.9				
			19	SS	21.7				
			20	TW	21.9				
			21	SS	21.8				
			22	TW	22.4				
			23	SS	22.1	27.9	18.0	9.9	
175.70	10.50	END of BOREHOLE							

FIGURE - 5.3

LOG OF BOREHOLE - WOODSLEE SITE 3

Vertical Scale: 1 to 75

SUBSURFACE PROFILE				SAMPLES		LABORATORY TESTING				
Elev. m	Depth m	DESCRIPTION	Symbol	Number	Type	Water content	Liquid limit	Plastic limit	Plasticity Index	Unit Weight
186.80	0.00	Ground Surface								
		Black clayey organic TOPSOIL		1	SS	25.3				
186.50	0.30			2	SS	23.7				
		fissured and fractured		3	SS	24.1	40.3	21.6	18.7	
185.30	1.50	brown-grey stiff brown very stiff vertical fractures		4	SS	21.4				
184.80	2.00	hard		5	SS	18.4	35.3	20.7	14.6	
				6	SS	18.7				
		SILTY CLAY		7	SS	18.2	32.9	20.9	12.0	
				8	SS	18.5				
183.15	3.65	grey very stiff		9	SS	19.3				
182.55	4.25	no apparent fractures		10	TW	19.8				
				11	SS	20.4				
181.75	5.05	stiff		12	TW	21.0				
				13	SS	20.8	31.7	19.1	12.6	
		with embedded sand and gravel		14	TW	20.2				
		(TILL)		15	SS	20.3				
				16	TW	20.0				
				17	SS	21.6				
				18	TW	22.0				
				19	SS	22.3	32.0	18.6	13.4	
				20	TW	22.7				
				21	SS	22.6				
				22	TW	22.8				
				23	SS	22.5				
176.30	10.50	END of BOREHOLE								

FIGURE - 5.4

LOG OF BOREHOLE - WOODSLEE SITE 4

Vertical Scale: 1 to 75

SUBSURFACE PROFILE				SAMPLES		LABORATORY TESTING				
Elev. m	Depth m	DESCRIPTION	Symbol	Number	Type	Water content	Liquid limit	Plastic limit	Plasticity Index	Unit Weight
186.70	0.00	Ground Surface								
186.55	0.15	Black clayey organic TOPSOIL		1	SS	24.2				
186.10	0.60	grey-brown brown-grey fissured and fractured		2	SS	20.5				
185.65	1.05	stiff hard vertical fractures		3	SS	21.7				
185.20	1.50	brown		4	SS	19.1	42.2	23.8	18.4	
		SILTY CLAY		5	SS	18.1				20.8
		with embedded sand and gravel		6	SS	17.3				
		(TILL)		7	SS	18.6	36.1	15.4	20.7	20.2
183.35	3.35	grey		8	SS	17.2				
				9	SS	18.9				
182.75	3.95	no apparent fractures		10	SS	18.1	37.5	23.2	14.3	
182.15	4.55	hard very stiff		11	TW	19.1				22.0
				12	TW	19.4				21.9
181.20	5.50	stiff		13	TW	19.8				22.2
				14	TW					
				15	SS	19.0				
179.85	6.85	END of BOREHOLE								

FIGURE - 5.5

WOODSLEE TEST SITE

SOIL CLASSIFICATION CHART

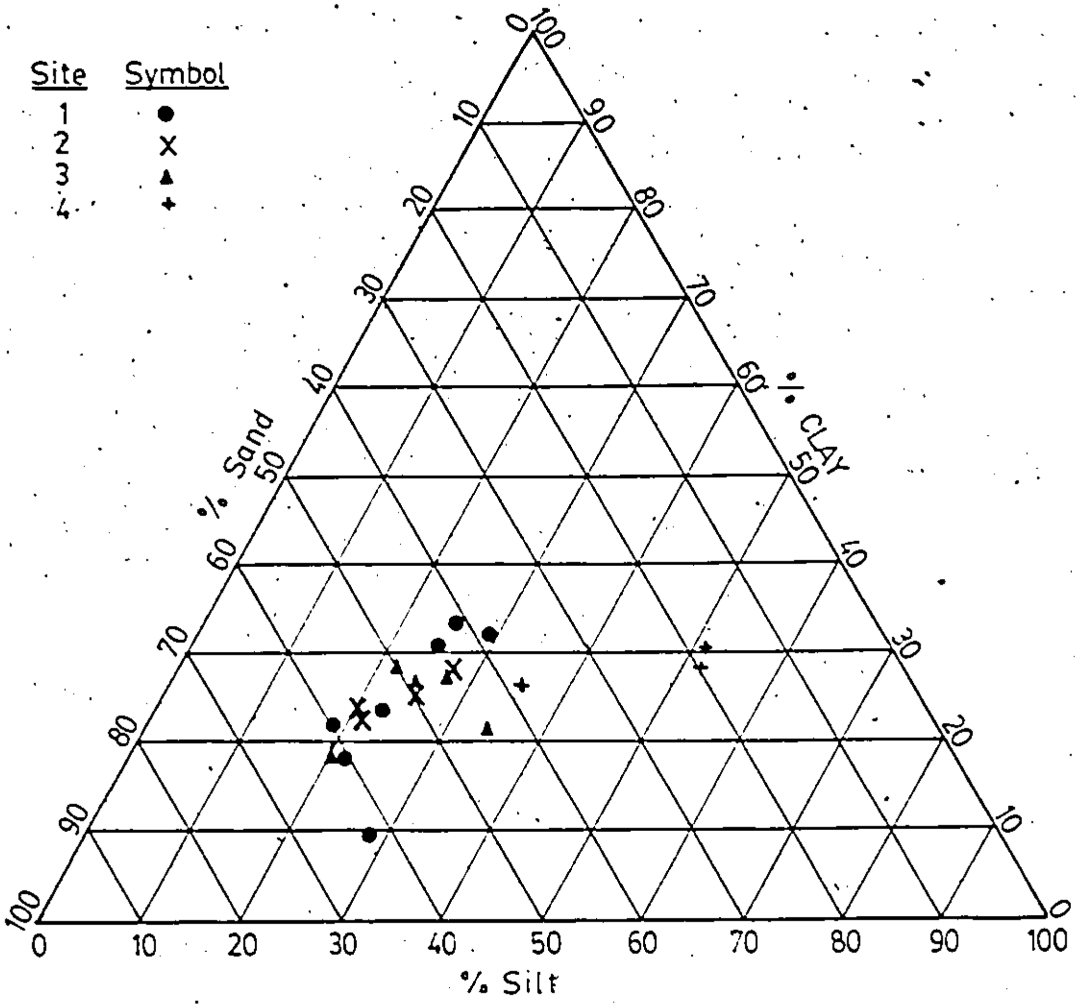
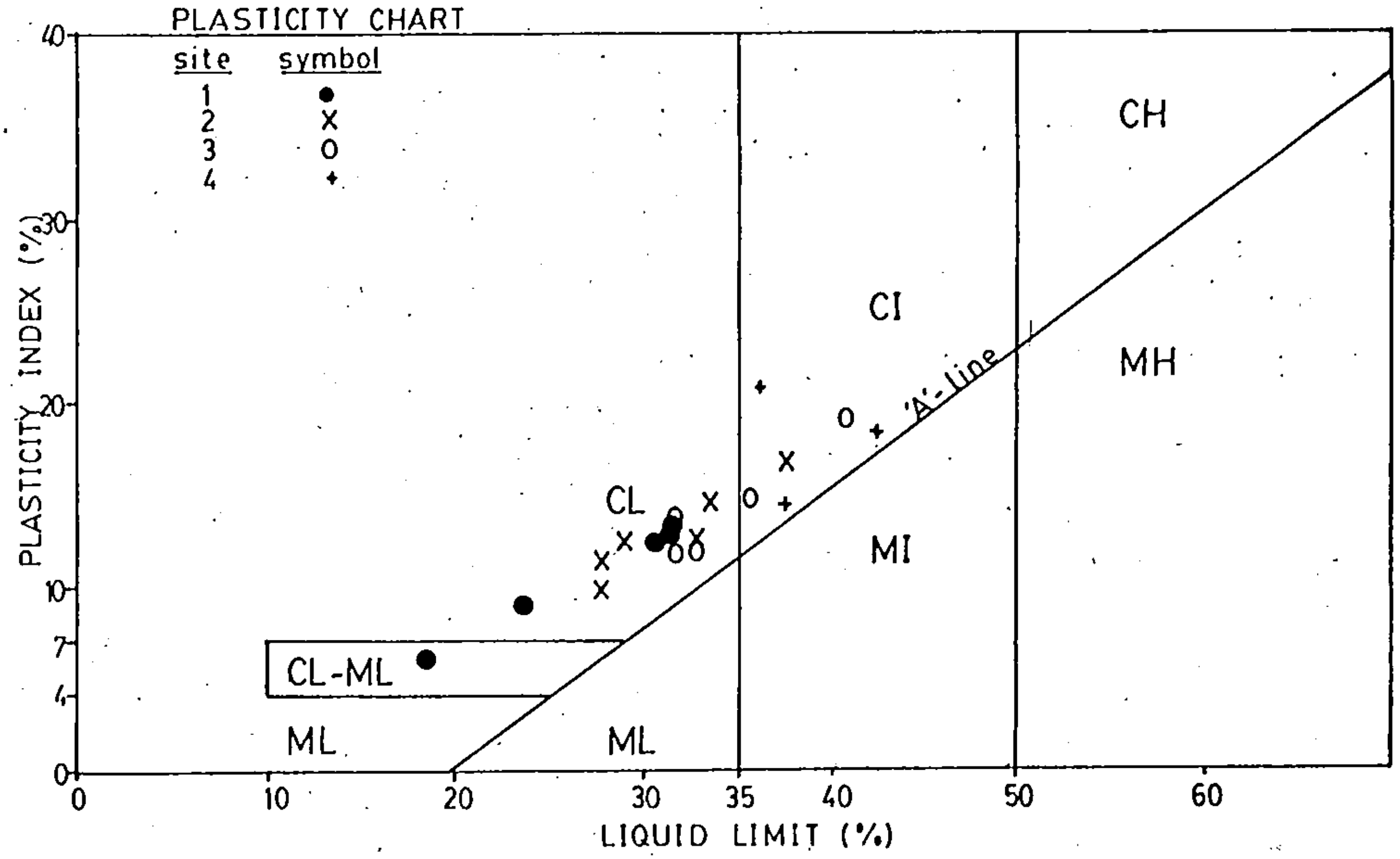


FIGURE - 5.6

WOODSLEE TEST SITE

FIGURE - 5.7

ATTERBERG LIMITS SUMMARY



The boreholes indicate a near surface profile consistent with the typical Brookston Clay soil profile described in detail in Section 2.3.2.1. The ground surface is covered by 150 to 300 mm of black clayey organic topsoil that has a moisture content of 24 to 26 per cent.

This topsoil layer is generally underlain by weathered silty clay till that has a colour ranging from mottled grey with brown partings to mottled brown-grey. The weathered zone of the silty clay till extends to a depth of 1.50 to 1.85 metres beneath the ground surface at the borehole locations. The till is severely fissured and fractured in the weathered zone and natural moisture content determinations indicated values between 19 and 23 per cent. A visual and tactile examination of the soil samples obtained, indicates the weathered silty clay till has a 'stiff' to 'very stiff' consistency.

At the location of Monitoring Site 2, the more northerly of the two observation wells (well 2-1) was not sampled. Whereas a silty clay till profile consistent with the other monitoring sites was encountered in the sampled southern well (well 2-2), sandy cuttings were recorded for the upper 450 mm at the location of well 2-1 and this well bored 'wet'. The location of this sand material is consistent with a small surficial deposit of sand plotted on the detailed soil map of the Woodslee Soil Research Centre (Experimental Farms Service, 1946).

The weathered zone of the silty clay till is underlain by brown desiccated material that contains vertical to sub-vertical fractures. These fractures often contain black and reddish brown scale. On the basis of the borehole results the spacing of these fractures may be as little as 50 mm, though not all of the samples obtained contained examples of fractured material. The natural moisture content of the desiccated material ranged from 17 to 19 per cent and a visual and tactile examination of the soil samples obtained, indicates the desiccated silty clay till has a 'very stiff' to 'hard' consistency. The brown desiccated silty clay extended to a depth of 3.35 to 3.95 metres below grade, which is some what less than the 4.5 to 9.0 metre base of the brown material recorded on water well logs from this site (Ontario Ministry of the Environment, 1977).

The brown desiccated till is underlain by grey plastic silty clay till. This plastic material tends to smear as sampled and there are no apparent fractures in the samples of the grey material obtained from this site except in the 600 mm of grey till directly beneath the desiccated zone of the silty clay. The natural moisture content of the grey silty clay till generally increases with depth. The range of natural moisture content was 19 to 23 per cent within the vertical limits of the investigation. The strength of the grey till decreases with depth. The upper 1.4 to 2.3 metres of the grey till has a 'very stiff' to 'hard' consistency but beneath this level the plastic silty clay has only a 'stiff' consistency. The grey silty clay extended beyond the vertical limits of the boreholes drilled at this site. As noted in Section 2.3.2.1, the water well records from this site indicate the grey silty clay extends to a depth of 34.5 to 36.0 metres below the ground surface and the base of the grey silty clay till is separated from the limestone bedrock by 1 to 2 metres of coarse sand and gravel.

5.1.3 Groundwater Conditions

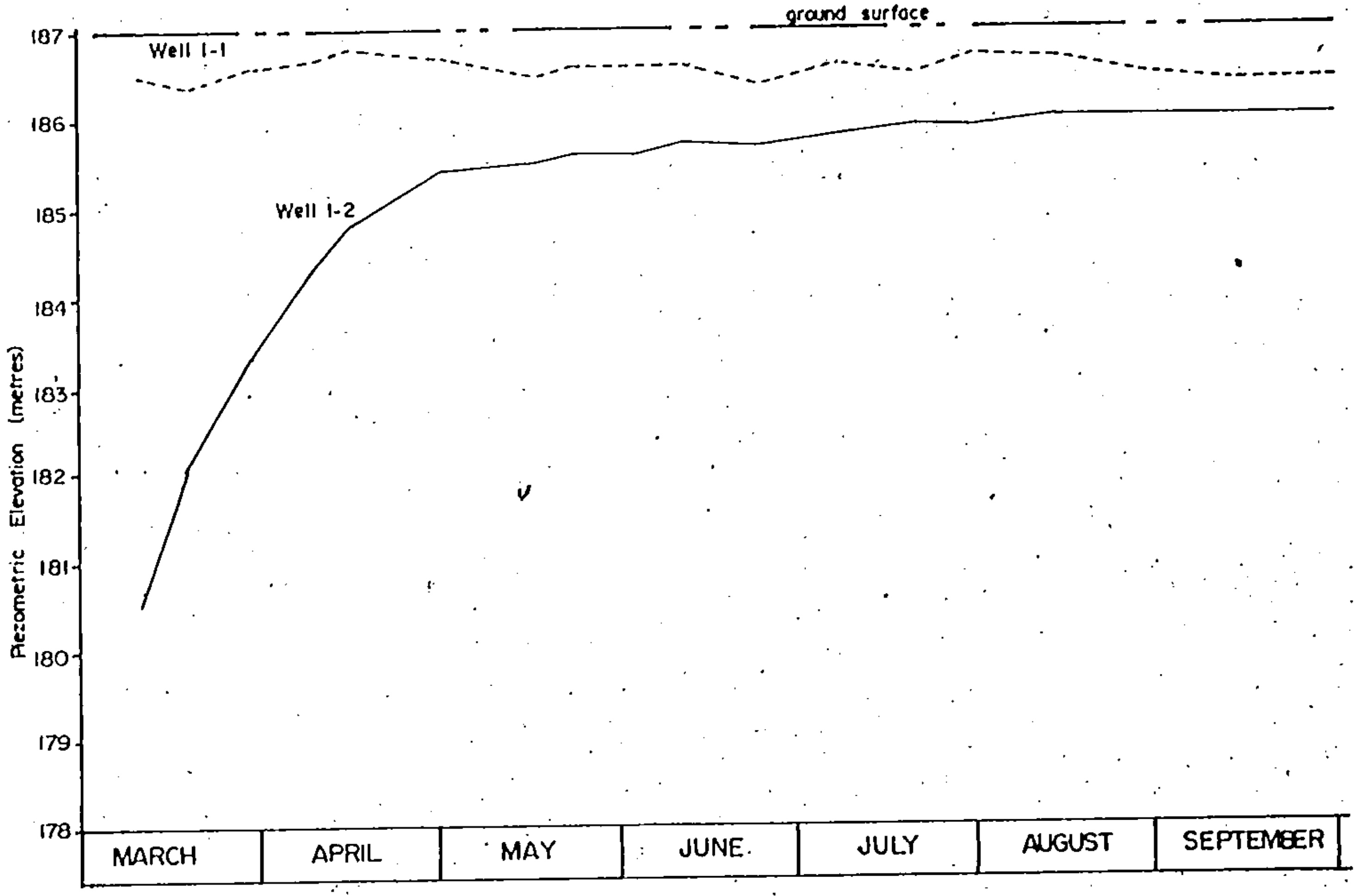
5.1.3.1 Observation Well Hydrographs

The groundwater level readings taken at the Woodslee test site between March and September, 1983, are tabulated in Appendix F. These readings are plotted as hydrographs for each of the observation wells on Figures 5.8 to 5.11.

WOODSLEE TEST SITE I

FIGURE- 5.8

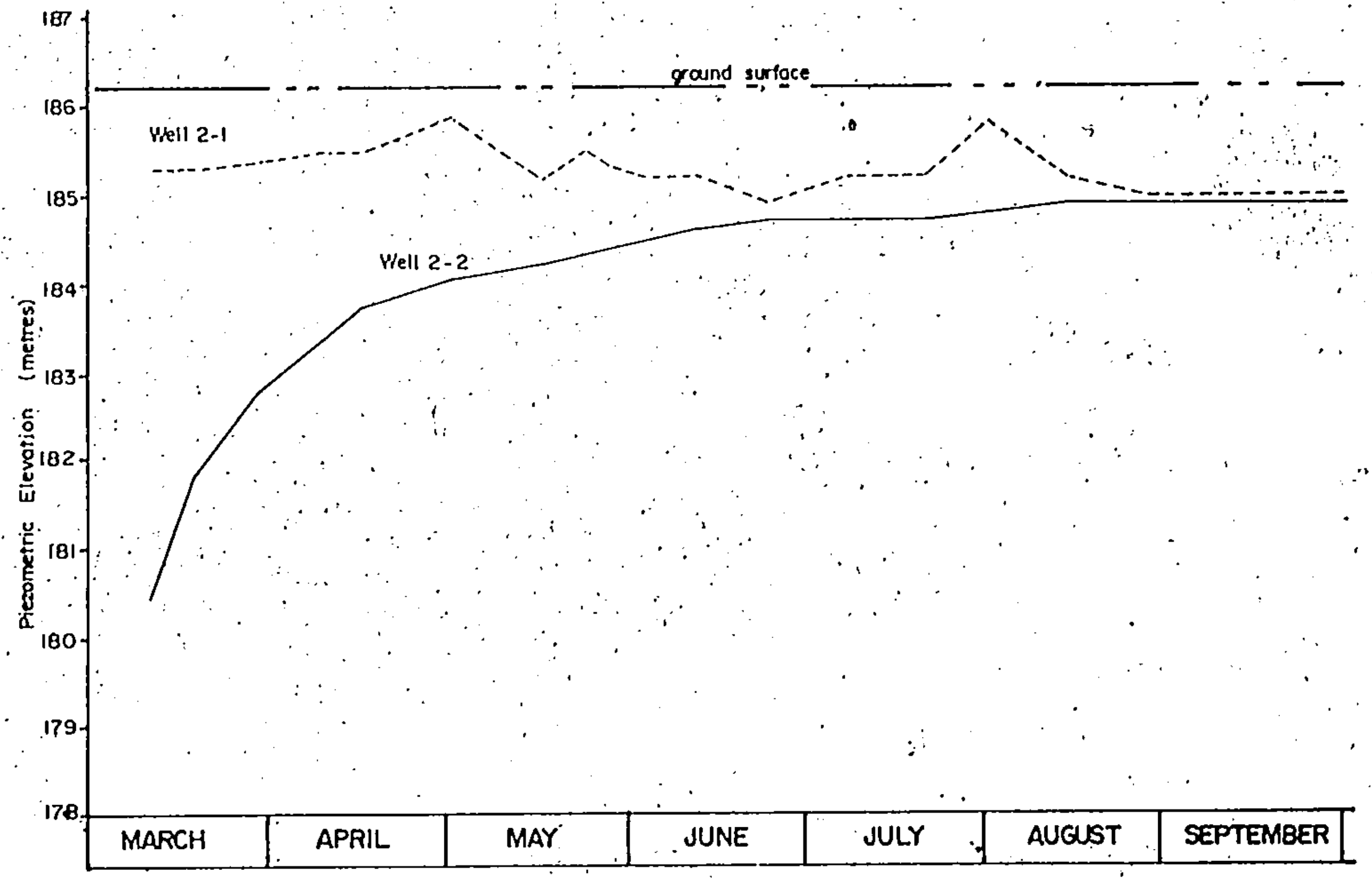
OBSERVATION WELL HYDROGRAPHS
(MARCH to SEPTEMBER 1983)



WOODSLEE TEST SITE 2

FIGURE- 5.9

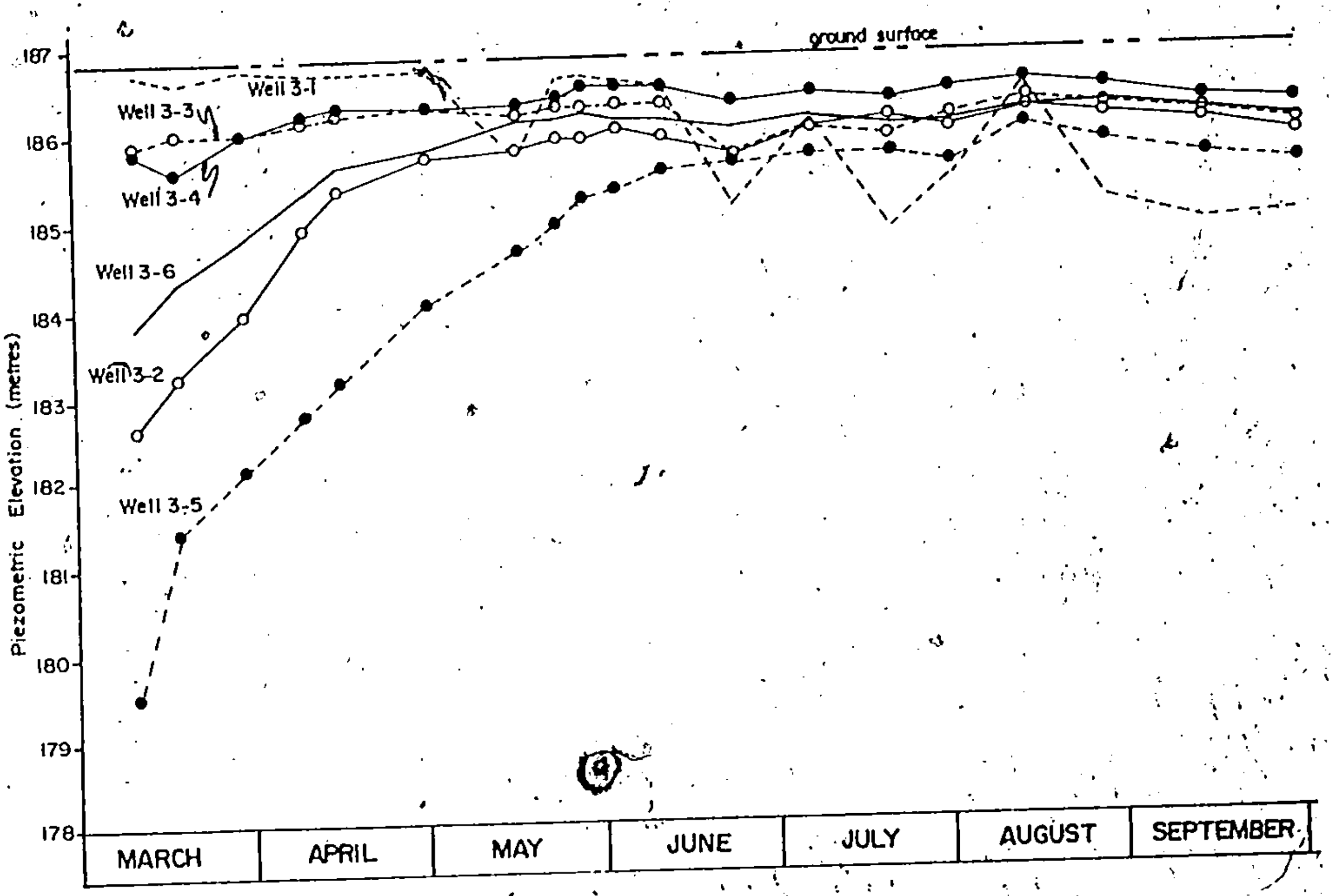
OBSERVATION WELL HYDROGRAPHS
(MARCH to SEPTEMBER 1983)



WOODSLEE TEST SITE 3

FIGURE- 5.10

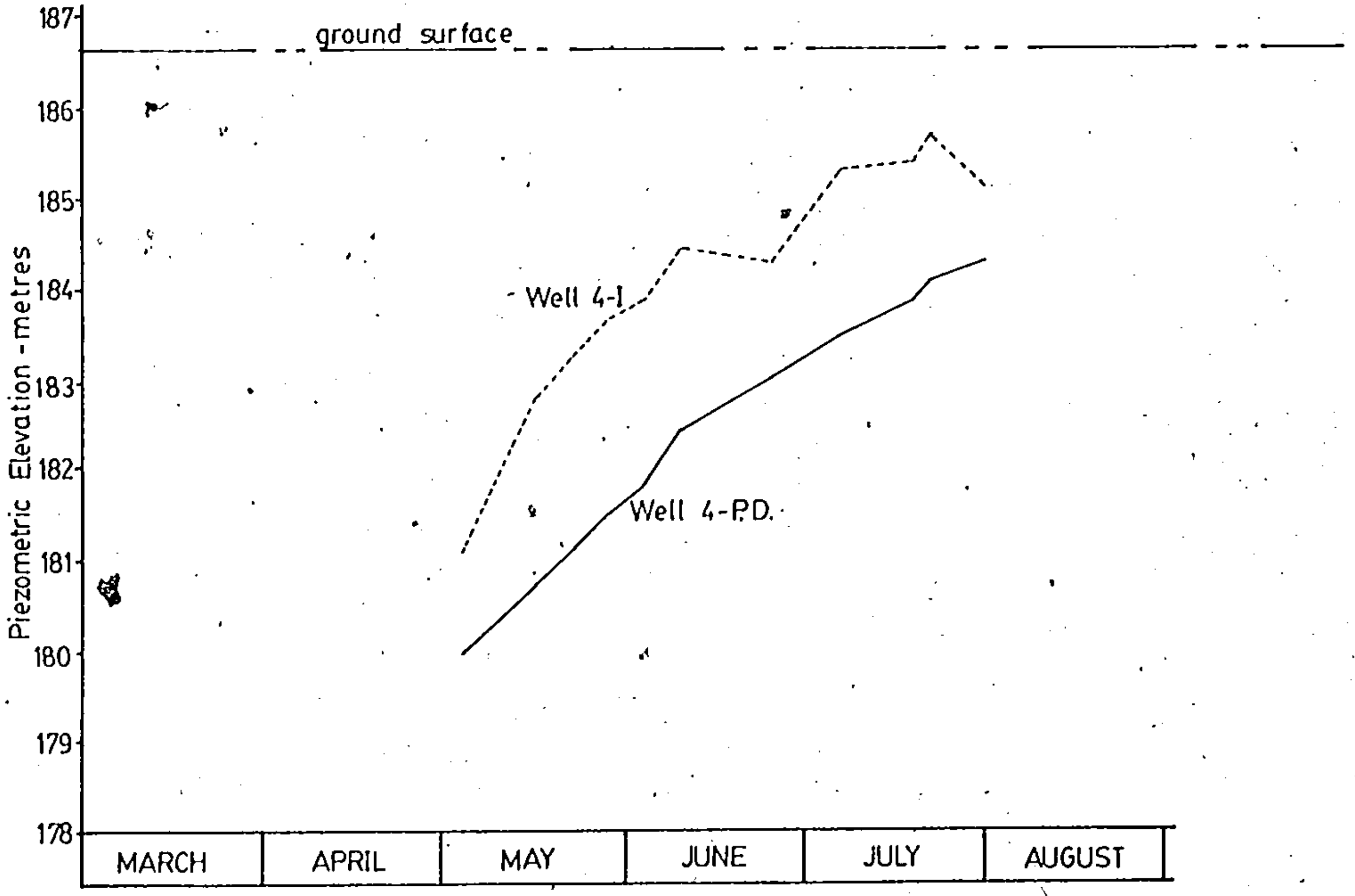
OBSERVATION WELL HYDROGRAPHS
(MARCH to SEPTEMBER 1983)



WOODSLEE TEST SITE 4

FIGURE- 5.11

OBSERVATION WELL HYDROGRAPHS
(MAY to AUGUST 1983)



The long screen water table wells 1-1 and 2-1 can be seen to have quickly established equilibrium with the water table. The level of the water table at Monitoring Sites 1 and 2 varied from as shallow a depth as 200 mm to as great a depth as 1.2 metres during the monitoring period.

The deeper piezometer installations which had screened lengths of only 1.5 metres, took almost the entire six months of the observation period to stabilize with respect to the <u>in situ</u> piezometric pressure in the silty clay surrounding the observation well screens.

At Monitoring Site 3 each of the observation wells was installed as a piezometer and all of the wells had identical 1.5 metre long well screens. During the two months following the installation of the wells, observation well 3-1 behaved predictably indicating a piezometric level approaching the level of the ground surface. This level was consistent with the water that ponded on the ground surface during this period. Observation well 3-1 began to exhibit anomalous responses near the beginning of May, a condition that continued throughout the monitoring period. It is believed that the erratic variations in the water level measured in this well are directly related to the proximity of a large oak tree to the well location. If the well responds to moisture demand from the tree roots then the level in the well could be expected to vary depending on the time of day, temperature and the moisture available to the tree from precipitation.

An examination of the hydrographs from the other five wells at Monitoring Site 3 show some complementary reaction to the major fluctuations in level measured in well 3-1. These complementary reactions are most likely indicative of an actual decline in the piezometric head since the severest of these trends can also be detected in the water table hydrographs from Monitoring Sites 1 and 2. It is possible that the moisture demand of the trees near Monitoring Site 3 accentuates the decline in the water table during periods of dry weather.

It is noted that wells 3-3 and 3-4 reached piezometric equilibrium with the soil surrounding the well screens in a period of less than four weeks whereas observation wells 3-2, 3-5, and 3-6 did not achieve similar equilibrium in less than three months.

The hydrographs obtained at Monitoring Site 4 are only representative of a three-month period because these wells were installed at a later time than at the other monitoring sites and it was necessary to discontinue monitoring earlier, to facilitate other testing carried out at this site. The available water level information from Monitoring Site 4 does suggest similarity of response to the other well installations.

5.1.3.2 Groundwater Flow

The observation well hydrographs indicate the water table at the Woodslee test site is generally less than one metre below grade. The water table in the south west area of the site (Monitoring Site 3) actually rises to the ground surface during the early Spring. Only at Monitoring Site 2 were water table levels more than one metre below grade recorded. The greatest depth to water table level was recorded during late August and September when the water table as indicated by observation well 2-1 was 1.2 metres below grade. The lower recorded water table level at the Monitoring Site 2 location is probably the result of the preferential drainage of this area by the surficial layer of sand.

The Woodslee test site is generally drained by a series of shallow (450 to 600 mm deep) field tiles, that have been installed a spacings of 7.5± metres. Only in the southwest area of the site are there no drainage tiles and it is in this area that the water table was measured closest to the ground surface.

A comparison of the water table well levels and the equilibrium piezometric levels, recorded in the piezometer type observation wells installed at Monitoring Sites 1, 2, and 3, clearly indicate the Woodslee test site is in a recharge area and groundwater movement is downward. A plot of the piezometric head variation with depth as measured at each of the monitoring sites is presented in Figure 5.12. The vertical gradient lines for Monitoring Sites 1 and 2 are based on two points because there are only two observation wells at each of these sites. At Monitoring Site 3, where there were six wells installed, there is sufficient scatter of the data points to make an obvious interpretation of the gradient line impossible. Linear regression was used to determine the best fit line of the vertical hydraulic gradient for the data from this site. As can be seen from an examination of the resulting vertical gradient lines plotted in Figure 5.12, the line derived from the regression analysis for Monitoring Site 3 is not inconsistent with the vertical gradient lines derived from Monitoring Sites 1 and 2. Based on the results of these observations the vertical gradient at the Woodslee test site varies from 0.01 to 0.06.

An examination of Figure 2.2, which indicates the relative position of the Woodslee test site in the Belle River drainage basin, suggests that the lateral flow of groundwater beneath the test site should be essentially east towards Belle River and somewhat north towards Lake St. Clair. An analysis of the observation well data indicates this is not the case. The plot of groundwater equipotential presented in Figure 5.13 is derived from the water table data at the monitoring sites on September 30, 1983. The orientation of the equipotential lines is essentially the same when the data from the deeper piezometers is used to generate an equipotential plot. It is therefore the indication of the observation well data that groundwater at the Woodslee test site flows to the east toward Belle River but the flow is southeast away from Lake St. Clair. This flow direction could be the result of influence by a minor tributary of Belle River that is located south and east of the Woodslee test site.

WOODSLEE TEST SITE

PIEZOMETRIC HEAD variation with depth

September 30, 1983

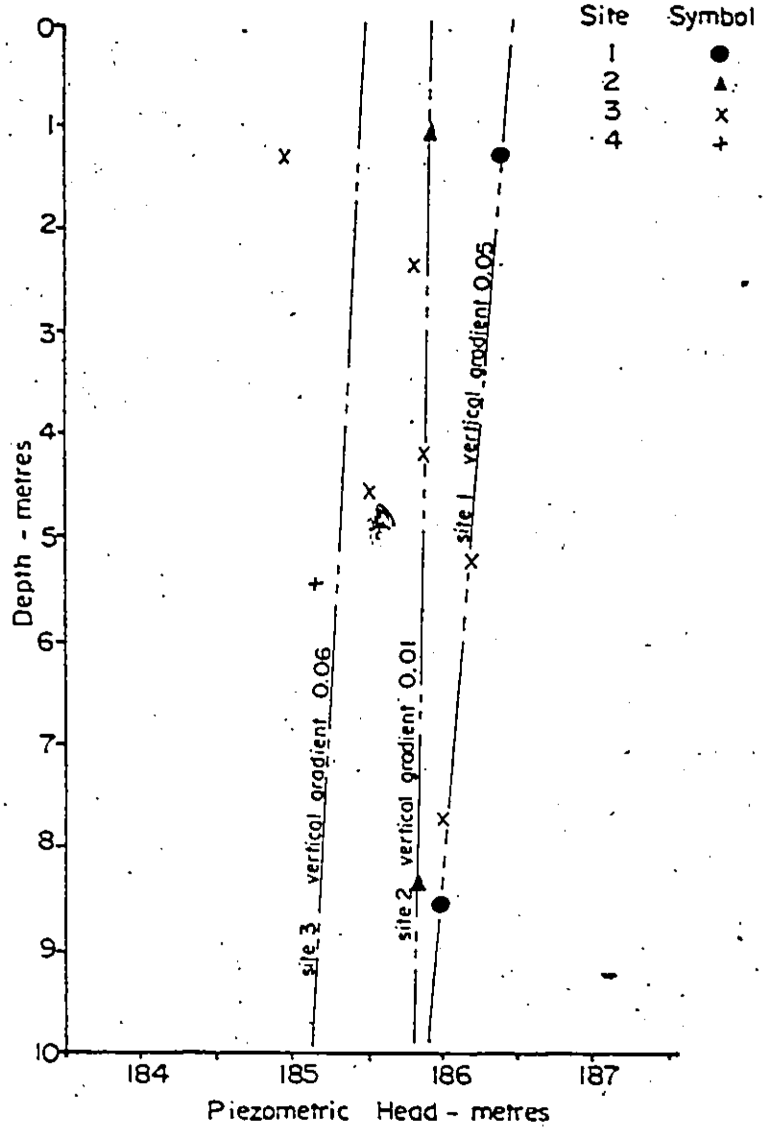
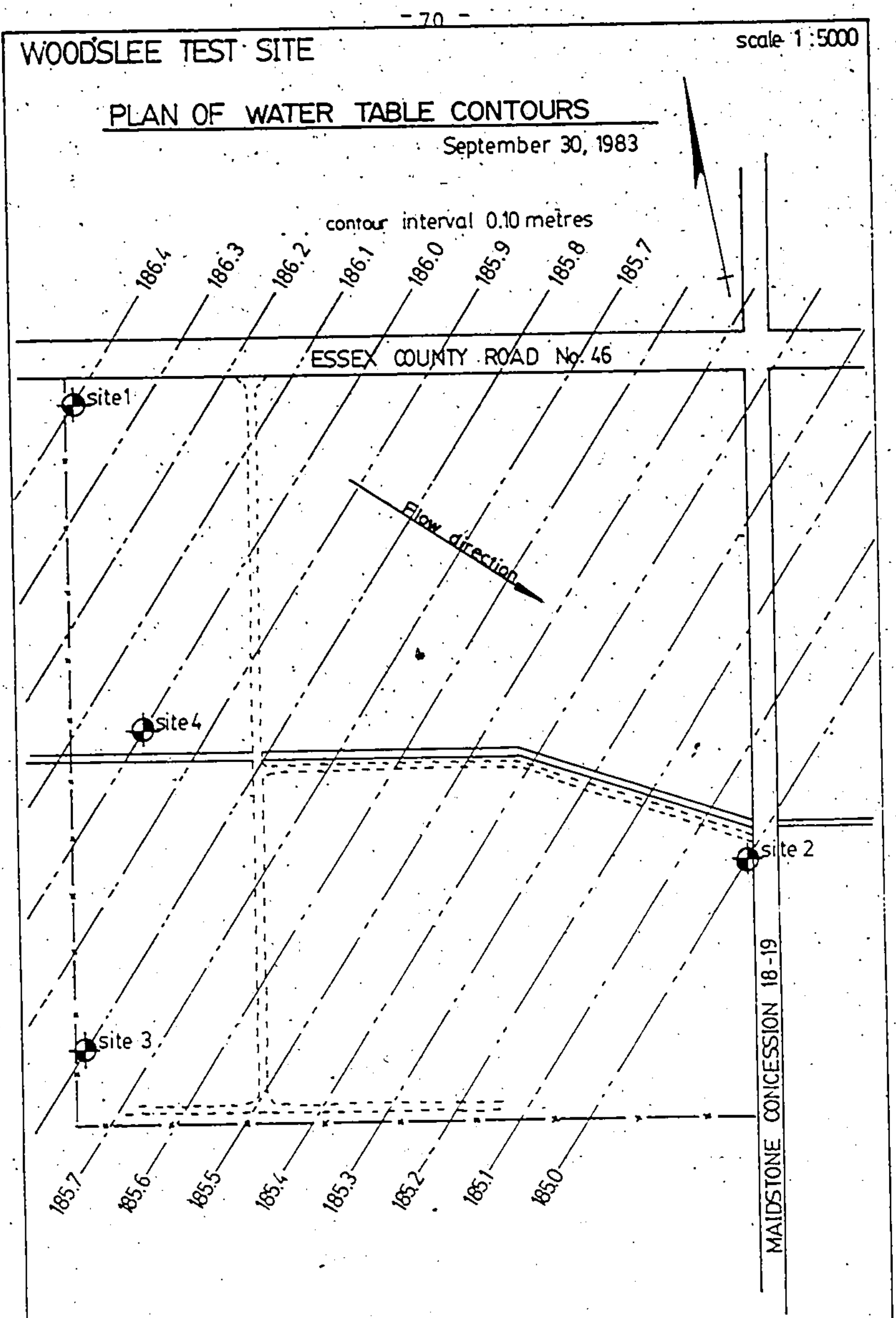


FIGURE - 5.12



WOODSLEE TEST SITE

PLAN OF WATER TABLE CONTOURS

September 30, 1983

FIGURE - 5.13

The horizontal component of the hydraulic gradient at the Woodslee test site is of the order of 0.002 based on these observations. Observation well data therefore indicate that the groundwater moves downward in response to a hydraulic gradient approximately one order of magnitude greater than the component of hydraulic gradient that induces lateral flow.

5.1.3.3 Electrical Conductivity

The groundwater at the Woodslee test site was found to have electrical conductivity in the range of 1000 to 3300 uS indicative of water that is fresh to slightly brackish.

Electrical conductivity readings were taken in the observation wells of the Woodslee test site at regular intervals during the six month monitoring period. It was found that the electrical conductivity fluctuated in the individual observation wells even when these wells were demonstratably at equilibrium with the groundwater surrounding the well screen. The magnitude of this fluctuation is a characteristic of each well installation. The electrical conductivity in all of the observation wells showed a tendency to decline from Spring to Autumn. The average electrical conductivity values from the measured data at each of the observation wells was plotted against the depth of the well screens and this plot is presented in Figure 5.14. An examination of this plot indicates a scatter range of the order of 2000 uS, but a trend to reduced electrical conductivity with increasing depth is apparent.

5.1.3.4 Environmental Isotopes

The concentration of oxygen-18 and tritium in samples of pore water extracted from soil samples taken at the Woodslee test site were determined and the results of these analyses are plotted at the

WOODSLEE TEST SITE

ELECTRICAL CONDUCTIVITY variation with depth

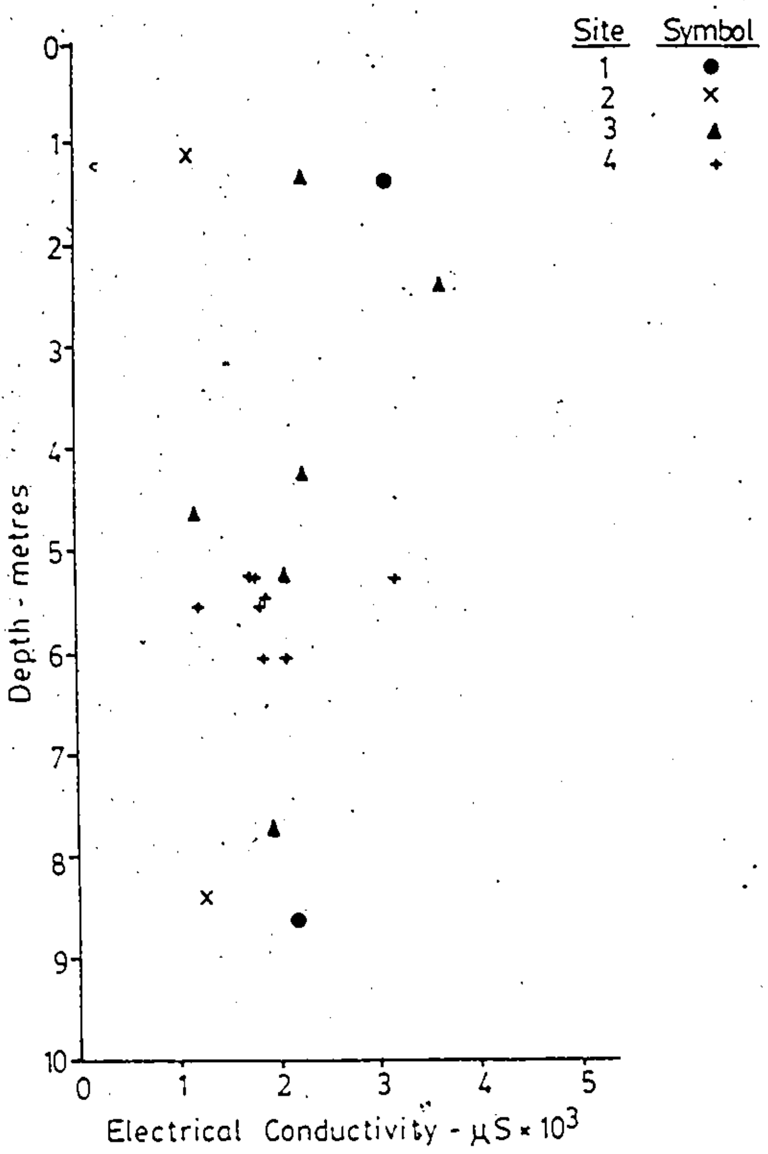


FIGURE - 5.14

corresponding sample depths in Figure 5.15. The results of the analyses for tritium concentration are accurate to only ±8 TU and the concentrations measured are plotted indicating this confidence interval for each of the measured concentrations. The confidence interval for the measured depletion of ^{18}O in the samples is ±0.2 $\delta^{18}O$ o/ooSMOW.

An examination of the tritium concentrations determined in the silty clay beneath the Woodslee test site suggests that there is generally a decrease in the tritium concentration with increasing depth at Monitoring Site 2. The tritium concentrations suggest that the pore water taken from depths of 7± metres and 10± metres entered the ground prior to 1953. That pore water taken from between the 7 and 10 metre levels was found to contain greater tritium concentrations, suggests that there are some preferential zones of flow in the silty clay. Mixing of new and old water is taking place at some locations in the till deposit.

At Monitoring Site 3 the tritium concentrations in the pore water samples taken from above a depth of 8± metres indicate a trend toward decreasing tritium concentrations with increasing depth, as is the case at Monitoring Site 2. The pore water samples taken from depths of 9± and 10± metres are however distinctly tritiated, consistent with substantial mixing of old and new pore water in the silty clay. These samples are therefore representative of younger pore water that has advanced to depth at a rate greater than the nominal rate of the site.

The oxygen-18 depletion in the pore water samples obtained, varies from approximately -9 to -13 $\delta^{18}O$ o/ooSMOW between depths of 4 to 10 metres respectively.

WOODSLEE TEST SITE

ENVIRONMENTAL ISOTOPE CONCENTRATION
variation with depth

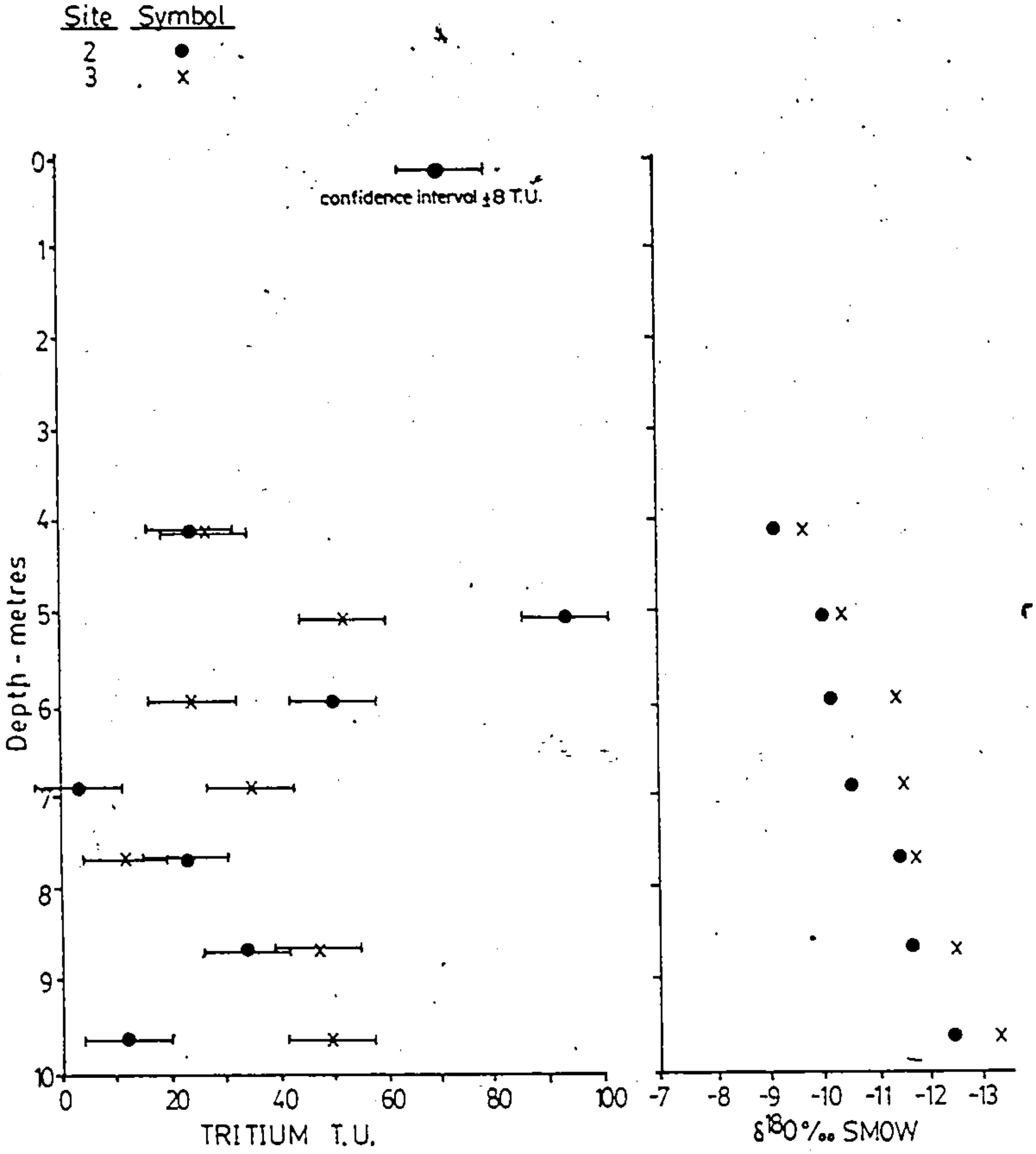


FIGURE - 5.15

5.1.4 Laboratory Hydraulic Conductivity Evaluation

5.1.4.1 Permeameter Test Results

The results of hydraulic conductivity tests carried out on samples of silty clay till from the Woodslee test site are tabulated in Appendix H. These results are plotted according to depth in Figure 5.16.

In total 20 separate samples of silty clay were placed in the permeameter. The flow through each sample was measured several times for each sample. The mean of the hydraulic conductivity values determined from each assessment of permeant flow through the sample are plotted in Figure 5.16.

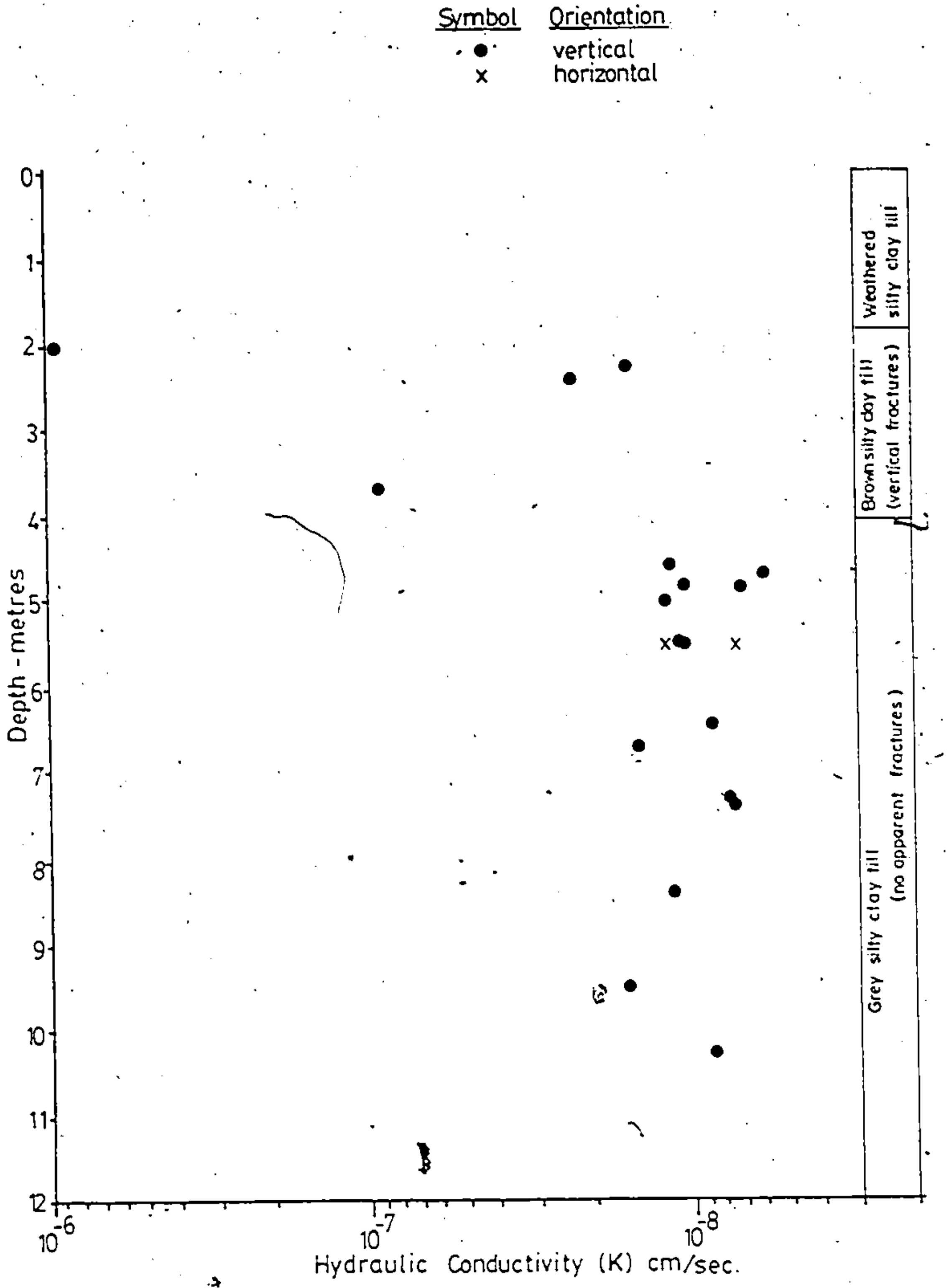
All of the hydraulic conductivity 'K' values from the measured flow values for each sample were assessed for variation of the 'K' value with the time of flow through the sample. It was found that there was no apparent variation in hydraulic conductivity with flow time in the test periods of 1 to 2 hours. The 'K' assessments for all of the samples were normally distributed about the mean hydraulic conductivity as determined from the range of measurements. The variation in flow measurements can be attributed to the systematic error associated with the measurement procedures and equipment. The standard deviation of the hydraulic conductivity values was in the range of 1.3×10^{-10} to 1.5×10^{-9} cm/sec.

Only four samples were tested from the upper four metres of silty clay till at the Woodslee test site. Intact, undisturbed samples of the 'very stiff' to 'hard' desiccated till were difficult to obtain and trim, particularly when the majority of the samples obtained contained some fracturing. The permeameter tests of the four samples that were obtained and sucessfully trimmed, indicate 'K' values ranging from 1.65×10^{-8} to 96.6×10^{-8} cm/sec. The two samples that were found to have 'K' values

WOODSLEE TEST SITE

FIGURE - 5.16

PERMEAMETER TEST RESULTS



of more than 10^{-7} cm/sec both contained visible fractures and the other two samples of the desiccated material did not.

The remaining sixteen permeameter tested samples from the Woodslee test site were taken from the plastic grey silty clay till found beneath a depth of 4± metres. None of these samples contained visible fissures or fractures.

One of the shelby tube samples of the silty clay till from Monitoring Site 4, taken from a depth of 5.5 metres, was divided into four separate samples to be tested in the permeameter. Two of these samples were tested in a vertical orientation and the other two were tested in a horizontal orientation. One of the vertically oriented samples and one of the horizontally oriented samples was tested using a saturated saline permeant, as opposed to the natural groundwater permeant that was used for the other samples tested. The results of these four tests indicated hydraulic conductivity values in the range of 0.7×10^{-8} to 1.15×10^{-8} cm/sec and the highest and lowest 'K' values measured were both obtained on samples oriented horizontally. There is therefore, no apparent variation in the hydraulic conductivity of the silty clay till associated with sample orientation or with the use of a saline permeant as opposed to a natural groundwater permeant. The duration of these tests was of the order of 1 or 2 hours. Longer exposure of the silty clay to the saline permeant could generate different results.

All of the permeameter tests carried out on samples of the grey plastic silty clay indicated hydraulic conductivities in the range of 0.58×10^{-8} to 1.68×10^{-8} cm/sec. The mean hydraulic conductivity was 1.0×10^{-8} cm/sec and the standard deviation was 3.2×10^{-9} cm/sec. An examination of the test results plotted in Figure 5.16 suggests that the range of hydraulic conductivity variation as indicated by the permeameter test results is independent of depth, below the 4 metre level.

5.1.4.2 One-Dimensional Consolidation Test Results

The results of one-dimensional consolidation tests carried out on four samples of silty clay till from Monitoring Site 4 of the Woodslee test site are plotted on Figures 5.17 and 5.18. Two of the samples tested were from a depth of 3 metres and the other two samples were from a depth of 6 metres. One sample from each depth was tested in a vertical orientation and the other sample from each of these depths was tested in a horizontal orientation.

As discussed in detail in Section 3.2.4, the hydraulic conductivity of a sample as derived from a consolidation test is dependent on the state of stress in the sample and the stress history of the soil. The plots of the consolidation test results include the variation of the soil void ratio with applied pressure, the variation of the coefficient of consolidation 'C_v' with applied pressure, and the variation of hydraulic conductivity with applied pressure.

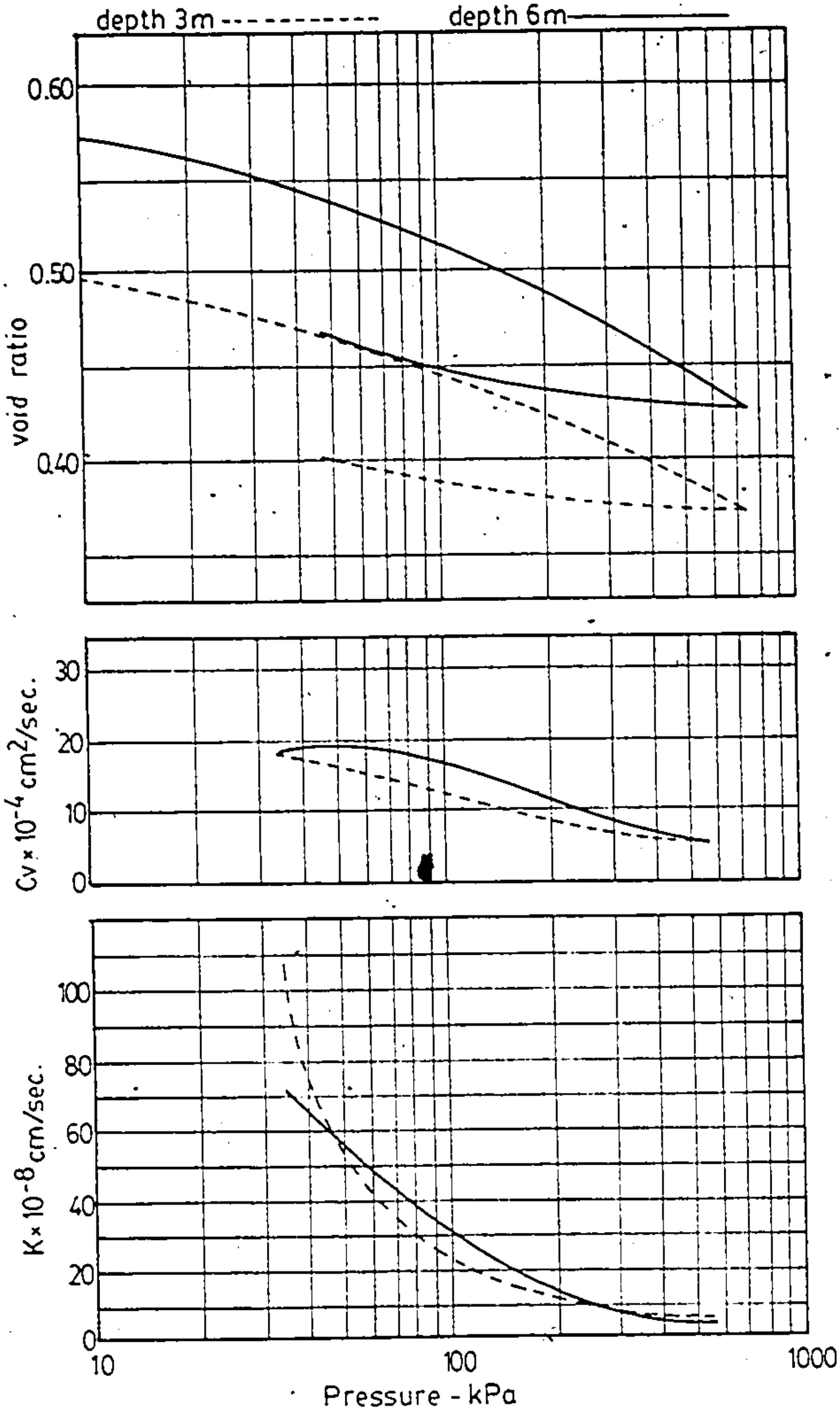
The silty clay till at the Woodslee test site is over consolidated. The silty clay has experienced greater effective stresses at some time in its history than the present overburden now exerts. The consolidation test results indicate that this over consolidation is greater at shallower depth. Over consolidation can be generated by a desiccation mechanism as opposed to simple applied loading. The desiccation of the upper layer of the silty clay till at the Woodslee test site suggests that this mechanism is the cause for the greater over consolidation of the shallower levels of till at this site. The shallower (3 metre depth) samples tested, therefore have a lower initial void ratio than the samples from the 6 metre depth, even though the present overburden pressures at 3 and 6 metres are of the order of 40 and 75 kPa respectively.

WOODSLEE TEST SITE

FIGURE- 5.17

CONSOLIDATION TEST RESULTS

vertical orientation

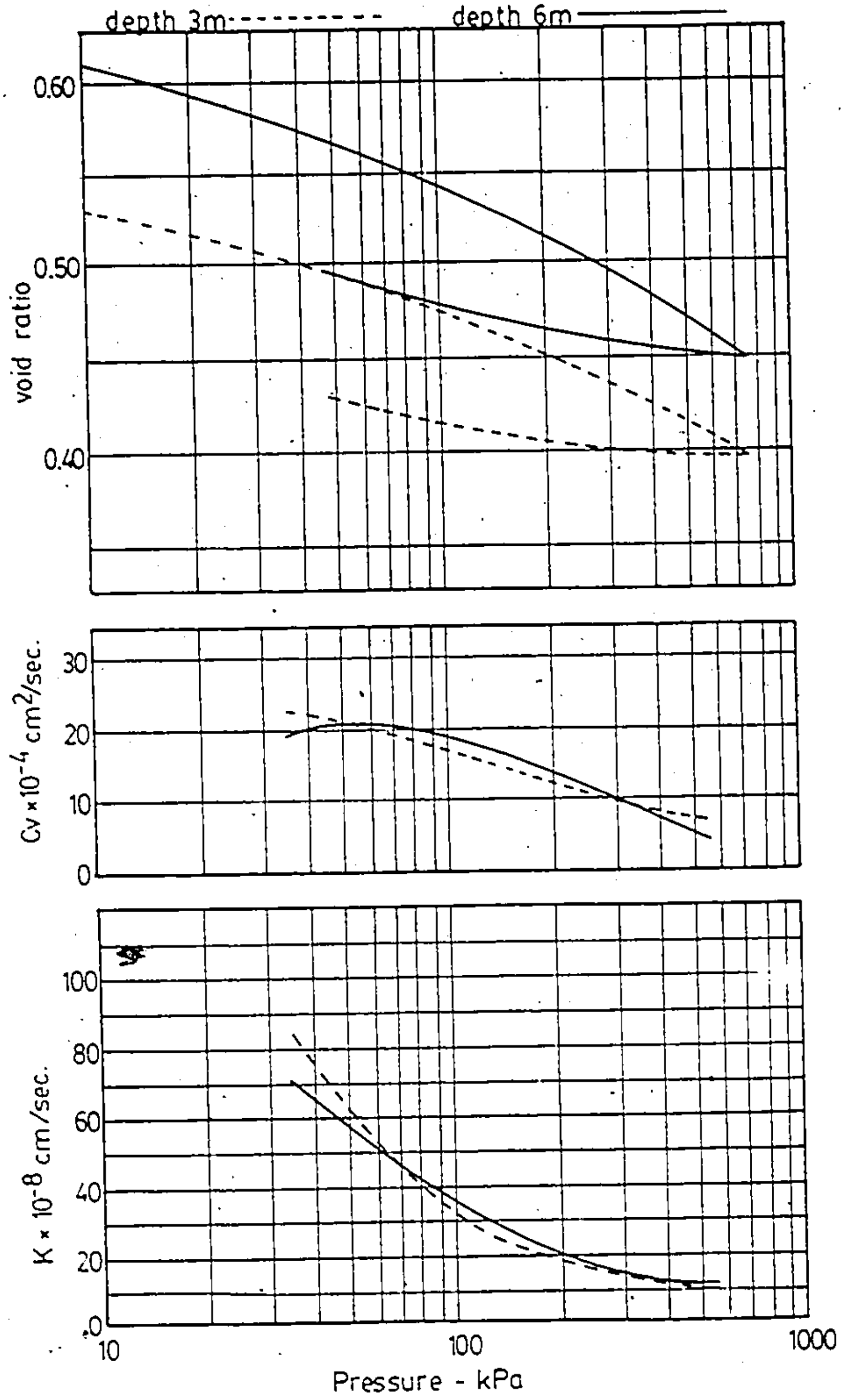


WOODSLEE TEST SITE

FIGURE- 5.18

CONSOLIDATION TEST RESULTS

horizontal orientation



The application of these present overburden pressures to the hydraulic conductivity versus pressure diagrams generated by the consolidation test results, indicates that the hydraulic conductivities of the silty clay for the 3 metre and 6 metre depths are of the order of 7 and 4 x 10^{-7} cm/sec respectively. The value of 'K' was also found to be independent of sample orientation based on these test results. The one-dimensional consolidation test derived hydraulic conductivity values are tabulated in Appendix H.

5.1.4.3 Three-Dimensional Consolidation Test Results

Only two samples of silty clay from the Woodslee test site were tested for hydraulic conductivity by the three-dimensional consolidation test method. The samples tested were from depths of 5 and 6 metres at Monitoring Site 4. The in situ overburden pressure at these depths is of the order of 65 and 75 kPa respectively.

The triaxial consolidation tests also indicated the silty clay till from the Woodslee test site is over consolidated. The hydraulic conductivity pressure curves developed from these tests indicated the silty clay samples from depths of 5 and 6 metres had 'K' values of the order of 8 x 10^{-8} and 11 x 10^{-8} cm/sec at pressures equivalent to the in situ pressure at the levels from which these samples were taken. These results are tabulated in Appendix H.

5.1.5 Field Test Results

5.1.5.1 Single Well Response Test Results

The results of the single well response tests carried out at the Woodslee test site are tabulated in Appendix H. The table lists the results of these tests for the ten observation wells installed at Monitoring Sites 1, 2, and 3 as well aity evaluations based on the observation well hydrographs are also tabulated in Appendix H under the heading 'hydrograph'.

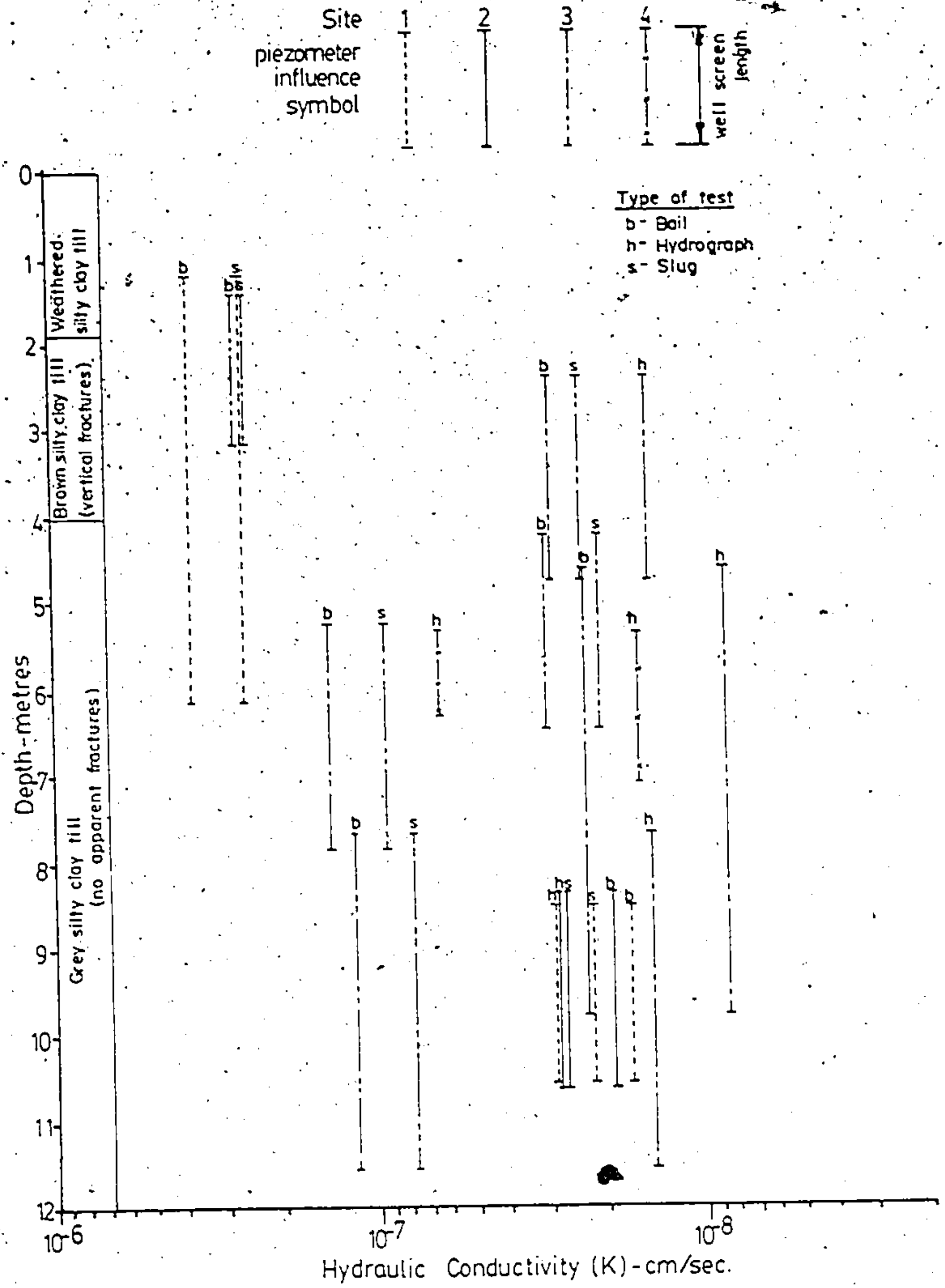
The single well response test results of slug, bail and hydrograph interpretation form are plotted in Figure 5.19, with the depth range of the observation well screen for each well indicated. In general when the hydraulic conductivity of the soil surrounding the observation well screens was evaluated by slug and bail tests or by bail and hydrograph interpretation, the 'K' values obtained for any one observation well were of the same order of magnitude and the actual 'K' values were relatively similar.

Variations in the test results from a single well can be attributed to random error generated by variances in the accuracy of the water level measurements and the interpretation of the curves that result from these measurements. The screen of the well and the associated sand pack are not uniform structures, and though every effort was made to surge and improve the well screen and sand pack configuration after the installation of the wells, it was still possible that a non-uniform gradation of soil existed around the well such that there could be a preferential direction of flow, either into or out of the well screen.

Wells 3-5 and 3-6, which had screens at 4.6 to 9.8 and 7.7 to 11.5 metres in depth respectively did not yield consistent values of 'K' for the various types of single well response tests. The results of the slug test at well 3-5 were suspect because the cap fell off of the well during the test period and rain water entered the well. There is however, an order of magnitude difference between the bail and hydrograph assessments of hydraulic conductivity from this well. The results of slug and bail tests carried out in observation well 3-6 are similar in magnitude but like well 3-5, there is an order of magnitude difference between the 'K' value assessed when a sudden head differential was introduced as opposed to the assessment based on the natural time lag associated with the well

WOODSLEE TEST SITE FIGURE- 5.19

SINGLE WELL RESPONSE TEST RESULTS



installation procedure. These test results suggest that there was a difference in the observation well screen configuration during the initial time lag period and the subsequent period when the single well response tests were performed. This could have been the result of inadequate well development after installation, in which case the results of the slug and bail tests would be more representative of the in situ hydraulic conductivity than the hydraulic conductivity values derived from the well hydrographs.

Only the results of the slug and bail tests carried out in Well 2-1 are not included in Figure 5.19. Well 2-1, with a screen from 1.0 to 6.2 metres below grade, intercepted a surficial deposit of sand, as was previously discussed. Since this well was designed as a water table well and had a long screened section, the screen apparently contacted the sand deposit beneath the seal level. Single well response tests in this well indicated a value of 'K' ranging from 1.33 x 10^{-2} to 1.39 x 10^{-2} cm/sec as could be expected for an observation well established in sand. The single well response test results obtained from observation well 2-1 are subsequently 5 to 7 orders of magnitude different from the hydraulic conductivity values obtained for well screens established in the silty clay till as plotted in Figure 5.19.

An examination of the plot of the single well response test results suggests three distinct ranges of hydraulic conductivity for the silty clay till. The majority of th test indicated a 'K' value in the range of 1.5 x 10^{-8} to 3 x 10^{-8} cm/sec. The well screens associated with thes results were installed between depth of 2.4 and 11.5 metres. Three of the wells tested indicated a hydraulic conductivity in the range of 0.60 x 10^{-7} to 1.5 x 10^{-7} cm/sec. The well screens that yielded these results were installed between depths of 5.2 and 11.5 metres. Two of the observation wells indicated hydraulic conductivity values in the range of 2.5 x 10^{-7} to 4.0 x 10^{-7} cm/sec. Significantly, these two observation wells were the shallowest of the wells installed, with the top of the screen from 1.2 to 1.4 metres below grade, where fractures may be present.

5.1.5.2 Borehole Dilution Test Results

The testing was performed in two wells at Monitoring Site 4, 4-I and 4-PD, and the results of these tests are presented as a semilogarithmic plot of electrical conductivity versus time in Figure 5.20.

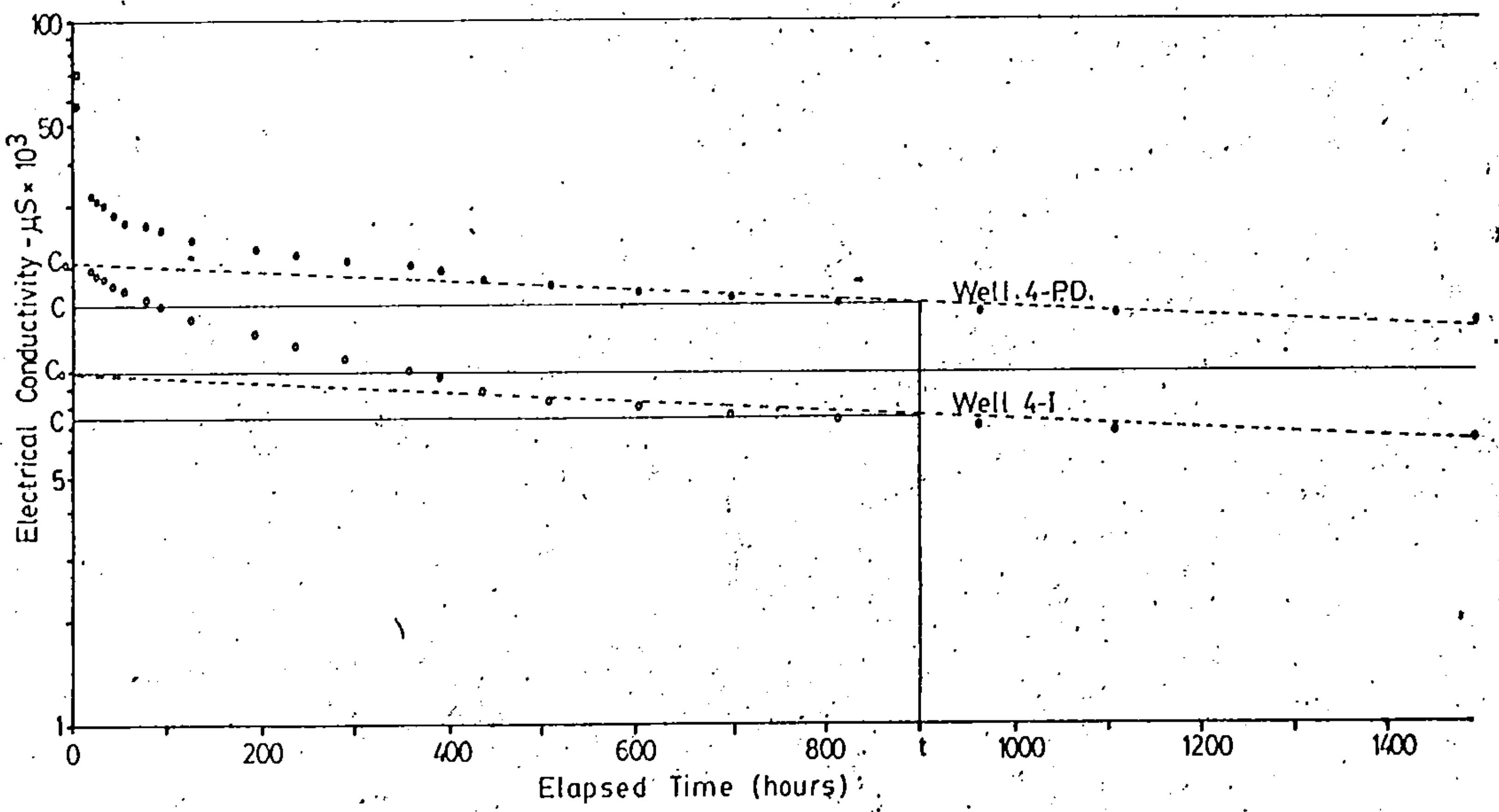
Equation (22) relates the rate of change in concentration of the tracer in the borehole, 'dC/dt', to the apparent average linear velocity 'v_a' of the water passing through the well screen and diluting the tracer. The solution of Equation (22) to determine the apparent average linear velocity, Equation (23), suggests that there will be a linear log-normal relationship between the tracer concentration (electrical conductivity) and elapsed time. An examination of the results from both of the point dilution tests carried out at the Woodslee test site indicates that such a linear relationship existed only after a significant period of time had elapsed in the test. The decrease in the log of electrical conductivity initially occurs at a greater rate than occurs later in the test, suggesting that the apparent tracer velocity is not constant throughout the test period.

In accordance with Equation (25), the apparent velocity of the groundwater as determined by the point dilution method is affected by the actual average linear velocity of the groundwater and the diffusion of the tracer in the groundwater. Diffusion occurs in accordance with Fick's first and second laws (Equations (20) and (21)) such that the diffusion induced component of apparent average linear velocity 'v_d' is compatible with the flow induced component of apparent average linear velocity. Diffusion of the tracer in the groundwater would not therefore affect the linearity of the log of concentration versus time plot. The initial curved

WOODSLEE TEST SITE

FIGURE - 5.20

BOREHOLE DILUTION TEST RESULTS



portion of this plot must therfore be the result of a variation in the actual average linear velocity of the water leaving the well screen.

The test procedure was examined to determine what factor would cause an increased flow rate at the start of the test, the influence of which would decline with time. It was immediately apparent that the insertion of the probe into the seal of the observation well would pressurize the well screen increasing the piezometric head in the screen and inducing a hydraulic gradient between the screen and the surrounding formation. This gradient temporarily alters the average linear velocity of the water passing through the screen and distorts the log-concentration versus time curve. The excess head in the well screen slowly declines to zero and at sometime during the test no longer influences the basic dilution relationship of Equation (23).

An elapsed time of 900 hours was selected intersecting the linear portion of the log conductivity versus time curves for the tests, and corresponding conductivity co-ordinates were determined as indicated in Figure 5.20. The linear portion of the curves was projected to time zero and the corresponding conductivity co-ordinate was recorded the effective initial concentration (C_o). The application of these values in Equation (23) yields apparent average linear velocities of 1.2×10^{-6} and 1.1×10^{-6} cm/sec for wells 4-I and 4-PD respectively.

5.1.5.3 Tracer Test Results

A single two well type tracer test was carried out at Monitoring Site 4 of the Woodslee test site and the procedure used for this testing is discussed in Section 4.1.6. Prior to the start of the test, the electrical conductivity of the groundwater in the injection well (4-D and the six receptor wells (4-R1 to 4-R6 inclusive) were monitored for a two month period. As has been discussed in Section 5.1.3.3, the electrical conductivity measured in an observation well fluctuates and the mean electrical conductivity measured in an observation well is particular to a well installation. It was therefore necessary to determine the mean electrical conductivity for each of the observation wells used in the tracer test and determine the natural range of electrical conductivity fluctuation in the wells. When an apparent concentration peak appeared in a receptor well it would then be possible to distinguish a natural variation of the conductivity readings from a variation induced by the sodium chloride tracer.

The tracer test results are plotted on Figures 5.21 and 5.22. The electrical conductivity measurements were recorded as variations from the mean electrical conductivity determined for each of the individual receptor wells as opposed to plotting the absolute electrical conductivity variation. The mean electrical conductivity of each well is bounded on each side by a border indicative of two standard deviations from the mean. The standard deviation designated is the mean standard deviation of all of the standard deviations of the electrical conductivity distributions in the receptor wells. The readings from the months of June and July prior to the injection of the tracer are plotted to a reduced horizontal time scale relative to the readings from the months of August and September when the tracer was in the ground.

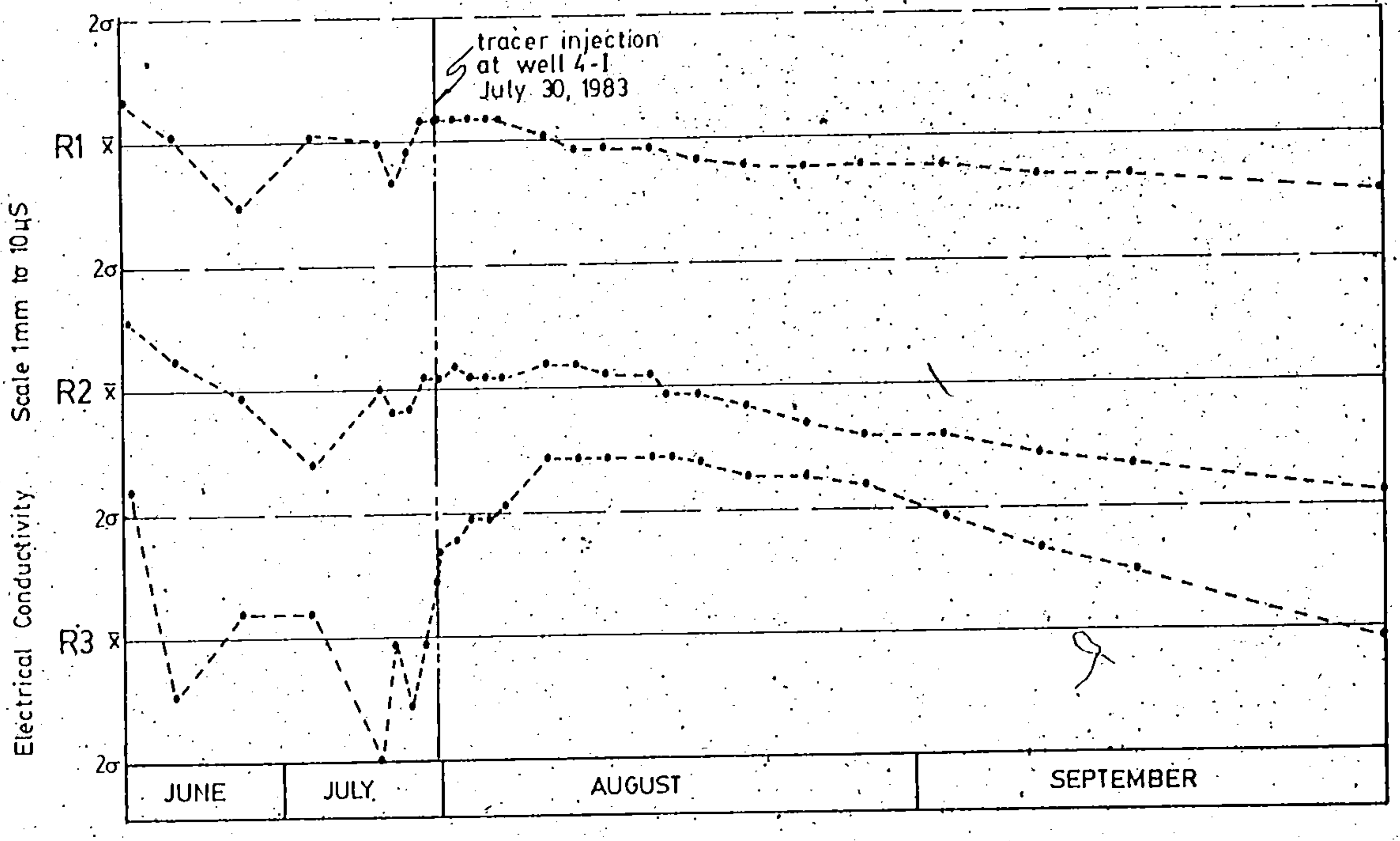
Examination of the tracer test plots indicates that only two of the observation wells in the receptor array, 4-R3 and 4-R6, responded to the injected tracer. Of these two wells, well 4-R6 is further from the injection well with a separating silty clay barrier 745 mm wide. It was at well 4-R6 that the tracer was first detected at an elapsed time of 26.75 hours. Well 4-R3 is separated from the injection well by only 415 mm of silty clay and yet it took 191 hours for the tracer to appear at this well location.

WOODSLEE TEST SITE

FIGURE- 5.21

TRACER TEST RESULTS

OBSERVATION WELLS R1, R2 and R3 - SITE 4

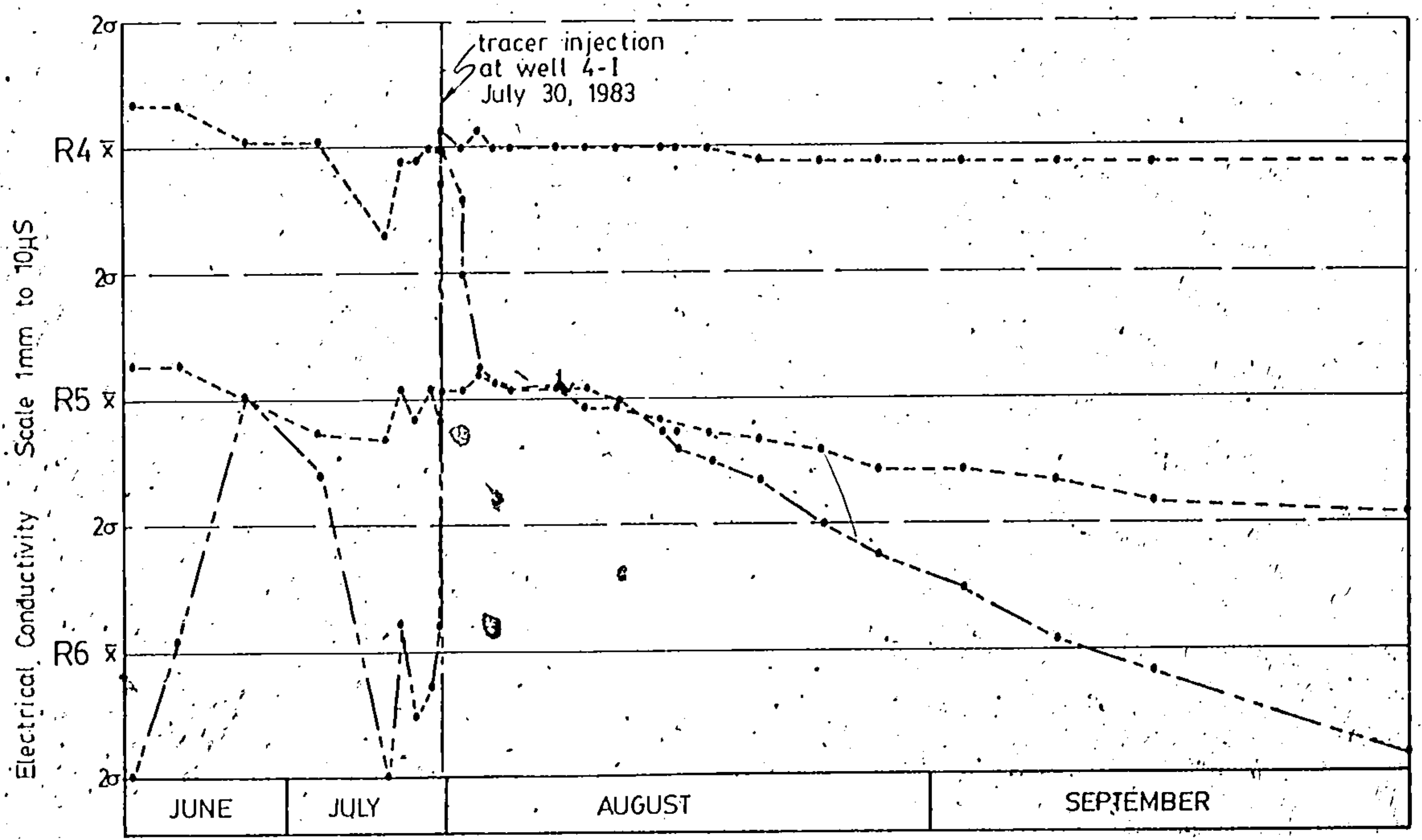


WOODSLEE TEST SITE

FIGURE -5.22

TRACER TEST RESULTS

OBSERVATION WELLS R4, R5 and R6 - SITE 4



The transfer rate of the tracer from the injection well to the receptor wells suggests the average linear velocity of the groundwater was 7.7 x 10^{-4} cm/sec to well 4-R6 and 6.0 x 10^{-5} cm/sec to well 4-R3.

The direction of groundwater flow as indicated by the tracer test results is approximately ten degrees north of east, approximately 45 degrees north of the flow direction indicated by the groundwater equipotential plot presented in Figure 5.13. This difference in flow direction is an indication of a local flow condition or that there is leakage of the tracer in directions inconsistent with the silty clay matrix material. This type of result could occur if there were cracks in the silty clay between the well screens.

5.2 West Windsor Test Site

5.2.1 Monitoring Site Locations

Monitoring Site 10 was located in the northeast corner of the Dome Petroleum Limited property portion of the West Windsor test site. The ground surface elevation in this area was measured at 181.30 metres. Monitoring Site 30 is approximately 250 metres west and 100 metres south of the Monitoring Site 10 location. The ground surface elevation measured at the location of Monitoring Site 30 was 181.80 metres. The area occupied by these two monitoring sites has the highest general grade elevation on the West Windsor test site. The land surface on the Dome Petroleum Limited portion of the West Windsor test site slopes toward the west and south. Monitoring Site 20 was also located on the Dome Petroleum Limited property, near the southeast corner, providing the maximum separation of the observation well sites possible on the property. The ground surface in this area was measured at 179.4 metres (ie., approximately 2 metres lower than Monitoring sites 10 and 30). The fourth monitoring site, Monitoring Site 40, was established as far to the

WEST WINDSOR TEST SITE

INSTRUMENTATION LOCATION PLAN

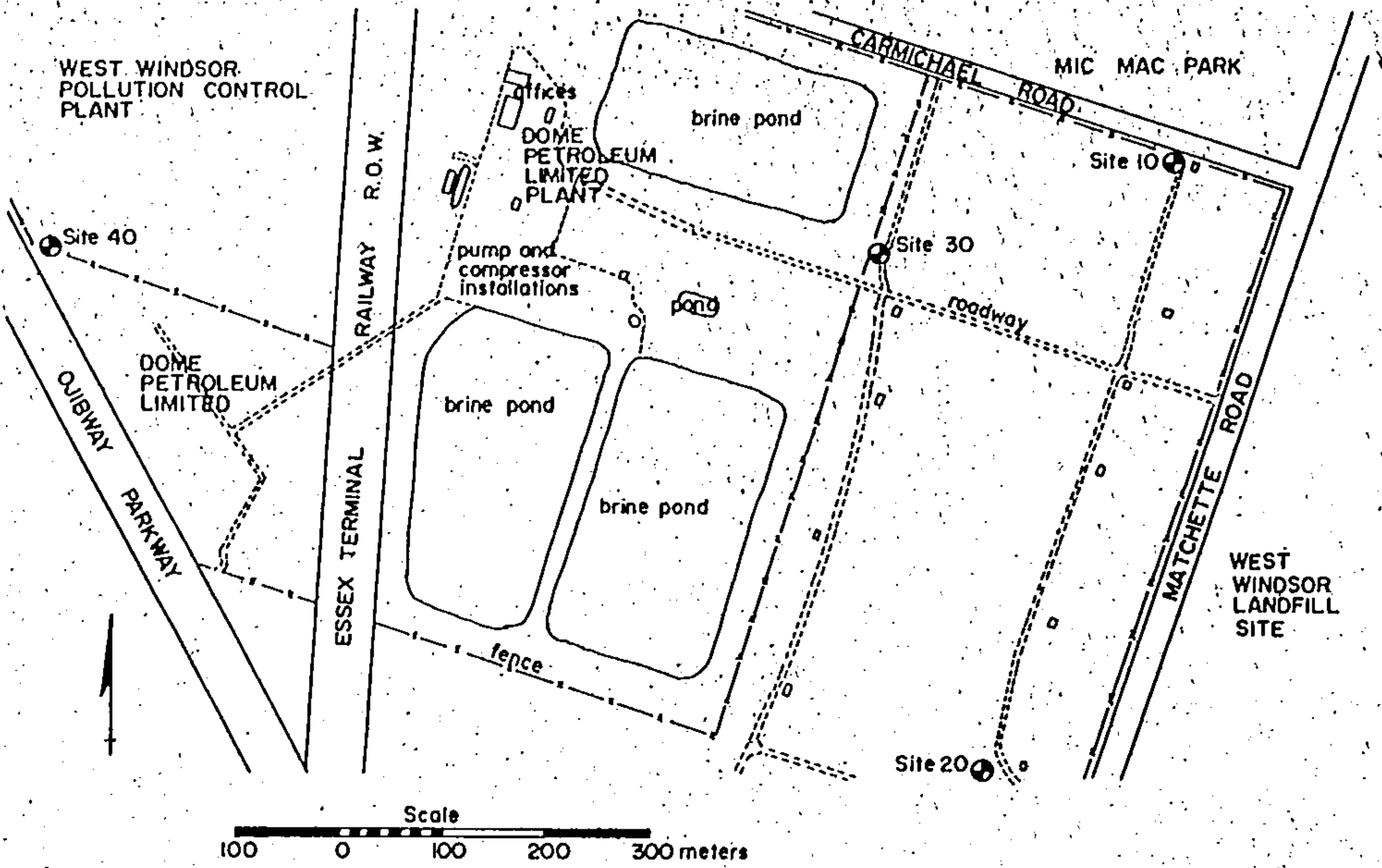


FIGURE- 5.23

west of the other monitoring sites as practically possible on the property of the West Windsor Pollution Control Plant. The ground elevation at this site is the lowest on the West Windsor test site. An average ground surface elevation of 177.9 metres was measured in this area. This level is 1.5 metres lower than the ground surface at Monitoring Site 2 and 3.5 to 4 metres lower than Monitoring Sites 10 and 30.

The locations of each of the monitoring sites are plotted on a plan of the West Windsor test site. This 'Instrumentation Location Plan' is presented in Figure 5.23. Each of the monitoring sites was installed on relatively flat grass covered ground. The area of Monitoring Site 10 is generally covered in brush type growth with a number of small trees, however, it was possible to locate the monitoring site such that the nearest of the trees is at least 15 metres from the observation wells. Two relatively small trees are located approximately 5 metres north of the observation wells at Monitoring Site 20 and at this monitoring site a shallow ditch approximately 600 mm deep is located 3 metres to the west of the observation wells. This ditch contained a small amount of water in the spring and was generally dry throughout the summer and autumn.

5.2.2 Soil Conditions

A detailed description of the soil conditions at each of the monitoring site locations is presented on the Borehole Logs, Figures 5.24 to 5.27, inclusive and the following is a summary of the subsurface conditions encountered.

The boreholes at Monitoring Site 20 penetrated 600 mm of fill material consisting of sand and sandy organic topsoil. This fill material was likely removed from the shallow ditch immediately adjacent to this monitoring site.

LOG OF BOREHOLE - WEST WINDSOR SITE 10

Vertical Scale: 1 to 75

SUBSURFACE PROFILE				SAMPLES		LABORATORY TESTING				
Elev. m	Depth m	DESCRIPTION	Symbol	Number	Type	Water content	Liquid limit	Plastic limit	Plasticity Index	Unit Weight
181.30	0.00	Ground Surface								
		Black sandy organic TOPSOIL		1	SS	17.1				
180.85	0.45	Loose to compact brown layered Fine to medium SAND		2	SS	16.7				
				3	SS	12.5				
				4	SS					
				5	SS					
178.85	2.45	Firm grey Varved SILTY CLAY		6	SS	23.9	22.6	11.1	11.5	
				7	SS	24.9				
				8	SS	27.0				
				9	SS	28.9	39.9	23.9	16.0	
				10	SS	29.4				
176.75	4.55	Soft grey SILTY CLAY with embedded sand and occasional gravel		11	SS	41.5				
				12	SS	45.8				
				13	SS	30.7	33.7	13.9	19.8	
				14	SS	36.5				
				15	SS	36.2				
				16	SS	32.9				
				17	SS	31.7	34.1	16.7	17.4	
				18	SS	30.1				
				19	SS	28.4				
				20	SS	27.1				
				21	SS	26.7				
				22	SS	20.8				
170.65	10.65	END of BOREHOLE								

FIGURE - 5.24

LOG OF BOREHOLE - WEST WINDSOR SITE 20

Vertical Scale: 1 to 75

SUBSURFACE PROFILE

Elev. m	Depth m	DESCRIPTION
17940	0.00	Ground Surface Black sandy organic TOPSOIL
179.25	0.15	Loose brown fine to coarse SAND
17880	0.60	Black sandy organic TOPSOIL
17865	0.75	Loose to compact brown Fine to medium SAND
177.90	1.50	Firm grey Varved SILTY CLAY
17530	4.10	Soft grey SILTY CLAY with embedded sand and occasional gravel
169.35	10.05	END of BOREHOLE

SAMPLES		LABORATORY TESTING				
Number	Type	Water content	Liquid limit	Plastic limit	Plasticity Index	Unit Weight
1	SS	23.7				
2	SS	17.3				
3	SS	24.0				
4	SS	23.1				
5	SS	23.8	24.4	16.6	7.8	
6	SS	22.7				
7	TW	23.2				
8	SS	24.4	27.0	18.9	8.1	
9	SS	27.5				
10	TW	31.0				
11	TW	28.2				21.5
12	SS	36.9				
13	SS	33.6	40.1	22.1	18.0	
14	SS	39.4				
15	TW	27.5				20.7
16	TW	23.6				
17	SS	26.3				
18	TW	27.0				
19	SS	35.2	30.9	19.6	11.3	
20	TW	16.4				
21	SS	30.5				
22	TW	20.3				

FIGURE - 5.25

LOG OF BOREHOLE-WEST WINDSOR SITE 30

Vertical Scale: 1 to 75

SUBSURFACE PROFILE				SAMPLES		LABORATORY TESTING				
Elev. m	Depth m	DESCRIPTION	Symbol	Number	Type	Water content	Liquid limit	Plastic limit	Plasticity Index	Unit Weight
181.80	0.00	Ground Surface								
181.50	0.30	Black sandy, organic TOPSOIL								
		Loose to Compact brown layered Fine to medium SAND		1	SS					
				2	SS	25.0				
179.50	2.30	Firm grey Varved SILTY CLAY		3	SS	25.8				
177.25	4.55	Soft grey SILTY CLAY with embedded sand and occasional gravel		4	SS	35.3				
				5	TW	33.8				
175.25	6.55	END of BOREHOLE								

FIGURE - 5.26

LOG OF BOREHOLE - WEST WINDSOR SITE 40

Vertical Scale: 1 to 75

SUBSURFACE PROFILE				SAMPLES		LABORATORY TESTING				
Elev. m	Depth m	DESCRIPTION	Symbol	Number	Type	Water content	Liquid limit	Plastic limit	Plasticity Index	Unit Weight
177.90	0.00	Ground Surface								
		Black sandy organic TOPSOIL		1	SS					
177.35	0.55	Loose to compact brown layered Fine to medium SAND		2	SS	8.1				
				3	SS	14.9				
176.55	1.35	Firm grey Varved SILTY CLAY		4	SS	24.6	29.4	20.2	9.2	
				5	SS	24.5				
				6	SS	23.1	29.3	18.9	10.4	
				7	SS	29.9				
				8	TW	25.0				
175.15	2.75	Soft grey SILTY CLAY with embedded sand and occasional gravel		9	TW	38.9				19.6
				10	TW	34.6				
				11	SS	38.7	42.7	24.9	17.8	
				12	TW	33.2				19.4
				13	TW	31.9				
				14	SS	48.9				
				15	TW	46.5				
				16	SS	43.6	43.4	21.4	22.0	
				17	TW	39.4				
				18	SS	38.4				
				19	TW	32.8				20.3
				20	TW	46.9				
				21	SS	29.9	28.7	16.9	11.8	
				22	TW	22.7				21.5
				23	TW	34.8				
167.40	10.50	END of BOREHOLE								

FIGURE - 5.27

All of the boreholes at the West Windsor test site penetrated a surficial layer of black sandy organic topsoil underlain by sand with a fine to medium grain size, a profile consistent with the typical Berrien Sand profile described in Section 2.3.2.2. This fluvial sand was deposited during the short-lived period of Lake Rouge, the last of the low level lakes that occupied this area after the retreat of the Wisconsinan glaciation (Vagners, 1972a). The sand deposit extends to a depth of 1.35 to 2.45 metres beneath the present ground surface. The greatest thicknesses of sand are located in the areas of Monitoring Sites 10 and 30 which are relatively high. Grain size analyses of selected samples of the fine to medium sand layer are presented in Appendix D. Standard penetration test results obtained in the sand indicate that this material has a 'loose' to 'compact' relative density.

As discussed in Section 2.3.2.2 the agricultural soil mapping of this area (Experimental Research Farms, 1947) indicates the surficial sand layers are underlain by silty clay till at a depth of 1 to 2 metres. The boreholes at the site revealed that the fine to medium sand deposited by Lake Rouge is underlain by grey silty clay. This silty clay deposit is varved (regularly layered) and may constitute the sediments of an earlier lacustrine depositional phase of Lake Rouge. The lacustrine silty clay extends to a depth of 2.75 to 4.55 metres beneath the present ground surface. The base level of the lacustrine silty clay deposit ranges from elevation 175.15 to 177.25 metres. The results of grain size analyses performed on selected samples of this silty clay deposit are presented as grain size distribution curves in Appendix D. Atterberg limit determinations were also completed on selected samples of the lacustrine silty clay and the results of these tests are presented on the borehole logs at the corresponding depths. These tests indicate the lacustrine silty clay has a low to medium plasticity. All of the samples tested for Atterberg limits indicate that the material can be plotted above the 'A'-line on the plasticity chart but the test results do plot very near the 'A'-line and the material could also be described as a silt-clay. The natural moisture content of the lacustrine silty clay ranges from 23 to 30 per cent and a visual and tactile examination of the soil samples obtained indicates this material has a 'firm' consistency.

Vagniers (1972a) notes that the Lake Rouge lacustrine deposits "may include some glaciolacustrine silt-clay". Some of the samples obtained from the West Windsor test site in the lower 300 to 600 mm of the lacustrine silty clay deposits were observed to contain small (50 mm width) inclusions of silty clay containing embedded sand. Where these inclusions were present the layering in the silty clay was observed to be formed around the inclusions.

At a depth of 2.75 to 4.55 metres beneath the present grade each of the monitoring sites is underlain by a deposit of glaciolacustrine silty clay that charateristically contains embedded sand and occasional gravel. The silty clay generally has a homogeneous appearance but examination of the samples obtained did indicate isolated lenses of material within the homogeneous mass that contain significantly more sand and silt. This grey silty clay extends beyond the vertical limits of all of the boreholes drilled for this investigation. As discussed in Section 2.3.2.2, the water well records (Ontario Ministry of the Environment, 1977) indicate that this clayey material extends to the bedrock level, 33 to 35 metres below grade and this has also been the experience of the author when drilling deep boreholes in this area for other investigations. Grain size distribution curves for select samples of the glaciolaustrine silty clay are presented in Appendix D. Atterberg limit determinations were performed on select samples of this material and these values are presented on the borehole logs at the corresponding depths. The Atterberg limit tests indicate that this silty clay deposit has a low to medium plasticity. Natural moisture content determinations for samples of the glaciolacustrine silty clay indicate this deposit has a moisture content of 35 to 40 per cent near the surface of the deposit. The lacustrine-glaciolacustrine interface in the silty clay deposits at this site is characterized by a 10± per cent variation in the natural moisture content of the silty clay. The natural moisture content of the glaciolacustrine silty clay generally decreases with increasing depth. At the vertical limit of the boreholes the moisture content of the silty clay was found to be of the order of 20 per cent. This decrease in moisture content with increasing depth is characteristic of a normally consolidated deposit of silty clay where the void ratio of the silty clay is directly related to the overburden pressure (i.e., the depth of the soil). A visual and tactile examination of the soil samples indicates the glaciolacustrine silty clay has a 'soft' consistency.

A summary of the grain size analyses for all of the soil deposits encountered beneath the West Windsor test site are presented on the 'Soil Classification Chart', (Figure 5.28). An 'Atterberg Limits Summary' for all of the samples obtained from this test site is presented in Figure 5.29.

5.2.3 Groundwater Conditions

5.2.3.1 Observation Well Hydrographs

The groundwater level readings taken at the West Windsor test site between April and September, 1983, are tabulated in Appendix F and hydrographs for each of the observation wells are plotted on Figures 5.30 to 5.32 inclusive.

Both the long screen water table wells, 10-1 and 20-1, and the deeper piezometers which had screen lengths of only 1.5 metres, 10-2 and 20-2, quickly established equilibrium with the in situ piezometric pressure in

WEST WINDSOR TEST SITE

SOIL CLASSIFICATION CHART

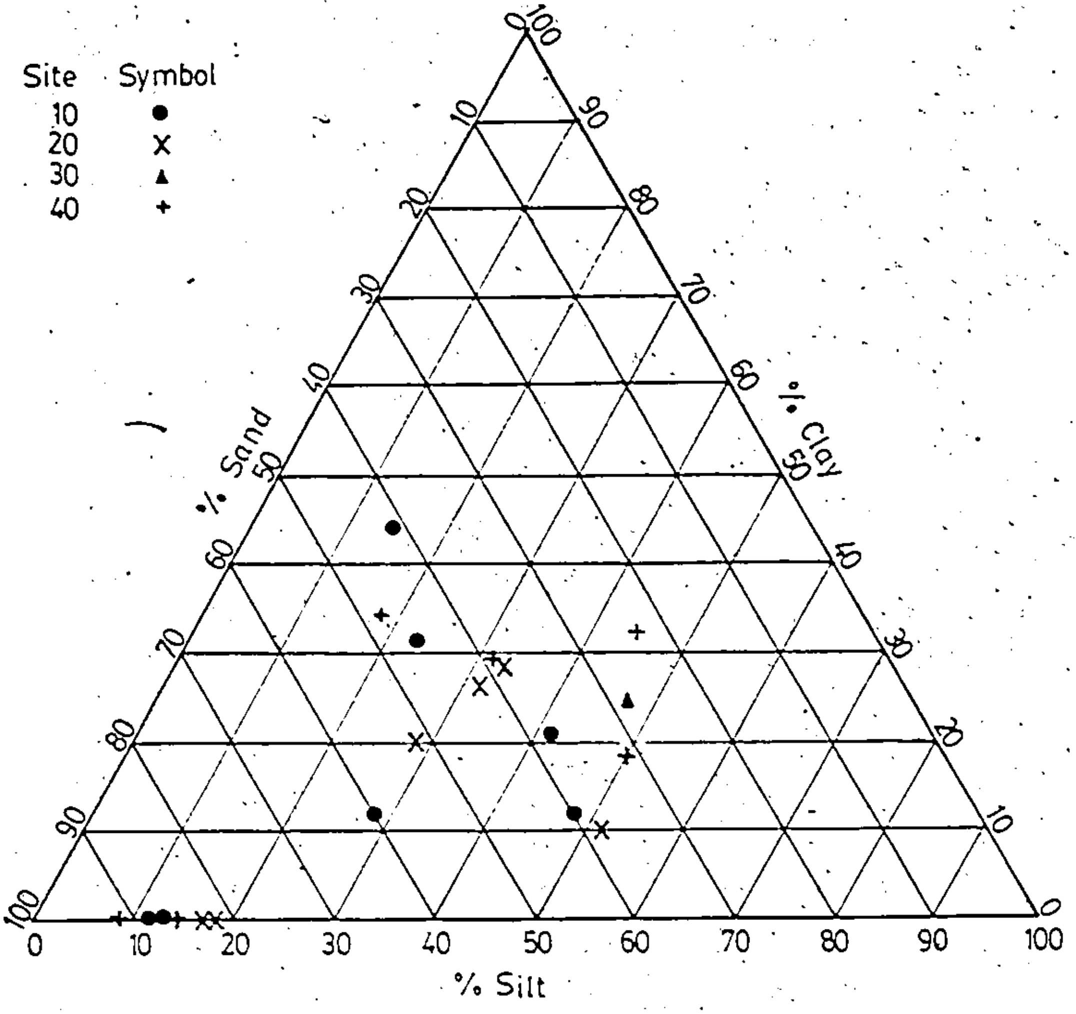
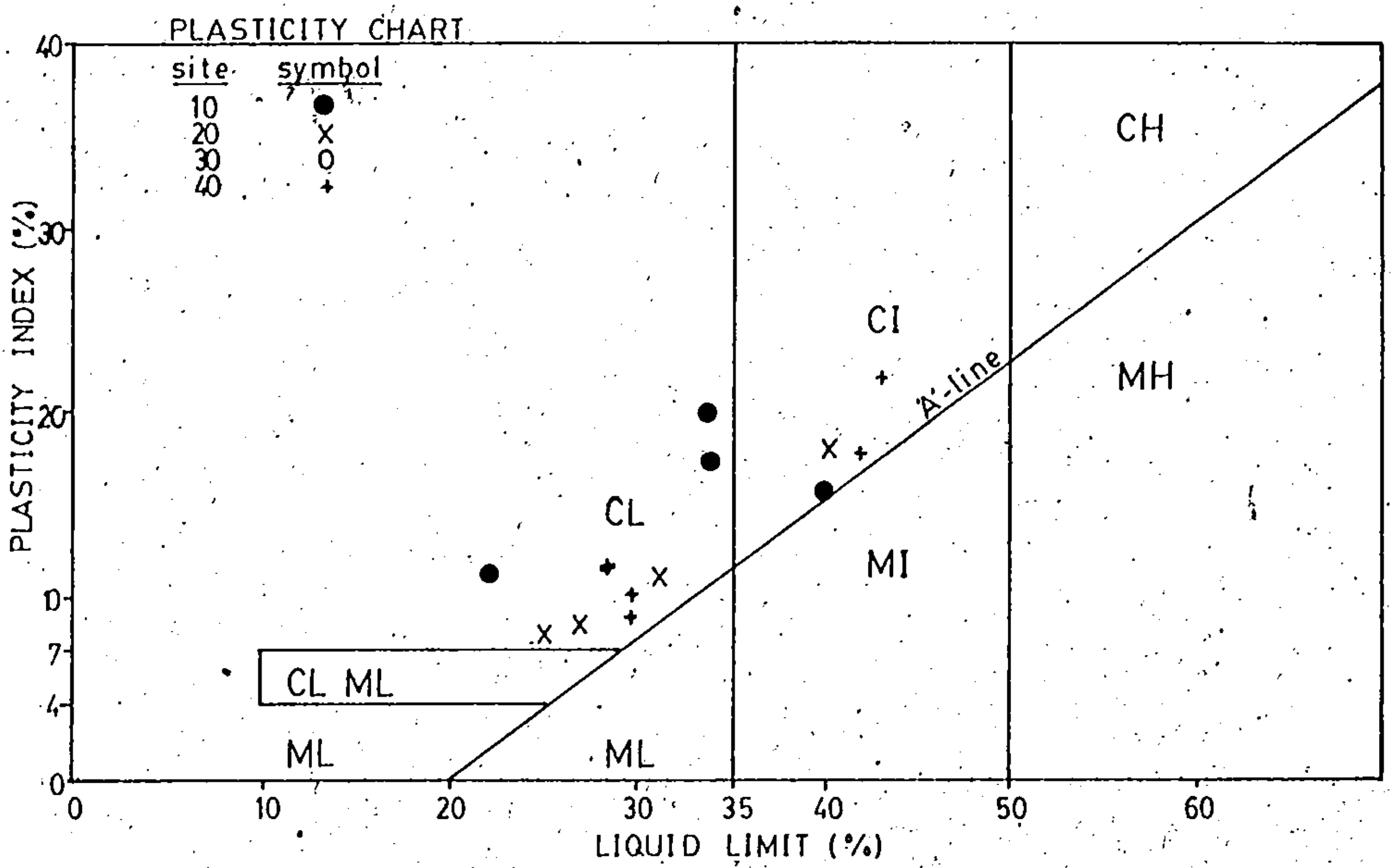


FIGURE- 5.28

WEST WINDSOR TEST SITE

FIGURE- 5.29

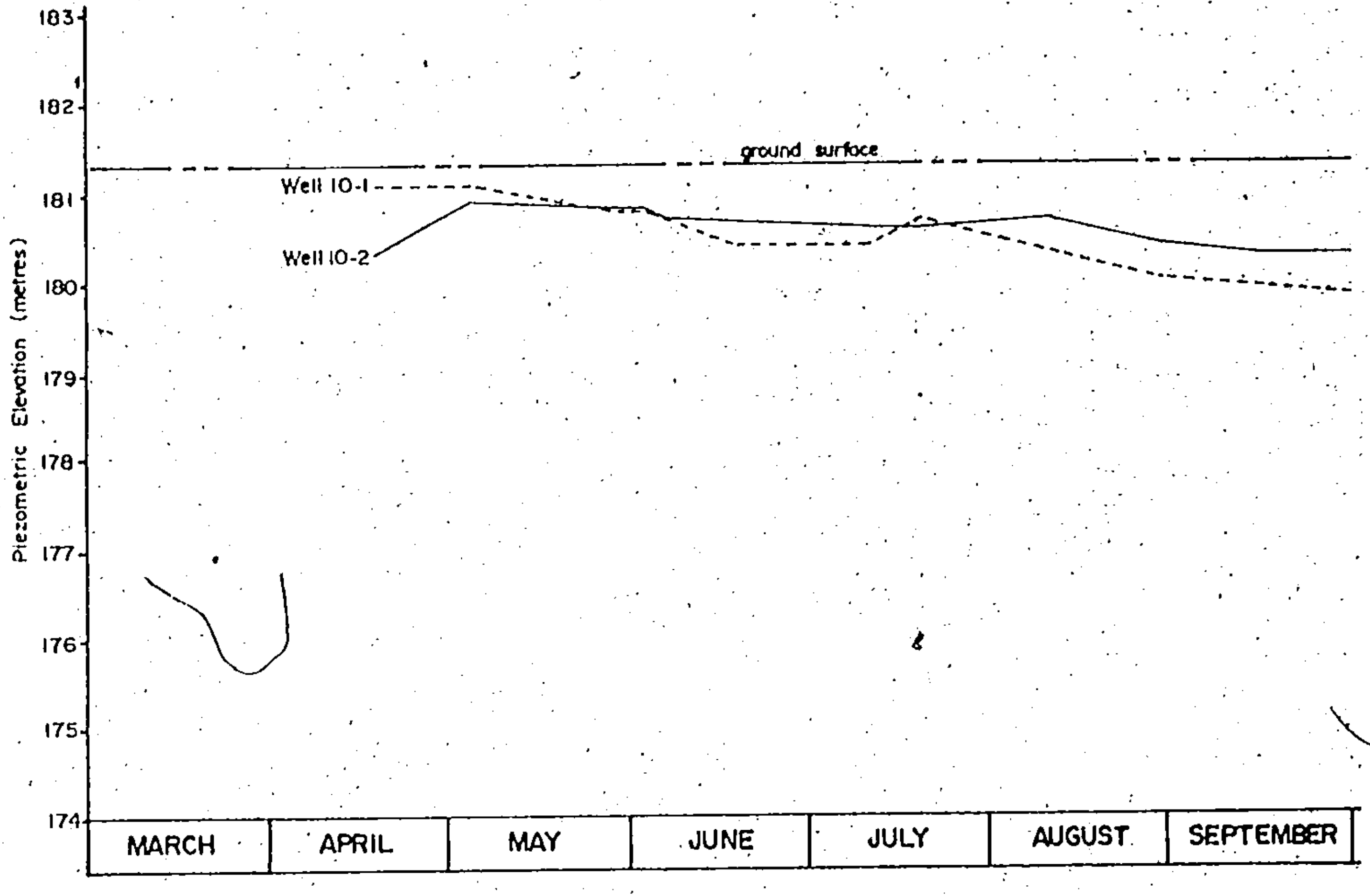
ATTERBERG LIMITS SUMMARY



WEST WINDSOR TEST SITE 10

FIGURE- 5.30

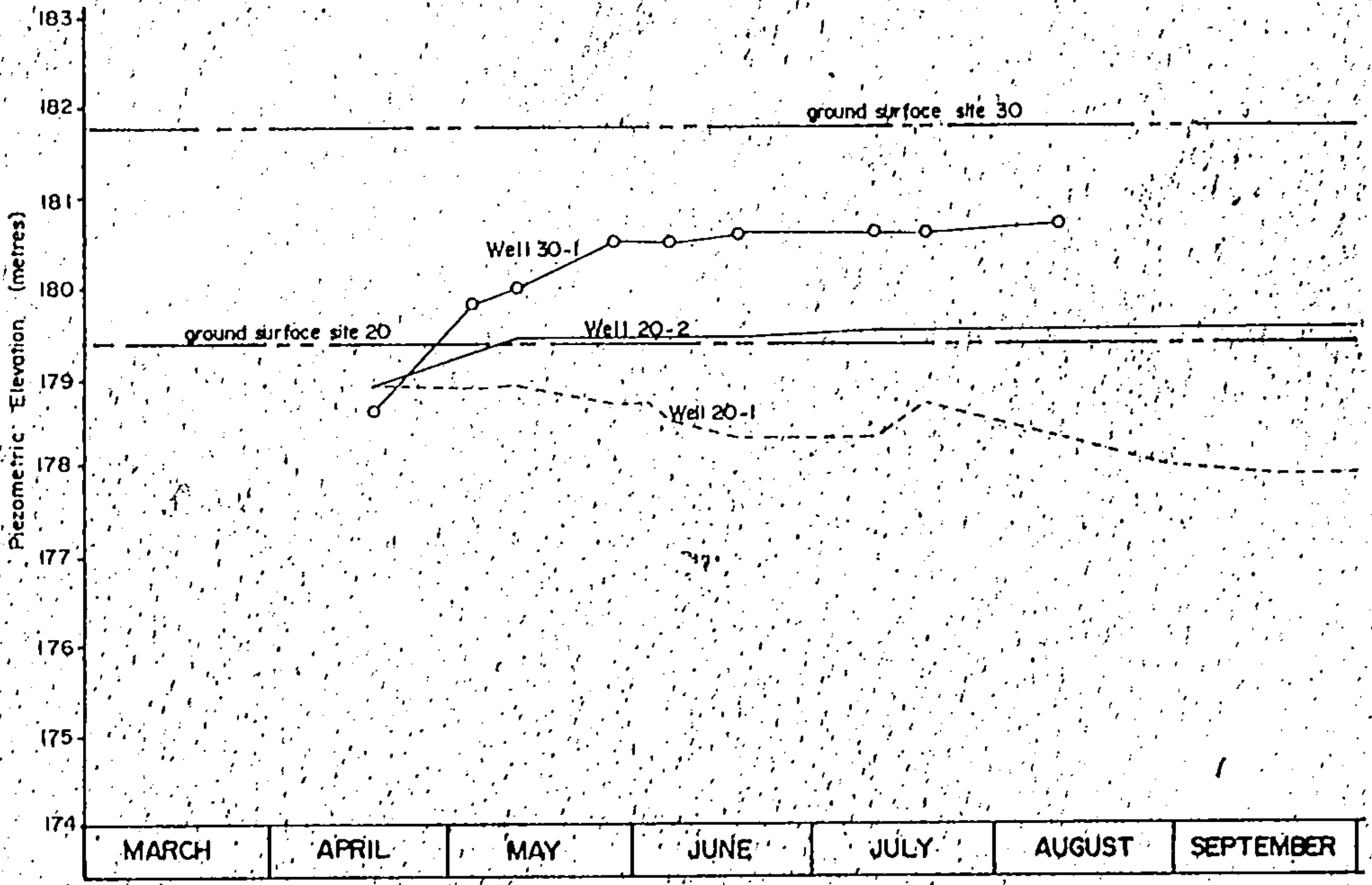
OBSERVATION WELL HYDROGRAPHS
(APRIL to SEPTEMBER 1983)



WEST WINDSOR TEST SITE 20 and 30

FIGURE- 5.31

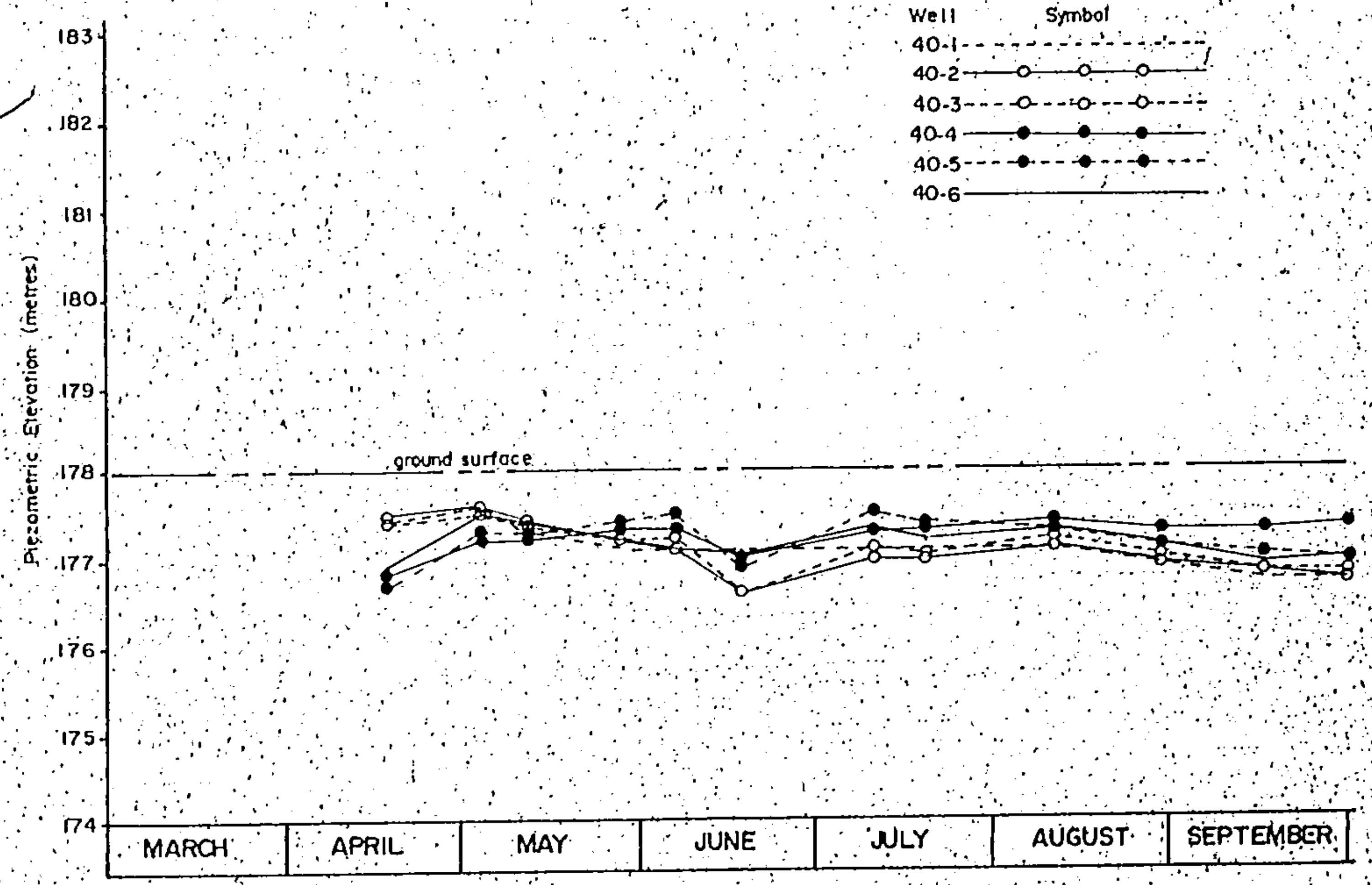
OBSERVATION WELL HYDROGRAPHS
(APRIL to SEPTEMBER 1983)



WEST WINDSOR TEST SITE 40

FIGURE- 5.32

OBSERVATION WELL HYDROGRAPHS
(APRIL to SEPTEMBER 1983)



the soil surrounding the observation well screens. Each of the observation wells installed at Monitoring Site 40 was installed as a piezometer and all of these wells had identical 1.5 metre long screens. These piezometers also established piezometric equilibrium within two weeks of the well installation.

Only the observation well at Monitoring Site 30, which had only a 600 mm long well screen, took any appreciable length of time to come to equilibrium with the in situ piezometric pressure. In the case of well 30-1 a period of approximately two months followed the observation well installation before equilibrium was established.

5.2.3.2 Groundwater Flow

The observation well hydrographs indicate the water table at the West Windsor test site is generally less than 1.5 metres beneath the ground surface. During the Spring the water table approaches the ground surface and lower areas of the site experience minor flooding. The water table level was found to decline from Spring to Autumn to a depth of 1 to 1.5 metres below grade.

An examination of Figure 2.2, which indicates the relative position of the West Windsor test site with respect to the surface drainage features of the area, suggests that the lateral groundwater flow beneath the test site should be essentially west towards the Detroit River and somewhat south towards Turkey Creek. An analysis of the water table well data confirms that this is the case. The plot of groundwater equipotentials presented in Figure 5.33 is derived from the water table data at each of the monitoring sites on September 30, 1983. The horizontal hydraulic gradient at the West Windsor test site is of the order of 0.004 based on these observations.

WEST WINDSOR TEST SITE

PLAN OF WATER TABLE CONTOURS

September 30, 1983

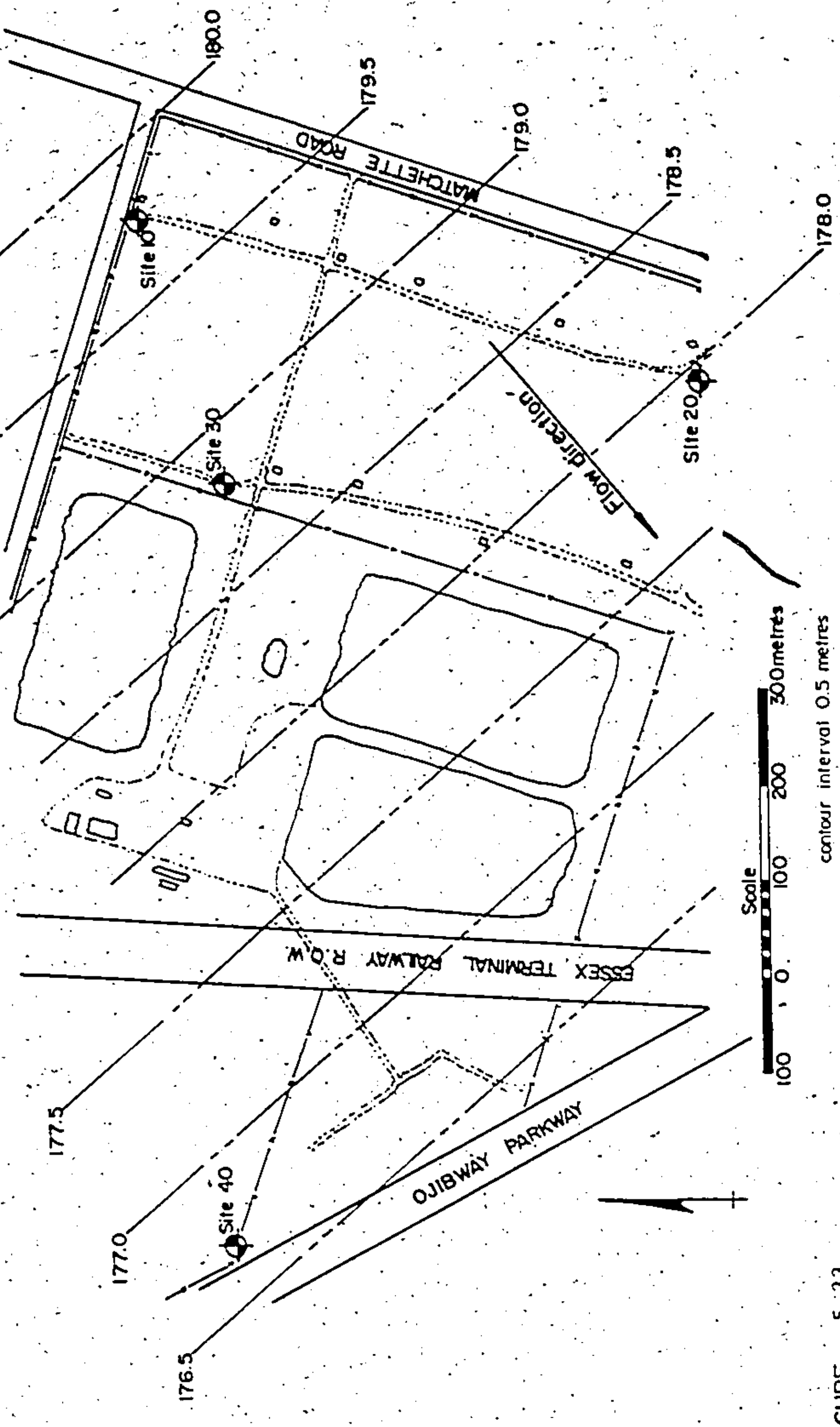


FIGURE - 5.33

A comparison of the water table well levels and the equilibrium piezometric levels recorded in the piezometer type observation wells installed at the monitoring sites, clearly indicates the West Windsor test site is in a groundwater discharge area, that is, the groundwater movement is upward. A plot of the piezometric head variation with depth as measured at each of the monitoring sites is presented in Figure 5.34.

The vertical gradient lines for monitoring sites 10 and 20 are based on two points because there are only two observation wells at these sites. At Monitoring Site 40, where there were six wells installed there is sufficient scatter of the data points that a linear regression analysis was used to define the best fit line of the vertical hydraulic gradient at this site. As can be seen from an examination of the resulting vertical gradient lines plotted in Figure 5.33, the line derived from the regression analysis for Monitoring Site 40 is consistent with the vertical gradient line determined from the data points obtained at Monitoring Site 10. At both of these sites the upward vertical gradient was found to be of the order of 0.07.

At Monitoring Site 20, the upward vertical gradient was found to be of the order of 0.22, approximately three times the gradient measured at Montoring Sites 10 and 40. The 'Plan of Groundwater Equipotential', Figure 5.33, indicates that Monitoring Site 20 is directly down gradient from the West Windsor Landfill Site that is located immediately east of the West Windsor test site. As noted in Section 2.2.2 this landfill site is substantially complete and has a ground surface elevation approximately 30 metres above the surrounding land areas. It is apparent that a groundwater mound has developed in the adjacent landfill site such that there has been a substantial increase in the hydraulic gradient in this area. It would be expected that there would be an almost vertical downward hydraulic gradient in the landfill site. Since the regional

WEST WINDSOR TEST SITE

PIEZOMETRIC HEAD
variation with depth

September 30, 1983

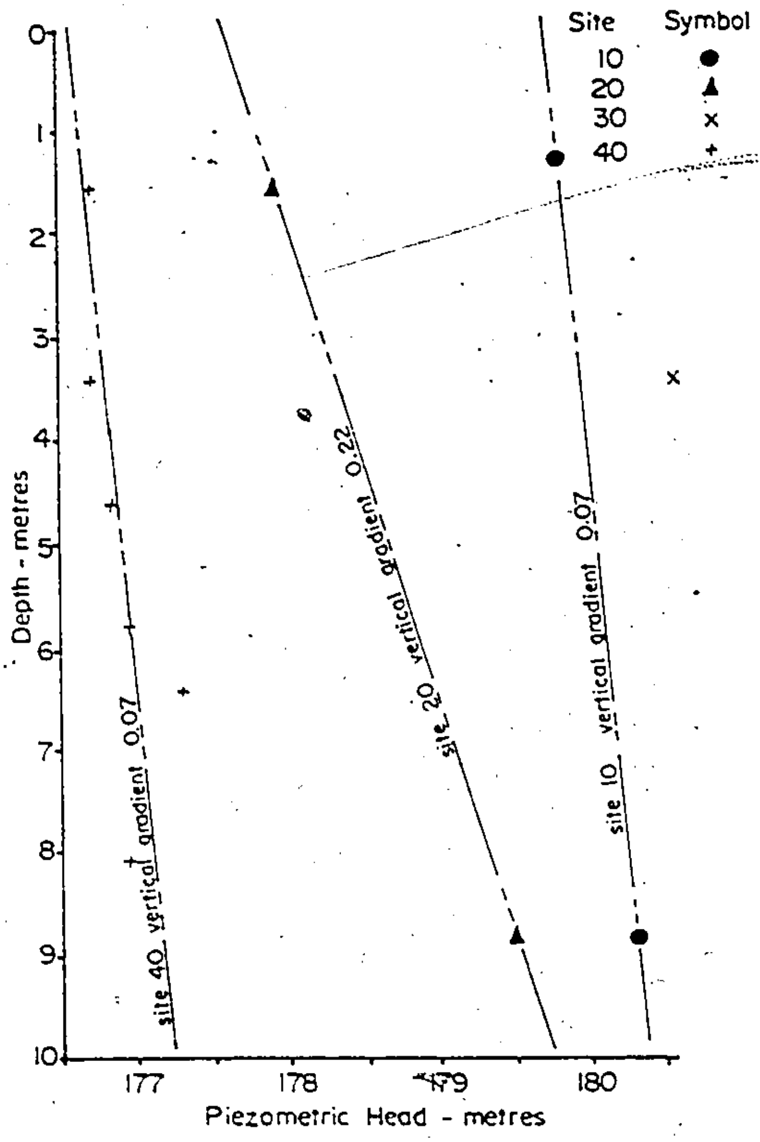


FIGURE - 5.34

groundwater flow in this area has an upward vertical gradient, the downward flow from the site deforms the groundwater flow path in the area of the landfill and as expected there are elevated upward vertical gradients downstream from the landfill site. It is in such an area of increased vertical gradient that Monitoring Site 20 is located.

The typical vertical hydraulic gradient at the West Windsor test site is of the order of 0.07, an order of magnitude greater than the horizontal hydraulic gradient.

5.2.3.3 Electrical Conductivity

The average electrical conductivity values from the measured data at each of the observations wells at the West Windsor test site is plotted corresponding to the depth of the well screen and presented in Figure 5.35.

The groundwater from Monitoring Sites 30 and 40 of the West Windsor test site was found to have electrical conductivity in the range of 1000 to 3000 microsiemens (uS) indicative of water that is fresh to slightly brackish.

At the location of Monitoring Site 20 electrical conductivity readings of 11000 to 15000 uS were recorded. The exceptionally high electrical conductivity of the groundwater in this area is further evidence that Monitoring Site 20 is within an area of groundwater influenced by the adjacent landfill site. High concentrations of dissolved solids are typical of contaminant plumes associated with landfill developments and it is apparent from the data collected at the West Windsor test site that the landfill adjacent to the site has generated a large contaminant plume that extends to a depth of at least 10 metres and has migrated several hundred metres beyond the actual landfill site property.

WEST WINDSOR TEST SITE

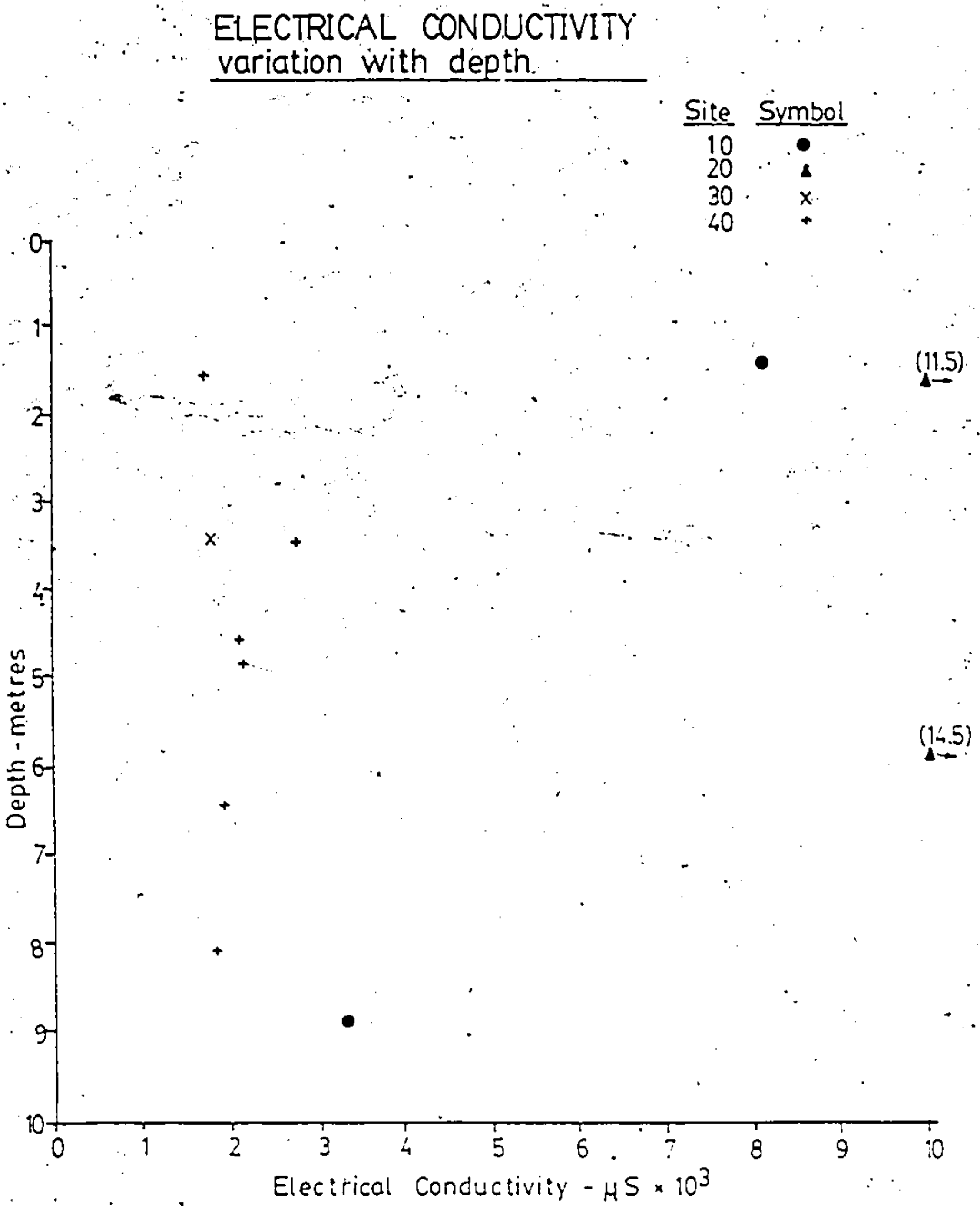


FIGURE - 5.35

Measurements in the observation wells at Monitoring Site 10 indicated that the shallow groundwater had elevated electrical conductivity of the same order of magnitude as measured at Monitoring Site 20. The deeper groundwater at Monitoring Site 10 has an electrical conductivity more similar to the groundwater at Monitoring Sites 30 and 40. Monitoring Site 10 is not down gradient of the landfill site, however, contaminants can migrate in a direction perpendicular to the hydraulic gradient by dispersion and the dispersion coefficient of the surficial sand deposits in this area will be relatively high compared to the underlying silty clay strata. The contaminant plume from the landfill site has therefore expanded laterally in the surficial sand to at least the area of Monitoring Site 10 but the contaminant plume has not yet extended as far in this direction in the silty clay strata because the dispersion coefficient of the silty clay is substantially less than for the sand.

5.2.3.4 Environmental Isotopes

The concentration of oxygen-18 and tritium in samples of pore water extracted from soil samples taken at the West Windsor test site were determined and the results of these analyses are plotted at the appropriate sample depths in Figure 5.36. As was the case at the Woodslee test site there is considerably more scatter of the tritium concentration in the pore water than scatter in the depletion of oxygen-18. This variation in scatter is obviously dependent on the dissimilarity of the confidence intervals of the results of the analyses for these two isotopes.

An examination of the tritium concentration *versus* depth plot indicates there is a distinct difference between the tritium distribution at Monitoring Sites 20 and 40. At Monitoring Site 40, it is immediately apparent that the pore water samples taken from beneath a depth of 6± metres have consistent tritium concentrations of the order of 10 TU or

WEST WINDSOR TEST SITE

ENVIRONMENTAL ISOTOPE CONCENTRATION variation with depth

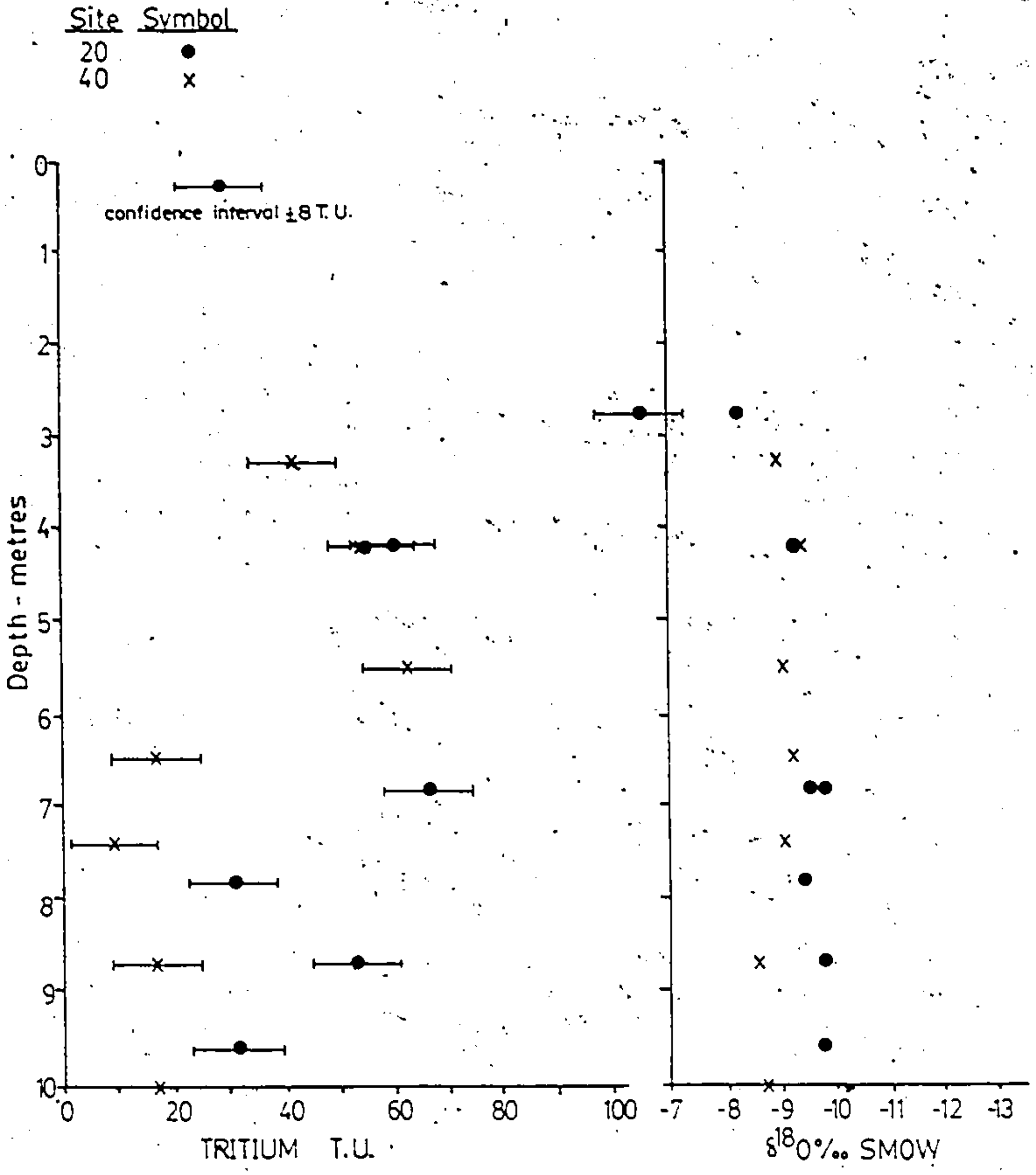


FIGURE- 5.36

less and as such it can be assumed that this water entered the ground prior to 1953. At Monitoring Site 20 the pore water from the ground surface to a depth of 10 metres entered the ground since 1953, all tritium concentrations measured from this monitoring site are in excess of 20 TU.

The oxygen-18 depletion in the pore water samples obtained, varies from -8 to -10 $\delta^{18}O$ o/ooSMOW at both of the monitoring sites

5.2.4 Laboratory Hydraulic Conductivity Evaluation

5.2.4.1 Permeameter Test Results

The results of hydraulic conductivity tests carried out on samples of silty clay from the West Windsor test site are tabulated in Appendix H. The results are plotted according to depth in Figure 5.37.

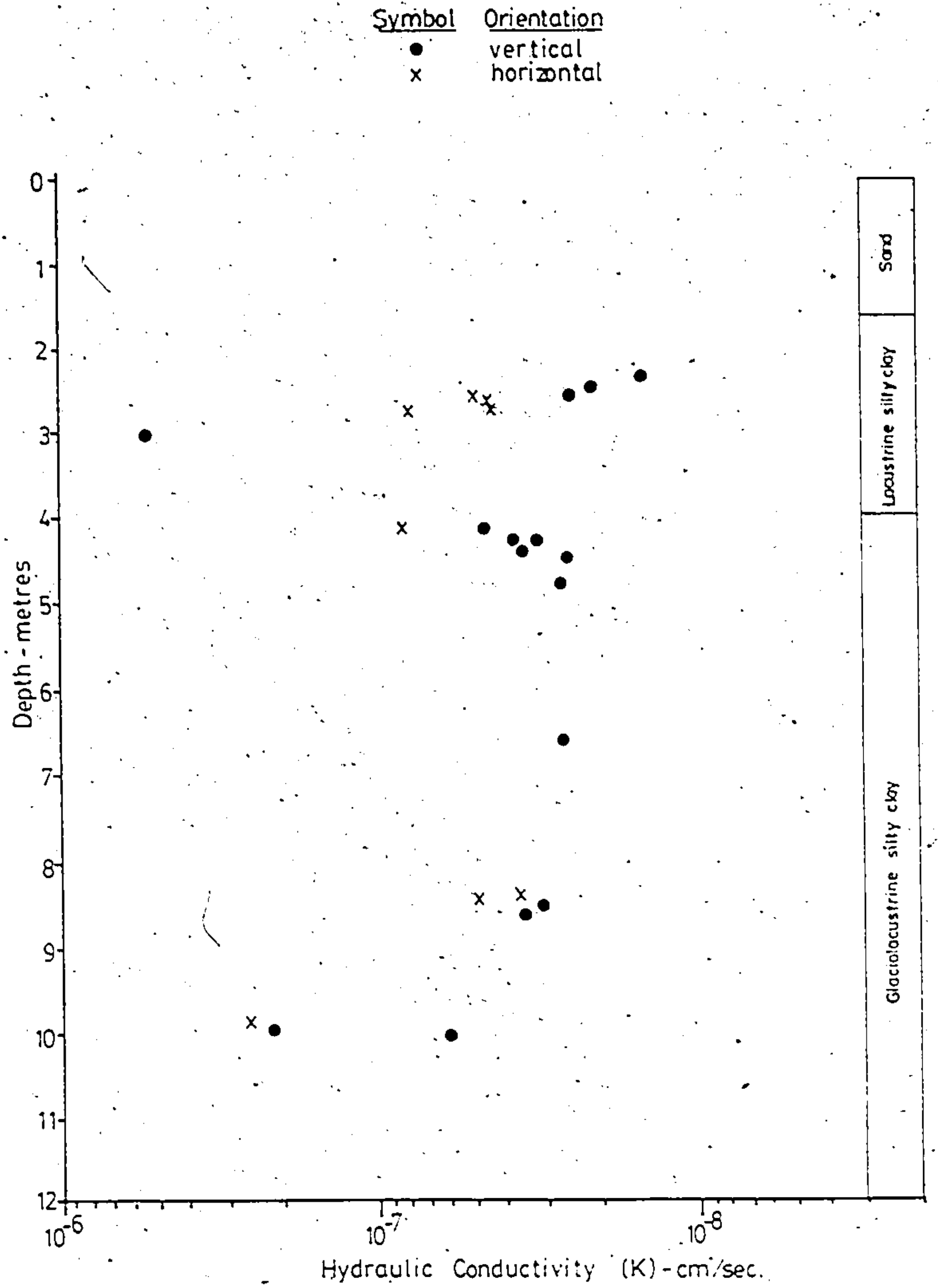
In total 23 separate samples of silty clay were placed in the permeameter. As was the case for the samples from the Woodslee test site, the flow through each of these samples was measured several times to determine the mean hydraulic conductivity of the particular sample. The standard deviation of the hydraulic conductivity values was in the range of 1×10^{-9} to 5×10^{-9} cm/sec, the result of random error in the test procedure.

Eight samples of the lacustrine silty clay layer encountered at the West Windsor test site were tested in the permeameter. One of the samples was from a split spoon taken at Monitoring Site 10, and the other seven samples were from one shelby tube taken at Monitoring Site 40. The sample taken from Monitoring Site 10 may have been somewhat disturbed. This was one of the first samples obtained and the purpose of the test was to determine the approximate order of magnitude of the hydraulic conductivity for the design of the other observation well installations. Of

WEST WINDSOR TEST SITE

FIGURE- 5.37

PERMEAMETER TEST RESULTS



the seven samples of varved silty clay taken at Monitoring Site 40, three were tested in a vertical orientation and four were tested in a horizontal orientation. The vertically oriented silty clay samples had hydraulic conductivities measured in the range of 1.5×10^{-8} to 2.5×10^{-8} cm/sec. The horizontally oriented samples had hydraulic conductivities measured in the range of 4×10^{-8} to 5×10^{-8} cm/sec.

There is a measurable variation between the horizontal and vertical hydraulic conductivity of the lacustrine silty clay sampled from the West Windsor test site and this variation is approximately half an order of magnitude.

The remaining fifteen samples from the West Windsor test site tested in the permeameter, were samples of glaciolacustrine silty clay from beneath a depth of 4 metres.

One of the shelby tube samples of this material (Sample 12, Site 40) was divided into five samples that were tested in a vertical orientation. Three of these samples were tested using a saturated saline permeant. One of the remaining samples was tested using the natural groundwater from the test site and the other was tested using a sample of natural groundwater from another site where the TDS of the groundwater is significantly less than at the West Windsor test site. The results of these hydraulic conductivity evaluations indicated the vertical hydraulic conductivity of the glaciolacustrine silty clay is in the range of 2.5×10^{-8} to 5×10^{-8} cm/sec. There is no apparent relationship between the hydraulic conductivity measured and the TDS of the permeant. The permeant low in TDS, provided the highest measured hydraulic conductivity values and the sample tested with the natural groundwater as a permeant provided the lowest of the measured hydraulic conductivity values. The samples tested with a saline permeant indicated hydraulic conductivity values between these two extremes.

At three separate levels in the glaciolacustrine silty clay, vertical and horizontal companion samples were tested (Samples 19, 20, and 22, Site 40). In all cases the hydraulic conductivities of the horizontally oriented samples were greater than or equal to the hydraulic conductivities measured for the vertically oriented companion samples. The actual magnitude of the variation in hydraulic conductivity evaluated for the vertically and horizontally oriented silty clay samples is sufficiently small as to be insignificant compared to the variations inherent in the permeameter testing procedure employed for this work. It is not possible to determine from the results of these tests if there is anisotropic hydraulic conductivity in the glaciolacustrine silty clay.

The range of hydraulic conductivity in the glaciolacustrine silty clay was generally measured to be between 2×10^{-8} and 8×10^{-8} cm/sec. The mean hydraulic conductivity value was 4×10^{-8} cm/sec and the standard deviation was 1.6×10^{-8} cm/sec. Two samples from a depth of 10 metres contained a portion of a more sandy and silty lens of material and the hydraulic conductivity measured from these samples was of the order of 2.5×10^{-7} cm/sec. An examination of the test results plotted in Figure 5.37 suggests that the range of hydraulic conductivity variation in the glaciolacustrine silty clay as evaluated by the permeameter, is independent of depth but is influenced by local variations in the composition of the deposit.

5.2.4.2 One-Dimensional Consolidation Test Results

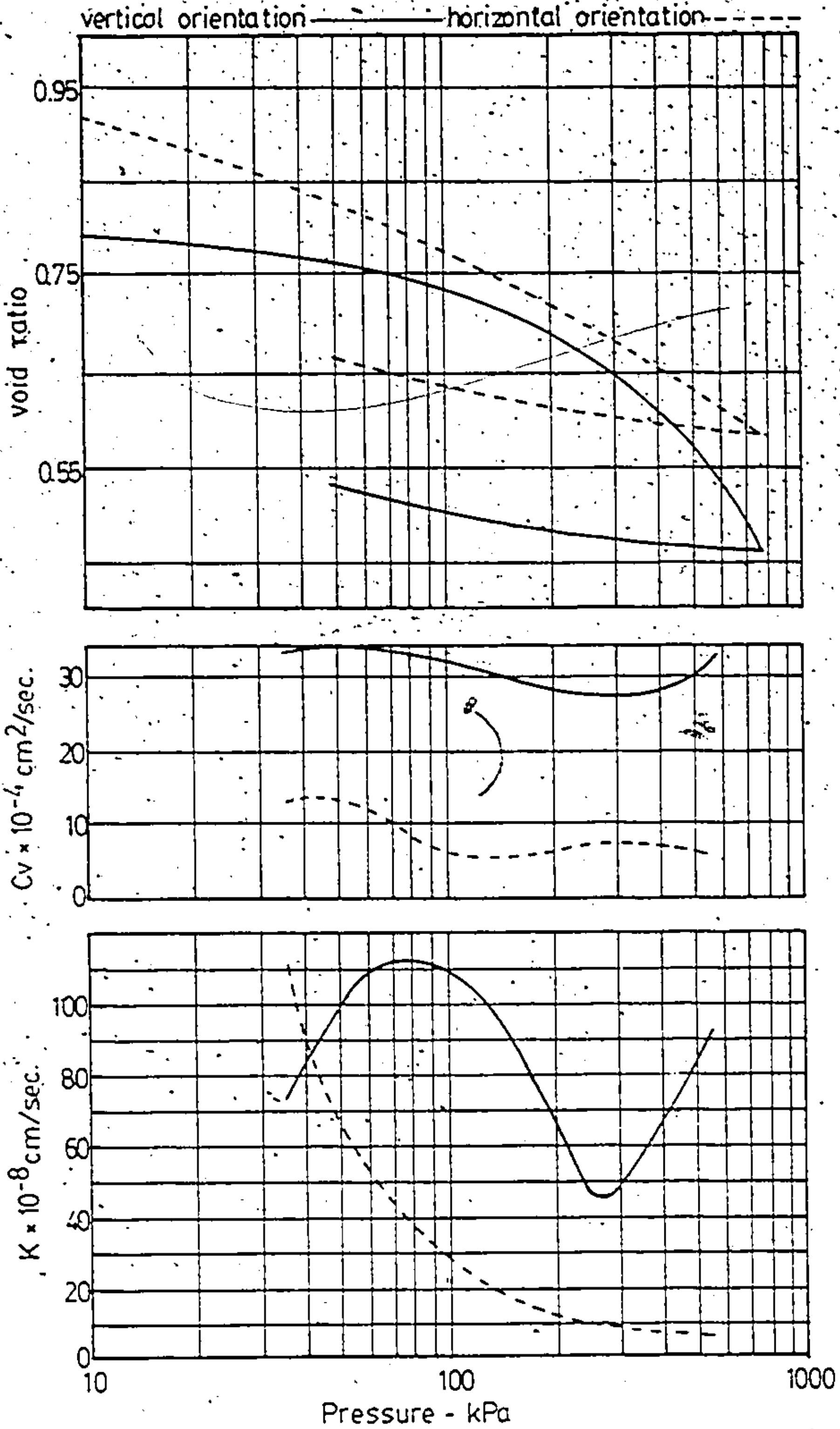
The results of one-dimensional consolidation tests carried out on two samples of glaciolacustrine silty clay from Site 40 of the West Windsor test site are plotted in Figure 5.38.

The samples were taken from a depth of 8.5 metres below grade at Monitoring Site 40. One sample was tested in a vertical orientation and the other in a horizontal orientation.

WEST WINDSOR TEST SITE FIGURE - 5.38

CONSOLIDATION TEST RESULTS

depth 8.5 metres



The silty clay at the West Windsor test site is normally consolidated based on the results of the consolidation tests performed. The moisture content distribution of the samples from this test site also suggested that this deposit was normally consolidated as discussed in Section 5.2.2.

It would be expected that two samples taken from essentially the same depth would have similar void ratios but this was not the case. The vertically oriented sample of silty clay contained a portion of a lense of material that was significantly more sandy and silty than the typical silty clay material encountered at the West Windsor test site. The void ratio of the vertically oriented sample was subsequently lower than the void ratio of the homogeneous sample of silty clay trimmed in a horizontal orientation.

The two samples of glaciolacustrine silty clay also behaved differently when tested in the odeometer. An examination of the consolidation test results presented in Figure 5.38, reveals that the hydraulic conductivity of the vertically oriented test sample both increased and decreased with an increase in applied pressure dependent on the stress range. The hydraulic conductivity of the horizontally oriented sample decreased with increases in applied stress. The variation in hydraulic conductivity response to applied pressure for different stress ranges that occurred for the vertically oriented sample can be attributed to the alteration of the heterogeneous sample fabric in the differing ranges of applied stress.

The <u>in situ</u> overburden pressure at a depth of 8.5 metres at Monitoring Site 40 has been estimated at 85 kPa. Based on this applied pressure value the hydraulic conductivity versus pressure curves for the tested samples indicate the <u>in situ</u> hydraulic conductivity of the silty clay would be 115 x 10^{-8} and 35 x 10^{-8} cm/sec for the vertical and horizontal samples respectively.

5.2.5 Field Test Results

5.2.5.1 Single Well Response Test Results

The results of the single well response tests carried out at the West Windsor test site are tabulated in Appendix H. The table lists the results of slug, bail and hydrograph interpretation type tests carried out in the 11 observation wells installed at the four monitoring sites.

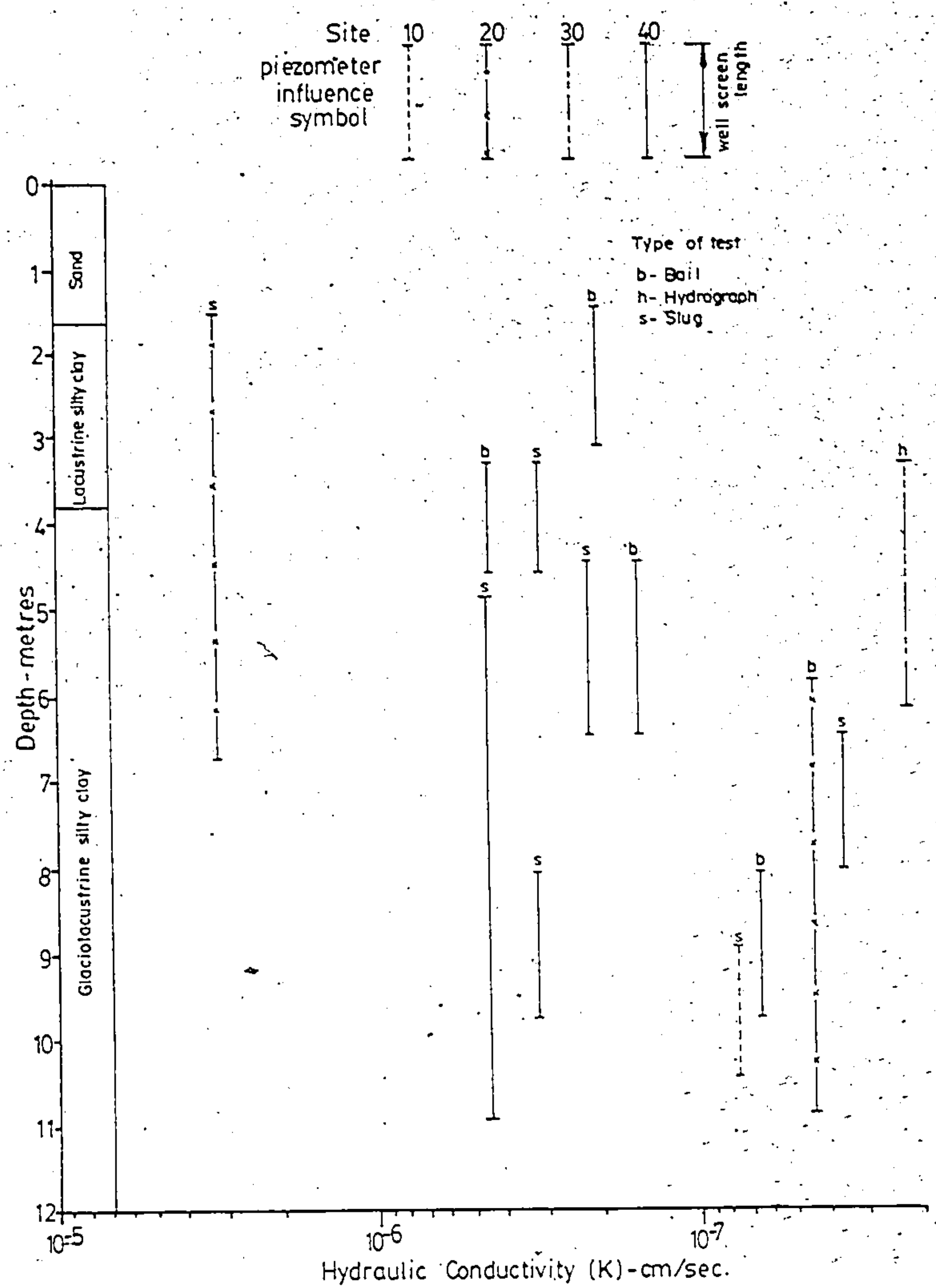
The geometry of the observation wells, water level depths in the wells relative to the screen depths and the response characteristics of the wells prevented the use of all types of single well response test in each of the observation wells. Only in three of the wells at Monitoring Site 40 were slug and bail tests carried out. Only the response time of the hydrograph of well 30-1 was adequate for interpretation as a single well response test.

For those wells where slug and bail tests were completed, two of the three indicated hydraulic conductivities of the same order of magnitude and similar value. The results from a slug test performed in observation well 40-5 indicated a hydraulic conductivity an order of magnitude greater than the results of a bail test performed in the same well, 3.2×10^{-7} and 6.7×10^{-8} cm/sec respectively. This apparent anomaly in the single well response test results may be attributable to contamination of the well screen by the bentonite sealing compound used when installing the well. If this is the case the bail test indicating a lesser hydraulic conductivity would likely be erroneous.

The results of the single well response tests of all forms are plotted in Figure 5.39, with the depth range of the observation well screen of each well indicated.

WEST WINDSOR TEST SITE FIGURE- 5.39

SINGLE WELL RESPONSE TEST RESULTS



7

Observation wells 10-1 and 20-1 contacted the fine to medium sand layer near the ground surface of the West Windsor test site though well 20-1 must have had only limited contact. The single well response tests in these two wells indicate hydraulic conductivity in the range of 0.3×10^{-5} to 1.3×10^{-5} cm/sec.

Single well response tests carried out in observation wells with screens established in the lacustrine and glaciolacustrine silty clay deposits, indicate a range of hydraulic conductivities from 2×10^{-8} to 45×10^{-8} cm/sec. The distribution of data obtained is not definitive but an examination of the distribution of the single well response test results generally suggests that the wells with screen areas shallower than 6 metres indicate hydraulic conductivities of 1.5×10^{-7} to 4.5×10^{-7} cm/sec whereas wells with screen areas completely beneath a depth of 6 metres indicate hydraulic conductivities 3×10^{-8} to 8×10^{-8} cm/sec.

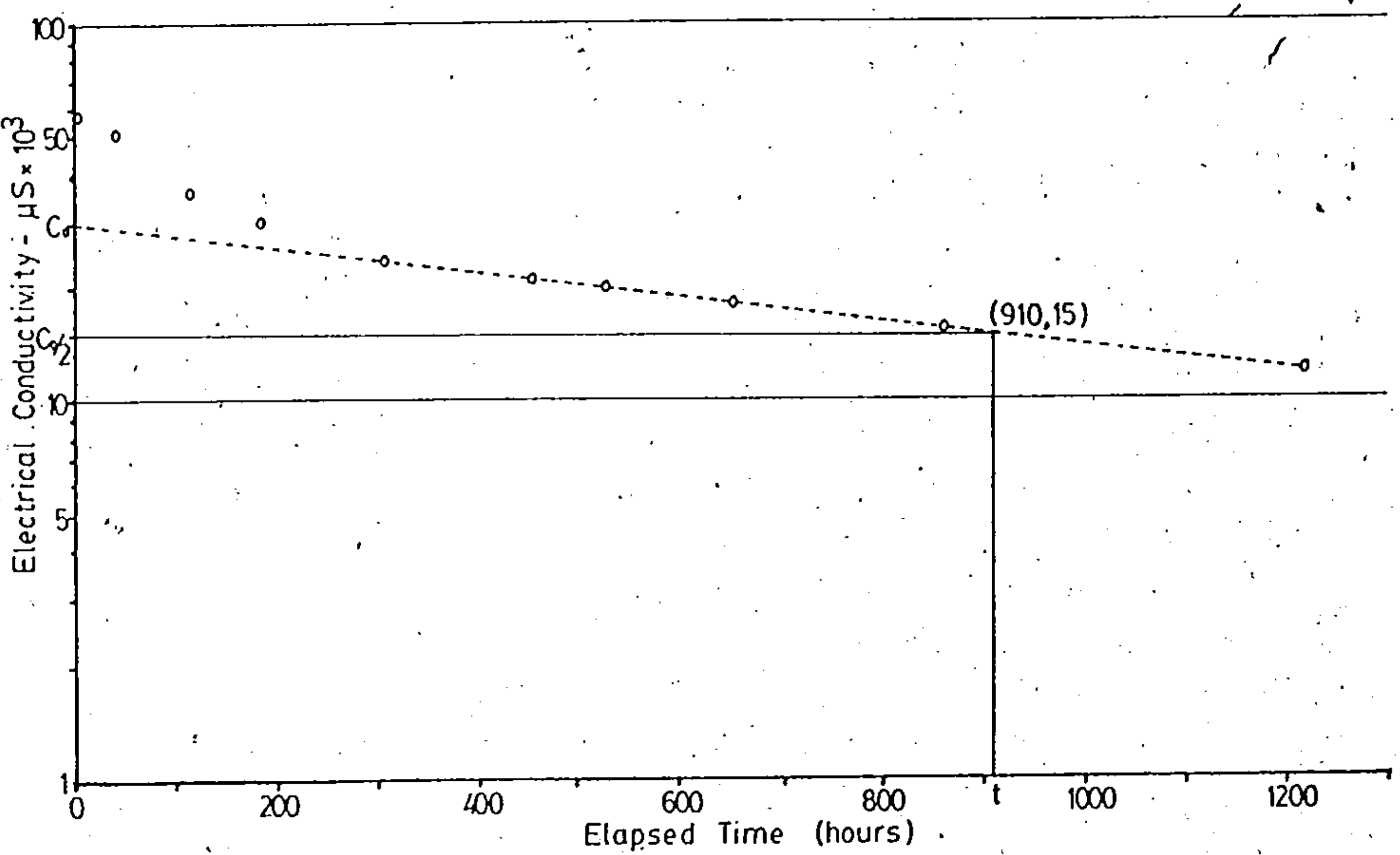
5.2.5.2 Borehole Dilution Test Results

The results of the borehole dilution test carried out in well 30-1 at the West Windsor test site are plotted in Figure 5.40. As was the case with the results of the borehole dilution tests carried out at the Woodslee test site and discussed in Section 5.1.5.2, a linear relationship only exists between the logarithm of electrical conductivity and time after a significant period of time has elapsed in the test. As was suggested in the discussions presented in Section 5.1.5.2, the initial non-linear portion of the borehole dilution test result curve is influenced by the excess pressure induced in the well screen when the conductivity probe is inserted.

WEST WINDSOR TEST SITE

FIGURE- 5.40

BOREHOLE DILUTION TEST RESULTS



An elapsed time of 910 hours was selected intersecting the linear portion of the log conductivity versus time curve for the test in well 30-1, and a corresponding conductivity co-ordinate was determined as indicated in Figure 5.40. The linear portion of the curve was projected to time zero and the corresponding conductivity co-ordinate was recorded as the effective initial conductivity (C_o). The application of these values in Equation (23) yields an apparent average linear velocity of 3.2 x 10^{-6} cm/sec.

6.0 DISCUSSION OF RESULTS

The two test sites selected for this study were underlain by silty clay deposits which have resulted from different depositional mechanisms and consequently have different textures and properties. The available Quarternary geological records were augmented by test borings at the two sites. Samples obtained from these borings were analysed to determine the index properties of the silty clays, natural moisture content distribution, and porosity.

The most recent of the silty clay deposits encountered, the lacustrine silty clay sampled from beneath the West Windsor test site, has not been previously documented. This material contains few particles larger than very fine sand and is obviously layered, yet the agricultural soil maps for the West Windsor test site area distinctly indicate the Berrien Sand deposits to be underlain by 'clay till'.

The glaciolacustrine silty clay encountered at depth beneath the West Windsor test site and the silty clay till penetrated at the Woodslee test site are characterized by ubiquitous embedded grains of sand and gravel size. The glaciolacustrine material primarily differs from the silty clay till by stress history. The till material is over consolidated, and at shallower depths, it is heavily over consolidated, whereas the glaciolacustrine silty clay was found to be essentially normally consolidated. The silty clay till therefore has a consistency that varies from 'hard' to 'stiff' and the glaciolacustrine silty clay was found to have only a 'soft' consistency.

Monitoring sites at the Woodslee and West Windsor test sites were constructed to evaluate the <u>in situ</u> groundwater conditions that are characteristic of these sites. A variety of test methods were selected to attempt to quantify the hydraulic conductivity of the three types of silty clay materials sampled at the test sites. These test methods included several laboratory techniques and in situ testing procedures. There was some variability in the values of hydraulic conductivity obtained by the various tests on the silty clay materials.

The hydraulic conductivity values for the silty clays, measured in the field and laboratory were used to estimate the average linear velocity of the groundwater flow based on the hydraulic gradients measured at the monitoring sites. The average linear velocities calculated from these factors were compared to the results of borehole dilution tests and well to well tracer assessments of average linear groundwater velocity.

6.1 Laboratory Hydraulic Conductivity Evaluation

Laboratory tests are generally inexpensive to perform and can be accomplished in a reasonable period of time. It is therefore practical to carry out large numbers of tests, particularily when comparative work is required with variable parameters. Significant among the accepted advantages of a laboratory testing program is the availability of established test methods that have been demonstrated to provide reproducible results. Laboratory evaluations of hydraulic conductivity were carried out on a number of samples from the Woodslee and West Windsor test sites. Laboratory testing was used to evaluate the hydraulic conductivity of the silty clay soil samples with natural groundwater permeants. Laboratory testing was also used to test for the effects of using permeants of higher and lower TDS than the natural groundwater.

6.1.1 Woodslee Test Site

The upper 4± metres of silty clay till at the Woodslee test site was obviously fissured or fractured. The hydraulic conductivity of samples taken from this material was evaluated using the permeameter and one dimensional consolidation test procedures. The samples of this fractured material were all taken with driven split spoon samplers because the silty clay in this zone was too hard to sample with shelby tube type samplers. The samples of the silty clay obtained were consequently disturbed to some degree by the sampling process and the maximum diameter of the samples was limited to 38 mm. It was apparent from a visual and tactile examination of the samples obtained that the silty clay material in this zone of the deposit was less than homogeneous. As noted in Section 5.1.2, not all of the samples obtained in the weathered and desiccated silty clay above a depth of 4± metres contained visible fissures or fractures. The samples of silty clay that were obtained intact from the split spoon sampler were difficult to trim for laboratory hydraulic conductivity testing without damaging the samples.

With the variations in the fissured and fractured silty clay material and the poor quality of the samples that were available for testing, it was not unexpected that there would be a significant scatter in the hydraulic conductivity test results obtained from these samples. The range of hydraulic conductivity indicated by the permeameter tests was between 1.65×10^{-8} and 96.6×10^{-8} cm/sec, a variation of two orders of magnitude. The one-dimensional consolidation tests for hydraulic conductivity indicated values of the order of 70×10^{-8} cm/sec., which lie within the range of the test results obtained from the permeameter.

The silty clay at the Woodslee test site beneath a depth of 4± metres is not as hard as the shallower material and shelby tube samplers were used to obtain samples of silty clay 73 mm in diameter, almost twice the size of the samples obtained at a shallower depth. The thin-walled shelby tube also disturbed the samples less and trimming of the grey plastic silty clay was comparatively easy. The embedded sand and gravel in the silty clay till did, however, necessitate care be taken to prevent creating voids when sizing the samples for the laboratory test apparatus. The size of the samples allowed the removal of the smeared silty clay on the sides of the sample caused by the sampling operation. It was not possible to trim the samples without leaving a thinner smear layer on the samples wherever they were cut.

There were no apparent fissures or fractures in the silty clay taken from below a depth of 4± metres at the Woodslee test site. The samples were all visually inspected prior to testing and found to be homogenous. Since the sampling procedures used to obtain the samples in this zone minimized the disturbance of the samples, it was not unexpected that there was only an order of magnitude scatter in the hydraulic conductivity values for the samples tested in the permeameter. The permeameter test results indicated hydraulic conductivities in the range of 0.6×10^{-8} to 1.7×10^{-8} cm/sec. The difference between the hydraulic conductivity of the silty clay samples as evaluated by one and three dimensional consolidation tests varied by a factor of 10 cm/sec. These tests however, indicated the hydraulic conductivity of the silty clay to be in the range of 8×10^{-8} to 40×10^{-8} cm/sec., as much as two orders of magnitude different from the hydraulic conductivity of similar material tested in the permeameter.

From the results of laboratory evaluations of hydraulic conductivity for samples from the Woodslee test site it appears that the upper 4± metres of the silty clay has a hydraulic conductivity as much as two orders of magnitude greater than the hydraulic conductivity of the silty clay from depths greater than 4± metres, as evaluated with the permeameter apparatus. This greater hydraulic conductivity can be directly attributed to secondary fissure and fracture permeability features in the shallow portion of the silty clay till. The testing procedure is sufficiently poor however, that the lower values of hydraulic conductivity obtained for the weathered and desiccated silty clay material are of the same order of magnitude as the hydraulic conductivity values obtained for the unfractured silty clay sampled from greater depth. Where the samples of the weathered and desiccated silty clay did not contain representative fissure or fracture features, measured hydraulic conductivity values are representative only of the intact silty clay matrix and the measured hydraulic conductivity values obtained are potentially misleading.

The hydraulic conductivity values obtained from consolidation tests on samples of the silty clay from beneath a depth of 4± metres are less than the values of hydraulic conductivity obtained for samples of the shallower silty clay tested by consolidation. The difference is less than one order of magnitude. The hydraulic conductivity values from consolidation testing of the plastic silty clay are therefore within the range of values determined by the permeameter for the shallower fissured and fractured silty clay material. Based on the consolidation test derived values of hydraulic conductivity from this site there is no significant variation in the hydraulic conductivity of the laboratory tested silty clay samples. Similar results were reported by Desaulniers (1981) for samples of silty clay tested for hydraulic conductivity by the consolidation test method.

6.1.2 West Windsor Test Site

Like the deeper silty clay at the Woodslee test site, both the lacustrine and glaciolacustrine deposits of silty clay from the West Windsor test site have a consistency that allowed for relatively undisturbed samples of material to be obtained using large diameter (78 mm), thin walled shelby tube samplers. The disturbance to these samples of silty clay as they were obtained was minimal. The samples of the lacustrine silty clay contained virtually no sand or gravel size particles and the glaciolacustrine silty clay from the West Windsor test site contained less embedded gravel size particles than did the silty clay till sampled at the Woodslee test site. The silty clay samples obtained at the West Windsor test site were noticably easier to trim to size for insertion in the laboratory test mechanisms. There was less smearing of the silty clay surfaces when the samples were trimmed and less chance of creating voids which develop when larger embedded particles are disturbed.

As discussed in Section 5.2.4.1, there was a measurable variation between the vertical and horizontal hydraulic conductivity of the lacustrine silty clay sampled at the West Windsor test site. The vertical hydraulic conductivity as determined by permeameter tests was found to range from 1.5 x 10^{-8} to 2.5 x 10^{-8} cm/sec and the horizontal hydraulic conductivity as determined by the same test method was found to range from 4 x 10^{-8} to 5 x 10^{-8} cm/sec. In both instances the standard deviation in the measured hydraulic conductivity of the samples of a single orientation was less than 10^{-8} cm/sec. The variation between the means of the vertical and horizontal hydraulic conductivity is 2.5 x 10^{-8} cm/sec. The ratio of horizontal to vertical hydraulic conductivity is therefore in the range of 1.6 to 3.3, similar to the 1.5 to 3.7 range reported by Chan and Kenney (1973) when samples of a varved clay from the New Liskard area were tested for anisotropic hydraulic conductivity.

The results of permeameter tests carried out on samples of glaciolacustrine silty clay from the West Windsor test site indicate a range of hydraulic conductivity of 2 x 10^{-8} to 8 x 10^{-8} cm/sec. There was no measurable variation between the vertical and horizontal hydraulic conductivity of the glaciolacustrine silty clay samples. The variation in the range of hydraulic conductivity in this material is significantly larger than the variation in the range of hydraulic conductivity measured by the same procedures in the lacustrine silty clay samples. As noted in Section 5.2.4.1 the horizontal hydraulic conductivity of the glaciolacustrine material was consistently greater than or equal to the vertical hydraulic conductivity for the samples tested in two orientations. The scatter of the test results obtained in this material was such that this variation of the vertical and horizontal hydraulic conductivity measurements was insignificant. The greater scatter of the permeameter derived hydraulic conductivity values for the glaciolacustrine silty clay as opposed to the values measured for the lacustrine silty clay samples can be attributed to the greater heterogeneity of the samples of glaciolacustrine material. This heterogeneity arises from variable quantities of larger embedded particles in the silty clay that affect the sampling and trimming processes.

Consolidation test evaluation of the hydraulic conductivity of the glaciolacustrine silty clay samples indicated a range of hydraulic conductivity from 35 x 10^{-8} to 115 x 10^{-8} cm/sec. There is an order of magnitude variation in the range of hydraulic conductivity as determined by the consolidation test procedure. This variation is however, distinctly attributable to local variations of the glaciolacustrine material as discussed in Section 5.2.4.2. The two order of magnitude to three order of magnitude difference between the hydraulic conductivity of the glaciolacustrine silty clay samples as measured in the permeameter and as measured in the odeometer cannot be attributed to variation of the material sampled from this deposit.

6.1.3 Factors Affecting Laboratory Test Results

It is apparent from the test results for samples obtained at both of the test sites that the variation in the hydraulic conductivity of the silty clay as determined by any of the test methods is directly related to the quality of the samples obtained. The amount of sample disturbance caused by the sampling procedure is very important to the consistency of the tests. The texture of the silty clay tested also dictated the accuracy that could be obtained in measuring the hydraulic conductivity of the samples. The more sand and gravel size particles embedded in the silty clay the greater was the apparent variation of the hydraulic conductivity of the material as measured in the laboratory. As the sand and gravel content of the silty clay samples increased, trimming of these samples without causing the formation of voids and excessive smearing of the samples became more difficult.

Olsen and Daniel (1981) detail a variety of factors affecting the results of laboratory tests to evaluate the hydraulic conductivity of fine-grained soils. Included in this discussion are the effects of sample preparation. The authors also list: improper saturation of the samples, alteration of the chemistry of the samples, and orientation of the samples. The samples placed in the permeameter for this study were saturated from the bottom up by flowing permeant and a sufficient flow period was allowed prior to testing to ensure that the hydraulic conductivity measurements made were independent of variation due to sample saturation (i.e., constant with time). The testing program for samples from both of the study sites investigated the sensitivity of the silty clay soils to variations in the chemistry of the permeant and it was found that the hydraulic conductivity of the low- to medium-plasticity silty clays was not measurably affected by variations in the salinity of the permeant. As has been previously discussed, only the hydraulic conductivity measurements in the obviously layered lacustrine silty clay were found to be dependent on sample orientation. The hydraulic conductivity of the glaciolacustrine silty clay and silty clay till samples was measurably isotropic.

All of the laboratory test procedures used in this study were carried out on relatively small samples of silty clay material. It was particularly apparent that samples of the fissured and fractured portion of the silty clay till encountered at the Woodslee test site were not always representative of the entire soil mass. Samples that contained examples of fissures and fractures indicated hydraulic conductivity values substantially different from those samples that did not contain secondary permeability features. Even those samples that did contain fissures and fractures may not have been representative of the deposit. If features too large to appear in the 38 mm diameter samples exist in the till deposit then even the most carefully trimmed sample of fissured and fractured material will not allow for an accurate laboratory evaluation of the hydraulic conductivity of this material. Fissuring and fractures were not the only features of the silty clay soils that affected the laboratory evaluation of hydraulic conductivity. To a large extent the presence of sand and gravel particles within the silty clay affects the laboratory test results because of the difficulties these particles present when trimming the samples for testing. When relatively small samples of material are tested the presence of larger particles in the samples can also significantly alter the effective cross-sectional area of the samples.

For samples from both of the test sites, hydraulic conductivity measured in the permeameter apparatus was demonstrated to be repeatable and the results obtained were apparently as consistent as the size and quality of the samples allowed. Only eight samples were tested for hydraulic conductivity by the consolidation test method. These tests included samples of silty clay till from the Woodslee test site and samples of the glaciolacustrine silty clay from the West Windsor test site. It was found that the hydraulic conductivities of the silty clay samples as determined in the odeometer apparatus was consistently greater than those of similar samples tested in the permeameter. The variation in the hydraulic conductivity-values obtained from the two types of tests was one to three orders of magnitude. This variation must be attributed to the difference in the test procedures or assumptions, since both types of tests are conducted on similar size specimens which required comparable amounts of trimming. Olsen and Daniel (1981) note that the classical theory of consolidation does not account for the structural viscosity of the soil. They report that variations between permeameter derived and consolidation derived hydraulic conductivity values have been previously documented in the range of one to three orders of magnitude, such as was found in this study.

6.2 Comparison of Laboratory and In Situ Test Results

Tests to evaluate the hydraulic conductivity of soils in the field require more preparation, time and expense than laboratory testing procedures. The use of field testing procedures is therefore generally limited to uses where there is reason to expect that the laboratory samples or testing procedures are not representative of the <u>in situ</u> conditions. Field testing for hydraulic conductivity also becomes viable when the consequences of incorrectly assessing the hydraulic conductivity will result in conditions so potentially damaging that the time and expense of a field testing programme becomes justified.

The hydraulic conductivity tests carried out at the two study sites provided results representative of the <u>in situ</u> hydraulic conductivity in each of the three types of silty clay deposits that were encountered.

6.2.1 Lacustrine Silty Clay - West Windsor Test Site

The results of the single well response tests at the West Windsor test site indicated that the wells with portions of the screened length above the 6± metre depth level had hydraulic conductivities in the range of 15×10^{-8} to 45×10^{-8} cm/sec. The lacustrine silty clay deposit at this site extended to depths of less than 4.6 metres, but it is assumed that the single well response test results from above 6± metres were influenced by this material.

Laboratory tests showed that the hydraulic conductivity of the lacustrine silty clay was anisotropic and that the horizontal hydraulic conductivity of the silty clay was greater than the vertical hydraulic conductivity. All of the probes installed in the lacustrine material were similar in length to diameter ratio so that there was no possibility of <u>in situ</u> estimation of the anisotropy of the hydraulic conductivity of the lacustrine deposit from the single-well response test results.

The geometry of the single-well response tests was such that it would be expected that the horizontal hydraulic conductivity of the silty clay would be measured by the <u>in situ</u> test procedure. The permeameter determination of the horizontal hydraulic conductivity of the silty clay indicated a range of 4×10^{-8} to 5×10^{-8} cm/sec. The hydraulic conductivity of the lacustrine silty clay was therefore measured to be as much as one order of magnitude greater by in situ testing than laboratory permeameter test results would indicate.

The sample size limitations imposed by laboratory techniques preclude the chance that laboratory tests will be completed on samples representative of in situ soil conditions. The variation between the laboratory test results and the single well response test results can be attributed to this scale factor. The lacustrine silty clay is a distinctly layered deposit and can be expected to contain layers of sediment that have a greater grain size and intrinsic permeability than other layers. In a relatively small sample of material tested in the laboratory it would only be by chance if a sample contained a layer representative of the most permeable of the layers that comprise the lacustrine silty clay deposit. The cross-section of soil exposed for testing by the single well response test method is substantially greater and it is more likely that a representative variety of the layers that comprise the deposit will be included in the sample section. The hydraulic conductivity, as measured by the single well response test, is therefore likely to be greater than the laboratory value because of the exposure of more permeable layers.

6.2.2 Glaciolacustrine Silty Clay - West Windsor Test Site

The results of single well response tests at the West Windsor test site generally indicated that the soil surrounding the wells screened beneath a depth of 6± metres has a hydraulic conductivity in the range of 3×10^{-8} to 8×10^{-8} cm/sec. These in situ hydraulic conductivity test results are representative of the glaciolacutrine silty clay deposit that extends to depth at this site.

Laboratory permeameter tests of the hydraulic conductivity of the glaciolacustrine silty clay indicated that this material was isotropic with respect to hydraulic conductivity. The permeameter test results indicated the hydraulic conductivity of this silty clay material to be in the range of

2×10^{-8} to 8×10^{-8} cm/sec. There is therefore substantial agreement between the results of the permeameter and in situ hydraulic conductivity test results for the glaciolacustrine silty clay deposit.

The consolidation test method of determining hydraulic conductivity indicated a range of 35×10^{-8} to 115×10^{-8} cm/sec for the glaciolacustrine material. It appears that the consolidation test method over estimated the hydraulic conductivity of the glaciolacustrine silty clay by one to two orders of magnitude.

6.2.3 Silty Clay Till - Woodslee Test Site

The single well response tests carried out in the observation wells with portions of the screens in the fissured and fractured silty clay till located less than 4± metres beneath the ground surface at the Woodslee test site indicate hydraulic conductivity in the range of 25×10^{-8} to 40×10^{-8} cm/sec. These values are within the range of hydraulic conductivity for this material as indicated by the laboratory permeameter and consolidation tests. The range of values obtained from the laboratory hydraulic conductivity evaluation of this material was so large, however, that there were laboratory measured values of hydraulic conductivity both greater than and less than one order of magnitude different from the measured in situ values.

Laboratory permeameter tests carried out on samples of the silty clay till from beneath a depth of 4± metres, below the level of material observed to contain fractures, indicated a range of hydraulic conductivity between 0.58×10^{-8} and 1.68×10^{-8} cm/sec. This range of values is similar to the range of hydraulic conductivity values measured in the majority of the observation wells with screens entirely beneath a depth of 2± metres. The in situ hydraulic conductivity values measured from the majority of these wells were in the range of 1.5×10^{-8} to 3×10^{-8} cm/sec.

The laboratory assessment of hydraulic conductivity on samples from beneath a depth of 4± metres using the consolidation test method indicated hydraulic conductivity in the range of 8×10^{-8} to 40×10^{-8} cm/sec. This range of values is an order of magnitude greater than the hydraulic conductivity values indicated by the permeameter tests and the single well response test results. As was the case for the glaciolacustrine silty clay at the West Windsor test site, the consolidation test method apparently over estimated the hydraulic conductivity of the silty clay till by more than an order of magnitude.

Some of the single well response tests carried out at the Woodslee test site in observation wells with screens located more than 4± metres below grade indicated hydraulic conductivity in the range of 6×10^{-8} to 15×10^{-8} cm/sec. This range of hydraulic conductivity is distinctly less than the range measured for the upper fissured and fractured portion of the silty clay till, but is significantly greater, by as much as an order of magnitude, than the range of hydraulic conductivity generally determined to be representative of the unfractured silty clay till. The single well response test assessments of hydraulic conductivity therefore suggest an aspect of the hydraulic conductivity evaluation at this site that was not indicated by the permeameter test results. The <u>in situ</u> hydraulic conductivity tests suggest that there is a secondary permeability feature at the site that affects some of the observation wells, likely the existence of fracturing in the plastic silty clay beneath a depth of 4± metres.

The influence of fractures on the effective porosity and hydraulic conductivity of clay and till materials has been studied in detail by Grisak (1974), Grisak <u>et al.</u> (1976), and Grisak <u>et al.</u> (1980). All of this work suggests that the influence of a fracture network on a deposit with relatively low hydraulic conductivity, such as a silty clay till, is to effectively increase the bulk hydraulic conductivity of the deposit by one to two orders of magnitude. The anomalous single well response test results obtained at the Woodslee test site are consistent with the existence of fractures in the silty clay till. Hanna (1966) reported fractures extending to depths of as much a 10 metres in a silty clay till deposit near Sarnia, Ontario. The samples of silty clay from beneath a depth of 4± metres at the Woodslee test site showed no visible signs of fractures. It has been the author's experience in other parts of Essex County, that fractures can be seen in the silty clay till when exposed in deep excavation faces at depths of more than 9 metres. As has been previously discussed, smearing on the surface of the plastic silty clay till samples likely masks any fractures that do occur in the samples obtained.

The in situ assessment of hydraulic conductivity at the Woodslee test site by the use of single well response tests indicates that the silty clay till deposits underlying the site are fractured to a depth of at least 10 metres, consistent with the findings of Hanna (1966). Contrary to the findings of Desaulnier (1981) the influence of these fractures on the hydraulic conductivity of the silty clay can be assessed by single well response tests. Only a small number of the wells at the Woodslee test site encountered fractures suggesting that the fracture spacing is greater than the diameter of the boreholes drilled to place the wells (165 mm) and that random chance determines whether an observation well will intersect one of the fractures in the silty clay.

Table 6.1 summarizes the hydraulic conductivity values of the major clayey deposits sampled for this study.

Table 6.1

Comparison of Laboratory and In Situ Test Results

Range of Hydraulic Conductivity Values x 10^{-8} cm/sec.

Test Method:	Consolidation	Permeameter	Single Well Response
Soil Type			
Lacustrine Silty Clay		4 to 5	15 to 45
Glaciolacustrine Silty Clay	35 to 115	2 to 8	3 to 8
Silty Clay Till (fractured)	75 to 77	2 to 97	25 to 40
Silty Clay Till (no apparent fractures)	8 to 40	1 to 2	2 to 15

6.3 Average Linear Groundwater Velocity

The ultimate reason for attempting to determine representative values of hydraulic conductivity for different soil deposits is to allow for the accurate application of Darcy's Law to predict the characteristics of a flow system. Many engineering and environmental assessments require an accurate prediction of specific discharge 'v' or the average linear groundwater velocity 'v̲' of a deposit as the premise for more advanced predictions in soil behavior or the transport of materials in the natural groundwater flow system. The range of the hydraulic conductivity values for the soils at the two test sites have been determined and the representativeness of these values have been discussed at length. It is of interest to estimate the average linear groundwater velocity of the silty clay deposits from the representative hydraulic conductivity values and correlate this information with the groundwater flow systems investigated at the two sites.

6.3.1 Estimation of 'v' from Hydraulic Conductivity Values

In Equation (19) it is demonstrated the average linear velocity of groundwater in a soil deposit depends on the porosity of the soil and the hydraulic gradient as well as the hydraulic conductivity.

The porosity of the silty clay soils at both sites can be determined from the void ratio measurements made as part of the consolidation tests performed. At the West Windsor Test Site it was found that the void ratio of the silty clays varied from 0.80 to 0.95. This range of void ratio corresponds to a range of porosity of 43 to 49 per cent and a median value of 46 per cent can be considered representative. The void ratio of the silty clay till at the Woodslee test site was found to vary from 0.50 to 0.60 corresponding to porosities of 33 to 38 per cent and a median value of 35 per cent is considered representative.

The horizontal component of the hydraulic gradient at the West Windsor test site was determined to be of the order of 0.004. The vertical component of the hydraulic gradient was determined to be generally of the order of 0.07. Where the influence of the West Windsor Landfill Site affects the gradient. A vertical component of hydraulic gradient of the order of 0.22 was determined. In either case the vertical component of the hydraulic gradient at this site indicates flow in an upward direction. It is apparent from an examination of these values that the horizontal component of hydraulic gradient at the West Windsor test site is so much less than the vertical component of the hydraulic gradient that a resolution of the vertical and horizontal components of hydraulic gradient indicates a flow direction that will be essentially vertically upward. In general the hydraulic gradient at the West Windsor test site will be of the order of 0.07 but in at least one portion of the test site (Monitoring Site 2) the hydraulic gradient will be of the order of 0.22.

The horizontal component of hydraulic gradient at the Woodslee test site was determined to be of the order of 0.002 and the vertical component of hydraulic gradient was determined to be of the order of 0.05 to 0.06 in a downward direction. The situation at the Woodslee test site is therefore similar to that at the West Windsor test site in that the vertical component of hydraulic gradient is substantially greater than the horizontal component of hydraulic gradient and flow can be expected to occur in an essentially vertical direction. The result is a resolved hydraulic gradient of the order of 0.05 to 0.06. At the Woodslee test site, however, flow will be in a downward direction.

These values were substituted into Equation (19) to determine the range of average linear groundwater velocity for the range of representative hydraulic conductivity values determined for each of the three silty clay deposits tested from the two study sites.

The lacustrine silty clay from the West Windsor test site was determined to have a hydraulic conductivity in the range of 15 x 10^{-8} to 45 x 10^{-8} cm/sec by in situ testing. Assuming a porosity of 0.46 and a hydraulic gradient of 0.07 the average linear groundwater velocity in the lacustrine silty clay could be expected to be in the range of 1 x 10^{-8} to 3 x 10^{-8} cm/sec. It is more relevant to discuss the average linear groundwater velocity in the silty clay materials in terms of distance per year. The average linear groundwater velocity of the lacustrine silty clay could be expected to be in the range of 1 to 3 cm/year.

The glaciolacustrine silty clay from the West Windsor test site was determined to have a hydraulic conductivity in the range of 3 x 10^{-8} to 8 x 10^{-8} cm/sec by both laboratory and in situ testing. Assuming a porosity of 0.46 and a hydraulic gradient of 0.07 the average linear groundwater velocity in the lacustrine silty clay could be expected to be in the range of 0.5 x 10^{-8} to 1.5 x 10^{-8} cm/sec or 0.25 to 0.50 cm/year.

The unfractured silty clay till from the Woodslee test site was determined to have a hydraulic conductivity in the range of 1.5×10^{-8} to 3×10^{-8} cm/sec by both laboratory and in situ testing. Assuming a porosity of 0.35 and a hydraulic gradient of 0.06 the average linear groundwater velocity in the till could be expected to be in the range of 0.25×10^{-8} to 0.5×10^{-8} cm/sec or 0.10 to 0.15 cm/year. The fractured silty clay till was determined to have a hydraulic conductivity in the range of 6×10^{-8} to 15×10^{-8} cm/sec by in situ testing. Assuming a porosity of 0.35 and a hydraulic gradient of 0.06 the average linear groundwater velocity in the fractured till would only be in the range of 1.0×10^{-8} to 2.6×10^{-8} cm/sec or 0.3 to 0.8 cm/year. The average linear groundwater velocity in the fractured silty clay till would be more than twice the average linear groundwater velocity in the unfractured material, but the velocity values are so small that the difference is only of the order of 0.5 cm/year.

6.3.2 Borehole Dilution Test Evaluation

Borehole dilution tests were carried out in the glaciolacustrine silty clay at the West Windsor test site and the silty clay till at the Woodslee test site. At the West Windsor test site an apparent average linear velocity of of 3.2×10^{-6} cm/sec was measured and at the Woodslee test site an apparent average linear groundwater velocity of 1.1×10^{-8} to 1.2×10^{-8} cm/sec was measured. These values are approximately two orders of magnitude in excess of the average linear groundwater velocities predicted at the site based on measured values of hydraulic gradient and hydraulic conductivity.

As discussed in Section 3.3.4, the apparent average linear groundwater velocity as determined by the borehole dilution test method is dependent on a number of factors relating to the geometry of the test well and the test procedures. Even if these factors are eliminated by the design of the test operation the apparent average linear groundwater velocity (v_a) is dependent on the actual average linear formation velocity ($\underline{v}$), as corrected to reflect the influence of the observation well (factor 'a'), and the apparent velocity of the tracer due to diffusion (v_d). The relationship of these factors is expressed in Equation (25) as follows:

$$v_a = a\underline{v} + v_d \tag{25}$$

The factor 'a' was estimated in accordance with the method suggested by Drost et al. (1968) at a value of 3.8 for the borehole dilution well configurations used for this study. Drost et al. (1968) noted that the effect of diffusion on the apparent average linear groundwater velocity was negligible if the average linear velocity of the flowing groundwater in the formation exceeded 3.5 x 10^{-4} cm/sec. The average linear groundwater flow velocity in the silty clay soils at the two test sites has been estimated at approximately two orders of magnitude less than this value, so that it is to be expected that a portion of the apparent average linear groundwater velocity measured in the borehole dilution tests is attributable to the apparent velocity of the tracer in the groundwater as a result of molecular diffusion.

If the apparent average linear groundwater velocities measured at the two test sites are substituted into Equation (25) together with the estimated average linear formation velocities as calculated based on the measurements carried out at the two test sites, then it is apparent that diffusion of the tracer is the primary mode of transport in the silty clay soils at the two sites. At the West Windsor test site the average linear velocity of the borehole dilution tracer by diffusive transport was of the order of 3.2 x 10^{-6} cm/sec or 100 cm/year as compared to an estimated average linear groundwater flow velocity of less than 1 cm/year. At the Woodslee test site the average linear velocity of the borehole dilution tracer due to diffusive transport was in the range of 1 x 10^{-6} cm/sec or 34 cm/year as compared to average linear groundwater flow velocities of 0.1 to 0.15 and 0.3 to 0.8 cm/year estimated for the unfractured and fractured silty clay till respectively. Goodall and Quigley (1977) reported similar apparent average linear velocities of transported substances, due to diffusion, in a silty clay till beneath a landfill near Sarnia, Ontario.

6.3.3 Tracer Test Evaluation

Based on the results of the borehole dilution tests carried out at the Woodslee test site it would be expected that a tracer injected into silty clay till at the injection well would have taken over a year to reach the nearest of the reception wells (4-R3) which was separated from the injection well by only 41.5 cm of silty clay till. In the actual tracer test as discussed in Section 5.1.5.3, the tracer travelled between the injection and reception wells in a period of days such that the tracer test results suggest the average linear velocity of the tracer was of the order of 10^{-4} to 10^{-5} cm/sec. These values suggest that a tracer would be expected to travel as much as 200 metres a year in the silty clay till if these velocities were representative of in situ conditions. It is not difficult to conclude that the observation well array installed for this study did not function as intended and that the tracer test results are not representative of the groundwater velocity at the Woodslee test site. Several possibilities exist to explain why the array of wells used for the tracer test study did not provide accurate results: (1) that the silty clay in the area of Monitoring Site 4 contained major fractures prior to drilling, (2) despite the best efforts of the driller to keep the observation well holes plumb during the boring operation, that the drill string wandered below grade so that the screens of some of the observation wells were substantially closer to the injection well at screen depth than they were at the ground surface, and (3) that the pressure from the augering process fractured the silty clay between the boreholes creating preferential seepage channels in the silty clay. The last of these possibilities is perhaps the most likely, though either of the other explanations for the failure of the tracer test array could have contributed to the anomalous results obtained from this test.

6.3.4 Implications of the Environmental Isotope Distributions

The process of diffusion apparently governs the transport of substances dissolved in the pore water of the silty clay deposits beneath the West Windsor and Woodslee test sites if diffusion occurs at the apparent average linear velocity measured for the saline tracer. The rate of transport is approximately in the range of 1 and 0.35 m/year at the West Windsor and Woodslee test sites, respectively.

6.3.4.1 Tritium

The transport of tritium in the ground is the result of both advective and difusive fluxes. At Woodslee, both the fluxes are downwards so that their effects are additive. Assuming that the tritium front moves at an apparent linear transport velocity of 35 cm/year at the Woodslee site (determined in the borehole dilution test), there should be no excess tritium beneath a depth of 10± metres. As discussed in Section 5.1.3.4, the pore water at Monitoring Site 2 has tritium concentrations of the order of 10 TU or less beneath a depth of 10± metres. The measured tritium distribution at this monitoring site is therefore consistent with the distribution predicted based on the apparent average linear groundwater flow velocity. Above a depth of approximately 8 metres at Monitoring Site 3 the tritium distribution is similar to that at Monitoring Site 2. There were two pore water samples taken from this site, at depths of 9 and 10 metres, that had tritium concentrations in excess of 40 TU units. These anomalous tritium concentrations could be caused by local preferential advective transport of tritium in the fractured silty clay till.

The same type of analysis applied to the distribution of tritium at the West Windsor test site must take into account that the West Windsor test site is in a discharge zone. The flow of groundwater at this site, will occur in a direction opposite the diffusion of the tritium in the groundwater. At the apparent average linear velocity of 99 cm/year (borehole dilution test), and a calculated average linear velocity owing to advection, of 0.5 to 3 cm/year (single well tests), the net advance of tritium into the groundwater would be expected to be of the order of 96 to 98 cm/year. At this rate, one could expect to find tritiated water at a depth of 27+ metres. As discussed in Section 5.2.3.4, the pore water at Monitoring Site 20 of the West Windsor test site has tritium concentrations in excess of 20 TU to the full depth of 10+ metres investigated by this study. The observed tritium distribution is consistent with the predicted distribution. The tritium distribution measured at Monitoring Site 40, however, indicates that the pore water in the silty clay is not tritiated beneath a depth of 6+ metres. Since the soil profile at both of these sites is similar there must be a reason that tritium has not diffused in the pore water at the same rate at both sites.

One possibility lies in the topography of the sand-silty clay interface. The information available suggests that the thickness of the sand deposit varies considerably, probably dependent on the original contours of the underlying silty clay strata. Where the surficial sand layer has been deposited within contained depressions in the silty clay surface, flow in the sand will be governed by the properties of the silty clay and there will be little flow of groundwater in the sand layer. In this case diffusion of tritium would occur in accordance with the rate predicted by the diffusion model (Monitoring Site 20). Where the surficial sand layer is not contained and flow occurs at a rate governed by the properties of the sand, a sufficient rate of flow could occur in the sand layer, even with a small hydraulic gradient, that would be of similar order of magnitude to the apparent average linear velocity of tritium due to diffusion such that diffusion of the tritium would appear to take place at a slower rate (Monitoring Site 40).

6.3.4.2 Oxygen-18

The concentration of ^{18}O in the soil pore water at the time the soil was formed remains unchanged unless it is mixed with water having a different concentration of oxygen-18 either by mechanical or difusive mixing.

The oxygen-18 distribution of the upper 10 metres of the Woodslee test site corroborates the findings of Desaulniers (1981). Desaulniers' oxygen-18 data suggests a decrease in oxygen-18 concentration throughout the soil profile to bedrock, such that an ^{18}O depletion in the order of -17o/ooSMOW was measured near bedrock at a depth of approximately 30 metres. Since the silty clay soil beneath the Woodslee test site is a glacial till material which was deposited during a climatic period which was distinctly cooler than the present, it is not surprising that the deepest soils have $\delta^{18}O$ values in the order of -17o/oo.

The plot of $\delta^{18}O$ <u>versus</u> depth at the Woodslee test site shows that there is a distribution of values from -9o/oo to -13o/oo between depths of 4 and 10 metres. It is apparent that if diffusion of ^{18}O occurred at a rate similar to the apparent average linear velocity of the saline tracer (36 cm/yr), the oxygen-18 concentration in the groundwater at a depth of 10 metres should be the same as that of the current rainfall; ie -10o/oo. That the pore water at a depth of 10 metres has a greater depletion in oxygen-18 than modern precipitation suggests that diffusion of ^{18}O in the soil pore water occurs at a slower rate than that measured for the saline tracer. This slower diffusion rate for ^{18}O is probably related to a substantially lower concentration gradient for ^{18}O than for the saline tracer.

If oxygen-18 diffuses at a slow rate, then advective transport, even at a rate of the order of 0.1 cm/year, could control the distribution of ^{18}O at the Woodslee test site. Since this site is in a recharge zone both advective and diffusive transport will act in the same downward direction. If we assume advective transport takes place at a rate of 0.1 cm/year and transport of the oxygen-18 takes place at a rate of similar magnitude, then the resulting distribution of ^{18}O would not be inconsistent with the distribution of the isotope observed at the Woodslee test site.

The West Windsor test site is located in a groundwater discharge zone, if the advective and diffusive transport rates of oxygen-18 are similar, as was postulated at the Woodslee test site, then there would be no advance of an oxygen-18 gradient in the silty clay deposits at this site. The borehole dilution test results indicate that the diffusion rate at West Windsor is three times that a Woodslee. This being the case, there would be a sufficient net transport rate for the oxygen-18 that we could expect isotope concentrations in the groundwater to at least the 10 metre depth consistent with the ^{18}O isotope concentration in modern precipitation. This expected distribution was recorded at the West Windsor test site. It will be necessary to determine the distribution of oxygen-18 in the deeper portions of the silty clay beneath the West Windsor test site to make a more accurate assessment of the net transport rate for this isotope that would be consistent with the distributions found at the Woodslee and West Windsor sites.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Summation

Three deposits of silty clay were sampled at the two test sites of this study. Lacustrine and glaciolacustrine silty clays were encountered at the West Windsor test site and silty clay till was penetrated at the Woodslee test site. A laboratory testing programme was carried out to assess the relative value of different testing procedures to determine representative ranges of hydraulic conductivity for these deposits.

Hydraulic conductivity values derived from consolidation test results were consistently greater than the values obtained from permeameter tests. The consolidation test method of determining hydraulic conductivity was found to be insensitive to variations in the samples. The reproducibility of the test was limited to approximately an order of magnitude. The permeameter test results are reproducible and the accuracy of the tests varied from less than half an order of magnitude to an order of magnitude, depending on the quality of the samples obtained and the number of sand and gravel size particles embedded in the silty clay samples.

Permeameter derived values of hydraulic conductivity for the glaciolacustrine silty clay and unfractured silty clay till were essentially similar to the results obtained from in situ hydraulic conductivity testing. The in situ and laboratory test values of hydraulic conductivity for the shallow silty clay till which is fissured and fractured at close intervals were of the same order of magnitude. The scatter of the permeameter test results for the fissured and fractured material makes the laboratory evaluation of hydraulic conductivity in this type of material of questionable value unless a sustantial number of tests are carried out.

The permeameter tested samples of the lacustrine silty clay did not provide a representative range of hydraulic conductivity values. Field testing to determine hydraulic conductivity indicates that in situ hydraulic conductivity is as much as an order of magnitude greater than indicated by the laboratory test results. Permeameter tested samples of the silty clay till did not indicate that there could be fractures throughout the till deposit and that these fractures contribute to the hydraulic conductivity of the deposit. Many natural deposits contain such secondary permeability features, seams of preferential drainage, fissuring and fractures, the results of laboratory tests to determine hydraulic conductivity should not be considered as representative of a deposit unless in situ testing verifies that the samples used in the laboratory testing programme are representative of the in situ conditions. Of the three silty clay deposits tested in this study only the hydraulic conductivity of the glaciolacustrine silty clay deposit could be accurately assessed from the laboratory test results.

The permeameter testing program was useful in establishing confidence in conservative nature of the sodium chloride tracer substance in the silty clays.For the 1 to 2 hour time frame of the permeameter test process, there was no variation in the hydraulic conductivity of the silty clays when a saline permeant was substituted for the natural groundwater permeant.

The porosity of the lacustrine and glaciolacustrine silty clays from the West Windsor test was found to range from 43 to 49 per cent and the porosity of the silty clay till from the Woodslee test site was in the range of 33 to 38 per cent. The observation well installations at the two sites indicate the groundwater table to be within 1 to 1.5 metres of the ground surface. The West Windsor test site is in a discharge zone and the hydraulic gradient is typically of the order of 0.07 with flow in an upward direction. The Woodslee test site is in a recharge zone and the hydraulic gradient is typically in the range 0.05 to 0.06 with flow in the downward direction. The horizontal component of the hydraulic gradient was determined to be of the order of 0.004 and 0.002 for the West Windsor and Woodslee test sites, respectively. Flow at both of the test sites was therefore essentially vertical.

On the basis of porosities, hydraulic gradients and hydraulic conductivity values, the average linear groundwater velocity was determined to be in the range of 1 to 3 cm/year for the lacustrine silty clay, 0.2 to 0.5 cm/year for the glaciolacustrine silty clay, and 0.1 to 0.8 cm/year for the silty clay till. Borehole dilution test results indicate that a tracer substance in the groundwater at the West Windsor and Woodslee test sites has an apparent average linear velocities of 99 and 36 cm/year respectively and the transport of a substance in the groundwater at the two sites is therefore dominated by diffusive rather than advective transport. The average linear velocity of a substance due to diffusive transport is approximately two orders of magnitude greater than due to advective transport.

The tritium concentration distribution at the Woodslee test site was found to be consistent with the measured apparent average linear transport velocities. This agreement suggests that the simple and inexpensive borehole dilution apparatus employed for this study could be very useful in contaminant transport studies in fine-grained soils. The tritium distribution at Monitoring Site 20 of the West Windsor test site was also found to be consistent with the apparent average linear velocity measured by the borehole dilution test. The transport of tritium at West Windsor Monitorng Site 40 is complicated by a surficial layer of fine to medium sand of variable thickness and it was found that tritiated water had not been transported to the extent predicted by the measured apparent average linear transport velocity. In areas of complicated groundwater movement, particularly where there are substantial flow rates, the use of the devise may be very limited.

The distributions of oxygen-18 at both the Woodslee and West Windsor test sites are consistent with the trends of the measured diffusion rates in the silty clay soils.

7.2 Suggested Improvements of Techniques

The monitoring wells at the test sites were installed using '1.5 inch' or '2 inch' size piping. There was consequently a substantial time lag in the wells before equilibrium with the in situ pore water pressures was achieved. The use of smaller diameter wells with less storage capacity would be preferable in future work.

At least one of the observation wells was affected by the proximity of a large tree. Special care and consideration should be exercised when installing observation wells in clayey soils to ensure that the wells are as far from trees as physically possible.

The accuracy of the hydraulic conductivity assessments for the silty clay soils tested in this study was obviously affected by the quality of the samples obtained. The most critical factor affecting the quality of the samples was the sand and gravel content in the glacial silty clay soils. The effects of these larger particles could be minimized by taking larger samples in the field and by using laboratory equipment that will accommodate significantly larger samples.

The borehole dilution apparatus employed was simple to construct, reusable and relatively inexpensive. The device is limited to use in fine-grained soils with relatively low apparent average linear velocities because of the period of time required after installation of the probe before the dilution measurements are unaffected by the pressure induced when the probe is inserted. The incorporation of a pressure relief valve that could be sealed after the probe is inserted, would alleviate this problem and extend the use of this device. This type of alteration would increase the cost and time of construction for the apparatus.

The tracer test installation did not function as intended and this failure must be related to the design of the observation well array and the method used to place these wells. The probes used require a '2 inch' size pipe for installation but the size of the boreholes could be reduced and the spacing increased. The advance of the drill holes could be regulated at a slow speed to decrease the possibility of over stressing the silty clay material between boreholes. If another attempt were made to carry out a well-to-well type tracer test at this site then the array should be both larger in areal extent and three-dimensional. The observation wells suggest that flow at the sites is essentially vertical and diffusion will occur in all directions. Vertical observation well arrays could be installed using the single pipe, multi-port observation well equipment now commercially available. Since transport from the injection well is expected to occur essentially by diffusion, the injection well should be a constant concentration source as opposed to the single 'tracer slug' type source used in this study. The constant concentration at the injection well will allow for an analytical solution of the differential mass balance equation needed to define transport in the silty clay soil.

7.3 Suggested Future Studies

The Quarternary geology in the area of the West Windsor test site has only been generally mapped. The significance of developing accurate profiles of this area should not be over looked. The delineation of the near surface deposits of sand and lacustrine silty clay (Lake Rouge) in this area could add valuable information to the geological history of the Lake St. Clair and Lake Erie basins, if information from the Detroit River shore area can be correlated with the beach deposits of these two adjacent lakes.

The lacustrine and glaciolacustrine soils encountered at the West Windsor test site are relatively weak by comparison to the silty clay till deposits that predominate in Essex County. The accurate mapping of these deposits would be particularly valuable as a basis for rational land use planning and the selection of an economical development strategy for the City of Windsor and other communities that occupy river front property.

The lacustrine silty clay sampled at the West Windsor test site has been shown to have a ratio of horizontal to vertical hydraulic conductivity in the range of 1.6 to 3.3. The laboratory test results from this study suggest that there may be a variation between the horizontal and vertical hydraulic conductivity of the glaciolacustrine silty clay deposit but the accuracy of the testing done in this study was insufficient to demonstrate the significance of this anisotropy. A testing program involving considerably more samples could be undertaken to determine if this anisotropy actually exists. If such a study is undertaken the largest possible samples should be obtained to avoid the effects of sample disturbance and the sand and gravel particles embedded in the silty clay.

The movement of groundwater in the surficial fine to medium sand layer at the West Windsor test site and the transport of substances in this layer to and from the underlying silty clay strata is apparently complex. The relationship between discharging groundwater from the glaciolaucustrine silty clay to the lacustrine silty clay to the surficial sand, each layer with a measurably greater hydraulic conductivity would be of interest particularly if the effects of diffusive transport can be studied in conjunction with the advective component of transport.

Information gathered as part of this study suggests that there is a substantial leachate plume extending from the West Windsor Landfill site, in the surficial sand and at depth in the silty clay deposits. The monitoring and delineation of this leachate plume would likely provide a considerable volume of information on the complex transport mechanisms that affect this area. The leachate plume from the West Windsor Landfill site has a high specific conductance. A geophysical survey of the landfill site area has been completed (Ali, 1984), and this survey can be used as a guide to plan the most effective locations for instrumentation of the site.

This study has confirmed a number of the findings of Desaulniers (1981) with regard to the movement and age of the pore water in the silty clay till, found at the Woodslee test site. There is much that could be learned from the comprehensive sampling and testing of the pore water in the silty clay till from the ground surface to the bedrock. Previous work was based on very limited sampling. For this study the sampling intervals were relatively frequent, but the extent of the investigation was limited.

Observation well 3-1 at the Woodslee test site was obviously effected by the moisture demands of an adjacent tree. Continuous monitoring of this well together with the installation and monitoring of tensiometers in the immediate area of the tree would provide valuable data for comparision with the precipitation and temperature data that are regularly collected at the Woodslee test site.

Diffusion is apparently the primary source of transport in the silty clay soils encountered at both of the test sites and there is a distinct scarcity of published information concerning the diffusion characteristics of fine grained soils and the relationship of these properties to groundwater transport of contaminants in general. This type of information is constantly becoming necessary with the ever increasing demands for safe but inexpensive disposal of contaminated substances. The development of a cost-effective laboratory testing procedure to measure the diffusion parameters of fine-grained soil samples and the design and testing of a field instrumentation scheme that could be used to accurately measure these parameters with reasonably consistent success, should be of primary concern for researchers and engineers endeavouring to work with these materials.

REFERENCES

Ali, Ja'Afar W., 1984. Geophysical Surveys of Groundwater Contamination at Three Sanitary Landfills in Essex County Ontario. Unpubl. M.Sc. thesis, University of Windsor, Windsor, Ontario, 246 pp.

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

Casagrande, A., 1948. Classification and Identification of Soils. Trans. ASCE, 113, pp. 901-992.

Chan, H.T. and Kenney, T.C., 1973. Laboratory Investigation of the Permeability Ratio of New Liskard Varved Soil. Canadian Geotechnical Journal, Volume 10, No. 3, pp. 453-472.

Chapman, L.J. and Putnam, D.F., 1966. The Physiography of Southern Ontario, Second Edition. Ontario Research Foundation, Toronto, 386 pp.

Dansgaard, W., 1964. Stable Isotopes in Precipitation. Tellus 16, pp. 436-468.

Darcy, H., 1856. Les fontaines publiques de la ville de Dijon. Victor Balont, Paris. (as referenced by Freeze and Cherry, 1979).

Day, M.J., 1977. Analysis of Movement and Hydrochemistry of Groundwater in the Fractured Clay and Till Deposits of the Winnipeg Area, Manitoba, M.Sc. thesis, University of Waterloo, Waterloo, Ontario, 210 pp.

Desaulniers, D.E., 1980. Origin, age and movement of pore water in argillaceous Quaternary deposits at four sites in southwestern Ontario. M.Sc. thesis, University of Waterloo, Waterloo, Ontario, 167 pp.

Desaulniers, D.E., Cherry J.A. and Fritz P., 1981. Origin Age and Movement of Pore Water in Argillaceous Quarternary Deposits at Four Sites in Southwestern Ontario, Journal of Hydrology, 50; pp. 231 - 257.

Drost, W., Klotz, D., Koch, A., Moser, H., Neumaier, F., and Rauert, W., 1968. Point Dilution Methods of Investigating Groundwater Flow by means of Radioisotopes, Water Resources Research, 4(1); pp. 125-146.

Elrick D.E. and Lawson D.W., 1967. Tracer Techniques in Hydrology, Proc. Instrumentation and Observation Techniques, Hydrology Symposium #7, Victoria B.C., National Research Council, pp. 155-187.

Experimental Farms Service, 1946. Woodlee Soil Research Centre - Soil Map, Agriculture Canada, unpublished.

Experimental Farms Service, 1947. Soils Map of Essex County, Ontario, Soil Survey Report No. 11, Department of Soils, Ontario Agricultural College, Guelph.

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

Goodall, D.C. and Quigley, R.M., 1977. Pollutant Migration from two Sanitary Landfill Sites near Sarnia, Ontario, Canadian Geotechnical Journal, Volume 14; pp. 223-236

Grisak, G.E., 1974. The Fracture Porosity of Glacial Till, Canadian Journal of Earth Sciences, 12: pp. 513-515.

Grisak, G.E., Cherry, J.A., Vonhof, J.A. and Blumele, J.P., 1976. Hydrogeological and Hydrochemical Properties of Fractured Till in the Interior Plains Region, Glacial Till, Special Publication 12, Legget, R.F. (ed.); Royal Society of Canada; pp. 304-335.

Grisak, G.E., Merritt W.F. and Williams, D.W., 1977. A Flouride Borehole Dilution Apparatus for Groundwater Velocity Measurements, Canadian Geotechnical Journal, Volume 14; pp. 554-561.

Grisak, G.E., and Pickens J.F., 1980. Solute Transport Through Fractured Media, 1. The Effect of Matrix Diffusion, Water Resources Research, Vol. 16, No. 4: pp. 719-730.

Grisak, G.E., Pickens J.F. and Cherry J.A., 1980. Solute Transport Through Fractured Media, 2. Column Study of Fractured Till, Water Resources Research, Vol. 16, No. 4: pp.731-739.

Hanna, T.H., 1966. Engineering Properties of the Glacial Lake Near Sarnia, Ontario, Ontario Hydro-Electric Power Commission, Res. Q.; pp 1-12; (as referenced by Desaulniers, 1981).

Hvorslev, M.J., 1951. Time-Lag and Soil Permeability in Groundwater Observations, U.S. Army Corps of Engineers, Waterways Experimental Station, Vicksburg, Mississippi, Bulletin 36, 50 pp.

J.D. Barnes Ltd., Surveyors, 1977. City of Windsor, Topographic Map, Scale 1/1000; Department of Public Works, Corporation of the City of Windsor, Windsor, Ontario.

Kaufman, W.J. and Orlob, G.T., 1956. An Evaluation of Ground-Water Tracers, Transactions, American Geophysical Union 37; pp. 297-306.

Lambe, T.W., 1951. Soil Testing for Engineers, John Wiley and Sons Inc., New York, N.Y., 165 pp.

Manheim, F.T., 1966. A Hydraulic Squeezer for Obtaining Interstitial Water from Consolidated and Unconsolidated Sediments, United States Geological Survey, Professional Paper 550-C; pp. C256-C261.

Olsen, R.E. and Daniel, D.E., 1981. Measurement of the Hydraulic Conductivity of Fine Grained Soils, Permeability and Groundwater Contaminant Transport, ASTM STP 746, T.F. Zimmie and C.O. Riggs (ed.); American Society for Testing and Materials; pp. 18-64.

Ontario Ministry of the Environment, 1977. Water Well Records for Ontario - Essex, 1946 - 1974, Water Resources Bulletin 2 - 19; Water Resources Branch.

Ontario Ministry of the Environment, 1980. Hydrogeologic Environments and the Susceptibility of Ground Water to Contamination, Map S100; Water Resources Branch.

Ontario Ministry of the Environment, 1981. Susceptibility of Ground Water to Contamination Windsor - Essex Sheet, Map S102; Water Resources Branch.

Ontario Water Resources Commission, 1971. Ground-Water Probability, County of Essex, Map 3107-1; Division of Water Resources.

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 Science Vol. 15: 162-169.

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

Perry, E.C. and Montgomery C.W., (ed.), 1982. Isotope Studies of Hydrologic Processes, Northern Illinois University Press, DeKalb, Illinois, pp. 118.

Sanford, B.V., 1969. Geology Toronto - Windsor Area, Geological Survey of Canada Map 1263A; Department of Energy Mines and Resources.

Slichter, C.S., 1905. Field Measurements of the Rate of Movement of Underground Water, U.S. Geological Survey, Water Supply Paper 140.

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 P2396, Geological Series; Ontario Ministry of Natural Resources.

Todd, D.K., 1959. Ground Water Hydrology; John Wiley and Sons, New York, 337 pp.

Vagners, U.J., 1972a. Quarternary Geology of the Windsor - Essex Area (Western Part), Southern Ontario; Preliminary Map P749, Geological Series; Ontario Department of Mines and Northern Affairs.

Vagners, U.J., 1972b. Quarternary Geology of the Windsor - Essex Area (Eastern Part), Southern Ontario, Preliminary Map P750, Geological Series; Ontario Department of Mines and Northern Affairs.

Vagners, U.J., Sado, E.V., and Yundt, S.E., 1973a. Drift Thickness of the Windsor - Essex Area (Western Part), Southern Ontario, Preliminary Map P.814, Drift Thickness Series; Ontario Division of Mines.

Vagners, U.J., Sado, E.V., and Yundt, S.E., 1973b. Drift Thickness of the Windsor - Essex Area (Eastern Part), Southern Ontario, Preliminary Map P.815, Drift Thickness Series; Ontario Division of Mines.

APPENDIX A

DETAILS OF OBSERVATION WELL INSTALLATION

WOODSLEE TEST SITE I

SITE and WELL INSTALLATION DETAILS

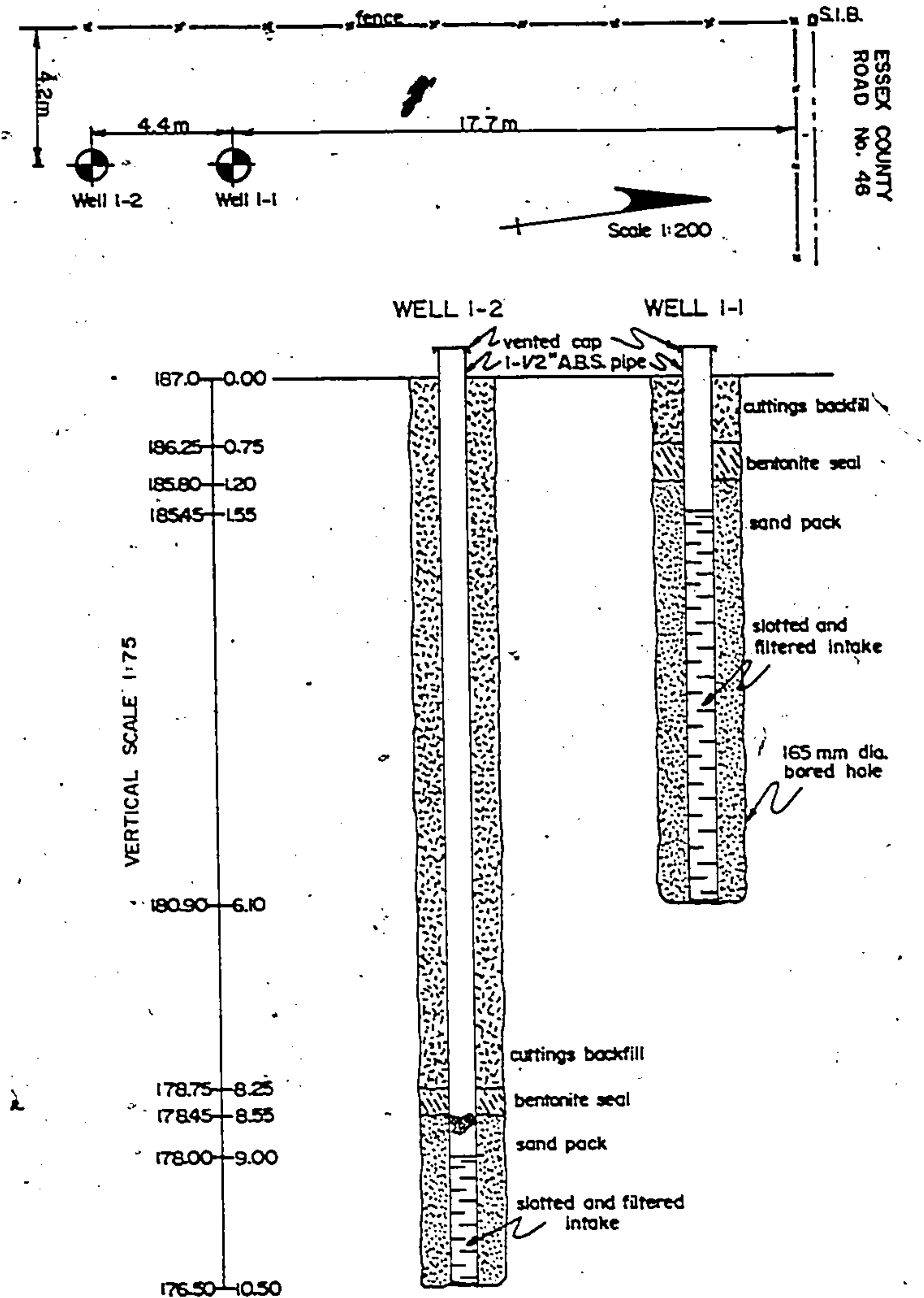


FIGURE- A.1

WOODSLEE TEST SITE 2

SITE and WELL INSTALLATION DETAILS

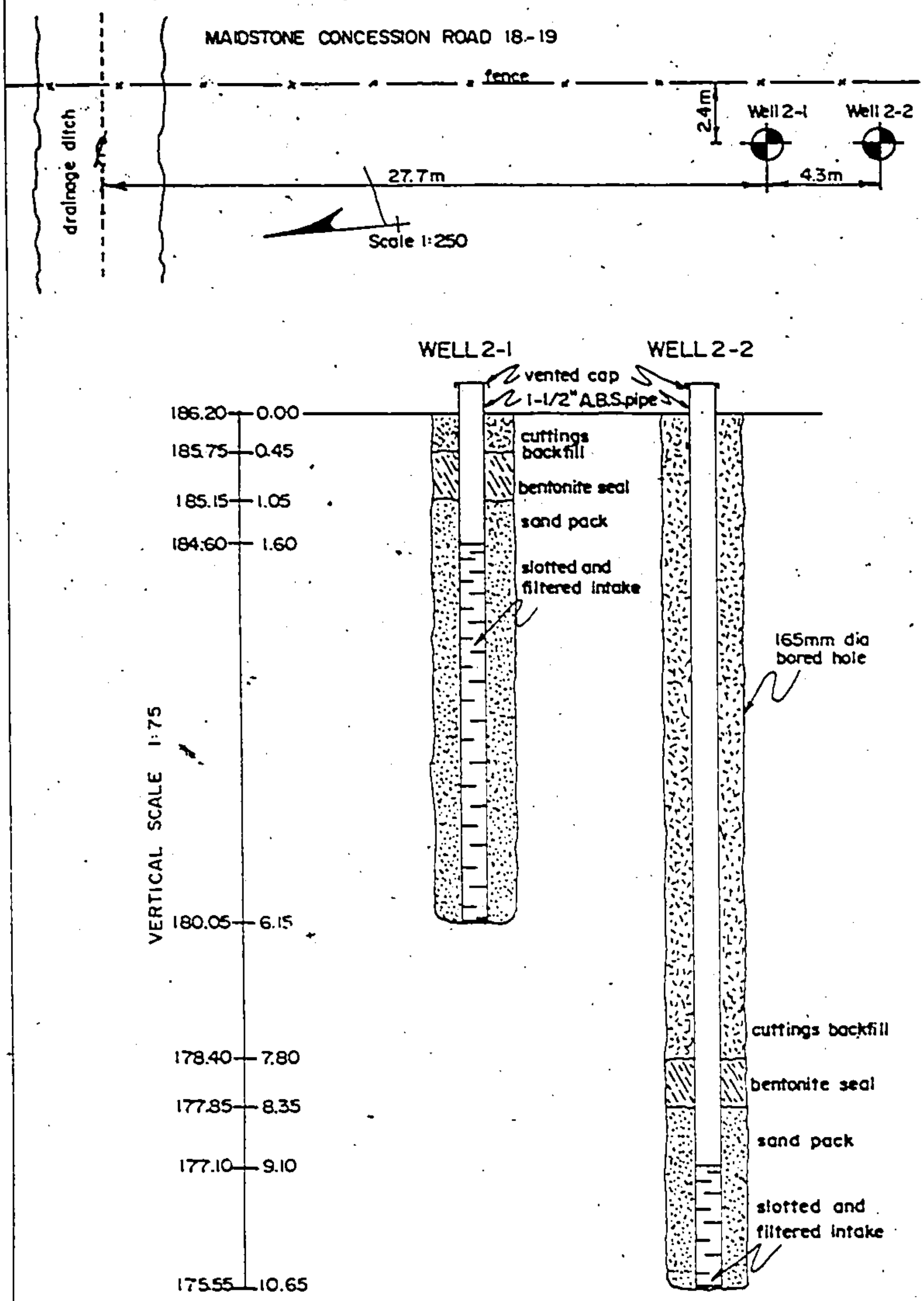


FIGURE - A.2

WOODSLEE TEST SITE 3

SITE and WELL INSTALLATION DETAILS

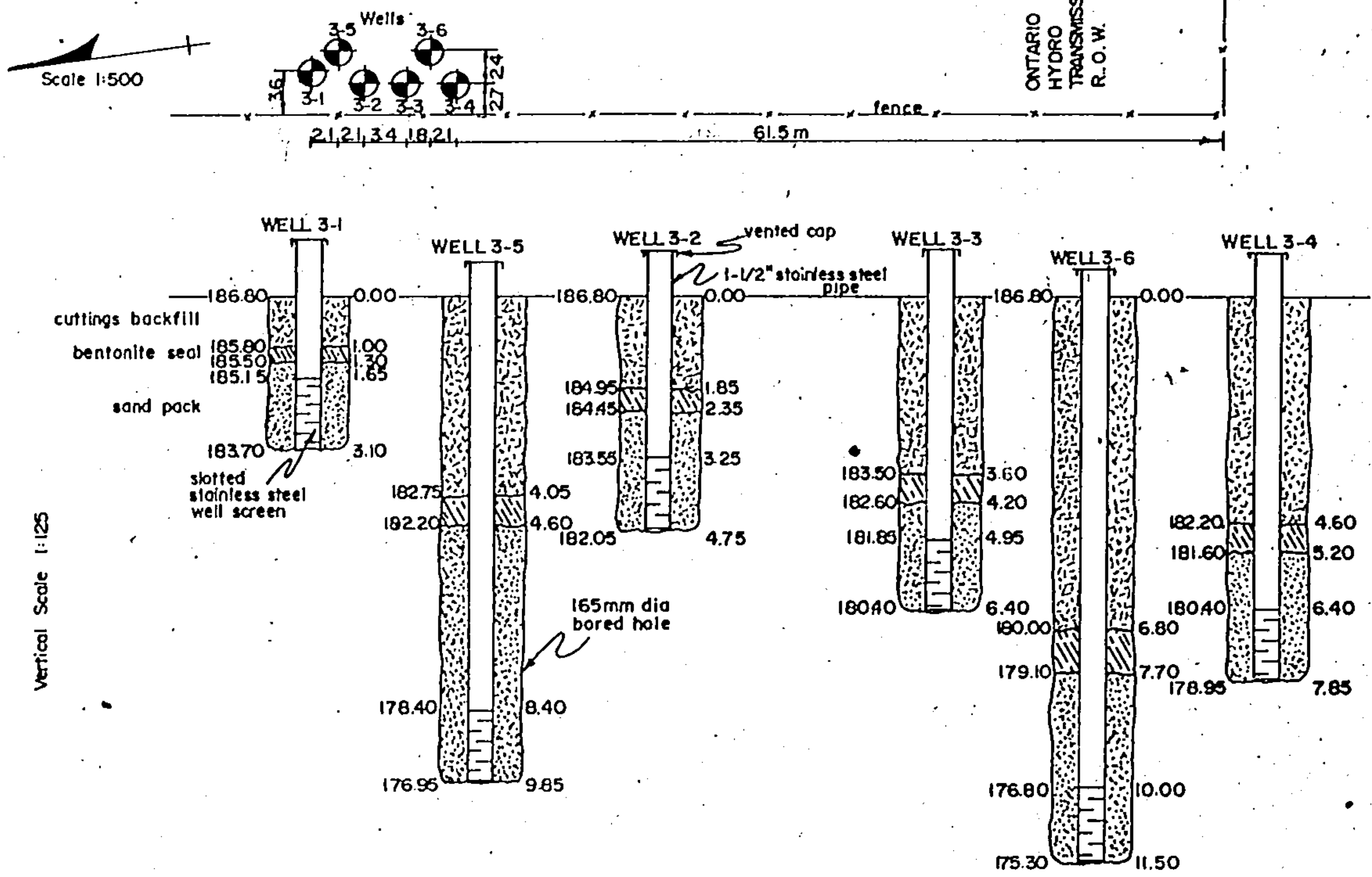
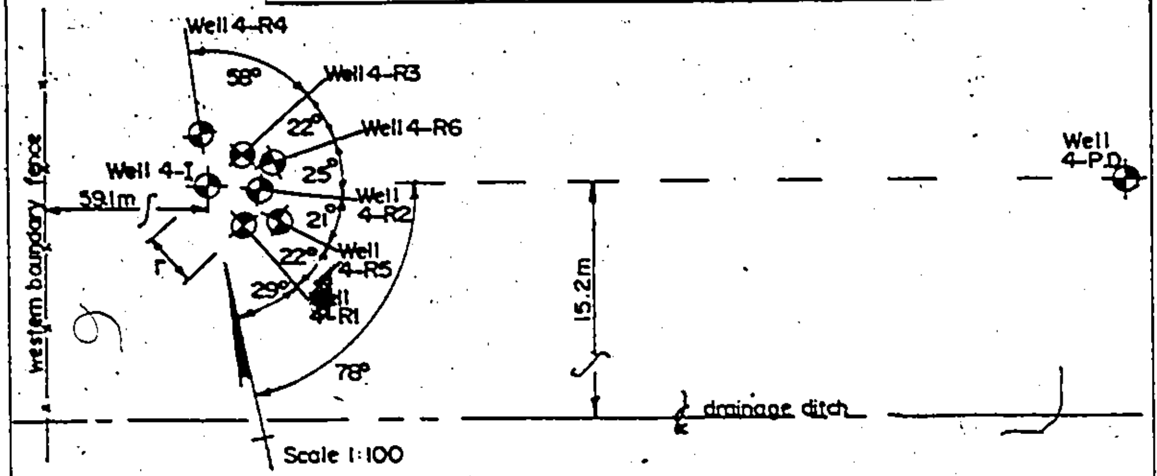


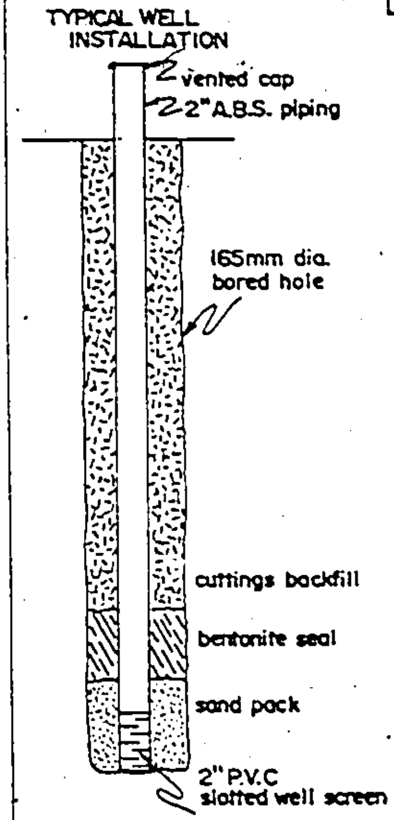
FIGURE - A.3

WOODSLEE TEST SITE 4

SITE and WELL INSTALLATION DETAILS

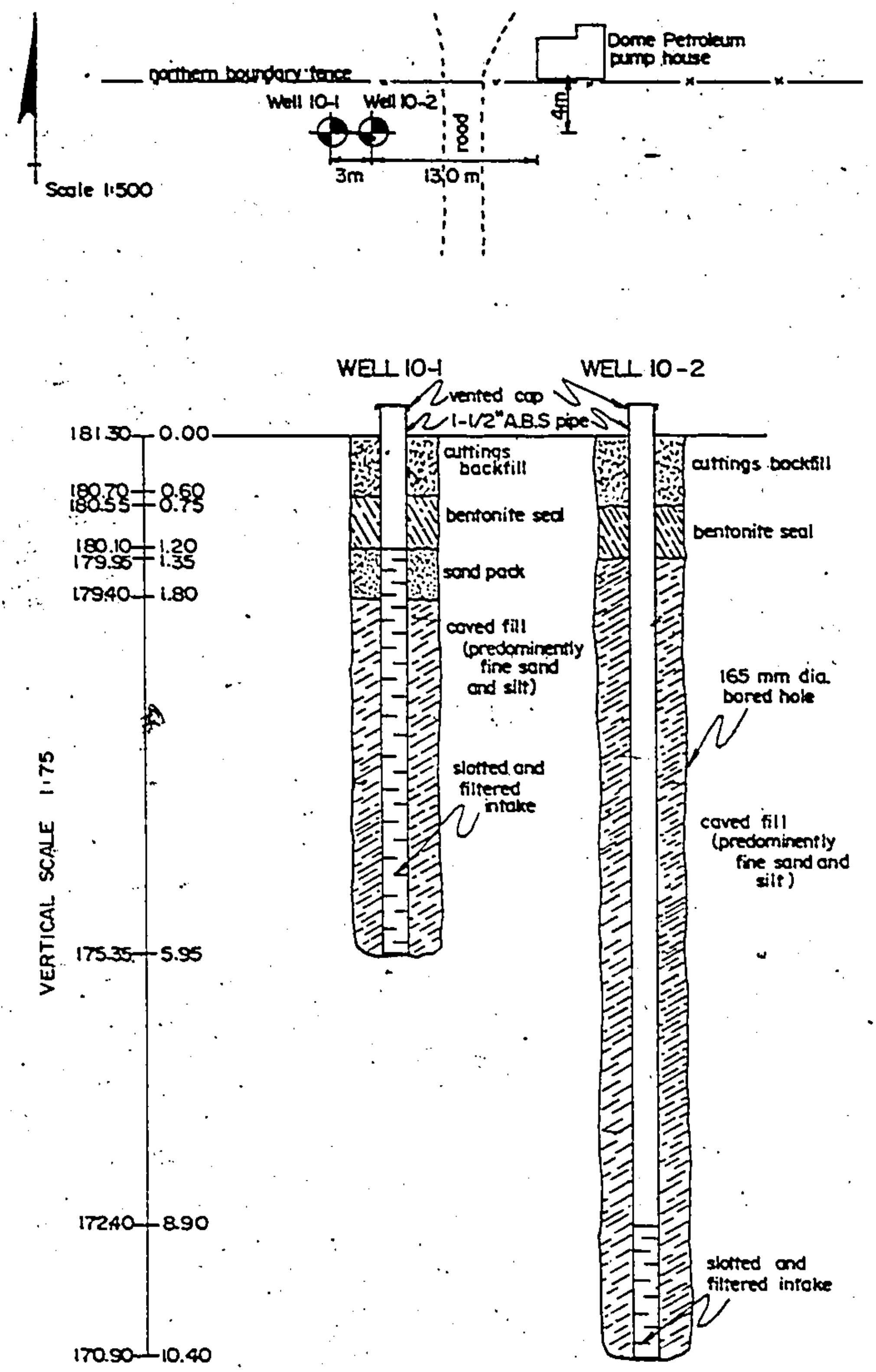


WELL	4-I	4-R1	4-R2	4-R3	4-R4	4-R5	4-R6	4-P.D.	
r	0	0.66	0.66	0.58	0.70	1.03	0.91	12.19	metres



WELL	4-I	4-R1	4-R2	4-R3	4-R4	4-R5	4-R6	4-P.D.
Ground surface Elevation	186.65	186.65	186.65	186.65	186.65	186.65	186.65	186.65
Top of Seal Elevation	182.00	181.95	181.80	182.00	181.95	181.30	181.40	181.90
Base of Seal Elevation	181.35	181.25	181.20	181.35	181.30	180.70	180.70	181.30
Top of Screen Elevation	181.00	181.10	180.95	180.90	180.90	180.45	180.30	180.15
Base of Well Elevation	180.40	180.50	180.35	180.30	180.30	179.85	179.70	179.55
Length of Sand Pack (metres)	0.95	0.75	0.85	1.05	1.00	0.85	1.00	1.75

FIGURE - A.4


WEST WINDSOR SITE 10

SITE and WELL INSTALLATION DETAILS

FIGURE- A.5

WEST WINDSOR SITE 20

SITE and WELL INSTALLATION DETAILS

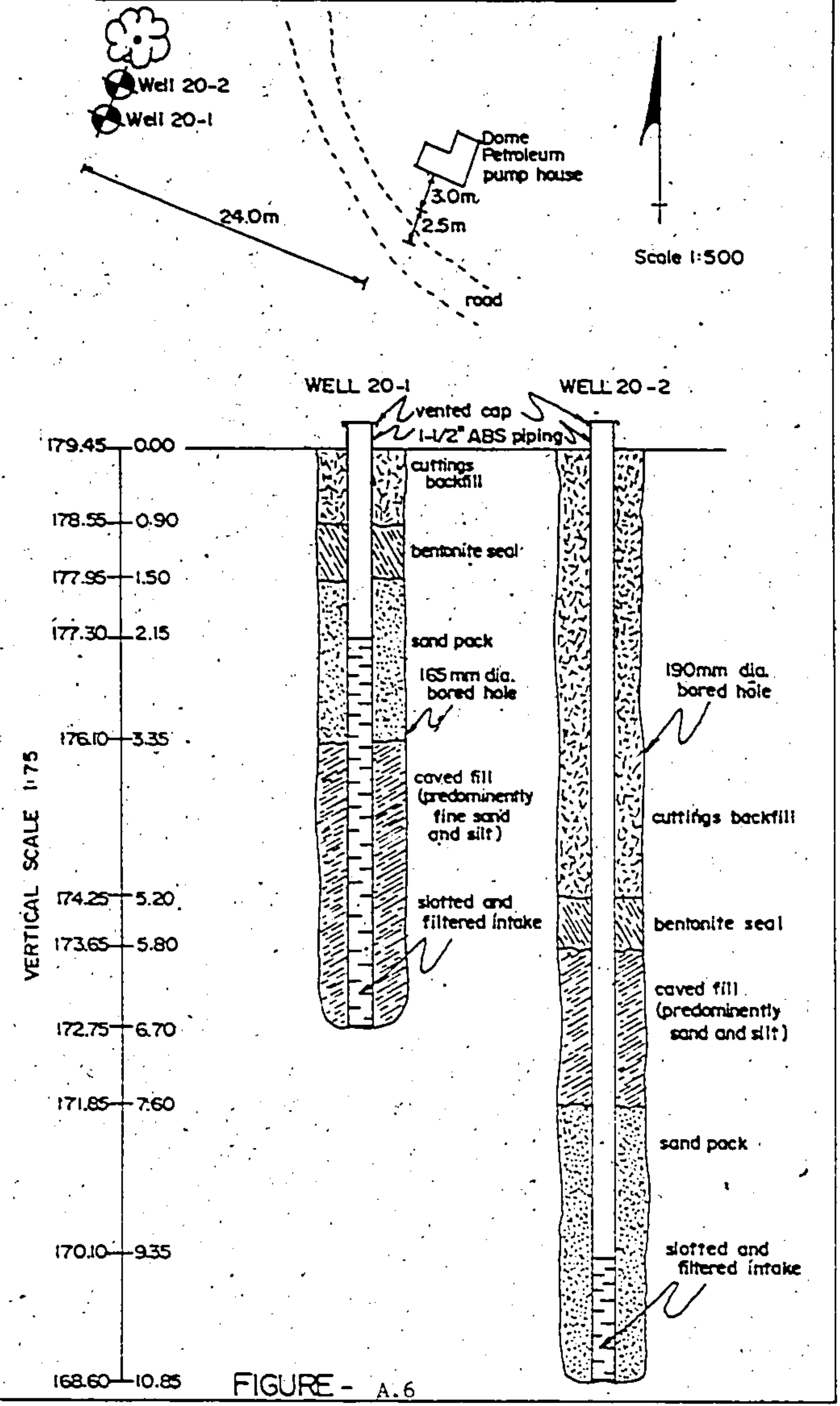


FIGURE - A.6

WEST WINDSOR SITE 30

SITE and WELL INSTALLATION DETAILS

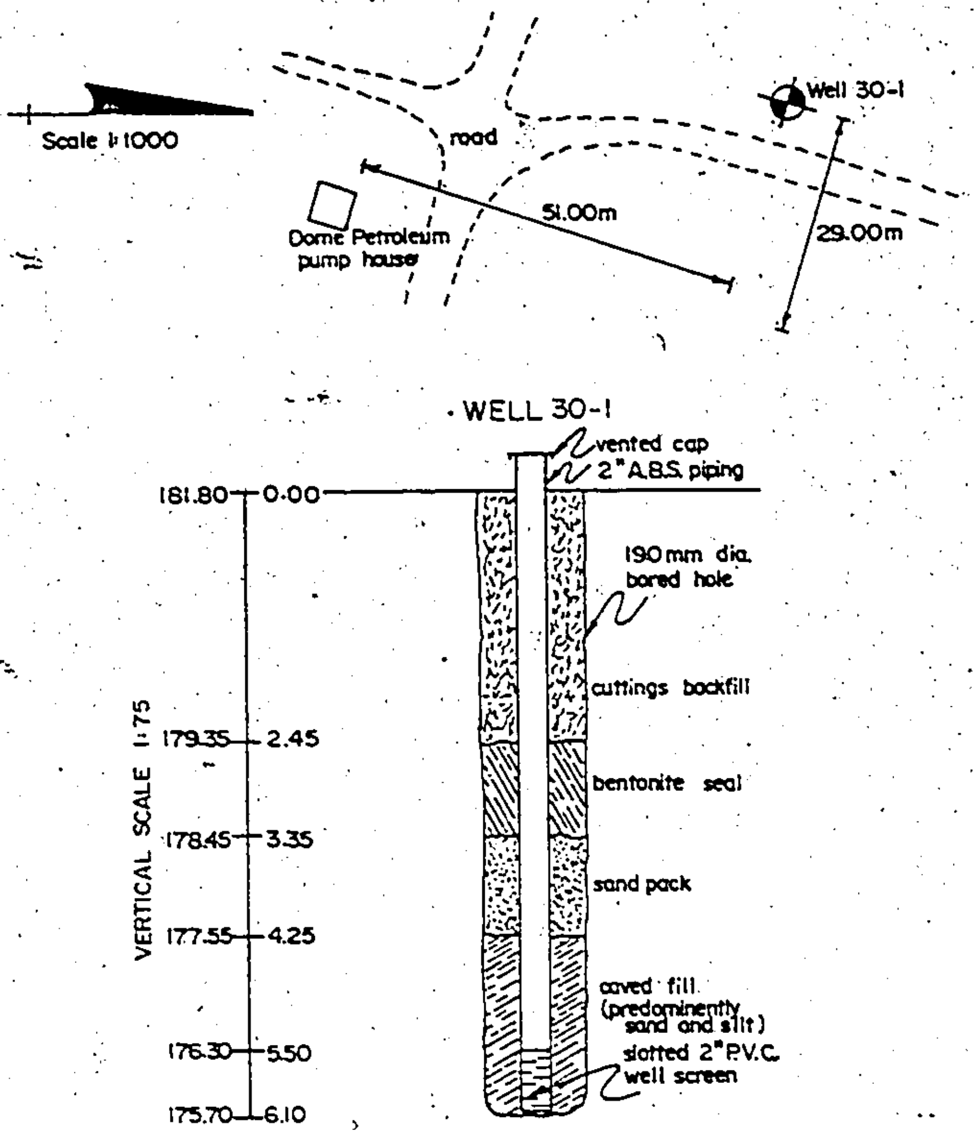


FIGURE- A.7

WEST WINDSOR TEST SITE 40 SITE and WELL INSTALLATION DETAILS

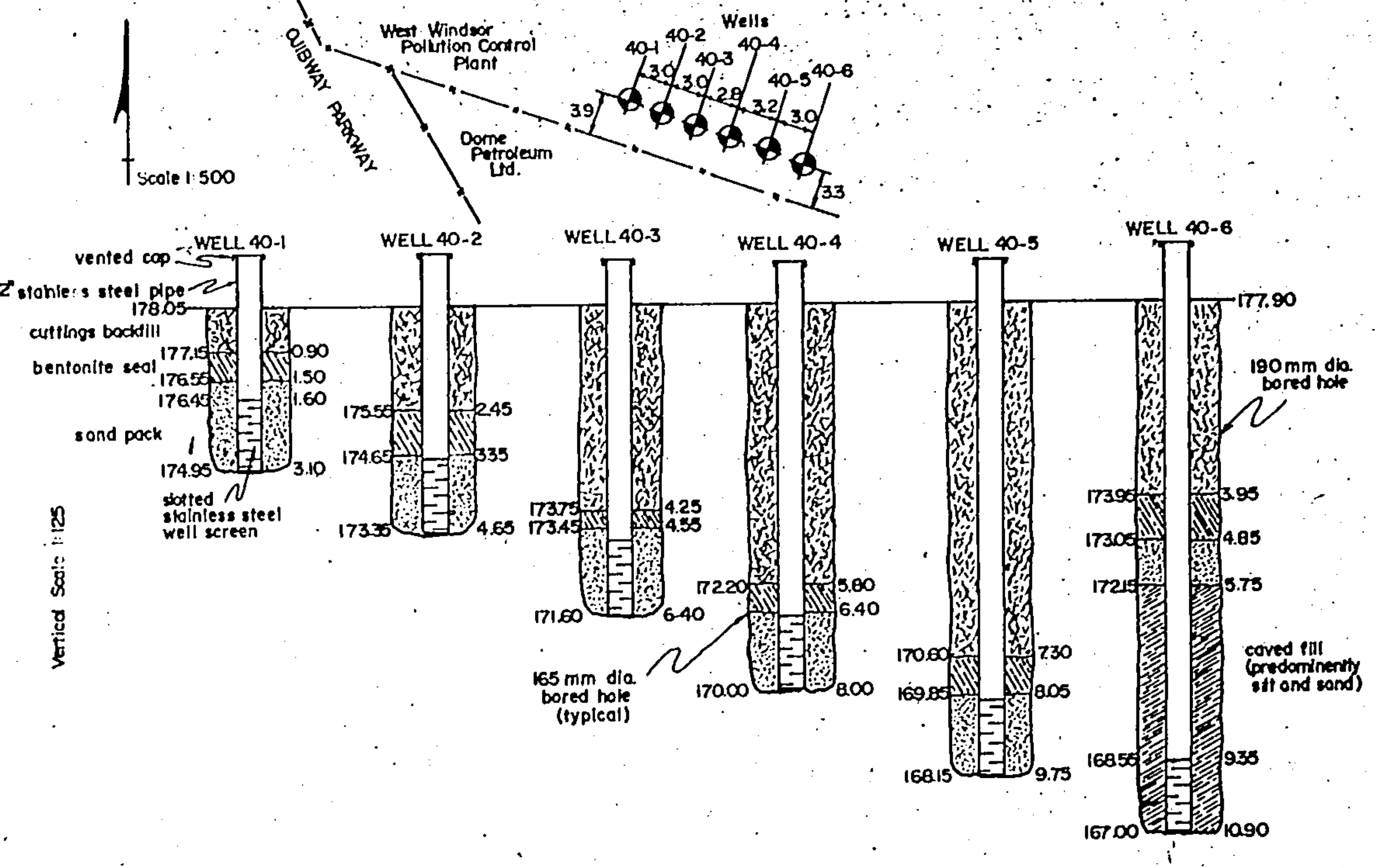


FIGURE- A.8

APPENDIX B

PORTABLE CONDUCTIVITY METER - SPECIFICATIONS

Manufacturer:	pHOX Systems Limited	
Model:	52	
Description:	A portable battery operated solution conductivity meter designed to make *in situ* measurements of electrical conductivity. The unit is fitted with a meter scale, calibrated in microsiemens and ppm of total dissolved solids.	
Range of Measurement:	0 - 10 microsiemens	0 - 5 mg/l (NaCl)
	0 - 100 "	0 - 50 "
	0 - 1000 "	0 - 500 "
	0 - 10,000 "	0 - 5,000 "
	0 - 100,000 "	0 - 50,000 "
	meter scale - 122 mm	
Temperature Compensation:	Fully automatic on all ranges at 2%/c° standardized to 25° C.	
Internal Power Supply:	2 x Mallory 9 volt. Life in excess of 12 months dependent on use. Power test facility.	
Measuring Probe:	Epoxy resin and carbon electrode assembly, fitted with cable and plug. Maintenance free, chemical resistant, maximum temperature 80° C.	

APPENDIX C

INTERIOR SEALED OBSERVATION WELL AND COMPANION SHEATHED CONDUCTIVITY PROBE - FABRICATION DETAILS

Sealed Observation Well

The interior seal of the observation well consists of a flexane rubber ring attached to the inside of the observation well casing as shown in Figure C.1. These ring sections were fabricated in quantity. The interior of a 300 mm piece of two inch size A.B.S. plastic piping was cleaned with A.B.S. primer and allowed to dry thoroughly. This piping was then placed in a pan vertically and supported. In the pan at the base of the piping was a patch of petroleum jelly that acts as a bottom seal and a releasing agent.

A 350 mm long piece of one inch size P.V.C. plastic piping coated with petroleum jelly was then positioned in the centre of the larger pipe and secured. The Devcon Flexane 60 liquid rubber components were mixed in accordance with the manufacturer's instructions and poured into the annulus between the larger and smaller pipes. After allowing several days for the flexane to thoroughly cure, the P.V.C. pipe was removed leaving a 300 mm long piece of two inch size A.B.S. pipe lined with a layer of flexane rubber. This piping was cut into six equal lengths and each of these pieces constitutes a completed interior seal ring for installation in an observation well.

Companion Sheathed Probe

The sheath of the conductivity probe provides protection for the probe as it is pushed through the seal in the observation well and a mechanism for this insertion procedure. A schematic diagram of the sheathed probe is presented in Figure C.1. Each of the probes was fabricated separately from sections of one inch size P.V.C. plastic piping 300 mm long.

TYPICAL OBSERVATION WELL with INTERIOR SEAL and the COMPANION SHEATHED CONDUCTIVITY PROBE for point dilution and tracer test studies

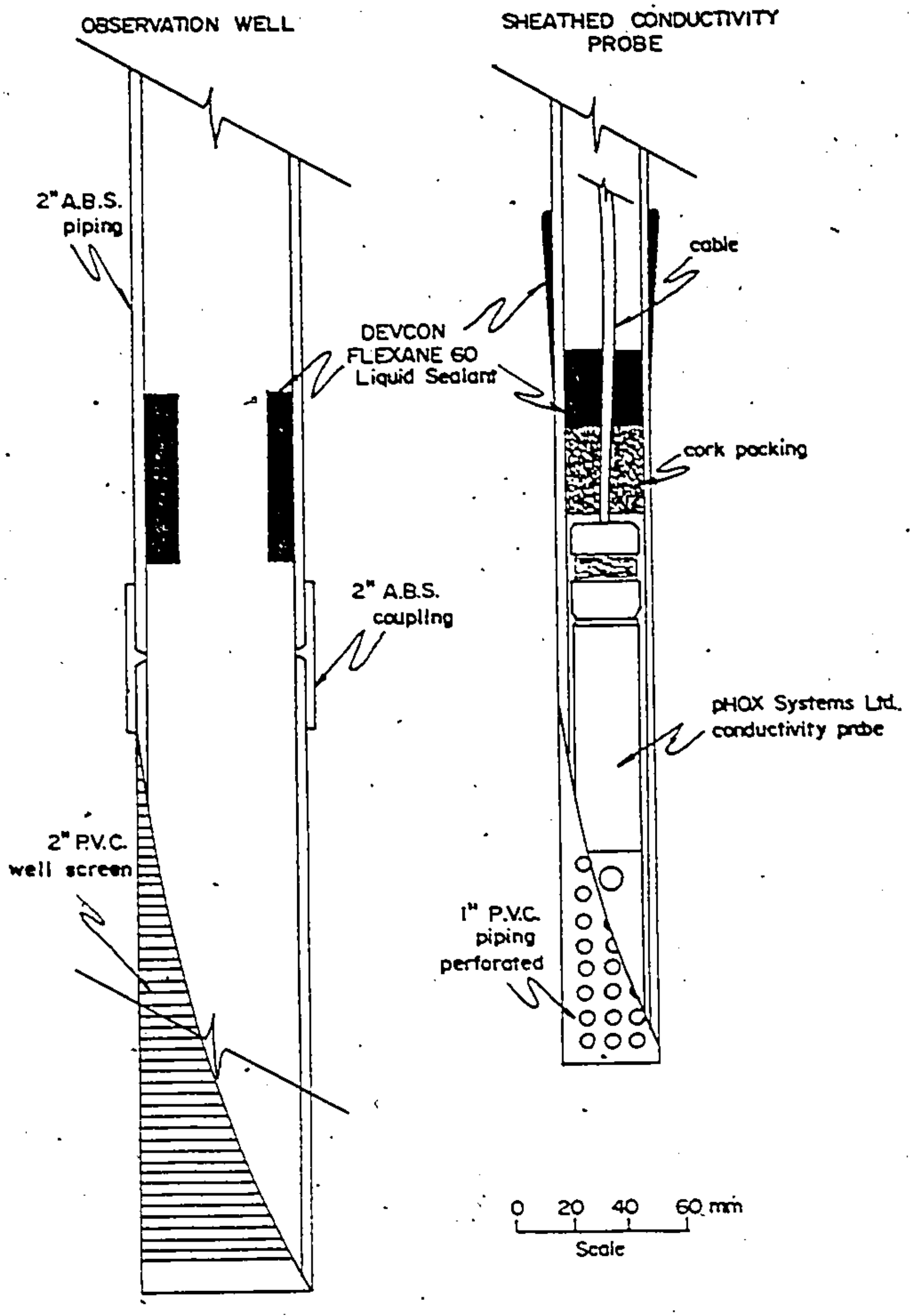


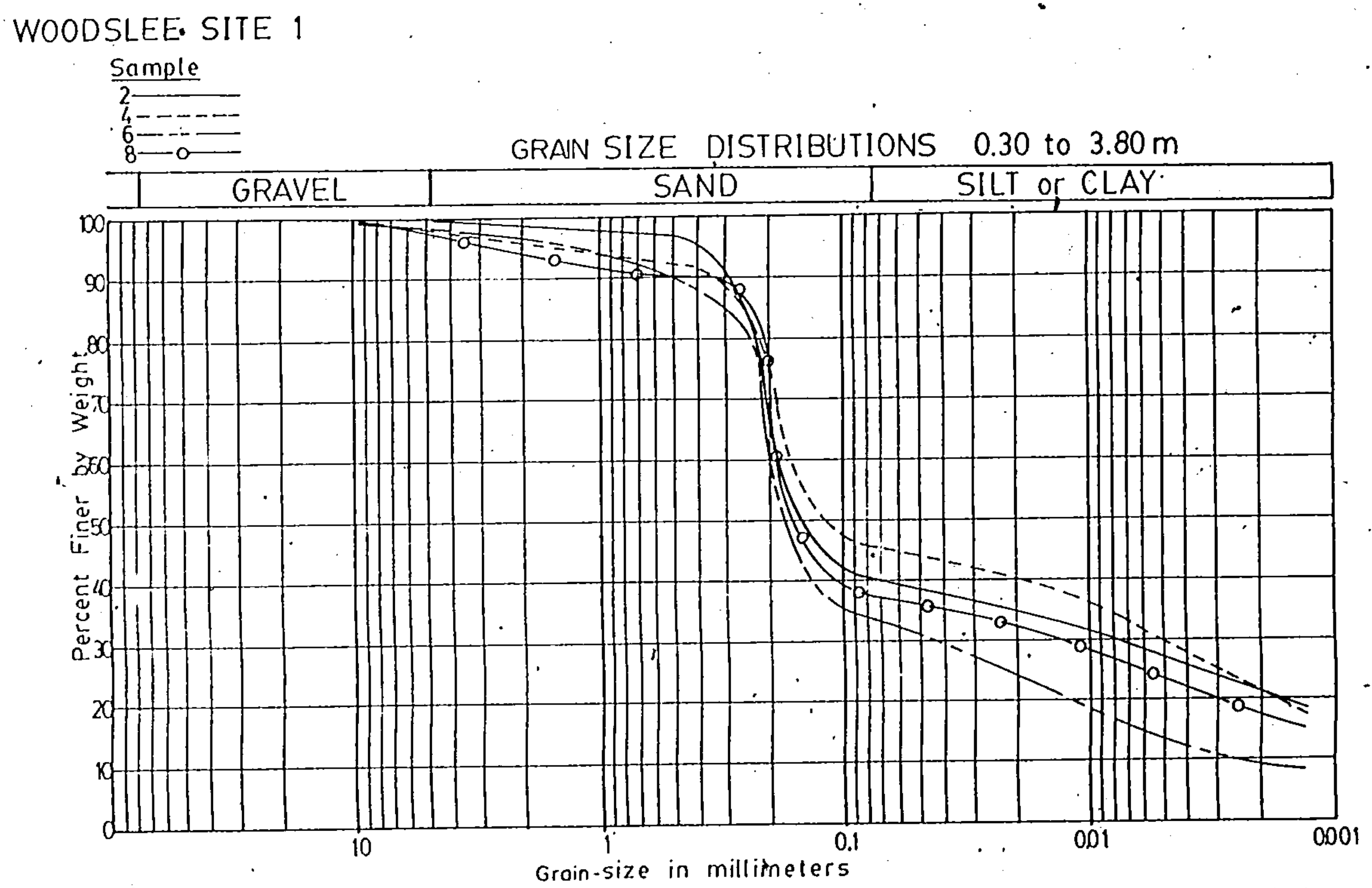
FIGURE - C.1

The lower 100 mm of the pipe was perforated with a drill and the cuttings removed. The piping was then thoroughly cleaned with P.V.C. primer. The cleaned pipe was then supported vertically with the perforated end downwards. The pHOX Systems Ltd. conductivity probe unit was lowered into the prepared pipe and suspended approximately 10 mm above the base of the pipe. A piece of split cork was then forced into the pipe around the cable of the probe and pressed down on to the probe top. A small quantity of Devcon Flexane 60 liquid was then prepared in accordance with the manufacturer's instructions. This liquid was poured into the piping on top of the cork packing until a seal at least 75 mm thick was in place. The flexane was then allowed to cure for several days.

The tapered flexane ring was formed on the exterior of the probe sheath by hanging the completed interior sealed sheath and probe with the perforated end of the pipe upward. A measure of correctly mixed flexane rubber liquid was then applied in a ring around the pipe sheath approximately 150 mm from the unperforated end of the probe sheath. The liquid flexane then flows down the outside of the probe sheath by gravity and as it cures the required tapered ring of flexane is created.

APPENDIX D

GRAIN SIZE ANALYSIS RESULTS



WOODSLEE SITE 1

GRAIN SIZE DISTRIBUTIONS 0.30 to 3.80 m

FIGURE - D.1

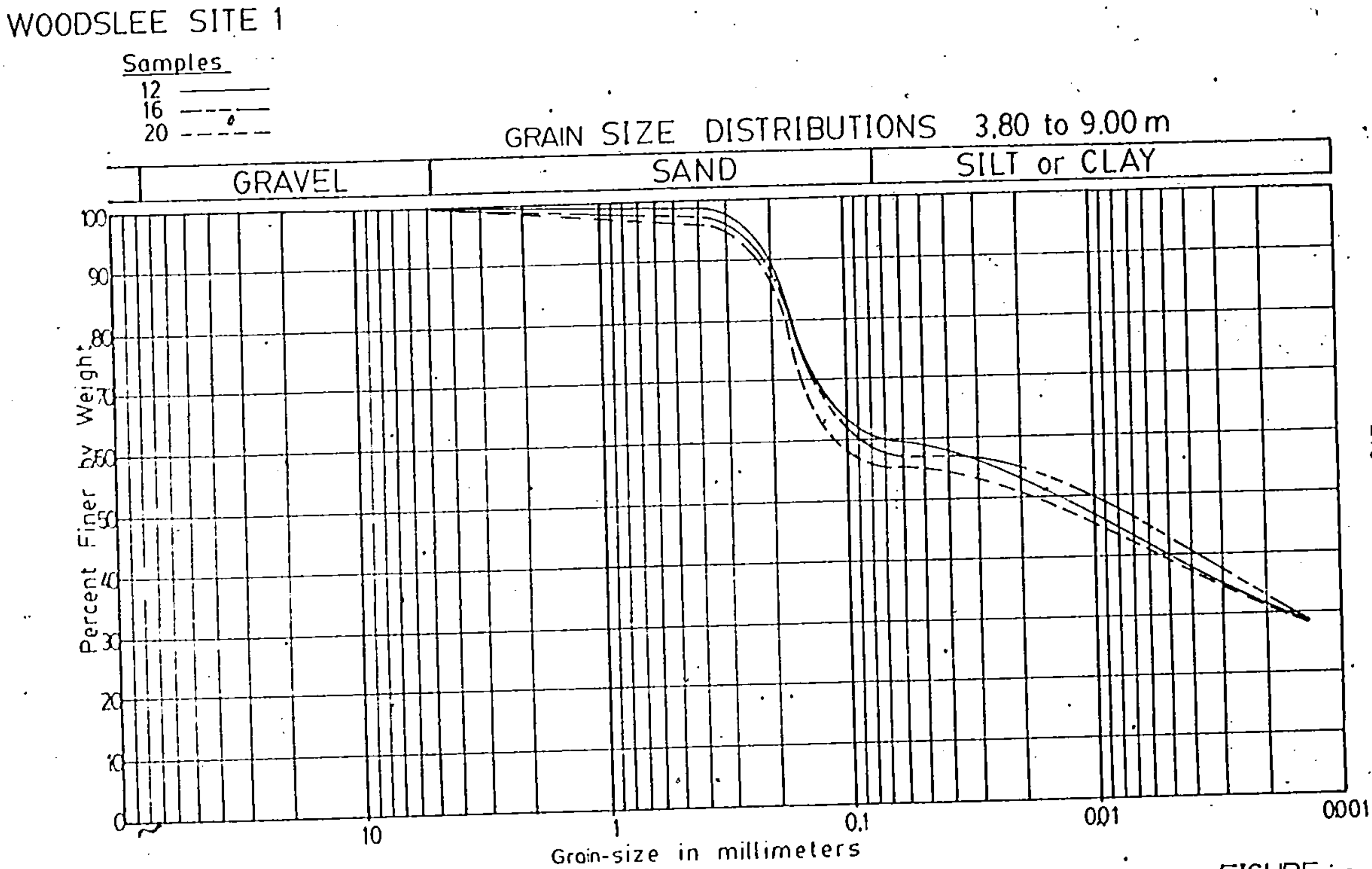

WOODSLEE SITE 1
Samples
12
16
20
GRAIN SIZE DISTRIBUTIONS 3.80 to 9.00 m
GRAVEL
SAND
SILT or CLAY
100
90
80
70
60
50
40
30
20
10
0
Percent Finer by Weight
10
1
0.1
0.01
0.001
Grain-size in millimeters

FIGURE - D.2

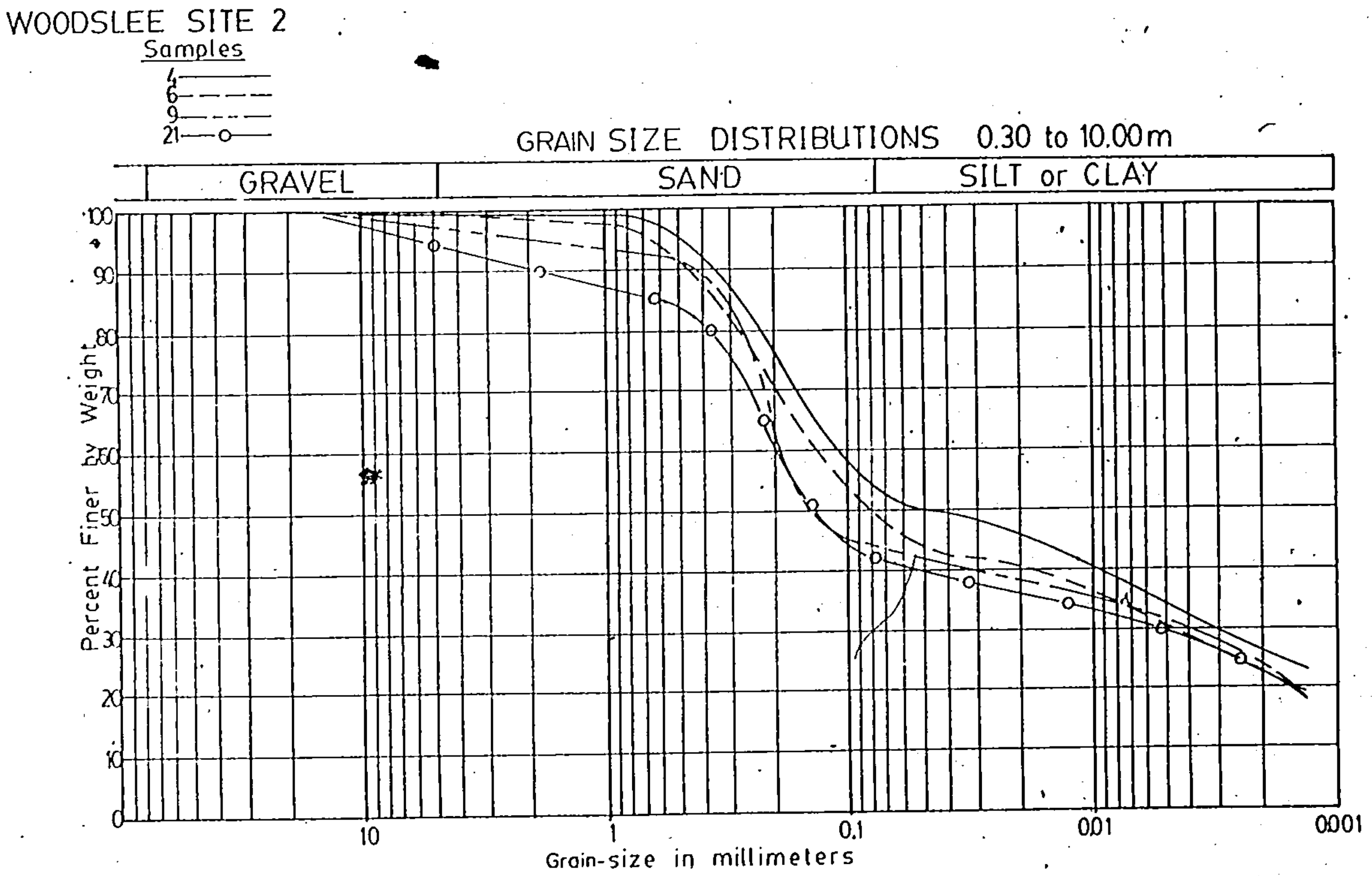

WOODSLEE SITE 2
Samples
4
6
9
21
GRAIN SIZE DISTRIBUTIONS 0.30 to 10.00m
GRAVEL
SAND
SILT or CLAY
Percent Finer by Weight
100
90
80
70
60
50
40
30
20
10
0
10
1
0.1
0.01
0.001
Grain-size in millimeters

FIGURE- D.3

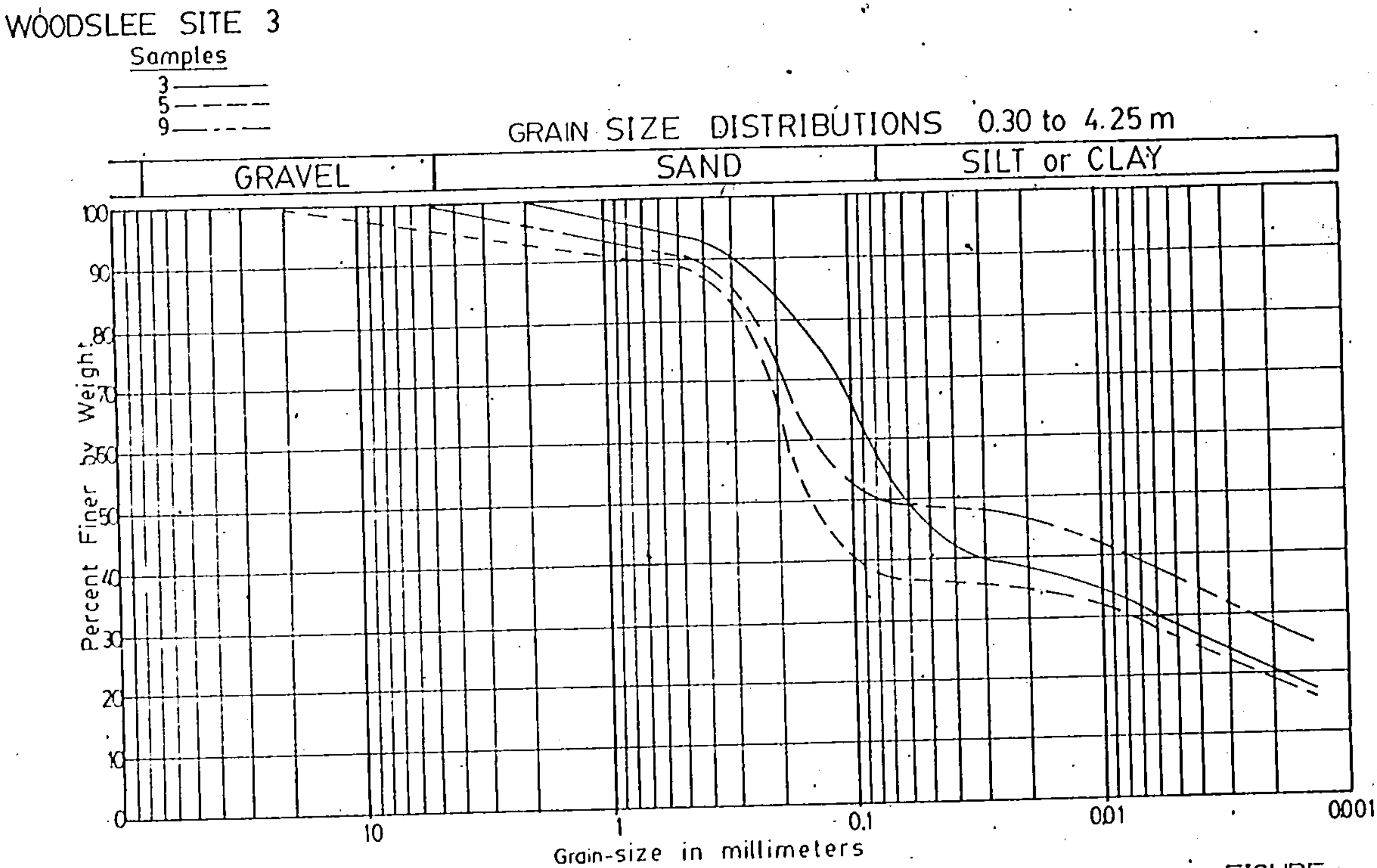

WOODSLEE SITE 3
Samples
3
5
9
GRAIN SIZE DISTRIBUTIONS 0.30 to 4.25 m
GRAVEL
SAND
SILT or CLAY
Percent Finer by Weight
100
90
80
70
60
50
40
30
20
10
0
10
1
0.1
0.01
0.001
Grain-size in millimeters

FIGURE - D.4

WOODSLEE SITE 3

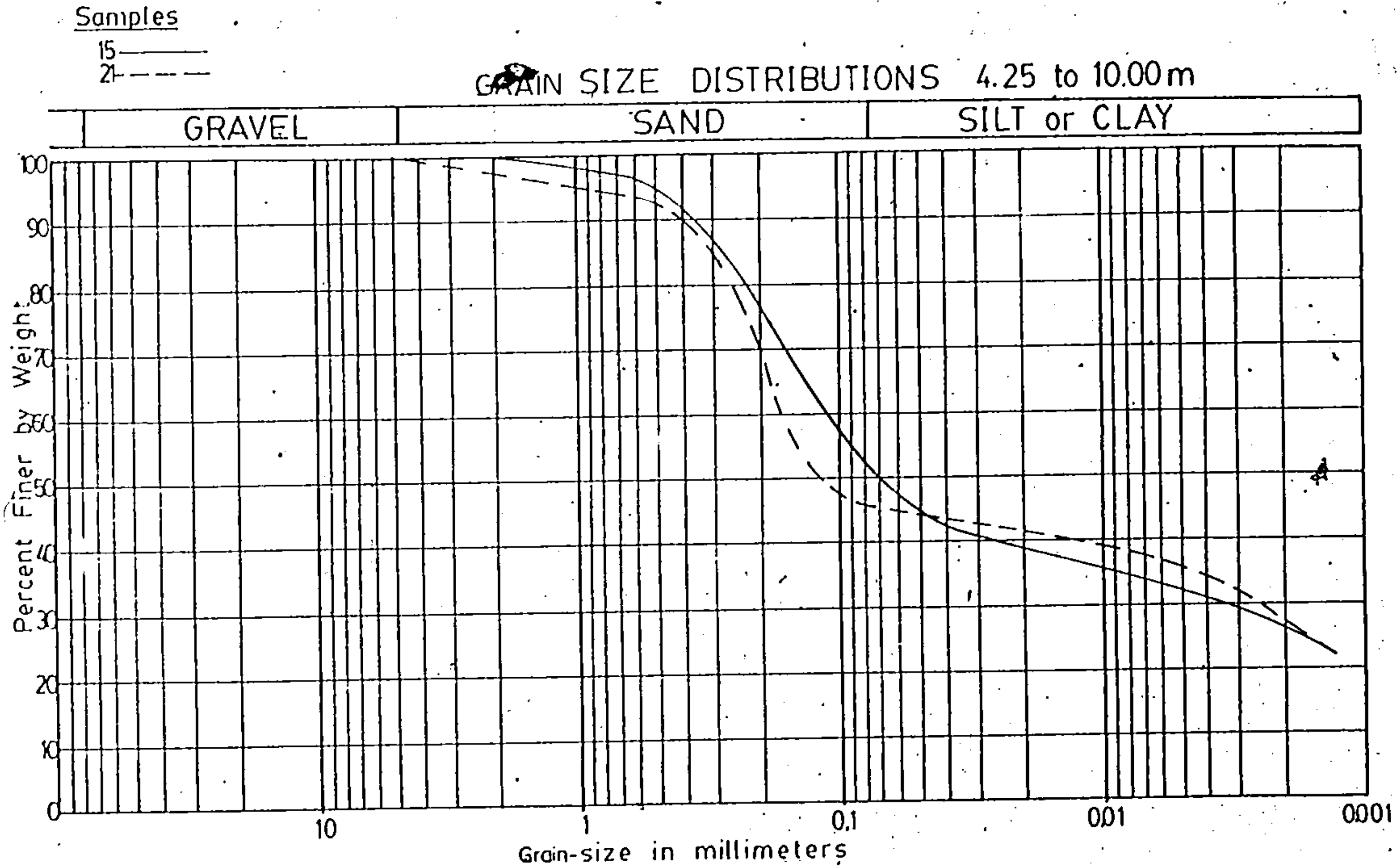


FIGURE - D.5

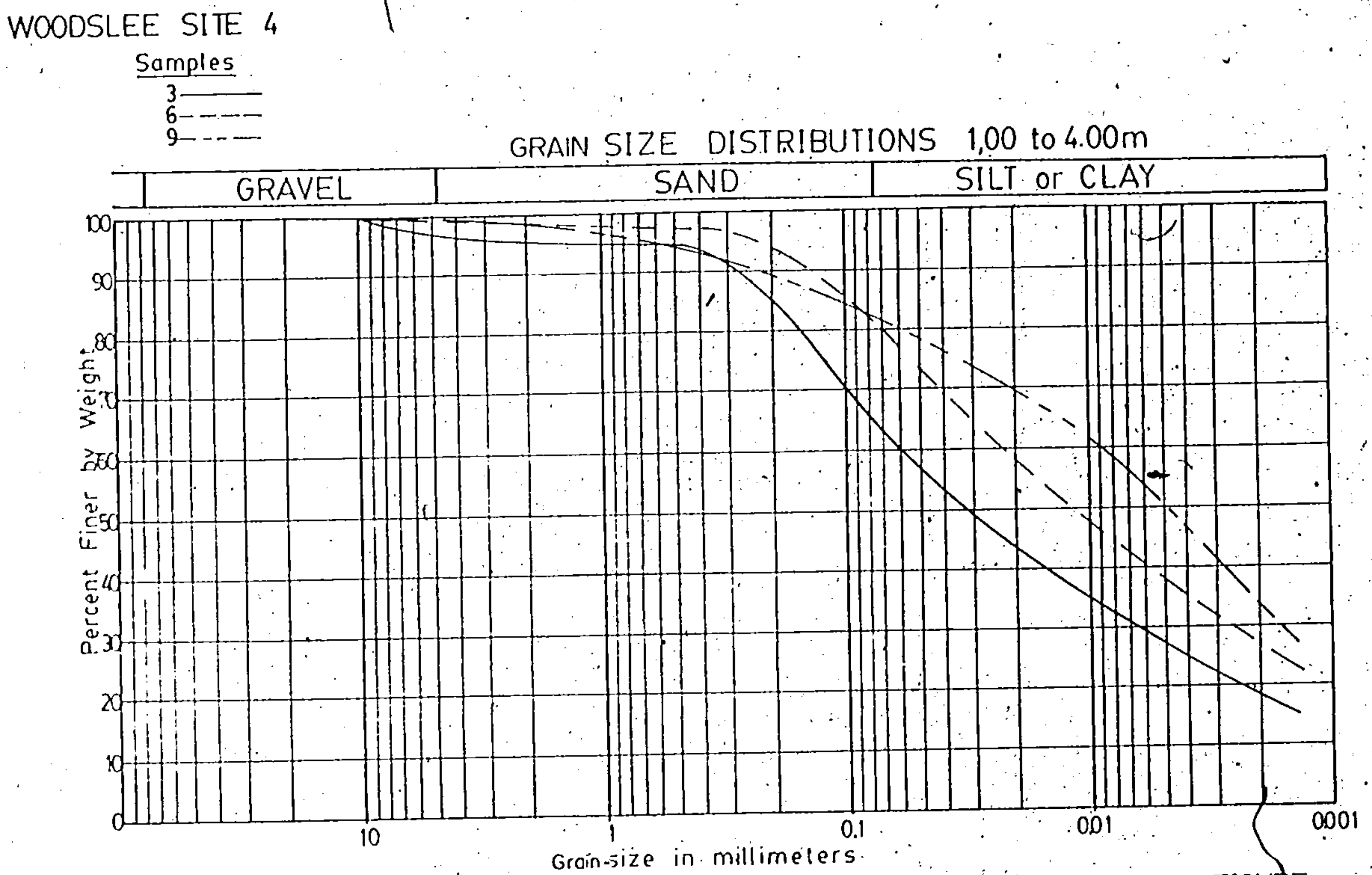

WOODSLEE SITE 4
Samples
3
6
9
GRAIN SIZE DISTRIBUTIONS 1,00 to 4.00m
GRAVEL
SAND
SILT or CLAY
100
90
80
70
60
50
40
30
20
10
0
Percent Finer by Weight
10
1
0.1
0.01
0.001
Grain-size in millimeters

FIGURE - D.6

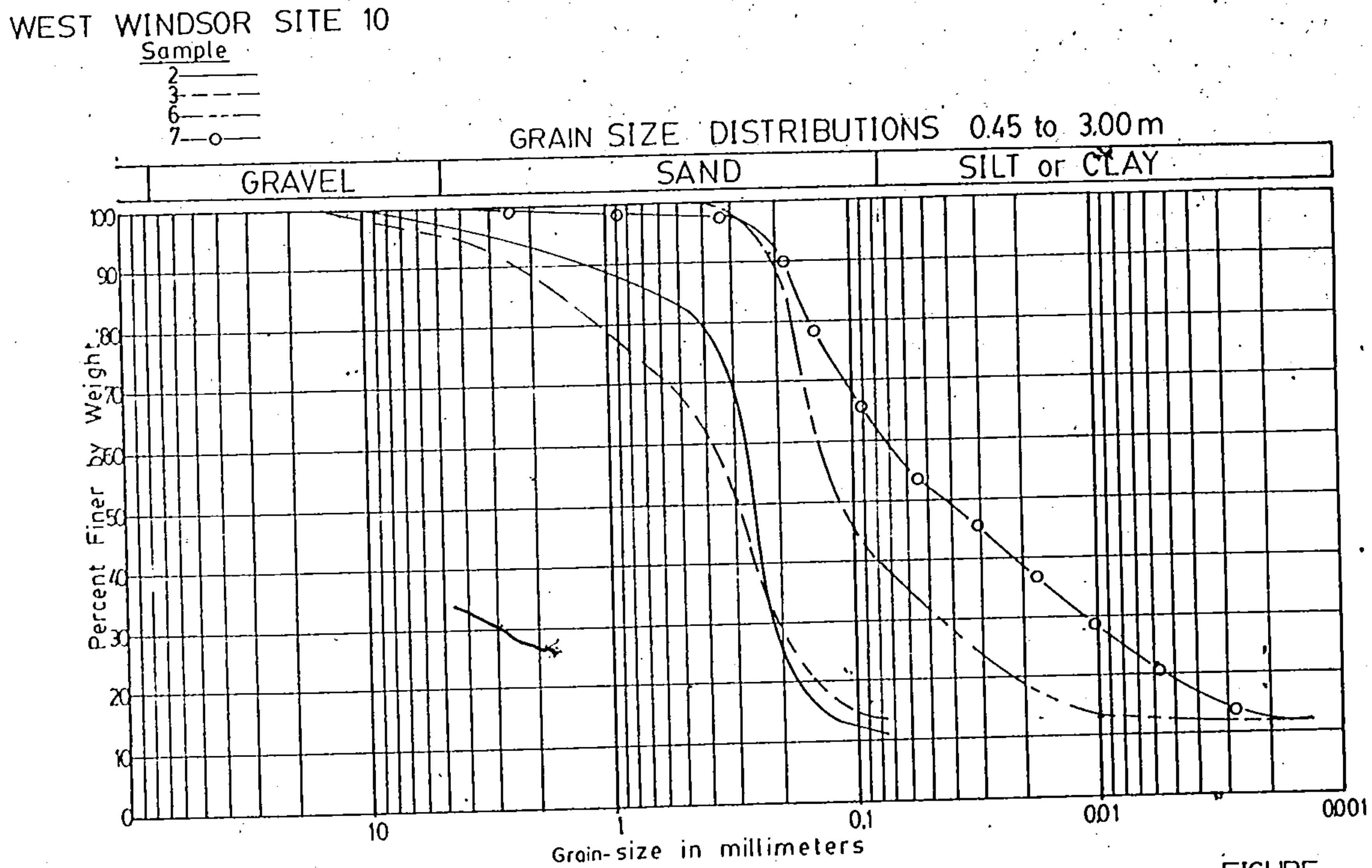

WEST WINDSOR SITE 10
Sample
2
3
6
7
GRAIN SIZE DISTRIBUTIONS 0.45 to 3.00m
GRAVEL
SAND
SILT or CLAY
Percent Finer by Weight
100
90
80
70
60
50
40
30
20
10
0
10
1
0.1
0.01
0.001
Grain-size in millimeters

FIGURE - D.7

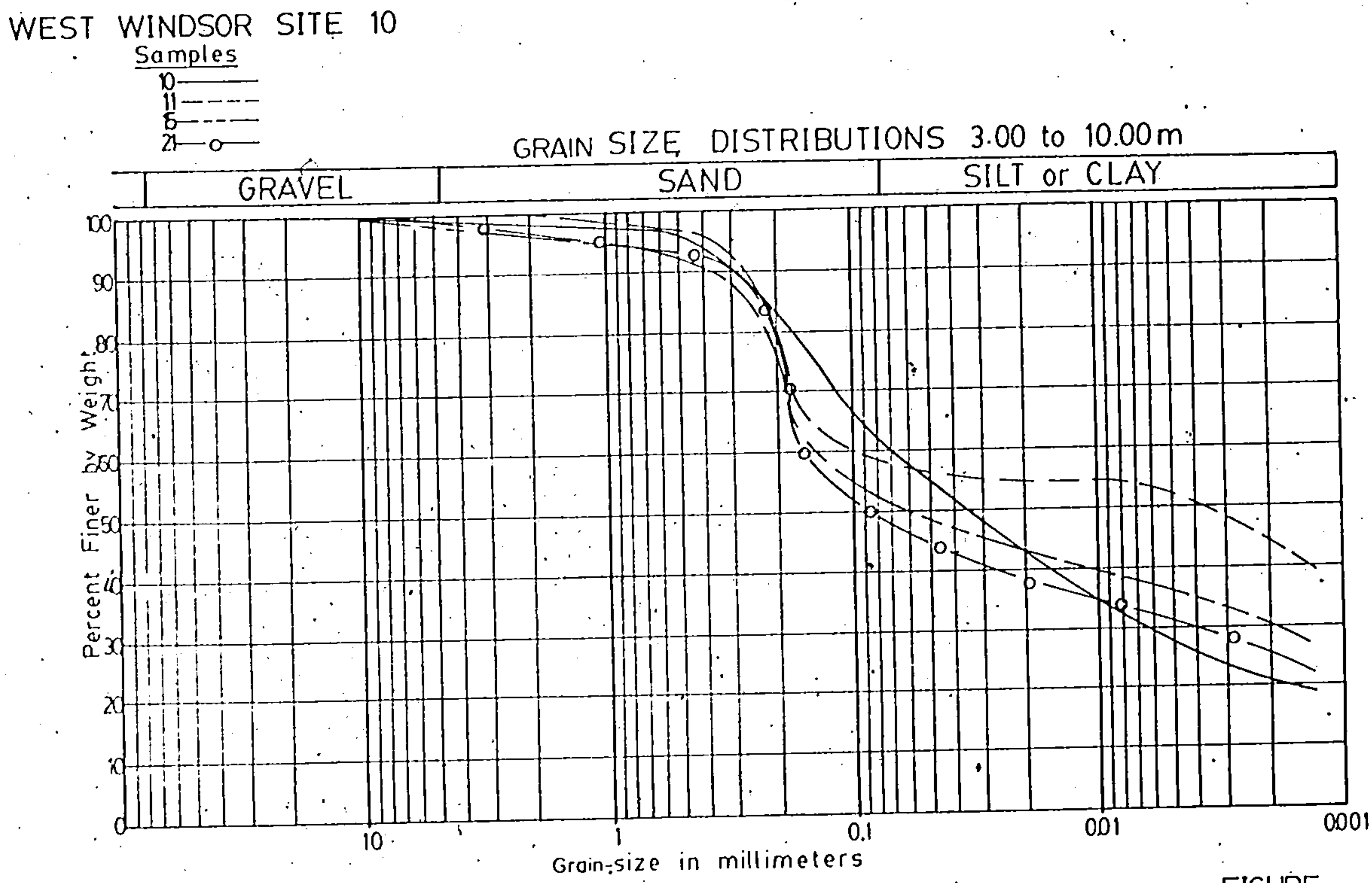

WEST WINDSOR SITE 10
Samples
10
11
16
21
GRAIN SIZE DISTRIBUTIONS 3.00 to 10.00m
GRAVEL
SAND
SILT or CLAY
Percent Finer by Weight
100
90
80
70
60
50
40
30
20
10
0
10
1
0.1
0.01
0.001
Grain-size in millimeters

FIGURE - D.8

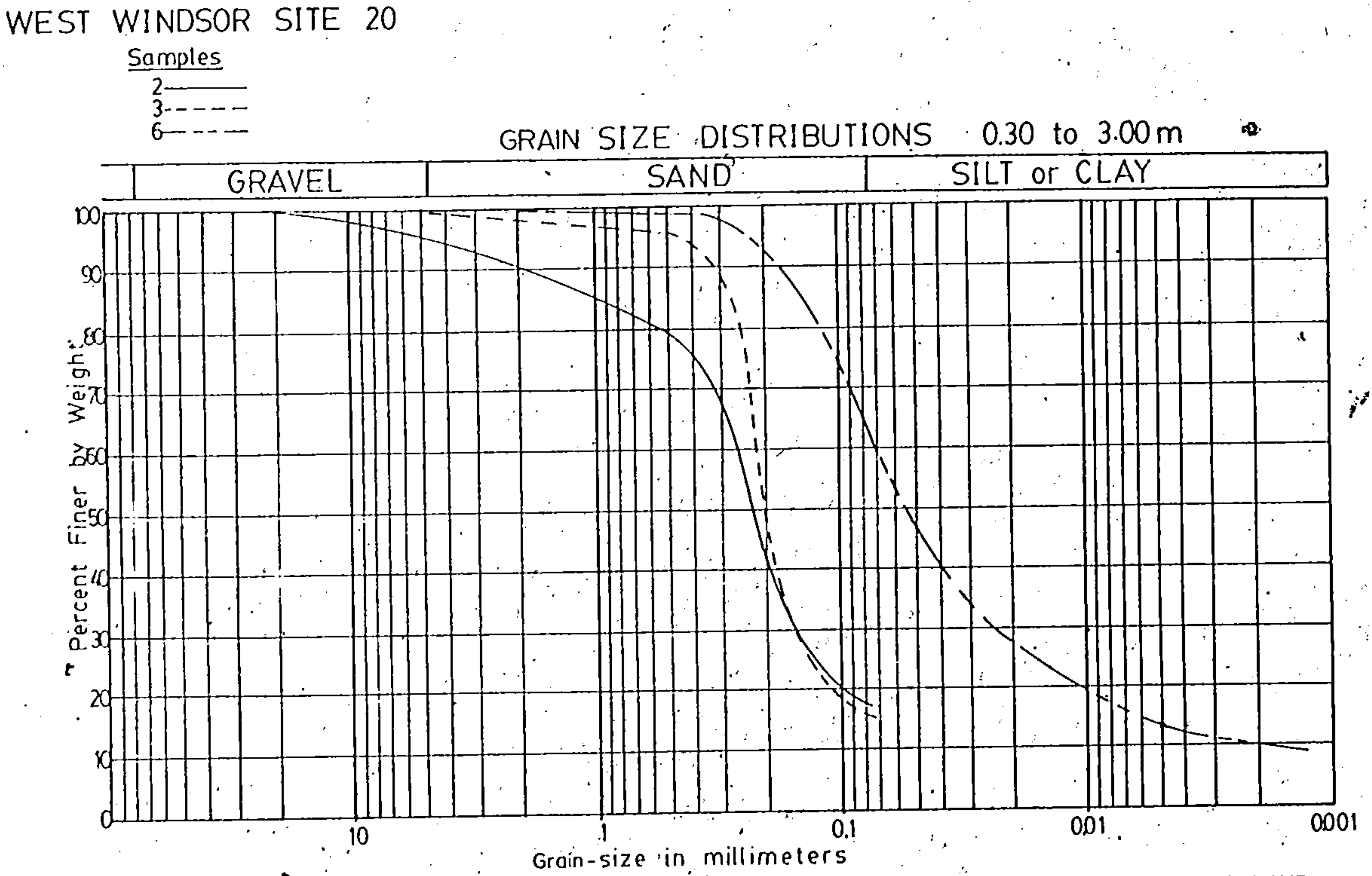

WEST WINDSOR SITE 20
Samples
2
3
6
GRAIN SIZE DISTRIBUTIONS 0.30 to 3.00 m
GRAVEL
SAND
SILT or CLAY
100
90
80
70
60
50
40
30
20
10
0
Percent Finer by Weight
10
1
0.1
0.01
0.001
Grain-size in millimeters

FIGURE- D.9

WEST WINDSOR SITE 20

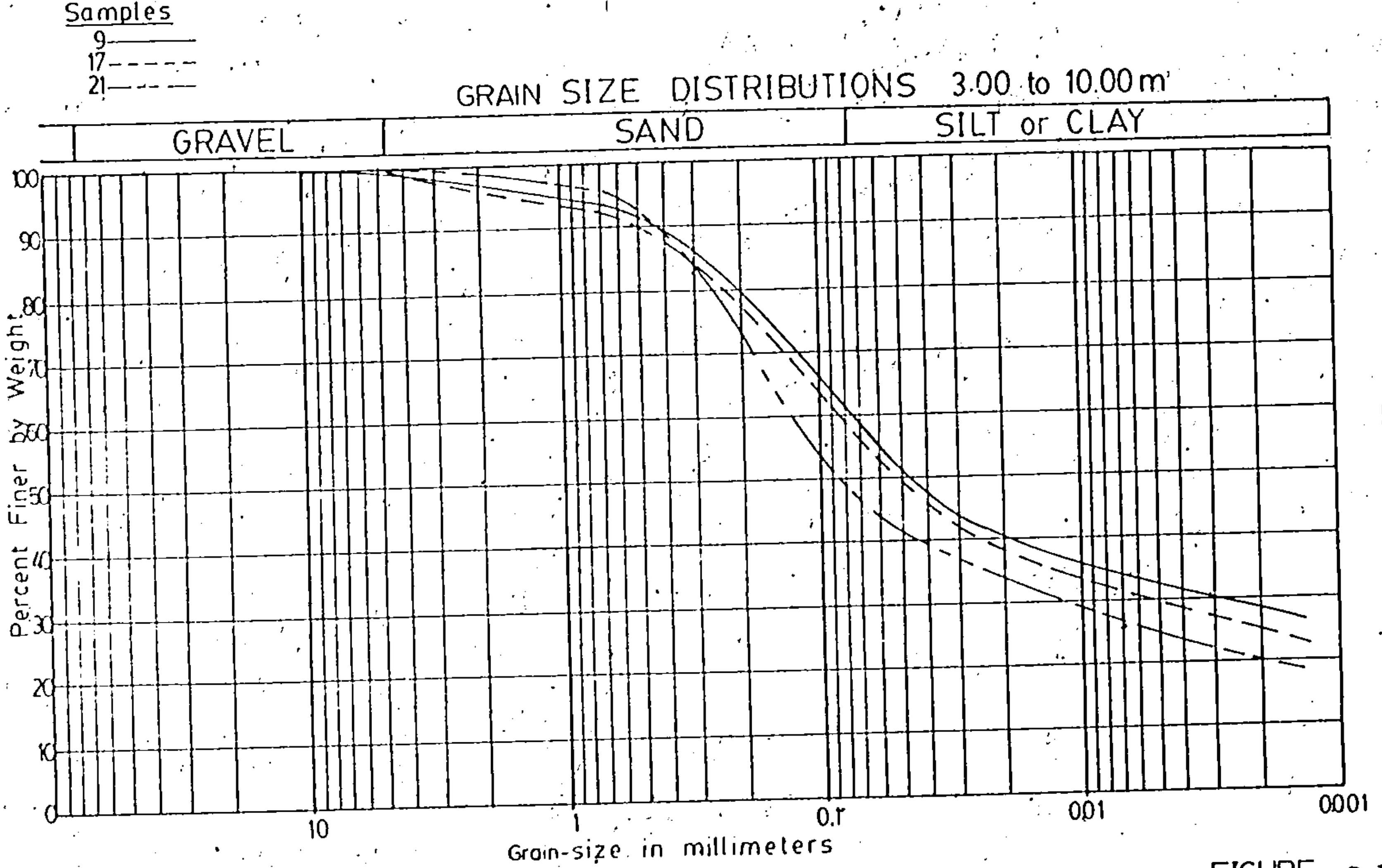


FIGURE - D.10

WEST WINDSOR SITE 30

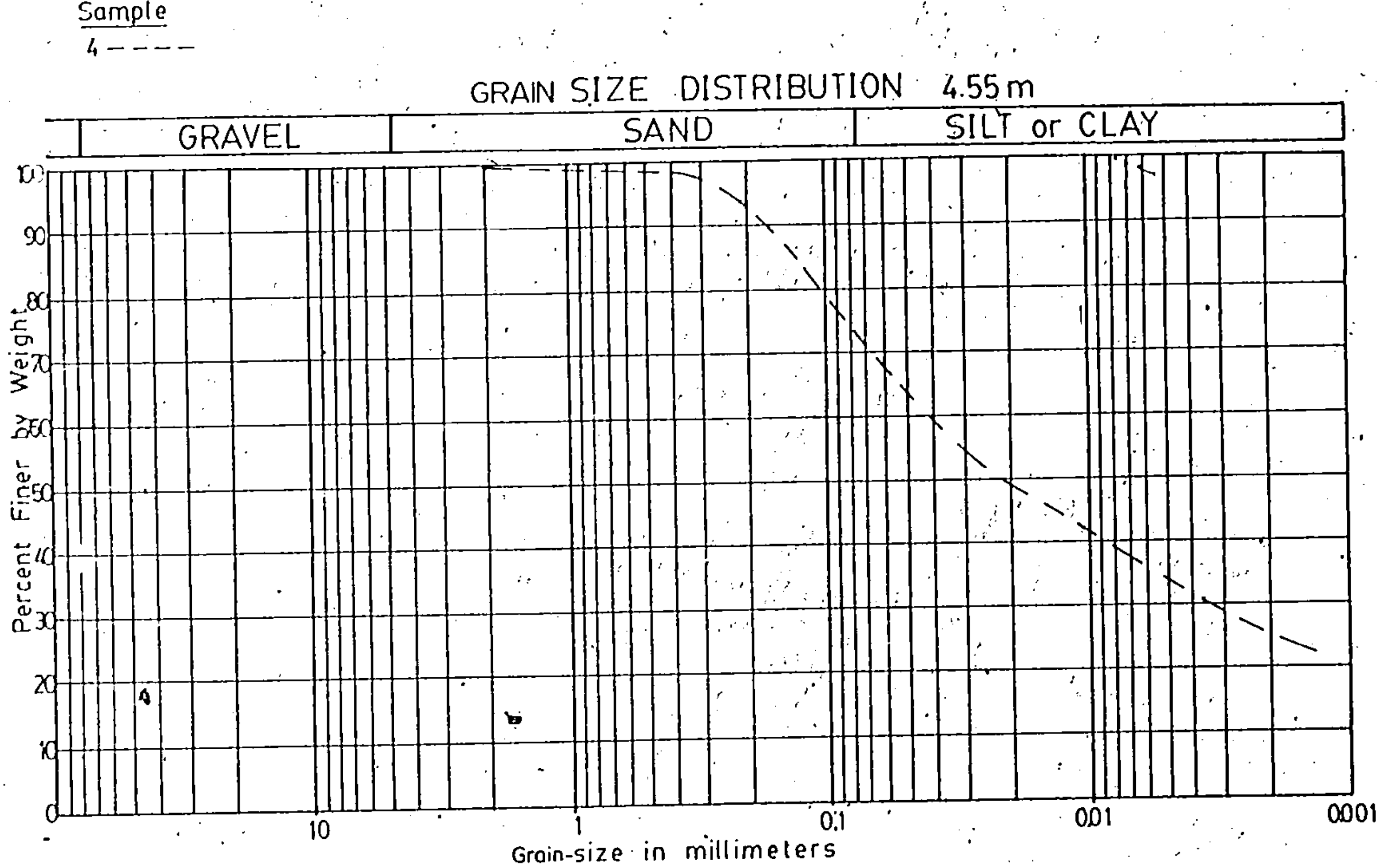


FIGURE.- D.11

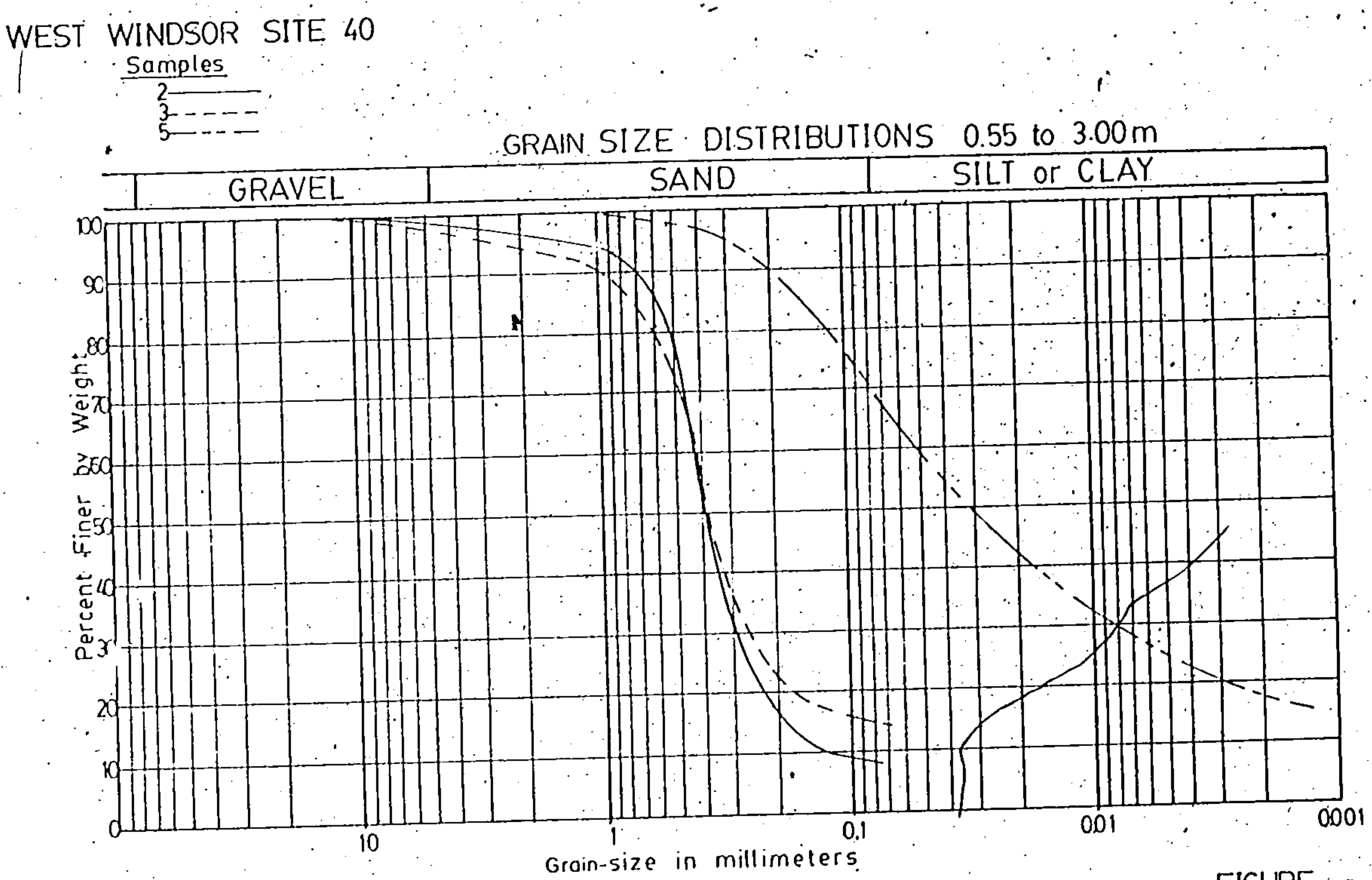

WEST WINDSOR SITE 40
Samples
2
3
5
GRAIN SIZE DISTRIBUTIONS 0.55 to 3.00m
GRAVEL
SAND
SILT or CLAY
Percent Finer by Weight
100
90
80
70
60
50
40
30
20
10
0
10
1
0.1
0.01
0.001
Grain-size in millimeters

FIGURE- D.12

WEST WINDSOR SITE 40

GRAIN SIZE DISTRIBUTIONS 3.00 to 9.00m

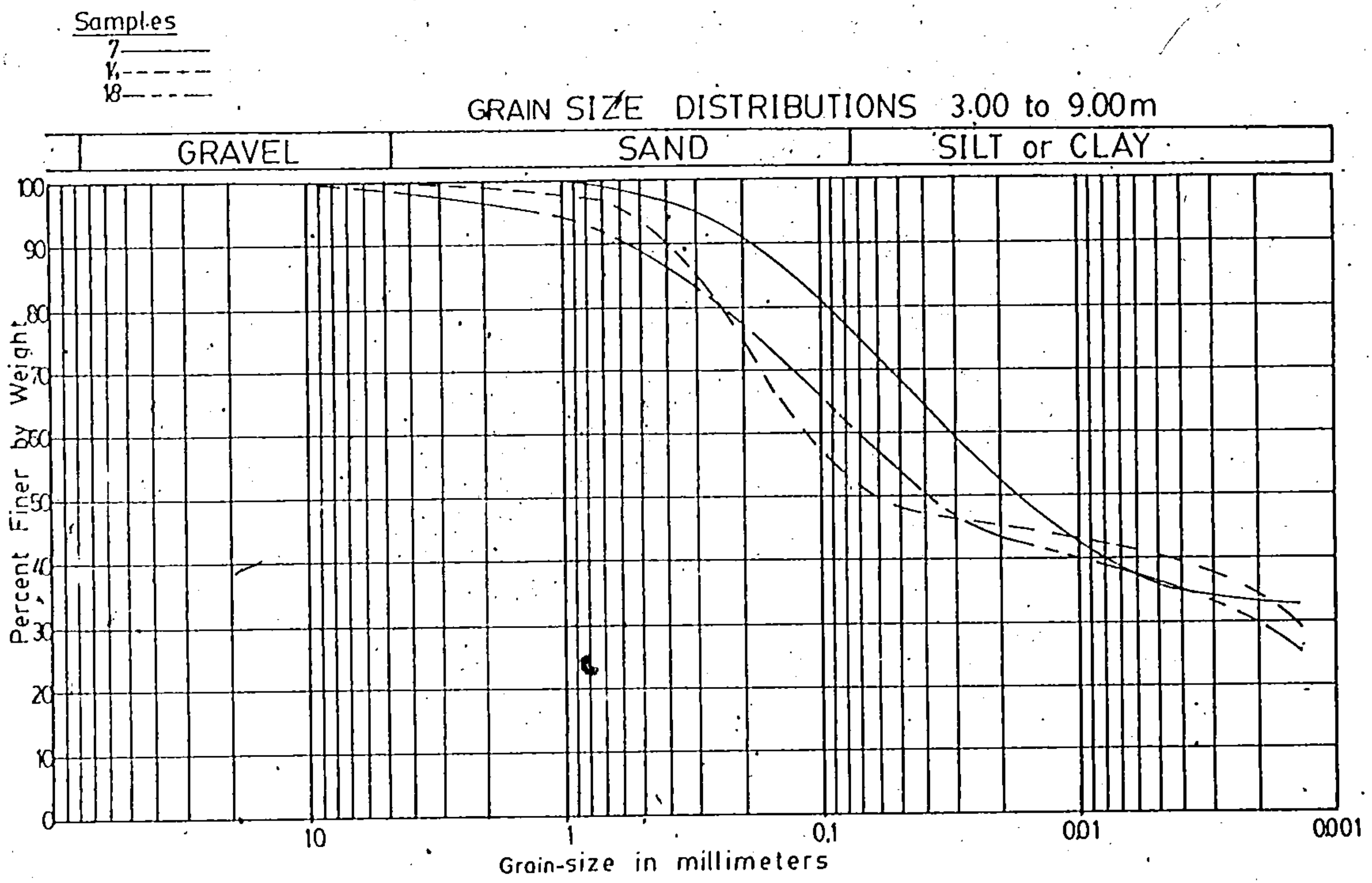


FIGURE - D.13

APPENDIX E

SCHEMATIC DIAGRAMS OF LABORATORY TEST APPARATUS

PRESSURE PERMEAMETER SCHEMATIC DIAGRAM

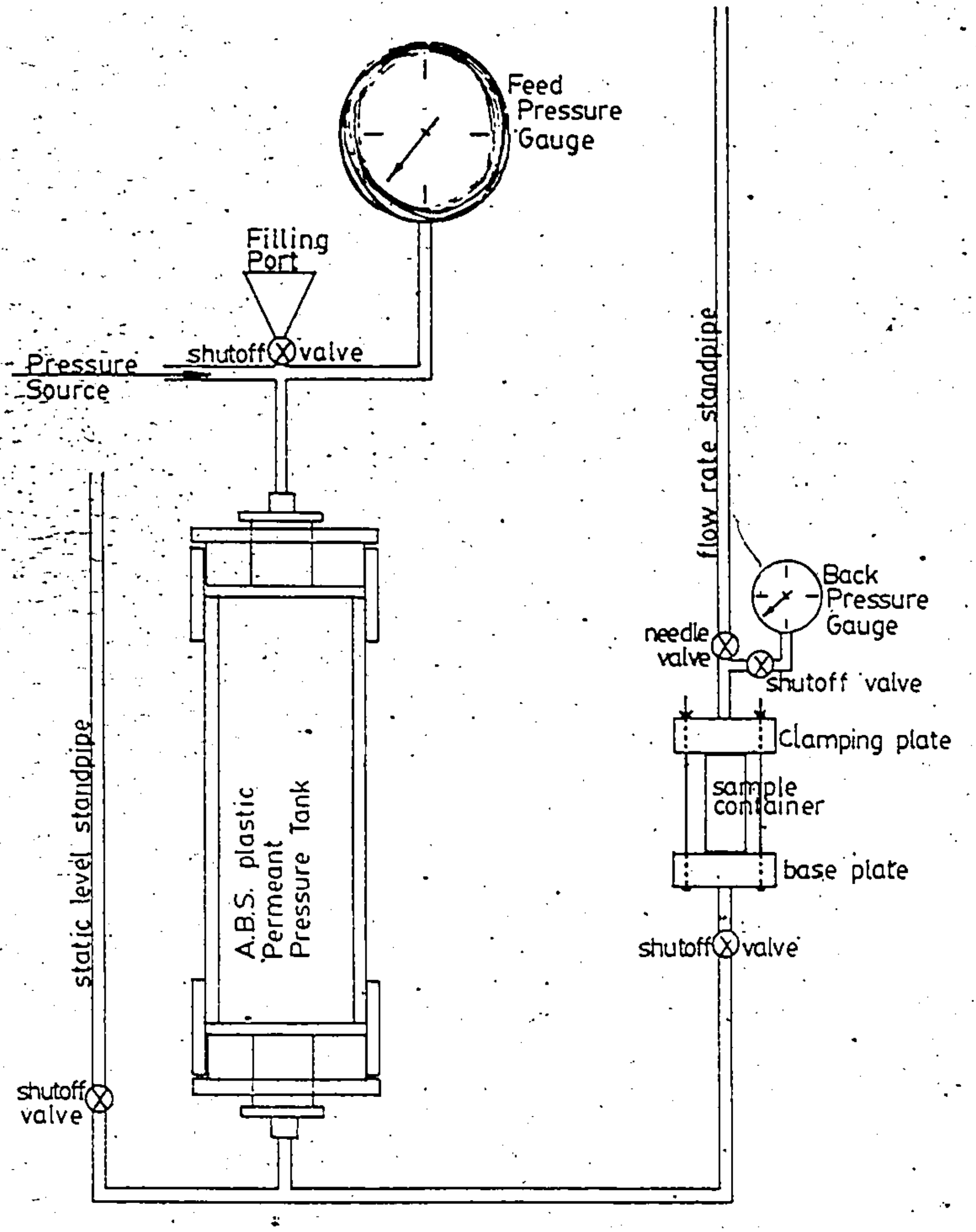


FIGURE - E.1

PNEUMATIC ODEOMETER SCHEMATIC DIAGRAM

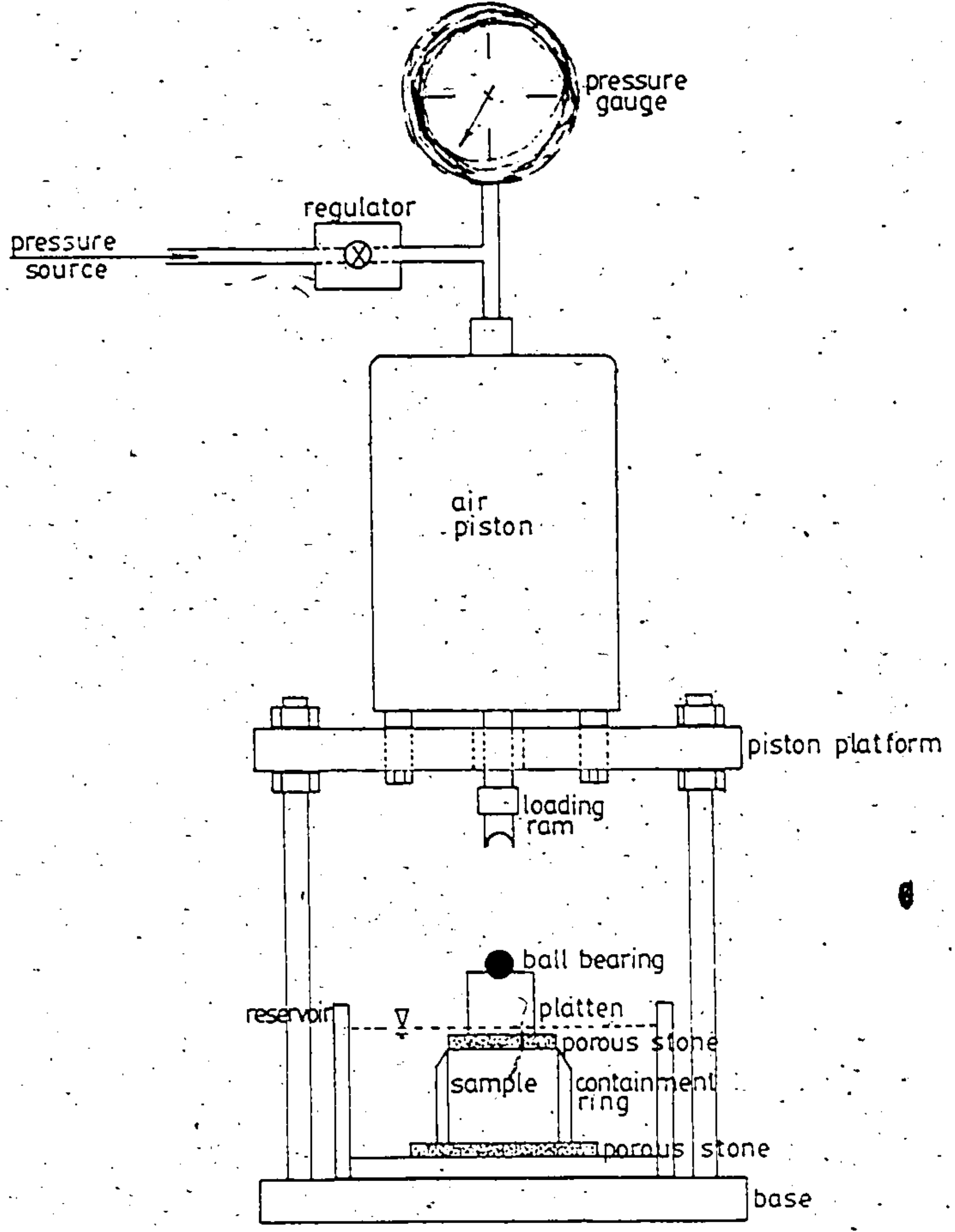


FIGURE - E.2

TRIAXIAL CONSOLIDATION SCHEMATIC DIAGRAM

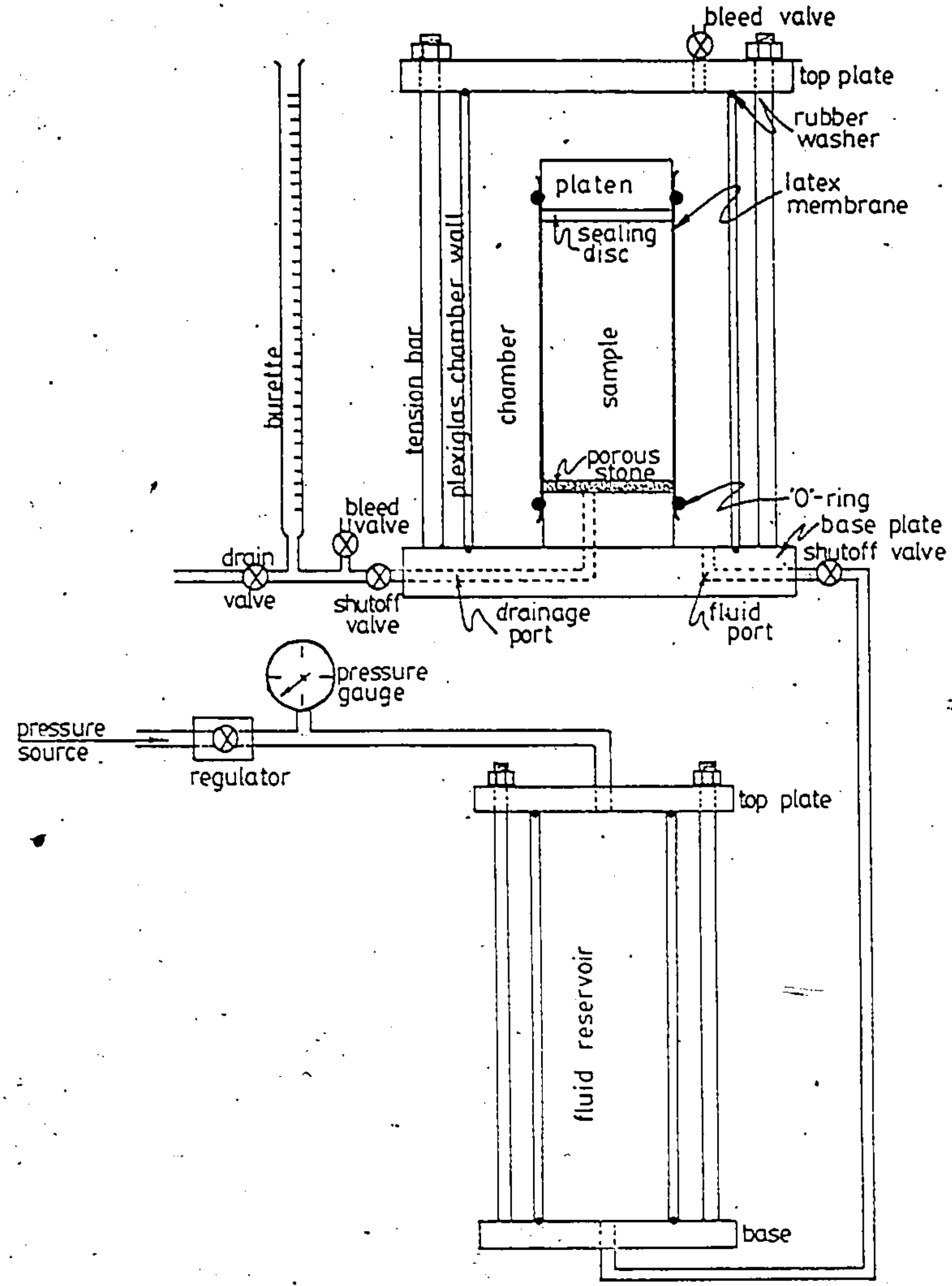


FIGURE - E.3

APPENDIX F

TABULATED WATER LEVEL OBSERVATIONS

WOODSLEE TEST SITE - WATER LEVEL OBSERVATIONS

Table F.1

Date (1983)	Well Number											
	1-1	1-2	2-1	2-2	3-1	3-2	3-3	3-4	3-5	3-6	4-I	4-PD
March 10	186.5	180.5	185.3	180.4	186.7	182.6	185.9	185.8	179.5	183.8		
March 18	186.4	182.1	185.3	181.8	186.6	183.2	186.0	185.6	181.4	184.3		
March 27	186.6	183.3	185.4	182.8	186.7	183.9	186.0	186.0	182.1	184.8		
April 8	186.7	184.3	185.5	183.4	186.7	184.9	186.1	186.2	182.7	185.3		
April 16	186.8	184.8	185.5	183.7	186.7	185.3	186.2	186.3	183.1	185.6		
May 2	186.7	185.4	185.9	184.0	186.7	185.7	186.3	186.3	184.0	185.8	181.1	180.0
May 17	186.5	185.5	185.2	184.2	185.7	185.8	186.2	186.3	184.6	186.1	182.9	180.7
May 23	186.6	185.6	185.5	184.3	186.7	185.9	186.3	186.4	184.9	186.1	183.3	181.1
May 28	186.6	185.6	185.3	184.4	186.7	185.9	186.3	186.5	185.2	186.2	183.7	181.5
June 2	186.6	185.6	185.2	184.5	186.6	186.0	186.3	186.5	185.3	186.1	183.9	181.8
June 10	186.6	185.7	185.2	184.6	186.5	185.9	186.3	186.5	185.5	186.1	184.5	182.4
June 23	186.4	185.7	184.9	184.7	185.1	185.7	185.7	186.3	185.6	186.0	184.5	183.0
July 6	186.6	185.8	185.2	184.7	186.1	186.0	186.0	186.4	185.7	186.1	185.3	183.5
July 19	186.5	185.9	185.2	184.7	184.8	186.1	185.9	186.3	185.7	186.0	185.4	183.9
July 31	186.7	185.9	185.8	184.8	185.4	186.0	186.1	186.4	185.6	186.0	185.1	184.3
August 14	186.7	186.0	185.2	184.9	186.5	186.2	186.3	186.5	186.0	186.2		
August 28	186.5	186.0	185.0	184.9	185.1	186.1	186.2	186.4	185.8	186.2		
Sept. 14	186.4	186.0	185.0	184.9	184.8	186.0	186.1	186.3	185.6	186.1		
Sept. 30	186.4	186.0	185.0	184.9	184.9	185.8	186.0	186.2	185.5	185.9		

WEST WINDSOR TEST SITE - WATER LEVEL OBSERVATIONS

Table F.2

	Well Number										
Date (1983)	10-1	10-2	20-1	20-2	30-1	40-1	40-2	40-3	40-4	40-5	40-6
April 18	181.1	180.3	178.9	178.9	178.6	177.4	177.5	177.4	176.8	176.7	176.9
May 4	181.1	180.9	178.9	179.3	179.7	177.6	177.6	177.5	177.2	177.3	177.5
May 11	181.0	180.9	178.9	179.4	180.0	177.3	177.4	177.4	177.2	177.3	177.4
May 28	180.8	180.8	178.7	179.4	180.5	177.1	177.2	177.2	177.3	177.4	177.2
June 2	180.8	180.8	178.7	179.4	180.5	177.1	177.1	177.2	177.3	177.4	177.1
June 6	180.6	180.7	178.5	179.4	180.5	177.1	177.1	177.2	177.3	177.5	177.1
June 17	180.4	180.7	178.3	179.4	180.6	177.1	176.6	176.6	177.0	176.9	177.0
July 10	180.4	180.6	178.3	179.5	180.6	177.1	177.0	177.1	177.3	177.5	177.3
July 19	180.7	180.6	178.7	179.5	180.6	177.1	177.0	177.0	177.3	177.3	177.2
August 10	180.3	180.7	178.3	179.5	180.7	177.1	177.1	177.2	177.4	177.3	177.3
August 29	180.0	180.4	178.0	179.5		176.9	176.9	177.0	177.3	177.1	177.1
Sept. 15	179.9	180.3	177.9	179.5		176.7	176.8	176.8	177.3	177.0	176.9
Sept. 30	179.8	180.3	177.9	179.5		176.7	176.7	176.8	177.3	176.9	176.9

APPENDIX G

ENVIRONMENTAL ISOTOPE ANALYSIS RESULTS

WOODSLEE TEST SITE - Environmental Isotope Analysis Results Table G.1

Monitoring Site	Sample	Depth (metres)	$\delta^{18}O$ (±.2) (o/ooSMOW)	^3H (±8) (TU)
2	10	4.1	-9.1	23
2	12	5.0	-10.0	93
2	14	5.9	-10.1	50
2	16	6.9	-10.5	3
2	18	7.8	-11.3	22
2	20	8.7	-11.7	33
2	22	9.6	-12.4	12
3	10	4.1	-9.7	26
3	12	5.0	-10.2	51
3	14	5.9	-11.3	23
3	16	6.9	-11.4	34
3	18	7.8	-11.6	11
3	20	8.7	-12.5	47
3	22	9.6	-13.3	49

WEST WINDSOR TEST SITE - Environmental Isotope Analysis Results Table G.2

Monitoring Site	Sample	Depth (metres)	$\delta^{18}O$ ($\pm .2$) (o/ooSMOW)	^{3}H (± 8) (TU)
20	7	2.7	-8.2	107
20	10	4.1	-9.2	55
20	16	6.9	-9.7	66
20	18	7.8	-9.4	31
20	20	8.7	-9.8	53
20	22	9.6	-9.7	33
40	8	3.2	-8.9	41
40	10	4.1	-9.3	54
40	13	5.5	-9.0	62
40	15	6.4	-9.2	16
40	17	7.3	-9.0	9
40	20	8.7	-8.5	16
40	23	10.1	-8.7	17

APPENDIX H

HYDRAULIC CONDUCTIVITY TEST RESULTS

WOODSLEE TEST SITE

Permeameter Test Results

Table H.1

Monitoring Site	Depth (metres)	Orientation	K x 10^{-8} cm/sec	permeant
1	3.7	vertical	9.62	natural
1	4.6	vertical	1.09	saline
1	6.7	vertical	1.64	natural
1	9.4	vertical	1.68	natural
2	2.2	vertical	1.65	natural
2	7.4	vertical	0.74	natural
2	8.3	vertical	1.17	natural
3	2.4	vertical	2.27	natural
3	4.7	vertical	0.58	natural
3	7.3	vertical	0.76	natural
3	10.2	vertical	0.88	natural
4	2.0	vertical	96.60	natural
4	4.8	vertical	0.71	natural
4	4.8	vertical	0.96	natural
4	5.0	vertical	1.17	natural
4	5.5	vertical	1.02	natural
4	5.5	vertical	1.04	saline
4	5.5	horizontal	1.14	natural
4	5.5	horizontal	0.72	saline
4	6.4	vertical	0.88	natural

WOODSLEE TEST SITE

One Dimensional Consolidation Test Results

Table H.2

Monitoring Site	Depth (metres)	Orientation	K x 10^{-8} cm/sec	In situ Pressure
4	3.0	vertical	75	40 kPa
4	3.0	horizontal	77	40 kPa
4	6.0	vertical	40	75 kPa
4	6.0	horizontal	45	75 kPa

Three Dimensional Consolidation Test Results

Table H.3

Monitoring Site	Depth (metres)	Orientation	K x 10^{-8} cm/sec	In situ Pressure
4	5.0	vertical	8.3	65 kPa
4	6.0	vertical	11.0	75 kPa

WOODSLEE TEST SITE

Single Well Response Test Results

Table H.4

Monitoring Site	Depth Range (metres)	K x 10^{-8} cm/sec. slug	bail	hydrograph
1	1.2 - 6.1	26.10	38.00	
1	8.6 - 10.5	2.10	1.73	2.95
2	1.0 - 6.2	1390000.00	1330000.00	
2	8.4 - 10.6	2.79	1.89	2.95
3	1.3 - 3.1	26.00	26.80	
3	2.4 - 4.8	2.35	2.93	1.50
3	4.2 - 6.4	2.05	2.99	
3	5.2 - 7.8	9.38	14.60	
3	4.6 - 9.8		2.33	0.85
3	7.7 - 11.5	7.77	12.60	1.45
4	5.3 - 6.2			6.32
4	5.4 - 7.1			1.65

WEST WINDSOR TEST SITE

Permeameter Test Results

Table H.5

Monitoring Site	Depth (metres)	Orientation	$K \times 10^{-8}$ cm/sec	permeant
10	3.0	vertical	54.00	saline
20	4.8	vertical	2.73	saline
20	6.5	vertical	2.72	natural
40	2.3	vertical	1.49	natural
40	2.4	vertical	2.04	natural
40	2.4	vertical	2.53	natural
40	2.5	horizontal	4.92	natural
40	2.5	horizontal	4.40	natural
40	2.6	horizontal	4.30	natural
40	2.6	horizontal	8.23	natural
40	4.1	horizontal	8.11	low ion
40	4.2	vertical	4.60	low ion
40	4.2	vertical	3.28	saline
40	4.3	vertical	3.74	saline
40	4.3	vertical	3.58	saline
40	4.4	vertical	2.64	natural
40	8.4	horizontal	3.63	natural
40	8.4	horizontal	4.90	natural
40	8.5	vertical	3.02	natural
40	8.5	vertical	3.48	natural
40	9.9	horizontal	26.04	natural
40	10.0	vertical	21.52	natural
40	10.0	vertical	6.00	natural

WEST WINDSOR TEST SITE

One Dimensional Consolidation Test Results

Table H.6

Monitoring Site	Depth (metres)	Orientation	K x 10^{-8} cm/sec	In situ Pressure
40	8.5	vertical	115	85 kPa
40	8.5	horizontal	35	85 kPa

Single Well Response Test Results

Table H.7

Monitoring Site	Depth Range (metres)	K x 10^{-8} cm/sec.		
		slug	bail	hydrograph
10	1.4 - 6.0		1340.00	
10	8.9 - 10.4	7.77		
20	1.5 - 6.7	317.00		
20	5.8 - 10.8		4.43	
30	5.4 - 6.3			2.32
40	1.5 - 3.1		19.8	
40	3.4 - 4.6	30.80	44.3	
40	4.6 - 6.4	21.10	16.2	
40	6.4 - 8.0	3.56		
40	8.0 - 9.8	31.90	6.7	
40	4.8 - 10.9	44.70		

VITA AUCTORIS

Timothy Gordon Orpwood was born in the city of Toronto, Ontario on March 3, 1954 and raised in the Borough of Scarborough. He attended the University of Toronto from 1973 to 1977 and graduated with a Bachelor of Applied Science degree in Geological Engineering. Having specialized in the Geotechnical option of this programme he was hired by Dominion Soil Investigation Inc. and worked in Toronto as a graduate engineer in training until 1979.

In 1979 he accepted a transfer to the Windsor office of Dominion Soil Investigation Inc. and the position of Project Engineer. He was registered as a Professional Engineer in the Province of Ontario that same year.

In 1980 he entered the University of Windsor as a part-time student in the Master of Applied Science programme in Geological Engineering.

Timothy Gordon Orpwood is currently the Assistant Branch Manager and Senior Project Manager for Dominion Soil Investigation Inc. in Southwestern Ontario. He has accepted a position with Transport Canada commencing September, 1984.