IRISH-DUTCH PEATLAND STUDY

GEOHYDROLOGY AND ECOLOGY

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CLARA BOG: A HYDROGEOLOGICAL STUDY

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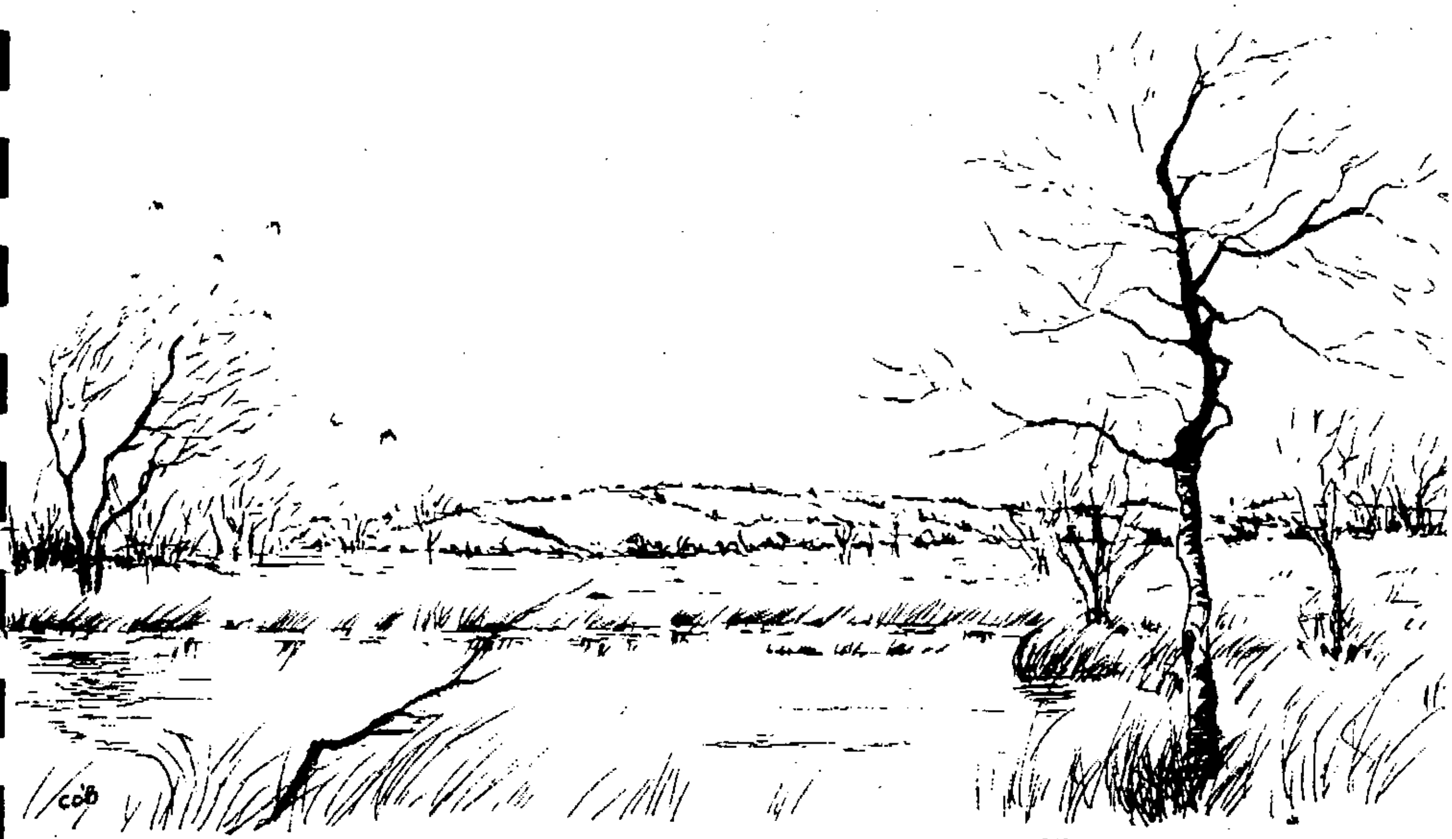

Sketch of Clara Bog by Catherine O' Brien, Clara, County Offaly.

Donal Daly

CLARA BOG: A HYDROGEOLOGICAL STUDY.

by

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INTRODUCTION.

1.1

Raised bog is a landform typical of those parts of the world experiencing high precipitation and relative humidity all year round. In this context the climate of Ireland is ideally suited to their development and indeed at one stage 16% of the country was covered in bog. Its' extent has been greatly reduced by human activities, notably the cutting of peat for fuel and electricity generation, both of which have accelerated markedly in the past few years with the mechanization of turf cutting by Bord na Mona, the Irish peat development authority. As a consequence of this exploitation intact raised bog has become rare phenomenon in Ireland and more especially in Western Europe as a whole.

In an effort to preserve some intact examples Clara Bog has been acquired by the Irish Wildlife Service and has held nature reserve status since 1982.

1.2

The bog is over 650 ha in extent and is situated in Co. Offaly in the Irish midlands (Fig. 1.1). The reserve contains numerous examples of typical raised bog vegetation, being dominated by various *sphagnum* species with *molinia* being more abundant in drier areas. In addition to this the area has one of the last remaining well developed soak systems in Western Europe, supporting anomalous minerotrophic vegetation in an otherwise ombotrophic habitat. Clara bog is an Area of Scientific Interest (A.S.I.) of international importance.*

1.3

Prior to acquiring reserve status the area was owned by Bord na Mona who preliminarily developed the eastern part of the bog by the construction of drainage channels. These have subsequently been blocked with variable degrees of success. Other anthropogenic effects visible in and around the area include the effects of burning, marginal drainage and most importantly continued peat cutting particularly along the southern margin where it constitutes a very serious threat to the existence of one of the soaks.

1.4

Previous work on raised bogs has been of a predominantly botanical aspect with little attention being paid to hydrological/hydrogeological components. In an attempt to understand the hydrodynamics of Clara Bog in detail a joint Irish-Dutch study between the Dutch government and the Irish wildlife service was undertaken since an effective conservation management policy for the bog requires a thorough understanding of the behaviour of the raised bog hydrology and hydrogeology.This project forms

* A glossary of ecological terms use in the text is contained in Appendix

part of the greater overall multidisciplinary study into the eco-hydrology of raised bogs.

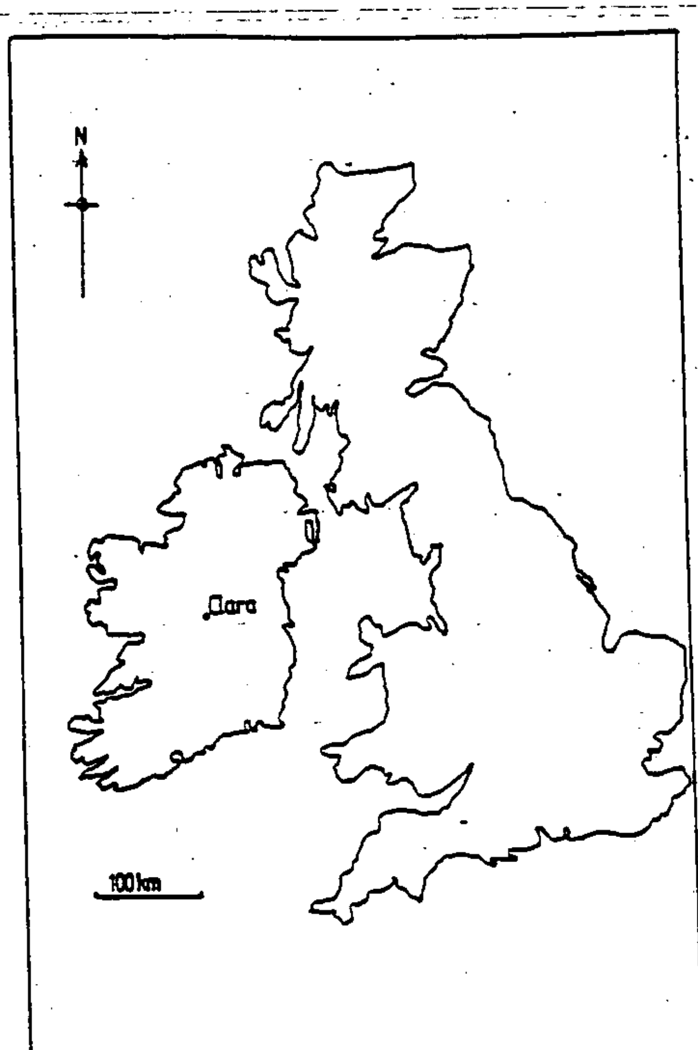


FIG. 1.1 A MAP OF BRITAIN AND IRELAND.

The projects objectives are threefold :

(1) To examine preliminarily the general peat hydrodynamics of the bog.

(2) To examine the interrelationship between the peat and the surrounding inorganic deposits.

(3) To investigate the origin of the soak systems, focussing particularly on the example on the eastern part of the bog known as Lough Roe.

In order to achieve the above a substantial field based input was required owing to the lack of relevant data. With this in mind an initial general overview of the bog and it's surroundings was taken followed by a more detailed study of a 1.0x1.5 km^2 area in the north east.

1.5

Work completed by other workers to date includes the construction of geological and geomorphological maps of the Clara bog district, a preliminary geophysical survey on the western part of the reserve and ecological/botanical assessments of sample areas around the soaks and in the adjacent bog. In addition to this detailed hydrological assessments have been initiated in the south western part of the bog. Rain gauges and a V-notch weir have been installed here with a view to obtaining a flow balance of the surrounding area. Data to date has been largely inaccurate due, in the main, to ineffective initial catchment delineation currently being rectified by accurate topographic levelling.

II

GEOLOGY

2.1 Introduction.

With few exceptions all previous geological work prior to this study has focussed primarily on solid geology. The area was initially mapped in 1837 during the first geological survey of the country. This however paid poor attention to Quaternary geology ,subsoils being subdivided into the broad categories of drift, bog & alluvium. Subsequent mapping has had a mineral exploration emphasis and consequently the first detailed Quaternary geological map of the Clara area were those completed in early 1990 as an initial component of this study. The map has been compiled and partially displayed in fig 2.1.

The geology of north Co. Offaly is dominated by Pleistocene & recent deposits, the former having a glacial origin. Bed-rock exposure in the area is rare and indeed has not been observed in the Clara district with the exception of an outcrop of limestone breccia to the north of Clara town exposed in the core of an esker. Despite this, pre-existing borehole data shows the area to be underlain by Carboniferous limestone. The overlying Pleistocene deposits are laterally very variable in texture and composition. The region is traversed by a series of east-west trending eskers surrounded by glacial tills of various forms. Subsequent

Holocene deposits are predominantly of organic or alluvial/lacustrine origin.

Prior to starting any hydrogeological investigation a detailed geological study was under taken of the bog and adjacent area with particular emphasis being placed on the 1.0 x 1.5 km^2 study area in the north-east.

2.3 Methodology: Geological investigation comprised of a three fold approach

(a) Geological mapping: The Quaternary deposits of the study area were mapped in the standard manner. The resulting map (Fig.2.2) is broadly similar to the previous work with only minor differences, the most notable of which is the presence of a thin band of gritty clay outcropping in the drains along the northern boundary of the peat. Exposure was locally very good.

(b) Hand augering: A Hiller-Borer hand auger was used to sample peat; samples being taken at 50cm intervals in a chamber of the same length thus providing a continuous core over the interval in which this lithology occurred. The peat was logged using the Von Post humification index (Von Post ,1926) as an indicator of gross decomposition of organic matter within the formation. This classification is based on a number of parameters (,which are easily determined in the field using the scale reproduced in appendix II,) and are as follows:

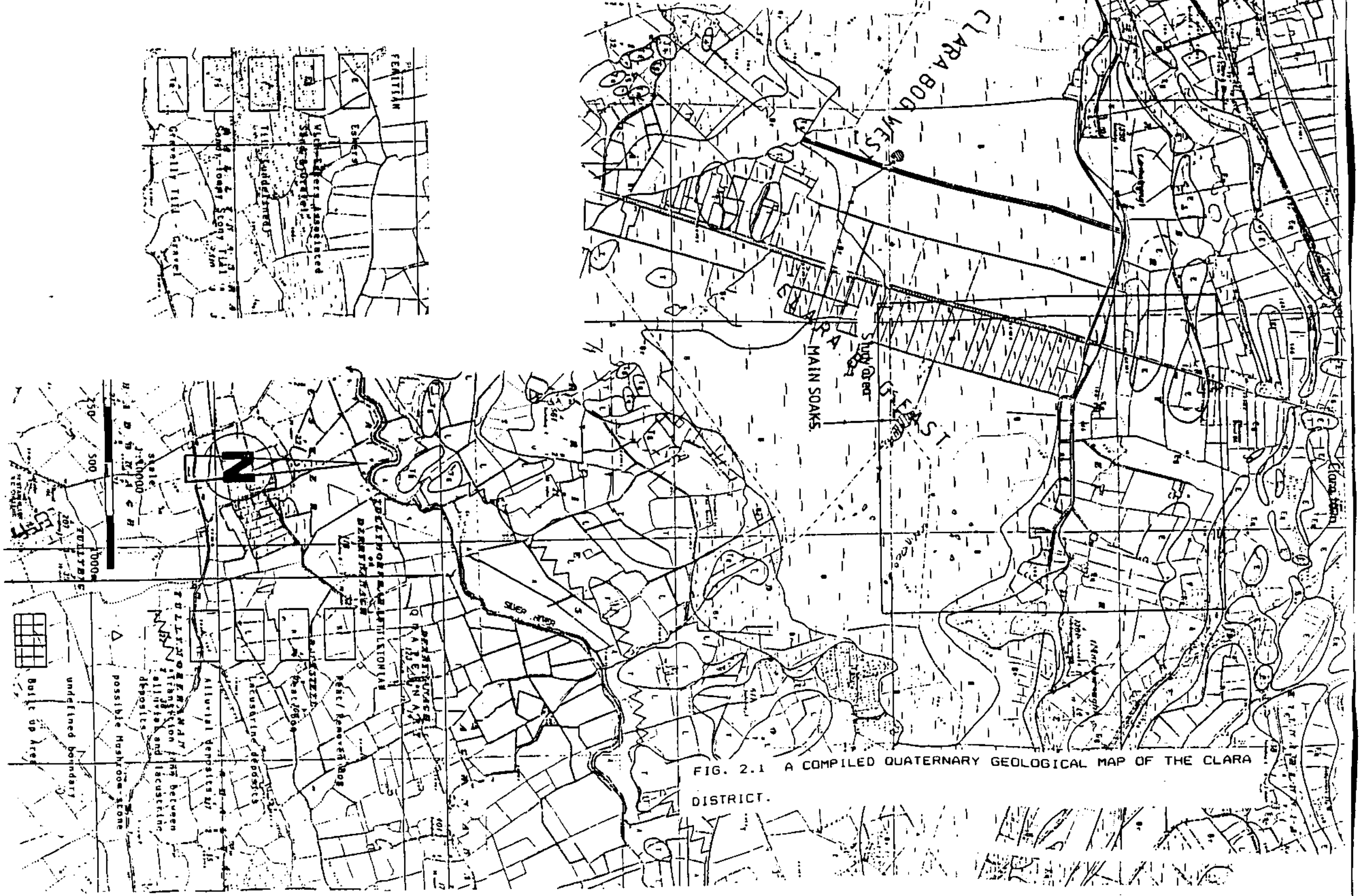


FIG. 2.1 A COMPILED QUATERNARY GEOLOGICAL MAP OF THE CLARA DISTRICT.

(i) The degree of botanical detail apparent from a sample .

(ii) The fraction of material escaping between the fingers when a hand sample is squeezed.

(iii) The colour of the water leaving a sample on squeezing.

Two transects ,A and B, were cored in a general direction perpendicular to the overall trend of the glacial and lacustrine deposits in the north. The resulting geology is displayed in figs. 2.3 & 2.4. Of these ,the western transect was investigated in more detail with coring taking place at 100m intervals from L. Roe to the northern margin of the reserve. Sampling locations were spaced at closer intervals approaching the reserve boundary in order to asses the effects of drainage on the bog. The main purpose of sampling along the eastern transect was to determine the degree of lateral variability which may occur.

(C) Drilling: In order to assess the subsurface succession an exploratory borehole (CLBH-1) was drilled in Dec. 1989 using rotary methods. The following succession was recorded:

0-6m	Peat.
6-10.5m	Blue clay.
10.5-16m	Glacial till/sand & gravel.
16m-	Carboniferous limestone.

At 11m artesian water was struck with a head of 1.8m above ground surface and an outflow of 1 litre/sec. at ground

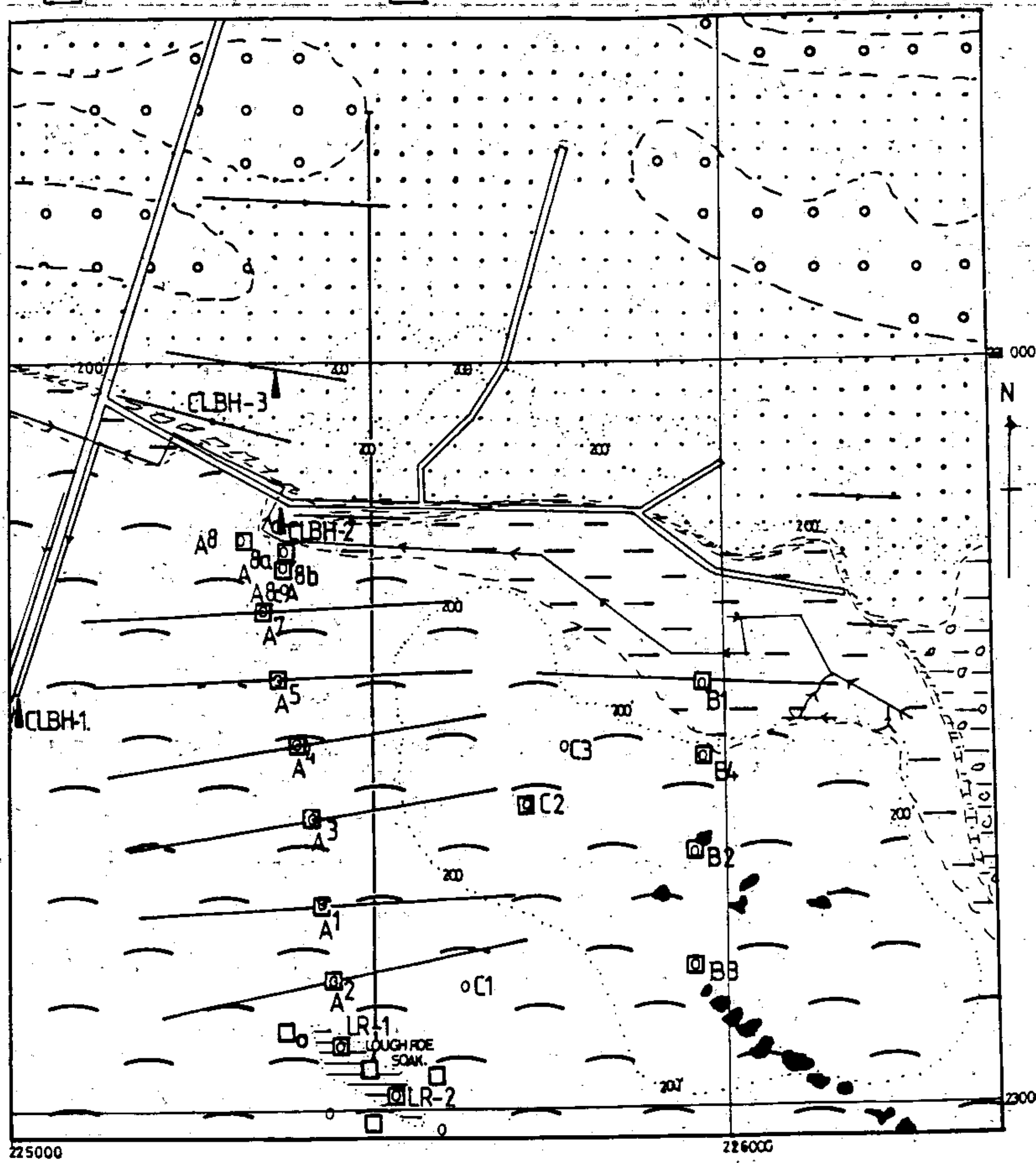
FIG. 2.2

A GEOLOGICAL MAP OF CLARA BOG AND ADJACENT ESKER STUDY AREA.

(WITH ADDITIONAL GEOPHYSICAL AND HYDROLOGICAL DATA).

KEY : 200 m — Line of dipole-dipole transect.

- Peat.
- Cutaway peat.
- Lacustrine clay.
- Clayey gravel/sand.
- Sand & gravel.
- Esker (Morphological feature)
- Coring location
- A^1 Piezometer nest station.
- CLBH-3 Drilling locality
- Flowing drain
- Resistivity spread.



surface. This borehole has subsequently been blocked although it is proposed to redrill to unit at a later date.

During the course of this project additional 2 holes were drilled. A percussion technique known as shell and auger drilling was employed in both. The technique involves driving casing into the ground before recovering samples by means of a bailer with a cutting shoe on it's base. On encountering limestone the bailer was replaced by a portable top drive coring unit to confirm Bed-rock, the lithology being drilled for another 5m.

Despite the slow nature of the percussion technique it has the advantage over more advanced methods of

(i) allowing more efficient recovery of unconsolidated deposits ,and

(ii) allowing greater accessibility to areas otherwise unavailable for drilling.

Of the holes drilled the first was completed as a piezometer nest (CLBH-2) and the second as a water supply well (CLBH-3) (see fig 2.2 for locations).

Standard penetration tests were undertaken at regular intervals in the CLBH-3. This technique is commonly used to determine the engineering properties of unconsolidated sediments. Unfortunately the method is highly empirical with no direct relationship between results and the hydraulic properties of the media encountered being apparent from the literature. In spite of this the method was employed semi-

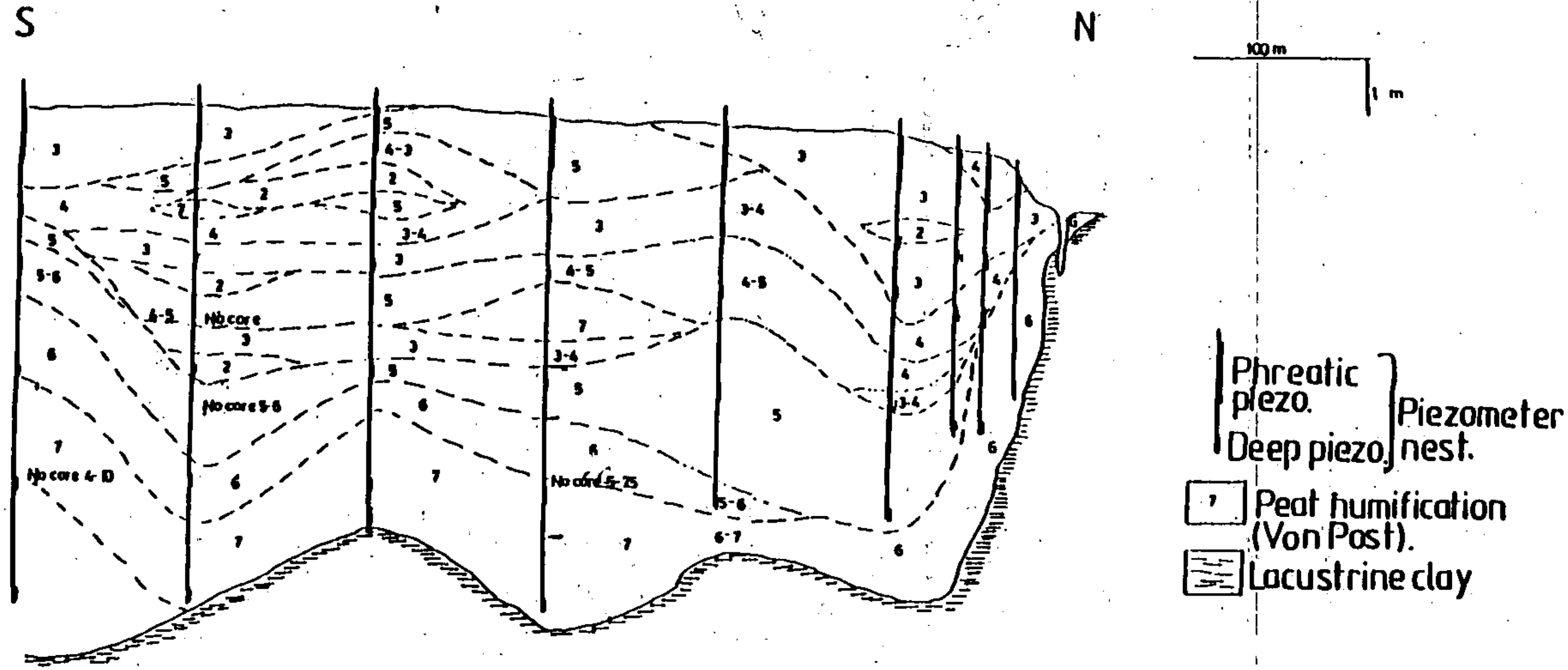
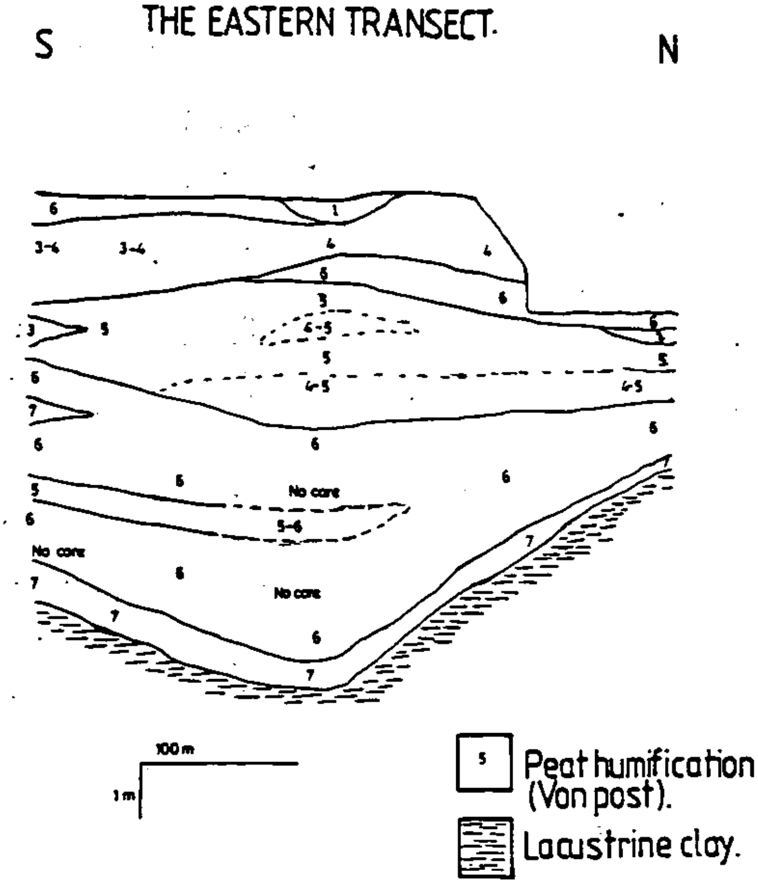


FIG. 2.3 A PROFILE OF PEAT HUMIFICATION ALONG THE WESTERN TRANSECT.

FIG. 2.4

A PROFILE OF PEAT HUMIFICATION ALONG THE EASTERN TRANSECT.



quantitatively to ascertain the degree of consolidation in the sequence.

A 140lb hammer was dropped from a height of 1m and the number of blows, N required to drive a split barrel sampler over 3 successive increments of 15cm were recorded .

Details of the completed holes and the associated successions encountered are illustrated in figs.2.3 and 2.4.

2.3 GEOLOGICAL SUCCESSION.

The lithologies encountered in order of decreasing age are summarized in table 2.1. Detailed descriptions of each formation are given below.

2.3.1 Carboniferous Limestone: Carboniferous Waulsortian Limestone was encountered in all cores drilled. Recovery was very good with in excess of 90% typically being recovered. The rock is almost entirely $CaCO_3$ with only small quantities of clay apparent.

2.3.2 Esker and associated Sand & Gravel: Sand and Gravel occurs at surface in the north of the study area. It forms topographically prominent linear esker ridges and associated hollows, these ridges separating the bog from the Brosna catchment further north. The deposits are well exposed in quarries within the eskers. The unit contains lenticular units of predominantly cobble and boulder sized material yet overall the formation is dominated by medium to be close to CLBH-1, the thickness of clay encountered there thought to approach a maximum.

2.3.5 Peat: Peat is the dominant formation covering the Clara area . Geologically 2 formations have been created intact and cut away peat reflecting normal and damaged areas where peat exposure may deviate from it's natural state. Peat thickness reaches a maximum in the Western part of the reserve where successions in excess of 10m have been recorded . Slightly thinner sequences have been observed in the study area. Greater depths are imagined to have once existed prior to road construction across the centre of the bog ,where development of peat usually reaches it's maximum extent. The construction of the road would have caused shrinkage and compaction of the peat; this in turn would have subdivided the bog's recharge mound.

A typical hydroseral succession of peats, as summarized in fig.2.8, is represented in the bog starting with nutrient rich basinal fen and lacustrine peats fed predominantly by runoff and groundwater grading up into more ombotrophic raised bog forms.Recognition of the former proved difficult due to high humifications in the lower layers ,wood and *phragmites* providing the only useful field indicators of it's presence.

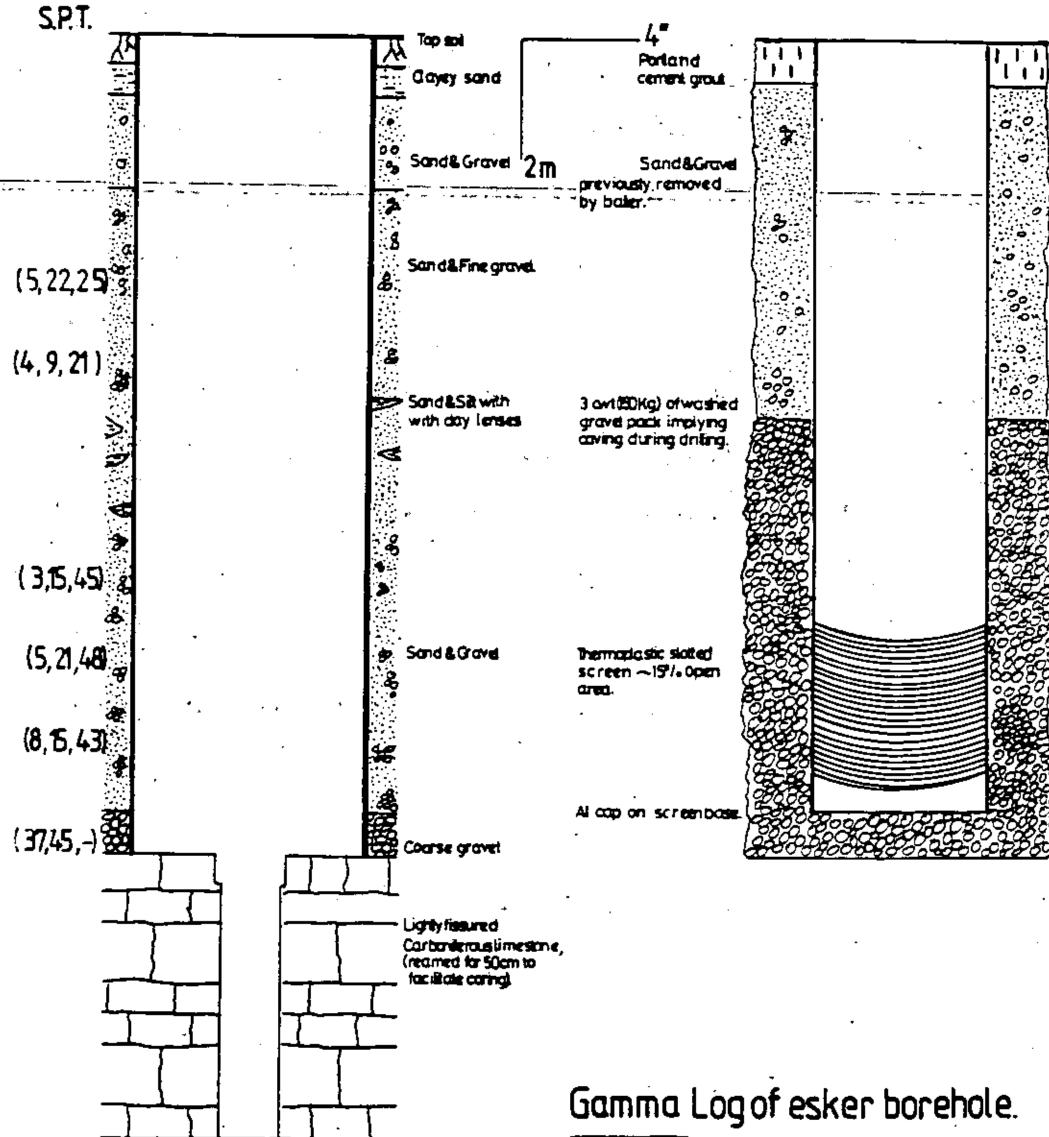
The degree of humification observed ranged from H_1 to H_{7-8}. In general this increased with depth although thin moderately decayed layers (H_4 to H_5) were commonly noted at

FIG. 2.5

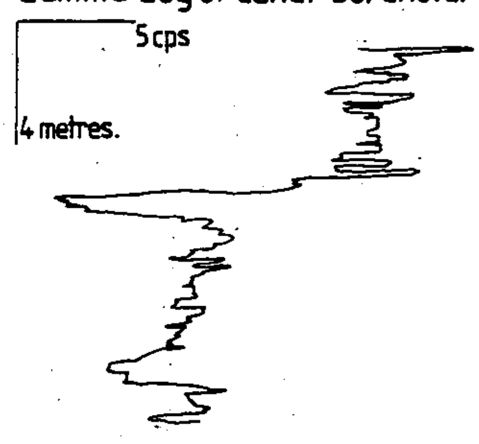
Well design for abstraction borehole on esker.

Drilling schedule & Lithological sequence

Well design detail.



Gamma Log of esker borehole.



permeabilities were therefore determined using equation (3) the possibility of the aforementioned complication being bourne in mind.

6.5 Overall results and hydrograph analysis:

(a) A water table contour map is illustrated in fig.6.2. Equipotentials reflect a recharge mounding in the centre of the study area flowing radially outwards ,generally towards the bog margins or the road with the tighter spacing of the lines approaching the former reflecting a marked decrease in permeability in the upper layers within this zone. The exception to this general pattern is the regime observed around Lough Roe the significance of which is discussed in chapter VIII .

(b) Representative hydrographs for central and near-marginal tracts of bog are illustrated in fig 6.3a and 6.3b respectively.

The plots indicate head fluctuation to be greatest in the upper metres of the system reflecting flow to be dominantly through these layers. In addition to this a striking point about both stations is the marked head difference observed through the profile reflecting downward head gradients. The magnitude of these gradients is appreciably greater in the near-marginal situation where water within the system is approaching it's point of discharge. This situation contradicts typical homogeneous groundwater flow approaching such a point in which the

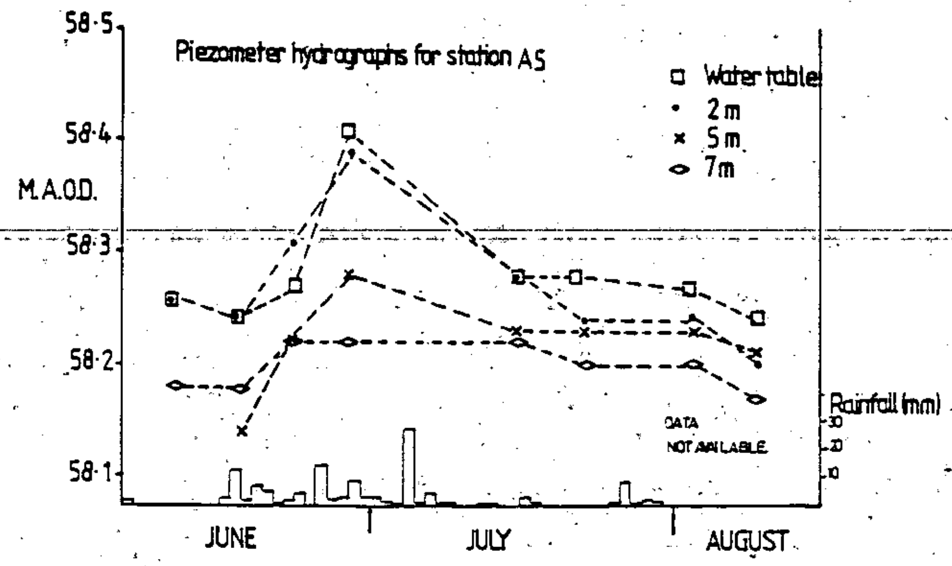
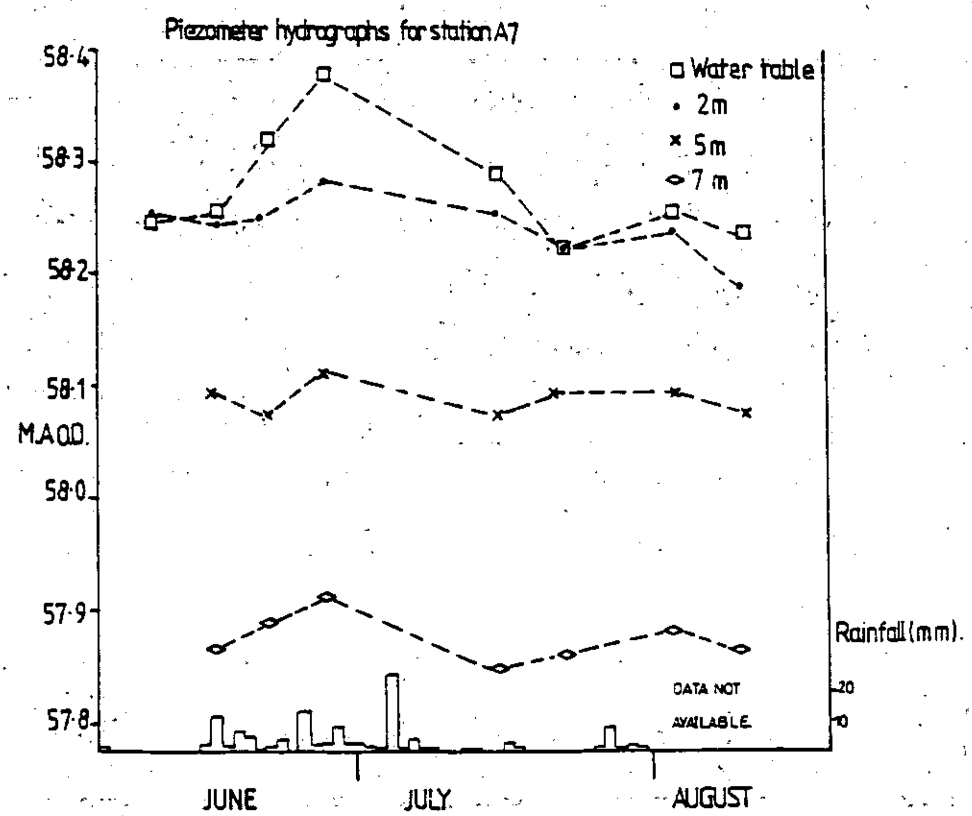


FIG. 6.3 . PIEZOMETER HYDROGRAPHS FOR STATIONS A5 AND A7.



sand which is well sorted and sub-angular to sub-rounded in shape. Cross stratification is well exposed in numerous outcrops in conjunction with synsedimentary slip faults which are occasionally apparent in sections of such exposures.

Although topographically more subdued ,the associated sand and gravel is believed to bear an overall similarity to the esker deposits although a larger proportion of finer material is envisaged reflecting the less energetic conditions of the margins of subglacial meltout in comparison to those in the centre. It is tentatively suggested that this may constitute the sandy till observed at depth in CLBH-2. Compositionally the deposits are dominated by $CaCO_3$ derived from limestone Bed-rock.

Table 2.1 Geological succession for Clara Bog (North-East)

Lithology	Age
Fen to raised bog peat.	Holocene.
Blue-grey Lacustrine clay.	Holocene.
Glacial till.	Pleistocene.
Boulder to medium sand esker deposits.	Pleistocene.
Massive to lightly fissured clean blue -grey limestone.	Lr. Carboniferous

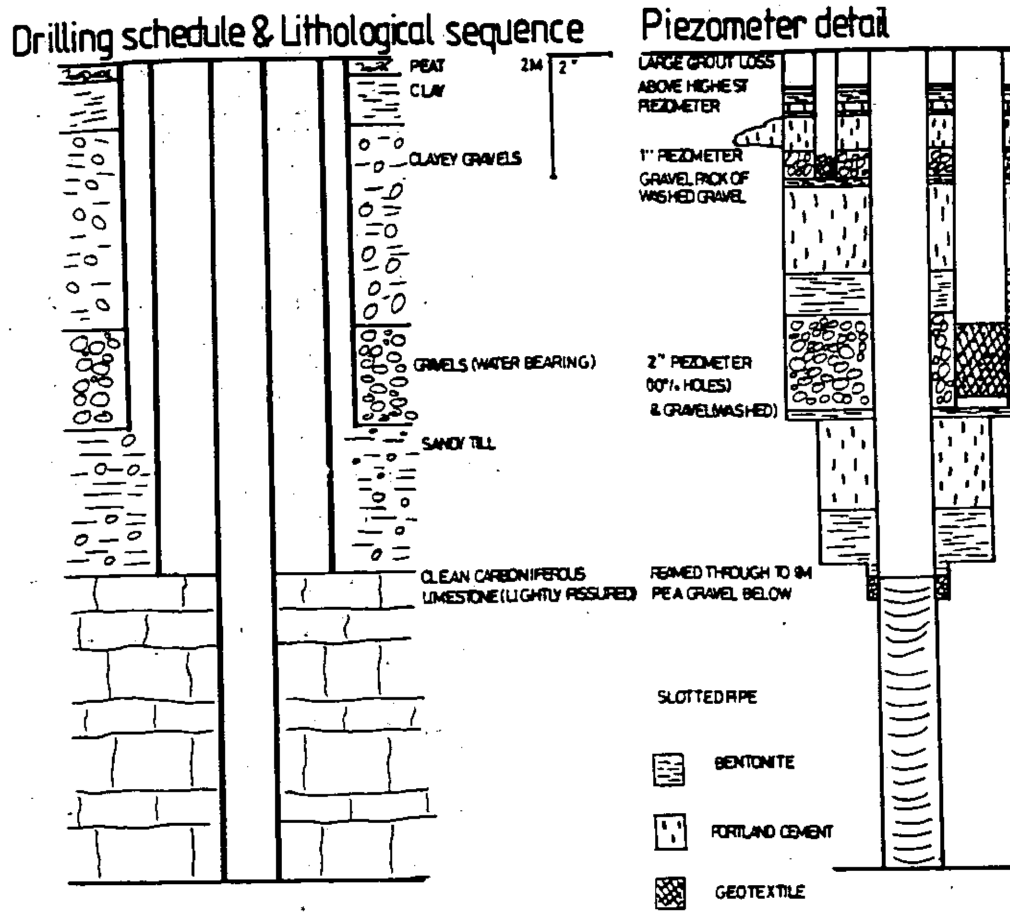
2.3.3 Till : Glacial tills are more typically found along the southern margin of the bog. They are texturally variable ranging from loamy to gravelly till/gravel.Along this southern boundary peat can be seen overgrowing or to have previously overgrown these deposits.In the study area to the north till can only be observed in the north-eastern section. It is typically clayey containing some coarser material up to granular grade although pebble sized clasts have been observed. This lithology has been encountered above more permeable water bearing gravels in CLBH-2 and has been termed Clayey gravel in the lithological log(fig.2.6).
It appears to grade vertically up into the overlying lacustrine clays.

2.3.4 Lacustrine Clay: The north-eastern sector of Clara bog is entirely underlain by blue-grey clay; this conclusion being based on the results of hand augering in the peat which consistently revealed clay to be the underlying deposit.

The texture of the unit is laterally variable from more gritty clays around the margin to an almost pure composition towards the southern limit of the study area. Previous work by Bord na Mona (fig2.7) indicated an irregular base to the peat, an observation confirmed during the course of this study. Sedimentologically the clay is envisaged blanketing a post-glacial topography with preferential deposition in hollows. The regional depo-centre is indicated by fig.2.4

FIG. 2.6

Well design for piezometer nest



the a

burning p reflecting high oxidation, possibly due to humification 1982. In addition to this similar inverted possible previo were observed at depth reflecting

Topographical es in peat growth (Ingram, 1983). shape being basically g naturally has a 'watch-glass' expression along the er large areas with steeper exaggerated as a result This expression has been increased compaction and su inal drainage causing apparent along the margins of Such features are marginal fen lagg has been removed. area where the

2.4 Conclusions.

2.4.1 Palaeogeography: A brief geologica the study area, based on the lithologies obser the Lower Carboniferous with the deposition of carbonate mud on a Waulsortian Mudbank lithifying to p a massive clean limestone before becoming uplifted jointed in subsequent structural events. No younger deposits are represented within the area until the end of the Late Pleistocene.

The end of the Pleistocene is regarded as a period of waning glacial activity having many depositional meltout features associated with it. These features produce the undulatory and ridged topography presently seen around the bog margins. The glacial tills of various textures deposited at glacier margins in addition to the esker sands and

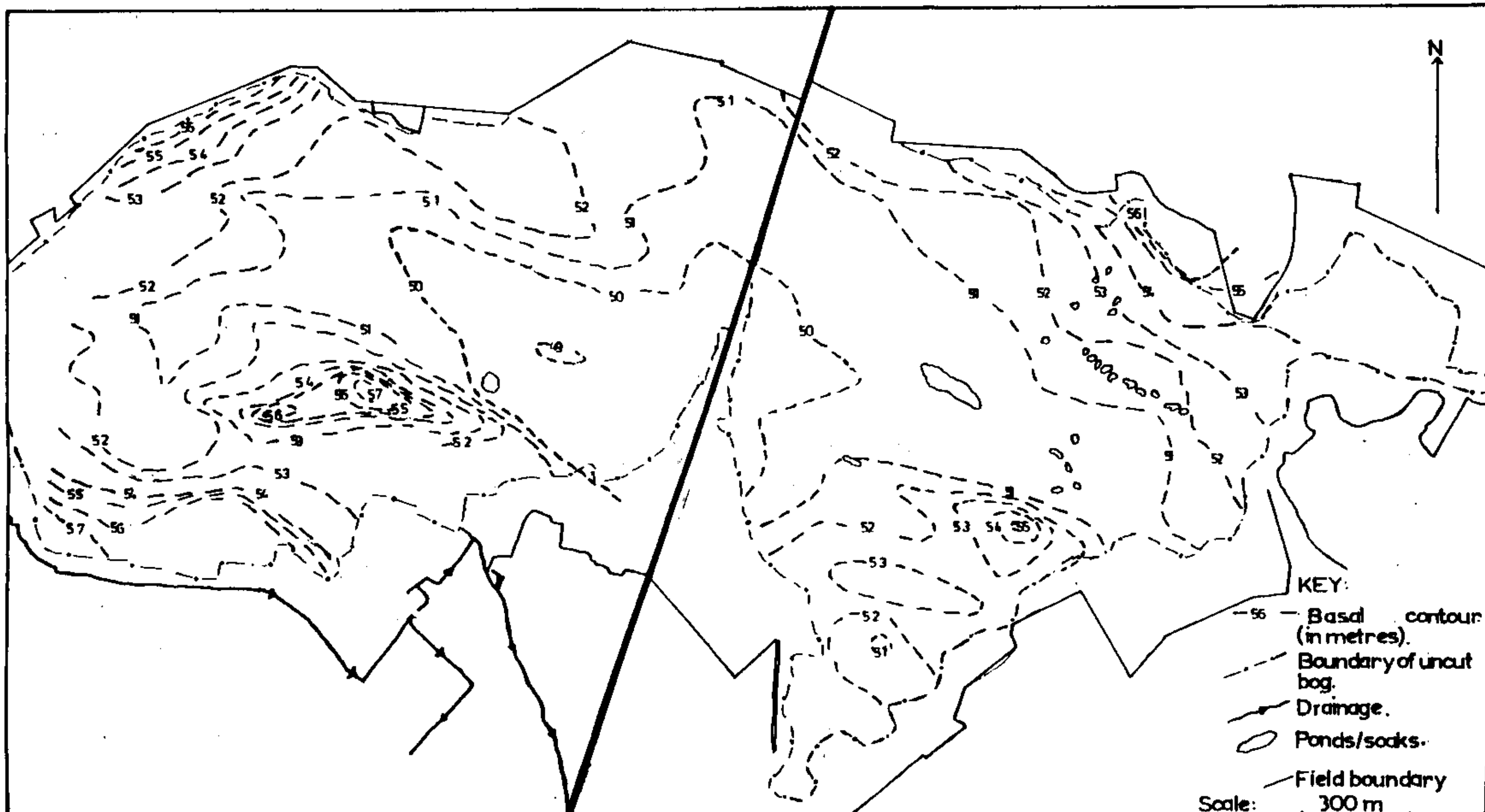


FIG. 2.7 A MAP OF THE BASE OF CLARA BOG.
(Modified from original 1974 Bord na Mona imperial data [in feet]).

gravels deposited subglacially by fluvio-glacial activity are typical of those observed in this region of the country.

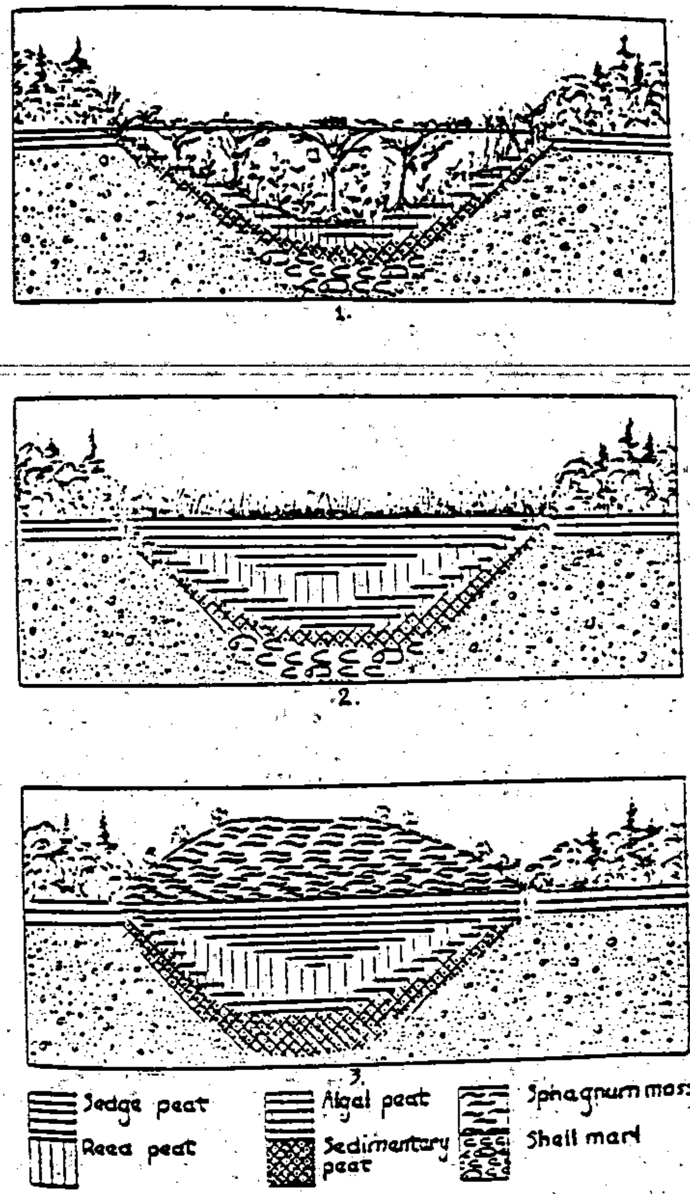
The thick lenticular deposits of predominantly cobbles and boulders with the esker system give an indication of the high energy environment locally prevalent in the area at this time. Finer materials approaching the esker margins reflects the generally calmer conditions prevalent here. The extent of these deposits below the bog is not known although possible recovery of sands and gravels from CLBH-1 suggest fluvio glacial activity may have extended that far. The ensuing melting of ice resulted in quieter depositional conditions reflected in finer overall grain sizes as the succession gets younger, as observed in CLBH-2.

Regionally the Early Holocene was dominated by the giant post-glacial lake, Lough Boora, a lobe of which extended into the area. Deposits of this period are dominated by lacustrine clays which blanket the post-meltout sub-aqueous topography. Compositionally the clays have variable degrees of purity, sandy fractions becoming more prominent toward the esker contact. A palaeoshoreline is tentatively proposed.

Progressively warmer Holocene conditions resulted in rapid vegetational colonization which in the course of hydroseral succession resulted in the gradual invasion of the lake by minerotrophic fen vegetation fed by nutrient rich runoff, in addition to possible groundwater seepage. This diverse vegetation gradually gave way to a more limited bog flora as the succession became more dominated by nutrient poor rainfall associated with increasing topographic elevation. Growth continued until the classic ecological succession culminated in the development fully ombotrophic raised bog in all localities, except for marginal lagg zones and where the soak systems are operational, thus completing the sequence observed to-day.

2.4.2 S.P.T. Results and Discussion: The S.P.T. values obtained throughout the course of testing at CLBH-3, with the exception of the final test yield a consistent pattern of a low initial value followed by succeeding markedly higher results. No barrel samples were recovered during the course of testing.

This absence of samples in addition the consistent variation in the results indicate an initial unconsolidated deposit underlain by a more rigid base. This situation frequently arises when the hole is not emptied of all material loosened during the course of drilling resulting in initial penetration into this material before more representative results are obtained. Such material is trapped in the barrel during testing before subsequent loss on barrel recovery. Bearing this situation in mind the final two values were summed to give N_{30}; the resulting plot against depth is shown in fig2.9. Comparison to standard values in B.S.I. 5930 showed the sequence to range from



Marsh–fen–bog transition: (1) shallow, open water stage; (2) fen stage; (3) raised bog stage. (From Waksman, 1942.)

FIG. 2.8 SUMMARISED HYDROSERAL SUCCESSION OF RAISED BOG DEVELOPMENT.

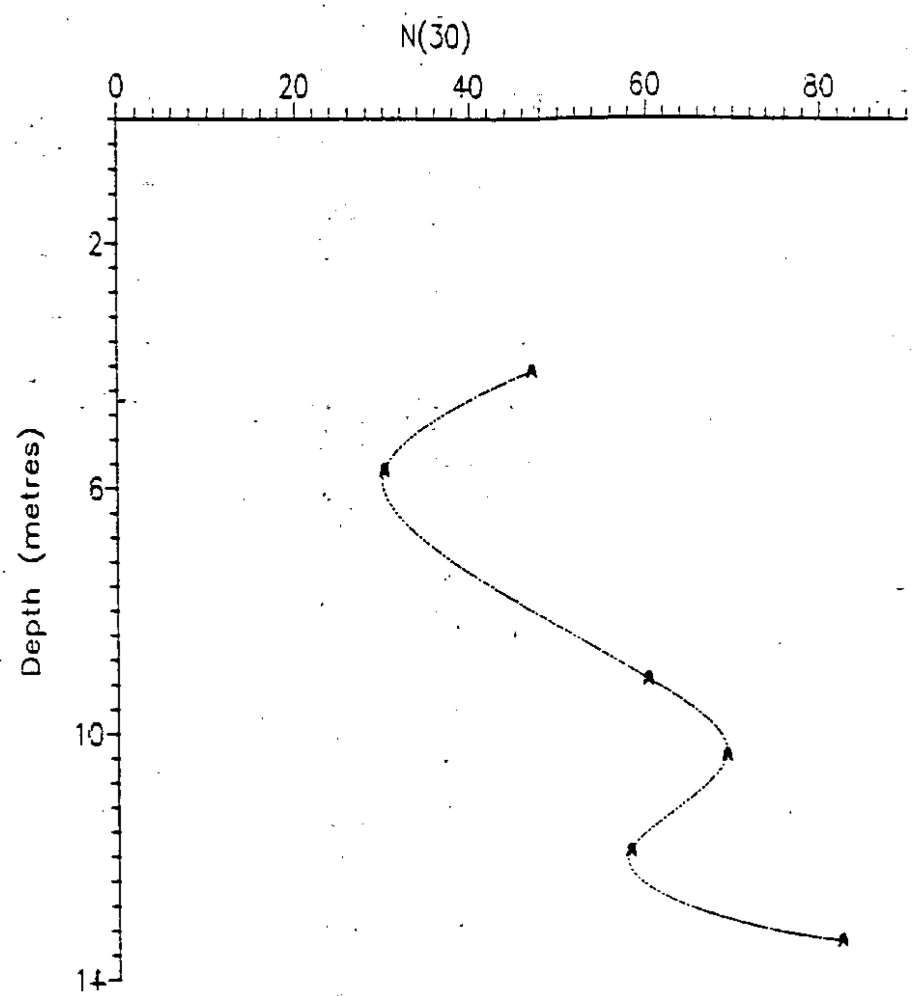


Figure 2.9 A PLOT OF N_{30} vs. DEPTH.

dense to very dense and it was therefore regarded as safe to withdraw the casing without fear of formational caving.

III

GEOPHYSICS.

3.1 Introduction.

In order to determine the nature of the subsurface geology a brief geophysical survey was undertaken. Geoelectrical techniques were preferred over seismics since the extreme unconsolidation associated with peat makes it very vulnerable to external vibration, most notably from traffic on the road crossing the bog. Offset Wenner and dipole-diploe methods were employed, the former providing a means of geo-electrical sounding and the latter a method of profiling to producing a pseudo-section.

3.2 Offset Wenner resistivity sounding.

3.2.1 Wenner resistivity theory: The apparent resistivity of a horizontally bedded lithology is determined using the Wenner technique by means of the formula :

$$p_a = 2 \pi a \delta V/I \qquad (1)$$

where p_a is apparent resistivity,

a is the spacing between electrodes ,

δV is the potential difference between voltage electrodes,

I is the current passed through the ground.

The Wenner technique maintains a constant a spacing between electrodes, the distance between which is gradually increased about a central fixed point. Using the Offset Wenner system equation (1) is modified to :

$$p_a = 2 \pi \delta V/I \, (D_1 - D_2)/2$$

The technique gives two readings for the same a spacing by altering the electrode layout as illustrated below:

c p p c D_1,

c p p c D_2.

The system has the following theoretical advantages:

(a) The degree of noise on the resulting curve is drastically reduced through the averaging facility.

(b) A good gauge of lateral variability is determinable.

(c) A non segmented curve is produced ,the analysis of which generally proves easier than the segmented plot derived from the Schlumberger technique.

3.2.2 Methodology: The survey employed an SAS 300 terrameter using a 4 count averaging facility with BGS multi-core cable and switch box. Where possible the maximum electrode spacing of 128m was measured; this didn't prove feasible in many cases however due to topographic and cultural effects. Soundings taken on the sands and gravels required the electrodes to be watered to provide effective contact due to dry nature of the ground.

10 Geo-electrical soundings were taken along line of section from Lough Roe to the eskers in the north. Measurements were centred on the points of coring/drilling whenever possible thus allowing some degree of calibration

in conjunction with a reduction in the requirement for levelling.

The method employed had the advantage over other electrical techniques of

(a) allowing measurement of Rα ,Rβ & Rτ* and thus a check on the quality of the readings taken using the tripotential relationship;

(b) allowing rapid measurement of resistivities at successively increasing intervals of 2^n where $-0.5 \leq n \leq 7$.

Limitations may arise due to the fixed position of the electrodes yet this has not proved to be a problem in this case.

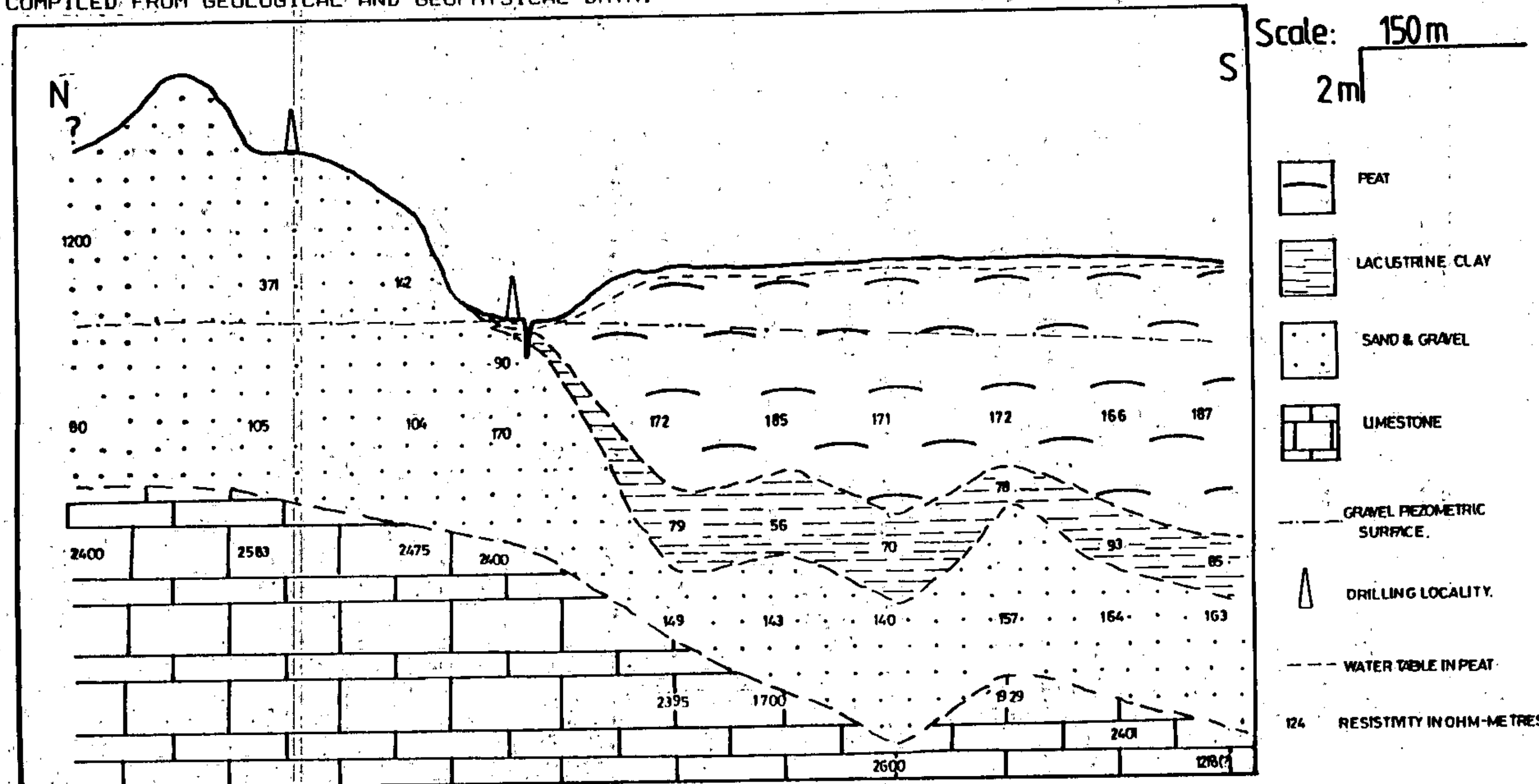
* Rα =	c	p	p	c
Rβ =	c	c	p	p
Rτ =	p	c	p	c

where p is a potential electrode and c is a current electrode .

3.2.3 Results:The resulting curves produced from the data in appendix II were initially analysed using auxiliary point methods. The resulting solutions were largely inaccurate. This was due primarily to the problems of equivalence and suppression, which were present in all soundings. Subsequent analysis using the program 'Resplot' provided more satisfactory results when account was taken of the known depths to given lithological boundaries.

FIG. 3.1 A CROSS SECTION OF CLARA BOG AND ADJACENT ESKER

COMPILED FROM GEOLOGICAL AND GEOPHYSICAL DATA.



SECTION COMPILED FROM GEOLOGICAL & OFFSET WENNER GEOPHYSICAL DATA

The resulting solutions are displayed in fig.3.1 .The resulting lithological resistivities are in general realistic and are discussed separately below.

(a) Limestone : The high resistivity of the limestone is in accordance with the idea of a slightly fissured lithology containing little water. Lower observed resistivities particularly below the bog may reflect more extensive weathering/fissuring although the southernmost result is questionable and may reflect another lithology, possibly laterite or alternatively a karstic feature/heavily jointed limestone.

(b) Sand and Gravel : The resistivity of this formation is seen to be laterally very variable decreasing toward the margin perhaps reflecting the hypothesized increased clay content.An accompanying resistivity drop in the second layer is believed to represent the water table in saturated gravels and has been calibrated thus. Saturated formational resistivities increase toward the south possibly reflecting a cleaner aquifer.The lithological log of CLBH-2 reflects the great variation in glacial deposits present in the area, the values of which have been bulked on extension below the bog resulting in slightly different results to those apparent on the esker.

(c) Lacustrine Clay: The low resistivity values of the clay are within the range expected for the lithology. The variable thicknesses suggested are in compliance with the sedimentological model, although not as large as those observed at CLBH-1.

(d) Peat: Depth of peat had previously been obtained by hand augering thus providing useful control to obtain resistivity of this unit. Values observed were higher than expected for such a high porosity medium, this being due to the low conductivity of the water (approx 120μS/cm measured at surface). An unusual feature of the soundings taken over peat is the necessity for a thin lower resistivity unit above the main unit. It is tentatively suggested that this represents a more highly humified layer within the zone of water table fluctuation, the increased humification lowering the resistivity.

3.2.3 Discussion & Conclusions.

The Offset Wenner method offers many practical and theoretical advantages over other geo-electrical techniques. In spite of this initial curve matching methods don't provide accurate values for depth or formational resistivity, sounding curves being complicated by the phenomena of equivalence and suppression. Calibration based on borehole data provides more accurate and consistent solutions; however this relies on correct interpretation of the different resistivity layers.

3.3 DIPOLE-DIPOLE SECTIONING.

3.3.1 The dipole-dipole method provides a means of producing geophysical 'pseudo-sections' along a transect by means of geo-electrical techniques.

3.3.2 Theory : The electrode arrangement as outlined in fig.4.2 is identical to that of the ß Wenner elecrode array differing only in that the current-voltage spacing is increased in multiples of a . The apparent resistivity is calculated as follows:

$$p_a = \pi\, n\, (n+1)\, (n+2)\, a\, R$$

where

n is the multiple of a separating the nearest current and potential electrodes,

and

R is the resistance read from the instrumentation.

All other symbols have their existing meanings.

The results are plotted as shown on fig.3.2 , these values being then contoured to produce the resulting pseudo-section.

3.3.3 Methodology: The technique employed an SAS 300 Terrameter and 4 coils of single core cable, the current coils being moved by increments of a after each reading up to a maximum value of n = 6 before voltage electrodes are moved by a single increment and the process repeated; the value of a in this case being 25m. Due to topographic and

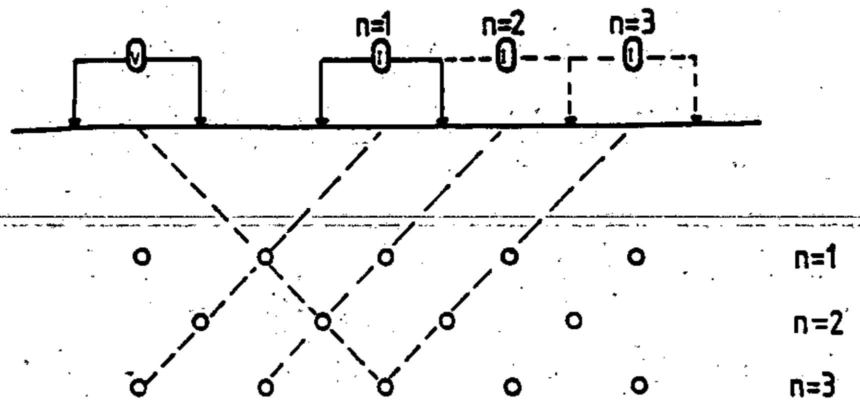


FIG. 3.2 DIPOLE-DIPOLE PSEUDO-SECTION CONSTRUCTION TECHNIQUE.

The three current-dipole positions correspond to three different multiples of the basic spacing. The measured values are plotted at the intersections of 45° slope lines from the centres of the current voltage dipoles.
(Milsom, 1989)

cultural effects the line of section was offset from that along which resistivity measurements were taken. Topographic effects were assumed negligible along the line of interest. Resulting data was plotted as shown in fig.3.3.

3.3.4 Results: Analysis of the resulting pseudo-section has been dealt with qualitatively (quantitative investigation generally proving complex and revealing little additional information in comparison to the Wenner approach).

The resulting resistivities bear slight resemblance to those derived from the previous method. However, a number of features are of interest in the section:

(a) Esker resistivities are generally lower than expected, possibly reflecting higher clay contents than previously imagined. Locally high surface resistivities are believed to reflect near surface boulders.

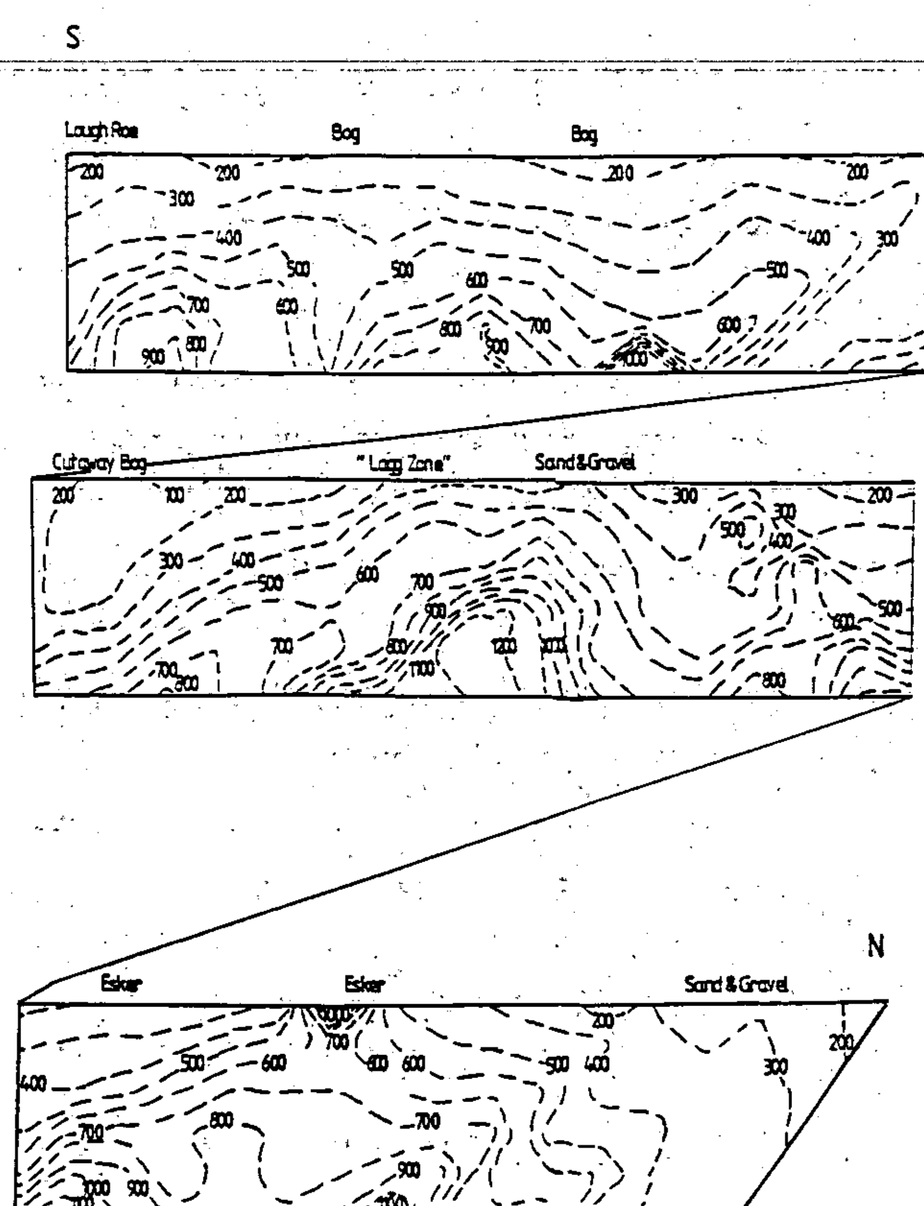
(b) A low resistivity unit at the bog margin reflects lacustrine clay dipping below the bog , this unit is not however detectable beyond this zone.

(c) Very high resistivities indicated at depth below the esker and occasionally below the bog are thought to reflect an irregular Bed-rock surface.

FIG. 3.3

Dipole–Dipole pseudosection from Laugh Roe to the eskers.

Scale: 100 metres   Contours in ohm-metres.



3.3.5 Conclusions: The nature of the dipole-dipole technique both in the field and in subsequent analysis make the method cumbersome and time consuming and reveals little useful data of any great significance. In addition to this the absence of any method of determining the quality of readings attaches a large degree of ambiguity to any qualitative and/or quantitative analysis.

3.4 Downhole geophysics.

3.4.1 Introduction : Casing in boreholes limits geophysical logs run to those not requiring direct lithological contact. A gamma log was run in CLBH-3 and proved particularly useful providing an unambiguous indicator of formational clay content, a parameter hard to determine from percussion drilling since fines are frequently lost on tipping the bailer.

3.4.2 Results & Conclusions : The resulting log is highly attenuated by casing yet despite this provides a good semi-quantitative contrast between lithologies. An upper clay rich unit is apparent before passing into a cleaner unit, which becomes more argillaceous with depth.

IV

HYDROLOGY

4.1 Climate

The climate of Clara bog and the surrounding area is typical of most of central Ireland being temperate and humid all year round. Rain gauges installed in the southern part of the reserve in October 1989 indicate a rainfall of approximately 850 mm/yr., the daily values showing good correlation with measurements taken in Mullingar 15km to the north and Birr 34km to the south-west.Other forms of precipitation form a negligible contribution to the above figure.

Assuming same degree of similarity is to be expected in other meteorological variables as rainfall then a potential evapotranspiration of roughly 450mm/yr. is to be expected (,although a marginally higher value may be more accurate due to the larger wind fetches in all directions in comparison to the weather stations). Monthly rainfall and evapotranspiration values for the year 1989/1990 are shown in table 4.1.

4.2 Surface water hydrology.

Surface drainage channels in the Clara area are limited to one natural stream to the south of the bog and a number of artificial drains on and adjacent to the reserve. Drainage is to the south to the Silver River which in turn drains into the River Brosna further north.

Table 4.1 Rainfall and P.E.(Penman) for weather stations at Birr and Mullingar for the period 1989/1990.

Date 1989	Mullingar Rainfall (mm)	Mullingar P.E.(Penman) (mm)	Birr Rainfall (mm)	Birr P.E.(Penman) (mm)
August	90.3	63	90	54
September	53.6	34	62.2	35
October	137.1	19	86.8	21
November	35.3	4	27.9	3
December	75.7	0	57.4	0
1990				
January	111.9	3	104.8	6
February	191.6	19	168.9	18
March	30.0	36.0	15.2	34
April	43.2	53	48.3	50
May	44.1	78	24.1	77
June	99.1	75	62.2	72
July	58(?)*	70(?)*	58(?)*	70(?)*
Total	989	454	805.8	440

* Data not available , values inferred from existing data by interpolation.

Marginal areas of the bog affected by the anthropogenic activities of have been observed to display sheet flow during periods of heavy rain. This is a result of burning, creating a low permeability algal film on the peat surface coupled with the effects of drainage ditches preventing effective regeneration of bog vegetation .

No surface hydrological data exists for the north-eastern study area. One main perennial drain exists at the junction of the peat and Lacustrine deposits .This is fed by a number of ephemeral channels containing water only during the winter period. No Discharge data were determinable for these features during the period of study, insufficient flow being present to merit the use of portable gauging methods such as flow gauges.

V

HYDROCHEMISTRY.

8.1 Introduction.

The hydrochemical characteristics of peat bogs are unusual and distinctive when compared to those of other hydrogeological environments with high organic contents and very low pH values being notable examples. This contrasts strongly with more typical inorganic deposits.

8.2 Methodology.

A brief field hydrochemical survey of the mire and surrounding margins was undertaken in an effort to distinguish broad hydrochemical groupings. Measurements of conductivity, pH and temperature were taken using WTW microprocessor temperature/conductivity and pH meters, calibration between 4 and 7 being used for the latter.

8.3 Results.

The results of the survey are shown in table 8.1. Locations are indicated on fig 5.1.

Two broad groupings are apparent from the survey

Type I: Low pH (4.01 - 4.80) and conductivity(70 - 120 uS/cm) in conjunction with high temperature(16-18°C).

Type II: High pH (5.8 - 7.0) ,high conductivity(200 - 800 uS/cm) and lower temperature (12 - 15°C)

Spatial variation of samples (fig 5.1) reflects a definite distribution pattern with Type I waters typical of

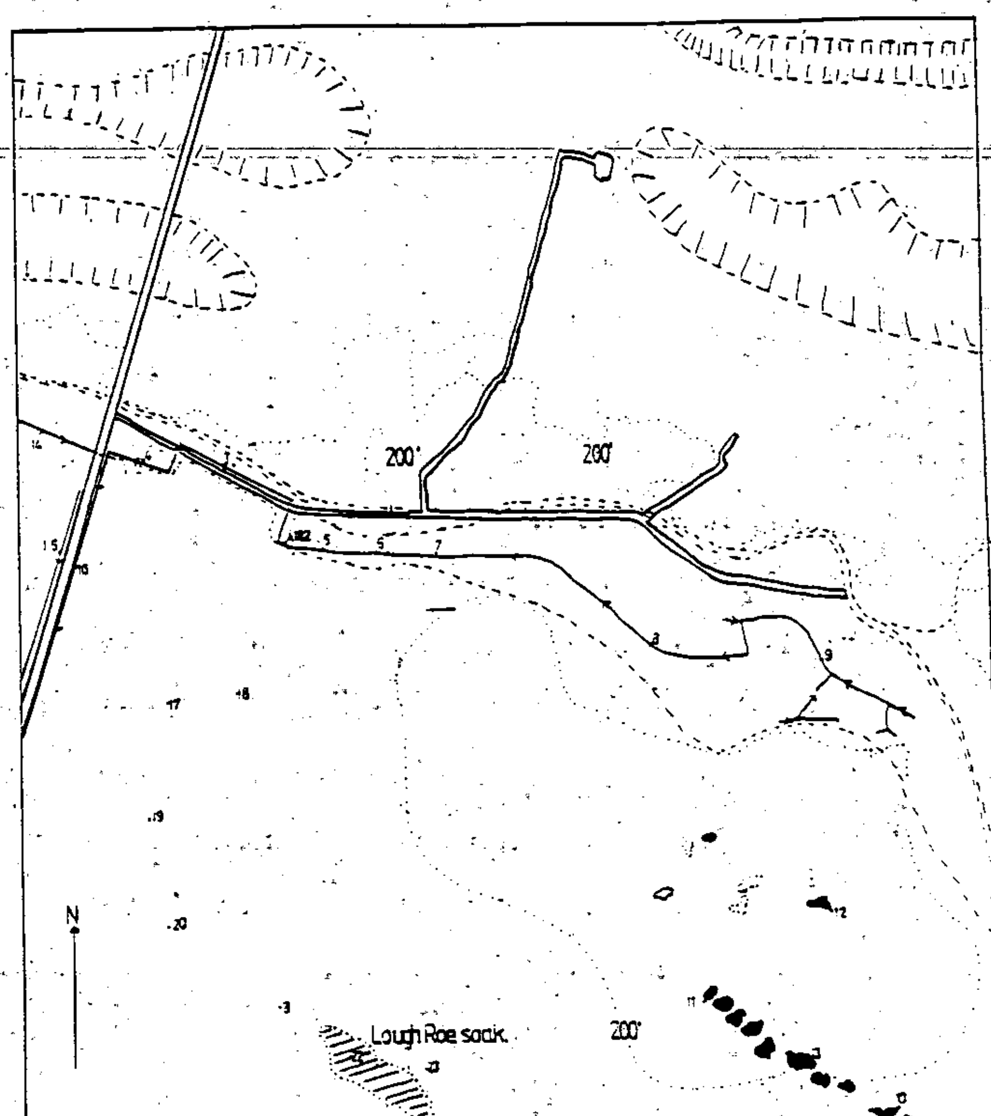


FIG. 5.1 A MAP OF FIELD HYDROCHEMICAL SAMPLING LOCALITIES.

Scale: 300 m · Sampling point.

Table 8.1 Hydrochemical data for Clara bog north-west.

Sample no.	Conductivity (uS/cm)	pH	Temperature (ºC)	Comment.
1	792	6.11	12.1	Gravel piezo. sample.
2	749	6.72	12.2	Limestone piezo sample.
3	639	6.68	14.3	Type II
4	901	6.80	14.3	Type II
5	516	---	---	-----
6	815	7.05	14.0	Type II
7	367	---	---	-----
8	302	5.02	13.4	Mixing(?)
9	204	5.07	12.7	Mixing(?)
10	79	4.03	19.9	Type I
11	93	4.01	18.0	Type I
12	115	---	---	---
13	99	---	---	---
14	445	5.02	16.5	Mixing(?)
15	249	---	---	----
16	610	6.43	14.8	Mixing(?)
17	123	----	---	-----
18	117	----	---	----
19	122	----	---	----
20	132	4.01	18.3	Type I
21	70	4.80	16.4	Type I
22	99	4.69	16.1	Type I
23	76	4.80	17.5	Type I

central parts of the reserve while Type II waters dominate those parts of the margin in contact with underlying formations.

8.4 Discussion and conclusions.

The low pH observed in samples from the bog is a consequence of 2 parameters

(a) Partial decomposition of organic matter producing various species of humic acid.

(b) The low concentrations of solid bases in peatland waters resulting in an inability in the system to buffer progressively higher acidity.

This latter point is confirmed by the low conductivities observed in type I waters, conductivity in this case being regarded as a gross indicator of total dissolved solids. These values are only marginally higher than average equivalent rainfall chemistry for the time of year. Water temperature at the time of measurement approaching ambient seasonal meteoric values .

Chemical profiling of the peat at Lough Roe and piezometer stations 2 and 3 (fig. 5.2) indicates the above phenomena to be primarily features of those upper layers which constitute the classical raised bog component of the ecological succession. Lower parts of the sequence representing fen stages have accordingly higher values in

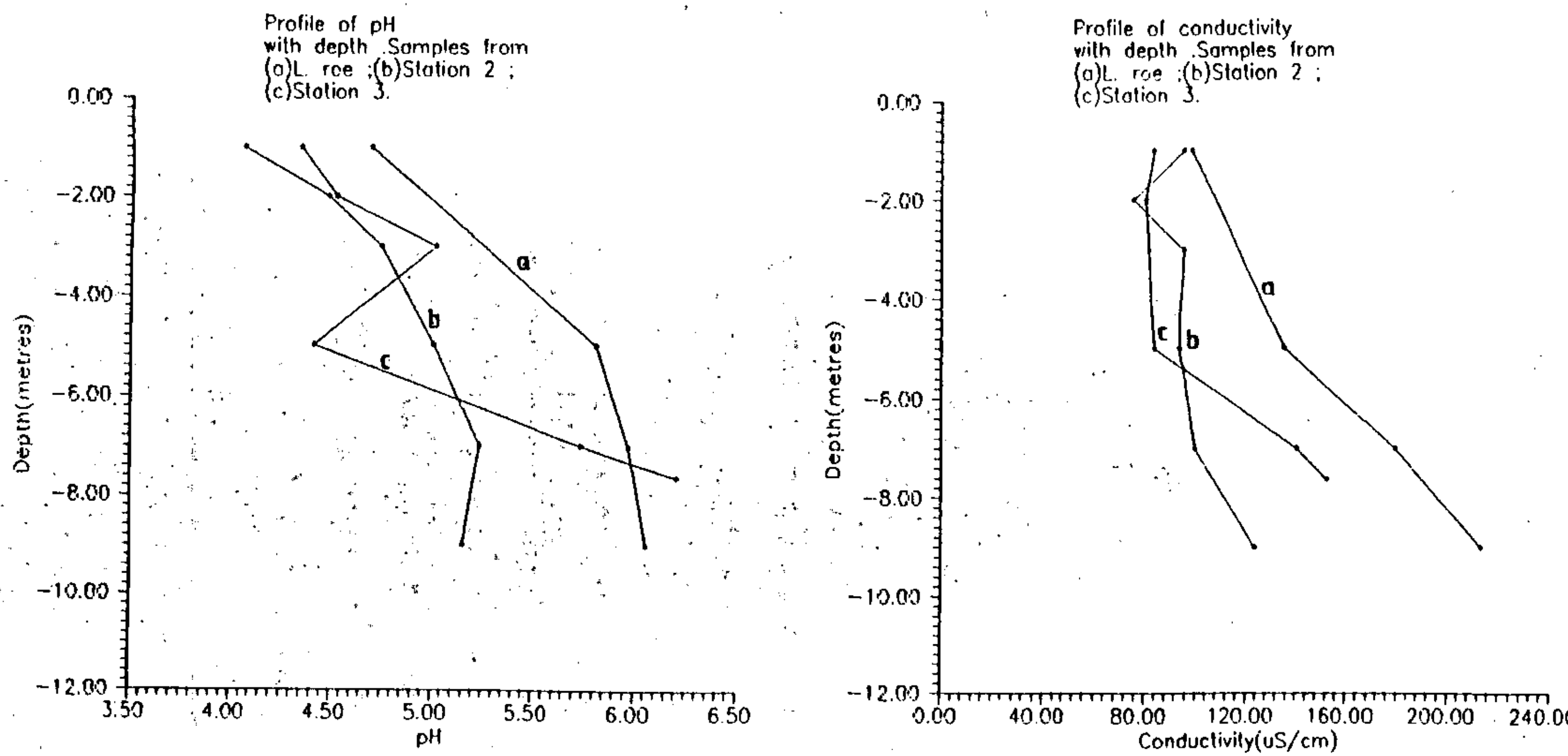


FIG. 5.2 CHEMICAL PROFILES OF CONDUCTIVITY AND pH WITH DEPTH FOR SAMPLED PIEZOMETER STATIONS.

accordance with the literature (based on typical data obtained from Shotyk 1986).

The chemistry of water type II contrasts strongly with that of the raised bog surface having markedly higher pH and conductivity in conjunction with lower temperature. An alternative origin is inferred based on these data. Comparison results derived from CLBH-2 after flushing reveals a close similarity between samples indicating Type II samples to be derived from an upwelling source in the underlying gravels; marginally lower conductivities reflecting some degree of dilution from the adjacent peat.

VI

HYDROGEOLOGY

6.1 Introduction & regional hydrogeology.

The following hydrogeological discussion has been subdivided for convenience into four separate subsections, each dealing with separate aspects of the study areas' hydrogeology.

No head data existed for the Clara bog region prior to the initiation of this overall project with no major abstractors are known to operate within the area. Aquifer definition was therefore lacking from the outset and was only determined during the course of this component of the study using the techniques outlined in the following sections.

Based on the data from the three boreholes drilled to date the regional flow pattern seems to follow a path broadly similar to that of the overlying surface drainage towards the Silver River in the south, although the exact direction is indeterminate. Initial topographical and terrain observations around the northern margin of the mire suggested some deviation from the overall tendency to occur within the peat.

SECTION 1: PEAT HYDROGEOLOGY

6.2 Peat hydrogeology

The hydrodynamic properties of peat makes it a complex and hydrogeologically interesting material. Investigation of these parameters often proves complex to analyse since deviation from some basic hydraulic principles may occur and has been proposed by numerous authors(e.g. Ingram et al, 1974).

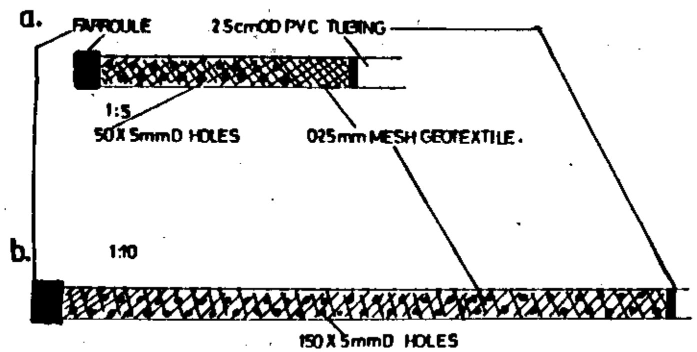
6.3 Methodology:

(a) Piezometer Installation: Determination of the hydrogeological regime of the peat required head data from various locations within and across the bog. To determine this a number of piezometer stations(nests) were installed along three approximately parallel transects across the area known as transects A, B and C in addition to those installed in Lough Roe (LR). Installation took place from the surface to the water table and to additional depths of 2m, 3m, 5m, 7m and 9m (where depth permitted). Reference to particular tubes has the following format :

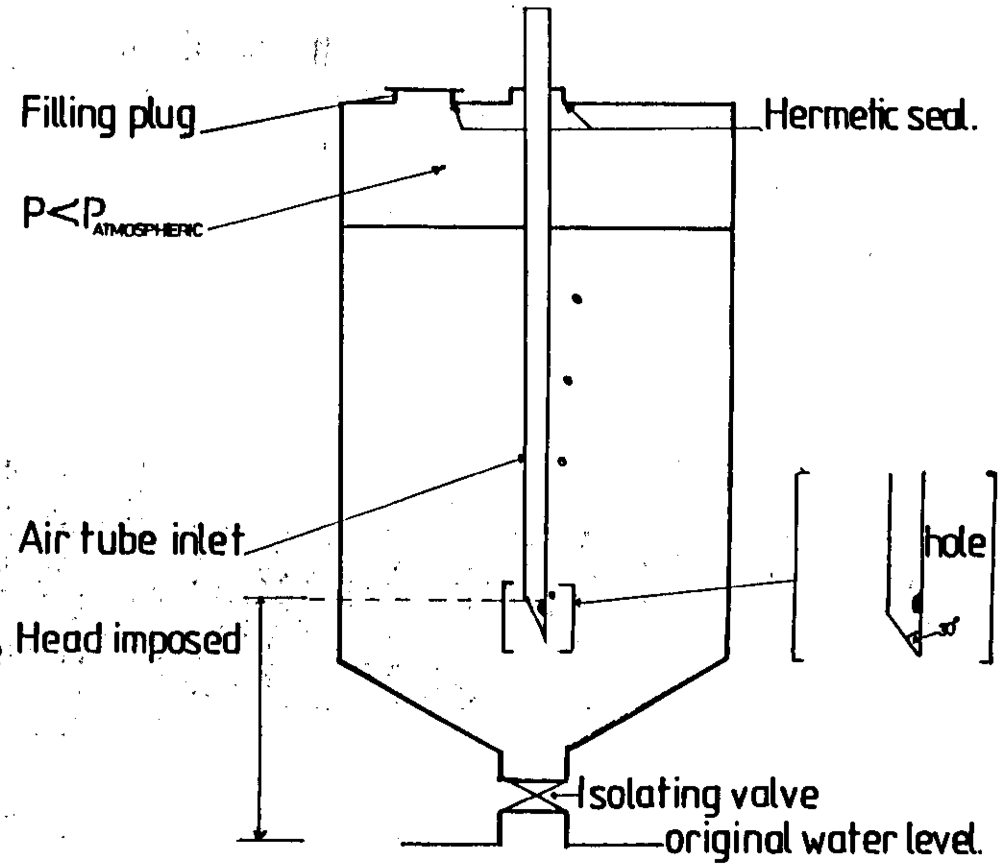
Transect-station number-piezometer depth.

The location of the various stations and transects are shown in fig(2.2).

The design and materials employed (6.1) are by practical and financial necessity simple and inexpensive. Pyrometers were installed either by pressing in by hand or, where substrate was firmer, by augering using a narrow



Diagrams illustrating materials & construction of (a)deep &(b) water table piezometers.



Schematic of constant head apparatus.

FIG. 6.1 DIAGRAMS ILLUSTRATING THE APPARATUS USED TO INVESTIGATE THE HYDRAULIC PROPERTIES OF THE PEAT.

diameter corer followed by pressing in of the slightly broader seepage tube; Installation by hammering was neither feasible or necessary. Blockage or smearing were not widespread possibly due to the more fibrous nature of peat contrasting with clay which tends to be more platey.

Following Installation, piezometers were filled with water from adjacent drains and left for one week to equilibrate. Tubes were then levelled to ordinance datum allowing heads relative to sea-level to be obtained. These values were measured at regular intervals throughout the course of the field work period.

(b) Piezometer tests: Investigation of the hydraulic conductivity of peat focussed essentially on piezometer testing. Tests of this form are preferred over more controlled laboratory methods since they represent a larger sample in addition to minimizing disturbance. Both rising and constant head tests were carried out. Piezometer test theory is discussed in section 6.4

Rising head tests involve the removal of a volume of water from the seepage tube using a portable suction apparatus followed by observation of recovering heads over the ensuing period. Approximately 75 cm^3 of water was removed during each test with recovery monitored over the following half hour period.

Constant head tests: Constant head testing involved the use of marriotte vessels (fig 6.1) to produce a fixed imposed head irrespective of resultant flow from the piezometer tip. The device is ideally suited to the task and in addition permits the variation of the imposed head thus allowing further investigation into peat hydraulics.

The relative merits of both systems of testing are outlined in table 6.1

Table 6.1 A tabulated comparison of the rising and constant head piezometer methods.

	Constant head	Rising head
Time	Time consuming.	Relatively quicker
Apparatus and	Bulky and cumbersome.	Portable.
Cost	Commercially expensive although cheap and simple to construct.	Inexpensive.
Water source	Required, volume depending on container size.	Not necessary.
Analysis*	Gibson (1963)	Hvorslev (1951)

* Neither method gives satisfactory results for Expandable media.

6.3 Piezometer test theory & Analysis:

(a) Rising head tests: Darcys' law states that the velocity of water through a medium is directly related to the hydraulic gradient across it by an empirical constant value known as the hydraulic conductivity:

$$V = - K\, dh/dl \qquad (1)$$

where V is the velocity through the medium,

dh/dl is the hydraulic gradient

and K is the hydraulic conductivity (permeability).

Equation (1) is the basis of groundwater flow equations and has been used by Hvorslev(1951) to derive subsequent formulae allowing the determination of hydraulic conductivity from variable head tests thus:

$$K = [A/S(t_2-t_1)]\ \ln(Y_2/Y_1) \qquad (2)$$

where A is the horizontal cross-sectional area of the seepage tube.

Y_1 & t_1 are the head and time measured at time 1,generally taken to be initial values.

Y_2 & t_2 are the head and time measured at time 2, values remaining variable.

S is the Piezometer shape factor derived by electrical analogue experiments, and employed here for a wellpoint in a uniform medium.

Hydraulic conductivity is therefore determined by plotting $\ln(Y_0/Y)$ against $t-t_0$.

A number of assumptions are attached to the initial derivation of which the most relevant are

(a) The tested medium is rigid

(b) Flow in the tube is steady state. The importance of these assumptions will be discussed in section 5.3.4.

(b) Constant head tests: Rycroft et al(1973) have shown constant head techniques to yield more consistent hydraulic conductivities than those obtained by variable head approaches. British Standards Institute document 5930 recommends calculation of Hydraulic conductivity after Gibson(1963) :

$$K = q_{infin} / (S \times Y_o) \qquad (3)$$

where q_{infin} is the steady state flow rate

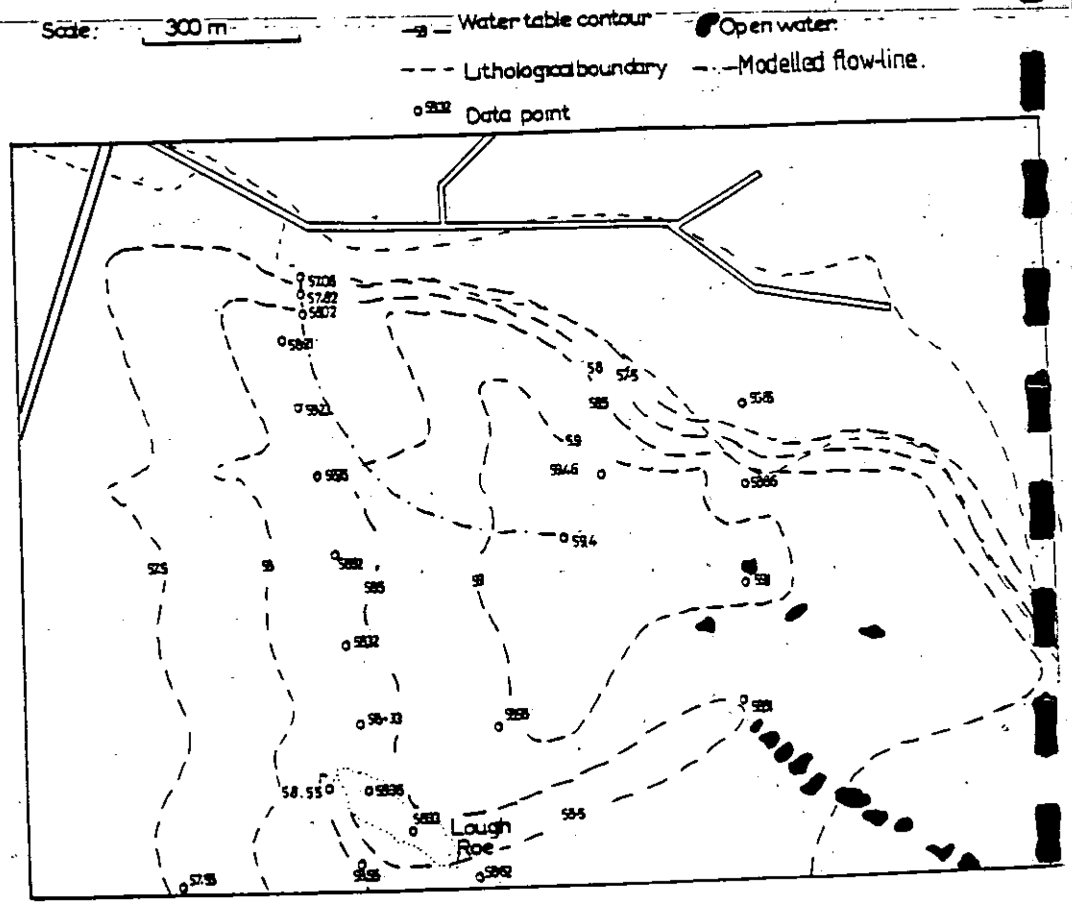
and Y_o is the imposed head.

The method was originally designed for use in flexible media under the assumptions of homogeneity and isotropy.

The value of K resulting from equation (3) is that operational under the regime of the imposed head. This value may not be the same as that operating under non-imposed conditions. Waine et al (1985), in support of the concept of non-Darcian flow in peat, presents a method of determining the value of hydraulic conductivity as a function of hydraulic gradient thus allowing calculation of operational permeabilities using a formula originally derived by Swartzendruber (1962). The method has been applied under controlled laboratory conditions an application to field based situations is neither feasible or relevant.

FIG. 6.2

EQUIPOTENTIAL MAP OF CLARA BOG. [8 AUGUST(1990)].



overall gradient would generally be in the opposite direction. Such a pattern may be produced however if the component of downwardly flowing water could be removed at an adequate rate to a higher permeability layer below: such a layer is therefore tentatively inferred.

The results of both sets of piezometer tests are summarized in fig(6.3) and displayed in greater detail in appendices(III & IV).

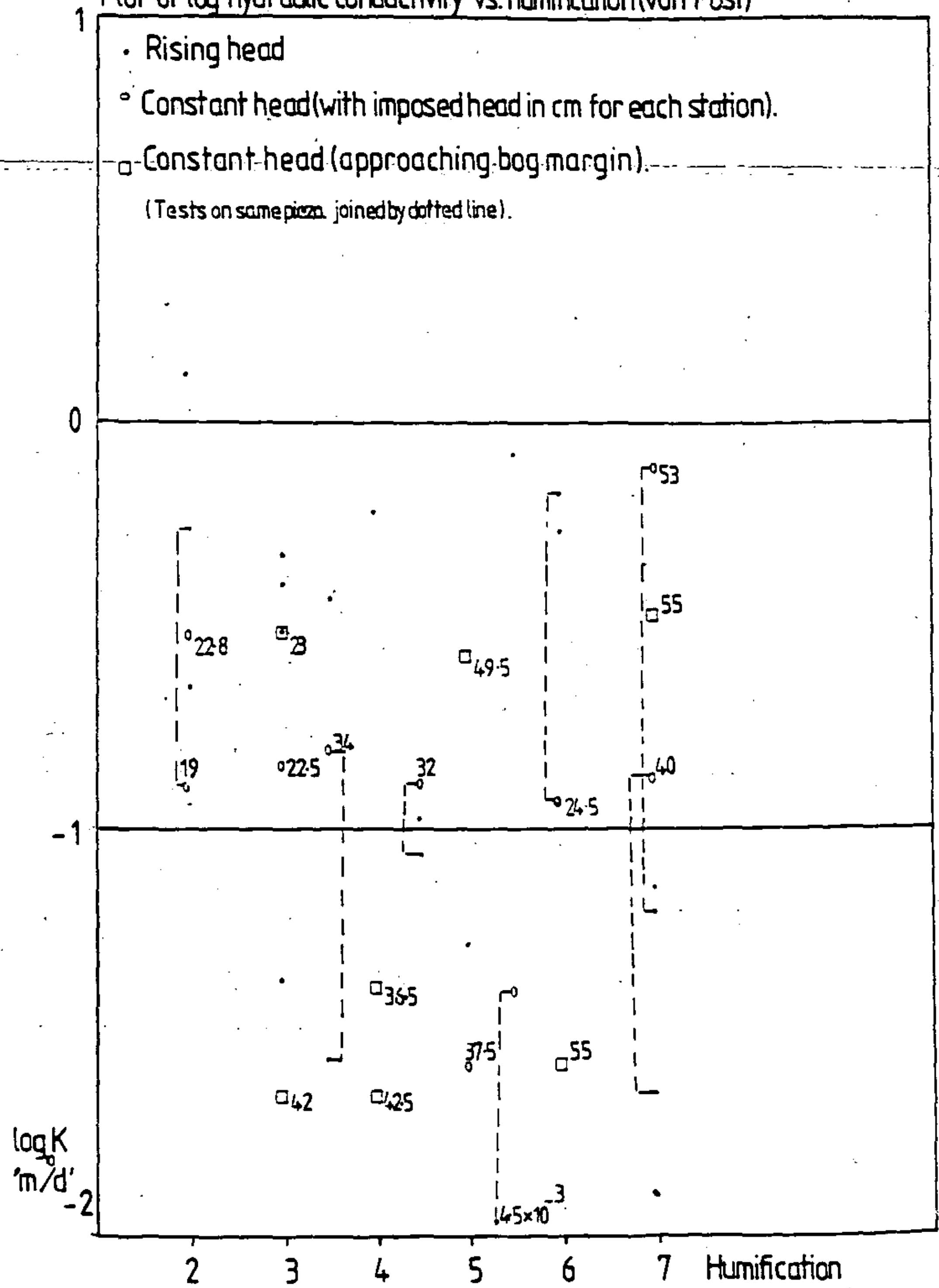
6.6 Discussion on the hydraulic conductivity of peat: The values of hydraulic conductivity observed in fig. 6.4 lie satisfactorily within the range of values quoted in the literature and reviewed by Chason and Siegal (1986). The results also agree with the observation by the same authors of no relationship exists between the permeability and humification. This however is in contradiction with work by other authors who claim such a relationship to be valid (Ingram, 1983). The possibility are therefore two fold:

(a) No relationship between conductivity and humification exists.

(b) The permeability/humification relationship may be valid but the methods and formulae used to determine hydraulic conductivity are incorrectly applied.

FIG. 6.4

Plot of log hydraulic conductivity vs. humification (Von Post)



The following discussion will focus primarily on this latter point.

The hydraulic conductivity of peat is an extensively reviewed and disputed subject. The dispute has arisen based on work initiated by Ingram et al (1974) and reviewed more thoroughly by Rycroft et al(1975).

Ingram noted that flow into or out of a seepage tube installed in humified peat varies in a non-linear manner with the artificial hydraulic gradient created. This is explained as a result of variation in the hydraulic conductivity of the medium, a constant value according to Darcy's law. Non-Darcian flow was therefore deduced. The same authors noted that tests in 'recharge' mode, i.e. adding water to the system, produced higher permeabilities than corresponding experiments in depletion mode.

The results of this work were explained conceptually as a consequence of changes in the effective porosity the medium. The porosity of peat frequently exceeds 90% of which less than 10% is effective porosity. The remaining portion is held within the lithology's structure by the capillary forces between partially decayed plant fibres. Variation in the imposed head is hypothesised to produce either dilation or contraction of the pore geometry depending on whether the operational head is increased or reduced. This phenomenon in turn causes an increase or decrease in hydraulic conductivity and thus explains non-Darcian behaviour.

In contrast to the above hypothesis Hemmond and Goldman(1985) reject the notion of non-Darcian flow claiming groundwater flow through peat does obey Darcy's law and the results of Ingram et al to be a consequence of inappropriate selection of piezometer test formulae. Instead they suggest that these results to be a consequence of variations in the effective stress applied during the course of the tests which would not normally be operational under undisturbed conditions. In the latter case hydraulic conductivity is effectively constant. Examination of rising head tests data are proposed to be as a consequence of reduction in water pressure resulting in greater total stress application to the matrix of the surrounding medium. This in turn results in a compression of the medium and a transient change in water content is produced during the initial stages of the test releasing additional water otherwise held by retentive forces. Rapid reductions in apparent permeability can therefore be explained as the restoration of previous undisturbed conditions.

Hemmond explains the non-linear behaviour of peat under increased hydraulic gradient in a similar manner claiming it to be due to the expansion of horizontal flow paths under increased water pressure and the associated decrease in effective stress on the matrix. Exponential behaviour observed at higher heads is a consequence of the changing of effective stress from a positive to a negative value yielding strongly non-linear behaviour.

Field data during the course of this project are in agreement with initial observations of Ingram et al with hydraulic conductivities apparently larger with as imposed head . However in contrast to the same authors conceptual hypothesis piezometer tests carried out in depletion mode do not yield consistently lower permeabilities than those obtained in recharge mode. When the values of constant imposed head are considered however it can be seen that the tests with lower values, typically less than 30cm, yield lower hydraulic conductivities than their rising head equivalents.

It would therefore appear that the data agree more with Hemmonds' Darcian hypothesis than the non-Darcian case proposed by Ingram et al with the former theory effectively explaining the observed behaviour in terms of effective stress. It is suggested that imposed heads below 30cm are unable to produce a vertical effective stress offset equal in magnitude (, but opposite in value,) to that produced by the corresponding rising head test. Higher imposed heads can offset this pressure change and in doing so produce a greater apparent permeability. It is therefore reasonable to agree with Hemond and Goldman and assume that groundwater flow through the peat in Clara Bog is essentially Darcian but through an expandable medium. This assumption is however tenuous since the approach used in obtaining the original permeability results is not strictly correct.

The behaviour of peat inferred in both Hypotheses discussed (,Darcian and non-Darcian,) imply that Hvorslev methods of analysing rising head test data in such a medium will produce inaccurate results. This is due deviations from the assumptions quoted in section 6.4.

Firstly, the medium through which water is flowing is clearly not rigid as is observed when the head applied is changed from one value to another resulting in variable responses not directly attributable to changes in hydraulic gradient alone i.e. recovery is initially more rapid in rising head cases, and outflow greater in constant head cases as the artificial head deviates more from static water level.

Secondly, the flow regime proposed by the Darcian hypothesis is clearly non-steady state from the outset; this phenomenon results in an over-estimation of the Hydraulic conductivity.

The behaviour of peat in view of the above features therefore implies that rising head methods are an inappropriate method for determination of peat permeability.

Inaccurate values of permeability are also obtained by constant head methods for the reason quoted in section 6.4 ,yet despite this, later steady state data does provide a reasonable approach for obtaining comparative hydraulic conductivities under the same imposed head. It must be noted however that no accurate field based method exists for the determination of in situ peat hydraulic conductivity.It therefore appears that constant head methods have the greater scope for accurate data acquisition with the best approximations of undisturbed permeability obtained at low imposed heads than variable head methods.

It must also be realized however, that various other parameters beside those discussed will influence data collected in the field. The most notable of these is the change in conditions adjacent to the piezometer caused by the weight of the observer which would, according to Hemmond change the total vertical stress.

6.7 Conclusions:

(a) The equipotential map of the study area indicates radial flow from a central recharge mound to be occurring with water draining toward the bog margins and the road. The regime to the south appears to be complicated by the soak system.

(b) Hydrograph analysis of representative central and near-marginal areas indicates most flow to be occurring in the upper layers. Downward head gradients are operational at both localities, the magnitude of which are greater at the near marginal piezometer station. A high permeability layer at depth is inferred in the latter case.

(c) Permeabilities obtained from piezometer tests indicate no relationship to exist between hydraulic conductivity and humification. This may actually be the case yet the inaccurate methods of piezometer test analysis employed have an undoubted additional influence. Darcian flow within the peat is tentatively proposed based on the apparent permeability results from various head differences created during testing. The conclusion must however be treated with caution because of the above-mentioned analytical complications.

Constant head methods offer the best potential method of obtaining comparative permeabilities. In addition to this the same method offers an approximate technique of acquiring undisturbed hydraulic conductivities under low imposed heads. The results of both techniques may be infleuenced by the weight of the observer on the test site.

6.8 Recommendations.

The following activities are recommended should additional work on this part of the bog be carried out.

(a) Additional piezometers should be installed in the area to allowing greater insight into head variation across of this part of the bog. Installation should focus particularly on the south where anomalous behaviour appears to be occurring.

(b) Monitoring of heads in all piezometers should be continued thus allowing a more accurate understanding of the bog's groundwater regime

(c) The Hvorslev variable head methods of analysis provides little useful information leading to an accurate value for peat permeability. Subsequent attempts to obtain such a result should focus on more accurate constant head techniques and associated steady state data. Heads imposed on the medium should be minimized. It is however realized that in view of the limitation of the minimum constant head applied by the marriotte vessel to ground level in conjunction with the downward head gradient operating over most of the bog it may be difficult to apply reasonable values. This may be partially overcome by testing during periods of higher groundwater head, i.e. during winter time.

SECTION 2: PUMP TEST ANALYSES..

6.9 Introduction.

The hydraulic conductivity/transmissivity of the pre-peat formations requires determination in order to determine possible relationships between the peat and adjacent lithologies. A number of pump tests were carried out on boreholes CLBH-2 and CLBH-3 to ascertain these parameters over a larger scale of interest equivalent than piezometer methods. The complex nature of the aquifer greatly complicates the idealized assumptions of analytical solutions.

6.10 Methodology.

A surface belt driven variable discharge diesel pump was used in all tests. 2" plastic hosing was connected to the intake an outflow couplings,the latter being extended to the margins of the lacustrine clay when pumping the unconfined esker gravels thus minimizing the possibility of recirculation. Groundwater was discharged into an adjacent drain during tests on CLBH-2 with the base being believed impermeable at the time but subsequently realized not to be. All discharges were measured intermittently by recording the time taken to fill a 5 gallon drum.

Despite the availability of gears little variation in pumping rate was apparent from preliminary tests completed on CLBH-3 and consequently discharge took place at a rate slightly below the maximum available . Time constraints resulted in no such investigations being carried out on either piezometer at CLBH-2. As a corollary to this no step tests were carried out and well losses thus remain an unknown parameter.

Monitoring of the piezometers at CLBH-2 while pumping CLBH-3 provided little response in the tests early stages and subsequent data acquisition focussed primarily on the pumping borehole.

No rainfall was recorded for the duration of the tests.

6.11 Analysis.

Analysis of data proved ambiguous due to the absence of information on the degree of turbulence in the system. In an attempt to determine the presence or absence of this component a Reynolds number was calculated using

$$R_e = (v \times D) / \Gamma$$

where R_e is the Reynolds number ,

v is the velocity of water in the well ,

D is the well diameter ,

Γ is the kinematic viscosity of water,

and where laminar $\leq 1500 \leq$ turbulent

Unfortunately no direct correlation between this number and the parameter C from Jacob's original step test analysis are known to exist and consequently well losses remain an unknown value beyond our knowledge of their existence. Despite this a number of analysis were undertaken bearing this in mind.

6.11.1 Double logarithmic plots: Log-log plots had various degrees of correspondence to model type curves. Pumped wells provided little useful information with valuable early data being absent due to well losses. Analyses for the CLBH-2 piezometers were carried out using Waltons leaky aquifer method despite the presence of pre-existing vertical head gradients at that locality.

6.11.2 Jacob plots: Straight line non-steady state pumping plots for were produced for all wells where data was available . The application of the method to the unconfined borehole is not strictly correct however some indication of T may be obtain by concentrating on earlier data where the effects of specific yield won't be as significant (although initial data must be largely ignored to satisfy the pre-existing Jacob approximations).

6.11.3 Theis recovery : The recovery method has the advantage over straight-line pumping methods of having strongly reduced well loss parameters particularly if less emphasis is placed on earlier data.The method therefore provides a more accurate means of transmissivity determination for single pumping boreholes .

6.11.4 Steady state methods: Simple radial flow equations were applied to data acquired towards the end of the test on CLBH-3 from the pumping well and gravel piezometer at CLBH-2.The steady-state condition was approximated based on the very slow rate of change of drawdown towards the end of the test. The transitional confined/unconfined nature of the aquifer complicates the situation greatly .In an attempt to asses the influence of this factor both conditions were analysed

(a) Steady state confined:

$$T = Q \ln(r_1/r_w) / 2 \pi (s_w - s_1)$$

(b) Steady state unconfined:

$$K = Q \ln(r_1/r_w) / \pi (2H - s_w - s_1).(s_w - s_1)$$

where Q = Discharge (m^3 d^{-1})

T = transmissivity (m^2 d^{-1})

K = Hydraulic conductivity (m d^{-1})

r_w , r_1 = Well radius and distance to piezometer (m)

s_w , s_1 = Drawdowns in pumping well and piezometer (m)

6.12 Results :

The results of the various representative analyses are shown in table 6.2 below, the source of each analysis indicated in parenthesis. The data from which the results are derived are displayed in appendix 6 in conjunction with the initial data .

	Esker gravel	Gravel (CLBH-2)	Clayey gravel (CLBH-2)	Limestone (CLBH-2)
Reynolds number.	10151	15363	not calculatable.	2193
T (m^2/day) (log-log) (Walton)	not calcula -table.	16.1 (Limestone pumping)	7.35 (Gravel pumping)	6.8 (Gravel pumping)
T (m^2/day) (Jacob)	1542.66 (Esker pumping)	20.336 (Gravel pumping)	11.2 (Gravel pumping)	31.376 (Gravel pumping)
		48.62 (Limestone pumping)	31.11 (Limestone pumping)	not calculata-ble.
T (m^2/day) (Theis recovery)	1136.7 (Gravel pumped)	28.899 (Gravel pumped)	18.3 (Esker pumped)	42.23 (Gravel pumped)

Esker gravels.	80% Efficient	100% Efficient
K (m/day) (Steady state)	242.31 (Confined)	181.226 (Confined)
	244.86 (Unconfined)	183.49 (Unconfined)

6.13.1 Discussion : The resulting values of T and K are variable although the various techniques employed all yield values similar to one another to within half an order of magnitude. Value of Transmissivity obtained in testing CLBH-2 are, in view of the hydraulic connection observed, overestimated. They do however provide a relative indication of permeability and are discussed thus.

6.13.2 Log-log :The lowest values derived for T in those holes analysable were from log-log methods i.e Waltons type curve method for leaky aquifers; this method employs all available data and consequently would be expected to give a more accurate result than the alternative approaches. Preliminary storage co-efficients yield totally erroneous results, reflecting that the value of effective well radius equivalent to that of the gravel pack is insufficiently small by at least 2 orders of magnitude.

6.13.3 Jacob: Log-linear plots for pumping data display variable amounts of scatter although those lines giving a good fit, namely at CLBH-2, appear to reflect a recharge source in their later data; this is most probably as a result of the pre-existing gradients prevalent at that location ,although some recharge may have been induced from the adjacent drain by penetrating through to the underlying clayey gravel.

Plots obtained from tests completed on the Limestone confirm it's slightly fissured nature. Even at low pumping rates periodically large drawdowns result in virtual well dewatering, believed to be a consequence of turbulence extending back into the adjacent fractures and thus preventing effective borehole/aquifer connection.

6.13.4 Theis recovery: Recovery data mirrors pumping data for tests carried out on CLBH-2 with a steep initial slope flattening off with time, the latter part of the data being used to obtain T values since it is believed to represent the prevailing conditions more effectively. Again, poor data correlation in some cases has made the corresponding calculated values ambiguous .

Results of data obtained from CLBH-3 indicate a lower transmissivity in comparison to the pumping analysis despite the effects of well losses in the latter case. This has been explained by Rushton(1978) as due to the domination of recovery data in abstraction boreholes by both aquifer storage and transmissivity. In contrast the abstraction phase is more dominated by the transmissivity close to the borehole and free water within it; the former therefore yields a lower value due to storativity and possible specific yield effects, neither of which are unfortunately determinable using standard pump test solutions in this case.

6.13.5 Steady state analysis: Results derived from the simple radial flow equations are very similar for confined and unconfined situations. The resulting values are under-estimations of permeability due to the omission of well losses in the formula. The effect can be seen to be quite significant based on an assumed 80% efficiency. Despite this resulting transmissivities are not drastically lower than those calculated from corresponding straight line solutions implying that although permeabilities decrease toward the bog corresponding values in the vicinity of the esker are similar to those surrounding the borehole.

6.14 Conclusions.

The situation under which testing took place is complex because

(a) No well loss parameters were available due to the functional inflexibility of the pump.

(b) Vertical flows present at CLBH-2 are not accounted for in any of the standard analytical solutions.

(c) Lithological conditions were very heterogeneous thus creating problems in the determination of permeabilities from given transmissivity values.

(d) The aquifer condition is transitional between confined and unconfined states.

(e) Transmissivities obtained from the piezometer nest tests at CLBH-2 are integrated over their saturated depth and are therefore overestimated if summed together (the situation with respect to vertical hydraulic connection was thought not to exist at the time).

In general the resulting values obtained by the various methods are consistent to within half an order of magnitude. Conditions are best approximated at CLBH-2 by Walton's leaky analysis although the value of radius required to obtain a correct value of storage remains unknown, beyond the fact that values of piezometer or gravel pack radii are inadequate.

Conditions determined at CLBH-3 are also ambiguous though values derived in pumping, recovery and steady-state modes are more or less the same although apparently rather high.

6.15 Recommendations.

In order to obtain more reasonable results from the current data the following are recommended:

(a) Step tests should be carried out on all boreholes previously pumped, a more flexible pumping system being recommended for CLBH-3.

(b) Monitoring of simple well head hydrochemistry be undertaken on any future tests allowing detection of recharge effects.

(c) Radial flow modelling of the system be undertaken, the method being ideally suited to the more complex situation presented here; it is felt that pump test approximations deviate too much from their simple assumptions to provide accurate values of T,K and S.

SECTION 3: GRAIN SIZE ANALYSES

6.16 Introduction.

It is generally recognised that grain size is a fundamental independent variable in controlling the permeability of unconsolidated sediments. Throughout the course of drilling samples were taken from the bailer at regular intervals and subsequently analysed by dry sieve methods. Semi-empirical formulae were employed to obtain a preliminary estimate of the hydraulic conductivity of various lithological sub-units encountered.

6.17 Theory.

An initial general relationship between grain size and permeability was derived by Hazen(1892) which states

$$k = C\ d^2 \quad \text{(mdarcies)} \qquad (6.a)$$

where k is the intrinsic permeability of the medium,
d is either the pore throat diameter or a representative grain size diameter,
C is a dimensionless constant usually relating to parameters such as path tortuosity and sorting.

The equation can be modified to determine hydraulic conductivity K using

$$K = C_1\ d^2 \quad \text{(cm/sec)} \qquad (6.b)$$

where $0.41 \leq C_1 \leq 1.46$.

d is usually taken as D_{90}, or d_{10} as in this case

6.18 Analysis:

Hydraulic conductivities were initially determined using equation 6.b before resulting values were integrated over the saturated thickness to produce an overall value of transmissivity. Comparison was then made with pumping borehole data (assuming 80% efficiency) before subsequent recalibration based on this value.

6.19 Results and discussion:

Permeabilities obtained from the preliminary analysis are displayed in tables 6.3 & 6.4. Correspondence with data derived from pump testing is variable. Results from CLBH-2 indicate a difference of over two orders of magnitude between the two approaches. This discrepancy is a consequence of a non-representative clay fraction which was lost from the bailer during tipping.

Analysis of the more arenaceous esker deposits proved more successful with very close correspondence between pump test and lower range Hazen values. Recalibration produced a value of C_1 = 0.5583, a result well within the standard range. Shepherd (1989) suggested that the main source of error lies not with the C_1 parameter but rather with the power relationship, indicating that the value of d^2 will produce an over-estimate of permeability preferring the use of d^n where n lies between 1.65 and 1.85. Using a value of C_1 = 0.935 a bulked value of n = 1.858 was determined, a result just outside the suggested empirical range.

6.20 Conclusions: (a) Although basically empirical in approach, the above methods of grain size analysis are a useful method of approximate permeability determination providing initial data are accurate.

(b) The success of the method in the more arenaceous deposits is due largely to the similarity in uniformity co-efficients in the lithologies encountered.

(c) The use of the method can be extended to the assessment of the relative contributions of various horizons to the overall transmissivity value obtained from a pump test provided recovery is systematically representative.

(d) The method has proved inaccurate in CLBH-2 in determining both permeabilities or relative contributions from various horizons. This has been a consequence of unrepresentative non-systematic sample recovery in addition to the large variation observed in uniformity co-efficients.

Table 6.3 Permeability determinations of CLBH-3 based on Hazen analysis

Sample Depth (m)	Strat. range (m)	d_{10} (mm)	K(m/day) (C_1=0.41)	K(m/day) (C_1=1.46)	U_c (d_{60}/d_{10})
1.0-1.4	1.0-2.5	0.04	0.5668	2.183	31.25
3.75-4.5	2.5-5.25	0.07	1.736	6.181	16.86
6.75-7.5	5.25-8.0	0.02	0.1417	0.505	17.5
8.5-8.7	8.0-12.7	0.18	11.477	40.87	22.67
11.25-12.0	8.0-12.7	0.8	226.71	807.32	37.5
12.75-13.5	12.7-13.5	2.0	1416.96	5045.76	14.0

Summing minimum values over saturated depth T =1622.8 m^2/day
Summing maximum values over saturated depth T =5778.4 m^2/day

Average Transmissivity = 3205.77 m^2/day.

Table 6.4 Permeability determinations of CLBH-2 based on Hazen analysis

Sample Depth (m)	Strat. range (m)	d_{10} (mm)	K(m/day) (C_1=0.41)	K(m/day) (C_1=1.46)	U_c (d_{60}/d_{10})
1.83	1.1-4.4	0.6	127.52	454.12	12.0
4.27	1.1-4.4	1.6	906.85	3229.3	17.5
4.57	4.4-6.1	0.45	71.73	255.44	6.22
5.33	4.4-6.1	0.5	88.56	315.36	9.80
7.01	6.1-8.5	0.98	340.00	1211.50	14.3
7.31	6.1-8.5	1.0	354.24	1261.44	20.0
7.62	6.1-8.5	0.6	127.52	454.12	16.7
7.92	6.1-8.5	0.63	140.6	500.67	59.5

Summing minimum values over saturated depth T = 786 m^2/day
Summing maximum values over saturated depth T = 2612 m^2/day
Average Transmissivity = 1699 m^2/day.

SECTION 4: AQUIFER DEFINITION.

6.21.1 Introduction: The initial infeasibility of aquifer definition has largely been overcome through the programme of investigations outlined above. The hydrogeological nature of the various formations is described below.

6.21.2 Carboniferous Limestone: Irish Waulsortian Mudbank Limestone is a typically massive carbonate lithology having poorly developed joint sets.As a consequence of this the lithology usually forms a poor aquifer across the country The near-perfect core recovery from the 5m of Bed-rock cored at both CLBH-2 AND CLBH-3 indicate that this formation is typical of the above case having a low overall transmissivity for the thickness penetrated. Pump testing on CLBH-2 has confirmed this with fissure dewatering reflecting the inability of local high permeability zones to supply adequate quantities of water even at low discharges.

6.21.3 Esker Sands and Gravels: Preliminary grain size analysis of arenaceous deposits recovered in the course of drilling indicates this formation to be at least two orders of magnitude more transmissive than any other unit and may be safely viewed as the main aquifer in the area.

6.21.4 Till/Clayey gravel: Preliminary field examination of the clayey gravels showed the formation to be highly argillaceous and was therefore initially regarded as an aquitard. This has not proven to be the case however, with pump testing revealing reasonable transmissivities although lower permeabilities are suspected in the upper layers on grading into lacustrine clay.

6.21.5 Lacustrine clay: The permeability of this unit has not been investigated and therefore remains unknown. However, initial textural observations indicate locally pure compositions suggesting a very low permeability as typical of the formation.

6.21.6 Peat: The highest heads observed in the area were those in the peat giving preliminary indications of the units' low permeability. Subsequent piezometer tests have confirmed this but due to complications in the methods employed exact determination of hydraulic conductivity is not possible. The formations' clay substrate is thought to isolate it from the regional hydrogeolgical regime in this part of the mire.

VII

MODELLING

7.1 Introduction:

Groundwater modelling provides a useful approach to the determination of various hydrogeological parameters unobtainable by other methods on the correct scale of interest, in addition to revealing the effects of various components on the overall behaviour of a hydrogeological regime. Many of these parameters are indeterminate using standard field hydrogeological techniques.

The numerical modelling approach to groundwater investigations does however pose problems if the number of unknown inputs to the system is large. This can, without control, result in various alternative solutions for the one data set. However, the sensible use of numerical modelling in conjunction with the reasonable conceptual hypotheses can minimize the possibility of such a situation occurring. Bearing this in mind a brief groundwater modelling exercise was undertaken with the following objectives:

(a) To obtain a more detailed insight into the hydraulic behaviour of peat.

(b) To gain an indication of groundwater activity on a scale encompassing both organic and inorganic formations.

Owing to the lack of time-variant and storage data steady-state models could only be run for both cases.

7.2 Theory: The steady-state version of the basic groundwater flow equation is as follows:

$$\delta/\delta x(T_x\ \delta h/\delta x) + \delta/\delta y(T_y\ \delta h/\delta y) + q = 0 \qquad (1)$$

where $T_{x,y}$ is the aquifer transmissivity in the x and y directions,

$\delta h/\delta x$, $\delta h/\delta y$ are the hydraulic gradients in the x and y directions,

and q is recharge.

Both models simulated are sectional and the situation is therefore modified ,transmissivities becoming hydraulic conductivities for a unit width of aquifer and $\delta h/\delta y$ becoming $\delta h/\delta z$. Equation (1) is solved here by finite element numerical approximations.

Finite element methods involve the incorporation of a number of triangular elements into a mesh. The computer program used employs the Galerkin finite element approximation which assumes linear approximations between the nodes of each element. The resulting data is then placed in a matrix and equation (1) subsequently solved by complex mathematics.

7.3 Methodology

The computer program used 'AQUA' (Vatnaskil Consulting Engineers) is a 2 dimensional modelling package. The code has the following advantages over other groundwater modelling packages of:

(a) Being very user friendly thus avoiding excessive time spent becoming familiar lengthy code and filing systems.

(b) Graphical display allows immediate assessment of the modelled systems behaviour.

(c) The systems small memory requirement means that it is possible to run the package on a P.C. without hardware requirements.

The model does however have a number of shortfalls

(a) Like all finite element methods the package reproduces accurate heads but associated flows are frequently incorrect(Rushton & Redshaw, 1979). In this sense finite difference methods are far superior.

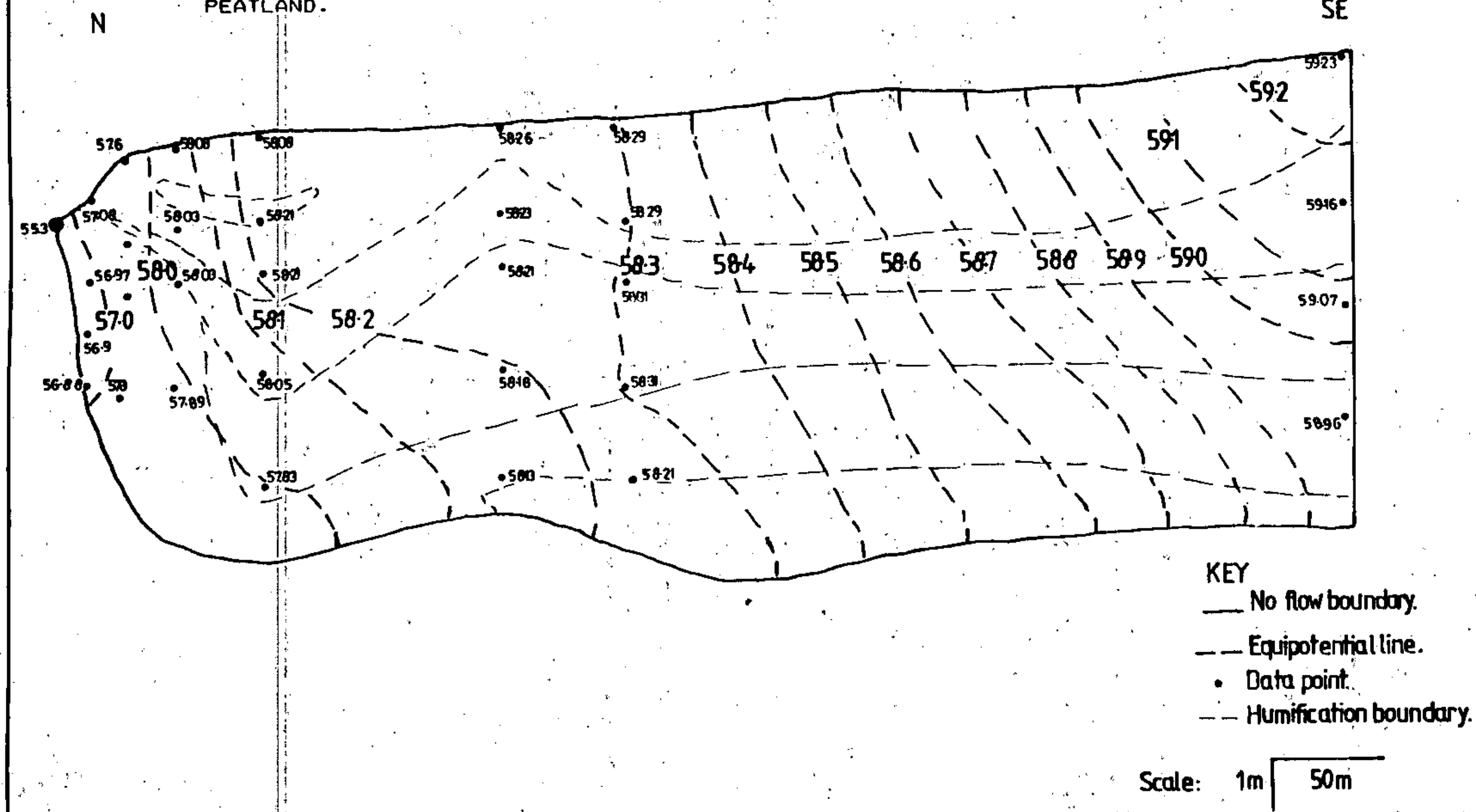
(b) The mathematics associated with finite element programs is complex and alterations of the computer code to reproduce more realistic simulations are difficult to achieve.

(c) The low power of P.C. systems mean that the model run time can be very long.(approx. 15 mins in the regional simulated case generated in this project).

<u>7.4</u> Hydrogeological modelling of peat.

<u>7.4.1</u> Model input: A sectional model of Clara bog was produced along the flow line indicated in fig. 6.2. The flow line extends from the central recharge mound to the clay substrated drain at the north margin. Extensive head data especially approaching the reserve boundary provide a good degree of control in calibration. The required head pattern is illustrated in fig. 7.1.

FIG. 7.1 FIELD DATA USED FOR MODEL CALIBRATION OF THE PEATLAND.



Flow traversing the recharge mound is not thought possible and this side of the mound has therefore been modelled as a no-flow boundary.Similar conditions were simulated for both the clay substrate, owing to the inferred low permeability of the unit, and the upper water table boundary, for mathematical convenience. The northern drain has been modelled as a constant head boundary with all flow discharging through this point.

The only input to the system is direct recharge the magnitude of which was initially determined using a Penman-Grindley soil moisture balance. The values of evapotranspiration and precipitation used are those illustrated in table 4.1. Runoff was taken as 10% of total precipitation and a root constant of 35mm assumed. The resulting values of recharge for Birr and Mullingar are 453 mm/yr and 362 mm/yr respectively. With regard to the current model these values are over estimations since little account has been taken of the low heads prevalent at this time of year due to the dominance of evapotranspiration. A recharge value for the system was therefore set below these values at 250 mm/yr.

Recharge was simulated within the model along the full length of the flow line to reflect the unconfined nature of the peat.

7.4.2 Calibration : Initial attempts to calibrate the model to within the 10 cm margin of error required regarded the peat as a homogeneous unit. This could not reproduce the required pattern satisfactorily. Subsequent simulations were attempted employing a layered permeability system in view of existing geological information. The model was then run using piezometer permeability data. Resulting heads were typically 1 metre below those observed.

Trials were then attemped using the humification/hydraulic conductivity relationship. Good correspondence was observed with the field data over much of the area although those results obtained approaching the margin were not satisfactory with vertical hydraulic gradients not adequately simulated. Marginal situations were therefore altered by decreasing the upper layer hydraulic conductivity thus simulating the compaction and reduction in permeability associated with drainage of peat (Hobbs, 1986). In conjunction with this a high permeability layer was inserted at depth as suggested in fig.(6.3). Correspondence was better but not satisfactory. Final calibration of the model was achieved by allowing the permeability of the upper layer to increase down hydraulic gradient (but keeping marginal conductivities low).

7.4.3 Sensitivity analysis: The results of a brief sensitivity analysis of the calibrated model are displayed in table 7.1. The model is seen to be most sensitive to recharge, constant head value and the permeabilities of marginal units. Permeabilities of the more distal units from the drain have less effect on the maximum head yet their alteration does change the overall flow pattern produced.

FIG. 7.2 INPUT USED TO SIMULATE THE REQUIRED HEAD PATTERN FOR THE MIRE MODEL.

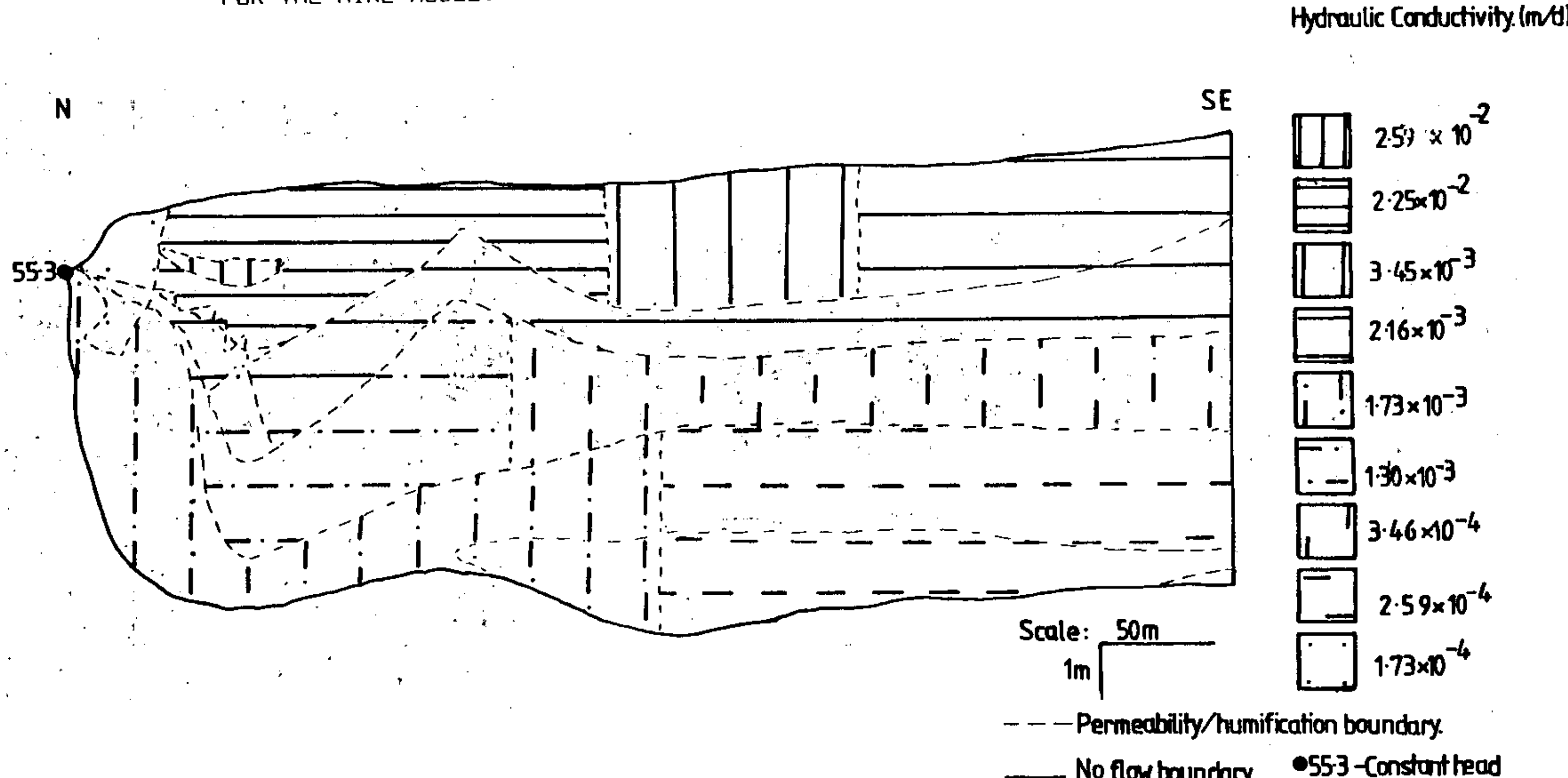
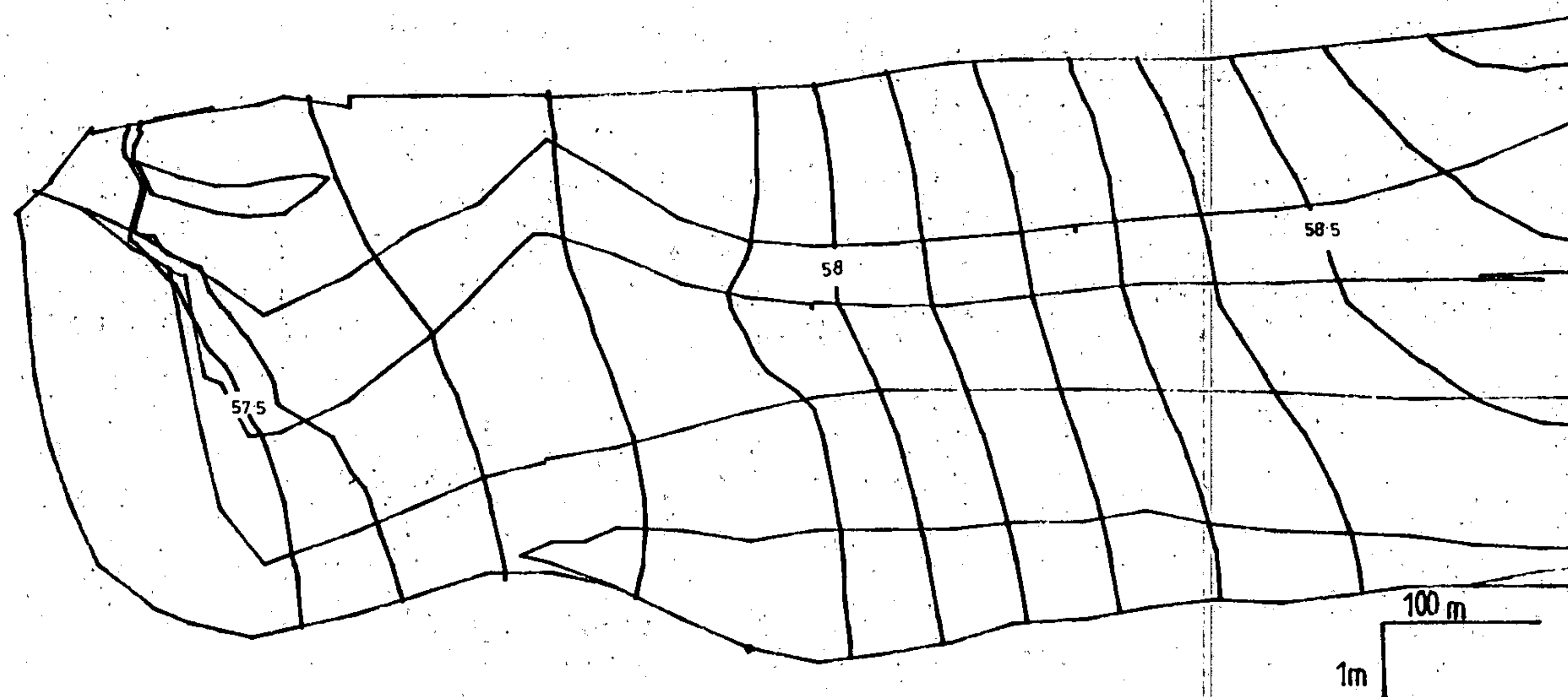


FIG. 7.3 Equipotential output of calibrated model of Clara Bog (NE).



Increasing both recharge and the head in the drain to simulate winter conditions produces a large increase in head above the present topographic surface. This may be partially resolved when it is remembered that the water level at the time of measurement was within low permeability catotelmic peats. A rise in the peat water table during the winter period would permit the higher more permeable acrotelm layer to become effective thus reducing heads to more realistic levels.

Table 8.1 Sensitivity analysis for Peatland Simulation.
Maximum heads for each simulation are shown.
Original maximum head: 59.23 m.

Component	Original value (m/sec)	20% increase	20% decrease
Upr. marginal peat permeabil -ity	$2x10^{-8}$	59.42 m	59.07 m
Lr. marginal peat permeabil -ity.	$1.5x10^{-8}$	59.67 m	58.9 m
Recharge	250 mm	60.01(300mm)	58.44(200mm)
Head in drain	55.3 m	59.53(55.6)	58.92(55.0)
Upper layer peat permeability (,intact Bog).	$2.0x10^{-8}$	59.33 m	59.14 m
Upper layer peat permeability (,bog margin)	$2.6x10^{-7}$	59.27 m	59.19 m
Second layer peat	$2.0x10^{-8}$	59.26 m	59.20 m
Third layer peat	$4.0x10^{-9}$	59.24 m	59.22 m
Lower layer peat (intact bog)	$2.3x10^{-8}$	59.24 m	59.21 m
Increase recharge and drain level.		60.31 m	-----

7.5 Modelling of organic and inorganic formations:

7.5.1 Model input: A brief regional model of both the organic and inorganic formations was attempted on completion of the peatland simulation. Expansion of the model required the boundary conditions to be altered. The situation is complicated by two parameters:

(a) The precise direction of regional flow is not known since exact head data is only available for CLBH-2 and CLBH-3. An approximate direction of flow is estimated based on additional winter head data from CLBH-1 further south before the hole was blocked. A southern regional gradient is tentatively suggested.

(b) The curve nature of the peat flow line departs significantly from the propsed regional gradient in its upper part approaching the recharge mound. Parallel flow lines can only therefore be achieved in that part of the region where the peat approaches the northern mire boundary.

The above complications have resulted in the following boundary conditions being applied to the model:

(i) The upper boundary is taken as the water table in both peat and inorganic units and is regarded as a no flow boundary.

(ii) Lateral Boundaries in the peat are as they were in the initial model. Those in the inorganic formations are constant head boundaries, introduced in an attempt to simulate the regional flow gradient. The northern head is known from CLBH-3 while that in the south has been estimate as described above. The same southern constant head is applied at the eastern peat boundary in an effort to resolve the deviation in flow directions by creating an orthogonal section across the regional gradient.

(iii) The lower boundary is tentatively taken as lying at depth within the limestone.

Permeabilities of the various inorganic formations were estimated using previous pump test data although that of the clay is unknown and has been preliminarily estimated as 0.1 mm/day. The extent of these units has previously been determined by borehole and geophysical data.

7.5.2 Calibration. Project time constraints have meant that only an approximate model calibration can be achieved. This involved reproducing the heads observed in CLBH-2 to within 10cm. Transmissivities used were those derived using steady-state and Walton leaky aquifer techniques. The resulting output had poor correspondence to reality when the horizon in which the pumped piezometer was placed was regarded as the only one contributing to discharge. This hypothesis is clearly incorrect in view of the good hydraulic connection observed between units and the resulting permeabilities are therefore over-estimations of the true situation.

A more realistic approach was then adopted in which the relative transmissivities were obtained and the maximum transmissivity redistributed in according proportion. The resulting simulation gave a reasonable fit to the required degree of accuracy. The resulting output is shown in fig 7.4.

7.5.3 Results: Qualitative sensitivity analysis based on the degree of deviation from the calibrated pattern have shown the model to be most sensitive to the following:

(a) The regional head gradient,

(b) Recharge,

and (c) The permeability of the clayey gravel. adjacent to the drain.

20% variations in the permeabilities of the inorganic formations produced little influence on the overall head pattern.

Despite its low permeability, flow through the clay is seen to reduce the maximum head observed in the peat by 50cm

FIG. 7.4 INPUT USED TO SIMULATE THE REQUIRED HEAD PATTERN FOR SECTION 7.4.2.

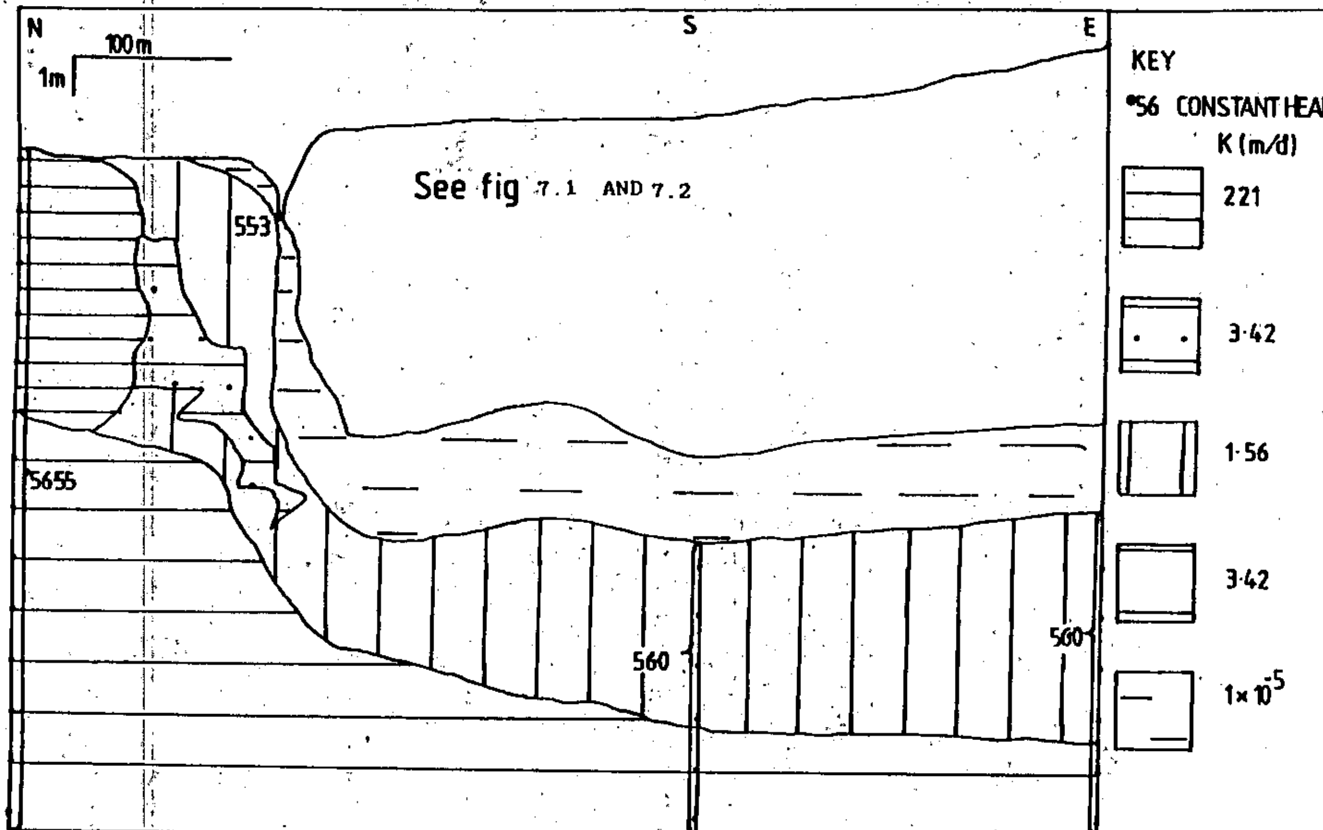
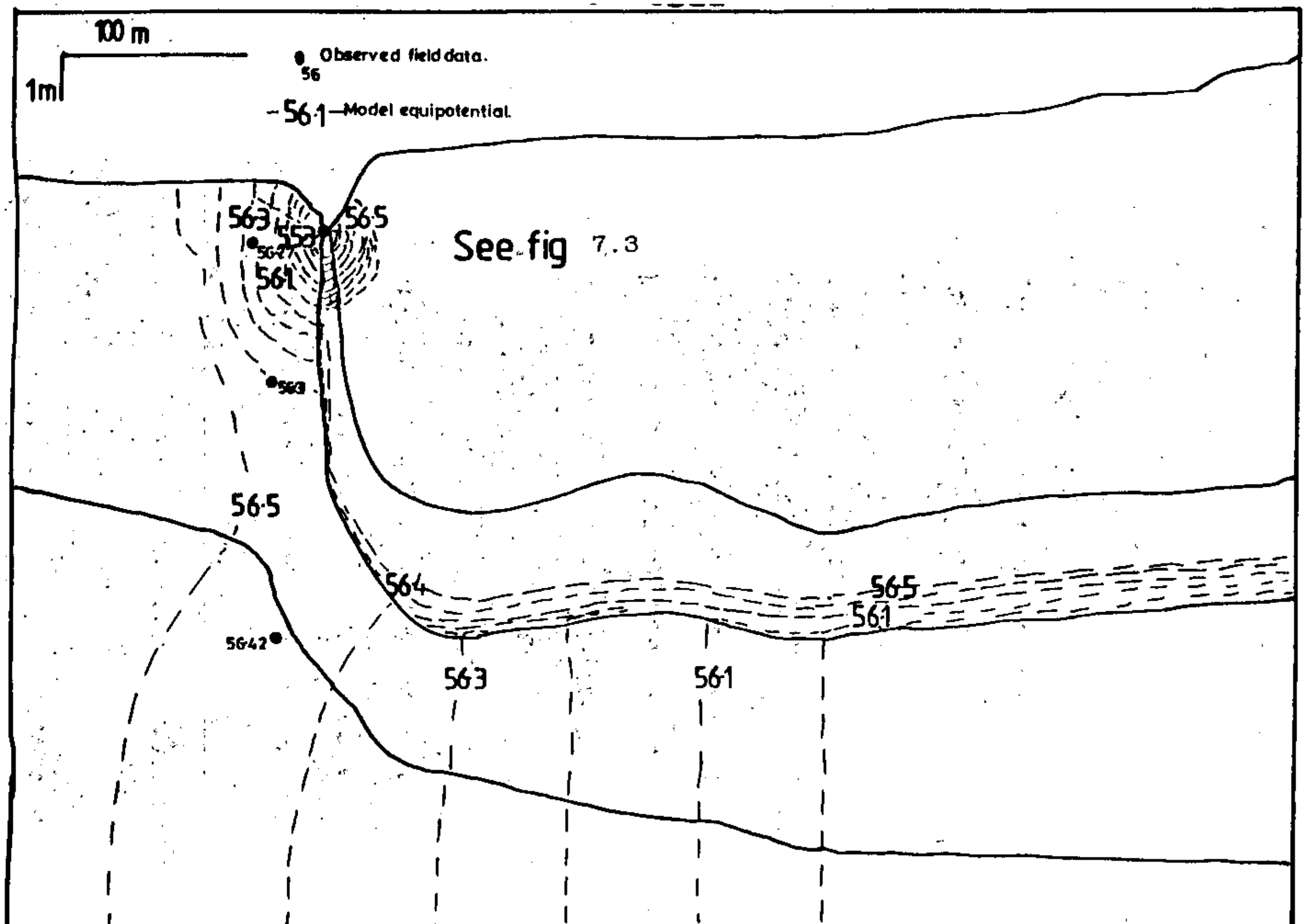


FIG. 7.5 OUTPUT FROM THE CALIBRATED MODEL OF THE BOG AND INORGANIC FORMATIONS.



in the calibrated state. This therefore implies that the permeabilities of the peat layers are actually lower than those used in section 7.4.

Flow from both inorganic and organic formations to the drain is perhaps the most striking feature of the model, its effect distorting the regional flow pattern by diverting water upward toward the outflow, effectively short circuiting the confining effect of the clay.

Removal of the drain (fig.7.6) was simulated by the removal of the constant head at that locality. A corresponding head build-up of 11m is notable in the peat. This unnatural head is a consequence of the permeability reduction associated with drainage and would not occur where intact lagg zone exists since permeability would have a substantially higher value.

7.5 Conclusions:

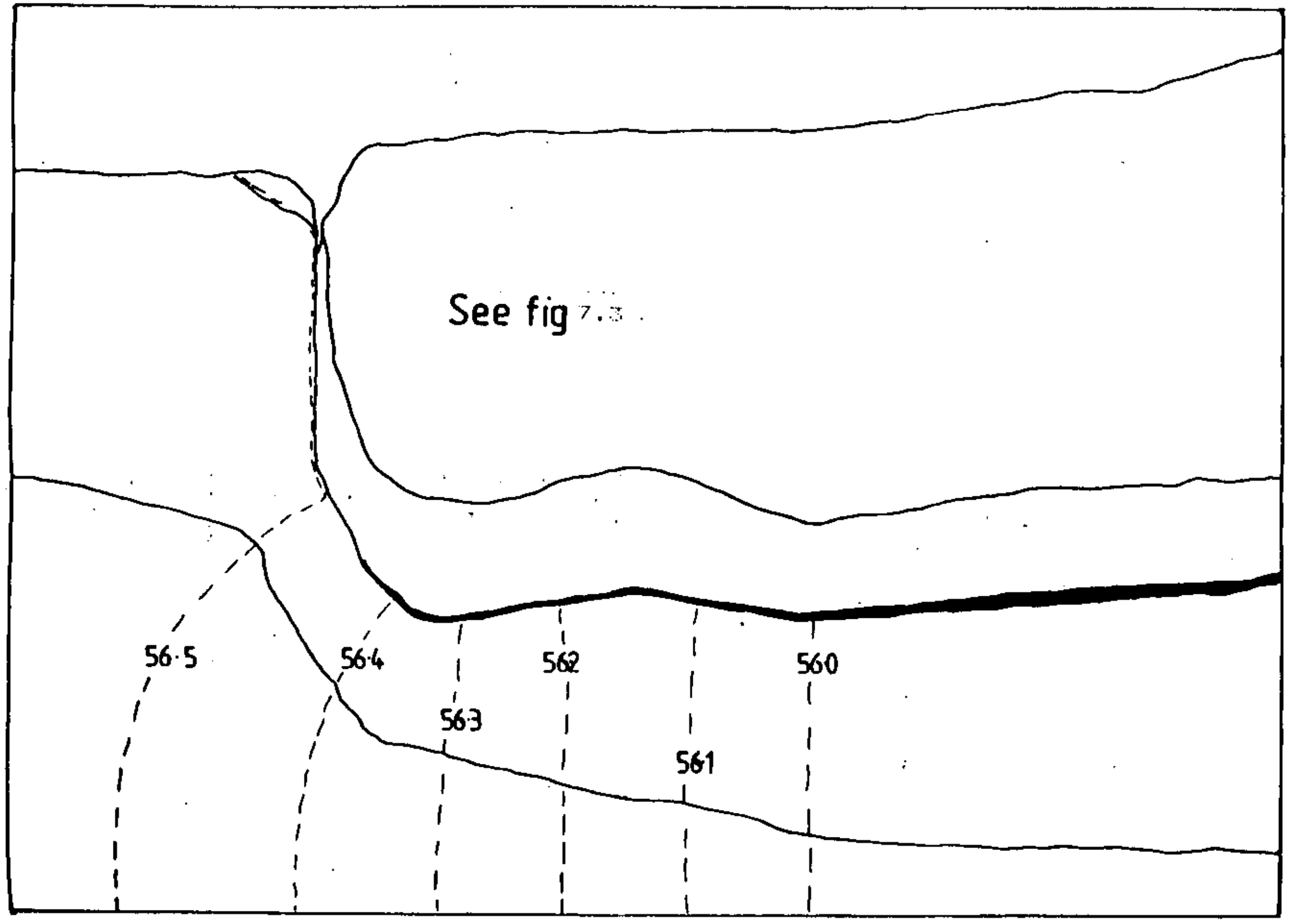
Application of groundwater modelling to the peatland and regional situations has illustrated the following points:

(1) The permeability of peat has been over-estimated by piezometer test methods.

(2) Heads observed in the field reflect a layered permeability system and show hydraulic conductivity decreasing with increasing depth and humification.

(3) The high permeability layer previously hypothesized to exist at depth is confirmed to exist, thus

FIG. 7.6 SIMULATED MODEL WITH MARGINAL DRAIN REMOVED.



indicating deviation from the proposed permeability/ humification relationship in areas affected by anthropogenic activity .

(4) The maximum heads observed on the bog are most strongly influenced by recharge and water level in the drain and, to a lesser extent, by marginal permeabilities.

(5) Simulations of winter conditions reproduced heads above the topographic surface of the bog but can be explained as a consequence of the omission of a high permeability upper acrotelm which lay above the water table at the time of measurement. Inclusion of unit data is imagined to reproduce more realistic results.

(6) Modelling of organic and inorganic formations on a larger scale proved difficult due mainly to the deviation of regional and peatland hydraulic gradients in addition to the unknown permeability of the lacustrine clay.

(7) The presence of the drain along the northern margin of the reserve distorts the regional flow pattern producing upwelling from the underlying Pre-Holocene deposits. confirming the original hydrochemistry-based hypothesis although flow through the Bed-rock still follows a regional trend.

(8) The low but finite permeability of the clay has reduced the maximum head in the overlying peat due to downward seepage of bog water into the underlying gravels.

(9) Simulations involving the removal of drain result in a more typical regional flow pattern although

heads in the overlying peat increase greatly. Such a situation does not occur in reality and is a consequence of low permeabilities developed in peat by the drainage process.

7.7 Recommendations.

The simulations above have been produced with much tenuous data, the values of which have been estimated either from literary sources or are based on scant regional information. In order to understand both regional and peatland groundwater flow more fully the following are recommended:

(a) Monitoring of all available heads in the area over a the forthcoming year.

(b) Additional boreholes should be drilled in the pre-peat deposits thus allowing more effective determination of regional flow gradients.

(c) An attempt should be made obtain the permeability of the Lacustrine clay which is an important controlling parameter in the operation of the system as a Whole.

(d) Attempts should be undertaken to determine storage parameters in all formations. This in conjunction with the time variant data which would be obtained from (a) would permit the development of a non steady-state model for the area.

VIII

THE ORIGIN OF THE CLARA BOG SOAK SYSTEM.

8.1 Introduction.

The final stage of the classical raised bog hydroseral succession is not observed in those parts of the Clara mire where soaks exist. The two best developed examples of these areas of the bog in which the vegetation is more typical of minerotrophic fen conditions, known as droggs in Scandinavian terminology, are found on either side of the road bisecting the reserve (, these parts of the bog being known as Clara East and Clara West respectively (fig. 2.1). They are thought by many authors to be the best remaining examples in Ireland (Bellamy, 1986). The origin of these features is enigmatic since they are often located near the highest part of the peat dome. A number of hypotheses have been presented to explain. These are

1. The spring mire hypothesis,
2. The surface drainage hypothesis,

and 3. The tension pool hypothesis.

8.2 Spring mire hypothesis.

Mires fed by groundwater, known as spring mires are not uncommon in wetland systems, examples being found at Pollardstown fen in Ireland (D.Daly, pers comm.) and Badley Moor fen in Britain (R.Andrews, 1989) .Such systems can often develop substantial hydraulic heads feeding nutrient rich ground water into the overlying mire. The high artesian head observed at CLBH-1 would appear to indicate that such a regime may be operational in the Clara soak systems. A number of facts make this system less plausible however:

(a) Levelling from CLBH-1 to Lough Roe on clara east (whose water table is v. slightly below the surface) showed a the lough to be 5.2m higher than the borehole locality. There is therefore a head difference of 3.4m operating against the upwelling water (, the artesian head in the borehole being 1.8m above ground level). This difference would easily offset any potential vertical flow from the underlying gravels.

(b) No anomalous hydrochemical parameters have been noted in either soak beyond a slightly higher pH above that of normal bog conditions at Lough Roe. This contrasts strongly with the situation observed in typical spring mire system where anomalously conductivities are observed at surface as in the case of Badley Moor fen. Profiling (fig. 5.2) has revealed marginally higher conductivities than those observed in the surrounding peat yet the values differ only by a factor of 1.25 from the full hydroseral section and are still far lower than those observed in the gravels at CLBH-2. Should the spring mire regime be operational in the soaks then significant dilution must be occuring.

(c) Coring down to the base of the peat consistently reveals lacustrine clay to be the underlying medium in all cases. This extremely low permeability unit would only allow insignificant upward seepage. It is appreciated that seepage may be occuring at a discrete point away from the soak yet no indication of this has been obtained in preliminary geophysical investigations.

Investigations into the origin of the soak has concentrated on Lough Roe with less emphasis being placed on the system on Clara west. A spring source may be more plausible here as a topographic mounding below the base of the peat visible on fig. 2.5 adjacent to the soak system yet no field hydrochemical anomaly has been observed to suggest such a regime.

8.3 Surface drainage hypothesis.

Surface runoff and groundwater flow are the two main methods employed by raised bogs to remove excess water. Experience of the water to flow results in increasing total dissolved solids many of which are important for plant growth. The focussing of flow into a local centre of drainage results in concentrating of nutrients at this locality thus allowing the development of more minerotrophic vegetation in an otherwise ombotrophic habitat.

This model was used by Bellamy(1986) to explain the origin of the soak system on Pollagh bog 10 km to the west of Clara Bog, now unfortunately cut away. Examination of aerial photographs of the bog reveal the presence of numerous internal surface drainage features many of which focus on the soak on Clara West. Similar features are notably lacking around Lough Roe. The water table equipotential map produced for this part of the bog (fig. 6.2) does however indicate focussed drainage toward the soak from the higher surroundings. This feature may however be an consequence of data point distribution and little credibility can be attached to the result without additional results.

On explaining the origin of the Pollagh system Bellamy (1986) noted the presence of a plug of marl protruding through the surrounding lacustrine clays indicating the presence of a former spring. It therefore appears that the soak was initially spring fed by mineral rich groundwater producing a fen botany while the surrounding areas were developing in the more classical manner into topographically higher *sphagnum* raised bog. Eventually the hydraulic head of the spring was offset, yet the soak's topographically lower position resulted in sustained focussing of drainage thus maintaining minerotrophic vegetation.

The presence of the previously mentioned mound adjacent to the western soak make this hypotheses very plausable for this locality, the presence of permeable glacial till below the peat being a common occurrence in this part of the reserve.

8.4 Tension pool hypothesis.

The process of raised bog growth results in the development of tensile stresses with increased height of the peat dome. Eventually the height of the dome can become so high that these stresses are greater than the tensile strength of the peat and tearing occurs producing fissures which fill with water giving open water pools arranged parallel to the contours of the dome.

The presence of open water results in the growth of algae such as *Zygogonium ericitorum* on the surface of the pools at particular times of the year. This plant photosynthesis producing large quantities of dissolved oxygen in the surrounding water thus increasing peat humification and actually reversing it's accumulation in a process called corrosive oxidation (Bellamy, 1986). The result of these chemical reactions is the breakdown of plant material lower down in the ecological succession releasing the nutrients trapped within them which in turn produces a botanical assemblage typical of more minerotrophic conditions.

Such pools are eventually overgrown by more ombotrophic vegetation with preferential growth commonly occuring across the surface resulting in still water bodies at depth.

Examination of the study area in Clara East reveals a notable lineament between the major axis of Lough Roe and the overall orientation of the 11 ponds further to the east. Based on the above theory it would appear that both features lay along contours of the elongate bog axis prior to topographic disturbance by road construction. The larger size of Lough Roe suggests forces of greater magnitude involved in it's formation in contrast to the more easterly ponds. As a corollary to this, assuming similar mechanical properties at both localities, it is reasonable to infer that the depth to which the initial fissure penetrated was greater than that of the ponds, thus exposing former more luxuriant fen vegetation to oxidation and release of nutrients. These nutrients would subsequently allow the development of fen vegetation thus producing a soak.

Aerial photographs indicate the extent of Lough Roe to have been formerly more extensive prior to the construction of initial topographic maps. The presence of still water bodies at depth surrounding the soak in conjunction with the highest humifications observed in the study area add further weight to the tension pool case.

This genetic model is less credible in the Clara west system as there are no marked lineaments apparent at this locality.

<u>8.5</u> Conclusions and recommendations: The soak systems of Clara Bog appear to have a Bi-genetic origin with the westerly system forming by spring activity followed by localized drainage while that in the east has formed by tensile fissuring. Localized drainage may form an important component of the Lough Roe nutrient supply yet without additional data acquisition this aspect remains uncertain.

The ambiguity resulting from hydrochemical parameters cannot be explained; however the concentration of nutrients required to produce more minerotrophic botanical assemblages is not quantitatively known and it is possible that values only slightly above background quantities are necessary.

The conclusions reached in this project are based on preliminary data. In order to gain further insight into the origin of the soaks the following are recommended :

(1) Coring on the mound adjacent to the western soak to determine the underlying lithology.

(2a) Major ion hydrochemical sampling and modelling along flow lines to determine rates of increase of elemental concentration.

(2b) Quantification of the nutrient requirements of those minerotrophic species observed in the soaks.

(3) Installation of additional piezoometers in addition to topographic levelling in the vicinity of both systems to determine the contribution of surface runoff.

IX

SUMMARY OF MAIN CONCLUSIONS.

10.1 Geology.

Detailed geological investigations of the north eastern part of Clara Bog by exposure mapping and drilling/coring show the near surface geology to be dominated by Quaternary formations. A conceptual palaeogeographical model shows these to be dominantly of fluvio-glacial, lacustrine and organic origin.

10.2 Geophysics.

The Offset-Wenner technique used to investigate the subsurface proved of little use when employed without calibration, due to equivalence and suppression in the resulting soundings. However, application of the method in conjunction with borehole data proved the method to be a valuable tool for subsurface investigation. The dipole-dipole method proved of little use in providing any additional data to that obtained by resistivity techniques.

10.3 Hydrology.

The climate of Clara Bog is believed to be very similar to the weather stations at Mullingar and Birr to the north and south-east. However a flow balance cannot be completed for the area due to an absence of run-off data.

10.4 Hydrochemistry.

Field hydrochemical measurements carried out on the bog and in the drain along the reserves' northern margin show two water types to exist, a low conductivity and pH, higher temperature water on the bog and a high conductivity and pH, lower temperature water in the drain. Comparison of the latter to the borehole chemistry suggests a source in the underlying pre-peat formations.

10.5 Hydrogeology.

Field hydrogeological investigations into the permeability of peat using constant head and rising head tests implied no relationship to exist between humification and permeability. Examination of the data and comparison with Darcian and non-Darcian models of groundwater flow through the medium showed the data to agree more with the former case although the conclusion is tenuous due to inaccurate methods of data analysis.

Pump test analysis employed to investigate the permeability of the pre-Holocene formations yields only approximate values due to deviations from idealized analytical solutions. Results from different analytical methods agree to within half an order of magnitude with one another. Steady-state and Walton methods are thought to be the most accurate approaches since deviations from the original assumptions are minimized in both cases.

Grain size analysis for clastic formations has proved useful in the preliminary determination of the permeability of the arenaceous units in CLBH-3. The loss of fines from the bailer on tipping has resulted in overestimated permeabilities by three orders of magnitude in the more argillaceous deposits of CLBH-2.

10.6 Groundwater modelling.

Modelling of groundwater flow in the peat shows piezometer methods to have overestimated permeability. An inverse relationship between permeability and humification is observed for undisturbed peat but is not bourne out in areas affected by anthropogenic activities where higher permeability H6 layers exist at depth.

The extension of the peat model to incorporate older inorganic formations is tenuous since neither the regional flow gradient or the permeability of the Lacustrine Clay are accurately known. Despite this, the effect of the drain along the northern margin is well illustrated and confirms hydrochemical evidence of upwelling at this locality. Downward seepage from the overlying peat through the clay is also illustrated and is an important controlling factor in the maximum head developed in the model.

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APPENDIX I

GLOSSARY OF ECOLOGICAL TERMS USED IN THE TEXT.

Acrotelm: Thin layer of unhumified peat found on a mire surface.

Bog: A wetland of ombotrophic vegetation.

Catotelm: Deposit of humified peat making up the bulk of raised bog deposits.

Fen: A minerotrophic wetland usually deriving its' nutrients from groundwater and surface runoff.

Humification: The process of decay in organic matter.

Lagg: The marginal area of a raised bog with a characteristic poor fen botany indicating the junction of mineral-rich and mineral poor waters.

Minerotrphic: Term used to describe vegetation deriving its' nutrients from mineral rich waters, usually groundwater and surface runoff.

Ombotrophic: Term to describe vegetation which derives its' nutrients predominantly from rainfall.

Peat: Partially decomposed organic matter.

Soak/Drogg: An area of raised bog containing a vegetation more typical of minerotrophic fen conditions.

Von Post Humification Index: Qualitative scale for the determination of the degree of decomposition of organic matter.See next page for full scale.

VON POST HUMIFICATION INDEX.

H_1: Completely unhumified plant remains from which almost colourless water can be squeezed.

H_2: Almost unhumified plant remains; squeeze water is light brown and almost clear.

H_3: Very poorly humified plant remains; squeeze water is cloudy and brown.

H_4: Poorly humified plant remains; peaty substance doesn't escape from between the fingers on squeezing.

H_5: Moderately humified plant remains; the structure is however clearly visible; squeeze water is dark brown and very cloudy. Some peat escapes between fingers.

H_6: Fairly highly humified plant remains; the structure (texture) is unclear.About a third of peat escapes between fingers.

H_7: Highly humified plant remains; about 1/2 escapes through fingers when squeezed. Water is dark brown.

H_8: V. highly humified plant remains. About 2/3 escape; only left with remanent wood and roots (resistants) etc.

H_9: Almost completely humified; almost all escapes through hands. Structure is absent.

H_{10}: Totally humified and amorphous. All peat escapes through fingers without any water squeezed out.

APPENDIX II

OFFSET WENNER RESISTIVITY DATA

RESISTIVITY SOUNDING NO.1 (CLARA BOG).

IRISH GRID REFERENCE:225 450 230 280

ELEVATION ABOVE DATUM: 55.49M

SPACING (METRES)	A	C	D1	D2	B	RESISTIVITY (Ω-METRES)	GEOL. ERROR	OPER. ERROR
0.5	49.1	47.8	31.9	39.4	3.51	112.00	21.04	0.045
1.0	31.0	28.8	18.8	26.9	2.21	143.66	35.29	0.000
2.0	17.2	16.05	12.1	13.7	1.13	161.98	12.41	0.000
4.0	8.48	7.92	6.3	6.65	0.57	162.73	5.40	0.001
8.0	4.66	4.42	3.4	3.31	0.24	168.64	2.68	0.000
16.0	2.94	2.77	1.96	1.98	0.20	198.00	0.66	0.009
32.0	2.87	2.31	1.56	1.73	0.18	330.14	10.11	0.133
64.0	2.15	1.96	1.47	1.50	0.16	597.15	1.48	0.001
128.0	1.72	1.63	1.28	1.09	0.99	951.42	16.56	0.001

Solution: Ωm Depth(m)

```
 119
------   0.38
 166
------   9.13
  93
------  11.53
 164
------  17.60
 2401
```

RESISTIVITY SOUNDING NO.2 (CLARA BOG).

IRISH GRID REFERENCE: 225 460 230 175

ELEVATION ABOVE DATUM: 58.37 M

SPACING (METRES)	A	C	D1	D2	B	RESISTIVITY (Ω-METRES)	GEOL. ERROR	OPER. ERROR
0.5	68.8	64.4	55.9	40.1	4.38	150.80	32.91	0.000
1.0	37.9	35.5	27.1	28.9	2.60	175.93	6.43	0.000
2.0	20.1	18.8	15.0	15.2	1.28	189.88	1.19	0.001
4.0	9.79	9.19	7.56	7.33	0.60	187.11	3.09	0.000
8.0	5.02	4.79	3.70	3.57	0.25	182.72	3.57	0.003
16.0	3.07	2.89	1.98	2.15	0.18	207.50	8.33	0.001
32.0	2.46	2.29	1.56	1.78	0.19	335.97	13.17	0.008
64.0	2.09	1.96	1.32	1.49	0.13	564.78	11.74	0.001
128.0	1.67	1.58	1.07	1.18	0.09	904.77	10.49	0.000

Solution: Ωm Depth(m)

```
 140
------  0.20
 187
------  9.51
 116
------ 13.50
 214
------ 18.64
 1001
```

RESISTIVITY SOUNDING NO.3 (CLARA BOG).

IRISH GRID REFERENCE: 225 435 230 380

ELEVATION ABOVE DATUM: 55.45M

SPACING (METRES)	A	C	D1	D2	B	RESISTIVITY (Ω-METRES)	GEOL. ERROR	OPER. ERROR
0.5	61.7	58.3	34.3	50.0	3.37	132.42	37.24	0.000
1.0	32.1	29.7	23.8	24.0	2.38	150.17	0.836	0.001
2.0	18.7	17.5	12.6	14.8	1.21	172.35	15.82	0.000
4.0	8.86	8.34	6.8	6.69	0.52	169.52	1.631	0.000
8.0	4.65	4.43	3.59	3.15	0.23	169.39	13.06	0.002
16.0	3.03	2.86	2.02	2.03	0.17	203.58	0.494	0.002
32.0	3.28	3.17	2.36	1.71	0.17	408.66	32.22	0.019
64.0	2.29	2.15	1.56	1.48	0.14	613.03	5.313	0.001
128.0	1.65	1.54	1.25	1.08	0.12	935.74	14.87	0.003

Solution: Ωm Depth(m)

```
   131
  ------  0.39
   172
  ------  7.55
    78
  ------  8.75
   157
  ------ 15.47
   1929
```

RESISTIVITY SOUNDING NO.4 (CLARA BOG).

IRISH GRID REFERENCE:225 410 230 480

ELEVATION ABOVE DATUM: 58.50

SPACING (METRES)	A	C	D1	D2	B	RESISTIVITY (Ω-METRES)	GEOL. ERROR	OPER. ERROR
0.5	58.1	54.9	41.2	36.9	3.2	122.68	11.01	0.000
1.0	30.2	27.8	22.9	22.7	2.4	143.26	0.877	0.003
2.0	17.7	16.5	14.1	12.4	1.2	166.94	12.72	0.000
4.0	9.01	8.48	6.74	6.77	0.5	169.77	0.444	0.001
8.0	4.24	4.05	3.30	2.95	0.2	157.08	11.20	0.003
16.0	2.41	2.27	1.58	1.69	0.1	164.32	6.301	0.002
32.0	2.14	2.00	1.38	1.41	0.1	280.48	2.150	0.003
64.0	1.92	1.79	1.28	1.27	0.1	511.50	0.786	0.004
128.0	1.59	1.48	1.05	1.13	0.1	875.83	7.530	0.005

Solution: Ωm Depth (m)

```
 103
------  0.3
 171
------  9.29
  70
------ 13.01
 140
------ 18.42
 2600
```

RESISTIVITY SOUNDING NO.5 (CLARA BOG).

IRISH GRID REFERENCE:225 380 230 575

ELEVATION ABOVE DATUM: 58.44 M

SPACING (METRES)	A	C	D1	D2	B	RESISTIVITY (Ω-METRES)	GEOL. ERROR	OPER. ERROR
0.5	55.2	52.6	33.1	38.3	2.58	112.11	14.66	0.000
1.0	30.1	27.8	19.8	24.7	2.29	139.64	22.27	0.000
2.0	17.5	16.3	12.4	13.8	1.23	164.61	10.53	0.000
4.0	8.97	8.39	6.72	7.01	0.59	172.53	4.224	0.001
8.0	4.73	4.48	3.48	3.37	0.24	172.15	3.211	0.002
16.0	2.56	2.39	1.74	1.89	0.17	182.46	8.595	0.000
32.0	2.08	1.99	1.34	1.36	0.09	271.13	1.706	0.002
64.0	1.85	1.74	1.22	1.15	0.11	476.72	6.158	0.001
128.0	1.50	1.37	1.09	0.96	0.13	825.56	12.567	0.005

Solution: Ωm Depth (m)

```
   125
------  0.6
   185
------  7.57
    56
------ 10.77
   143
------ 16.02
  1700
```

RESISTIVITY SOUNDING NO.6 (ESKER).

IRISH GRID REFERENCE:225 395 230 915

ELEVATION ABOVE DATUM: 60.96M

SPACING (METRES)	A	C	D1	D2	B	RESISTIVITY (Ω-METRES)	GEOL. ERROR	OPER. ERROR
0.5	56.3	53.8	48.4	46.2	2.15	148.60	4.651	0.002
1.0	12.2	11.3	11.8	8.67	0.89	64.246	30.42	0.001
2.0	9.62	9.09	6.70	6.15	0.52	80.740	8.560	0.001
4.0	6.23	5.76	4.43	4.48	0.45	111.96	1.122	0.003
8.0	3.62	3.38	2.77	2.47	0.26	131.70	11.45	0.005
16.0	2.84	2.67	1.83	1.90	0.17	187.69	3.749	0.001
32.0	2.69	2.53	1.73	1.71	0.16	345.22	0.931	0.001

Solution: Ωm Depth (m)

Ωm	Depth (m)
29	
	0.45
142	
	4.12
104	
	11.55
2475	

RESISTIVITY SOUNDING NO.7 (CLARA BOG).

IRISH GRID REFERENCE: 225 370 230 660

ELEVATION ABOVE DATUM: 58.39

SPACING (METRES)	A	C	D1	D2	B	RESISTIVITY (Ω-METRES)	GEOL. ERROR	OPER. ERROR
0.5	52.1	49.5	34.8	35.7	2.71	110.74	2.550	0.002
1.0	33.5	31.8	26.7	19.7	1.73	145.86	30.02	0.001
2.0	17.2	16.1	14.2	12.4	1.16	167.01	13.69	0.000
4.0	8.64	8.06	6.86	6.38	0.58	166.37	7.250	0.000
8.0	4.65	4.42	3.47	3.27	0.23	169.39	5.935	0.000
16.0	2.9	2.74	1.87	2.01	0.17	195.08	7.163	0.002
32.0	2.6	2.43	1.72	1.65	0.16	337.48	4.468	0.001
64.0	2.25	2.09	1.58	1.44	0.16	605.60	9.429	0.001
128.0	1.68	1.55	1.18	1.21	0.13	960.67	2.260	0.001

Solution: Ωm Depth (m)

```
 121
------  0.39
 172
------  8.16
  79.6
------ 11.18
 149
------ 15.6
2395
```

IRISH GRID REFERENCE: 225 485 230 785

ELEVATION ABOVE DATUM: 57.08M

RESISTIVITY SOUNDING NO.8 (LAGG ZONE).

SPACING (METRES)	A	C	D1	D2	B	RESISTIVITY (Ω-METRES)	GEOL. ERROR	OPER. ERROR
0.5	13.4	12.6	34.8	35.7	0.88	27.37	21.82	0.000
1.0	9.38	8.83	6.06	6.77	0.54	40.31	11.07	0.000
2.0	6.49	6.06	4.44	4.55	0.43	56.49	2.447	0.000
4.0	5.29	5.04	3.46	3.55	0.25	88.09	2.568	0.001
8.0	4.60	4.40	3.10	2.71	0.20	146.0	13.43	0.000
16.0	3.94	3.66	2.60	2.53	0.28	257.9	2.729	0.001
32.0	3.91	3.67	2.52	2.54	0.24	508.7	0.791	0.001

Solution: Ωm Depth (m)

Ωm	Depth (m)
40	Joint resistivity(clay & lagg peat)
------	1.2
90	
------	4.5
170	
------	8.5
2400	

RESISTIVITY SOUNDING NO.10 (ESKER).

IRISH GRID REFERENCE: 225 345 230 950

ELEVATION ABOVE DATUM: 62.76M

SPACING (METRES)	A	C	D1	D2	B	RESISTIVITY (Ω-METRES)	GEOL. ERROR	OPER. ERROR
0.5	111.7	107.4	71.4	80.6	4.98	238.76	12.11	0.006
1.0	56.4	51.5	44.5	42.2	5.00	272.37	5.306	0.002
2.0	35.6	33.4	25.5	26.4	2.26	326.09	3.468	0.002
4.0	17.97	16.8	12.4	14.8	1.16	341.68	17.14	0.002
8.0	7.82	7.25	5.05	6.85	0.40	299.08	30.25	0.021
16.0	4.18	3.96	2.87	2.77	0.24	283.49	3.546	0.004
32.0	3.48	3.19	2.26	2.29	0.18	457.41	1.132	0.014
64.0	3.05	2.88	2.06	1.97	0.18	810.88	4.314	0.002

Solution: Ωm Depth (m)

```
 189.5
------ 0.43
 371.0
------ 6.53
 105.0
------ 13.2
 2583
```

RESISTIVITY SOUNDING NO.11 (ESKER).

IRISH GRID REFERENCE:225 425 231 200

ELEVATION ABOVE DATUM: 64.50 M

SPACING (METRES)	A	C	D1	D2	B	RESISTIVITY (Ω-METRES)	GEOL. ERROR	OPER. ERROR
0.5	198.7	190.9	129	128	8.02	406.05	1.005	0.001
1.0	158.7	144.5	111	98.6	14.3	658.16	11.74	0.001
2.0	108.8	97.7	86.3	78.8	11.1	1037.35	9.085	0.000
4.0	50.2	48.0	45.5	34.1	2.12	1000.28	28.64	0.002
8.0	13.48	13.17	10.7	10.8	0.31	538.59	1.027	0.000
16.0	3.74	3.37	3.28	2.64	0.39	297.57	21.62	0.005
32.0	3.92	3.75	1.81	3.07	0.17	490.29	51.79	0.001
64.0	2.66	2.44	1.57	2.12	0.24	741.32	30.00	0.008

Solution: Ωm Depth (m)

```
  300
------  0.4
 1200
------  6.55
   80
------ 13.30
 2400           -QUESTIONABLE RESULT.
```

APPENDIX IV

CONSTANT HEAD TEST DATA.

SAMPLE CONSTANT HEAD CALCULATION USING GIBSON(1963) FORMULA

Volume released per 1cm drop in marriot vessel = $350cm^3$

Using Gibson formula for constant head

$K = Q_{infin} / S Y_c$

where Q_{infin} is flow rate (m^3 / day) (steady state),

S is Shape factor (m),

Y_c is imposed head (m).

$S = 2 \pi l / \ln[l/d + \{1 + (l/d)^2\}^{1/2}]$

where l is length of open section (m),

d is internal diameter of tube(m).

Taking data from piezometer A3-1 for first half hour.

Y_c=0.225m Level drop = 0.23-0.217 = 1.3cm

= 455 cm^3/half hour

= 9.1×10^{-4} m^3/hour

l = 0.16m & d = 0.021m

=> S = 0.365

therefore $K = 9.1 \times 10^{-4} / 0.365 \times 0.225$

$= 2.63 \times 10^{-1}$ m/day.

Piezometer A 1-2 Humification H3

Imposed head(cm) 22.8 Shape factor 0.365

Time (Hrs.)	Vessel level (cm)	Level dropped (cm)	Flow x10⁻² (m^3/day)	K (m/Day)
0.66	21.0	2.0	3.36	0.40
1.0	19.7	1.3	2.18	0.26
1.5	18.6	1.1	1.85	0.22
2.0	17.8	0.8	1.34	0.16
2.5	16.3	1.5	2.52	0.30
3.0	15.5	0.8	1.34	0.16
3.5	14.6	0.9	1.51	0.18
4.0	13.6	1.0	1.68	0.20
4.5	13.0	1.6	2.69	0.31
5.0	12.3	0.7	1.18	0.14
7.0	9.3	1.0	2.52	0.30

Piezometer A 1-5 Humification H2

Imposed head(cm) 27.0 Shape factor 0.365

Started at 23cm vessel level.

Time (Hrs.)	Vessel level (cm)	Level dropped (cm)	Flow x10⁻² (m^3/day)	K (m/Day)
0.5	22.3	0.7	1.12	0.12
1.0	21.5	0.8	1.34	0.14
1.5	20.3	1.2	2.00	0.20
2.0	19.8	0.5	0.84	0.08
2.5	18.9	0.9	1.51	0.15
3.0	18.0	0.9	1.51	0.15
3.5	17.0	1.0	1.68	0.16
4.0	16.5	0.5	0.84	0.08
4.5	15.7	0.7	1.12	0.12
5.0	15.0	0.7	1.12	0.12
5.5	14.3	0.7	1.12	0.12
6.0	13.5	0.8	1.35	0.14

Piezometer A 1-9 Humification H_7(?)

Imposed head(cm) 40.0 Shape factor 0.365
Started at 23cm vessel level.

Time (Hrs.)	Vessel level (cm)	Level dropped (cm)	Flow x10^{-2} (m^3/day)	K (m/Day)
0.5	21.0	3.0	5.04	0.34
1.0	19.4	1.6	2.69	0.18
1.5	17.7	1.7	2.86	0.19
2.0	16.2	1.5	2.52	0.17
2.5	14.7	1.5	2.52	0.17
3.0	13.6	1.1	1.85	0.13
3.5	12.3	1.3	2.18	0.15
4.0	11.2	1.1	1.85	0.13
4.5	10.0	1.2	2.02	0.14
5.0	8.9	1.1	1.85	0.13
5.5	7.5	1.2	2.02	0.14
6.0	6.5	1.0	1.68	0.11

Piezometer: A 5-5 Humification: H5

Imposed head(cm) 40 Shape factor: 0.365

Initiallevel : 23.5 cm.

Time (Hrs.)	Vessel level (cm)	Level dropped (cm)	Flow x 10^{-2} (m^3/Day)	K x 10^{-2} (m/Day)
0.5	23.2	0.3	0.50	3.45
1.0	22.5	0.7	1.12	7.67
1.5	22.0	0.5	0.84	5.75
2.0	21.5	0.5	0.84	5.75
2.5	21.2	0.3	0.50	3.45
3.0	20.8	0.5	0.84	5.75
3.5	20.5	0.3	0.50	3.45
4.0	20.3	0.2	0.34	2.30
4.5	19.9	0.4	0.67	4.60
5.0	19.5	0.4	0.67	4.60
5.5	19.3	0.2	0.34	2.30
6.0	19.0	0.3	0.50	3.45

Piezometer A 5-5 (new setting)

Imposed head: 0.45 Initial level: 22.3

Time (Hrs.)	Vessel level (cm)	Level dropped (cm)	Flow x 10^{-2} (m^3/Day)	K x 10^{-2} (m/Day)
0.5	20.6	1.7	2.86	17.40
1.0	19.2	1.4	2.35	14.30
1.5	18.5	0.7	1.18	7.18
2.0	17.9	0.6	1.01	6.15
2.5	17.2	0.7	1.18	7.18
3.0	16.6	0.6	1.01	6.15
3.5	16.1	0.5	0.84	5.11
4.0	15.9	0.2	0.34	2.04
4.5	14.3	0.6	1.01	6.15

Piezometer: A 5-2 Humification: H_4

Imposed head(cm) 34 Shape factor: 0.365m

Initial level 23cm

Time (Hrs.)	Vessel level (cm)	Level dropped (cm)	Flow x10-2 (m³/day)	K (m/Day)
0.5	20.5	2.5	4.21	0.32
1.0	19.8	0.7	1.18	0.09
1.5	17.3	1.5	2.52	0.20
2.0	15.9	1.4	2.35	0.19
2.5	14.4	1.5	2.52	0.20
3.0	13.8	0.6	1.01	0.08
3.5	11.7	2.1	3.53	0.28
4.0	10.0	1.7	2.86	0.23
4.5	8.8	1.2	2.00	0.16

Piezometer: A 8b-2 Humification: H_4

Imposed head(cm): 42 Shape factor: 0.365m

Initial level: 23cm

Time (Hrs.)	Vessel level (cm)	Level dropped (cm)	Flow x10-3 (m³/day)	K x10-2 (m/Day)
0.5	22.5	0.5	8.40	0.58
1.0	22.0	0.5	8.40	0.58
1.5	21.5	0.5	8.40	0.58
2.0	21.1	0.4	6.72	0.44
2.5	21.0	0.1	1.68	0.11
2.55	20.7	0.3	6.05	3.95
3.25	20.4	0.3	6.05	3.95
3.55	20.4	0.0	----	----
4.25	20.2	0.2	3.36	0.22
4.55	20.0	0.2	3.36	0.22

Piezometer: A 8c-5 Humification: H6

Imposed head(cm): 49.5 Shape factor: 0.365m

Initial Level: 23.0

Time (Hrs.)	Vessel level (cm)	Level dropped (cm)	Flow $x10^{-2}$ (m^3/day)	K $x10^{-1}$ (m/Day)
0.53	15.0	8.0	12.6	6.97
1.0	10.4	4.6	7.73	4.28
1.5	6.5	6.5	6.55	3.63
2.0	3.5	3.6	2.69	2.69

Piezometer: A 8a-3 Humification: H6

Imposed head(cm) 55.0 Shape factor: 0.365m

Initial Level: 23.0

Time (Hrs.)	Vessel level (cm)	Level dropped (cm)	Flow $x10^{-3}$ (m^3/day)	K $x10^{-2}$ (m/Day)
0.75	22.8	0.2	2.24	1.10
1.33	22.5	0.3	4.32	2.15
1.83	22.3	0.2	3.36	1.67
2.33	22.1	0.2	3.36	1.67
2.83	22.1	0.0	----	----
3.33	21.9	0.2	3.36	1.67
3.83	21.7	0.2	3.36	1.67
4.33	21.4	0.3	5.04	2.51
4.916	6.8	1.2	2.02	1.08
5.416	5.6	1.2	2.02	1.08
5.916	4.5	1.1	1.85	0.99

Piezometer: A 8a-2 Humification: H8

Imposed head(cm) 34.5 Shape factor: 0.365m

Initiallevel: 23.0

Time (Hrs.)	Vessel level (cm)	Level dropped (cm)	Flow x10-3 (m3/day)	K x10-3 (m/Day)
0.75	22.9	0.1	1.12	8.89
4.33	22.8	0.1	2.34	1.85

Piezometer: A 8b-5 Humification: H8

Imposed head(cm) 51.0 Shape factor: 0.365m

Initial Level: 23.0

Time (Hrs.)	Vessel level (cm)	Level dropped (cm)	Flow x10-2 (m3/day)	K x10-1 (m/Day)
0.5	19.3	3.7	6.22	3.34
1.0	17.3	2.0	3.36	1.80
1.5	16.0	1.3	2.20	1.17
2.0	14.3	1.7	2.85	1.53
2.5	12.8	1.5	2.52	1.35
3.0	11.6	1.2	2.02	1.08
3.5	10.4	1.2	2.02	1.08
4.0	9.2	1.2	2.02	1.08
4.416	8.0	1.2	2.02	1.08
4.916	6.8	1.2	2.02	1.08
5.416	5.6	1.2	2.02	1.08
5.916	4.5	1.1	1.85	0.99

Piezometer: A 8b-3 Humification: H8

Imposed head(cm) 42.5 Shape factor: 0.365m

Initial level 23cm

Time (Hrs.)	Vessel level (cm)	Level dropped (cm)	Flow x10⁻² (m³/day)	K x10⁻² (m/Day)
0.33	22.3	0.7	1.76	11.37
0.83	21.7	0.6	1.01	6.50
1.25	21.0	0.7	1.41	9.10
1.75	20.5	0.5	0.84	5.40
2.25	20.0	0.5	0.84	5.40
2.75	19.8	0.2	0.34	2.20
3.25	19.3	0.5	0.84	5.40
3.75	19.1	0.2	0.34	2.20

Piezometer: A 8a-4 Humification: H8

Imposed head(cm) 55.0 Shape factor: 0.365m

Initial level 23cm

Time (Hrs.)	Vessel level (cm)	Level dropped (cm)	Flow x10⁻² (m³/day)	K (m/Day)
0.5	14.4	8.6	14.44	0.72
1.08	9.0	5.4	7.78	0.39
1.58	5.2	3.8	6.38	0.32

Piezometer: A 8c-2 Humification: H_3

Imposed head(cm): 23 Shape factor: 0.365m

Initial level 23cm

Time (Hrs.)	Vessel level (cm)	Level dropped (cm)	Flow $\times 10^{-2}$ (m^3/day)	K $\times 10^{-1}$ (m/Day)
0.5	19.6	3.4	5.71	6.80
1.0	17.3	2.3	3.86	4.60
1.5	15.3	2.0	3.36	4.00
2.0	13.4	1.9	3.19	3.80
2.5	11.9	1.5	2.52	3.00
3.0	10.4	1.5	2.52	3.00
3.5	9.0	1.4	2.35	2.80
4.0	7.5	1.5	2.52	3.00

Piezometer: A 8c-3 Humification: H_2

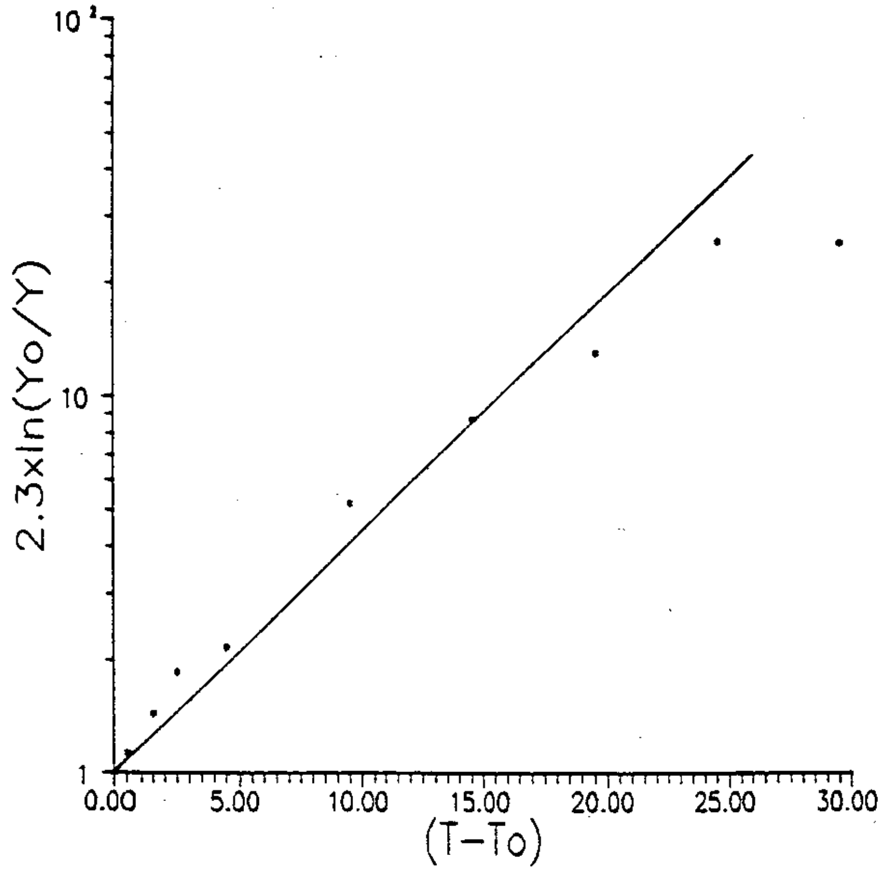
Imposed head(cm) 36.5 Shape factor: 0.365m

Initial level: 23.0 cm

Time (Hrs.)	Vessel level (cm)	Level dropped (cm)	Flow $\times 10^{-2}$ (m^3/day)	K $\times 10^{-2}$ (m/Day)
0.42	22.2	0.8	6.12	12.1
1.0	22.1	0.1	0.14	1.08
1.5	21.4	0.7	0.12	8.83
2.0	20.7	0.7	0.12	8.83
2.5	20.4	0.3	0.54	4.05
3.0	20.1	0.3	0.54	4.05
3.5	19.8	0.3	0.54	4.05

APPENDIX III

RISING HEAD TEST DATA



HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A1-2

TIME (mins) (t-to)	Yo/Y
0.5	1.13
1.5	1.44
2.5	1.86
4.5	2.167
9.5	5.20
14.5	8.67
19.5	13.0
24.5	26.0
29.5	26.0

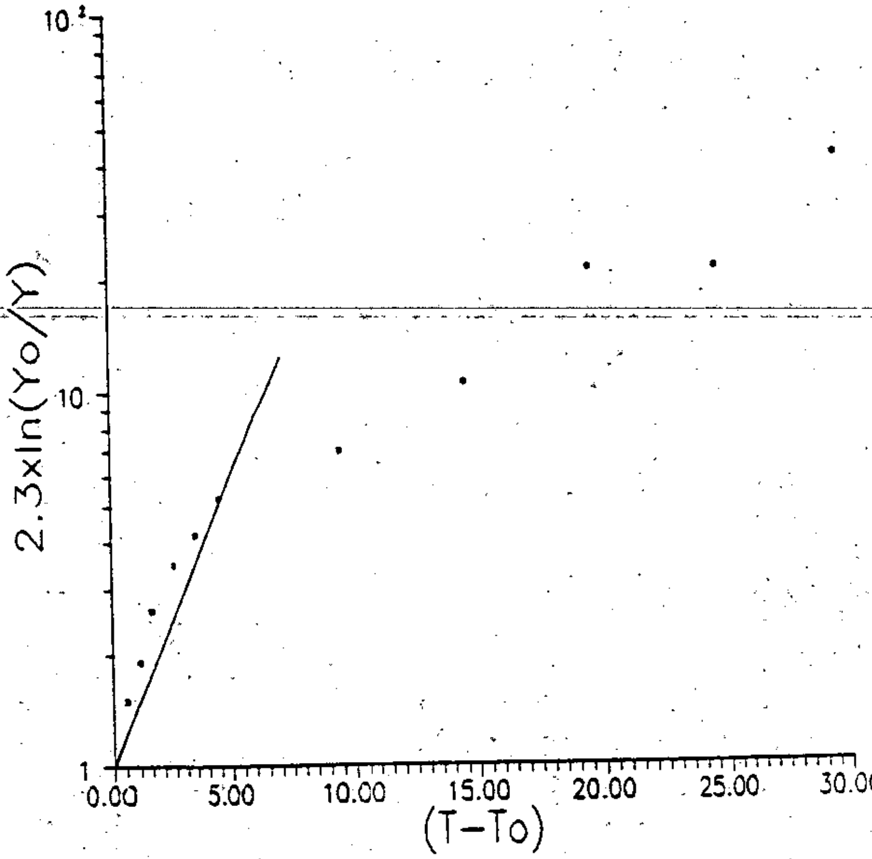
Y_o=26.0 cm

S =36.85 cm

A = 3.464cm^2

$K=Ax[\ln(Y_o/Y_2)-\ln(Y_o/Y_1)/[(t_2-t_o)-(t_1-t_o)]$
therefore

$K=2.27x10^{-1}$ m/day



HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A1-5

TIME(mins) (t-to)	Yo/Y
0.5	1.50
1.0	1.91
1.5	2.625
2.5	3.5
3.5	4.2
4.5	5.25
9.5	7.0
14.5	10.5
19.5	21.0
24.5	21.0
29.5	42.0

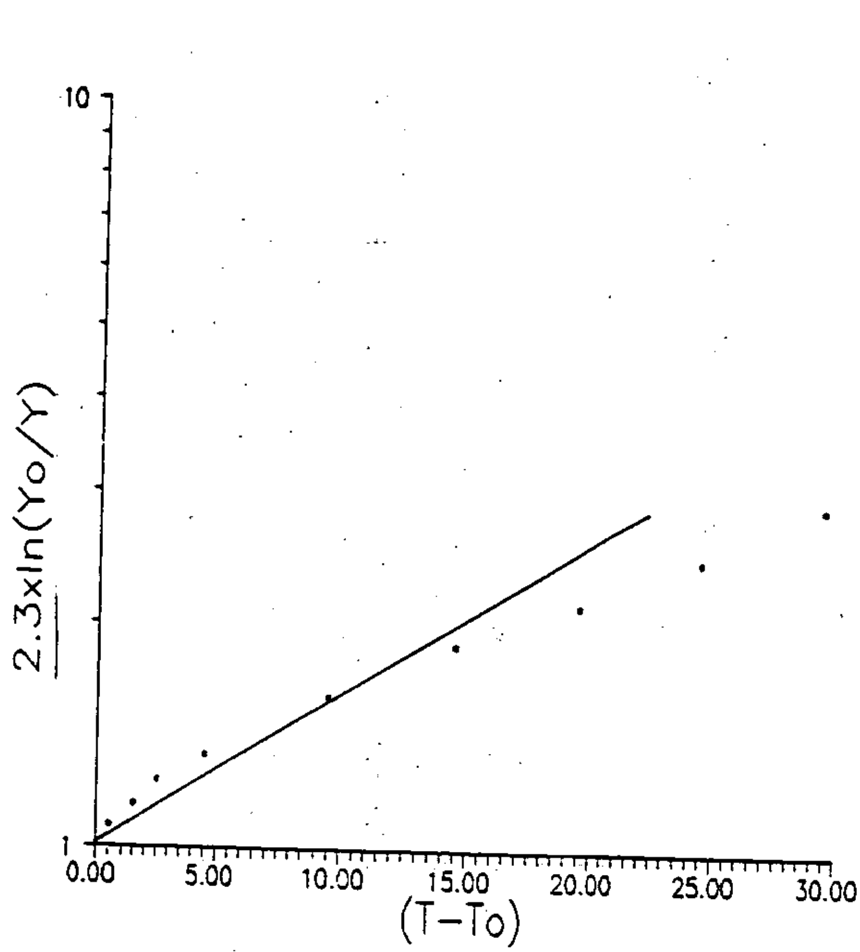
Y_o=14.0 cm

S =36.85 cm

A = 3.464cm²

$K=Ax[\ln(Y_o/Y_2)-\ln(Y_o/Y_1)/[(t_2-t_o)-(t_1-t_o)]$
therefore

$K=6.77\times10^{-1}$ m/day



HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A1-7

TIME(mins) $(t-t_0)$	Y_0/Y
0.25	1.074
0.75	1.09
1.75	1.21
2.75	1.52
3.75	1.94
4.75	2.33
9.75	2.92
14.75	3.88

Y_0=35.0 cm

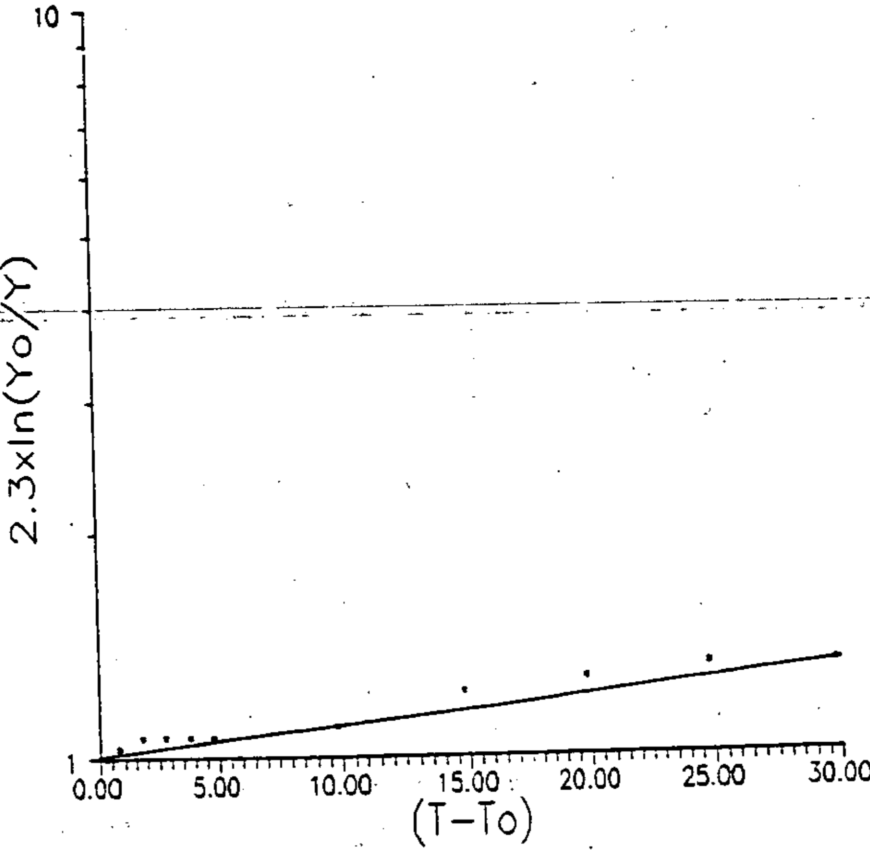
S =36.85 cm

A = 3.464cm^2

$K=Ax[\ln(Y_0/Y_2)-\ln(Y_0/Y_1)/[(t_2-t_0)-(t_1-t_0)]$

therefore

$K=6.19x10^{-2}$ m/day



HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A1-9

TIME(mins) (t-te)	Ye/Y
0.25	1.000
0.75	1.030
1.75	1.065
2.75	1.065
3.75	1.065
4.75	1.065
9.75	1.100
14.75	1.220
19.75	1.270
24.75	1.320
29.75	1.320

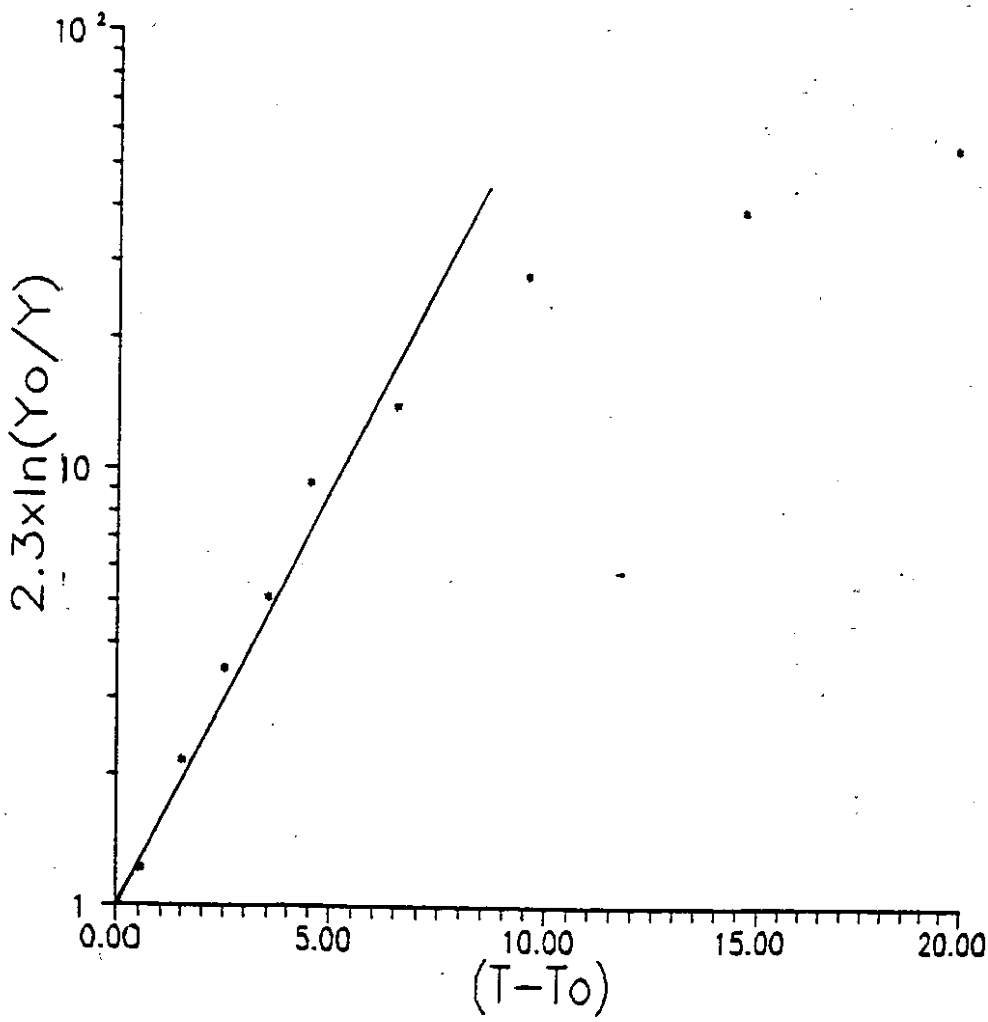
Y_e=33.0 cm

S =36.85 cm

A = 3.464cm^2

K=Ax[ln(Y_e/Y_2)-ln(Y_e/Y_1)/[(t_2-t_e)-(t_1-t_e)]
therefore

K=2.256x10^{-1} m/day



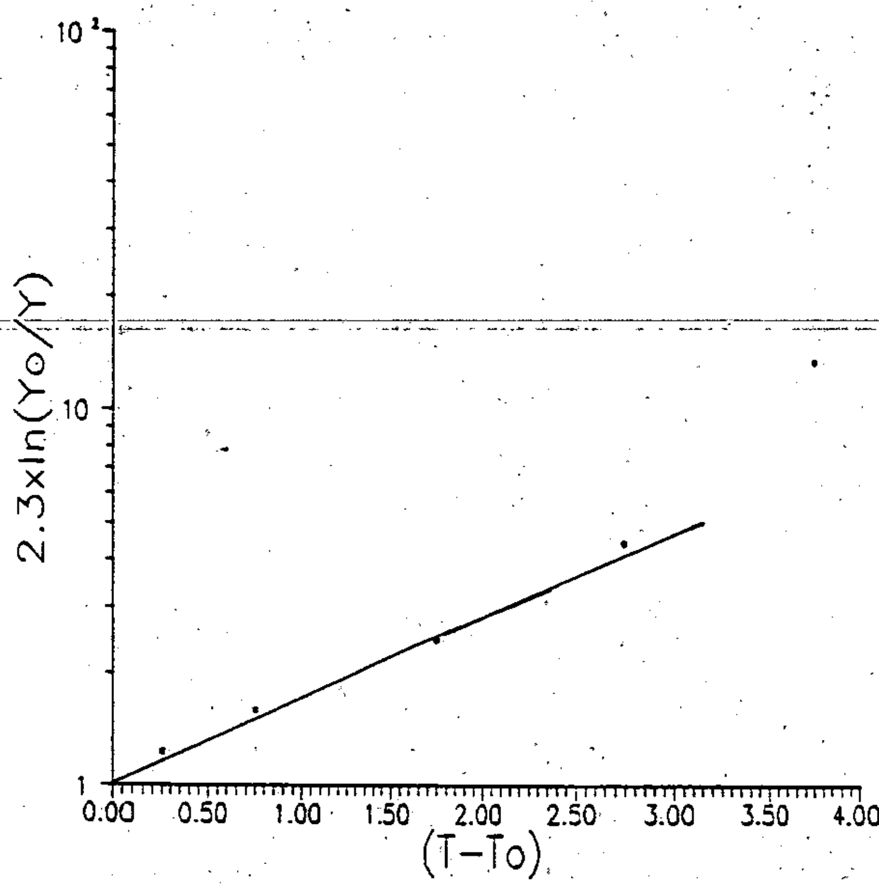
HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A 2-2

TIME (t-te)	Ye/Y
0.5	1.217
1.5	2.154
2.5	3.500
3.5	5.091
4.5	9.330
6.5	14.000
9.5	28.000
14.5	40.000
19.5	56.000

Ye=23.0 cm

S =36.85 cm

A = 3.464cm^2



HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A2-3

TIME(mins) (t-to)	Yo/Y
0.25	1.227
0.75	1.588
1.75	2.455
2.75	4.500
3.75	13.50

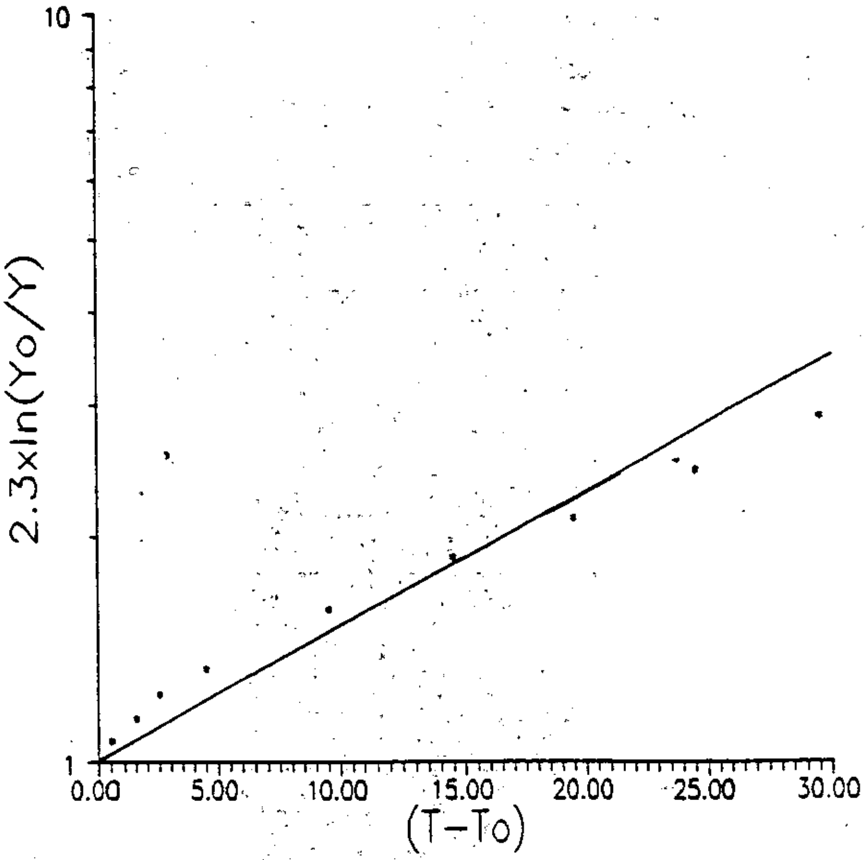
Y_o=27.0 cm

S =36.85 cm

A = 3.464cm^2

$K=Ax[\ln(Y_o/Y_2)-\ln(Y_o/Y_1)/[(t_2-t_o)-(t_1-t_o)]$
therefore

$K=8.46\times10^{-1}$ m/day



HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A 2-7

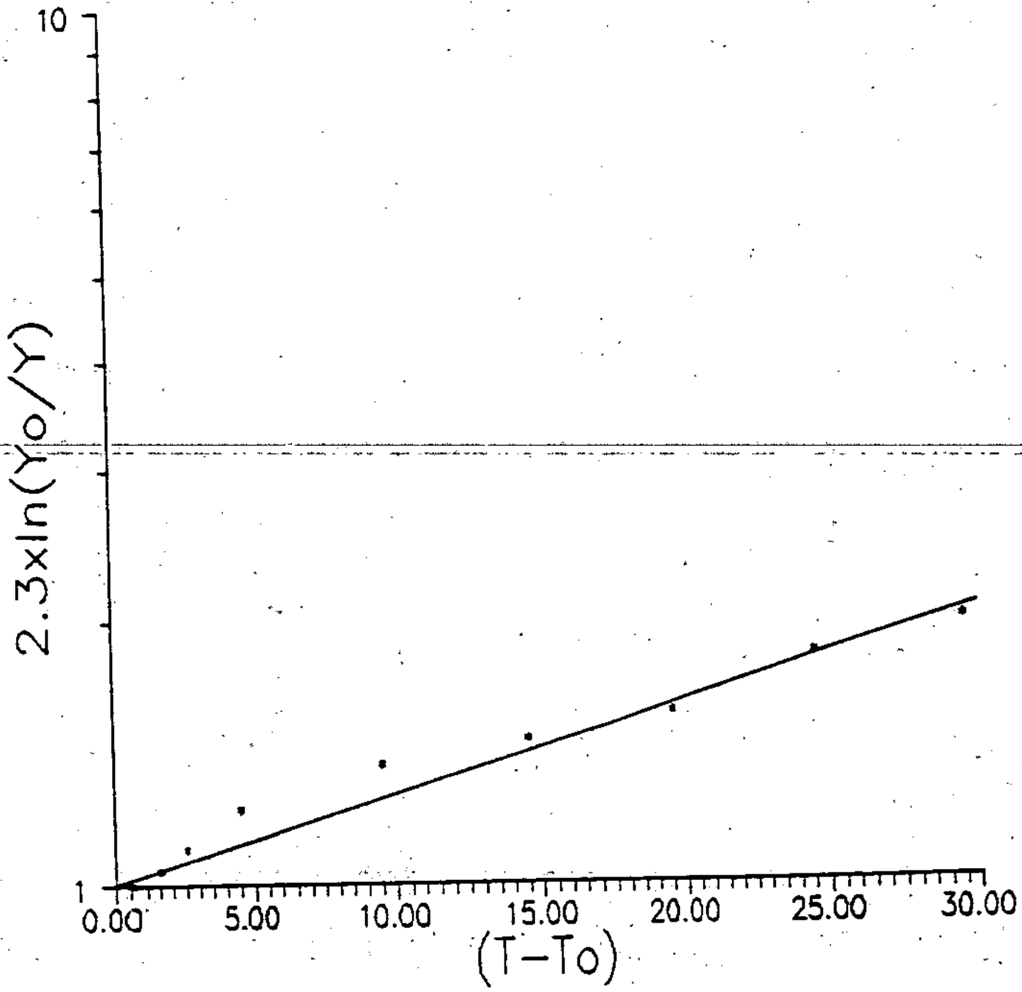
TIME (mins) (t-te)	Ye/Y
0.5	1.067
1.5	1.143
2.5	1.231
4.5	1.330
9.5	1.600
14.5	1.880
19.5	2.130
24.5	2.460
29.5	2.910

Y_e=30.0 cm

S =36.85 cm

A = 3.464cm²

$K = A x [\ln(Y_e/Y_2) - \ln(Y_e/Y_1)/[(t_2-t_e)-(t_1-t_e)]$
therefore
$K = 7.2 x 10^{-2}$ m/day



HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A3-2

TIME(mins) (t-to)	Yo/Y
0.5	1.00
1.5	1.04
2.5	1.10
4.5	1.22
9.5	1.375
14.5	1.467
19.5	1.571
24.5	1.83
29.5	2.00

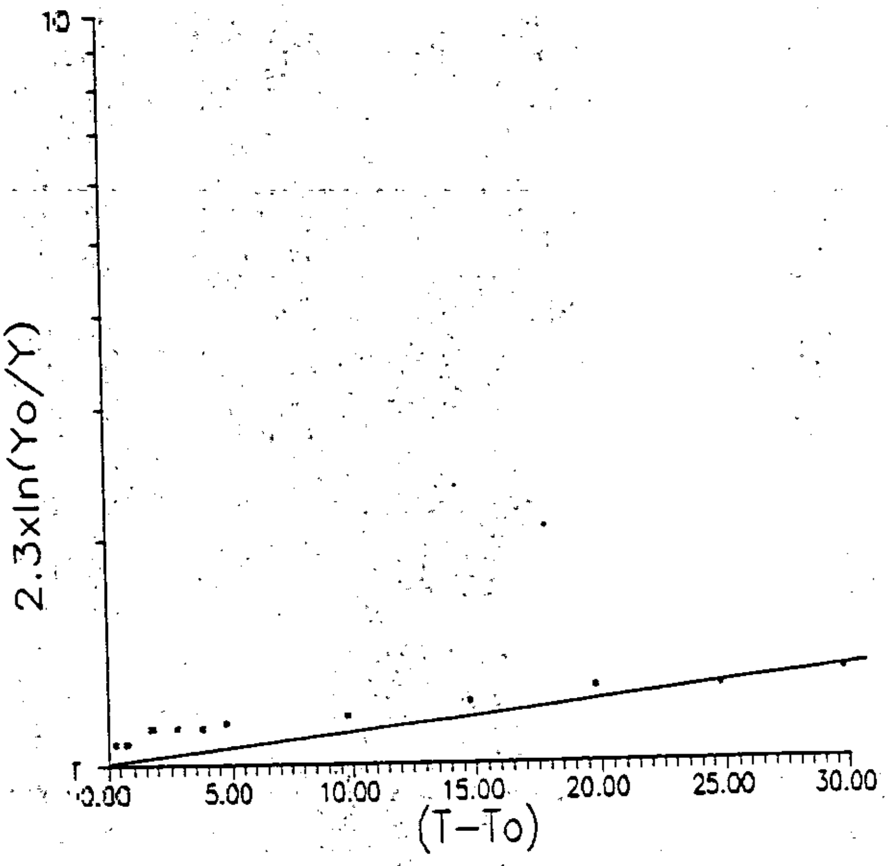
Y_0=22.0 cm

S =36.85 cm

A = 3.464 cm^2

K=Ax[ln(Y_0/Y_2)-ln(Y_0/Y_1)/[(t_2-t_0)-(t_1-t_0)]
therefore

K=5.2x10^{-2} m/day



HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A3-3

TIME(mins) (t-te)	Ye/Y
0.25	1.070
0.75	1.070
1.75	1.120
2.75	1.120
3.75	1.120
4.75	1.137
9.75	1.160
14.75	1.210
19.75	1.261
24.75	1.261
29.75	1.318

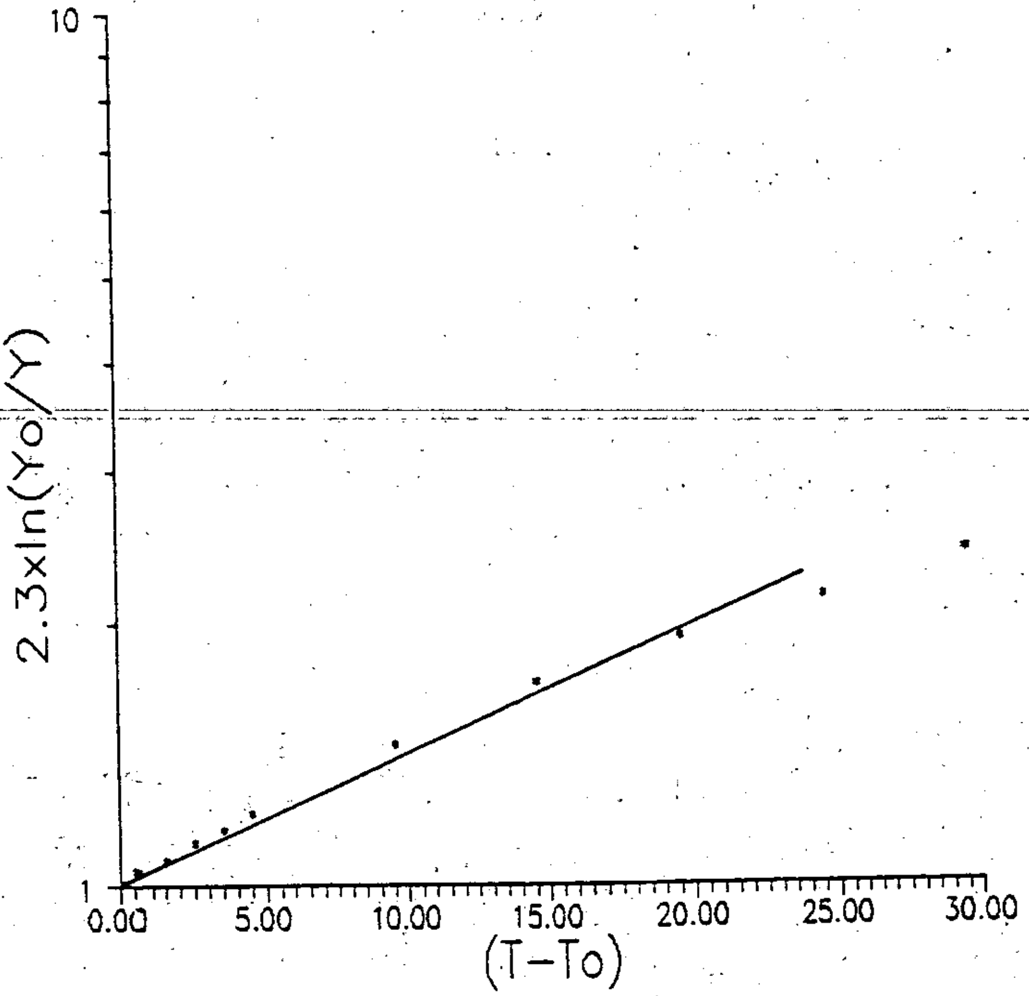
Ye=29.0 cm

S =36.85 cm

A = 3.464cm^2

K=Ax[ln(Ye/Y$_2$)-ln(Ye/Y$_1$)/[(t$_2$-te)-(t$_1$-te)]
therefore

K=4.3x10^{-2} m/day



HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A3-5

TIME(min) $(t-t_0)$	Y_0/Y
0.5	1.04
1.5	1.07
2.5	1.12
3.5	1.16
4.5	1.21
9.5	1.45
14.5	1.71
19.5	1.93
24.5	2.15
29.5	2.42

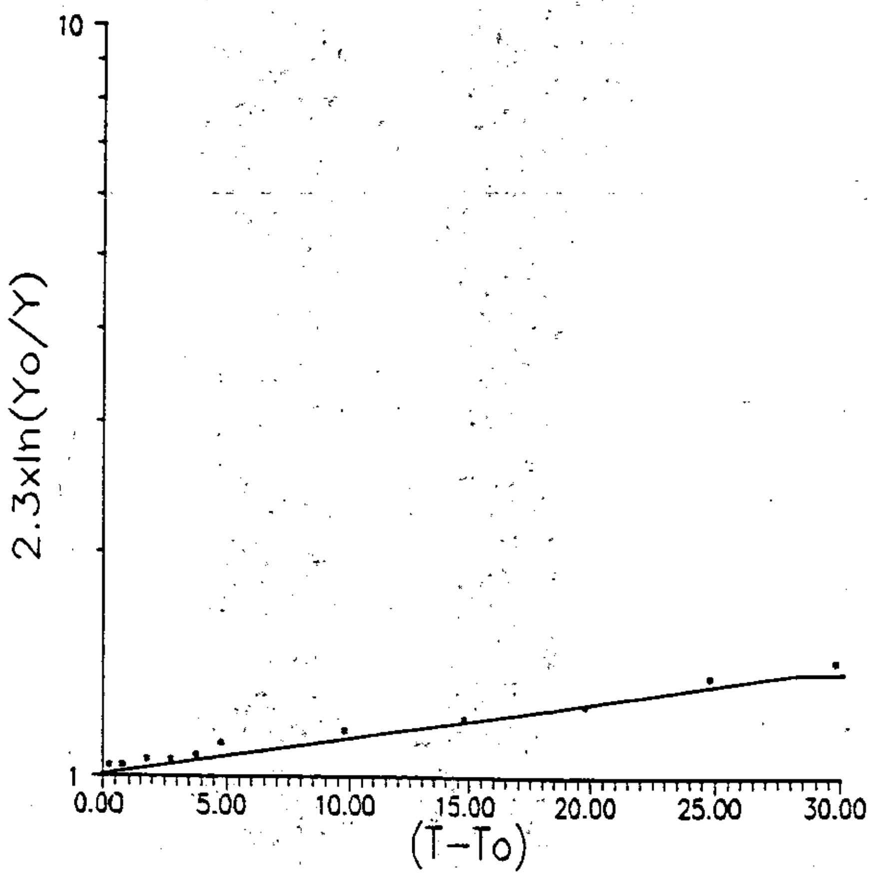
Y_0=29.0 cm

S =36.85 cm

A = 3.464cm^2

$K=Ax[\ln(Y_0/Y_2)-\ln(Y_0/Y_1)/[(t_2-t_0)-(t_1-t_0)]$
therefore

$K=2.2x10^{-2}$ m/day



HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A3-7

TIME(mins) (t-tø)	Yø/Y
0.25	1.034
0.75	1.034
1.75	1.053
2.75	1.053
3.75	1.070
4.75	1.110
9.75	1.154
14.75	1.200
19.75	1.250
24.75	1.364
29.75	1.429

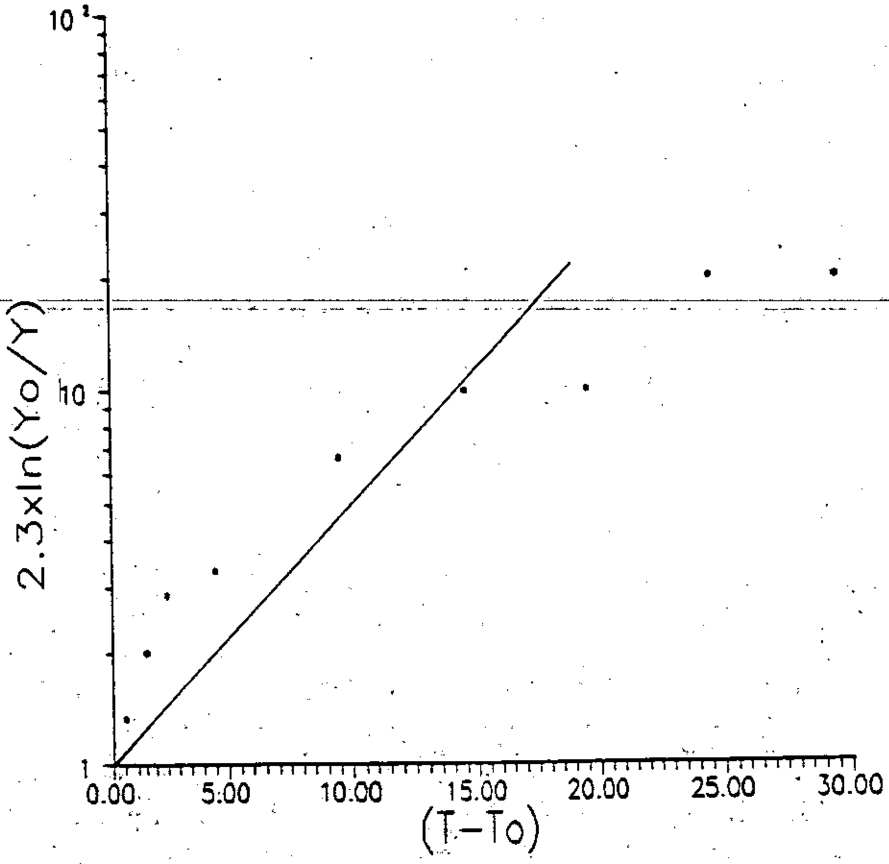
Yø=30.0 cm

S =36.85 cm

A = 3.464cm²

$K=Ax[\ln(Y_0/Y_2)-\ln(Y_0/Y_1)/[(t_2-t_0)-(t_1-t_0)]$
therefore

$K=2.26x10^{-2}$ m/day



HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A4-2

TIME(mins) (t-te)	Ye/Y
0.5	1.33
1.5	2.00
2.5	2.86
4.5	3.33
9.5	6.67
14.5	10.0
19.5	10.0
24.5	20.0
29.5	20.0

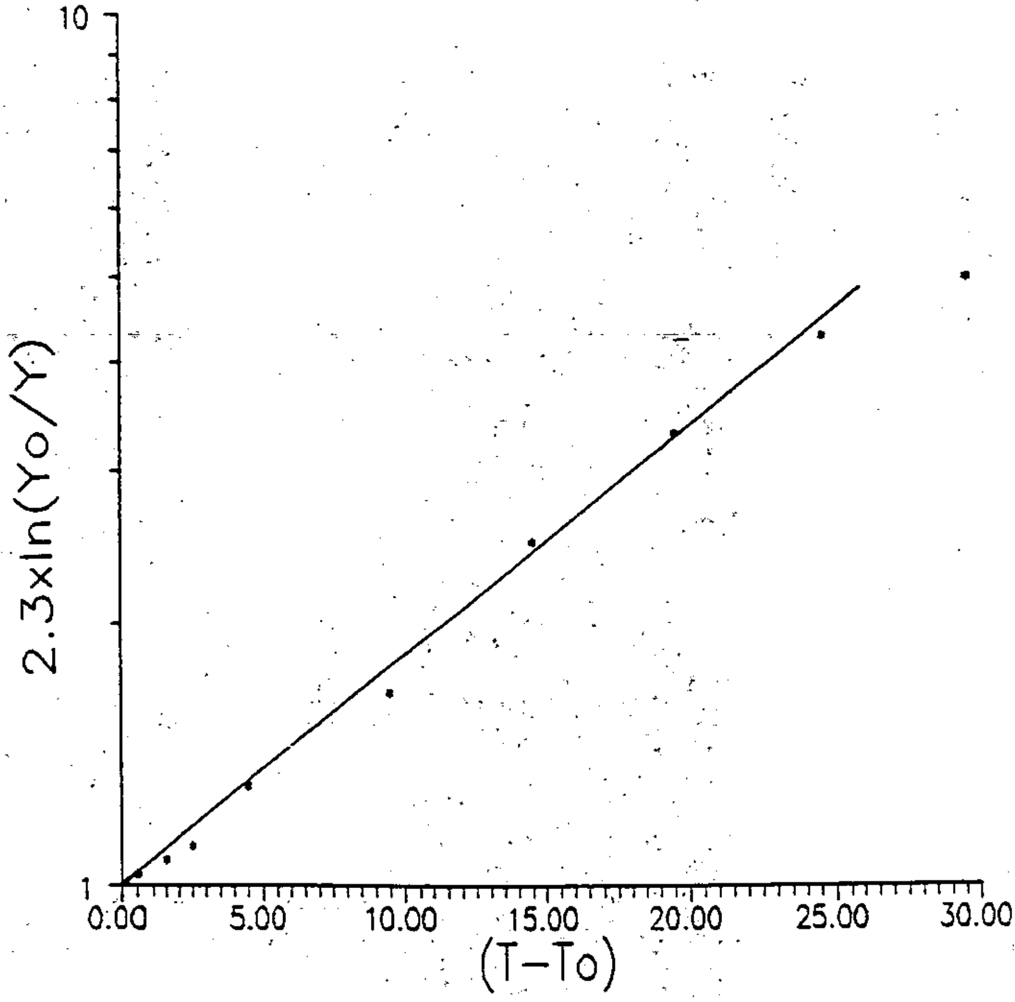
Y_e=20.0 cm

S = 36.85 cm

A = 3.464cm^2

$K=Ax[\ln(Y_e/Y_2)-\ln(Y_e/Y_1)/[(t_2-t_e)-(t_1-t_e)]$
therefore

$K=3.11x10^{-1}$ m/day



HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A4-3

TIME(mins) $(t-t_0)$	Y_0/Y
0.5	1.03
1.5	1.07
2.5	1.11
4.5	1.30
9.5	1.67
14.5	2.50
19.5	3.33
24.5	4.29
29.5	5.00

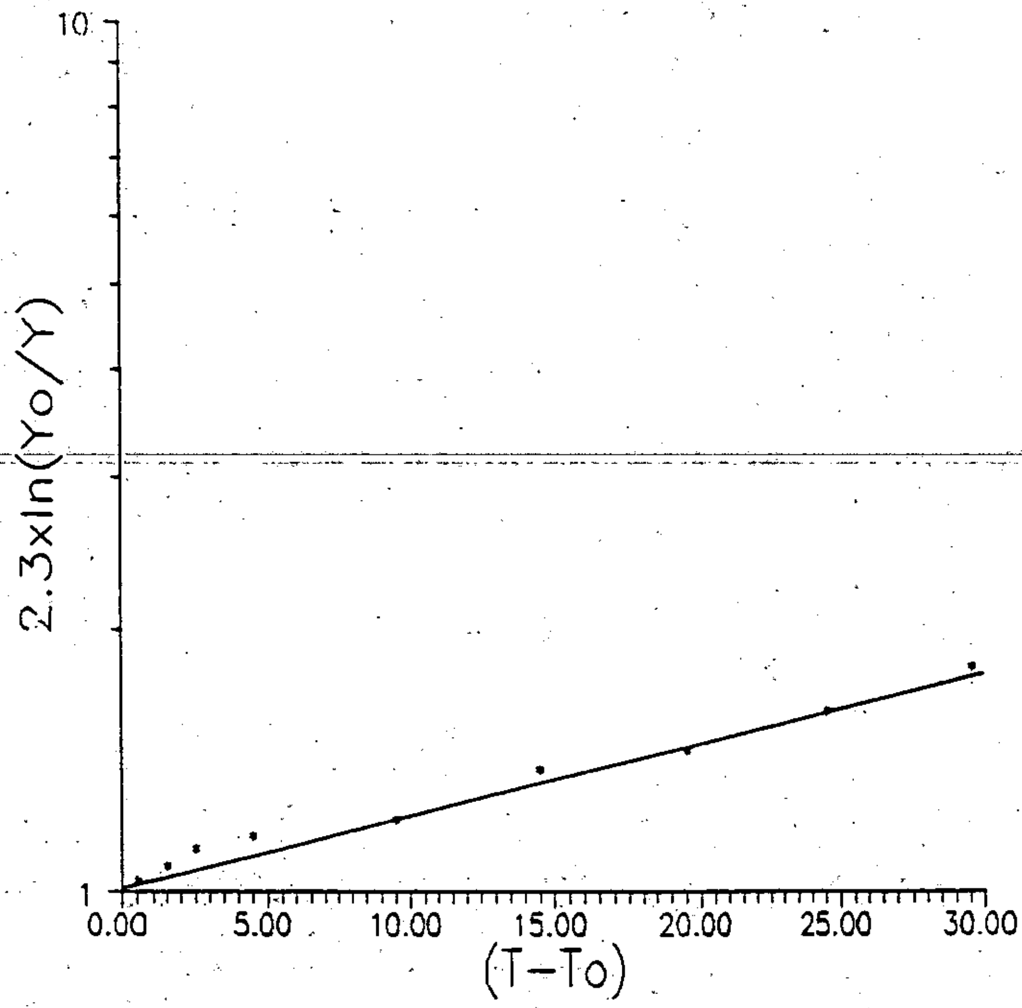
Y_0=30.0 cm

S =36.85 cm

A = 3.464cm^2

$K=A\times[\ln(Y_0/Y_1)-\ln(Y_0/Y_2)/[(t_2-t_0)-(t_1-t_0)]$
therefore

$K=8.46\times10^{-2}$ m/day



HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A4-5

TIME(mins) $(t-t_0)$	Y_0/Y
0.5	1.03
1.5	1.07
2.5	1.12
4.5	1.16
9.5	1.21
14.5	1.381
19.5	1.450
24.5	1.610
29.5	1.810

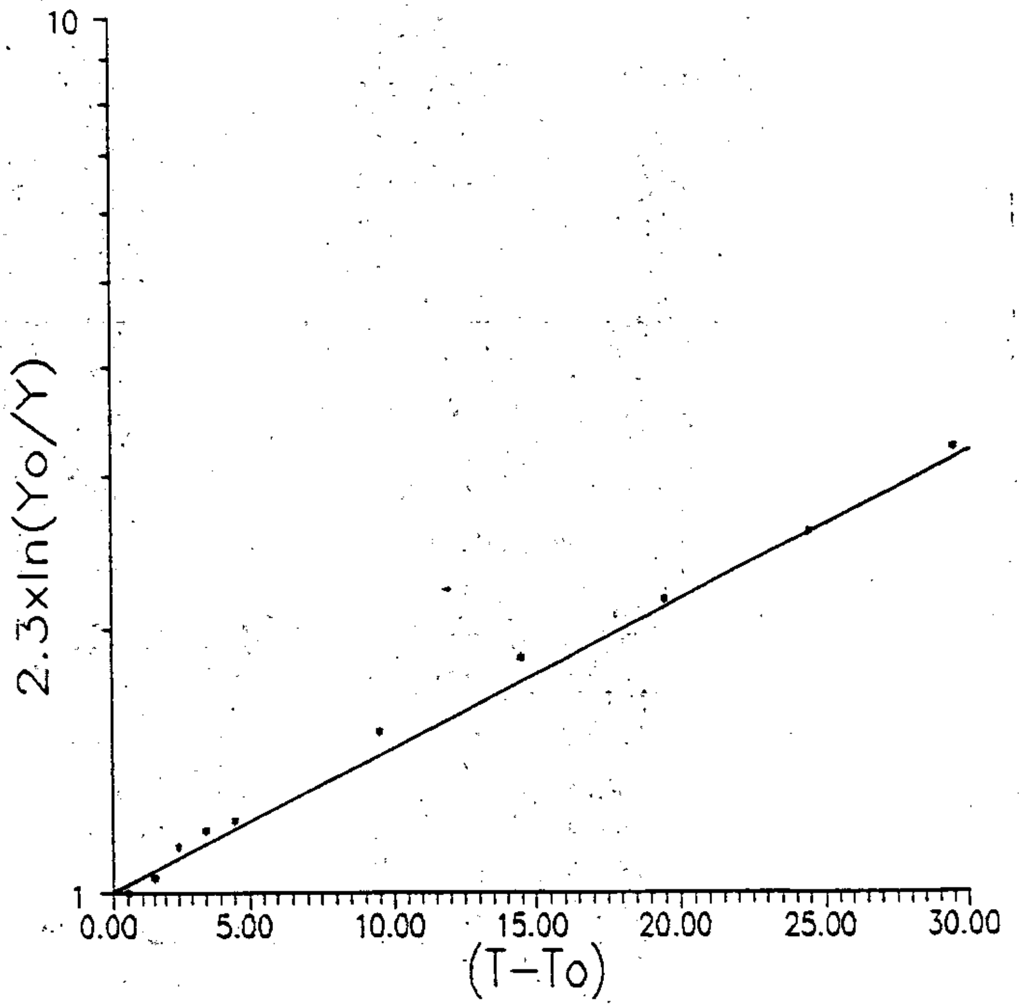
Y_0=29.0 cm

S =36.85 cm

A = 3.464cm^2

$K=Ax[\ln(Y_0/Y_2)-\ln(Y_0/Y_1)/[(t_2-t_0)-(t_1-t_0)]$
therefore

$K=4.51x10^{-2}$ m/day



HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A4-7

TIME(mins) (t-t0)	Y0/Y
0.5	1.00
1.5	1.04
2.5	1.13
3.5	1.18
4.5	1.21
9.5	1.53
14.5	1.86
19.5	2.167
24.5	2.60
29.5	3.25

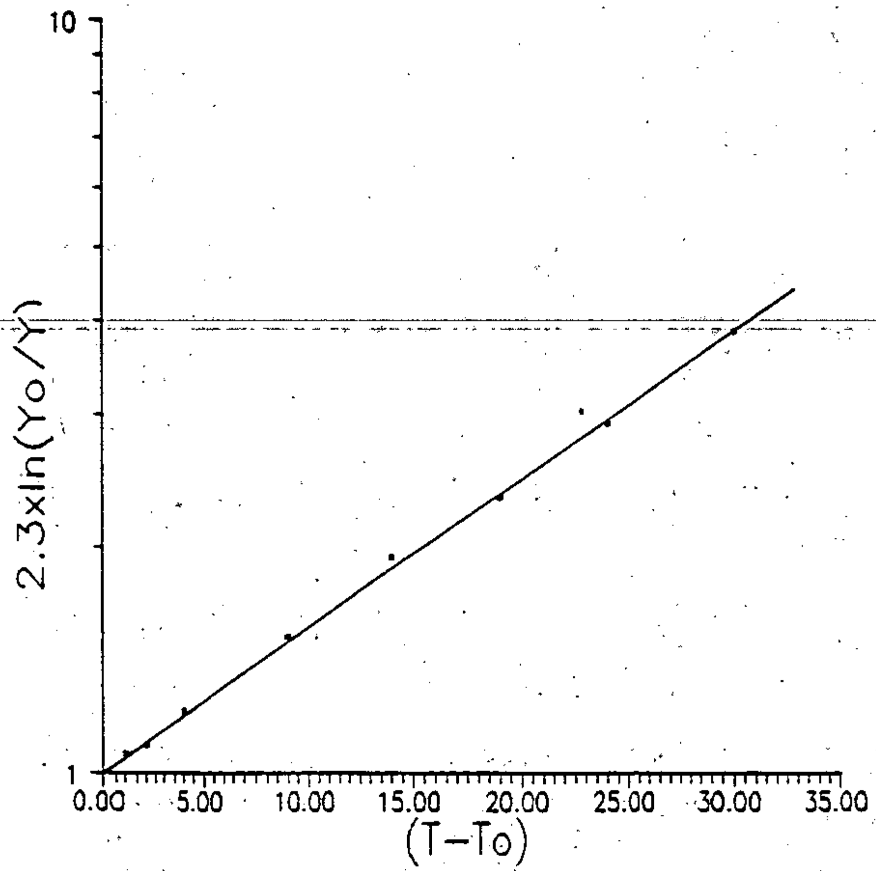
Y_0=26.0 cm

S =36.85 cm

A = 3.464cm^2

$K=Ax[\ln(Y_0/Y_2)-\ln(Y_0/Y_1)/[(t_2-t_0)-(t_1-t_0)]$
therefore

$K=5.96x10^{-2}$ m/day



HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A 4-9

TIME(mins) (t-to)	Yo/Y
1.0	1.06
2.0	1.09
4.0	1.21
9.0	1.52
14.0	1.94
19.0	2.33
24.0	2.92
29.0	3.88

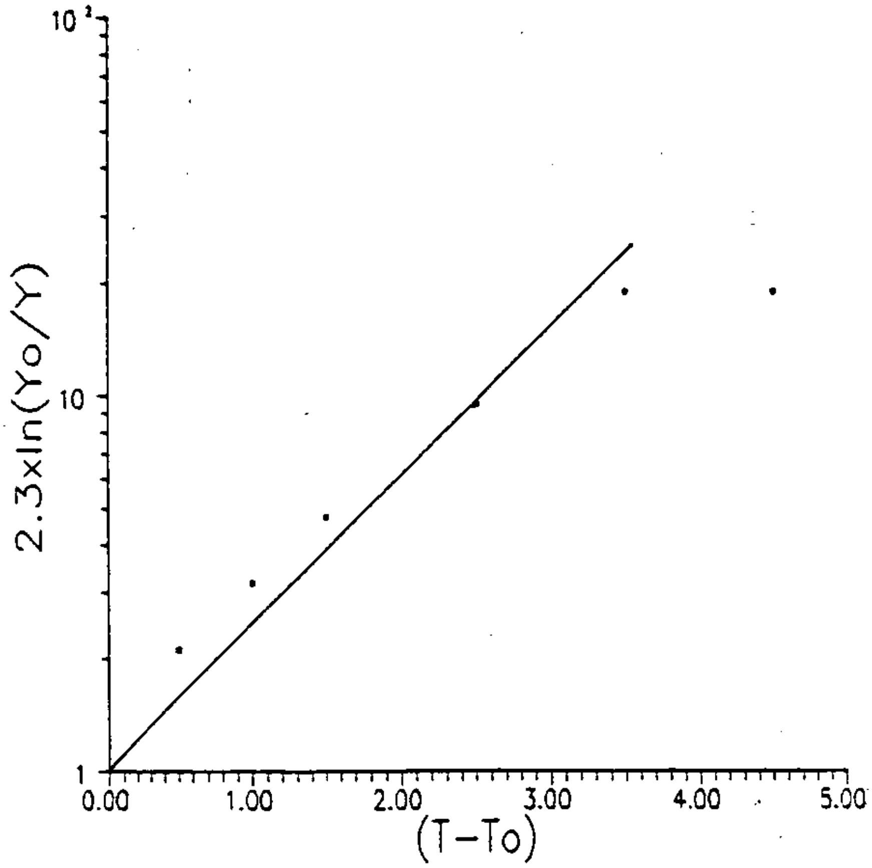
Y_o=35.0 cm

S =36.85 cm

A = 3.464 cm^2

$K = A \times [\ln(Y_o/Y_2) - \ln(Y_o/Y_1) / [(t_2 - t_o) - (t_1 - t_o)]$
therefore

$K = 6.19 \times 10^{-2}$ m/day



HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A5-2

TIME(mins) $(t-t_0)$	Y_0/Y
0.25	1.12
0.75	1.40
1.75	1.90
2.75	2.33
3.75	3.11
4.75	4.00
9.75	7.00
14.75	14.0
19.75	28.0
24.75	28.0

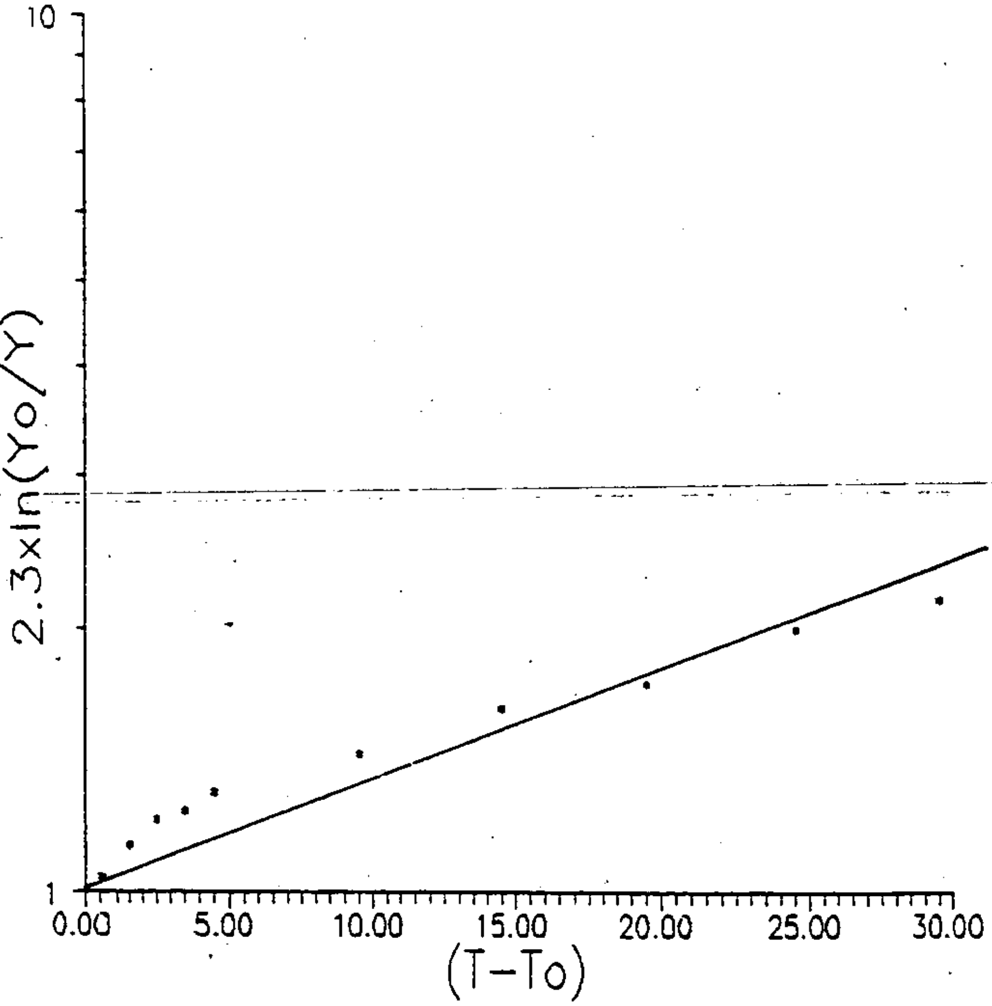
Y_0=28.0 cm

S =36.85 cm

A = 3.464cm^2

$K=A\times[\ln(Y_0/Y_2)-\ln(Y_0/Y_1)/[(t_2-t_0)-(t_1-t_0)]$
therefore

$K=3.73\times10^{-1}$ m/day



HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A5-3

TIME(mins) (t-t0)	Y0/Y
0.5	1.04
1.5	1.13
2.5	1.21
3.5	1.24
4.5	1.30
9.5	1.44
14.5	1.625
19.5	1.733
24.5	2.00
29.5	2.167

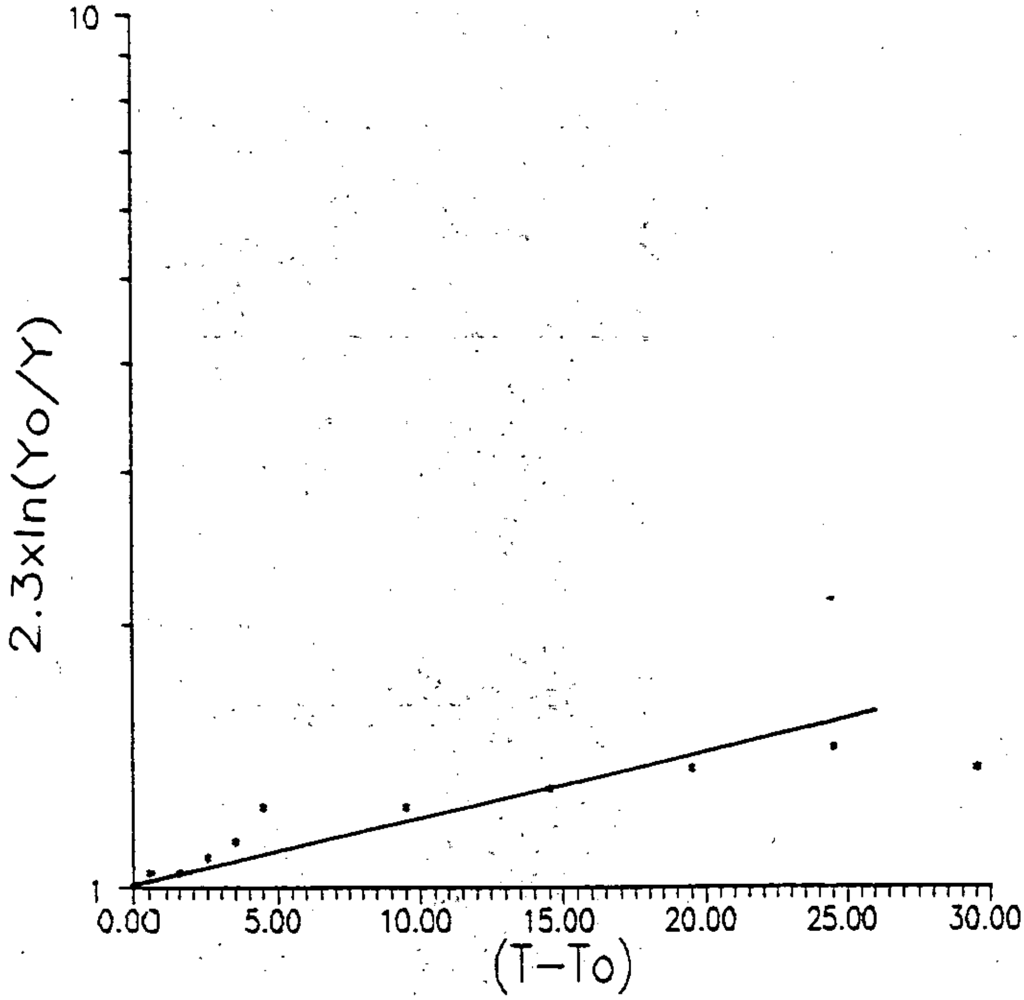
Y_0=26.0 cm

S =36.85 cm

A = 3.464cm^2

K=Ax[ln(Y_0/Y_2)-ln(Y_0/Y_2)/[(t_2-t_0)-(t_1-t_0)]
therefore

K=1.08x10^{-1} m/day



HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A 5-5

TIME(mins) (t-to)	Yo/Y
0.5	1.04
1.5	1.04
2.5	1.08
3.5	1.13
4.5	1.24
9.5	1.24
14.5	1.30
19.5	1.40
24.5	1.44
29.5	1.63

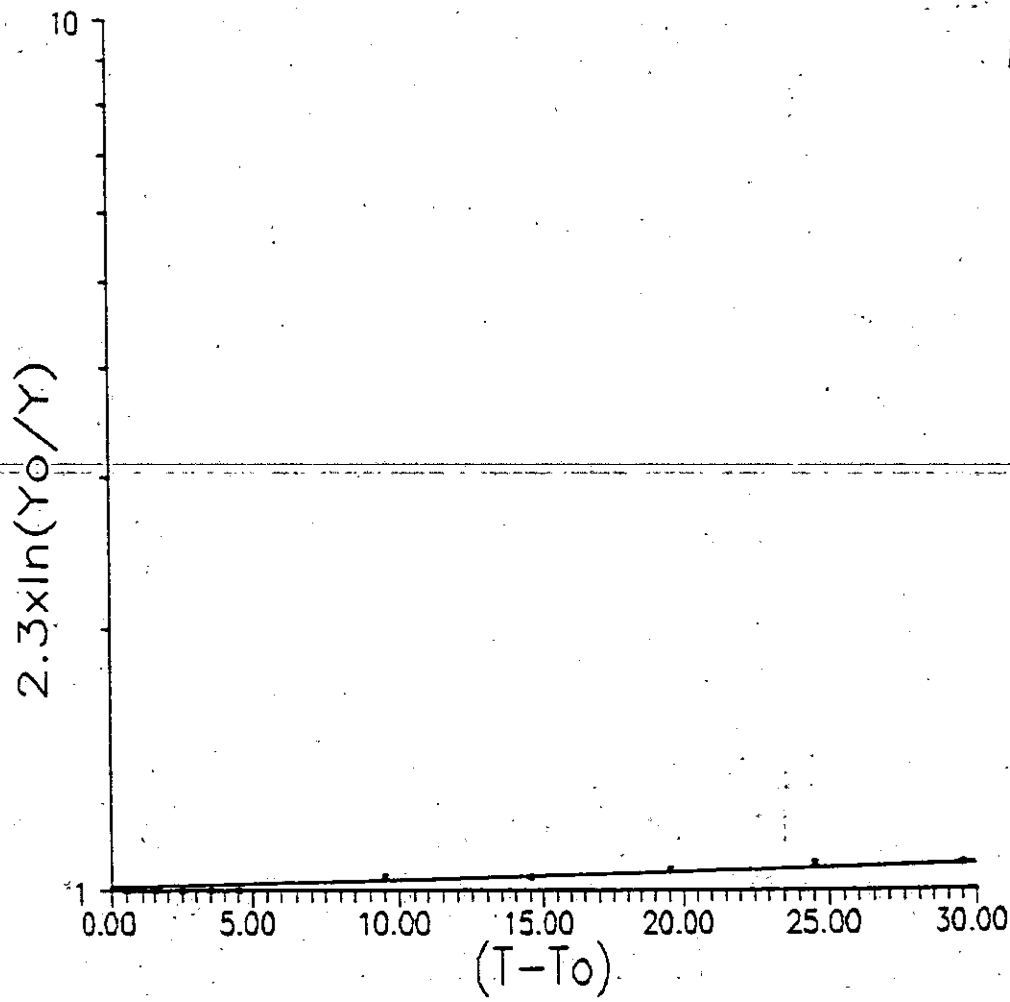
Y_o=26.0 cm

S =36.85 cm

A = 3.464cm^2

$K=Ax[\ln(Y_o/Y_2)-\ln(Y_o/Y_2)/[(t_2-t_o)-(t_1-t_o)]$
therefore

$K=3.38x10^{-2}$ m/day



HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A5-7

TIME(mins) $(t-t_0)$	Y_0/Y
0.5	1.00
1.5	1.00
2.5	1.00
3.5	1.00
4.5	1.04
9.5	1.04
14.5	1.04
19.5	1.06
24.5	1.07
29.5	1.07

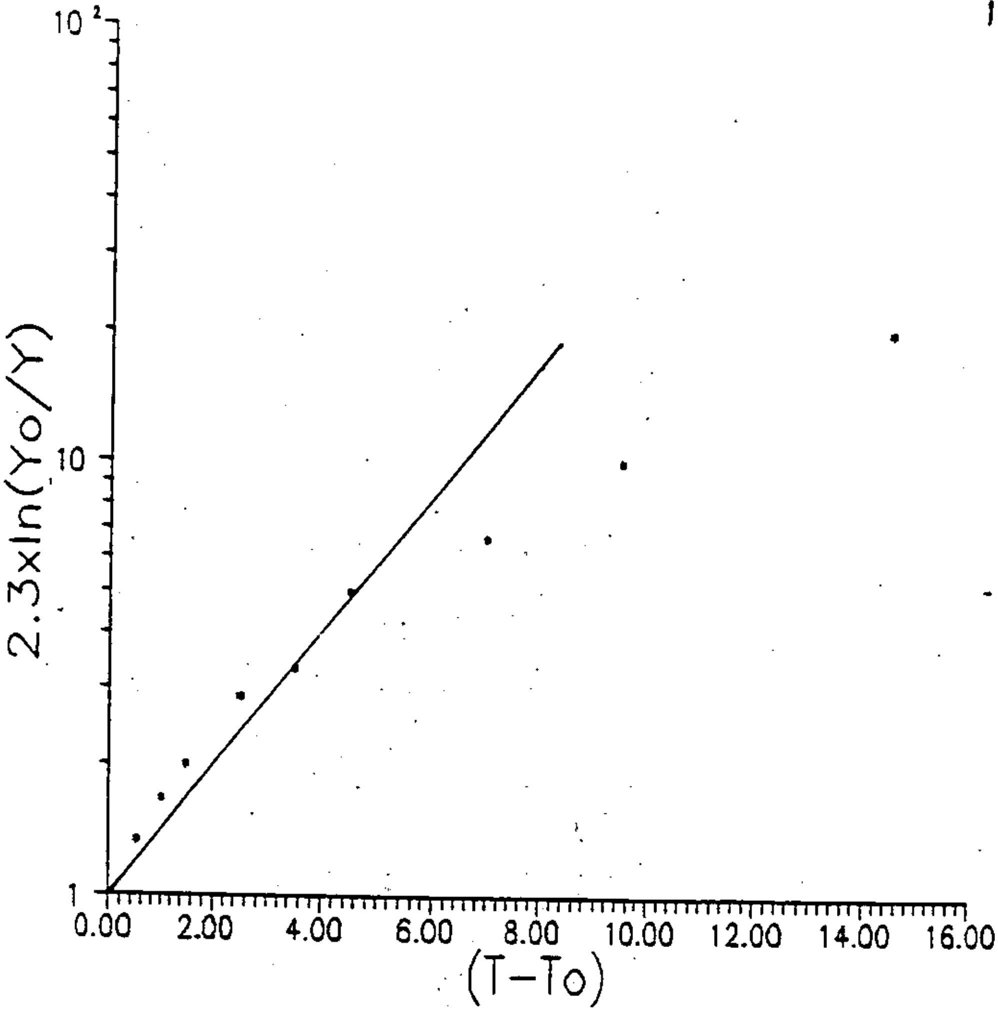
Y_0=29.0 cm

S =36.85 cm

A = 3.464cm^2

$K=Ax[\ln(Y_0/Y_2)-\ln(Y_0/Y_2)/[(t_2-t_0)-(t_1-t_0)]$
therefore

$K=4.512x10^{-3}$ m/day



HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A7-2

TIME(mins) ($t-t_0$)	Y_0/Y
0.5	1.33
1.0	1.67
1.5	2.00
2.5	2.85
3.5	3.33
4.5	5.00
7.0	6.67
9.5	10.0
14.5	20.0

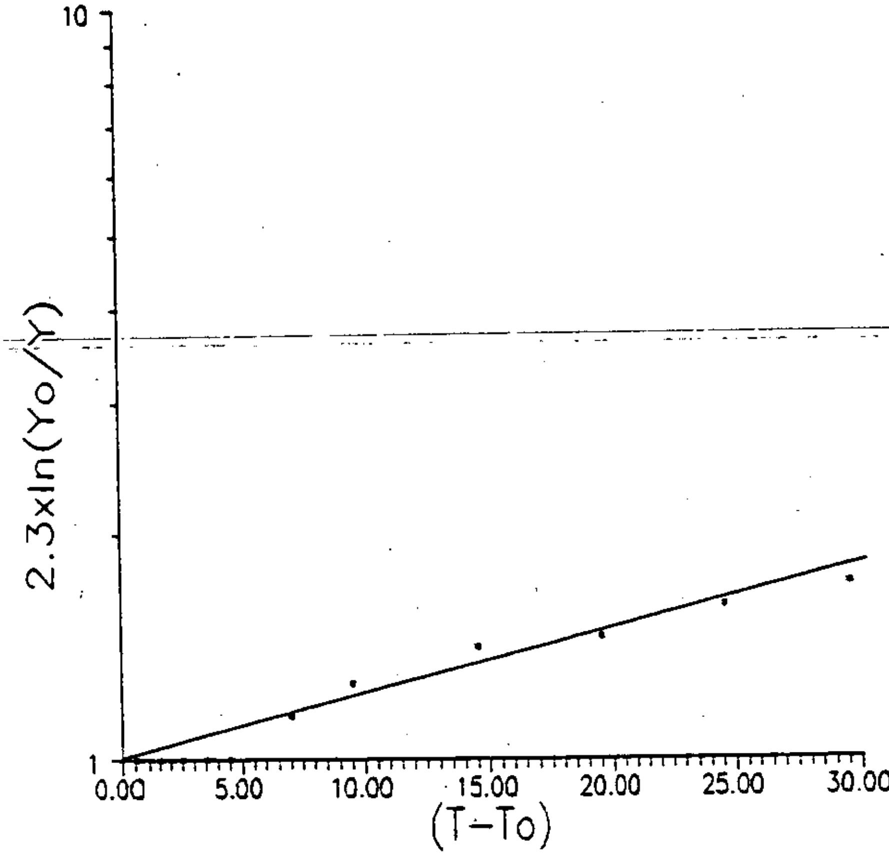
Y_0=26.0 cm

S =36.85 cm

A = 3.464cm^2

K=Ax[ln(Y_0/Y_2)-ln(Y_0/Y_2)/[(t_2-t_0)-(t_1-t_0)]
therefore

K=5.41x10^{-1} m/day



HVORSLEV RISING HEAD TEST
FOR PIEZOMETER A7-5

TIME(mins) $(t-t_0)$	Y_0/Y
0.5	1.00
1.5	1.00
2.5	1.00
3.5	1.00
4.5	1.00
7.0	1.143
9.5	1.263
14.5	1.412
19.5	1.455
24.5	1.60
29.5	1.71

Y_0=26.0 cm

S =36.85 cm

A = 3.464cm^2

$K=Ax[\ln(Y_0/Y_2)-\ln(Y_0/Y_1)/[(t_2-t_0)-(t_1-t_0)]$
therefore

$K=2.7x10^{-2}$ m/day

APPENDIX V

PUMP TEST DATA

PUMP TEST DATA FOR PUMPED LIMESTONE PIEZOMETER

AT CLBH-2 (GRAVEL PIEZO. OBSERVATION DATA)

Time(mins)	Drawdown(m)
0.0	0.00
0.5	0.02
1.0	0.04
2.0	0.05
2.5	0.06
3.0	0.06
3.5	0.06
4.0	0.06
4.5	0.06
5.0	0.06
6.0	0.06
7.0	0.06
8.0	0.06
9.0	0.065
10.0	0.06
15.0	0.09
20.0	0.09
25.0	0.09
30.0	0.09
35.0	0.09
40.0	0.09
45.0	0.09
55.0	0.09
60.0	0.09

S.W.L. = 0.73m BELOW TOP OF TUBE.

$T = 2.3\ Q / 4\pi\ \delta s$ (Jacob)

$Q = 85\ m^3$ /day

$\delta s = 0.032$ m

=> T = 48.62 m^2 /day.

$T = (Q / 4\pi s).W(u, r/l)$ (Walton).

=> T = 16.1 m^2/day (Specific storage indeterminate since r unknown).

PUMP TEST DATA FOR PUMPING LIMESTONE PIEZOMETER

AT CLBH-2 (LIMESTONE PIEZO. OBSERVATION DATA)

Time(mins)	Drawdown(m)
0.0	8.54
0.5	5.36
1.0	2.74
1.5	1.88
2.0	1.20
3.0	0.40
4.0	0.20
5.0	0.13
6.0	0.10
0.7	0.08
8.0	0.06
9.0	0.06
10.0	0.05
15.0	0.03
20.0	0.025
25.0	0.015
30.0	0.02
45.0	0.01
60.0	0.00

S.W.L = 0.60m below top of tube.

Transmissivity indeterminate from data.

PUMP TEST RECOVERY DATA FOR CLAYEY GRAVEL PIEZOMETER AT CLBH-2 (GRAVEL PIEZO. PREVIOUSLY PUMPED)

Time since pumping ended.(mins)	Drawdown(m)	t/t'
5.0	0.97	37.00
6.0	0.92	31.00
7.0	0.90	26.70
8.0	0.86	23.50
9.0	0.84	21.00
10.0	0.82	19.00
11.0	0.81	17.36
12.0	0.77	16.00
13.0	0.75	14.85
14.0	0.73	13.90
15.0	0.68	13.00
17.0	0.64	11.59
19.0	0.60	10.47
20.0	0.58	10.00
25.0	0.52	8.20
30.0	0.45	7.00
35.0	0.42	6.14
40.0	0.38	5.50
45.0	0.36	5.00
60.0	0.30	4.00
85.0	0.26	3.12

S.W.L.= 0.77m below top of tube.

$T = 2.3\ Q / 4\ \pi\ \delta S$ (Theis recovery)

$Q = 60\ m^3/day$

$\delta s = 0.6\ m$

$T = 18.3\ m^2/day$.

Piezometer: A 5-7 Humification: H8

Imposed head(cm) 40.5 Shape factor: 0.365m

Initiallevel 22.7

Time (Hrs.)	Vessel level (cm)	Level dropped (cm)	Flow $x10^{-2}$ (m^3/day)	K (m/Day)
1.16	20.6	2.1	1.51	10.1
1.5	20.2	0.4	0.67	4.5
2.0	19.4	0.8	1.31	9.0
2.5	18.9	0.5	0.84	5.63
3.0	18.4	0.5	0.84	5.63
3.5	17.5	0.9	1.51	1.01
4.0	16.9	0.6	1.01	6.75
4.5	16.4	0.5	0.84	5.63
5.0	16.0	0.4	0.67	4.50
5.5	15.7	0.3	0.50	3.40
6.0	15.4	0.3	0.50	3.40
6.5	15.2	0.2	0.34	2.25

Piezometer: A 4-9 Humification: H7

Imposed head(cm) 33.0 Shape factor: 0.365m

Initiallevel: 23 cm.

Time Hrs.)	Vessel level (cm)	Level dropped (cm)	Flow $x10^{-1}$ (m^3/day)	K (m/Day)
0.25	18.0	5.0	1.68	1.38
0.5	13.6	4.4	1.48	1.21
1.0	7.0	6.6	1.11	0.91
1.5	2.0	5.0	0.84	0.69

Piezometer: A 7-2 Humification: H_2

Imposed head(cm) 66.0 Shape factor: 0.365

Initiallevel : 24.3 cm.

Time	Vessel level	Level dropped	Flow	K
			x 10^{-2}	x 10^{-1}
(Hrs.)	(cm)	(cm)	(m^3/Day)	(m/Day)
0.5	21.8	2.5	4.20	4.18
1.0	19.9	1.9	3.19	3.18
1.5	18.5	1.4	2.35	2.34
2.0	16.9	1.6	2.69	2.68
2.5	15.7	0.9	1.51	1.50
3.0	14.3	1.4	2.35	2.34
3.5	12.9	1.4	2.35	2.34
4.0	11.5	1.4	2.35	2.34
4.5	10.2	1.3	2.18	2.17

Piezo. A7-2 (new setting)

Imposed head: 0.305 Initialvalue: 22.7

Time	Vessel level	Level dropped	Flow	K
			x 10^{-2}	x 10^{-1}
(Hrs.)	(cm)	(cm)	(m^3/Day)	(m/Day)
0.5	19.3	3.4	5.70	5.12
1.0	16.9	2.4	4.03	3.62
1.5	14.5	2.4	4.03	3.62
2.0	12.5	2.0	3.36	3.02

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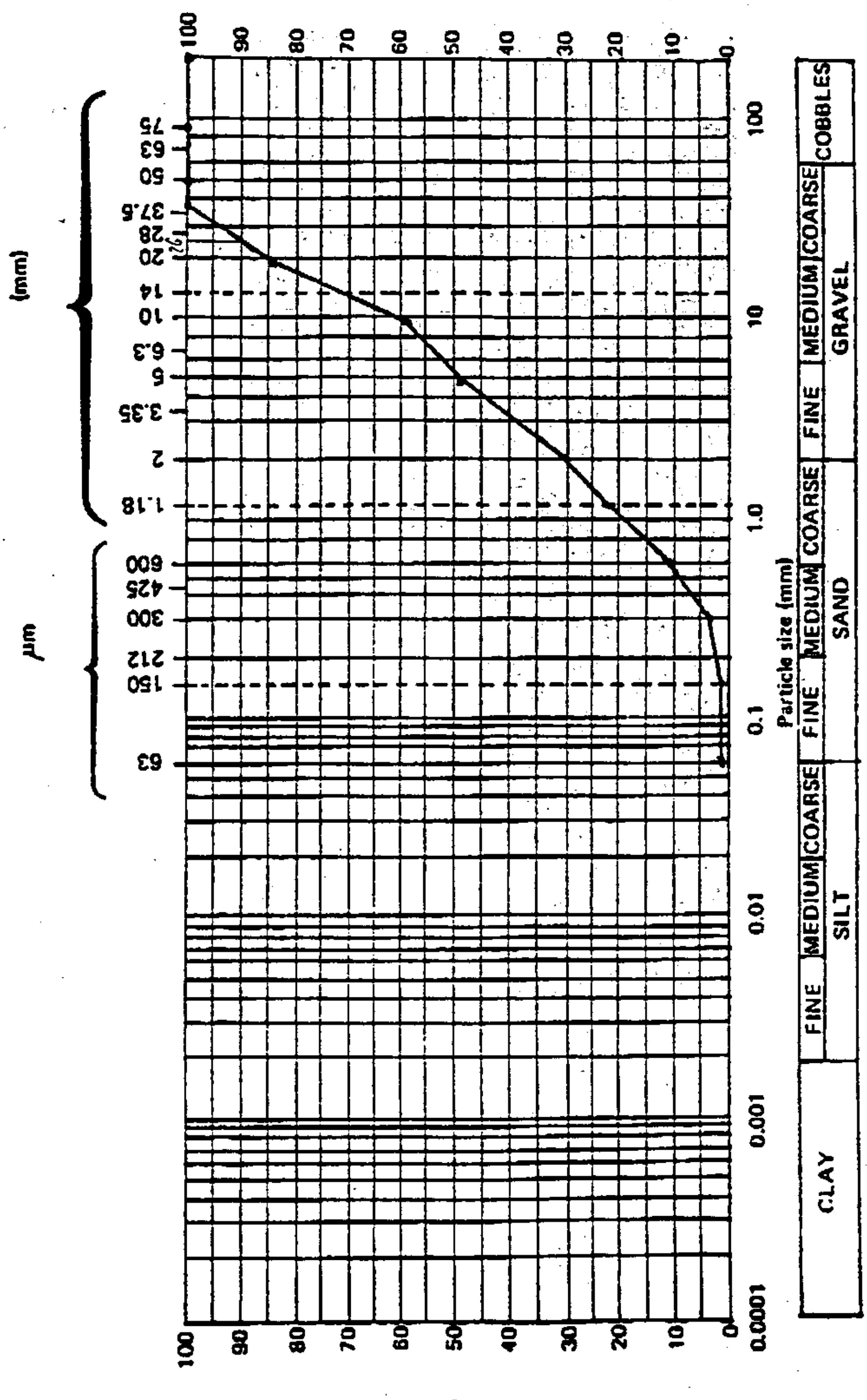
...port No. 1534	PARTICLE SIZE ANALYSIS	IGSL
...tract	GEOLOGICAL SURVEYS IRELAND	Borehole No. CLBH-2
...hod of Test	Dry	Sample No. 27
		Depth
...mple Description	Grey sandy GRAVEL	



PUMP TEST RECOVERY DATA FOR LIMESTONE PIEZOMETER

AT CLBH-2 (GRAVEL PIEZO. PREVIOUSLY PUMPED)

Time since pumping ended (mins)	Drawdown (m)	t/t'
1.5	0.43	121.00
2.5	0.36	73.00
3.5	0.31	52.00
4.5	0.28	41.00
5.5	0.26	33.73
6.5	0.24	28.70
7.5	0.22	25.00
8.5	0.21	22.18
9.5	0.20	19.94
10.5	0.19	18.14
11.5	0.18	16.65
12.5	0.17	15.40
13.5	0.16	14.50
14.5	0.16	14.30
16.0	0.16	12.25
18.0	0.14	11.00
20.0	0.13	10.00
25.0	0.12	8.20
30.0	0.10	7.00
35.0	0.09	6.14
40.0	0.08	5.50
45.0	0.07	5.00
60.0	0.06	4.00
85.0	0.05	3.11

S.W.L.= 0.60m below top of tube.

$T = 2.3\ Q / 4 \pi \delta S$ (Theis recovery)

$Q = 60\ m^3/day$

$\delta s = 0.26$ m

$T = 42.23\ m^2/day$.

PUMP TEST RECOVERY DATA FOR LIMESTONE PIEZOMETER

AT CLBH-2 (LIMESTONE PIEZO. PREVIOUSLY PUMPED)

Time since pumping ended(mins)	Drawdown(m)	t/t'
0.0	8.54	-----
1.0	2.74	61.00
1.5	1.88	41.00
2.0	1.20	31.00
3.0	1.00	21.00
4.0	0.20	16.00
5.0	0.13	13.00
6.0	0.10	11.00
7.0	0.08	9.57
8.0	0.06	8.50
9.0	0.06	7.67
10.0	0.05	7.00
15.0	0.03	5.00
20.0	0.025	4.00
25.0	0.015	3.40
30.0	0.02	3.00
45.0	0.01	2.30

S.W.L = 0.60m below top of tube.

Transmissivity indeterminate from data.

PUMP TEST RECOVERY DATA FOR GRAVEL PIEZOMETER

AT CLBH-2 (GRAVEL PIEZO. PREVIOUSLY PUMPED)

Time since pumping ended. (mins)	Drawdown(m)	t/t'
0.5	0.87	361.00
1.0	0.70	181.00
2.0	0.63	91.00
3.0	0.59	61.00
4.0	0.55	46.00
5.0	0.51	37.00
6.0	0.48	31.00
7.0	0.46	26.70
8.0	0.44	23.50
9.0	0.42	21.00
10.0	0.40	19.00
11.0	0.38	17.36
12.0	0.37	16.00
13.0	0.35	14.85
14.0	0.34	13.90
15.0	0.33	13.00
17.0	0.31	11.59
19.0	0.30	10.47
20.0	0.28	10.00
25.0	0.25	8.20
30.0	0.22	7.00
35.0	0.20	6.14
40.0	0.18	5.50
45.0	0.17	5.00
60.0	0.13	4.00
85.0	0.11	3.12

S.W.L.= 0.77m below top of tube.

$T = 2.3\ Q / 4\pi\ \delta S$ (Theis recovery)

$Q = 60\ m^3/day$

$\delta s = 0.38\ m$

$T = 28.9\ m^2/day$.

PUMP TEST RECOVERY DATA FOR GRAVEL PIEZOMETER

AT CLBH-2 (LIMESTONE PIEZO. PREVIOUSLY PUMPED)

Time since pumping ended (mins)	Drawdown (m)	t/t'
0.0	0.09	-----
3.5	0.07	18.14
4.5	0.06	14.33
6.0	0.04	11.00
7.0	0.04	9.57
8.0	0.03	8.50
9.0	0.03	7.67
10.0	0.03	7.00
15.0	0.02	5.00
20.0	0.02	4.00
25.0	0.01	3.40
30.0	0.01	3.00

S.W.L. = 0.77m below top of tube.

$T = 2.3\,Q / 4\pi\,\delta S$ (Theis recovery)

$Q = 8.46\ m^3/day$

$\delta s = 0.51\ m$

$T = 30.36\ m^2/day$.

PUMP TEST DATA FOR PUMPED LIMESTONE PIEZOMETER

AT CLBH-2(CLAYEY GRAVEL PIEZO. OBSERVATION DATA).

Time(mins)	Drawdown(m)
0.0	0.00
3.0	0.005
3.5	0.005
4.0	0.005
4.5	0.005
5.0	0.005
6.0	0.015
7.0	0.020
8.0	0.025
9.0	0.025
10.0	0.025
15.0	0.055
20.0	0.045
25.0	0.045
30.0	0.045
35.0	0.055
40.0	0.055
45.0	0.065
60.0	0.065

S.W.L.= 0.77m below top of tube.

$T = (Q / 4 \pi s).W(u ,r/l)$ (Walton).

$S = 4 T t / r^2$.

(r value indeterminate therefore S not calcuatable)

$T = 1.93$ m²/day approx.

PUMP TEST RECOVERY DATA FOR CLAYEY GRAVEL PIEZØ. AT CLBH-2 (LIMESTONE PIEZOMETER PREVIOUSLY PUMPED).

Time since stoped	Drawdown(m)	t/t'
0.0	0.075	18.14
3.5	0.065	14.33
4.5	0.055	11.00
6.0	0.055	9.57
7.0	0.055	8.50
8.0	0.055	7.67
9.0	0.050	7.00
10.0	0.045	5.00
15.0	0.035	4.00
20.0	0.025	3.40
25.0	0.015	3.00
30.0	0.005	

S.W.L.= 0.77m below top of tube.

T = 2.3 Q / 4 π δS (Theis recovery)

Q = 8.46 m^3/day

δs = 0.047m

T = 33.9 m^2/day.

PUMP TEST DATA FOR PUMPED GRAVEL PIEZOMETER

AT CLBH-2(PUMPING WELL DATA).

Time(mins)	Drawdown(m)
0.0	0.00
0.5	0.97
2.0	1.13
3.0	1.22
4.0	1.28
5.0	1.33
7.0	1.40
9.0	1.47
10.0	1.49
15.0	1.59
20.0	1.65
25.0	1.73
30.0	1.77
45.0	1.85
60.0	1.89
75.0	1.92
90.0	1.945
105.0	1.97
120.0	1.99
150.0	2.01
180.0	2.04

S.W.L.= 0.73m below top of tube.

$T = 2.3\ Q\ /\ 4\ \pi\ \delta s$ (Jacob)

$Q = 60.0\ m^3/day$

$\delta s = 0.047m$

$T = 33.9\ m^2/day$.

PUMP TEST DATA FOR PUMPED GRAVEL PIEZOMETER

AT CLBH-2(LIMESTONE PIEZO. OBSERVATION DATA).

Time(mins)	Drawdown(m)
0.0	0.00
1.5	0.10
2.5	0.19
3.5	0.25
4.5	0.28
6.0	0.32
8.0	0.38
10.0	0.40
15.0	0.45
20.0	0.48
25.0	0.51
30.0	0.53
45.0	0.57
60.0	0.59
75.0	0.61
90.0	0.615
105.0	0.625
120.0	0.63
150.0	0.64
180.0	0.65

S.W.L. = 0.6m below top of tube

T = (Q / 4 π s).W(u ,r/l) (Walton).

Q = 60 m^3/day

s = 1.4m : t = 1.4 min

W(u,r/l) = 2: u = 1

=> T = 6.8 m^2/day

Specific storage indeterminate r = 0.25

give nonsense value of 41.05

PUMP TEST DATA FOR PUMPED GRAVEL PIEZOMETER

AT CLBH-2(LIMESTONE PIEZO. OBSERVATION DATA).

Time(mins)	Drawdown(m)
0.0	0.00
1.5	0.00
2.5	0.05
3.5	0.11
4.5	0.16
6.0	0.22
8.0	0.36
10.0	0.45
15.0	0.63
20.0	0.74
25.0	0.88
30.0	0.95
45.0	1.10
60.0	1.17
75.0	1.20
90.0	1.23
105.0	1.25
120.0	1.28
150.0	1.33
180.0	1.36

PUMP TEST DATA FOR PUMPED LIMESTONE PIEZOMETER

AT CLBH-2(PUMPING BOREHOLE DATA).

Time(mins)	Drawdown(m)
0.0	0.00
2.0	7.87
10.0	8.52
15.0	9.32
20.0	8.70
25.0	8.55
30.0	>8.97
35.0	8.80
40.0	>9.02
45.0	9.50
55.0	8.54
57.0	8.83
60.0	8.54

S.W.L. = 0.60 m below top of tube.

Data not analysable.

PUMP TEST DATA FOR PUMPING GRAVEL BOREHOLE.
(PUMPING BOREHOLE DATA).

Time since pumping started. (mins)	Drawdown (metres)
0.00	0.00
0.5	0.11
1.0	0.11
2.0	0.11
3.0	0.115
5.0	0.12
10.0	0.13
15.0	0.13
20.0	0.135
25.0	0.14
30.0	0.135
45.0	0.135
60.0	0.135
90.0	0.135
120.0	0.135
180.0	0.135
240.0	0.14
300.0	0.145
360.0	0.145
385.0	0.145

S.W.L. = 6.41 m below top of casing.

Drawdown in gravel piezo at end of test = 0.02

$T = 2.3\ Q\ /\ 4\ \pi\ \delta S$ (Jacob)

$Q = 118.0\ m^3/day$

$\delta s = 0.014\ m$

$T = 1542.66\ m^2/day$.

PUMP TEST RECOVERY DATA FOR ESKER BOREHOLE

Time since pumping stopped (mins)	Drawdown (metres)	t/t'
0.00	0.145	-----
0.25	0.07	1789
0.50	0.06	895
1.00	0.05	448
2.00	0.03	224.5
3.00	0.03	149
5.00	0.035	90.4
10.00	0.025	45.7
15.00	0.02	30.8
20.00	0.02	23.35
25.00	0.02	18.88
30.00	0.02	15.90
45.00	0.015	10.93
60.00	0.01	8.45
90.00	0.01	5.967
100.00	0.01	5.47

S.W.L. = 6.41 m below top of well.

$T = 2.3\ Q / 4\ \pi\ \delta S$ (Jacob)

$Q = 118.0\ m^3/day$

$\delta s = 0.019\ m$

$T = 1136.70\ m^2/day$.

APPENDIX VI

GRAIN SIZE ANALYSIS DATA

PARTICLE SIZE ANALYSIS

IGSL

Report No.

Contract: G.S.1

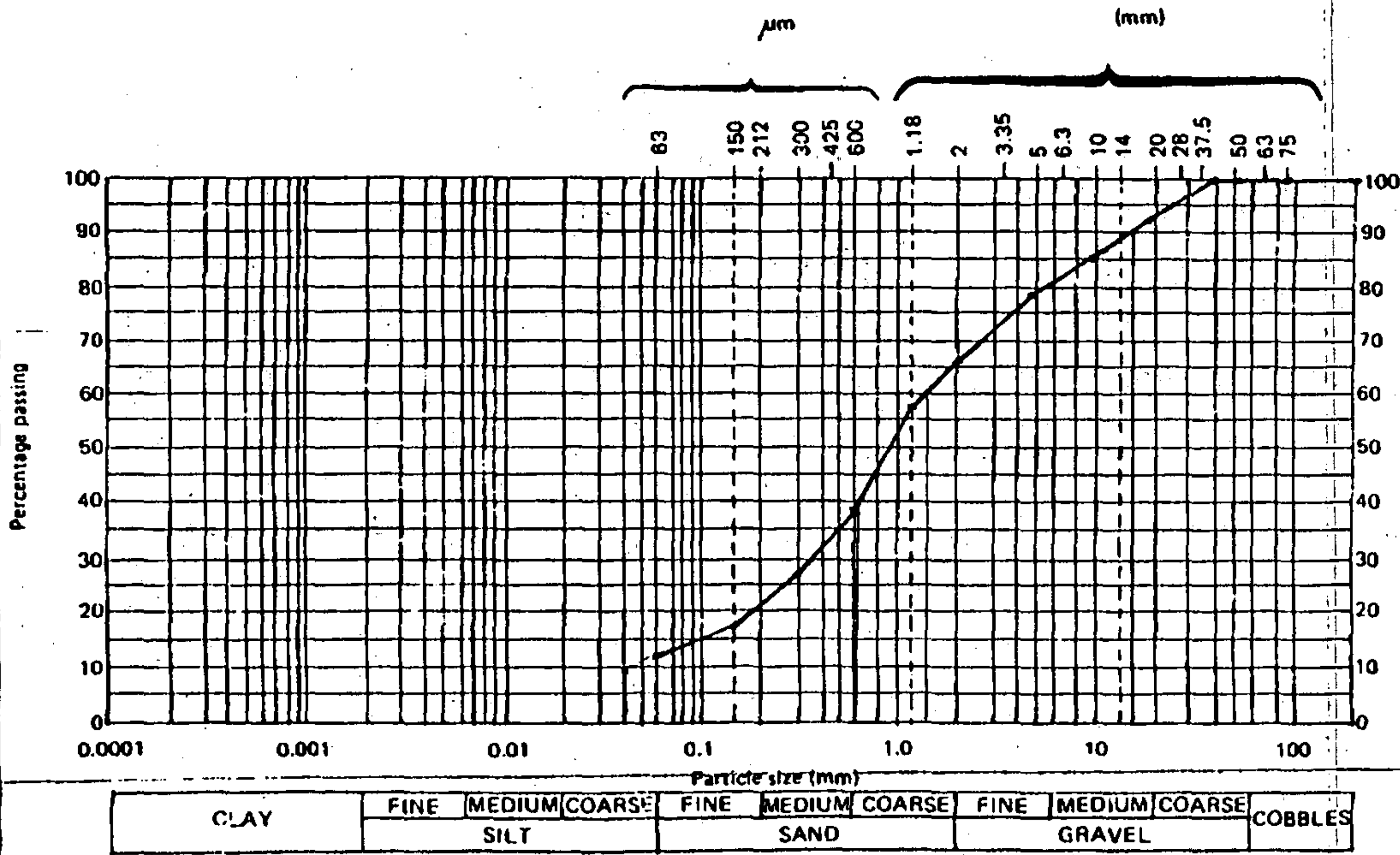
Method of Test: W/S

Sample Description

Borehole No.: CLBH-3

Sample No.: 11... 90

Depth: 1.0 - 1.40



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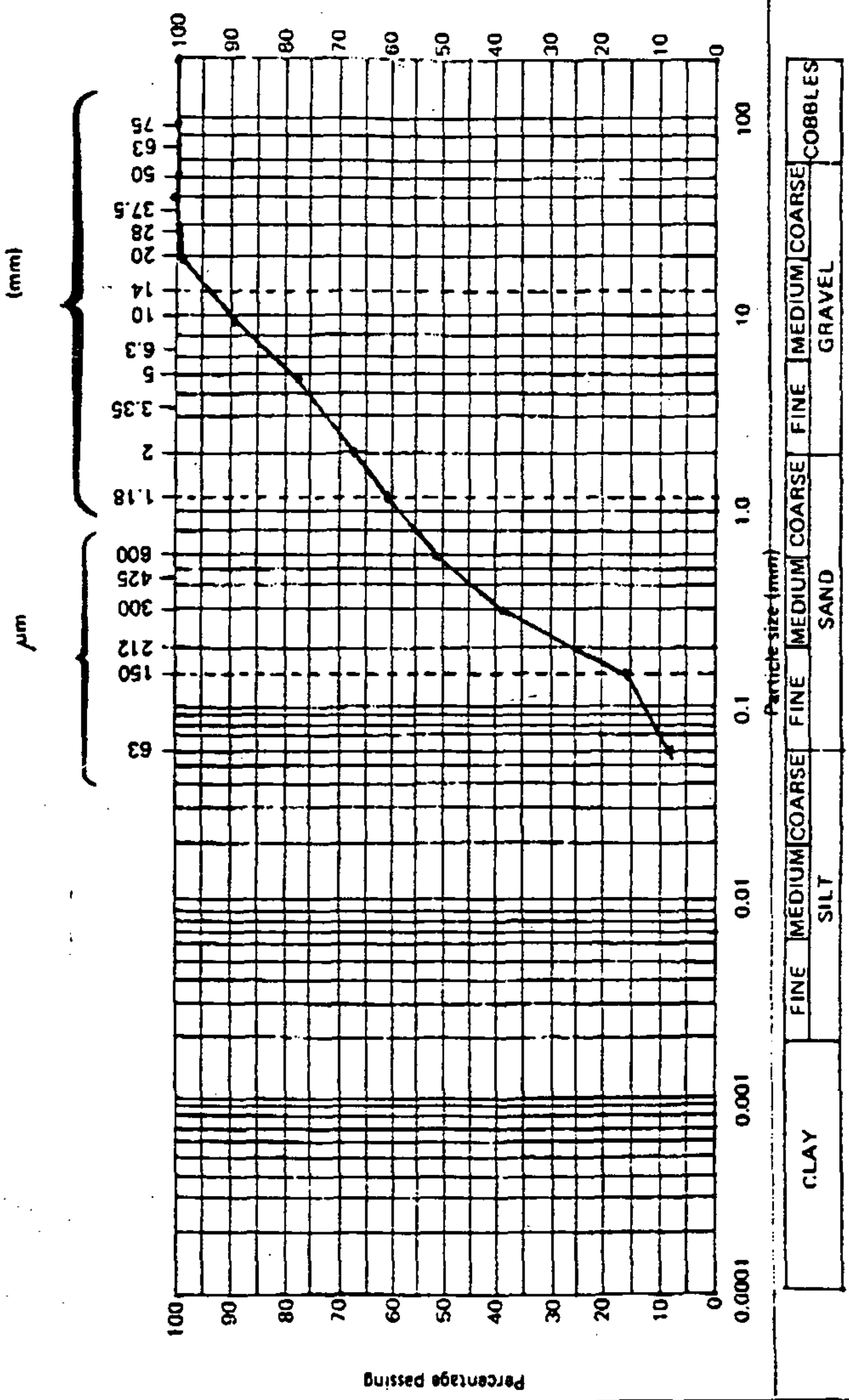
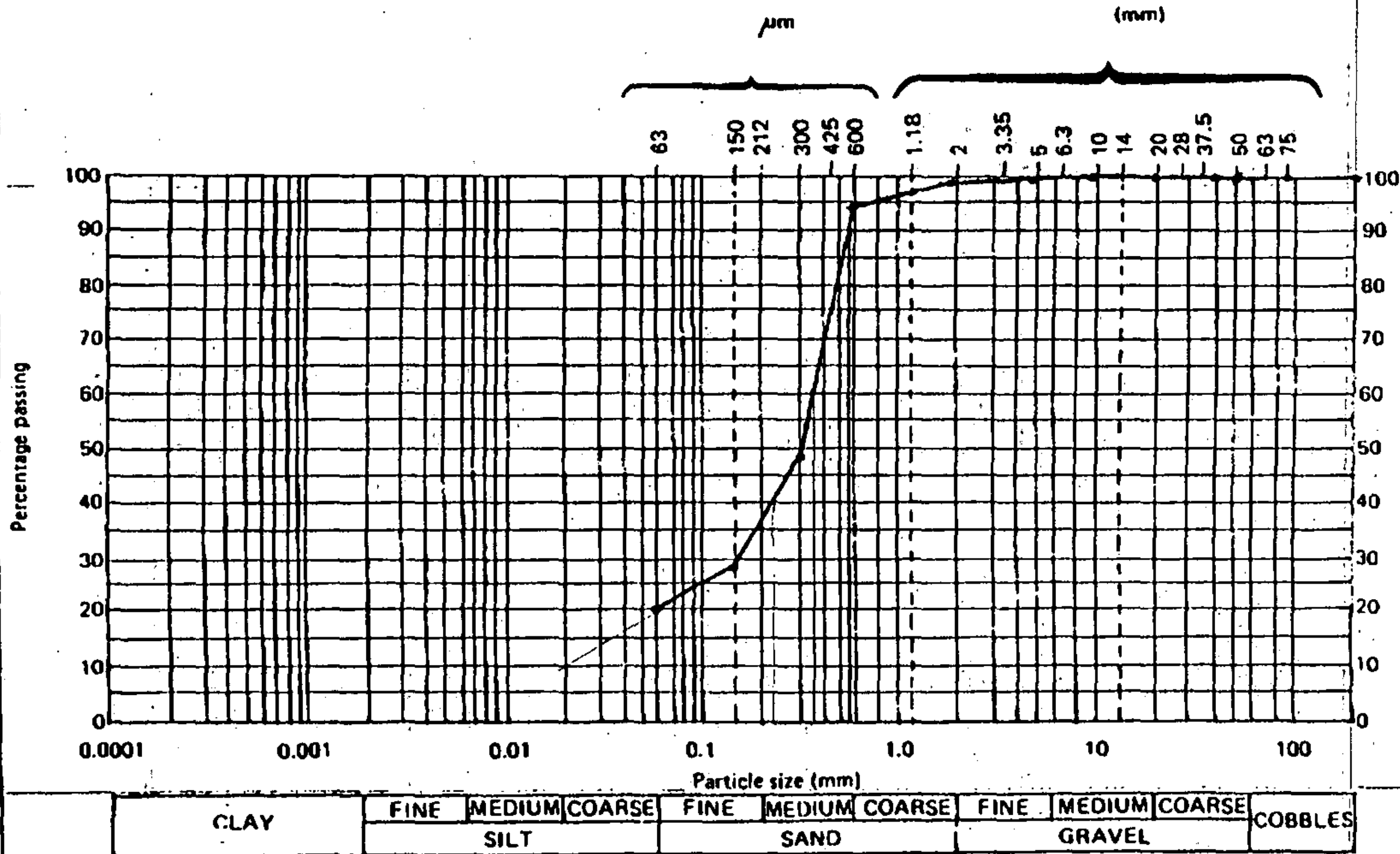
Report No.	PARTICLE SIZE ANALYSIS	IGSL
Contract G 1		Borehole No. ELBH-3
Method of Test ~/1/5		Sample No. 11 - 90
		Depth 3.75 - 4.50

Sample Description





PARTICLE SIZE ANALYSIS

IGSL

Report No.

Contract 651

Method of Test W/C

Sample Description

Borehole No. CLBH-3

Sample No. C4-3 11-90

Depth 6.75 – 7.50

184

PARTICLE SIZE ANALYSIS

IGSL

Report No.

Contract

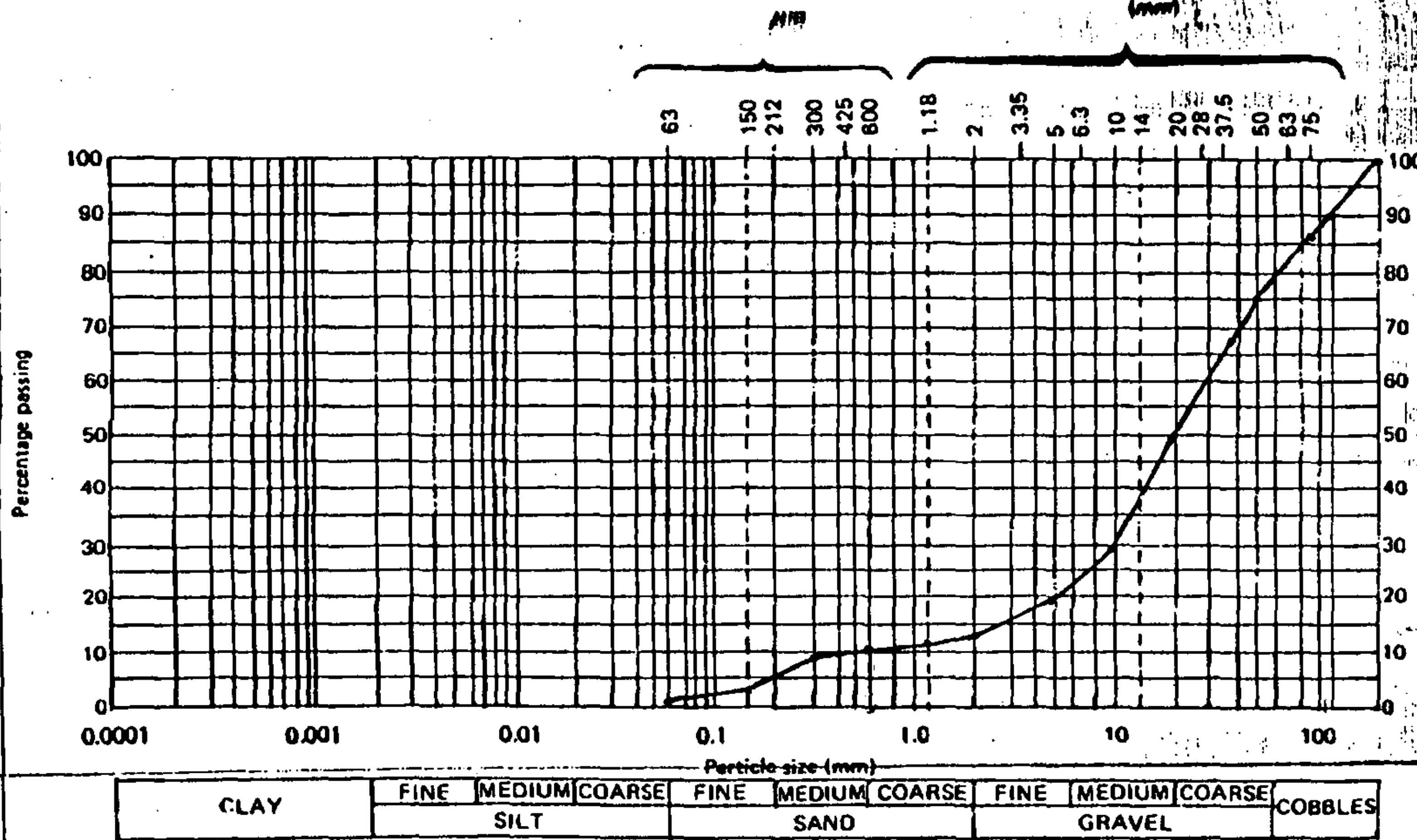
Method of Test

Sample Description

Borehole No. CL BH-3

Sample No. [illegible] 11-90

Depth [illegible]



PARTICLE SIZE ANALYSIS

IGSL

Report No.

Contract C S /

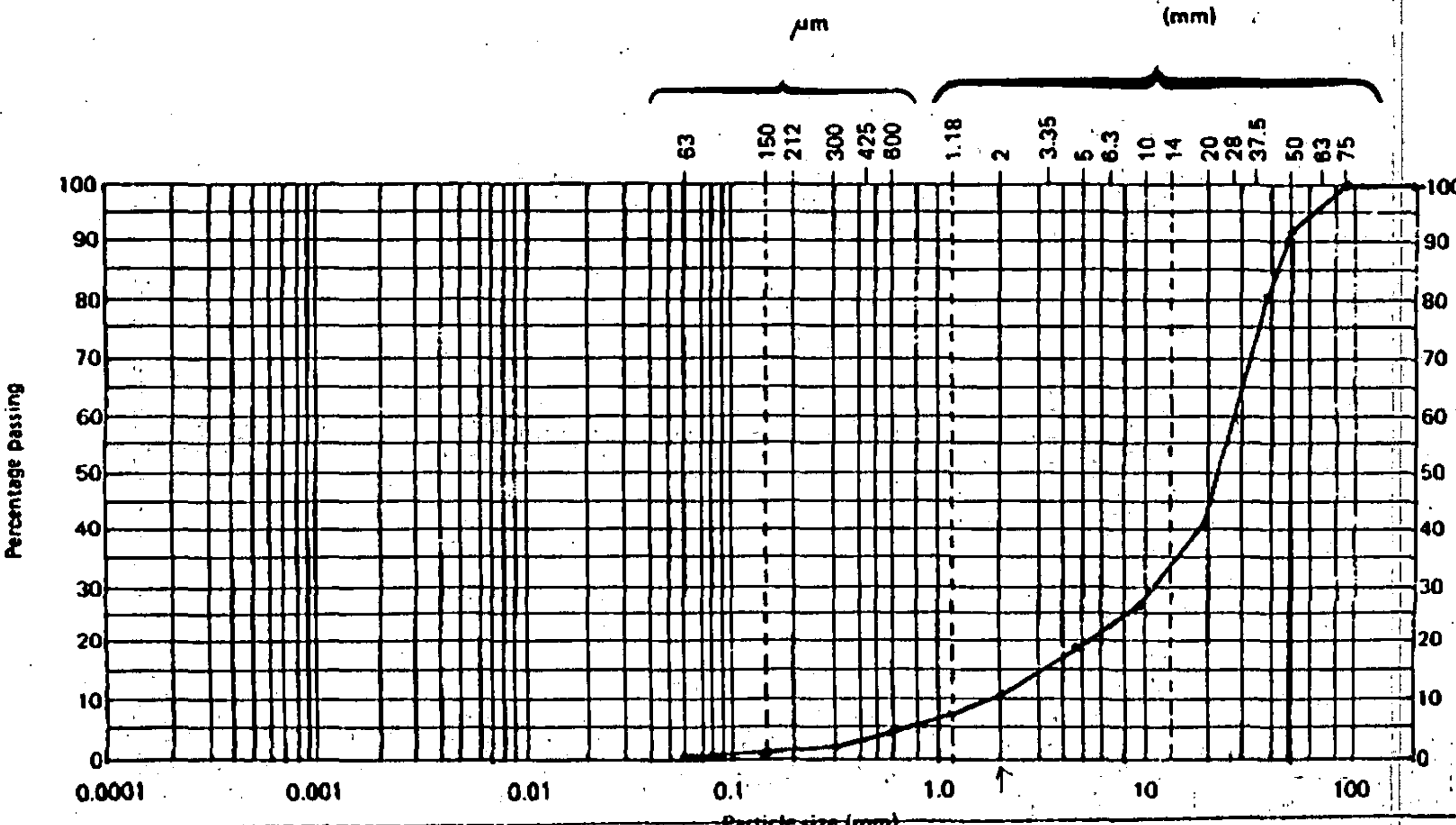
Method of Test S/S

Sample Description

Borehole No. CBH-3

Sample No. C6.3 11-90

Depth 12.75 - 13.50

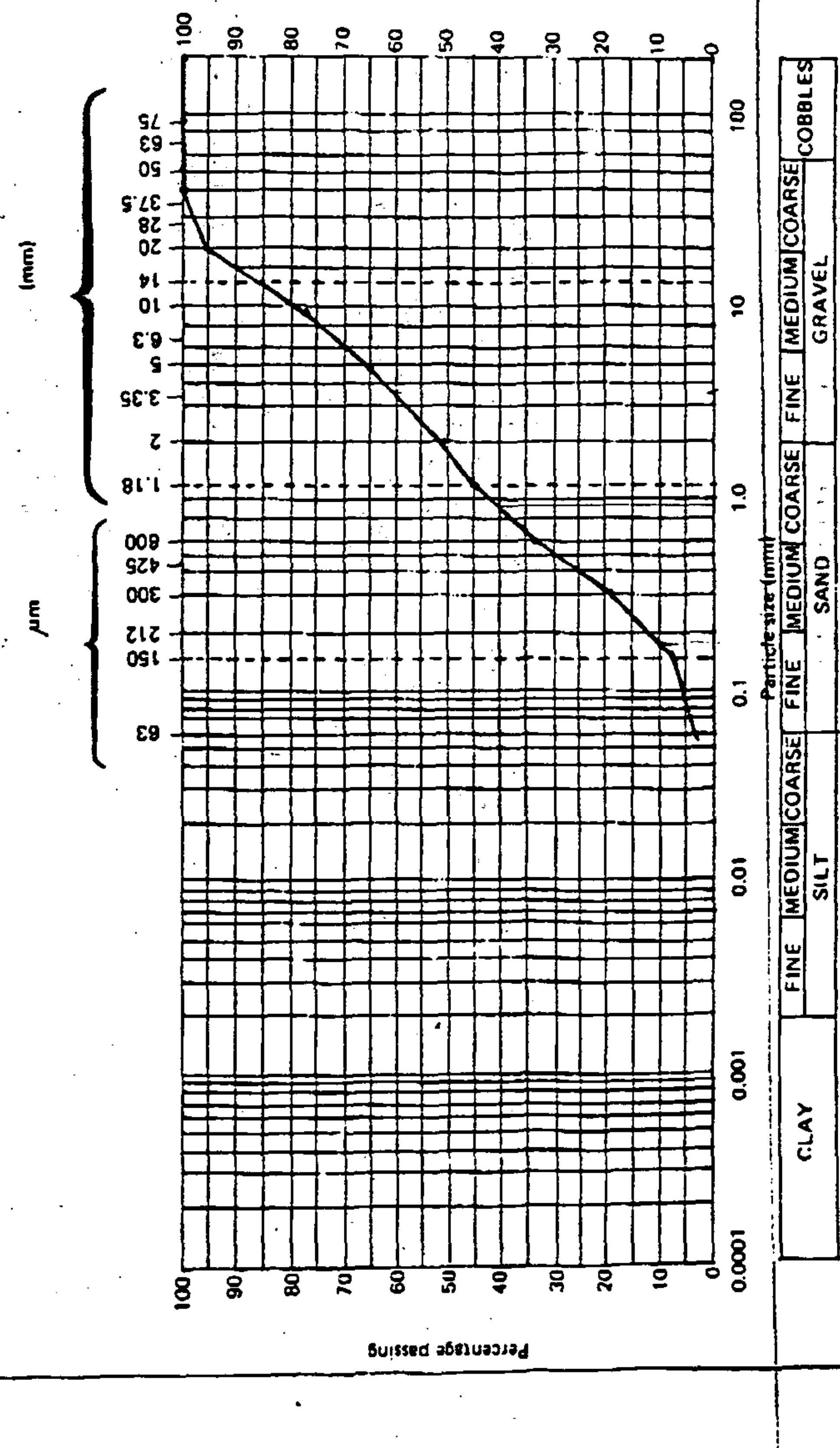


CLAY	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	COBBLES
	SILT			SAND			GRAVEL			

PARTICLE SIZE ANALYSIS

IGSL

Report No.	
Contract	GSI
Method of Test	U75
Borehole No.	CLBH-3
Sample No.	CL3 11-90
Depth	[illegible]
Sample Description	



PARTICLE SIZE ANALYSIS

Report No. 1534

Contract: GEOLOGICAL SURVEYS IRELAND

Method of Test: Dry

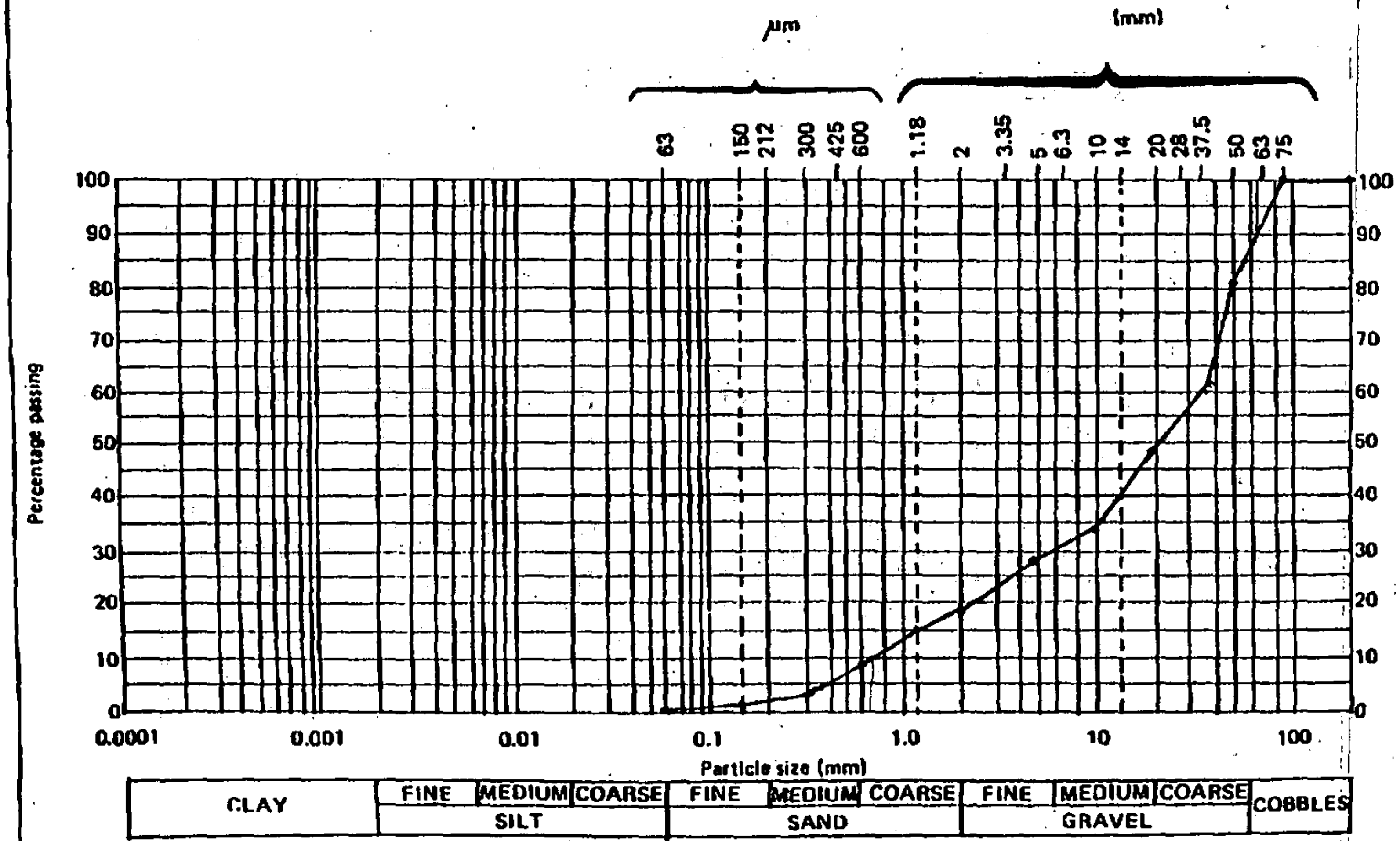
Sample Description: Grey sandy GRAVEL

Borehole No. CCBH-2

Sample No. 28

Depth

IGSL



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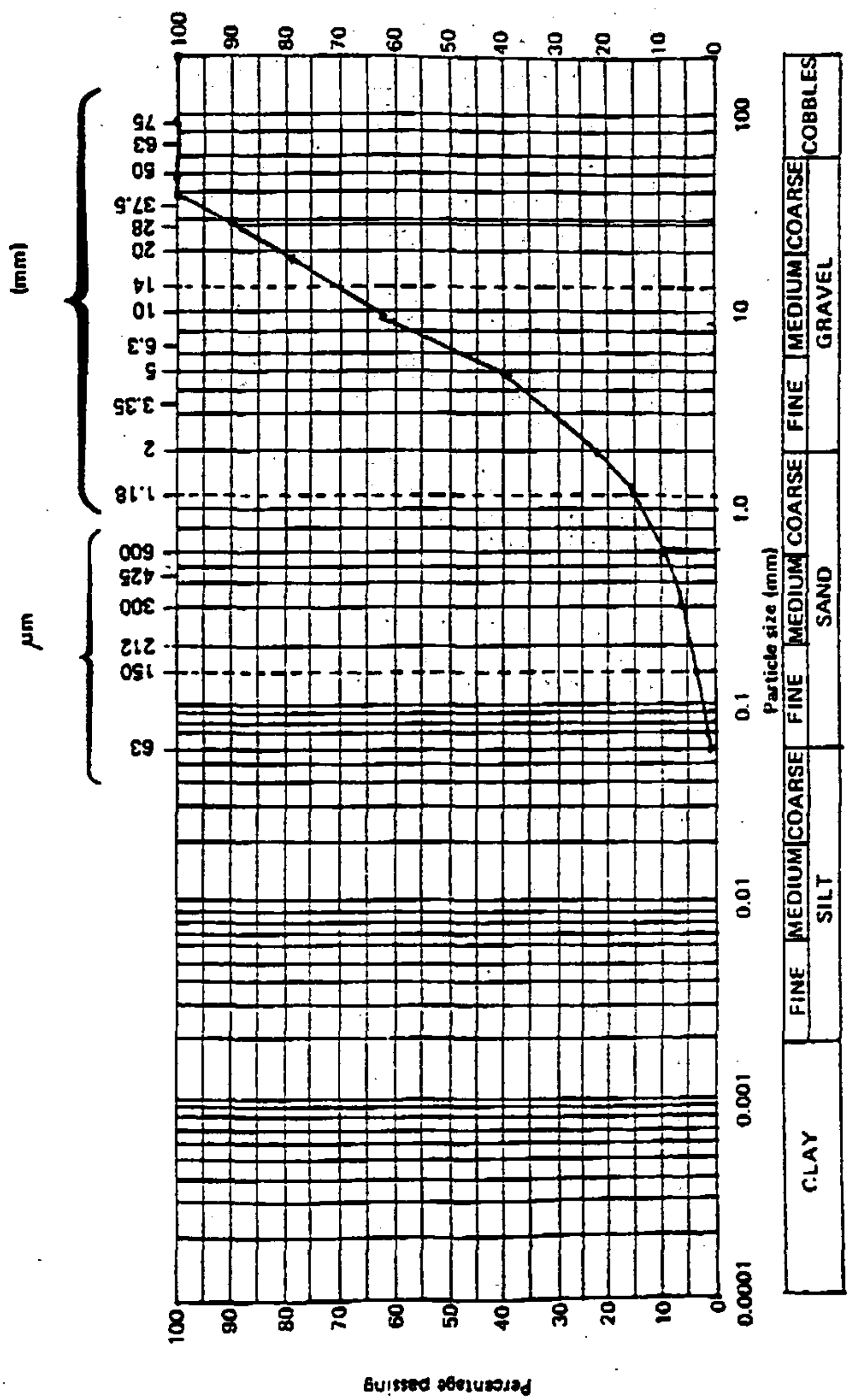
Report No. 1534	PARTICLE SIZE ANALYSIS	IGSL
Contract: GEOLOGICAL SURVEYS IRELAND		Borehole No. [illegible]-2
Method of Test: Dry		Sample No. 3
		Depth
Sample Description: Grey sandy GRAVEL		



10 SEP '90 14:11 353 1 681782

PARTICLE SIZE ANALYSIS

IGSL

Report No. 1534

Contract: GEOLOGICAL SURVEYS IRELAND

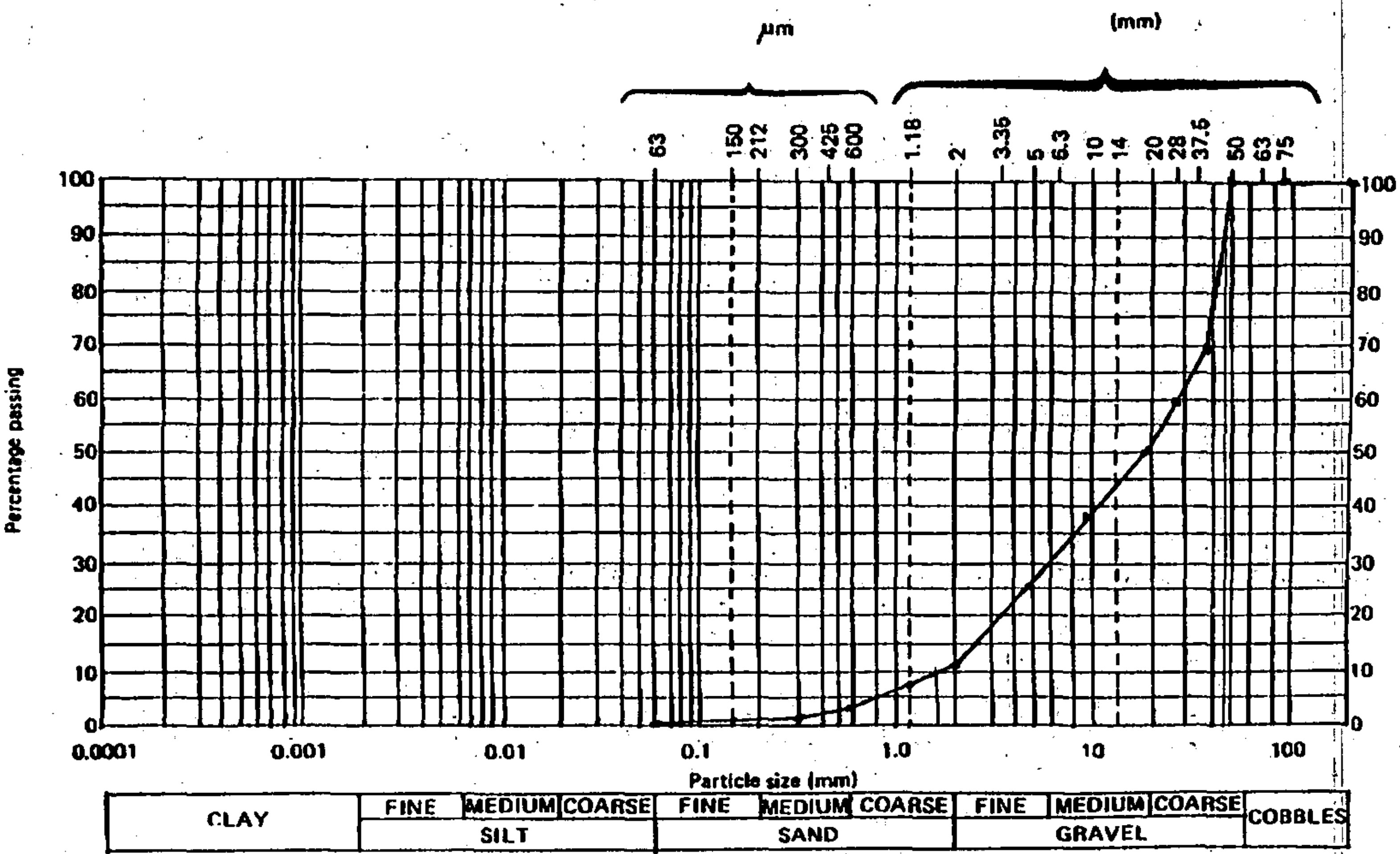
Method of Test: Dry

Sample Description: Grey sandy GRAVEL

Borehole No. CU4-2

Sample No. 11

Depth: 12 to 14'



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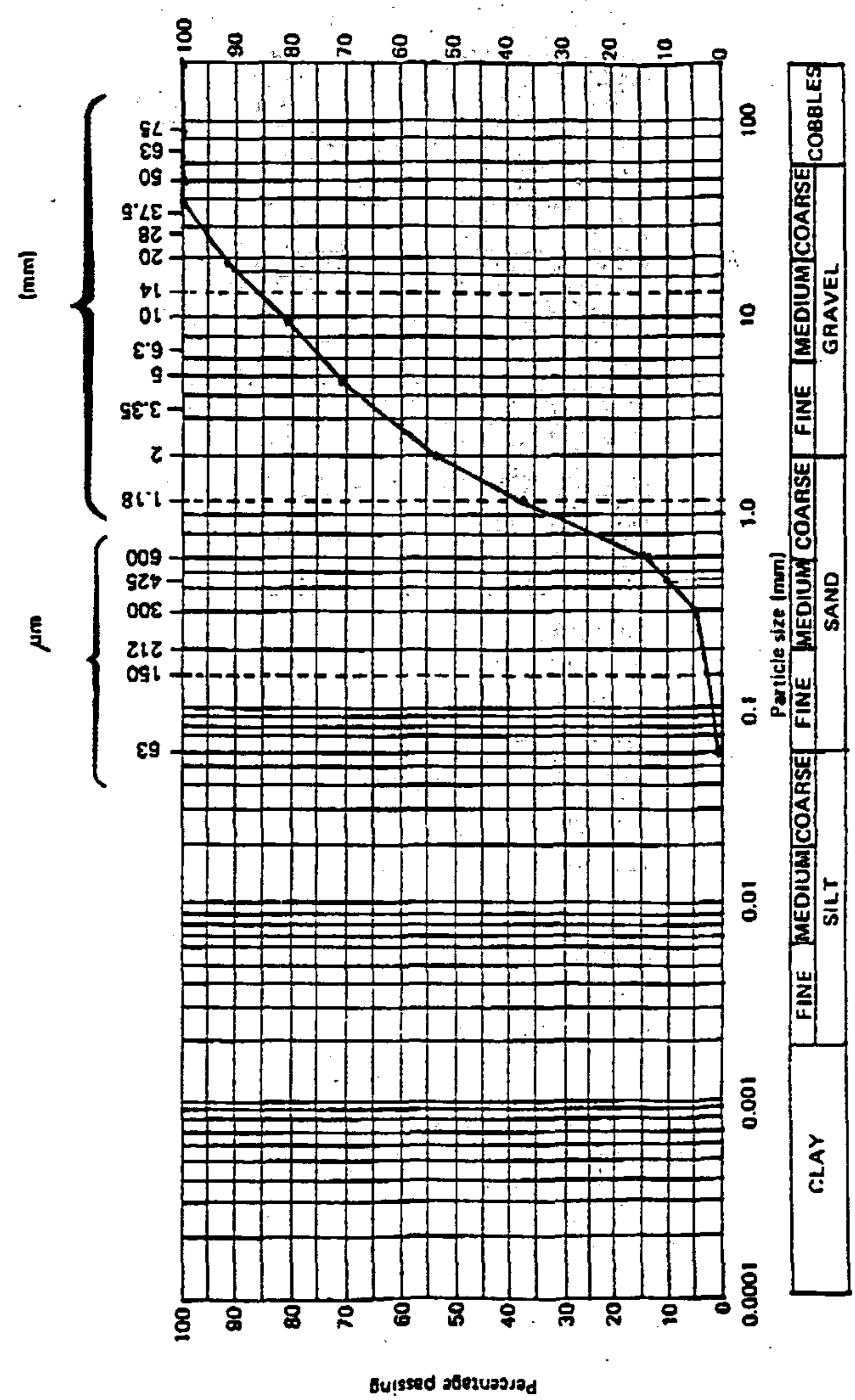
Report No. 1534	PARTICLE SIZE ANALYSIS	IGSL
Contract	GEOLOGICAL SURVEYS IRELAND	Borehole No. CLBH-2
Method of Test	Dry	Sample No. 12
		Depth
Sample Description	Grey SAND and GRAVEL	



PARTICLE SIZE ANALYSIS

IGSL

Report No. 1534

Contract: GEOLOGICAL SURVEYS IRELAND

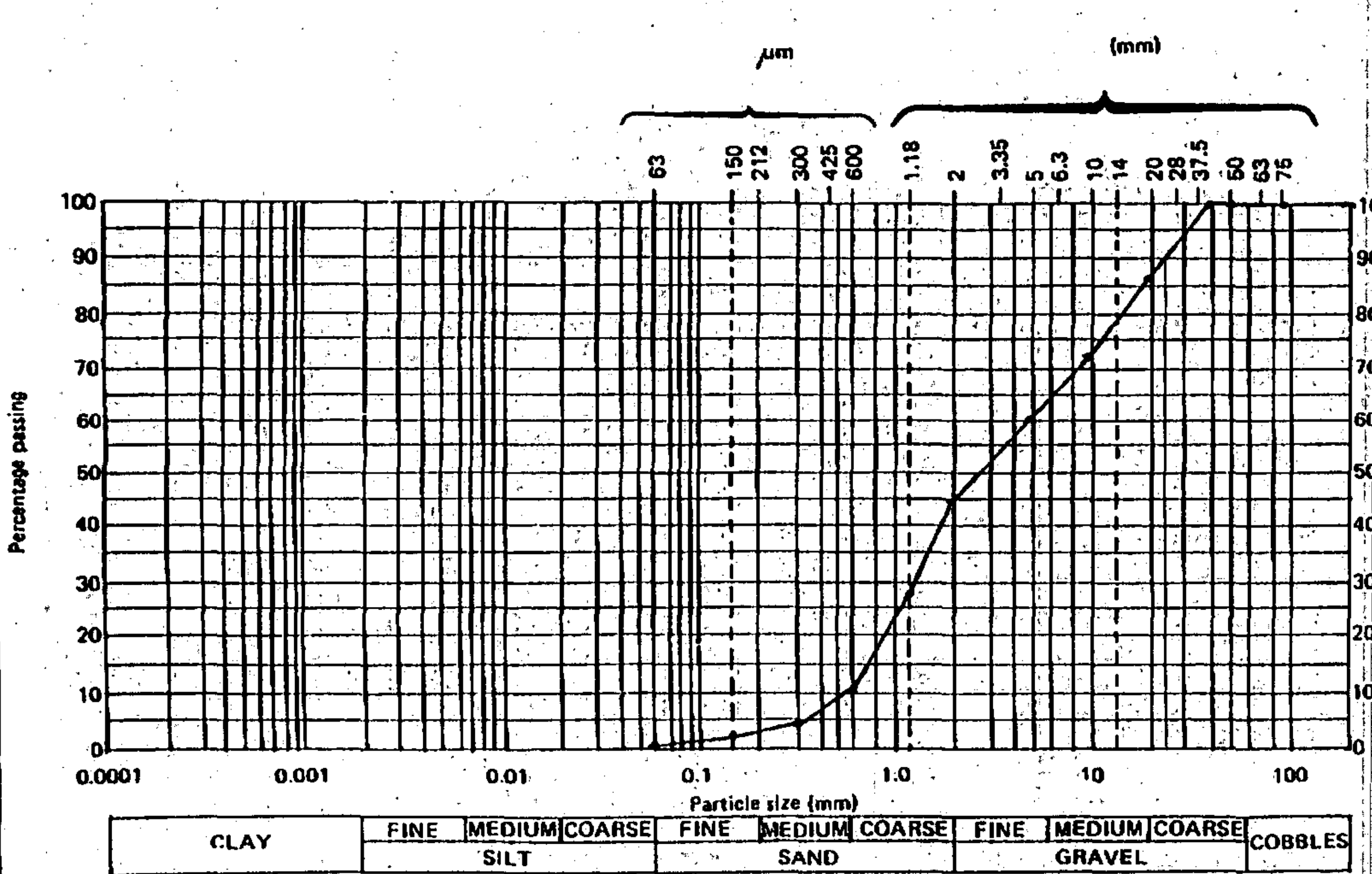
Method of Test: Dry

Sample Description: Grey very sandy GRAVEL

Borehole No. Cugy 2

Sample No. 15

Depth 17 to 18'



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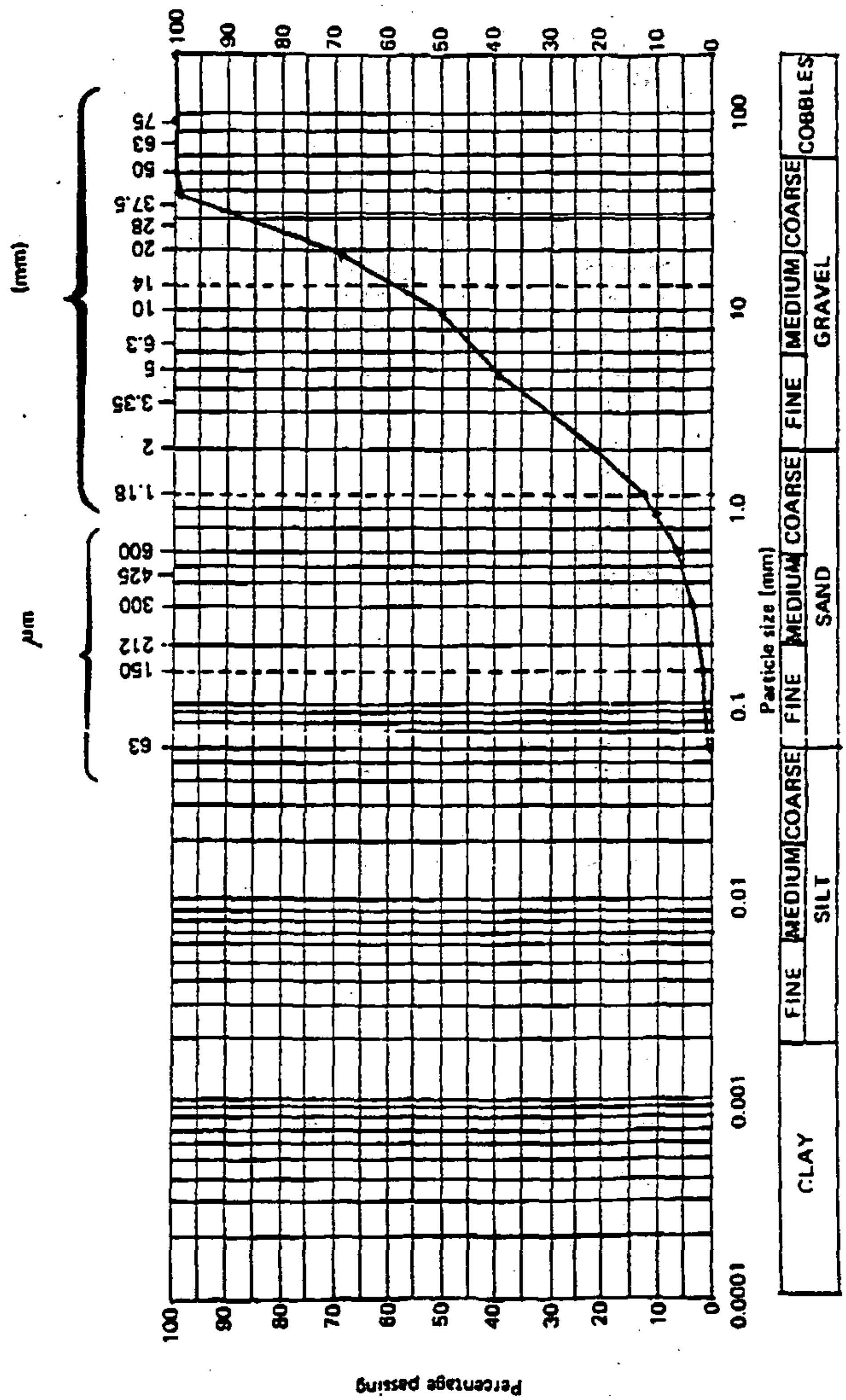
Report No. 1534	PARTICLE SIZE ANALYSIS	IGSL
Contract: GEOLOGICAL SURVEYS IRELAND		Borehole No. CWH-2
Method of Test: Dry		Sample No. 19
		Depth
Sample Description: Grey sandy GRAVEL (one large cobble omitted from grading analysis)		



Report No. 1534

PARTICLE SIZE ANALYSIS

Contract: GEOLOGICAL SURVEYS IRELAND

Method of Test: Dry

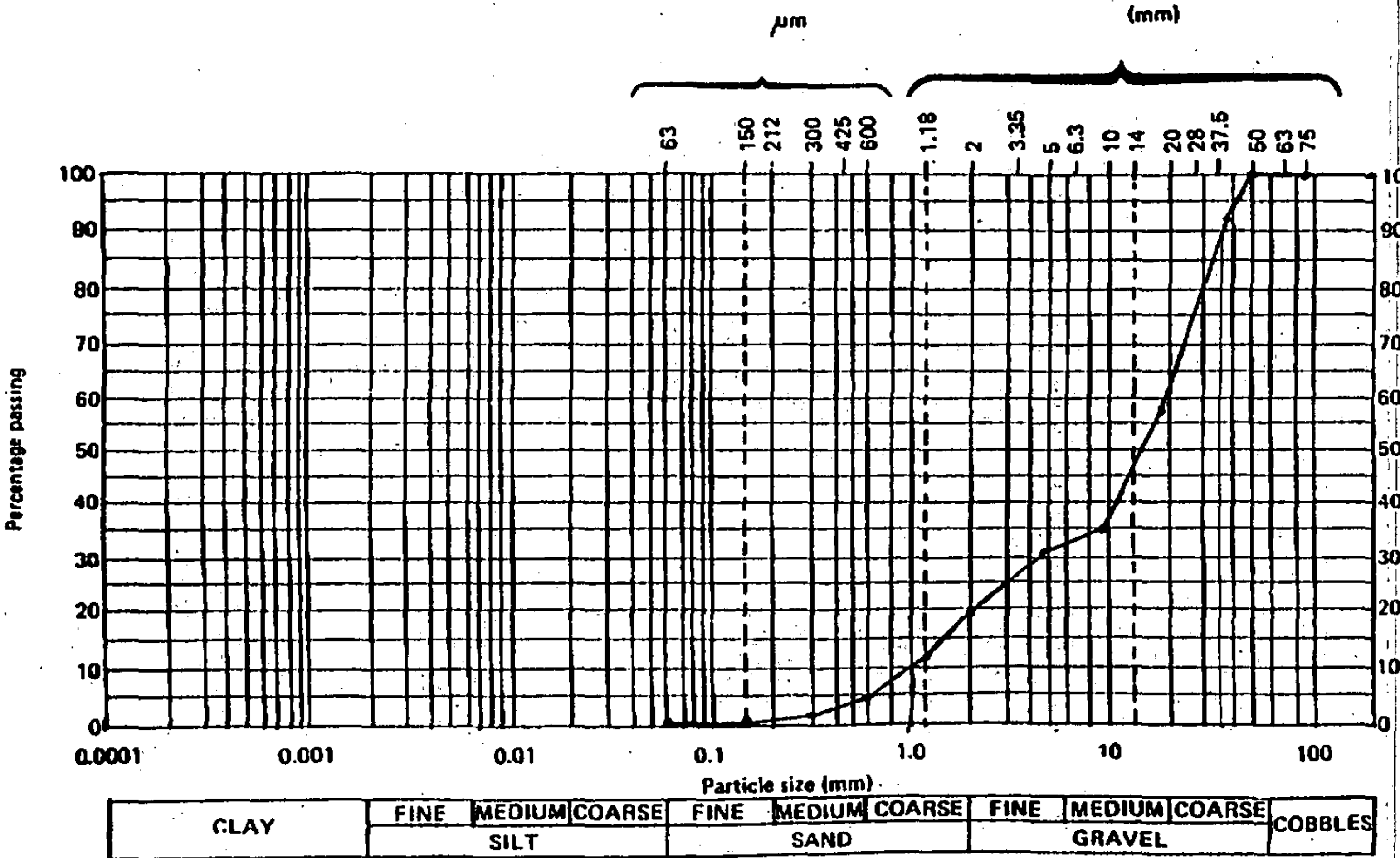
Sample Description: Grey sandy GRAVEL

Borehole No. CL34 - 2

Sample No. 26

Depth

IGSL



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