DRAINAGE AND SUBSIDENCE IN A RAISED BOG

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CLARA BOG

"The bog, known locally as Brook Bog, lies 2km south of the town on the road to Rahan and is mostly contained in the townlands of Erryarmstrong and Errymaryboro. It is one of the largest, relatively intact, raised bogs in Ireland. The uniqueness of its fauna, flora and soak systems was such as to cause it to be purchased from Bord na Mona by the Wildlife Service of the Office of Public Works in 1986. It was subsequently declared a National Nature Reserve in 1987 to coincide with the European Year of the Environment."

Clara, a pictorial record
Offaly Historical and Archaeological Society
Publ. Esker Press, Tullamore, Ireland
1992

ACKNOWLEDGEMENTS

Many thanks must go to Paul Johnston of Imperial College for supervising this project. His help and advice in all aspects of the work undertaken were invaluable. I would also like to thank Jacob Tompkins of Imperial College, Ray Flynn and Donal Daly of the Geological Survey of Ireland, and all of the other students involved in the bog project whilst I was in Clara, for their guidance and help with fieldwork so freely given on numerous occasions.

I would like to say a special thank you to all of the people of Clara for their warm welcome, and for making it so hard for me to leave. In particular to the Tempanys who became my second family for the duration of my stay in Ireland, and to the "Devs", for the nights out in the Dolphin, Rabbittes, the Mill House ...., but more so for their friendship which I truly hope will be ongoing.

ABSTRACT

As a continuation of an investigation into the hydrological effects of a bog road, a detailed study into the drainage and subsequent subsidence characteristics of a raised bog was undertaken. This study involved extensive field investigations to determine present states of drainage and subsidence, the reconstruction of the profile of the bog before subsidence commenced, and the development of a conceptual model to describe the link between drainage and subsidence. Proposals for the conservation and future management of the bog were made involving the total cessation of all turf cutting, and various options to reverse the present hydraulic gradients driving the drainage and subsidence processes.

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1.0 INTRODUCTION

Clara bog project is a collaboration of Dutch, Irish, and more recently English scientists and students, studying the hydrology, ecology and geology of raised bogs with a view to their ongoing conservation. On the Irish side, support and funding is provided by:

Wildlife Service, Office of Public Works
Geological Survey of Ireland
Trinity College Dublin
University College Galway
Sligo Regional Technical College

on the Dutch side by:

Dutch State Forestry
University of Amsterdam
Agricultural University of Wageningen

and on the English side by:

Imperial College, London
The National Rivers Authority

The project commenced in October of 1989, and is due to end this year. It is hoped that the information gathered over this three year period will enable the Wildlife Service, who own 70% of the bog, to make appropriate management programmes for raised bogs, and will help the Dutch government to regenerate bog growth in the Netherlands.

1.1 Objectives of the study

The objectives of this MSc project are threefold:

a) To investigate the role of drainage and subsequent settlement in the dynamics of bog hydrology.
b) Once the above has been established, to develop a conceptual model of the system of drainage and settlement occurring in Clara bog.
c) To use the above to determine how best to continue the conservation effort at present underway on

Clara bog.

1.2 Peat bogs and their formation

Ireland has a particularly high annual rainfall, which together with a fairly low temperature, results in low levels of evapotranspiration. This in turn results in waterlogged soils, especially in geological basins, so providing the ideal conditions for bog formation:

a) An anaerobic environment which prevents the growth of the bacteria and fungi essential for the complete breakdown of plant material.
b) stagnant, mineral deficient groundwater, and
c) due to the growth of bog mosses (such as the sphagnum species), which absorb the cations in rainwater so releasing hydrogen, a high acidity.

The various forms of peat bogs commonly found in Ireland are summarised in fig.1.1.

Raised bogs, also known as ridge raised bogs, high bogs, red bogs, and raised mires, are found in the Midlands of Ireland where the average annual rainfall is 800-900mm and are the deepest of the Irish peatlands. They are composed of the waterlogged remains of the bog moss, sphagnum - forming the catotelm, and a surface layer of living vegetation - the acrotelm. The stages of raised bog formation are summarised in fig.1.2.

A fully developed raised bog, such as Clara bog, is fed solely on rainwater. Much of this rainwater collects on, or is held close to the surface of the bog through the spongelike action of the sphagnum moss, however, a large portion is lost through runoff and via an internal drainage system called a soak.

1.3 The properties of peat

1.3.1 Inhomogeneity

Because of the lenticular fashion of bog regeneration, as described by Dooge (1972), the resulting deposit is neither homogeneous nor random. Thus considerable changes in hydrological behaviour may be encountered at different depths and areas of a given bog. The main significance of this feature is the difficulty in incorporating it into a hydrological model.

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FIG. 1.2
THE DEVELOPMENT STAGES FROM A LAKE TO A RAISED BOG.

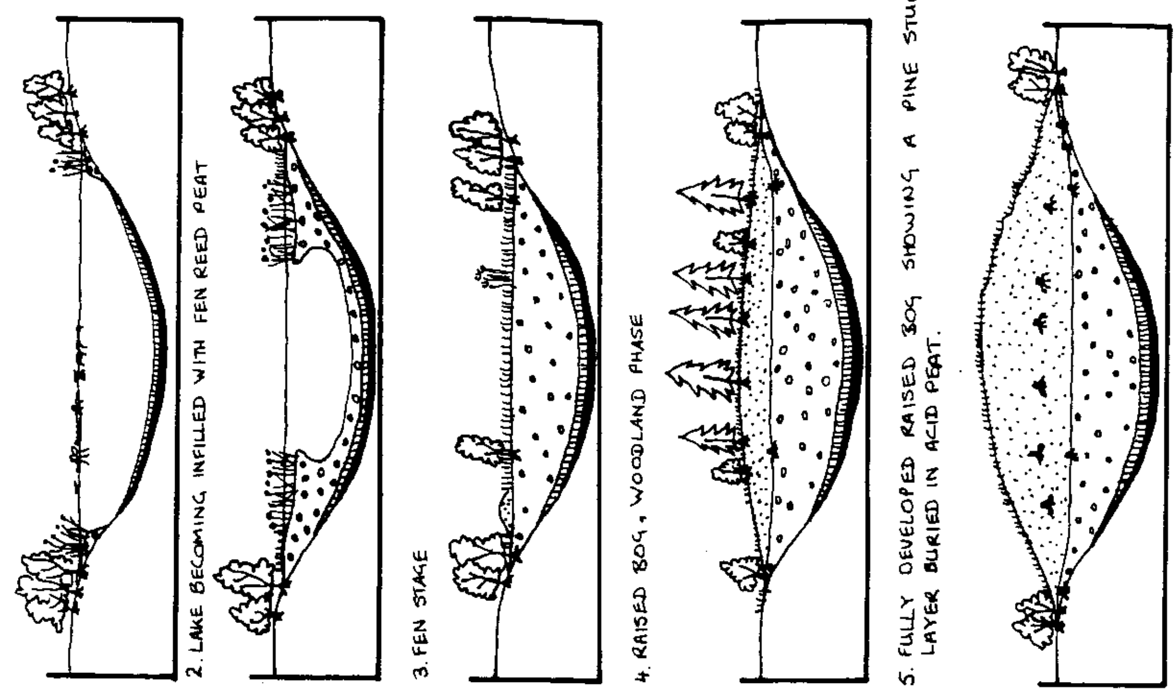
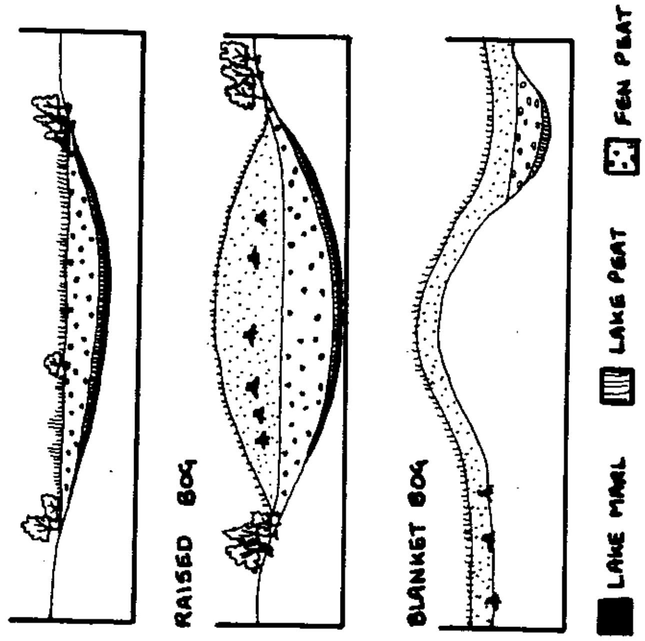


FIG. 1.1
TRANSVERSE SECTIONS OF IRISH PEATLAND TYPES



Clara Bog Project County Offaly, Ireland	EWRE Dept. Civil Eng. Imperial College	Drawn: H.S.	Job No.
PEATLAND CLASSIFICATION & RAISED BOG DEVELOPMENT STAGES. (AFTER BELLAMY)	Scales: N.T.S.	Checked	Date: SEPT. '92
		Drawing No.: FIGS. 1.1, 1.2	Rev.

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1.3.2 Water content

Peat typically has porosities in excess of 90%, the pore volume being made up by water. Hayward and Clymo (1982) postulated three categories of retention:

a) Intracellular water held within the internal cells under a suction of less than 10 kPa.
b) Interparticulate water held by capillary forces in any part of the sphagnum or peat under a suction exceeding 10 kPa. This would include adsorbed water.
c) Adsorbed water retained under a suction not exceeding about 20 MPa.

Whereas all the water can be removed by oven drying at 105 degrees celsius, only water in categories a and b can be expelled by consolidation, and only water in category a is likely to participate in gravity drainage flow. The bulk of the water is held as intracellular and interparticulate water, the proportion of each, and the total quantity depending chiefly on the structure and morphology of the various plants present, and on the degree of humification. Drainage of the peat will also influence the proportions and quantity.

1.3.3 Permeability

Permeabilities in peat are highly variable. In the acrotelm, values vary from 1 m/s in the surface litter to 3.0 e-5 m/s towards its base (Ingram, 1983). The permeability of the catotelm is, however, of more interest, and is dependent on the following factors (Ingram 1983):

a) The botanical composition
b) The degree of humification
c) The bulk density
d) The fibre content
e) The void ratio
f) The drainable void ratio
g) The surface loading

Typical values, quoted by Ingram (1983), range from 5.0 e-3 m/s to 6.0 e-10 m/s.

In addition to the abovementioned variability in permeabilities of peat, much research in this area suggests that it does not behave in a classical Darcian fashion, with permeabilities increasing as the applied hydraulic gradient is increased. Various models have been put forward to describe this change in permeability, including work by Rycroft et al (1975), and Swartzendruber (1962). This will be further discussed in section 4.0 of this report.

1.3.4 Subsidence

The principal causes of subsidence in peat can be summarised as:

a) Shrinkage
Because of the very high water content of peat, desiccation by drainage and evapotranspiration will cause substantial losses in volume. Part of this volume can be recovered through rewetting, although not all. According to Schothorst (1977) and Maas (1972), irreversible shrinkage decreases with length of cultivation.

b) Compression
As a result of drainage, cultivation and crop roots, a moisture tension is built up. This may result in capillary forces causing a compression of the soil matrix through a reduction in pore volume. Irwin (1972) showed the effect of this to be equivalent to an imposed loading of 3 kg/cm^2, and varying with water table depth.

c) Settlement
Upon drainage, the buoyant support of water is lost, so requiring the peat structure to support more of its own weight. Irwin (1972) and Schothorst (1977) showed this process to result in a load of 1 g/cm^2 for each cm fall in the water table.

d) Consolidation
This process is generally associated with an imposed load (machinery, buildings etc), and occurs as primary, elastic consolidation, followed by secondary, creep consolidation. It is the secondary, creep consolidation which is of the most significance in an organic soil, unlike mineral soils, where the primary, elastic consolidation plays the major role in subsidence. This is a well documented subject, and many models have been suggested to describe the process, in particular work by Wilson et al (1965), Barden (1968 & 1969), Berry and Poskitt (1972), and Kogure and Ohira (1977). This subject will be further discussed in section 4.0 of this report.

e) Biological oxidation
This occurs both in the conversion of organic material into CO2 and H2O, and in transformations through biochemical and physico-chemical processes into humus - a relatively stable, dark, colloidal, polyelectrolyte which is the site of many interactions between soils, plants and microbes (Paul 1970, Mathur 1971).

Most workers in the field seem to agree that shrinkage is the main cause of the initial subsidence occurring due to drainage, but that biological oxidation plays a major role in the long run (Stephens & Spier 1970, Eggelsmann 1976, Schothorst 1977).

The rate of subsidence occurring due to the above factors will vary for each particular environment, and so any model developed will be unique to that environment. Rayment and Mathur listed the main factors controlling the rate of subsidence as being:

a) Type of material - losses due to drainage have been shown to be greater in high bogs than in low moor or rich fen peats, whereas losses due to oxidation are greater in low moor than in high moor bogs (Eggelsmann 1976). Other factors include stage of decomposition (rate of decomposition decreases as extent of decomposition increases), degree of humification (humification increases the proportion of those micropores holding water, so creating a condition of anaerobiosis), and initial bulk density (Kuntze (1976) stated that peats with sphagnum origins should subside further than those which are woody).
b) Climate - subsidence due to oxidation has been shown to be linked logarithmically with rainfall and temperature (Eggelsmann 1976).
c) Water table - Many studies have shown that water table depth is the most important factor determining microbial decomposition, as it controls the moisture/air equilibrium in the top layer (Stephens and Spier 1970, Harris et al 1962, Clayton 1943, Neller 1943, and Roguski 1973).
d) Nature of plant cover - subsidence due to oxidation decreases with increasing plant cover. Water losses due to evapotranspiration will also vary with varying types and extent of plant cover.
e) Soil reaction (pH) - affects rate of biological oxidation.
f) Initial thickness of the peat - Zubtsev and Dubrova (1974) showed that the thicker the peat, the greater the absolute net subsidence. This of course implies that within a single bog, drainage problems arise where the thickest part of the bog, usually the centre, subsides the most.
g) The C/N ratio - According to Mathur (1977), the wider the C/N ratio, the greater the potential for degradation.
h) Time - The rate of subsidence due to biological activity has been shown to decrease with the duration of cultivation (Roguski 1973).
i) Inhibition of biological oxidation - as discussed by Mathur and Rayment (1977).

1.4 Clara bog

Clara bog, situated in the north of County Offaly, Southern Ireland, and with an area if 665 ha, is one of the largest remaining midland raised bogs (see fig.1.3), and is classed as an Area of Scientific Interest (A.S.I.) of international importance. It also has an intact soak system. This is an area of nutrient rich open water which is part of the drainage system. The bog lies in a depression between an esker complex to the north, and glacial till deposits to the south. The bedrock geology is Wulsortian limestone (see fig.1.5). Prior to acquiring reserve status, the area was owned by Bord na Mona, who preliminarily developed the eastern part of the bog for cutting by the construction of drainage channels. These have subsequently been blocked with varying degrees of success (see fig.1.6). In addition to this, the bog has been, and is currently mined for fuel by individuals who own about 30% of the bog on the peripheral zones (negotiations are now underway to safeguard these portions), the southern end is particularly damaged by periodic cutting (see fig.1.4). Much of the original bog area has been cut in previous times, and this land is used for agricultural purposes. Consequently, the periphery of a large part of the bog is surrounded by a drain. Afforestation of cutover bog to the south east may also have effects on the bog hydrology.

Most significant to the stability of the bog hydrology, however, appears to be the construction of the 'new bog road', over 150 years ago, along with large drainage channels either side. The road runs along a depression on the bog surface such that the surface is up to 6m lower than the highest part of the bog on either side of it. Although it was first thought that the road was constructed along a naturally occurring depression, it has since been realised that it is the road itself which has caused the present topography, as the drainage channels carry water from the bog. The extent of the subsidence is evident by the poor condition of the road; extensive pot-holing and an undulating surface, due to differential settlement, and also by the tearing of the acrotelm, forming gaping cracks, close to the road, where the tension developed by the high levels of subsidence has exceeded the tensile strength of this fibrous layer (see fig.1.7). It is this subsidence which forms the basis of this study.

1.5 Previous work

The aim of the 1991 project was to attempt to assess the hydrological effects of the bog road traversing the bog. Four transects of piezometer nests were installed at 60 degrees to the road to follow flow lines as closely as possible (see fig.1.8). Flow to the drainage channels alongside the road is at this angle rather than perpendicular due the influence of the turf cutting and subsequent drainage at the southerly end of the bog. From this data, flow nets were constructed, showing the radius of influence of the road drains to extend beyond the furthermost piezometer nests, ie beyond 600m from the road. Density measurements were undertaken in an attempt to reconstruct the original profile of the bog, and hence determine just how disruptive the construction of the road has been. And finally, numerous in situ permeability tests were conducted and used in the hydrological modelling of the bog flow regime.

It was concluded that the road and its drains had caused more than 6m of subsidence, and had in effect caused two domes from what was originally a single domed raised bog. This subsidence was causing a considerable increase in density, and decrease in peat permeability in the vicinity of the road. It was

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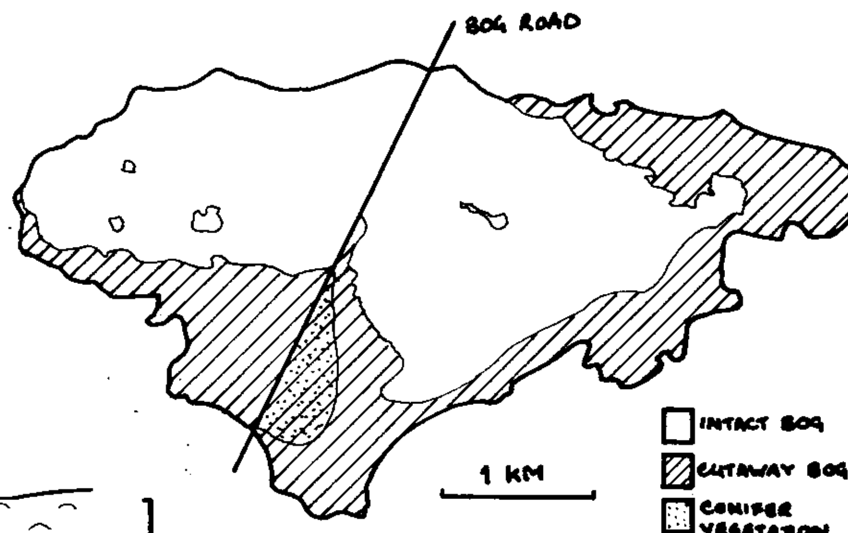
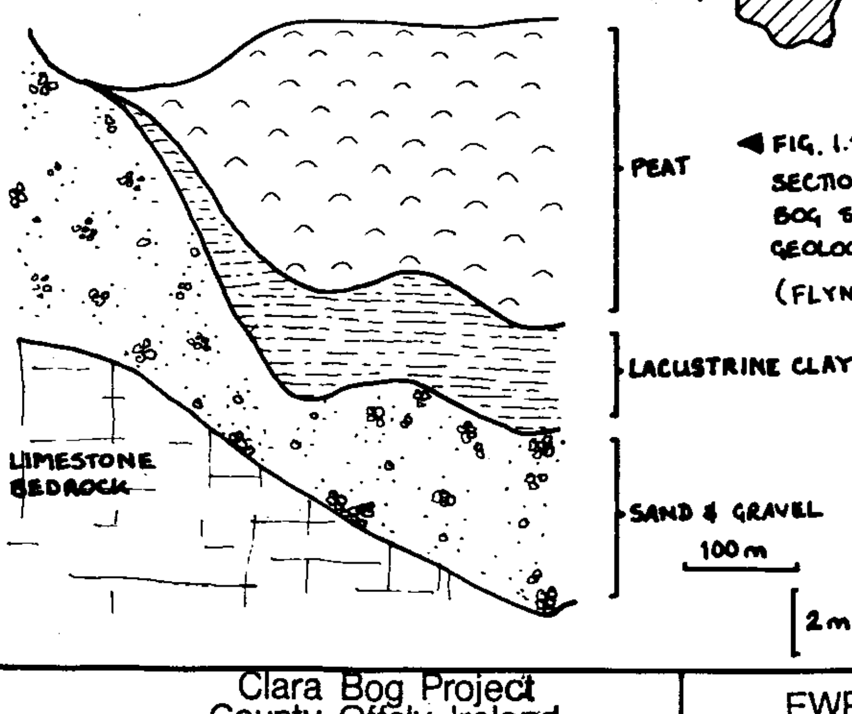
◄ FIG. 1.3
LOCATION MAP OF CLARA TOWN, CO. OFFALY, IRELAND.

► FIG. 1.4
MAP OF CLARA RAISED BOG SHOWING EXTENT OF CUTTING
(IPCC 1990)





◄ FIG. 1.5.
SECTION THROUGH EDGE OF CLARA BOG SHOWING TYPICAL BASIN GEOLOGY.
(FLYNN 1990)

Clara Bog Project County Offaly, Ireland	EWRE Dept. Civil Eng. Imperial College	Drawn: HS.	Job No.
CLARA BOG ; GENERAL DETAILS.		Checked	Date: SEPT. '92
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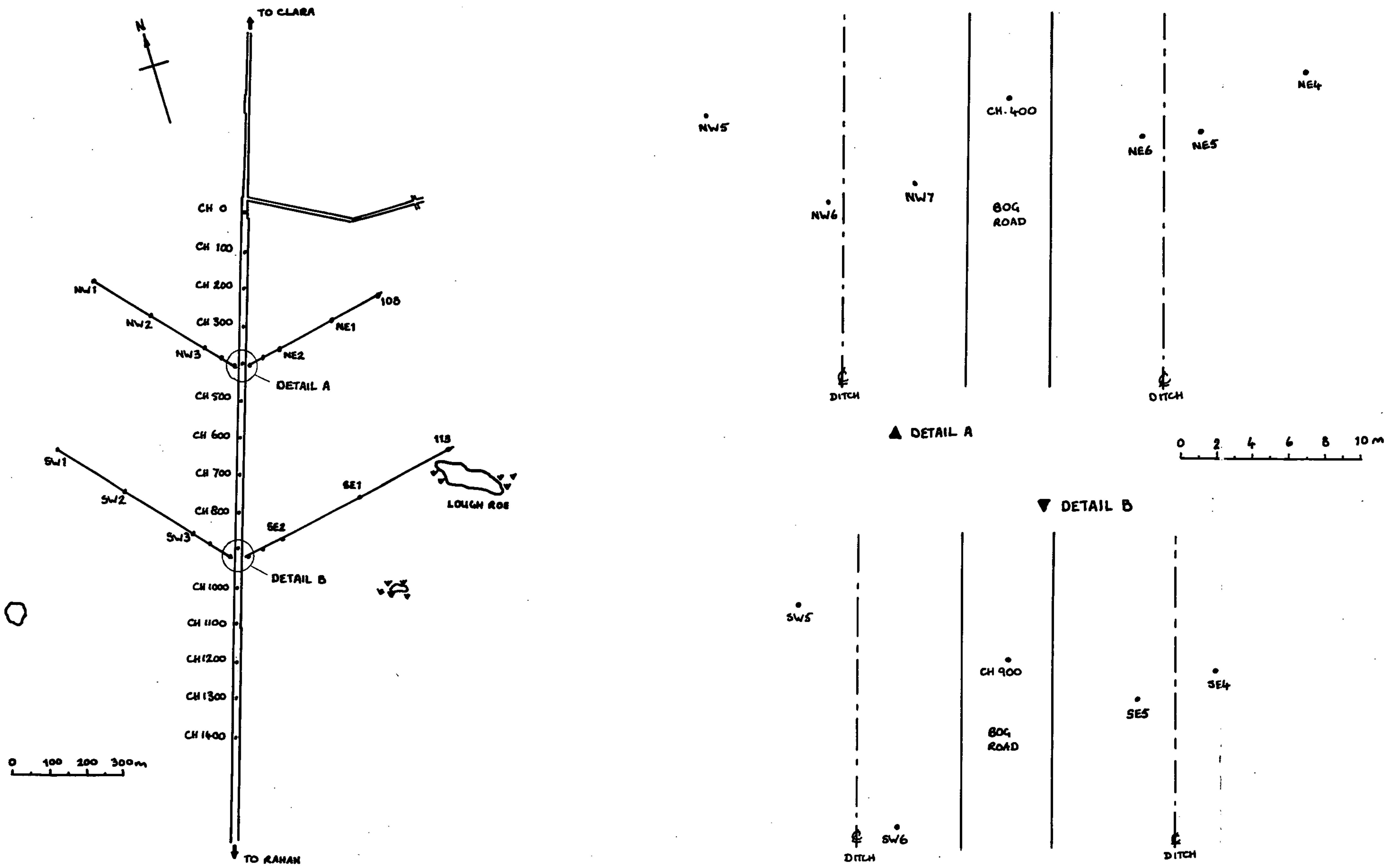

Notes

PIEZOS NW7, NW6, NE5, NE6, SW6 & SE5 INSTALLED IN 1992, ALL OTHERS INSTALLED BY J BELL IN 1991.

No.	Date	Revision

Clara Bog Project
County Offaly, Ireland

LOCATION MAP OF PIEZOMETER STATIONS

Drawn	Date	Checked	Date	Approved	Date
H.S.	SEPT. '92				

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Scale 1:10 000 & 1:200

Job No.

Client Drawing No. FIG. 2.1

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LGM Drawing No.

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recommended that the drains be dammed to raise the water level, although an extensive study on the effect this would have on the surrounding farmland would be necessary first.

1.6 Detailed objectives

It is proposed that in this study, the work of J Bell may be extended, with more attention being paid to the flow regime very close to the road. Also, a refinement of the method of determining in situ permeabilities will be attempted, using very low applied heads. Finally, a conceptual model for the flow regimes of the bog will be developed, running from the construction of the road to the present day, and into the future to try and predict future settlements. It is hoped that the above work will further develop the understanding of the role of drainage and settlement in the conservation of peatlands, and will aide in the development of conservation management strategies.

2.0 INVESTIGATIVE WORK

2.1 Set-up of the 1992 project

2.1.1 Installation of piezometers

In order to further assess the flow regime close to the road, it was necessary to install more piezometer nests in this vicinity. The closest nests from 1991 were as much as 8m from the drainage ditches either side of the road, and although they indicated a slight upward hydraulic gradient, this needed to be confirmed. Therefore a total of 6 additional nests were installed, the locations as shown in fig.1.8. Because of the dense vegetation close to the drains, it was not always possible to follow the line of the original transects. In addition to this, all of the existing piezometers were dipped to the base to confirm the depths that they reached to, and were subsequently labelled to this effect.

The piezometers were read on a fortnightly basis for the duration of the project (ten weeks) to determine whether the flows varied with time. The readings are displayed in appendix F.

2.1.2 Levelling

Although an extensive record of ground levels along the transects was compiled in 1991, it was necessary to relevel the tops of each piezometer tube and the adjacent ground for two reasons:

- Because of the very spongy nature of the peat (especially on the higher areas of the bog), trying to use a dumpy level is likely to give very large errors. If levelling on solid ground, an accuracy of 5 to 10mm is possible with the equipment available, but this accuracy drops to below 75mm when levelling on the soft bog. Therefore it was necessary to confirm that the levels obtained in 1991 were correct.
- It was also important to ascertain whether the bog had subsided at all either due to seasonal drying, or due to drainage, since the 1991 readings had been taken.

The levels obtained are shown in appendix B and, when compared to those obtained last year, can be seen to be different by a consistent amount, ie the whole transect showing a similar change in level, suggesting that the difference is due to an error rather than any subsidence. The average differences in elevation being:

North West transect; -155mm
North East transect; +5mm

South West transect; -2mm

South East transect; +60mm

In 1990 the O.P.W. set bolts in the road at chainages of 100m, which were levelled to a reasonable accuracy. These were also relevelled to ascertain whether any settlement of the road had occurred over this two year period. It can bee seen from the levels obtained (see appendix B), that settlements of up to 25mm have occurred, and that these are not likely to be due to an error in the levelling as the first and the last bolts (both on the stable periphery of the bog, ie unlikely to subside over a period of just two years), show no subsidence at all.

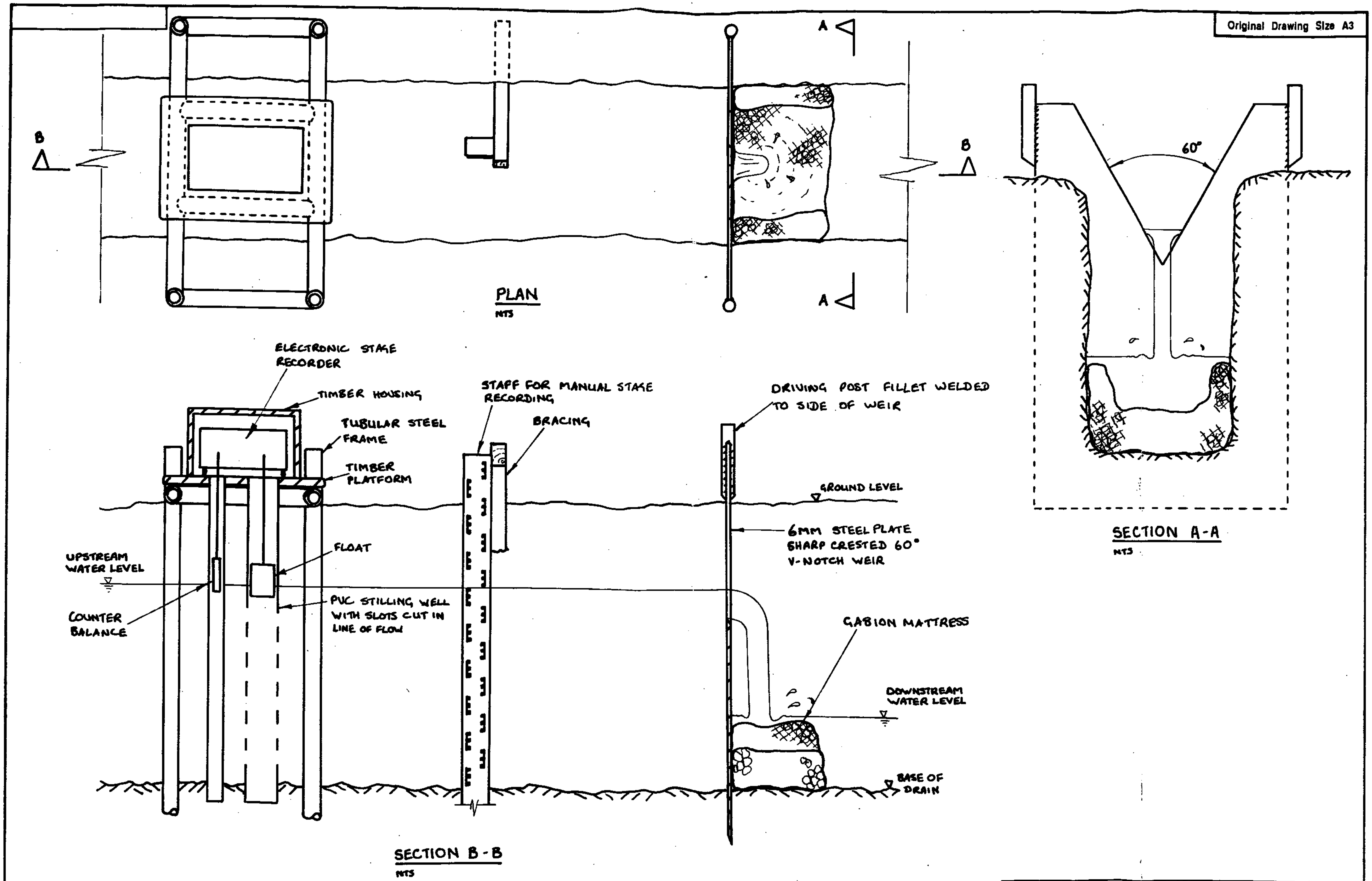
2.1.3 Flow measurement in the drainage ditches

When computing the water balance for the 1991 study, the flow from the bog via the drains was calculated from the mannings estimation of discharge from hydraulic radius, roughness coefficient, channel slope, and area of flow. As the ditches are highly non-uniform, this is a very inaccurate method of measurement. However, by the beginning of this study, v-notch weirs had been installed in the drains; on the east side at chainage 300m, and on the east and west sides at chainage 900m. The measurement of these was by means of measuring the water level against a timber post driven into the drain a little upstream of the weir, and no calibration had been undertaken with a view to producing a rating curve. It was therefore necessary to install easy to read staffs for manual recording, and platforms for the installation of electronic stage recorders (see figs.2.2, 2.3). Simple 'bucket and stopwatch' measurements at varying stages were then carried out (see fig.2.4) to produce a rating curve (see fig.2.5). Also, due to problems of leakage, the south eastern weir had to be removed, elongated by welding on an additional section at the base, and reinstalled a little upstream where the bank was more stable (see fig.2.6). Finally, gabion mattresses were placed downstream of each of the weirs to remove a large portion of the energy in the flow coming over the weirs at high flows, so preventing the bank erosion which was the primary cause of the leakage occurring at the south eastern weir. All of this work was carried out by Iain Blackwell of Imperial College, myself, and technicians of the Geological Survey of Ireland.

2.2 Measurement of subsidence

2.2.1 Taking samples

In order to determine the extent of subsidence of the peat matrix, it was necessary to sample the peat at each piezometer station, and because the settlement is differential with depth, at various depths. In the 1991 study, this was done at 8 of the piezometer locations using a hand auger with a 50cm long semi-



Notes	No.	Date	Revision	Clara Bog Project County Offaly, Ireland FLOW MEASUREMENT STATION TYPICAL DETAIL	Drawn H.S.	Date SEPT. '92	Checked	Date	Approved	Date

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Scale N.T.S.
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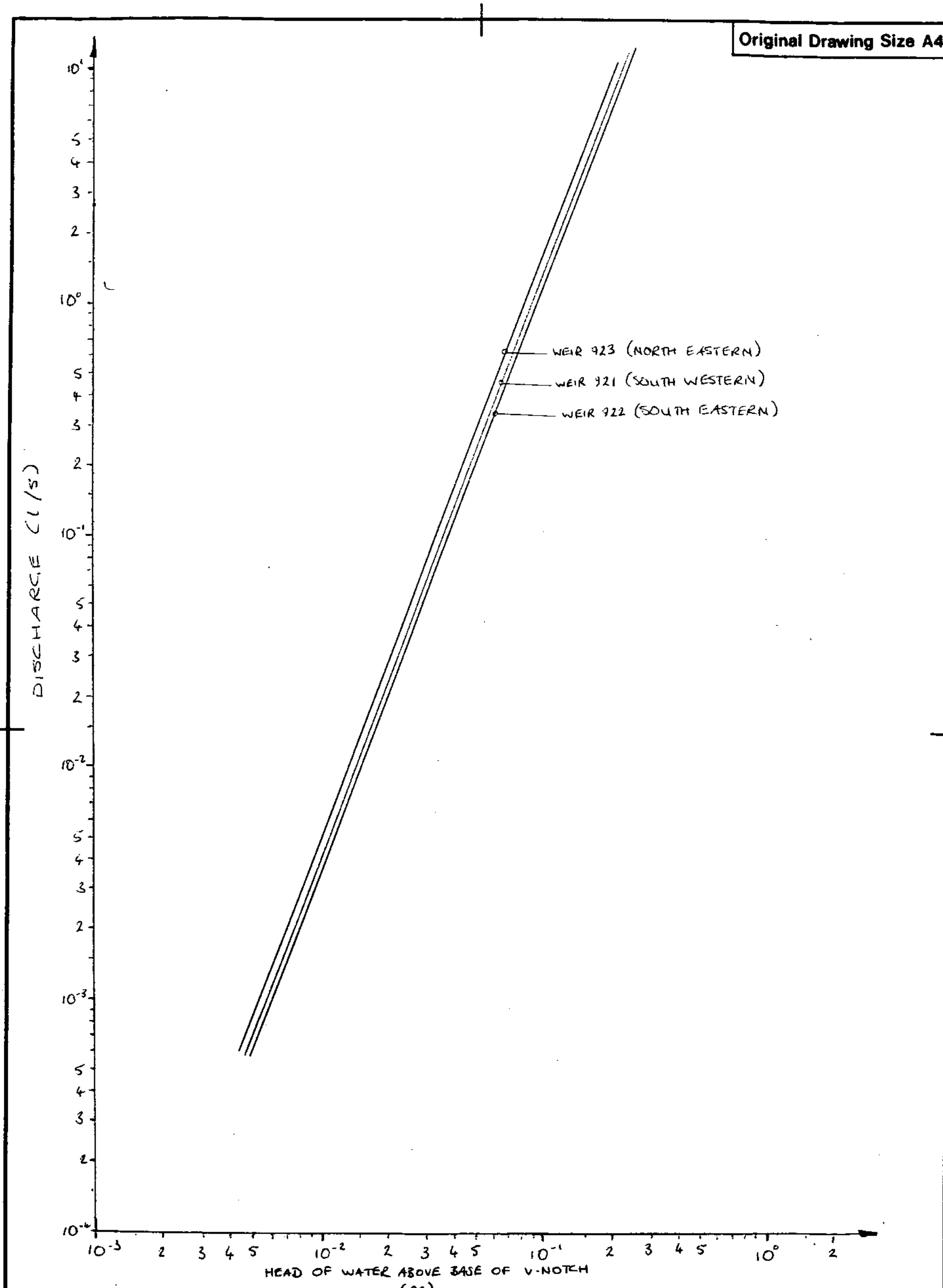

Clara Bog Project County Offaly, Ireland	EWRE Dept. Civil Eng. Imperial College	Drawn: H.S.	Job No.
RATING CURVES FOR V-NOTCH WEIRS INSTALLED IN ROADSIDE DRAINS		Checked	Date: SEPT. '92
	Scales: AS SHOWN	Drawing No.: FIG. 2.5.	Rev.

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cylindrical chamber at the end. Ideally, sampling would produce undisturbed, full recovery samples, but because of the very soft nature of the peat - almost liquid at the high points of the bog, this was impossible, and both deformation and squeezing out of water occurred. Drilling for this study was using a Dausnoski sampler. This consists of a 30cm long, completely enclosed chamber, which it was felt would produce a less disturbed sample than the hand auger, although full recovery was still not possible. Once recovered, the samples were sealed in plastic bags to prevent any loss of water, and transported to the workshop for testing (see fig.2.8).

2.2.2 Testing samples

The original intention of sampling was to determine the bulk density of the peat, and thus calculate the extent of settlement in the same fashion as the 1991 study (as described in section 3.1). In order to do this, it was necessary to determine the volume of the sample. As many of the cores were incomplete and/or too soft to retain their own shape once removed from the sampler, it was not possible to obtain the volume by just taping, and this is likely to have been a contributing factor to the errors obtained in the 1991 study (ie water %ages by volume well in excess of 100%). Therefore volumes were obtained by a method of water displacement, as shown in fig.2.9. After this was done, the samples were weighed, oven dried at 105 degrees (any higher temperature may cause charring or oxidation), and reweighed, so allowing the masses of water and dry material to be determined.

2.2.3 Subsidence calculations

The results of the above testing are shown in appendix C, and it is clear that the bulk densities obtained bear little resemblance to the extent of subsidence, with similar values being obtained across the length of the transect. In addition, because of the time required to measure volumes in this way, density appears to be an inappropriate parameter to use for the calculation of subsidence.

In classical soil mechanics, the parameter of void ratio is used to describe and predict consolidation and settlement, where:

$$e = \frac{V_v}{V_s}$$

e = *void ratio*

V_v = *volume of voids*

V_s = *volume of solids*

and for a saturated medium, as is the case for the peat sample:

$$e = \frac{V_w}{V_s}$$

$$= \frac{M_w\ \rho_w}{M_s\ \rho_s}$$

$$= Sg_s\ \frac{M_w}{M_s}$$

V_w = *volume of water*

M_w = *mass of water*

M_s = *mass of solids*

ρ_w = *density of water*

ρ_s = *density of solids*

Sg_s = *specific gravity of solids* = $\frac{\rho_s}{\rho_w}$

This definition is acceptable for mineral soils where the specific gravity of the medium remains constant (usually that of silica; 2.65), but for an organic soil such as peat, the specific gravity varies due to:

- the varying degree of humification
- the range of plant material which might be contributing to the soil (ie sphagnum or woody peats), and
- the chemical adsorption of water

Measurements of specific gravity carried out on the peat (by the method described in fig.2.10), showed it to vary from 0.19 on the high points of the bog to 0.83 close to the road. This significant increase in specific gravity is caused by the lowering of the water table as drainage occurs, thus allowing oxygenation of the soil and the subsequent development of an aerobic environment, ideal for the growth of the fungi and bacteria responsible for the breakdown of plant material. Therefore, the use of void ratios to calculate the subsidence occurring since the construction of the road would neglect the volume loss due to biological oxidation (humification). As this process accounts for a more than fourfold reduction in the volume of solids, subsidence may be considerably underestimated.

It was therefore decided to use the ratio of mass of water to mass of solid, as this would combine the settlement due to water loss through drainage, with the volume loss through biological oxidation. It has the added benefit of being a very quick and easy parameter to measure, giving consistent and accurate values.

2.3 Assessment of drainage

2.3.1 Methods of determining in situ permeabilities

Because of the highly inhomogeneous nature of peat as discussed in section 1.3.1, and the difficulties in obtaining undisturbed samples for testing in the laboratory, it is necessary to test permeabilities in the field. There are, at present, two methods available for measuring in situ permeabilities:

a) Rising/falling 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 coefficient of permeability, or hydraulic conductivity:

$$v = -k \frac{dh}{dl} \quad \text{..........(2.1)}$$

v = *velocity through the medium*

k = *permeability*

$\frac{dh}{dl}$ = *hydraulic gradient*

Equation (2.1) is the basis of groundwater flow equations, and has been used by Hvorslev (1951) to derive subsequent formulae allowing the determination of permeability from variable head tests:

$$k = \frac{A}{S}\,(t_2 - t_1)\,\ln\frac{y_2}{y_1}$$

A = *cross-sectional area of the seepage tube*

S = *piezometer shape factor derived through electrical analogue experiments*

t = *time*

y_1, y_2 = *head at time* t_1, t_2

k is thus determined by plotting ln(Y1/Y2) against (t2-t1). Assumptions in this method include requirements that:

- the tested medium is rigid
- flow in the tube is steady state

b) Constant head tests

The calculation of permeability after Gibson (1963) is covered in BS 5930 Site Investigations which states that:

$$k = \frac{q_{fin}}{S y_0}$$

q_{fin} = *steady-state discharge*

y_0 = *applied head*

This method was first developed for use in flexible media under the assumptions of homogeneity and isotropy. The constant imposed head is provided by a Marriotte vessel, as shown in fig.2.11.

A comparison of the above two methods was made by Flynn (1990):

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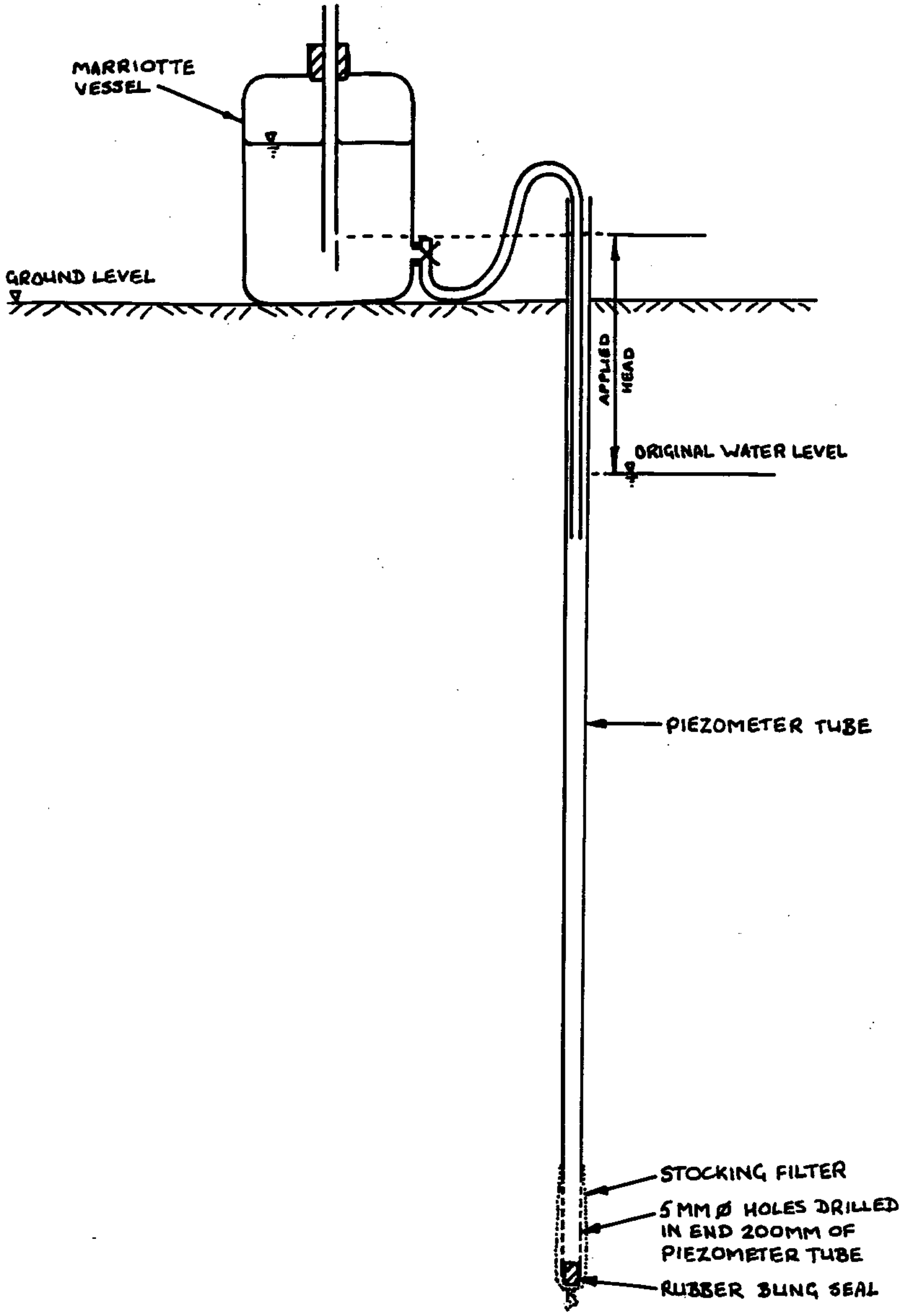

Clara Bog Project County Offaly, Ireland	EWRE Dept. Civil Eng. Imperial College	Drawn: H.S.	Job No.	
CONSTANT HEAD PERMEABILITY TEST METHOD ONE		Checked	Date: SEPT. '92	
	Scales: N.T.S.	Drawing No.: FIG. 2.11		Rev.

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Factor	Constant head	Rising head
Time	time consuming	quick
Apparatus	bulky	portable
Cost	commercially expensive, but simple & cheap to construct	inexpensive
Water source	required	not necessary

Although from the above comparison the rising head may appear a more appropriate method to use, as discussed in section 1.3.3, peat does not behave in a Darcian fashion, and so calculating permeability from a rising or falling head test, where the applied head is constantly changing is clearly more difficult to justify. In addition to this, it has been noted by Ingram et al (1974) that the permeability also changes depending on whether the peat is under recharge or depletion, hence providing a further argument against rising head tests.

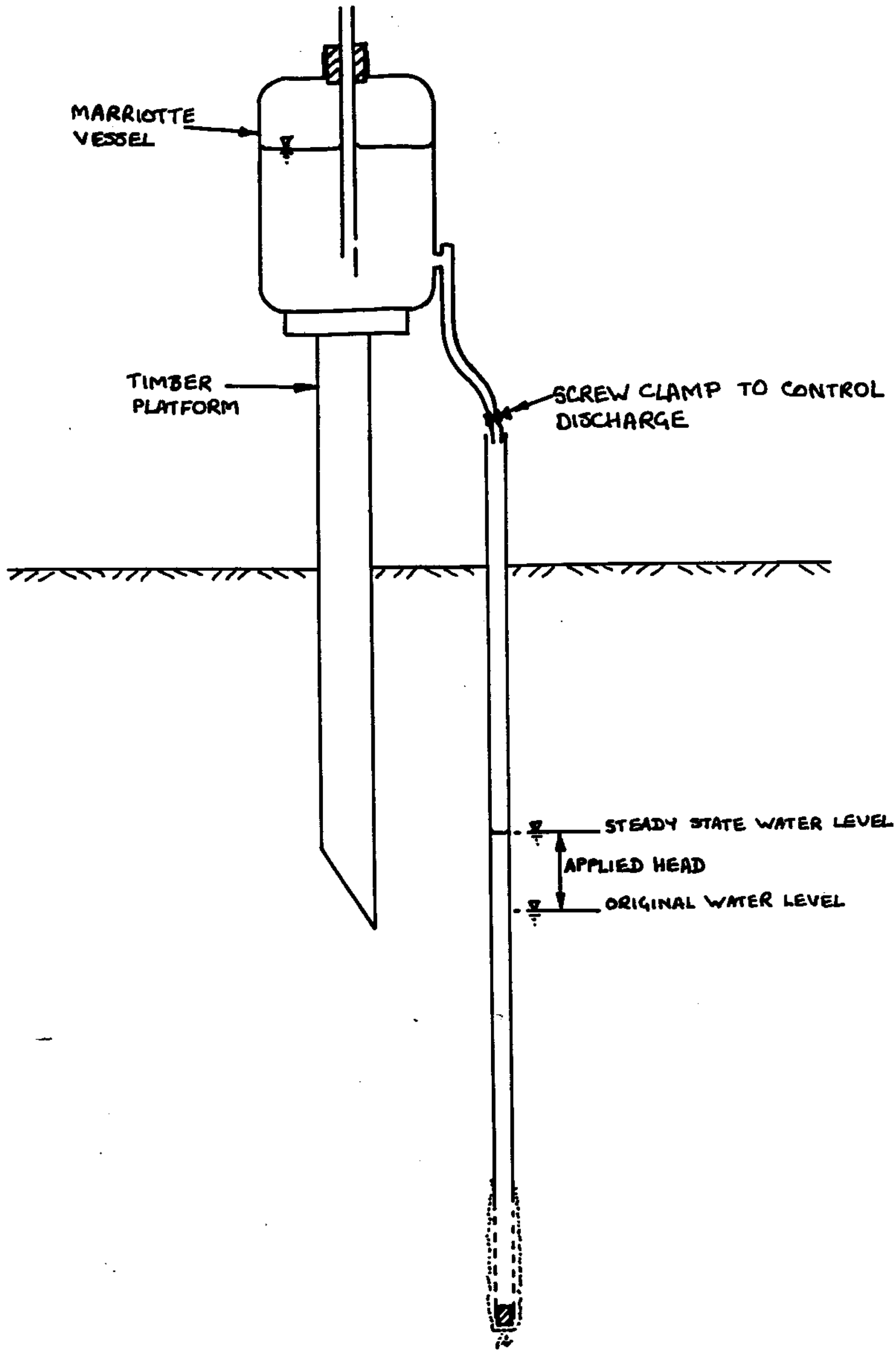
As a result of the abovementioned factors, the permeability tests carried out in the 1991 study were of the constant head form.

2.3.2 The modified constant head test

It has already been mentioned that, according to Rycroft (1975) and Swartzendruber (1962), the permeability of peat increases with increasing hydraulic gradient. It is therefore arguable that the constant head method described above will give higher values of permeability than those actually occurring as it involves applying much higher heads than those naturally occurring in the field. There is also the problem of possible rupturing of the peat matrix under such artificially high pressures. It was therefore proposed that in this project a modified constant head test be developed, which would involve only tiny increases in hydraulic gradient, so deviating as little as possible from the naturally occurring state of drainage.

The basis of the modified constant test is shown in figs.2.12, 2.13. A platform had to be constructed as the flows were so small (ml/min) that a siphon could not be set up without an airlock forming, and a screw clamp had to be used to control the flows as the marriotte vessel tap was not sensitive enough. As the water level in the piezometer had to be continuously monitored throughout the test to determine when a steady state condition had been reached, a very thin dipmeter was used which could be inserted alongside the discharge pipe without disturbing the test. This consisted of a piece of graduated rigid

Original Drawing Size A4



Clara Bog Project County Offaly, Ireland	EWRE Dept. Civil Eng. Imperial College	Drawn: H.S.	Job No.
CONSTANT HEAD PERMEABILITY TEST METHOD TWO		Checked	Date: SEPT. '92
	Scales: N.T.S.	Drawing No.: FIG. 2.12	Rev.

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electrical wire with bared wires at the bottom and a battery and bulb at the top, so that when the bottom touched the water surface, the circuit was completed, and the bulb lit up.

The main problem with this test was trying to get the marriotte vessels to deliver a constant, very small discharge. However, this is a fault of the apparatus, and not of the method itself. Ideally, a peristaltic pump should be used running off a battery. The varying heads and discharges with time for all of the tests carried out are shown in appendix C, and a summary of permeabilities obtained using both this method and the original constant head test are shown in fig.2.14.

A consideration with all methods previously discussed for measuring permeability is that the piezometer tubes used are designed to measure the horizontal conditions, as the inlet holes are drilled in the side, and the end is stoppered off (see fig.2.11). This is particularly relevant for an organic soil medium, such as peat, which exhibits such markedly anisotropic hydraulic properties. A piezometer for measuring the vertical permeability only would consist of just a butt ended tube. If a few values for both horizontal and vertical permeabilities could be obtained, then a ratio could be established, Kh/Kv, and the horizontal permeabilities could be adjusted to account for the actual direction of flow. This would be particularly important in the vicinity of the drains where the vertical flow component is comparable to the horizontal flow component.

Piezometer Station	Permeability (m/s) 1991	1992
113 2m		5.22 e-06
113 3m		1.30 e-06
113 5m		2.82 e-06
SE1 2m	3.88 e-06	2.10 e-06
SE1 5m	3.46 e-07	4.78 e-07
SE1 8m	1.60 e-06	2.02 e-06
SE2 2m	3.20 e-06	1.58 e-06
	3.20 e-06	1.50 e-06
	3.20 e-06	1.18 e-06
SE2 5m	5.16 e-08	1.12 e-07
	5.16 e-08	9.80 e-08
SE3 2m	1.46 e-07	4.40 e-07
SE3 3m	2.60 e-08	6.97 e-08
	2.60 e-08	1.88 e-07
SE3 4m	2.23 e-06	8.20 e-07
SE4 2m	3.83 e-07	1.80 e-07
	3.83 e-07	7.74 e-08
SE4 3m	2.10 e-06	5.38 e-07
SE4 4m	6.22 e-08	1.27 e-07
SE5 2m		1.08 e-07
		7.23 e-08
SE5 3m		1.10 e-07
SE5 4m		1.27 e-07

Fig.2.14 Summary of permeability data

3.0 RECONSTRUCTION OF THE ORIGINAL BOG PROFILE

3.1 Method used in the 1991 study

As mentioned in section 2.2.2, the estimations of subsidence in the 1991 study were based on changes in density along the transects, as compared to the density of peat at an area of the bog believed to be undisturbed, where:

$$\frac{\rho_a}{l+x} = Z_\rho$$

$$\frac{W_a}{l+x} = Z_w$$

ρ_a, W_a = average dry density, weight of organic matter per unit volume of the peat column at a given location

Z_ρ, Z_w = average dry density, weight of organic matter per unit volume of the reference/undisturbed peat column

l = length of the peat column at the given location

x = subsidence

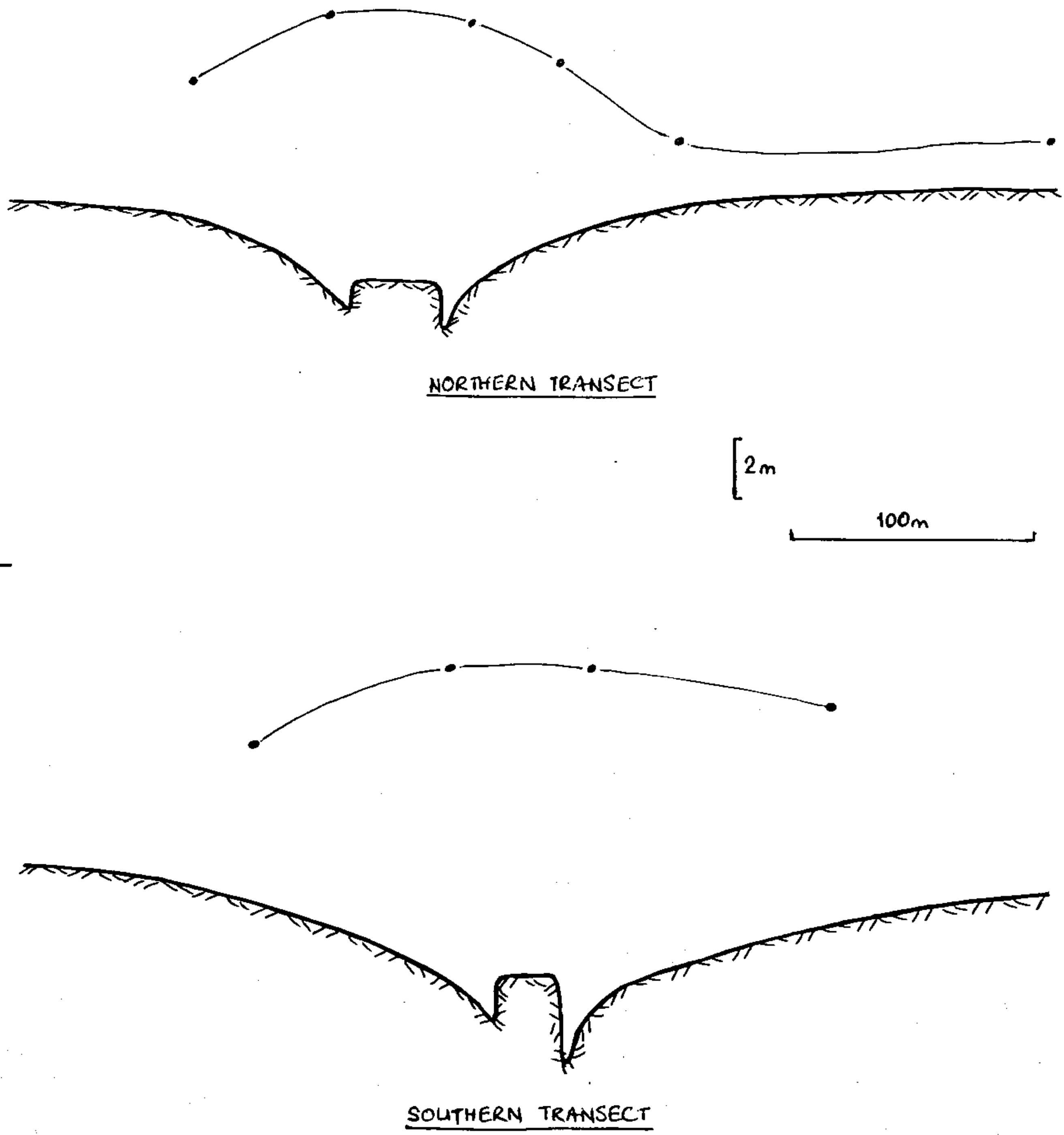
The profiles obtained by this method are shown in fig. 3.1.

3.2 Method used in this study

As discussed in section 2.2.3.1, the estimation of settlement for this study is to be based on the ratios of mass of water (Mw) to mass of solids (Ms). A raised bog is formed mainly of sphagnum peat, which is responsible for the majority of settlement under drainage (Kuntze 1976), with an underlying layer of fen peat. For this reason, the settlement of the two layers will be considered separately.

For each layer, the largest value of the Mw/Ms ratio was used as a reference, ie it was assumed that the peat at this location was unaffected by drainage, and was therefore in its original state. This occurred at piezometer station 108 (the last station on the north east transect). From classical soil mechanics,

Original Drawing Size A4



Clara Bog Project County Offaly, Ireland	EWRE Dept. Civil Eng. Imperial College	Drawn H.S.	Job No.
RECONSTRUCTED BOG PROFILES AS DERIVED IN THE 1991 STUDY.		Checked	Date SEPT. '92
	Scales AS SHOWN	Drawing No. FIG. 3.1.	Rev.

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$$x = d_2 \frac{e_1 - e_2}{1 + e_2} \quad \ldots\ldots\ldots\ldots (3.1)$$

d_2 = *final depth*

e_1 = *initial void ratio*

e_2 = *final void ratio*

And for a saturated medium:

$$e = Sg_s \frac{M_w}{M_s}$$

Sg_s = *specific gravity of solids*

M_w = *mass of water*

M_s = *mass of solids*

However, as the specific gravity of the solids is not a constant, and is a contributing factor to the subsidence, it is proposed to replace e in eqn (3.1) with e/Sgs, hence the subsidence relationship becomes:

$$x = d_2 \frac{(\frac{M_w}{M_s})_1 - (\frac{M_w}{M_s})_2}{1 + (\frac{M_w}{M_s})_2}$$

The results of this analysis are shown in the table in fig.3.2, and the subsequent profile reconstruction is shown in fig. 3.3. The information used to construct the existing profile having been extrapolated from drilling data gathered by O. Bloetjes (1992), combined with the results of drilling conducted in this study (see figs. 3.4 a & b).

The reconstruction is based both on the calculated points of the original profile, and considering the natural shape of the bog and its formation process (as shown in fig.1.2). It was the omission of this latter point which resulted in such an unnaturally shaped original profile in the 1991 study. It can be seen that the subsidence is considerably more pronounced in the southern transect, corresponding with the extensive cutting occurring at this end of the bog. The radius of influence appears to extend much further on the south west transect than on any of the other areas. This also suggests that a considerable part of the settlement occurring at the south end of the bog is due to the peripheral cutting, rather than solely due to the influence of the road.

3.3 The dating of the bog road

It is widely accepted that the long term subsidence of an organic soil is due to secondary (creep) rather than primary (elastic) settlement. Primary settlement occurs as a result of the dissipation of excess porewater pressures, so increasing the effective stresses in the soil skeleton. These excessive porewater pressures are associated with an applied load, in this case the imposed load of the bog road. Secondary settlement is the slow, continued compression that occurs after the excess pore pressures have dissipated, and is driven by gravity drainage, as is occurring in Clara bog as water flows towards the drains either side of the road. This secondary, creep settlement follows a log-normal relationship, first described by Buisman and Gray (1936).

The earliest level data available for the bog road is from a 1910 ordnance survey map. From this information, the settlement occurring over the past 80 years can be determined (see fig.3.5). As the original bog elevation has been estimated, by plotting settlement against the log of time, the time required for the settlement occurring since the road was constructed until 1910 can be estimated, and hence the age of the road can be established. It is to be expected that the two transects would follow a different rate of settlement (and therefore a different slope on the settlement-log time plot), as they are undergoing different drainage conditions. Work by Hanrahan and Rogers (1981) on a road also in County Offaly, Ireland, used the relationships:

$$y_e = 0.02\ B\ \frac{q}{s}$$

$$y_c = 10^{-4}\ [21\ (\frac{q}{s})^3 + 39\ (\frac{q}{s})^{1.78}\ \log t]\ \frac{B}{s}$$

34

Original Drawing Size A3

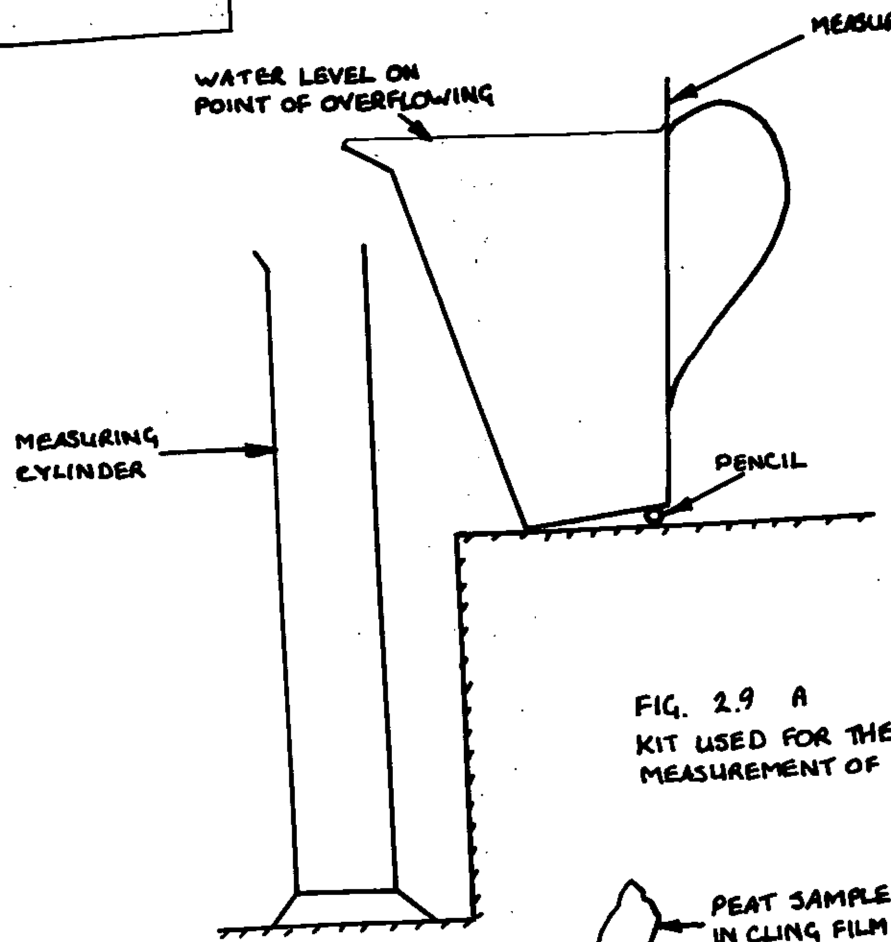

FIG. 2.9 A
KIT USED FOR THE VOLUME MEASUREMENT OF PEAT SAMPLES

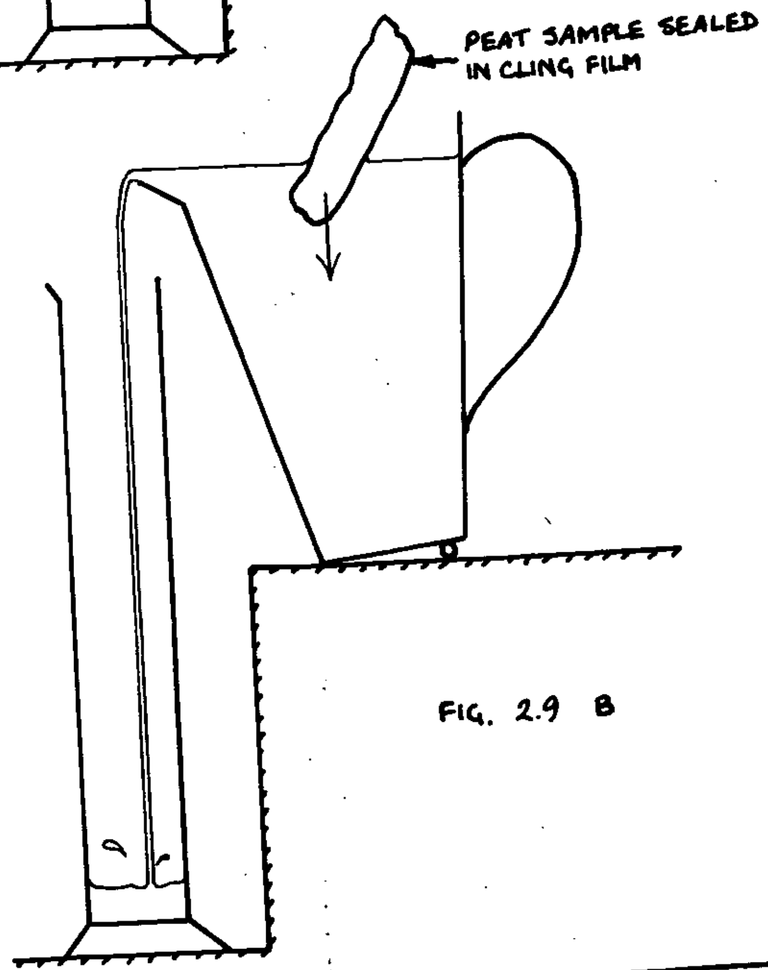

FIG. 2.9 B

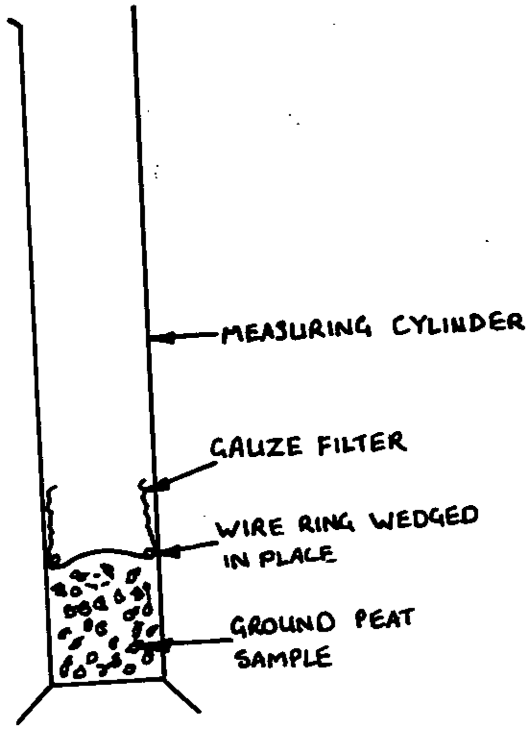

FIG. 2.10 A
KIT USED FOR MEASURING THE SPECIFIC GRAVITY OF PEAT SAMPLES

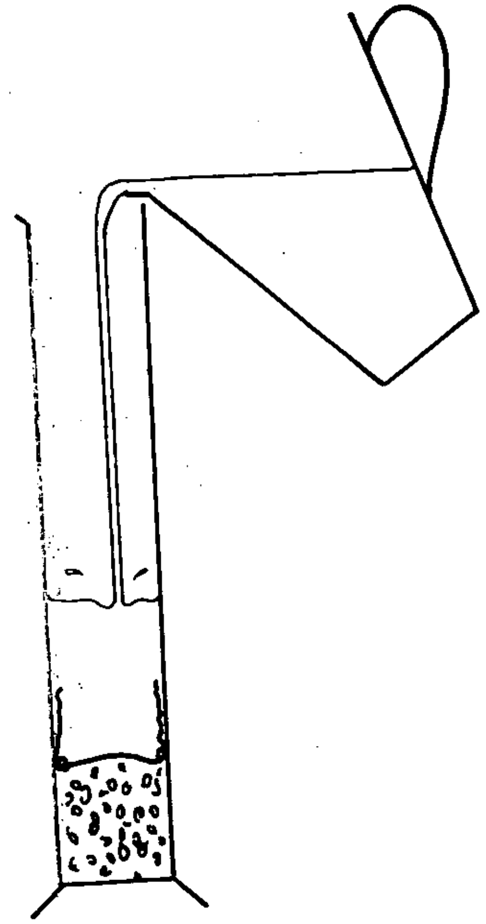

FIG. 2.10 B
A KNOWN VOLUME OF WATER IS ADDED TO COVER THE SAMPLE & FILTER, & THE PEAT LEFT TO FULLY ABSORB THE WATER FOR 48 HRS., WHEN THE WATER LEVEL IS NOTED.

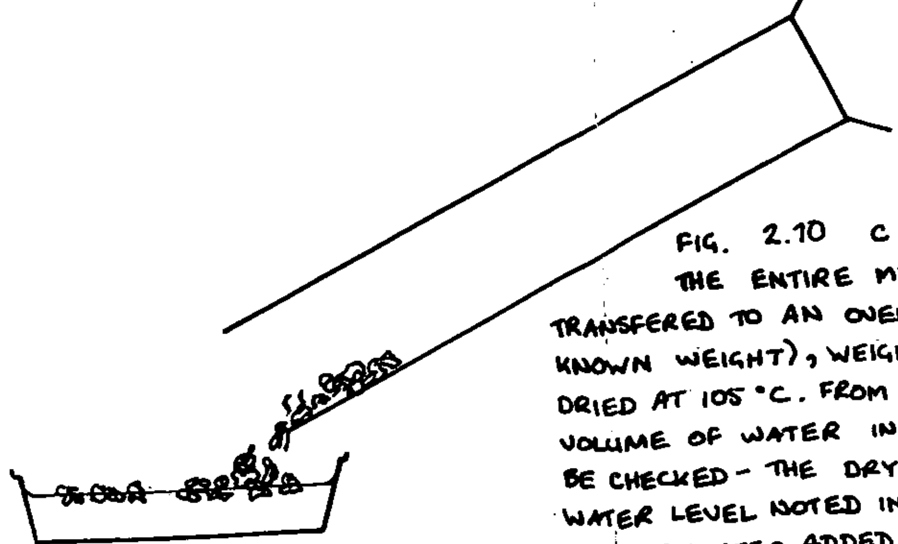

FIG. 2.10 C
THE ENTIRE MIX IS THEN TRANSFERED TO AN OVENPROOF TIN (OF KNOWN WEIGHT), WEIGHED, & OVEN DRIED AT 105 °C. FROM THE WET WT., THE VOLUME OF WATER INITIALLY ADDED CAN BE CHECKED - THE DRY VOLUME BEING THE WATER LEVEL NOTED IN FIG 2.10 B - VOLUME WATER ADDED - VOLUME DISPLACED BY WIRE & GAUZE FILTER.

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Scale: N.T.S.

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Client Drawing No.: FIGS. 2.9, 2.10

Rev.

LGM Drawing No.

Notes

VOID RATIO / DENSITY MEASUREMENT KIT

WWW

WW

CALCULATION OF SETTLEMENTS FROM Mw/Ms RATIOS
ORIGINAL RATIOS TAKEN; SPHAGNUM PEAT = 29.62
FEN PEAT = 19.25

DEPTHS IN METRES

PIEZO ST.	SPHAGNUM PEAT DEPTH	Mw/Ms	ORIG. DEPTH	SETTLEMENT	FEN PEAT DEPTH	Mw/Ms	ORIG. DEPTH	SETTLEMENT	TOTAL SETTLEMENT
113	6	29.34	6.054	0.054	3.5	16.126	4.103	0.603	0.657
SE1	6.75	24.36	8.097	1.347	2.75	16.48	3.162	0.412	1.759
SE2	3.5	18.46	5.409	1.909	2.5	14.38	3.243	0.743	2.652
SE3	2.5	11.12	6.025	3.525	2.25	10.6	3.795	1.545	5.07
SE4	0.5	9.76	1.344	0.844	3	12.64	4.355	1.355	2.199
SE5	0.5	6.6	1.838	1.338	2.5	7.42	5.64	3.14	4.478
108	5.5	29.62	5.5	0	3.25	19.25	3.25	0	0
NE1	5	16.24	8.668	3.668	3.25	12.06	4.912	1.662	5.33
NE2	4	18.38	6.206	2.206	3	10.74	5.004	2.004	4.21
NE3	3	15.18	5.522	2.522	2	11.39	3.174	1.174	3.696
NE4	1.5	13.56	3.048	1.548	2.5	10.42	4.277	1.777	3.325
NE5	1.5	8.26	4.623	3.123	2.5	10.94	4.105	1.605	4.728
NE6	1	9.24	2.813	1.813	2	9.2	3.795	1.795	3.608
NW1	6	29.02	6.116	0.116	2	7.7	4.381	2.381	2.497
NW2	6	27.7	6.388	0.388	1	18.36	1.044	0.044	0.432
NW3	4.5	21.54	6.045	1.545	1.5	16.06	1.765	0.265	1.81
NW4	2	16.62	3.396	1.396	2	17.74	2.153	0.153	1.549
NW5	1.5	15.76	2.671	1.171	1.5	15.3	1.842	0.342	1.513
SW1	6	23.78	7.359	1.359	3.75	14.86	4.726	0.976	2.335
SW3	4.5	14.1	8.838	4.338	2.25	11.58	3.521	1.271	5.609
SW5	1.5	9.52	2.707	1.207	2.5	11.76	3.861	1.361	2.568

Fig.3.2

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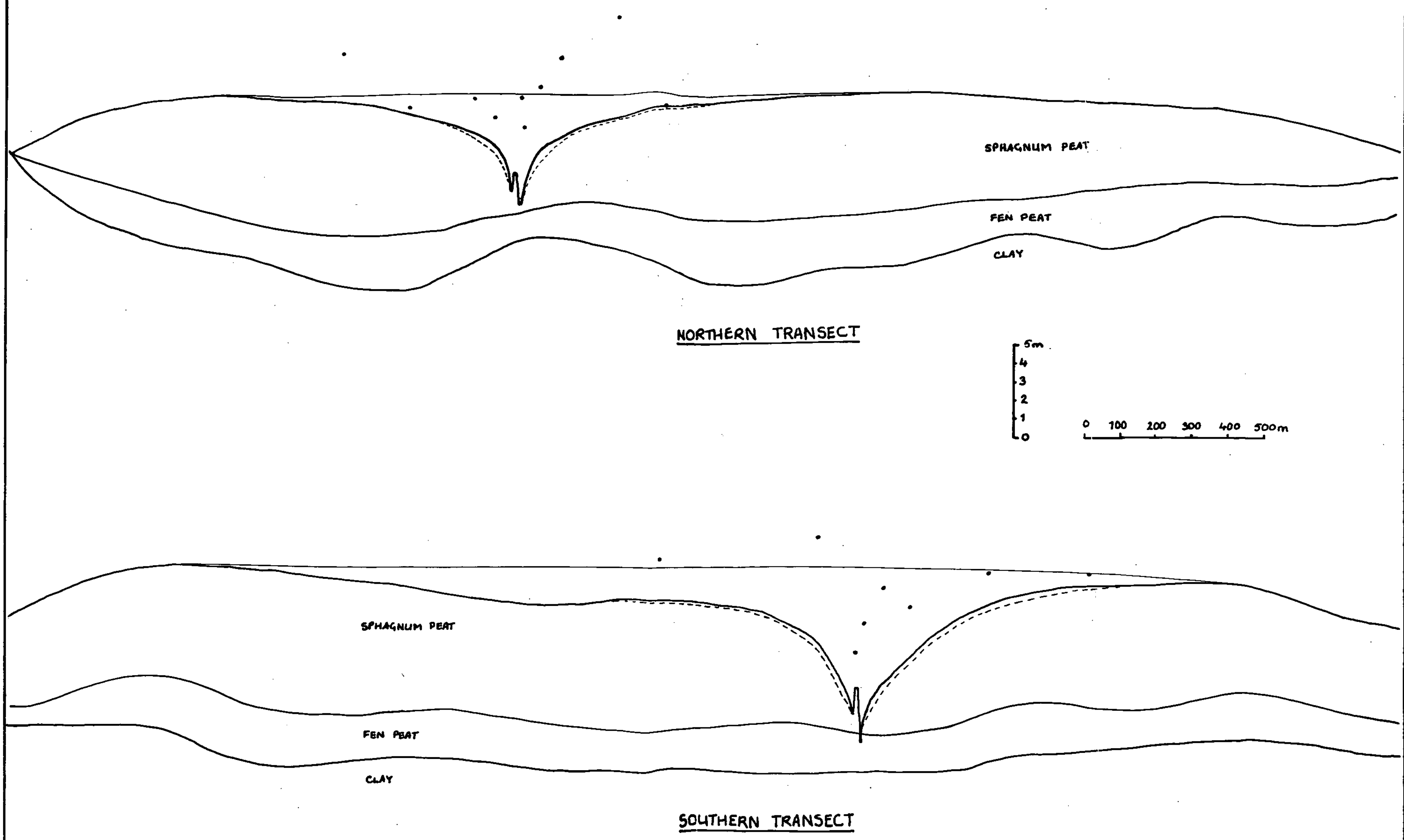

Notes

——— RECONSTRUCTED PROFILE

- - - - WATER TABLE PROFILE

No.	Date	Revision

Clara Bog Project
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RECONSTRUCTED BOG PROFILES

Drawn	Date	Checked	Date	Approved	Date
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Scale 1:10 000 HORIZ.
1:200 VERT.

Job No.

Client Drawing No. FIG. 3.3

Rev.

LGM Drawing No.

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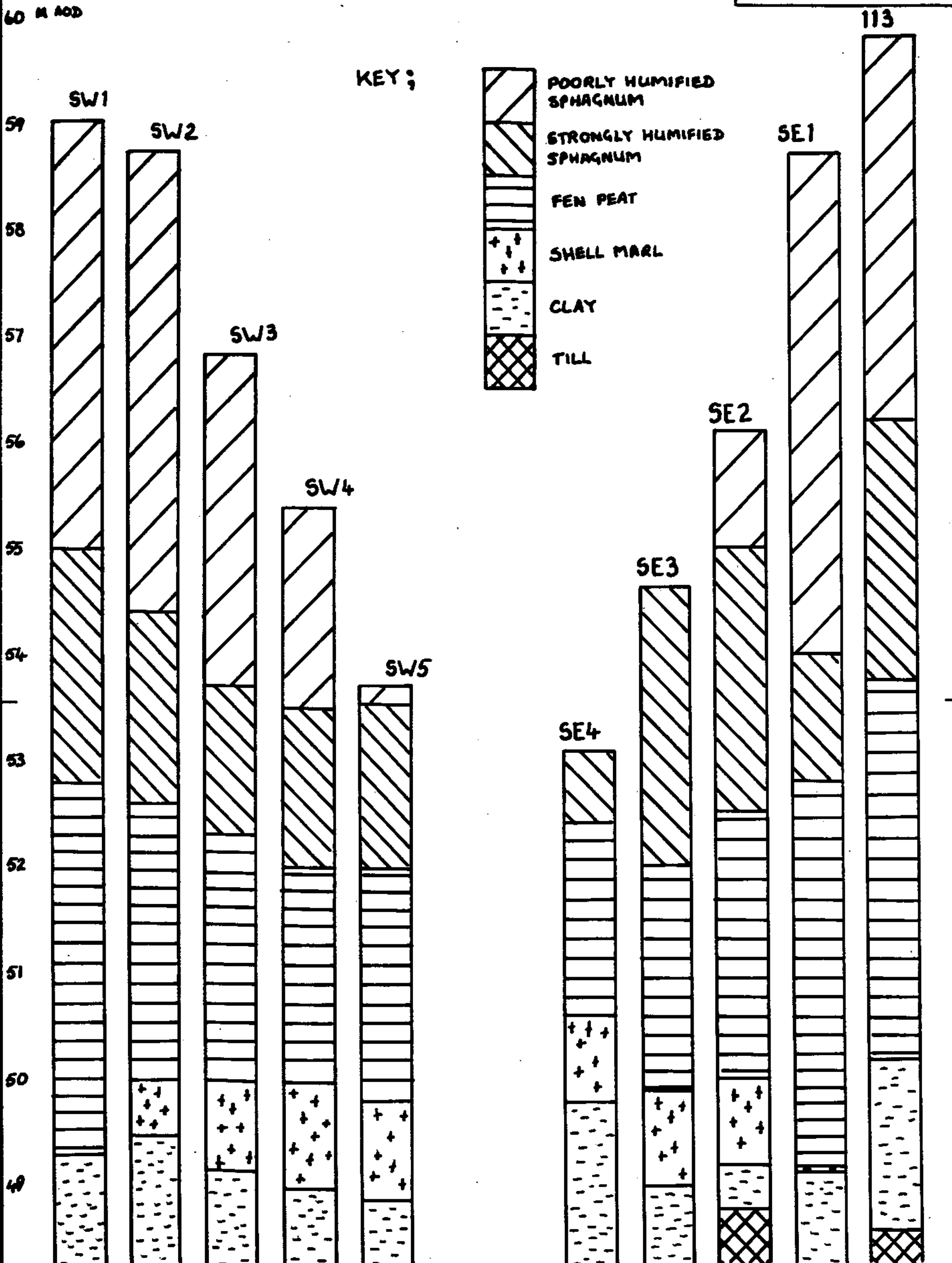
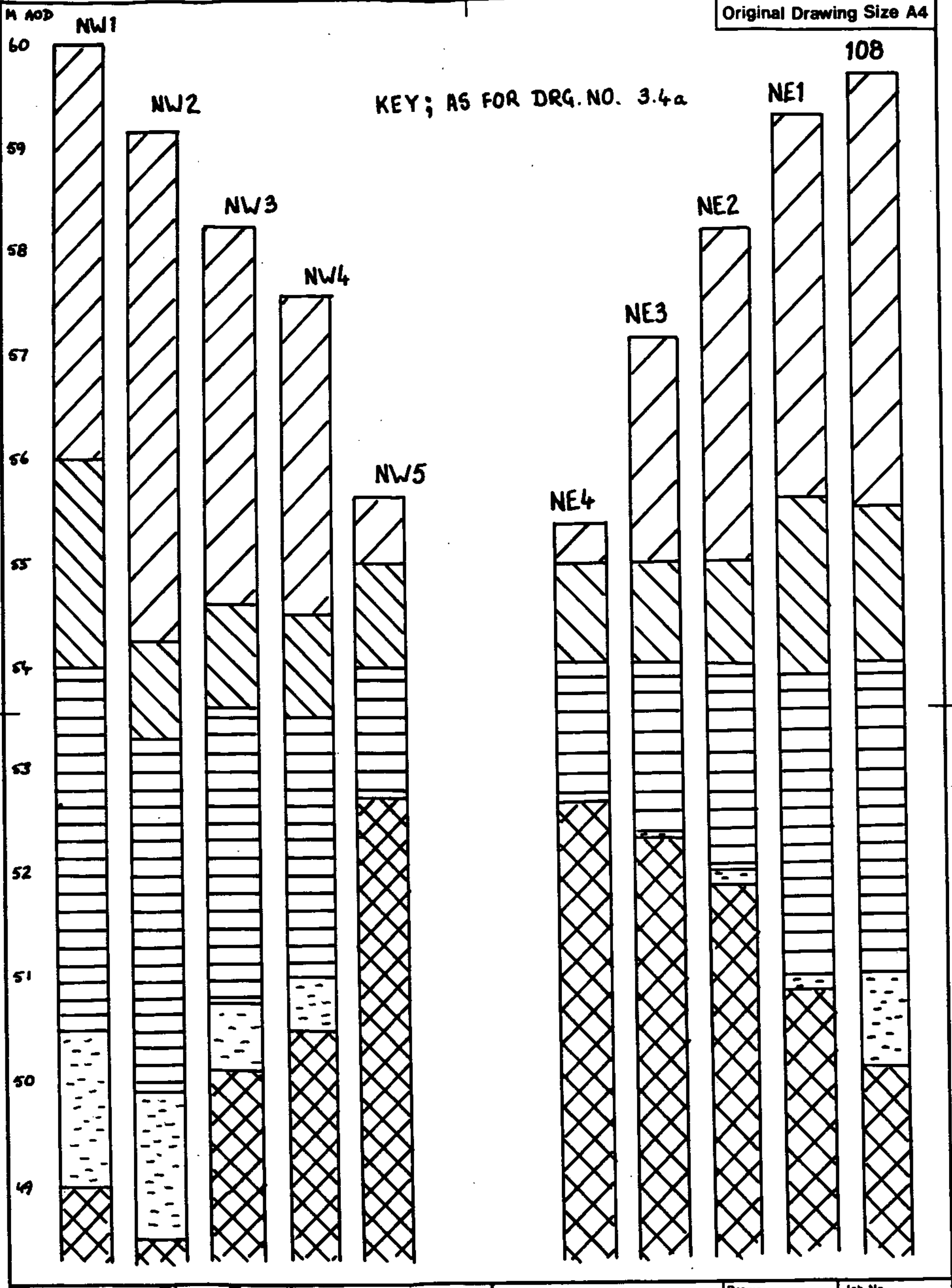
Original Drawing Size A4



Clara Bog Project County Offaly, Ireland	EWRE Dept. Civil Eng. Imperial College	Drawn: H.S.	Job No.
EXTRAPOLATED DRILL LOGS SOUTHERN TRANSECT		Checked	Date: SEPT. '92
	Scales: 1:50 VERT	Drawing No.: FIG. 3.4a	Rev.

A&F Royal Ltd

Original Drawing Size A4



Clara Bog Project County Offaly, Ireland	EWRE Dept. Civil Eng. Imperial College	Drawn: H.S	Job No.
EXTRAPOLATED DRILL LOGS NORTHERN TRANSECT		Checked	Date: SEPT. '92
	Scales: 1:50 VERT.	Drawing No.: FIG. 3.4b	Rev.

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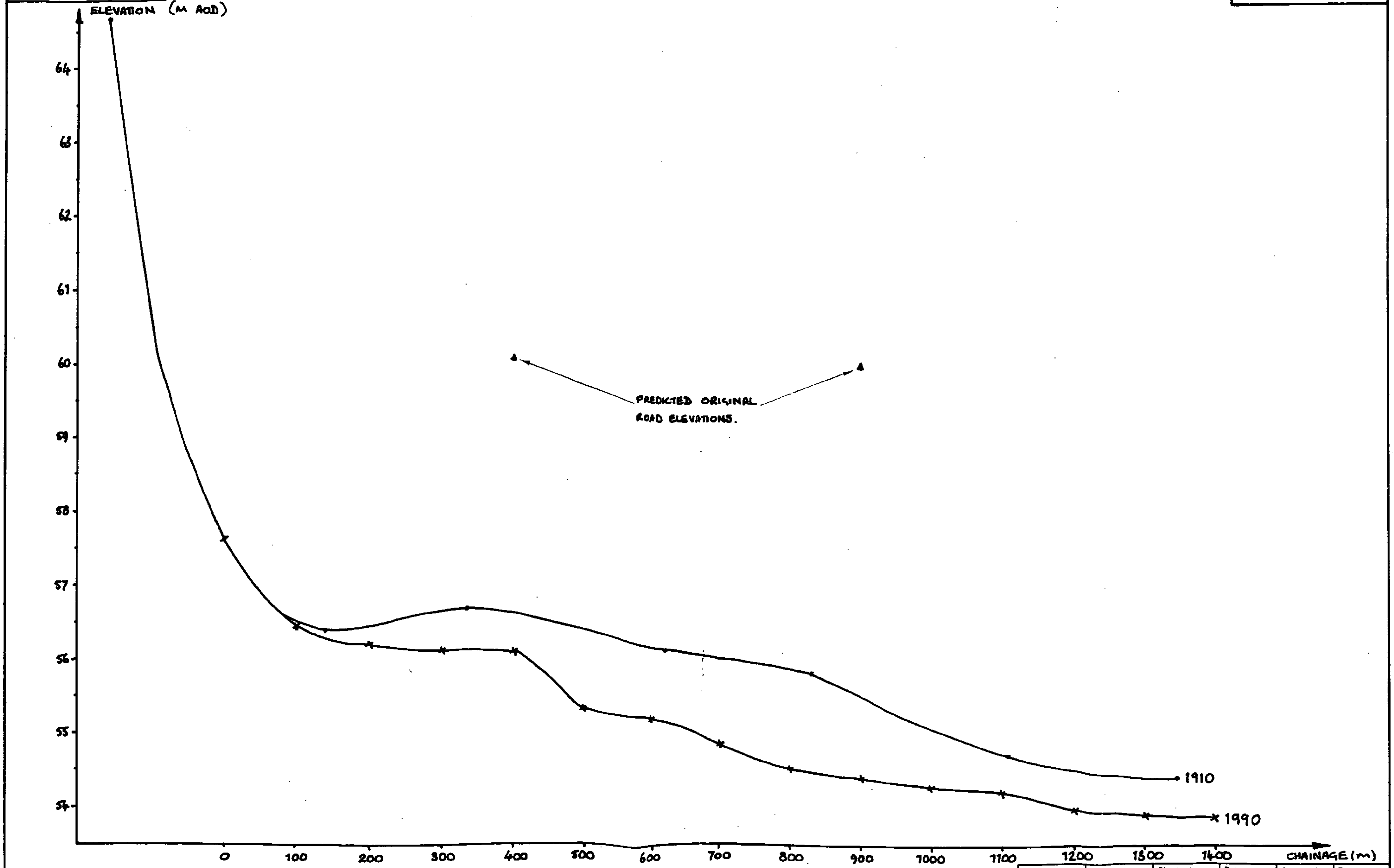
Original Drawing Size A3



Drawn H.S.	Date SEPT. '92	Checked	Date	Approved	Date

Notes

No.	Date	Revision

Clara Bog Project
County Offaly. Ireland

BOG ROAD PROFILES SHOWING EXTENT OF SETTLEMENT.

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Scale AS SHOWN
Job No.
Client Drawing No. FIG. 3.5
Rev.
LGM Drawing No.

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y_e = *elastic settlement*

y_c = *creep settlement*

B = *width of road*

q = *applied load*

s = *shear strength of the soil*

t = *time (mins)*

So as a guide to the initial primary settlement, by taking

B = 5m

q = 9 kN/m^2 (a core through the road showed the hardcore foundation to be 0.5m thick, which according to BS 6031 Earthworks, this has a unit weight of 18 kN/m^3)

s = 5 kN/m^2 (the value used by Hanrahan and Rogers)

it can be seen that Ye = 0.18m, and

Yp	t
0.046	12 hrs
0.057	7 days
0.068	70 days
0.079	2 yrs

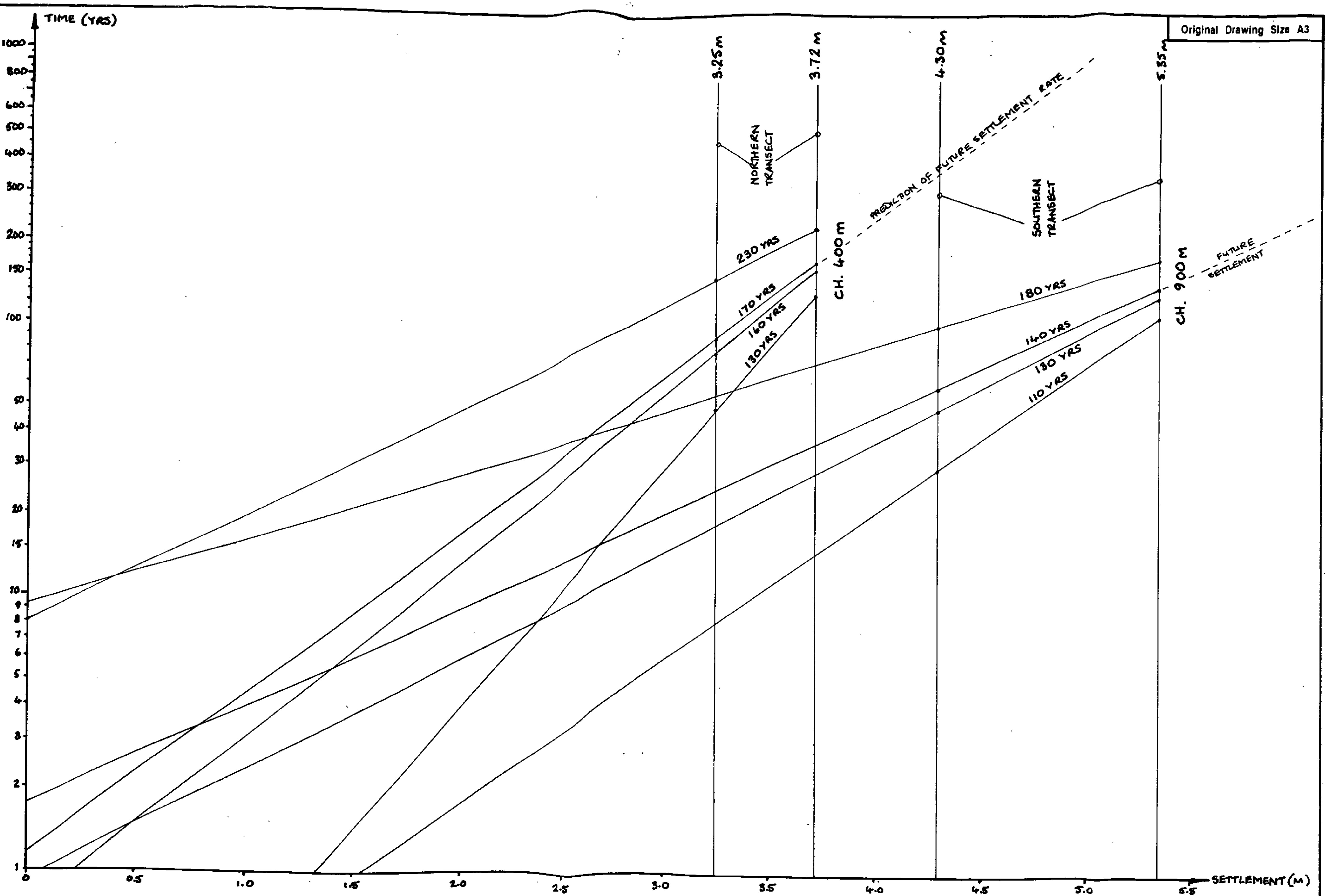
From the above, the initial elevation was reduced by 0.18m, and time zero was arbitrarily taken as one year.

In order to backdate to the time of zero subsidence, it is necessary to estimate the date when the road was constructed, and mark on the log-normal plot the settlement occurring at the present, and at eighty years previous (settlements obtained from O.P.W. survey for the present, and from the 1910 O.S. map for the eighty years previous; see fig.3.5). By trial and error, the slope of the log-linear plot can be made to pass through the point of zero time (taken as one year).

The resulting plot is shown in fig.3.8, and both transects suggest an age of about 150 years for the road. By extending the plots, the ongoing rates of settlement can be seen to be very slow with approximately

0.5m of settlement likely to occur over the next 200 years.

Original Drawing Size A3



Drawn	Date	Checked	Date	Approved	Date
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Notes

No.	Date	Revision

Clara Bog Project
County Offaly, Ireland

SETTLEMENT VS. LOG TIME FOR CH. 400 & CH. 900 ON THE BOG ROAD

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Client Drawing No. FIG. 3.8

Rev.

LGM Drawing No.

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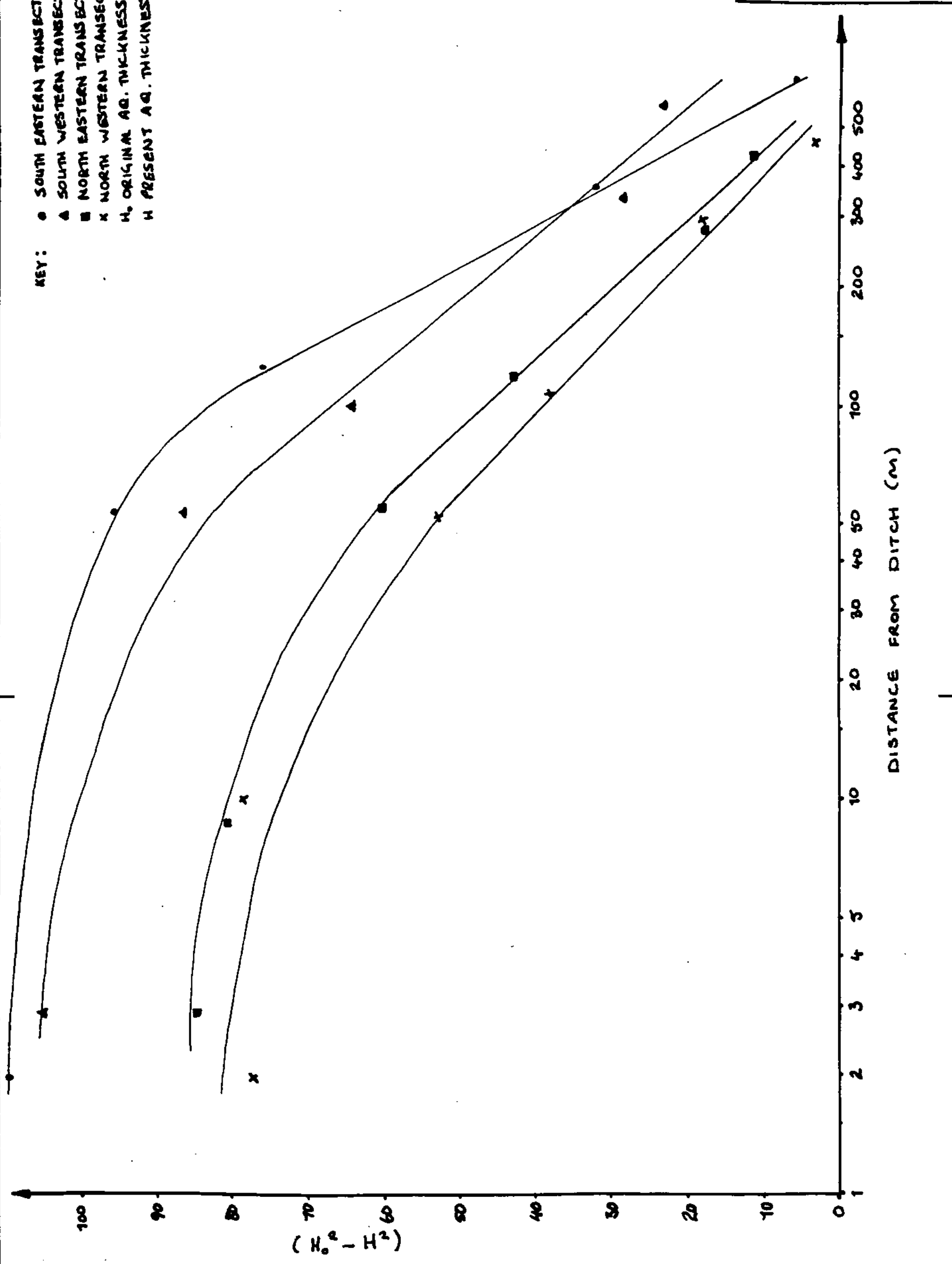
Original Drawing Size A4



Clara Bog Project County Offaly, Ireland	EWRE Dept. Civil Eng. Imperial College	Drawn HS.	Job No.
WATER TABLE DRAWDOWN VS. LOG DISTANCE FROM DITCH PLOT FOR ALL TRANSECTS		Checked	Date SEPT. '92
	Scales AS SHOWN	Drawing No. FIG. 4.1	Rev.

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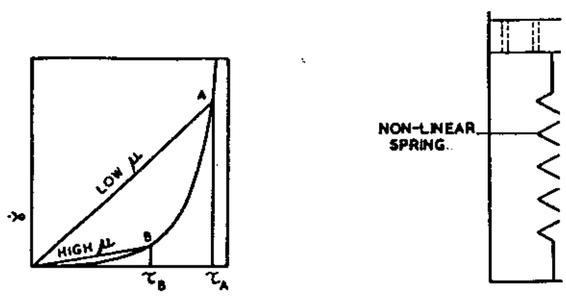
4.0 DEVELOPMENT OF A CONCEPTUAL MODEL TO DESCRIBE THE DRAINAGE AND SUBSEQUENT SUBSIDENCE OF CLARA BOG.

The majority of the work to date on the modelling of the subsidence of peat, has been involved with subsidence due to an applied load, rather than that due to water loss through drainage. Models tend to concentrate on the rates of change of the void ratio, and the rates of dissipation of excess porewater pressures which occur when a load is applied. Barden (1968) and Berry and Poskitt (1972) developed complex rheological models with two degrees of freedom, involving non-linear, damped spring and dashpot arrangements. These types of model are unsuitable for this situation as the subsidence is due to water being lost through gravity drainage, rather than flow induced by the dissipation of excess porewater pressures.



(left). Variation of effective vis

(right). Proposed non-linear rheological :

Where research has looked into the subsidence of peat under drainage, it has invariably been from the point of view of how best to drain the peat so that it can be cut and used as a valuable resource, rather than trying to understand a process which has been ongoing for hundreds of years, with a view to slowing, or even halting that process. It was therefore decided to concentrate on the water flow from the bog and the subsequent drawdown of the water table that this would induce. Because of the huge water content of the peat, this drawdown in the watertable would also represent the surface elevation of the bog, until such time as the peat became so compacted that it was strong enough to support its own weight. Once this has occurred, the two profiles will separate (from the sections in fig.3.3, a process which can be seen to be occurring in the proximity of the drains).

4.1 Modelling the groundwater flow regime

The flow regime involved in Clara bog is clearly not steady state. Because of the huge values of subsidence involved, both the areas of flow and the matrix permeabilities are constantly decreasing. In a mineral soil, classical soil mechanics state that a condition of steady state will eventually develop, the time necessary for this to occur being dependent upon the soil permeability.

According to the Dupuit-Thiem equations, steady state drainage produces a drawdown curve which follows a log-normal relationship, such that for a given discharge, and a homogeneous, isotropic medium,

$$Q = \Pi k \frac{h_1^2 - h_2^2}{\ln \frac{l_1}{l_2}}$$

Q = *discharge*

l = *distance*

h_1, h_2 = *thickness of unconfined aquifer at distances* l_1, l_2

k = *coefficient of permeability*

Hence by plotting the deviation in the water table from the predicted original bog surface elevation, against the log of the distance from the drain, the flow regime can be classified as either steady-state (producing a log-linear plot), or a transient-state (producing a curved plot). By inspection of fig.4.1, the drainage appears to be transient in the close proximity of the drains, but tending towards a steady-state condition beyond about 50m. The curve in the plot may be due partly to the decreasing permeability of the peat in this area. Also from this plot, the radius of influence of the drains can be estimated by extrapolating the linear tails of the plots to cut the line of drawdown = 0. Doing this gives values of 900m for the southern transects, and 600m for the northern transects. This compares favourably with the reconstructed profiles shown in fig.3.3

4.1.1 Transient flow models

When the water level in a drain is lowered, the water elsewhere throughout the soil is then at an excess head with reference to the lowered level in the drain. The excess being dissipated by horizontal flow towards the drain (if the drain is assumed to penetrate the aquifer fully). The phreatic water surface profile describing transient horizontal flow to an infinitely long trench, is given by:

Original Drawing Size A3

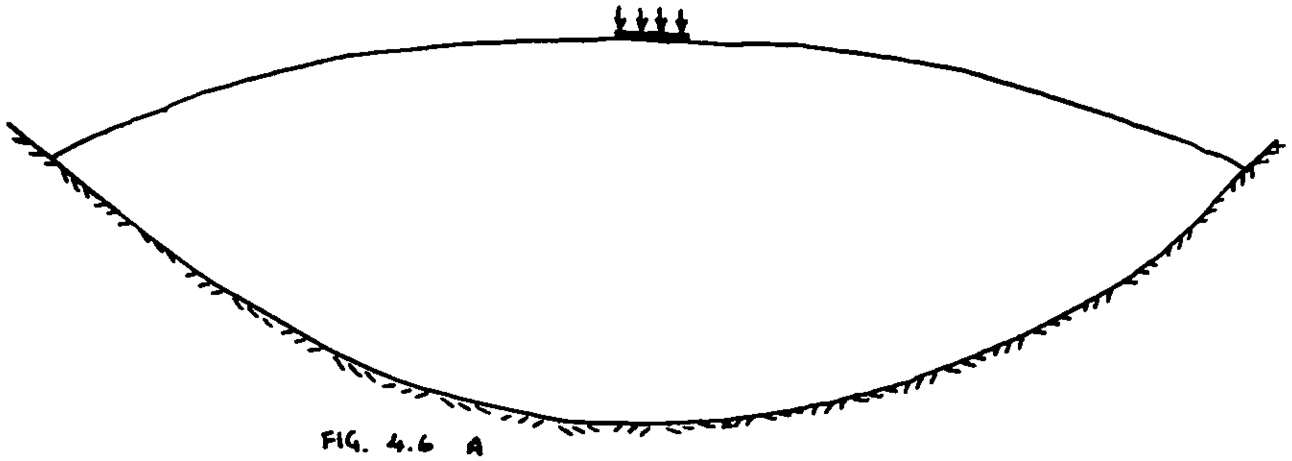


FIG. 4.6 A

ROAD CONSTRUCTION ; IMPOSED LOADING

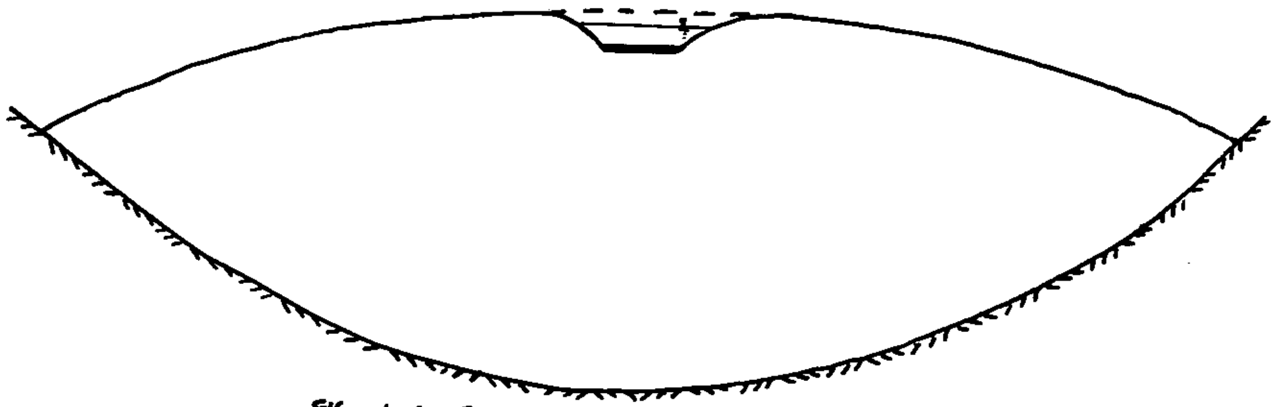


FIG. 4.6 B

ELASTIC SETTLEMENT OCCURS CAUSING A DEPRESSION IN THE VICINITY OF THE ROAD, & HENCE FLOODING OF THE ROAD.

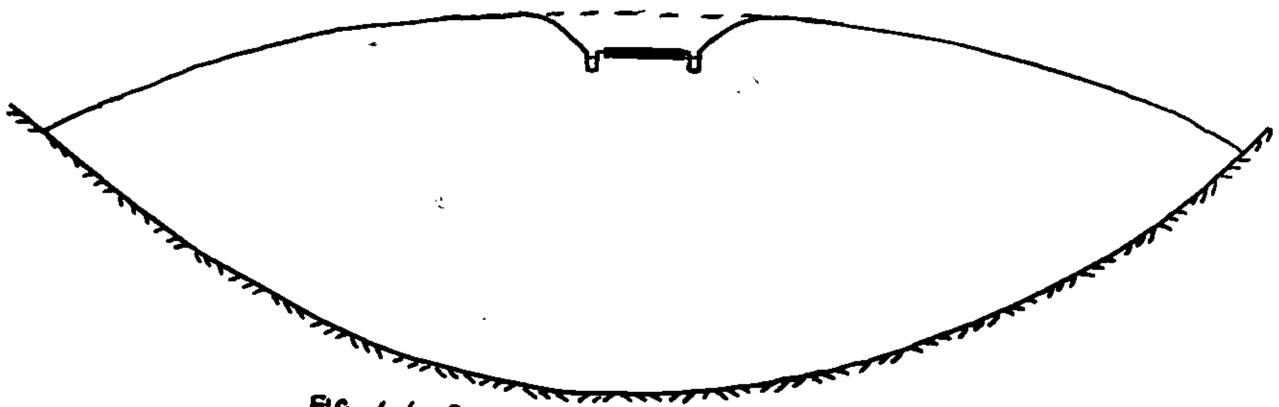
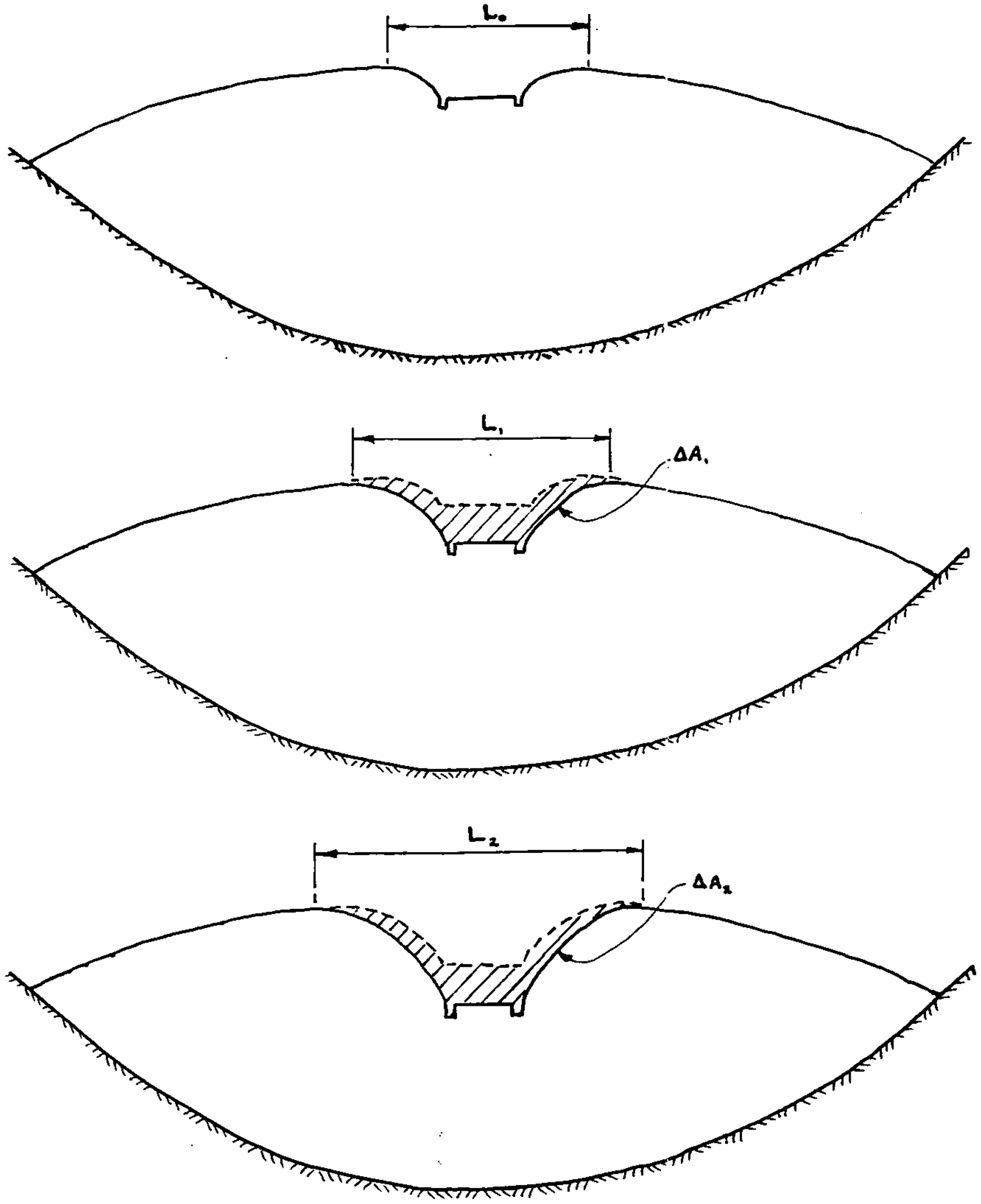


FIG. 4.6 C

TO ALLEVIATE THE FLOODING & HENCE MAKE THE ROAD PASSABLE, DRAINAGE DITCHES ARE CUT EITHER SIDE.



▲ FIG. 4.7

Notes

L = CATCHMENT LENGTH

ΔA = CHANGE IN CROSS-SECTIONAL AREA OF BOG

No.	Date	Revision

Drawn	Date	Checked	Date	Approved	Date
HS.	SEPT. '92				

EWRE
Dept. Civil Eng.
Imperial College

Scale

Job No.

Client Drawing No. FIGS. 4.6, 4.7.

Rev.

LGM Drawing No.

$$C \frac{\partial^2 h}{\partial x^2} = \frac{\partial h}{\partial t}$$

C = coefficient of consolidation for x-directional flow

h = excess head at time t

x = horizontal distance along a streamline

In addition to describing the way the groundwater profile changes with time, the above relationship allows the computation of the rate of increase of the zone of influence. This would be a valuable tool in assessing the extent of the problem facing those attempting to conserve the bog. There are, however, several problems associated with applying a transient-state flow model of this form:

- Determining the coefficient of consolidation.

This can be approximated from a plot of void ratio against the log of time, which could be obtained from the settlement - log time plots used in section 3.0 of this report, where:

$$C = \frac{\Delta e}{\log t}$$

e = void ratio

t = time

However, the slopes for the northern and southern transects are different (C should remain constant for a given soil), and the slope is highly sensitive to the time chosen to represent zero, ie taking one week rather than one year would add another one and a half log cycles. This is, therefore, a very unstable method for determining C. The alternative is to compute C from the relationship:

$$C = \frac{k}{m\,\gamma_w}$$

m = coefficient of unit volume change determined experimentally:

$$m = -\frac{\Delta e}{1+e_0}\frac{1}{\Delta\ \sigma_v}$$

σ_v = *vertical normal stress*

γ_w = *unit weight of water*

k = *permeability*

Problems here arise from the permeability constantly changing with settlement, and also from the determination of the coefficient of unit volume change. This can be done in the lab by conducting oedometer (one dimensional consolidation) tests, posing problems of obtaining undisturbed samples (as discussed in section 2.0 of this report), and, because of the very large strains involved, problems of side friction (taking up to 50% of the applied stress), and reduced permeabilities (by as much as a factor of a hundred) as reported by Sarsby and Vickers (1986). Alternatively, an un situ plate load tests can be done involving the measurement of consolidation with applied load from a jack, difficulties in this case being the construction of bracing for the jack - as the peat is so soft, ground anchors or jacking against a JCB are not feasible. Also, the fibrous acrotelm tends to distort the test due to its high tensile strength, with Landva and La Rochelle (1983) reporting up to 40% of the applied load being carried by the acrotelm.

- Defining the boundary conditions

Because the bog settles as the water table drops, many of the parameters governing the behaviour of the model change, such as the depth of the aquifer, the permeabilities and the location of the groundwater divide and hence the area of the bog contributing to the flow regime (see fig.4.2).

- Solving the second order differential equations

This requires a large computational effort, and necessitates the introduction of many simplifying assumptions.

4.1.2 Steady state flow models

By combining the principals of continuity with Darcys' law (as defined in section 2.3.1 of this report), the Laplace equation for two dimensional, steady-state, saturated groundwater flow has the form:

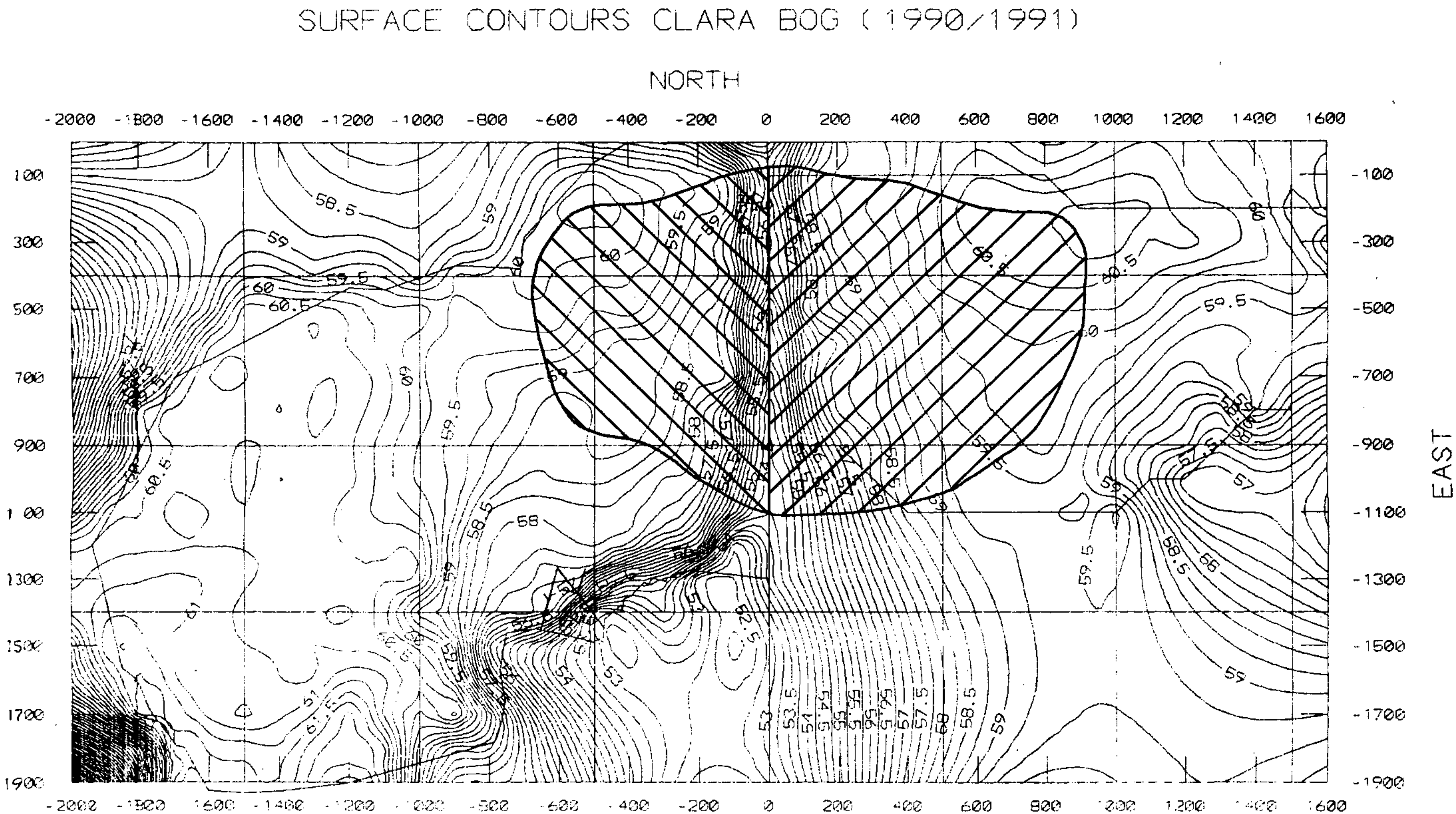


Fig.4.2 Catchment area of the bog between the transects (ch. 400m to ch. 900m), derived from inspection of the ground surface contours. Total area = 123.6 ha

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = 0$$

This assumes a homogeneous, isotropic medium, and is complicated by the fact that the flow region is bounded by the phreatic surface - the shape of which is unknown. To overcome this, Dupuit and Forchheimer (1886) made the simplifying assumptions:

- for small inclinations of the free surface, streamlines may as taken as horizontal
- the velocity of the flow is proportional to the slope of the free water surface, but independent of the depth of flow

These assumptions reduced the model to a one dimensional flow system:

$$\frac{\partial^2 h^2}{\partial x^2} + \frac{\partial^2 h^2}{\partial y^2} = 0$$

See fig 4.3, with:

- the three dimensional boundaries being replaced by fictitious vertical boundaries, curving only in the horizontal plane
- no boundaries having accretion from above or below
- only one dependent variable, h
- no non-linear boundary conditions at the free surface
- the ability to apply the principal of superposition

Work in the field of irrigation further developed the theories of gravity drainage to ditches, with Hooghoudt (1940) proposing a model including both horizontal and vertical flow components, and allowing for the possibility of a layered soil, recharge, and the drains not fully penetrating the aquifer (see fig.4.4):

$$q = \frac{8\, k_b\, D\, h + 4\, k_a\, h^2}{L^2}$$

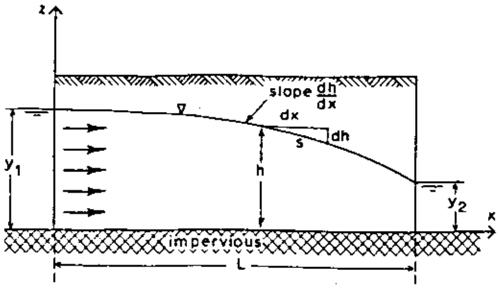
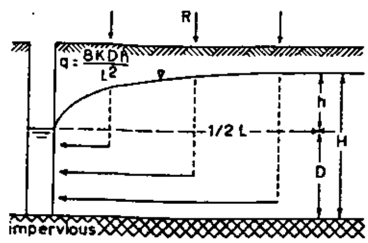


Fig.4.3 Steady flow in an unconfined aquifer, illustrating Dupuit's assumptions.



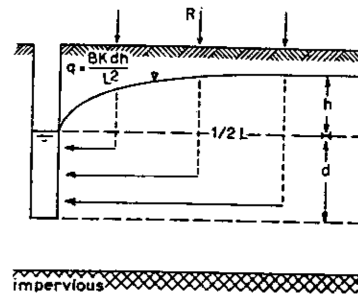
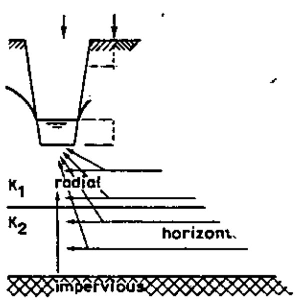
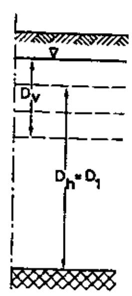


Fig.4.4 The concept of the equivalent depth to transform a combination of horizontal and radial flow into an equivalent horizontal flow.

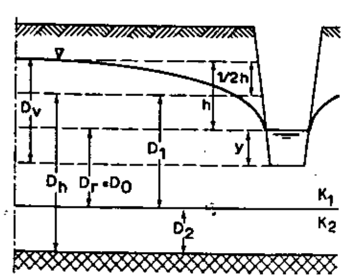


Geometry of two-dimensional flow towards drains according to ERNST (1962).

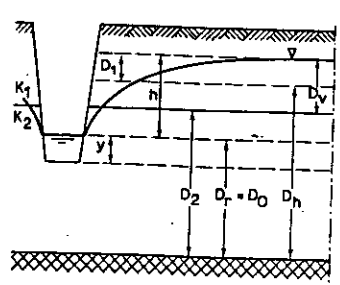


Geometry for a hom

◅ **Fig.4.5**



Geometry of the Ernst equation for a two-layered soil with the drain in the upper layer.



Geometry of the Ernst equation for a two-layered soil with the drain in the lower layer.

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Ref: Drainage Principles and Applications, International institute for land reclamation and improvement (ILRI), 1983		Checked	Date
	Scales	Drawing No.	Rev.

q = *flow per unit length of drain*

k_a, k_b = *permeabilities of the soil above, below the base of the drains*

D = *thickness of the aquifer below the base of the drain*

L = *drain spacing*

h = *greatest head occurring above the drain water level*

This was followed by various other models along the same lines, for example the work by Kirkham (1958), Ernst (1962), and Dagan (1964), all tending towards iterative solutions and the use of nomograms.

With the growing availability of computing facilities, the manual solution of groundwater flow problems is becoming obsolete - being replaced by the use of finite difference and finite element groundwater modelling packages which are now sophisticated enough to cope with varying values of permeability and complex geometries. It should, however, be remembered that these packages are built up from the same theories and simplifying assumptions as the models discussed above, and although they allow the quick analysis of complicated flow problems, the accuracy of the results obtained will be dependent on the suitability of the model to the given problem, and on the quality of the data entered.

4.2 The modelling of Clara bog

The process of subsidence occurring on Clara bog was initiated by the construction of the bog road, inducing the primary, elastic settlement as calculated in section 3.3 of this report. This settlement of 0.18m was sufficient to cause flooding of the road, and hence necessitated the construction of the drainage channels either side of the road (see fig.4.6). The result of this was the formation of a local groundwater divide, inducing gravity drainage towards the road. As this drainage occurs, the groundwater divide spreads outwards, as described in fig.4.7, resulting in an enlarged catchment area.

The processes occurring on Clara bog extend over a very long time period, and as such can be considered as being steady-state in the short term. This is substantiated by the plots of piezometer readings shown in appendix F, which show only slight fluctuations over a ten week period, and by the exercise carried out in section 4.1, where it was shown that the flow regime approaches a steady-state at a distance of 50m from the road. Therefore the conceptual model proposed for Clara involves the use of steady-state drainage theory, applied in time steps to allow for the adjustment of the constantly changing model

WWW

CALCULATION OF HYDRAULIC GRADIENTS AT THE PIEZOMETERS IN THE EXISTING DRAINAGE STATE AND THOSE OCCURING DURING THE CONSTANT HEAD PERMEABILITY TESTS

PIEZO	VERTICAL HEAD NATURAL	VERTICAL HEAD APPLIED	VERTICAL DISTANCE	VERTICAL GRADIENT NATURAL	VERTICAL GRADIENT APPLIED	HORIZONTAL HEAD NATURAL	HORIZONTAL HEAD APPLIED	HORIZONTAL DISTANCE	HORIZONTAL GRADIENT NATURAL	HORIZONTAL GRADIENT APPLIED	TOTAL HYDRAULIC GRADIENT NATURAL	TOTAL HYDRAULIC GRADIENT APPLIED
SE5 D	0.310	1.090	0.870	0.356	1.253	0.836	1.616	2.125	0.393	0.751	0.530	1.461
SE5 C	0.060	0.265	1.005	0.060	0.264	0.526	0.731	2.125	0.248	0.344	0.255	0.434
SE5 B	0.055	1.325	0.910	0.060	1.456	0.466	1.736	2.125	0.219	0.817	0.227	1.670
	0.055	0.595	0.910	0.060	0.654	0.466	1.606	2.125	0.219	0.817	0.227	0.807
SE4 D	0.202	0.647	0.587	0.344	1.102	0.767	1.212	2.125	0.361	0.570	0.499	1.241
SE4 C	0.000	0.180	1.021	0.000	0.176	0.565	0.775	2.125	0.266	0.365	0.266	0.405
SE4 B	0.005	0.715	1.350	0.004	0.530	0.595	1.305	2.125	0.280	0.614	0.280	0.811
	0.005	0.595	1.350	0.004	0.441	0.595	1.185	2.125	0.280	0.558	0.280	0.711
SE3 D	0.047	0.303	2.012	0.023	0.151	1.332	1.682	50.000	0.027	0.034	0.035	0.155
SE3 C	0.047	0.317	2.012	0.023	0.158	1.551	1.821	50.000	0.031	0.036	0.039	0.162
	0.047	0.547	2.012	0.023	0.272	1.551	2.051	50.000	0.031	0.041	0.039	0.275
SE3 B	0.038	0.338	1.013	0.038	0.334	1.594	1.894	50.000	0.032	0.038	0.049	0.336
SE2 C	0.153	0.470	1.880	0.061	0.250	1.591	2.216	71.000	0.022	0.031	0.065	0.191
SE2 B	0.152	0.289	3.022	0.050	0.096	1.672	1.809	71.000	0.024	0.026	0.056	0.099
	0.152	0.262	3.022	0.050	0.087	1.672	1.732	71.000	0.024	0.025	0.056	0.090
	0.152	0.168	3.022	0.050	0.056	1.672	1.698	71.000	0.024	0.024	0.056	0.061
SE1 D	0.160	0.005	3.000	0.053	0.002	2.639	2.804	232.000	0.011	0.012	0.055	0.012
SE1 C	0.160	0.685	3.000	0.053	0.228	2.749	3.274	232.000	0.012	0.014	0.055	0.228
SE1 B	0.015	0.090	3.000	0.005	0.030	1.914	1.989	182.000	0.011	0.011	0.012	0.032
113 D	0.030	0.050	1.500	0.020	0.033	1.214	1.234	286.000	0.004	0.004	0.020	0.033
113 C	0.062	0.091	2.550	0.024	0.036	1.261	1.326	286.000	0.004	0.005	0.025	0.036
113 B	0.032	0.087	1.015	0.032	0.086	1.257	1.318	286.000	0.004	0.005	0.032	0.086

Fig.4.11

parameters as the process of subsidence proceeds. This approach to handling the transience of the drainage process in the long term avoids the many problems discussed in section 4.1.1.

The model consists of two systems - the northern transect, and the southern transect. To begin with, the geometry of the reconstructed bog profiles, along with the slight depression caused by the road and the drainage channels (arbitrarily taken to be the same depth as they are now), are entered into a steady-state groundwater modelling package such as FLOWNET. The analysis can be reduced to a two dimensional flow problem by considering a unit width of flow, and as the transects run along the streamlines. Various parameters will remain constant for the duration of the subsidence process:

- The recharge rate will be taken as the mean annual rainfall. Although there are very large seasonal fluctuations in rainfall, the subsidence process has been ongoing for so long that these fluctuations are negligible for the time scale being considered. Ideally a mean annual rainfall should be calculated from a record of at least ten years duration, but as no record of this length exists for the area under consideration, this is not possible. There is an hourly rainfall record for Clara bog west which has been running for three years (see appendix D). This has been reduced to a daily record, and, where the data was intact for a long enough period, to a monthly record. From this, mean monthly values can be calculated, their sum being the mean annual rainfall:

MONTH	MEAN MONTHLY RAINFALL (MM)
JAN	63.60
FEB	59.25
MAR	56.17
APR	52.10
MAY	16.40
JUN	81.15
JUL	53.70
AUG	60.60
SEPT	37.15
OCT	104.30
NOV	46.70
DEC	74.00
TOTAL	705.12

This value appears to be quite low for the midlands of Ireland, where rainfalls in the region of 850mm/yr are considered the norm.

- Evapotranspiration will also be taken as a mean annual value for the same reasons as discussed for the rainfall. There is insufficient climatological data available for Clara bog to be able to calculate the penman potential evaporation occurring. However, data is available for Mullingar (15km to the north) and Birr (34km to the south west). By comparing the rainfall data at each of these stations with that for Clara (see fig.4.8), it was decided to use an average of the two sets of data (this may be an underestimate due to the larger wind fetches in all directions in comparison to the weather stations. Ideally the evapotranspiration for such a unique environment should be determined by employing a lysimeter). According to Ingram (1983), the evapotranspiration occurring on a raised bog is comparable to the penman potential evaporation, hence the value taken for the mean annual is the sum of the mean monthly values for the duration of the record, which is 422.53mm/yr.

- The runoff coefficient will also be assumed to remain constant, and was calculated by Blackwell (1992) from rainfall and drain discharge records for a storm occurring on 23/07/92, and taking the catchment area from a contour map of the area (see fig.4.2) as being 0.005. It should be noted, however, that during severe storm events, sheet flow has been observed to occur, which would result in a much higher value for the runoff coefficient.

- The clay basin will act as a no flow boundary at the base of the model - the geometry of this will remain the same for all time steps.

- An arbitrary depth of flow in the drains of 0.75m can be taken, considering the present flows (as measured by the v-notches), bed slope and channel roughness, as representing the mean annual depth, although this is very approximate.

For the first iteration, the permeabilities entered will vary with depth, because of the stratified nature of the peat, but will be constant across the section. The values taken for this being those determined experimentally (via the constant head test as described in section 2.3.2 of this report), for the piezometer station 113, as this most closely resembles the initial, unsubsided state of the bog. The groundwater profile will be the same as the ground level profile.

Having entered the above data, the model may be run to determine the steady-state flow rate for each transect, and the steady-state groundwater profile. Then, by superimposing this groundwater profile onto the initial groundwater profile, the volume of water lost from the bog during this iteration can be

Date	Clara	Birr	(Birr-Clara)^2	Mullingar	(Mull-Clara)^2	Average	(Ave-Clara)^2
01.91		77.50		84.80		81.15	
02.91	78.30	60.90	302.76	92.40	198.81	76.65	2.72
03.91	69.40	54.60	219.04	91.40	484.00	73.00	12.96
04.91		105.60		127.10		116.35	
05.91	5.00	4.40	0.36	4.50	0.25	4.45	0.30
06.91	83.90	91.20	53.29	78.50	29.16	84.85	0.90
07.91		65.90		42.10		54.00	
08.91	41.50	74.14	1065.37	37.14	19.01	55.64	199.94
09.91	51.70	50.10	2.56	50.90	0.64	50.50	1.44
10.91	77.20	97.40	408.04	101.10	571.21	99.25	486.20
11.91		88.10		101.30		94.70	
12.91	55.50	33.20	497.29	70.63	228.92	51.92	12.85
01.92	63.60	65.40	3.24	75.90	151.29	70.65	49.70
02.92	40.20	41.00	0.64	60.90	428.49	50.95	115.56
03.92	76.60	86.80	104.04	90.80	201.64	88.80	148.84
SUM			2656.63		2313.42		1031.427

Fig.4.8 Comparisons of rainfall data

(Monthly totals in mm)

determined (see fig.4.7b). Hence, knowing the rate of flow and the volume of flow, the time taken for this 'steady-state' to occur can be established.

For the second iteration, the groundlevel profile will be replaced with the groundwater profile obtained after the first iteration (because the water content of the peat is in excess of 90%, the ground level will drop at the same rate as the water level until such time as the peat becomes compacted enough to support some of its own weight), and the permeabilities will be replaced, if necessary, with values corresponding to the new depth of peat (see fig.4.9). By running the model again, a new steady-state flow rate will be established because of the increased catchment area (as illustrated in fig.4.7c) and altered permeabilities. By the same process as for the first iteration, a volume of flow leaving the bog can be calculated, and hence a time for this to occur can be established.

By continuing this process until the present bog profile is achieved, and by summing all of the time steps, the model can be compared to the dating of the road carried out in section 3.3, and if necessary, some of the parameters can be altered to try to achieve a better fit of the model to reality. Comparison can also be made with the known road elevations as measured in 1910, 1990, and 1992 (see appendix B). It is unfortunate that there isn't a longer flow record for the drains as, if a mean annual flow could be calculated for the present drainage regime of the bog, then this could be used, along with the present catchment area (as shown in fig.4.2) and values for runoff coefficient, rainfall and evapotranspiration, to further calibrate the model.

Once the model has been calibrated, it can be run for the purpose of predicting future rates of subsidence, although the problem then arises of what values of permeability to use as the level of the bog drops to below its present elevation, as no measurements for this condition exist.

4.3 The changing permeability of peat as subsidence commences

Ideally, a model should be able to run on the given initial parameters rather than relying on an input of measured values for each time step. Because of this and the abovementioned problem of what values of permeabilities to use once subsidence exceeds present levels, it was decided to attempt to derive a separate model describing the way that permeability changes as subsidence occurs. Such a model would have the added advantage of allowing permeability values to be adjusted to reflect naturally occurring hydraulic gradients, rather than those occurring during the constant head tests.

It has been established from previous studies, that the permeability of peat is dependent on five factors:

1) The chemistry of the water flowing through it; the adsorption complex being affected by a change in chemistry (Hobbs 1986). This factor is of minor importance only, as the permeability tests were conducted using water collected from the drains. However, as discussed in section 2.2.3.1, the bog water close to the drains is more aerated due to the lower groundwater table, and will therefore be richer in nutrients.
2) The temperature of the fluid flowing through the soil matrix; as temperature increases, the viscosity of bog water, decreases, and hence the permeability of the peat increases. However, Waine et al (1985) found mire water to be largely Newtonian in bulk, and for the temperature range of 3 - 9 degrees celsius, the affect of temperature on permeability to be negligible.
3) The extent of compaction; as the peat becomes more compact, the void ratio decreases significantly, hence reducing the area available for fluid flow through the soil matrix.
4) The degree of humification; because of the colloidal nature of well humified peat, its permeability is much lower than that for fibrous peat. This factor is in turn dependent on the above two points.
5) The hydraulic gradient driving the drainage; as discussed in section 1.3.3, peat does not behave in a classical Darcian fashion.

From the measurements taken of permeability, water content, and specific gravity of the organic content, as described in sections 2.2 and 2.3, it may be possible to link the last three factors with permeability, if the nature of the relationship can be established.

4.3.1 The variance of permeability with hydraulic gradient

There are two models, to date, which attempt to describe the non-Darcian transmission of water through peat:

- Swartzendruber (1962) proposed:

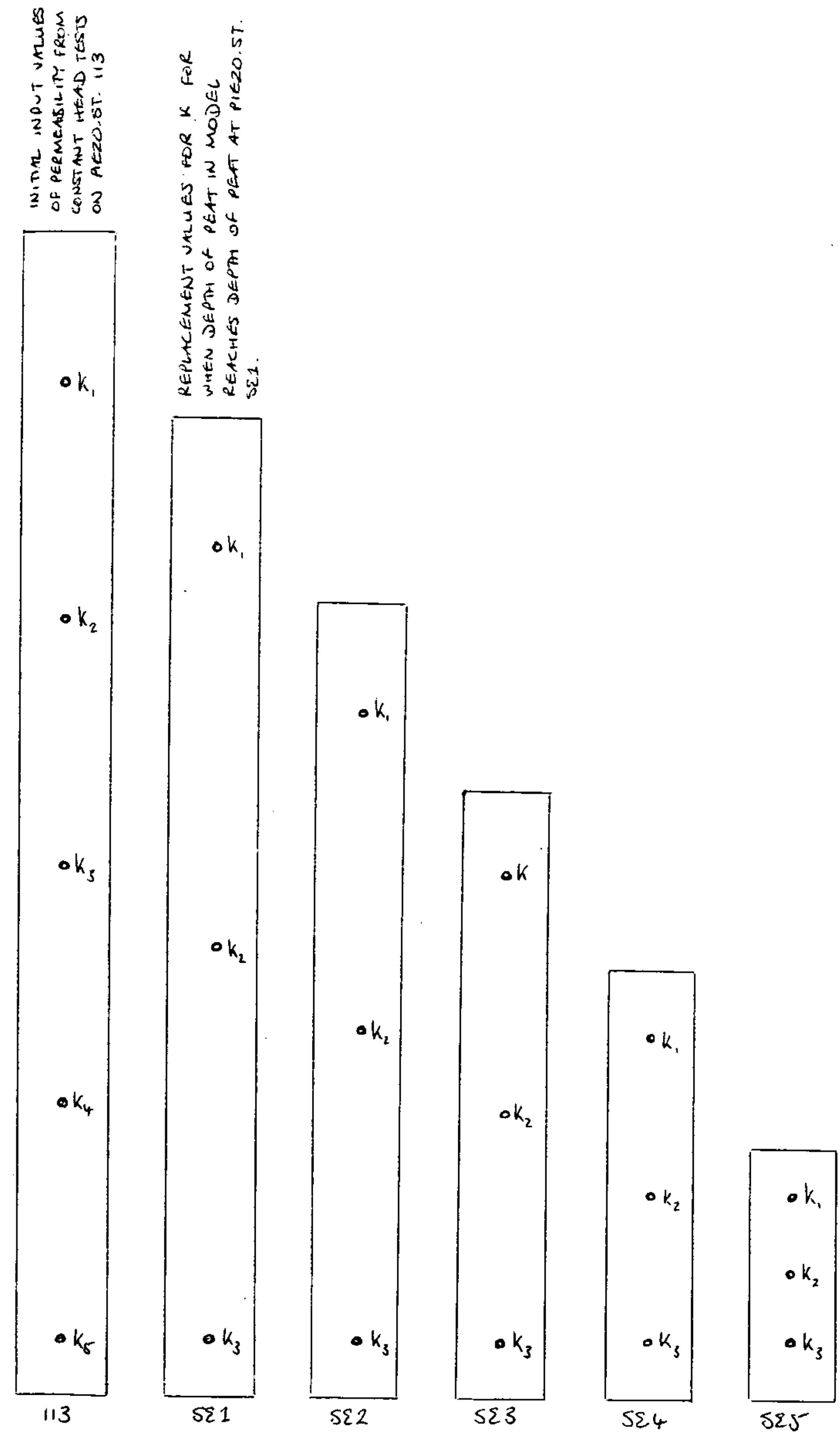
$$v = B\left(i - J_A[1 - \exp(-C\,i)]\right)$$

$$i = hydraulicgradient$$

$$v = flow\ velocity$$

$$B, J_A, C = adustable\ parameters$$

and the permeability is hence given by:



Clara Bog Project
County Offaly, Ireland

EMPIRACLE METHOD OF SELECTING PERMEABILITY PARAMETERS FOR USE IN THE SUBSIDENCE MODEL, AS THE DEPTH OF PEAT DECREASES.

EWRE
Dept. Civil Eng.
Imperial College

Drawn: H.S.	Job No.		
Checked	Date: SEPT. '92		
Scales: N.T.S.	Drawing No.: FIG. 4.9.	Rev.	

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$$k(i) = B\left(1 - J_A\left[\frac{1 - \exp(-C\,i)}{i}\right]\right)$$

- Rycroft et al (1975) proposed:

$$v = a_1 + a_2\, i^2$$

$$a_1,\ a_2 = constants$$

leading to:

$$k(i) = a_1 + a_2 i$$

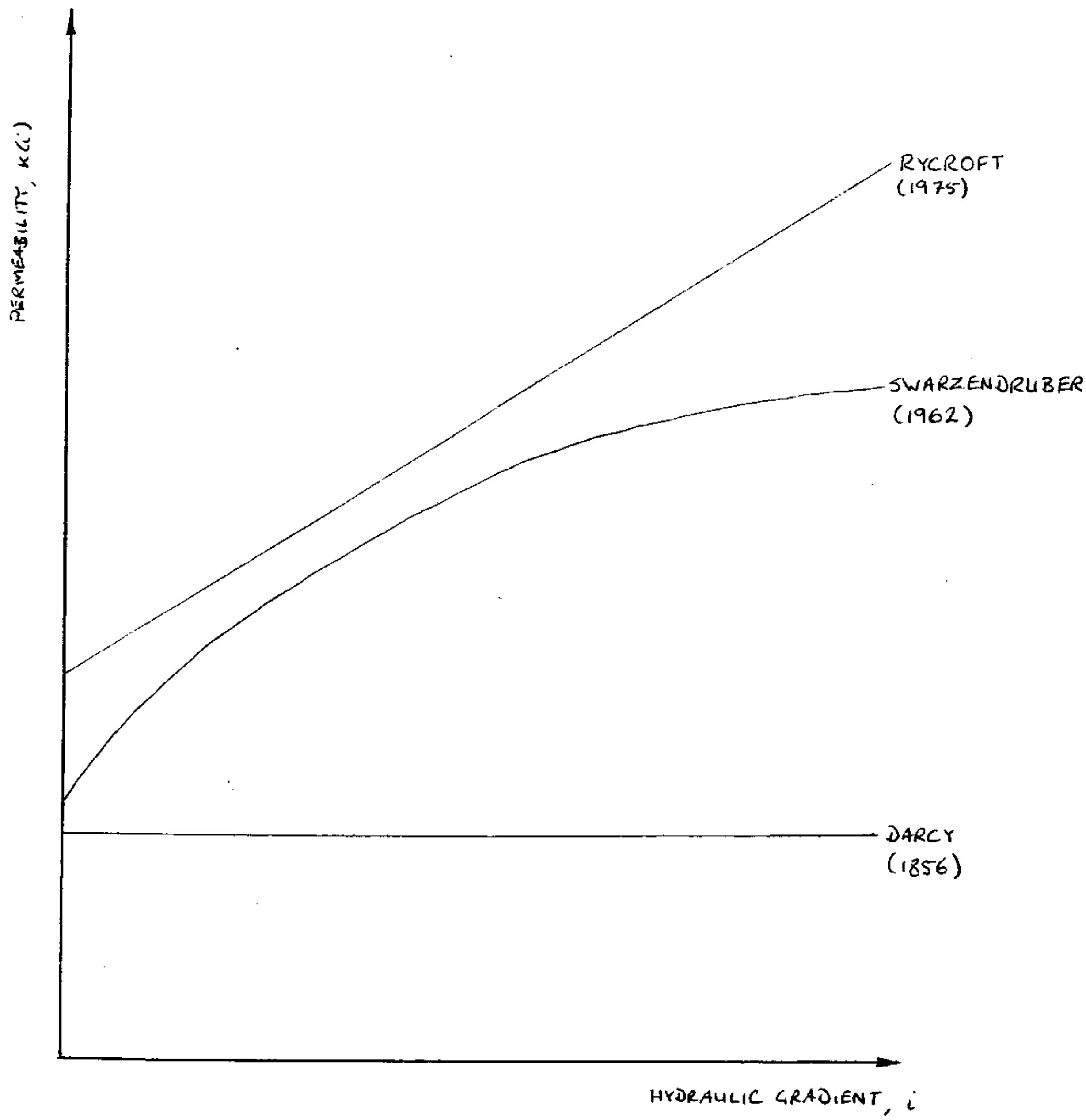
A graphical comparison of the above two relationships with a Darcian matrix being is shown in fig.4.10.

The former relationship is clearly a more complex model, and allows for the tendency of k towards a limiting value at large values of hydraulic gradient, as reported by Waine et al (1985) in controlled laboratory tests. However, the determination of the three adjustable parameters from lab. tests poses a problem due to the difficulties of carrying out undisturbed sampling. For this reason, and because the hydraulic gradients involved were small compared to those used by Waine et al, it was decided to adopt the latter relationship.

In order to determine the constants for the model proposed by Rycroft, it was necessary to calculate the hydraulic gradients which were present during the constant head tests for each piezometer station, and each depth tested. This was done by considering the hydraulic gradient acting horizontally, and then vertically, and then deriving the total gradient from Pythagoras' theorem. A summary of this data being displayed in the table in fig.4.11.

4.3.2 The variance of permeability with compaction and degree of humification

It has been established by many workers in the field that the permeability of peat decreases logarithmically with increasing density, although other relationships have also been established:



Clara Bog Project County Offaly, Ireland	EWRE Dept. Civil Eng. Imperial College	Drawn: H.S.	Job No.
VARIATION OF APPARENT HYDRAULIC CONDUCTIVITY, K(i), FOR THREE TYPES OF FLOW RELATIONSHIP.		Checked	Date: SEPT. '92
	Scales: N.T.S.	Drawing No.: FIG. 4.10.	Rev.

- Korpijaakko and Radforth (1970) proposed a link between the permeability of sphagnum peat from raised bogs, with both degree of humification and dry density of organic matter - both relationships being of a log-linear form.
- When considering the permeabilities of North German peats, Loxham and Burghardt (1986) found a near log-linear relationship between permeability and moisture content.
- When under load, Hanrahan (1954) found a log-log relationship between void ratio and permeability for an Irish sphagnum peat.

It was decided to use the relationship linking density to permeability as it is the most widely accepted, and because it in turn can be linked to both void ratio (representing the degree of compaction), and the specific gravity of the organic matter (representing the degree of humification) by the expression:

$$\rho_b = \rho_w \left(\frac{Sg_s + e}{1 + e}\right)$$

ρ_b = *bulk density*

ρ_w = *density of water*

e = *void ratio*

Sg_s = *specific gravity of the organic solids*

Although all attempts to accurately measure bulk density from peat samples were unsuccessful (both in this study and in the 1991 project), values can be derived from measurements of void ratio and specific gravity obtained as described in section 2.2.3.1, using the above relationship.

4.3.3 A combined relationship

So, from the above relationships:

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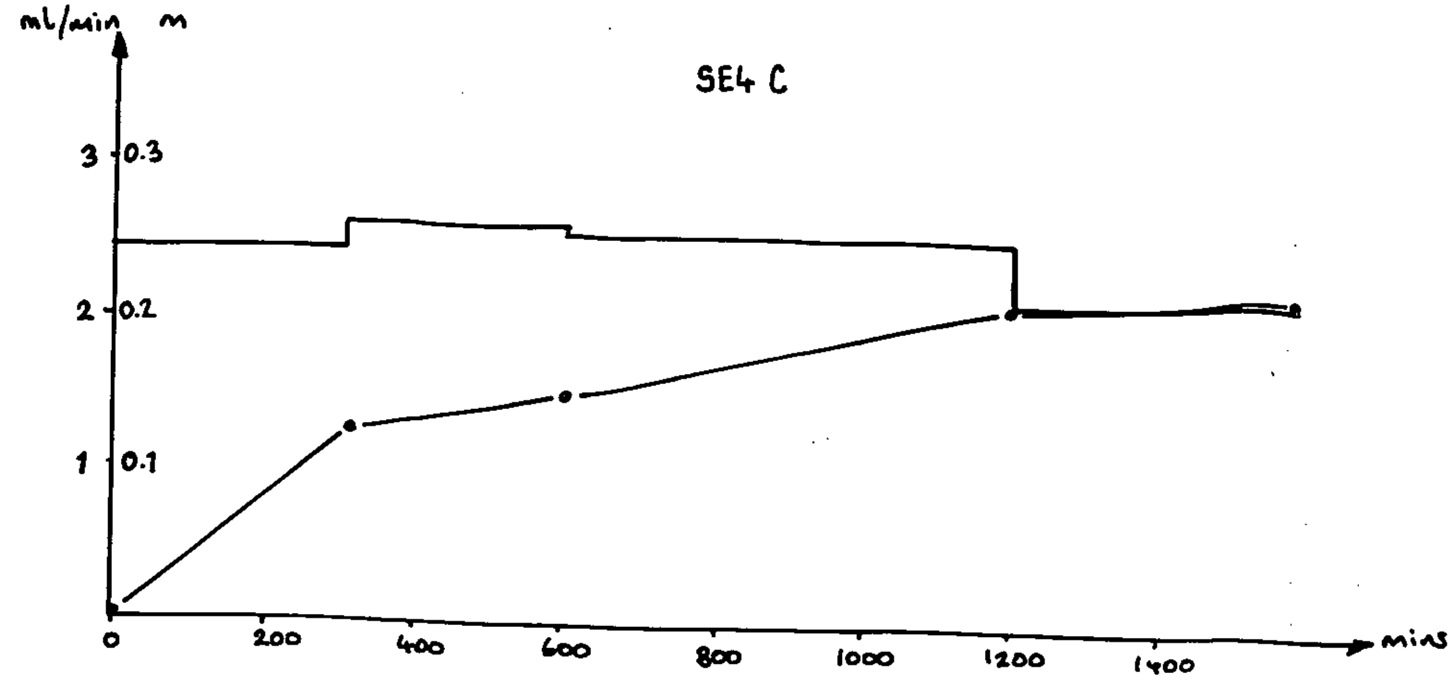

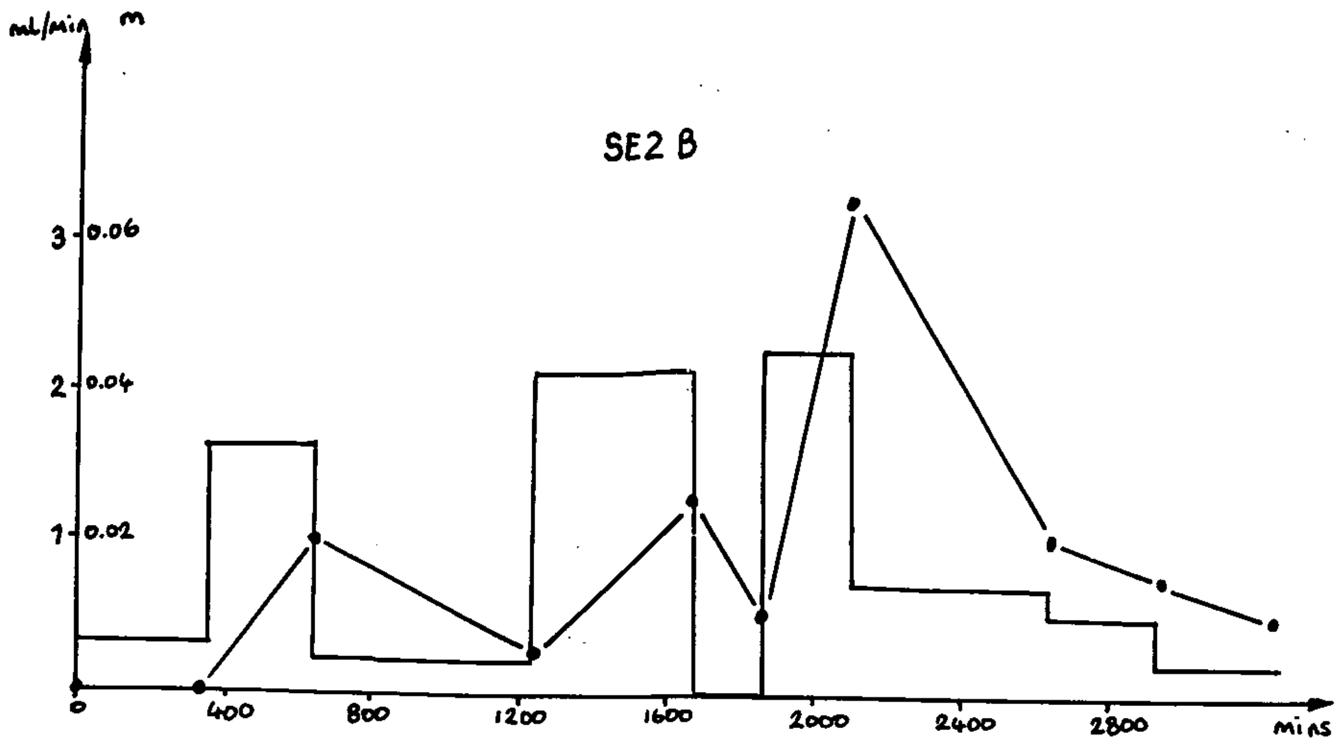

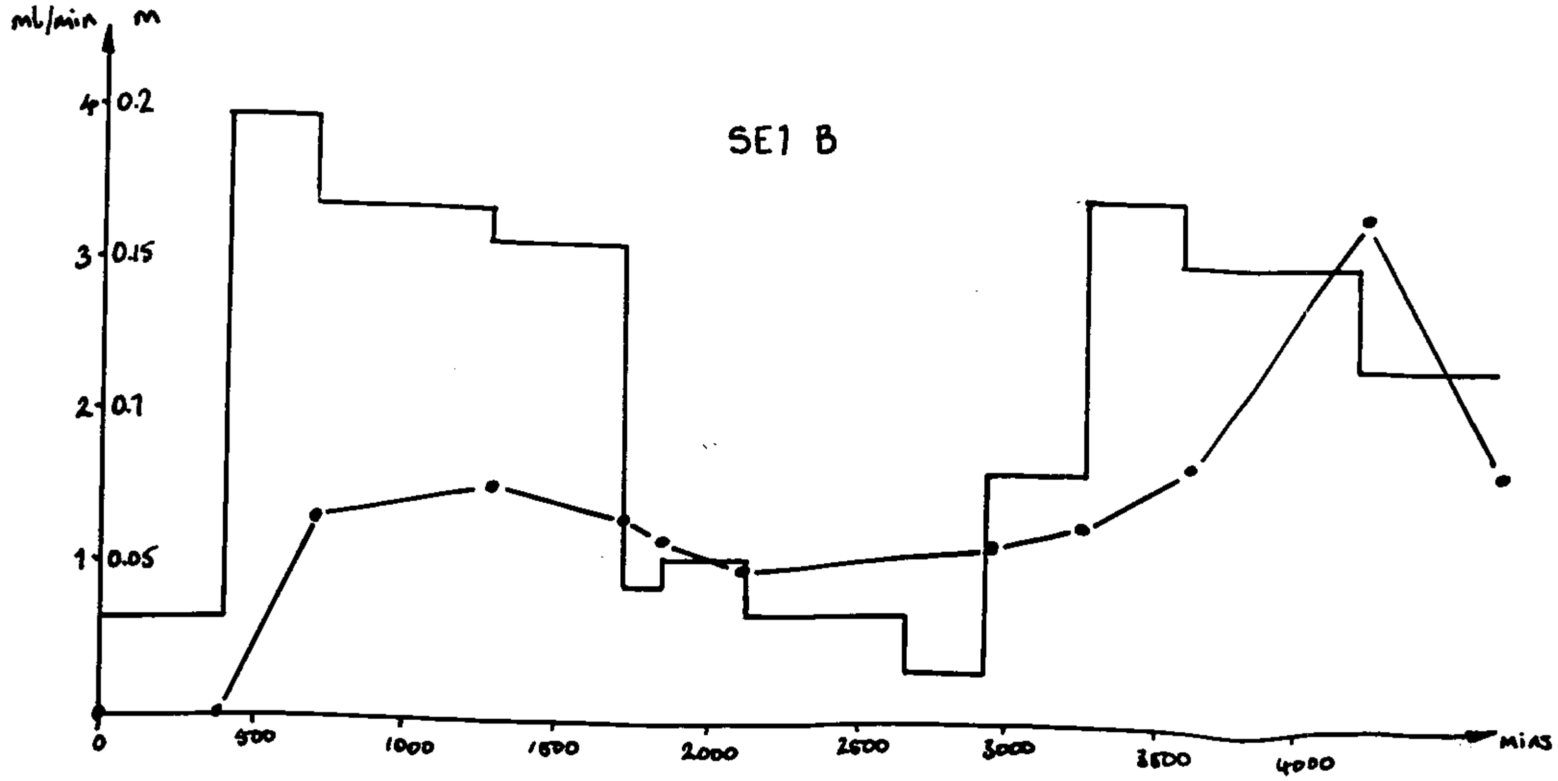

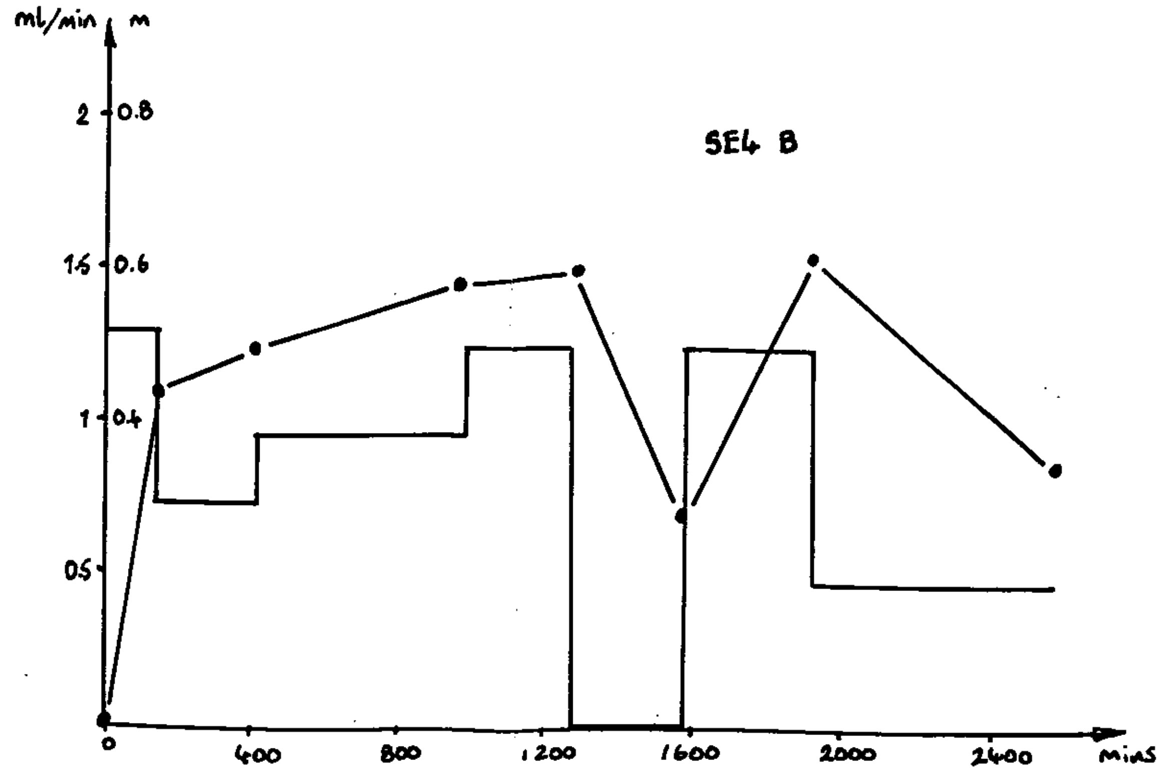

Notes

——— DISCHARGE

—•——•— APPLIED HEAD

No.	Date	Revision

Clara Bog Project
County Offaly, Ireland

PERMEABILITY DATA; DISCHARGE & CORRESPONDING APPLIED HEAD WITH TIME. PIEZOS SE4C, SE2B, SE1B, SE4B

Drawn	Date	Checked	Date	Approved	Date

EWRE
Dept. Civil Eng.
Imperial College

Scale: AS SHOWN
Job No.
Client Drawing No.
Rev.
LGM Drawing No.

A&F Royal Ltd

$$k(i) = a_1 + a_2\, i$$

$$\log k(\rho) \propto \rho$$

when combined give:

$$k = a^{\rho}\,(b + c\, i)$$

$$a,\, b,\, c = \textit{constants}$$

with the constants b and c cancelling the necessity of the first constant, a.

Therefore, if values are known for permeability, hydraulic gradient, and density for each of the constant head tests conducted, then the data can be fitted to the above relationship in order to determine the constants. It was decided to do this by a method of least squares, taking estimates as starting values, and calculating the difference between the predicted value of k (from the density and hydraulic conductivity values with the estimated parameter values) and the value of k measured in the constant head tests. Hence the error in the estimate would be given by:

$$err = k - c_{\rho}(a + b\, i)$$

In order to prevent positive errors cancelling negative errors, the square of the error should be taken, and to remove any bias due to the range of the k values, log values should be used. Hence the total error of the fit is given by:

$$err = \Sigma_{j=1}^{j=n}\, [\log k_j - (\rho_j \log c + \log(a + b\, i_j))]^2$$

$$n = \textit{number of data points}$$

Using this, one parameter can be held constant, whilst the other is altered until a minimum error is found, then this parameter can be held constant whilst the first is altered to find a minimum. This procedure is then reiterated to find a minimum error for the two parameters. This requires a high computational effort, and is therefore best done using a computer. Any package designed to minimise a function would be suitable, such as the NAG algorithm, or less complex, the downhill simplex algorithm. However, due to limitations of time and resources, a simple fortran program was prepared to perform the iterations, and is shown in appendix E.

By performing the above iterations, and setting the constant a arbitrarily to 2.0, a minima was reached at b = 1 e-04, and c = 3 e-08. By plotting the field measured values for permeability against those predicted by these constants in the above relationship, an indication of the closeness of fit can be obtained. This plot is shown in appendix E, and indicates a number of outliers which are likely to reduce the accuracy of the model. A further source of error is the very large value of the constant a, arbitrarily chosen, in relation to the size of the constant b, which was obtained in the minimisation procedure. In order to obtain a better fit, it would be necessary to rerun the minimisation with the data points responsible for the severe outliers removed, and a much smaller value taken for the constant, a.

5.0 DISCUSSION AND CONCLUSIONS

5.1 Further work

Because of time restrictions, it was not possible to satifacorily complete much of the work started on this project. There is therefore much scope for further studies in this area.

The conceptual model developed to describe the subsidence process could be applied using the data gathered in this study and a groundwater modelling package, as described in section 4.2. In order to perform a satisfactory calibration of the model, it is necessary to calculate a water balance for the present drainage conditions. This would involve waiting for a longer flow record from the drainage channel measurement stations (and hence derive an annual outflow from the catchment). However, an approximation of the outflows could be made by considering field measurements of hydraulic gradients and permeabilities. Through the application of the model, a more detailed description of the future behaviour of the bog could be attained, including not only rates of subsidence, but also rates of increase of the zone of influence of drainage.

The refitting of the hydraulic gradient and density data to the field measured permeabilities as described in section 4.3 would enable a relationship to be formed describing the change in permeability as subsidence commences. This would be a valuable tool both in the modelling process, and in any comparisons made between the various methods available for measuring in situ permeabilities. If the resulting relationship proved to be unsatisfactory, alternative forms could be experimented with, such as applying the Swartzendruber model for k(i) rather than the Rycroft model, or using other indicators of compaction and humification rather than density (as discussed in section 4.3.2).

5.2 The conservation of Clara bog

Although it was not possible to conduct a water balance (due to insufficient drain flow data), and hence determine the volume of water being lost from the bog each year, it has been established that a loss is occurring, and is causing the ongoing subsidence of the bog surface. However, the prediction of future settlements for the road as conducted in section 3.3 indicate that only 0.5m of further subsidence can be expected to occur over the next 200 years, suggesting that the road is approaching a state of equilibrium, and that, in the short term, any action towards the cessation of its subsidence would be obsolete. This therefore poses the question of where the damage to the bog is occurring. As the zone of influence for the drainage process has been shown to extend so far out from the road, it is likely that the higher points of the bog are still undergoing detrimental rates of settlement, even if the central region is approaching a steady condition.

It must then be decided just how much of a conservation effort for Clara is required, the problem of conservation being to maintain the bog as a dynamic entity, ie in a form which allows it to survive. In the short term this implies the prevention of further damage by halting the peripheral turf cutting, but in the long term, it will be necessary to reverse the hydraulic gradients causing the drainage of the bog. The question then to be asked is whether it is sufficient merely to halt these processes, or are measures required to begin the restoration of the bog to its original profile? This key issue has to be addressed before a conservation program can be established.

5.2.1 Proposals for regeneration

Extensive studies to determine the ideal conditions for bog regeneration have been conducted by scientists throughout Europe, especially in the Netherlands where nearly all naturally occurring peatlands have been destroyed. Streefkerk and Casparie (1989) classified three mechanisms for regeneration:

- from an open water situation, as in the initial bog formation process.
- from floating scragh.
- from between tussock vegetation.

The first two options involve extensive flooding, whilst the latter requires a more gradual, controlled raising of the water table. Whichever method is adopted, the controlling factor is the raising of the groundwater level, with a view to reversing the hydraulic gradients driving the drainage process.

The conventional method for raising the water table elevation in peatland conservation projects is to block off all drainage ditches with peat dams. This has already been done for the shallow drains on Clara east, and has in some cases been reasonably successful (see fig.1.7). However, the water loss from Clara bog is, in the main, via the deep roadside drains, which remain intact. Blocking these drains would inevitably raise the water level in the bog, slowing the subsidence process, but would result in the flooding of the road, so making it impassable. The road would then act as one large drainage channel along the length of the bog, and the loss of water from the bog would continue, albeit at a slower rate. In order to halt the drainage process completely, it would be necessary to block off the depression caused by the road. This could be done in one of two ways:

- By the construction of a large dam structure at the southern end of the bog (about six metres in height), allowing for the depression to become impounded. This would form the first two regeneration conditions as proposed by Streefkerk and Casparie (1989), or, if impoundment was undertaken in a more controlled fashion, (by stepped construction of the dam, or by the use of an outlet structure through the dam), this would form the latter condition. It would also be necessary to demolish and remove the road.

- If it was considered acceptable to keep the two distinct halves of the bog separate, the level of the road could be raised to just above its original elevation, so allowing flooding of the bog either side. The options available for this being:

a) The construction of an embankment; this poses the problem of very high loadings, so adding to the problems of subsidence. This cannot be alleviated by the use of lightweight geotextiles because of the reducing properties of bog water. The use of dried peat has been adopted as a lightweight fill for railway embankments in the past, and may be suitable as it doesn't expand on rewetting. However, the volumes which would be required make this an unlikely solution. Again, the construction and subsequent impoundment could either be done in one go, or in controlled steps.
b) The construction of a viaduct by piling through the peat and into either the clay, or underlying limestone (depending on loads and bearing capacities involved). From a purely engineering point of view, this would appear to be the best solution, but both the funding necessary for such a project, and the aesthetic impact would be a major drawback.

In addition to preventing the water loss from the bog via the road drains, it is imperative for the peripheral cutting of turf to be stopped, as this has been shown to be contributing substantially to the drainage process, especially in the south western area of the bog. To further aid regeneration, the removal of trees and shrubs from the heavily drained zones of the bog would be necessary.

The problems associated with such a scheme are numerous, including:

- Obtaining planning permission for the demolition of the road and construction of the dam for the first option - planning permission for the construction of the second option wouldn't be as much of a problem, as it doesn't involve the permanent closure of the Rahan road.
- Purchase of all peripheral zones of the bog still in private ownership
- Public opposition due to the loss of easy access to Rahan - either permanently for the first option, or temporarily (during construction) for the second option, and the necessary cessation of all turf cutting on the bog.
- Obtaining the considerable funding which would be required, especially in the early stages for the construction and demolition works, but also later on for sustaining the ongoing maintenance and management program.

The problem of funding is likely to be the main factor controlling the choice of scheme. Because of the scientific importance of Clara bog, it is possible that it would qualify for an E.C. grant to cover some of the costs involved in its conservation. Also, as funding for the present research was obtained from the Irish Office of Public Works, Wildlife Service (who own 70% of the bog), and the Dutch State Forestry, it is possible that they would be interested in further funding. Aside from this, funding would have to come from private sources.

5.2.2 A management plan

It is essential for such a conservation scheme to have a well developed management plan overseeing both the technical aspects of regeneration, and the handling of the inevitable outside interest that the project would generate. This would involve the permanent employment of a site warden, plus the involvement of conservation volunteers. Visitors must be carefully supervised so that their activities do not conflict with the conservation effort. A wet bog surface is very susceptible to damage from trampling; it has been found that a single footprint on a bog can still be seen up to two years later. Therefore, paths and boardwalks need to be erected to direct visitors, and carparks need to be made available. Educational material should be prepared and presented in an information centre, or by means of a permanent poster board. Ideally, guides should be employed during peak visitor periods to answer questions.

The situation at present in Clara is hindered by the fact that the Dutch-Irish study was set up as a temporary project, and although the bog is a nature reserve, and has been declared as a Site of Scientific Interest, full use has not been made of its potential for development as a tourist attraction. Various leaflets describing the importance of the bog as a nature reserve, and its flora and fauna have been prepared, but as there is no information centre, visitors do not generally get to see them. However, once a year, during the annual festival in the town, an information centre is set up, and bog tours are organised. From the interest shown during this week, it is clear that there is much scope for further development.

Before the instigation of a conservation program, it is important to conduct a full feasibility study, covering not only aspects concerning the mechanics of bog conservation and their associated financial implications, but also the socio-economic factors concerning the town and its residents. Clara has little local industry, and the improvement of present levels of tourism would result in job creation in the service industry, with an increased demand for bed and breakfast accommodation, shops, and possibly also holiday centres catering for walking and cycling holidays in the area. Such local improvements would hopefully serve to offset any public opposition to the scheme.

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APPENDIX B

Level data

ROAD LEVEL DATA

CHAINAGE (M)	ELEVATIONS IN METRES ABOVE ORDNANCE DATUM 1910 O.S. MAP	1990 O.P.W. SURVEY	1992
0	57.620	57.620	57.620
100		56.470	56.468
140	56.400		
200		56.220	56.204
300		56.140	56.124
335	56.700		
400		56.130	56.155
500		55.350	55.327
600		55.200	55.190
620	56.200		
700		54.820	54.813
800		54.530	54.526
830	55.800		
900		54.410	54.403
1000		54.290	54.287
1100		54.220	54.217
1110	54.700		
1200		53.960	53.945
1300		53.890	53.880
1350	54.400		
1400		53.890	53.872

PIEZOMETER LEVEL DATA

PIEZO REF	TOP ELEV m AOD	BOT ELEV m AOD	GL m AOD
NW1 A	60.355	PHREATIC	59.961
NW1 B	60.373	57.913	
NW1 C	60.373	54.898	
NW1 D	60.361	51.961	
NW2 A	59.576	PHREATIC	59.173
NW2 B	59.585	57.090	
NW2 C	59.588	54.113	
NW2 D	59.598	51.118	
NW3 A	58.681	PHREATIC	58.249
NW3 B	58.661	56.191	
NW3 C	58.631	53.166	
NW3 D	58.649	50.249	
NW4 A	57.946	PHREATIC	57.571
NW4 B	57.934	55.464	
NW4 C	57.934	52.459	
NW4 D	57.946	50.546	
NW5 A	56.079	PHREATIC	55.619
NW5 B	56.066	53.591	
NW5 C	56.059	52.709	
NW5 D	56.049	51.614	
NW6 A	56.117	PHREATIC	55.677
NW6 B	56.125	53.685	
NW6 C	56.110	52.670	
NW6 D	56.100	51.660	
NW7 A	56.278	PHREATIC	55.838
NW7 B	56.295	53.855	
NW7 C	56.263	52.823	
108 A	60.116	PHREATIC	59.666
108 B	60.113	57.556	
108 C	60.101	57.006	
108 D	60.091	54.591	
108 E	60.091	52.586	
NE1 A	59.667	PHREATIC	59.257
NE1 B	59.660	57.195	
NE1 C	59.662	54.177	
NE1 D	59.647	51.177	
NE2 A	58.584	PHREATIC	58.181
NE2 B	58.569	56.089	
NE2 C	58.614	54.064	
NE2 D	58.571	51.596	
NE3 A	57.573	PHREATIC	57.146
NE3 B	57.573	55.093	
NE3 C	57.558	54.098	
NE3 D	57.536	52.066	
NE4 A	55.765	PHREATIC	55.375
NE4 B	55.788	55.318	
NE4 C	55.773	52.298	
NE4 D	55.765	51.055	
NE5 A	55.927	PHREATIC	55.514

NE5 B	55.934	53.494	
NE5 C	55.926	52.486	
NE5 D	55.744	51.494	
NE6 A	55.544	PHREATIC	55.171
NE6 B	55.636	53.196	
NE6 C	55.636	52.196	
SW1 A	59.392	PHREATIC	59.022
SW1 B	59.415	56.955	
SW1 C	59.422	53.952	
SW1 D	59.452	50.952	
SW2 A	59.150	PHREATIC	58.740
SW2 B	59.160	56.685	
SW2 C	59.155	53.665	
SW2 D	59.150	50.670	
SW3 A	57.215	PHREATIC	56.820
SW3 B	57.198	54.723	
SW3 C	57.205	51.740	
SW3 D	57.210	49.720	
SW4 A	55.780	PHREATIC	55.379
SW4 B	55.779	53.319	
SW4 C	55.789	51.309	
SW4 D	55.777	49.287	
SW5 A	54.082	PHREATIC	53.702
SW5 B	54.102	51.642	
SW5 C	54.107	50.637	
SW5 D	54.122	49.632	
SW6 A	54.394	PHREATIC	54.009
SW6 B	54.414	51.974	
SW6 C	54.479	51.039	
SW6 D	54.509	50.069	
113 A	60.210	PHREATIC	59.790
113 B	60.232	57.725	
113 C	60.240	56.710	
113 D	60.173	54.160	
113 E	60.193	52.660	
113 F	60.179	50.630	
SE1 A	59.094	PHREATIC	58.704
SE1 B	59.104	56.634	
SE1 C	59.104	53.634	
SE1 D	59.124	50.634	
SE2 A	56.492	PHREATIC	56.072
SE2 B	56.459	53.994	
SE2 C	56.447	50.972	
SE2 D	56.492	49.092	
SE3 A	55.032	PHREATIC	54.622
SE3 B	55.025	52.590	
SE3 C	55.032	51.577	
SE3 D	55.055	49.565	
SE4 A	53.511	PHREATIC	53.078
SE4 B	53.511	51.071	
SE4 C	53.526	50.051	
SE4 D	53.538	49.463	
SE5 A	53.782	PHREATIC	53.372
SE5 B	53.772	51.332	

SE5 C	53.767	50.327
SE5 D	53.897	49.457

PIEZOMETER DATA
SUMMARY

PIEZO REF	HEAD 11.06 0	HEAD 25.06 14	HEAD 09.07 28	HEAD 23.07 42	HEAD 06.08 56	HEAD 20.08 70
NW1 A	59.950	59.815	59.885	59.870	59.860	59.905
NW1 B	59.923	59.833	59.878	59.873	59.868	59.883
NW1 C	59.758	59.663	59.728	59.723	59.708	59.723
NW1 D	59.821	59.661	59.726	59.706	59.696	59.726
NW2 A	59.231	59.096	59.166	59.156	59.141	59.176
NW2 B	59.190	59.095	59.160	59.130	59.135	59.160
NW2 C	58.998	58.908	58.968	58.958	58.953	58.968
NW2 D	58.858	58.738	58.798	58.793	58.788	58.798
NW3 A	58.216	57.991	58.126	58.081	58.071	58.131
NW3 B	58.121	58.001	58.061	58.051	58.051	58.066
NW3 C	57.861	57.771	57.811	57.801	57.776	57.781
NW3 D	57.859	57.769	57.814	57.794	57.769	57.779
NW4 A	57.506	57.176	57.276	57.251	57.241	57.276
NW4 B	57.304	57.214	57.259	57.234	57.224	57.259
NW4 C	57.249	57.154	57.199	57.164	57.149	57.199
NW4 D	57.366	57.256	57.281	57.261	57.251	57.246
NW5 A	55.609	55.399	55.499	55.489	55.474	55.494
NW5 B	55.631	55.516	55.581	55.576	55.576	55.596
NW5 C	55.689	55.554	55.629	55.619	55.624	55.639
NW5 D	55.769	55.644	55.719	55.689	55.684	55.699
NW6 A	55.697	55.617	55.612	55.597	55.592	55.617
NW6 B	55.735	55.555	55.630	55.625	55.620	55.645
NW6 C	55.780	55.640	55.705	55.700	55.690	55.715
NW6 D	54.400	55.730	55.810	55.800	55.805	55.815
NW7 A	55.743	55.428	55.598	55.578	55.518	
NW7 B	55.670	55.535	55.615	55.595	55.595	
NW7 C	55.668	55.613	55.673	55.653	55.653	
108 A	59.596	59.505	59.526	59.531	59.526	59.566
108 B	59.566	59.531	59.523	59.518	59.518	59.533
108 C	59.555	59.530	59.516	59.511	59.501	59.511
108 D	59.357	59.329	59.321	59.321	59.316	59.326
108 E	59.148	59.115	59.106	59.106	59.106	59.106
NE1 A	59.252	59.087	59.177	59.157	59.147	59.182
NE1 B	59.175	59.090	59.120	59.130	59.125	59.135
NE1 C	59.117	59.032	59.072	59.062	59.052	59.062
NE1 D	58.872	58.767	58.827	58.827	58.817	58.802
NE2 A	58.159	57.919	58.064	57.999	57.984	58.069
NE2 B	58.069	57.979	58.019	57.989	57.979	57.999
NE2 C	58.169	57.864	58.074	58.014	57.984	58.044
NE2 D	57.651	57.561	57.601	57.596	57.591	57.591
NE3 A	57.048	56.693	56.853	56.773	56.748	56.858
NE3 B	56.908	56.793	56.788	56.778	56.768	56.773
NE3 C	56.818	56.728	56.748	56.728	56.693	56.693
NE3 D	56.731	56.626	56.651	56.636	56.626	56.621
NE4 A	55.435	55.285	55.355	55.355	55.345	55.350
NE4 B	55.388	55.228	55.298	55.288	55.288	55.293
NE4 C	55.298	55.143	55.193	55.183	55.178	55.193
NE4 D	55.315	55.145	55.235	55.230	55.200	55.235
NE5 A	55.187	54.987	54.957	54.967	54.962	55.007

NE5	B	55.259	55.084	55.149	55.134	55.129	55.144
NE5	C	55.331	55.106	55.161	55.146	55.156	55.161
NE5	D	55.229	55.064	55.134	55.124	55.119	55.124
NE6	A	54.924	54.704	54.754	54.754	54.739	54.734
NE6	B	54.626	54.906	54.956	54.941	54.931	54.951
NE6	C	55.256	55.076	55.141	55.121	55.116	55.131
SW1	A	58.962	58.862	58.907	58.902	58.882	58.902
SW1	B	58.895	58.815	58.880	58.840	58.830	58.850
SW1	C	58.687	58.582	58.632	58.627	58.622	58.632
SW1	D	58.472	58.382	58.432	58.402	58.377	58.402
SW2	A	58.680	58.570	58.640	58.620	58.605	58.620
SW2	B	58.680	58.600	58.645	58.635	58.630	58.635
SW2	C	58.670	58.595	58.635	58.605	58.580	58.575
SW2	D	58.630	58.520	58.565	58.540	58.530	58.540
SW3	A	56.735	56.495	56.605	56.520	56.520	56.625
SW3	B	56.603	56.498	56.513	56.488	56.473	56.493
SW3	C	56.350	56.235	56.275	56.210	56.200	56.235
SW3	D	56.340	56.210	56.240	56.205	56.185	56.220
SW4	A	55.000	54.840	54.950	54.850	54.825	54.955
SW4	B	54.954	54.809	54.799	54.784	54.759	54.744
SW4	C	54.989	54.829	54.849	54.799	54.794	54.799
SW4	D	54.907	54.827	54.857	54.797	54.787	54.787
SW5	A	53.267	52.922	53.002	52.952	52.957	53.057
SW5	B	53.207	53.092	53.152	53.112	53.112	53.167
SW5	C	53.202	53.087	53.127	53.117	53.122	53.172
SW5	D	53.257	53.142	53.202	53.177	53.187	53.217
SW6	A	53.109	52.894	52.984	52.909	52.914	53.039
SW6	B	53.114	52.964	53.014	52.984	52.984	53.034
SW6	C	53.099	52.999	53.049	53.024	53.009	53.054
SW6	D	53.099	52.999	53.059	53.029	53.019	53.054
113	A	59.842	59.748	59.776	59.750	59.740	59.790
113	B	59.759	59.715	59.718	59.707	59.712	59.712
113	C	59.738	59.697	59.700	59.675	59.675	59.690
113	D	59.676	59.634	59.634	59.613	59.603	59.623
113	E	59.644	59.605	59.597	59.583	59.583	59.573
113	F	59.610	59.562	59.556	59.544	59.509	59.509
SE1	A	58.614	58.344	58.509	58.464	58.424	58.504
SE1	B	58.469	58.374	58.419	58.414	58.409	58.414
SE1	C	58.449	58.364	58.404	58.399	58.394	58.394
SE1	D	58.304	58.204	58.249	58.239	58.234	58.254
SE2	A	55.882	55.722	55.772	55.712	55.692	55.712
SE2	B	55.879	55.689	55.754	55.704	55.679	55.689
SE2	C	55.632	55.597	55.617	55.552	55.537	55.537
SE2	D	55.877	55.712	55.767	55.707	55.692	55.702
SE3	A	54.392	53.972	54.157	54.032	54.042	54.152
SE3	B	54.160	54.015	54.045	54.015	54.005	54.035
SE3	C	54.082	53.982	54.012	53.977	53.942	53.942
SE3	D	54.035	53.925	53.955	53.930	53.905	53.900
SE4	A	52.586	52.371	52.471	52.421	52.421	52.496
SE4	B	52.600	52.401	52.461	52.426	52.421	52.486
SE4	C	52.541	52.366	52.426	52.396	52.391	52.421
SE4	D	52.718	52.568	52.628	52.598	52.608	52.638
SE5	A	52.702	52.312	52.297	52.242	52.192	52.472
SE5	B	52.517	52.362	52.362	52.297	52.272	52.372

SE5 C	52.517	52.377	52.382	52.357	52.332	52.377
SE5 D	52.812	52.667	52.697	52.667	52.677	52.697

APPENDIX C

Test data

WWWW

SAMPLE	VOLUME cc	WET MASS g	DRY MASS g
SE5 2M	62.0	59.7	7.2
SE4 3M	103.5	94.1	6.9
SE1 8M	122.5	94.4	5.4
SE2 5M	84.0	81.5	5.3
SE3 2M	60.0	61.8	5.1
SE4 2M	121.5	94.7	8.8
SE1 5M	91.0	91.4	3.1
SE1 2M	59.5	61.6	2.9
113 2M	114.5	94.5	2.7
SE2 2M	74.0	72.0	3.7
113 5M	117.5	93.9	1.6
113 3M	90.0	87.3	3.4
113 7M	122.0	90.7	6.4
113 9M	121.0	91.1	5.6
113 2M	83.5	82.2	1.6
SE3 3M	123.5	112.6	9.7
SE3 2M	121.5	121.8	10.0
113 5M	112.5	106.8	5.1
SE5 3M	120.0	94.5	11.1
SE5 1M	97.0	93.6	12.3
108 2M	31.5	35.1	1.1
108 3M	70.0	73.3	2.5
108 3M	48.5	54.0	2.8
NE3 5M	100.0	107.9	10.6
108 7M	96.0	100.9	6.5
108 5M	107.5	104.9	4.2
NE5 4M	114.5	116.7	10.3
NE5 2M	101.5	102.4	9.4
NE6 1M	119.5	109.5	10.7
108 2M	35.5	37.3	2.1
NE6 2M	62.0	53.8	5.4
NE5 3M	121.5	118.1	9.4
NE6 3M	105.0	107.8	10.3
NW3 2M		115.0	5.1
NW4 5M		74.8	6.1
NW1 2M		128.4	3.2
NW4 2M		68.7	3.9
NW2 5M		115.0	4.9
NW2 7M		96.8	5.0
NW1 8M		105.3	12.1
NW5 3M		112.5	6.9
NW2 2M		81.4	2.4
NW3 4M		129.9	2.4
NW1 5M		75.6	3.8
NW4 5M		125.5	4.5
SW1 2M		91.7	3.7
NW5 2M		40.2	2.4
SW1 5M		118.5	6.5
NW3 6M		126.2	7.4
SW1 8M		94.4	7.0

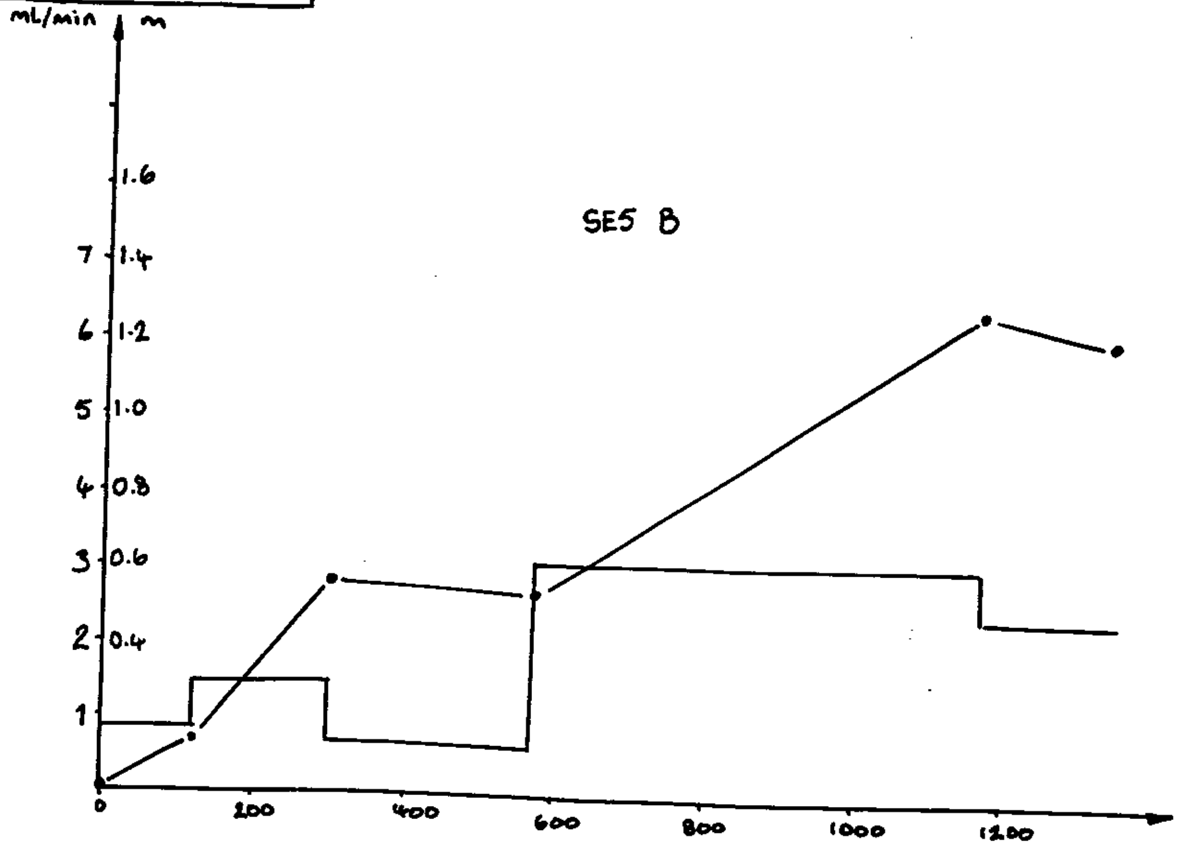
WWW

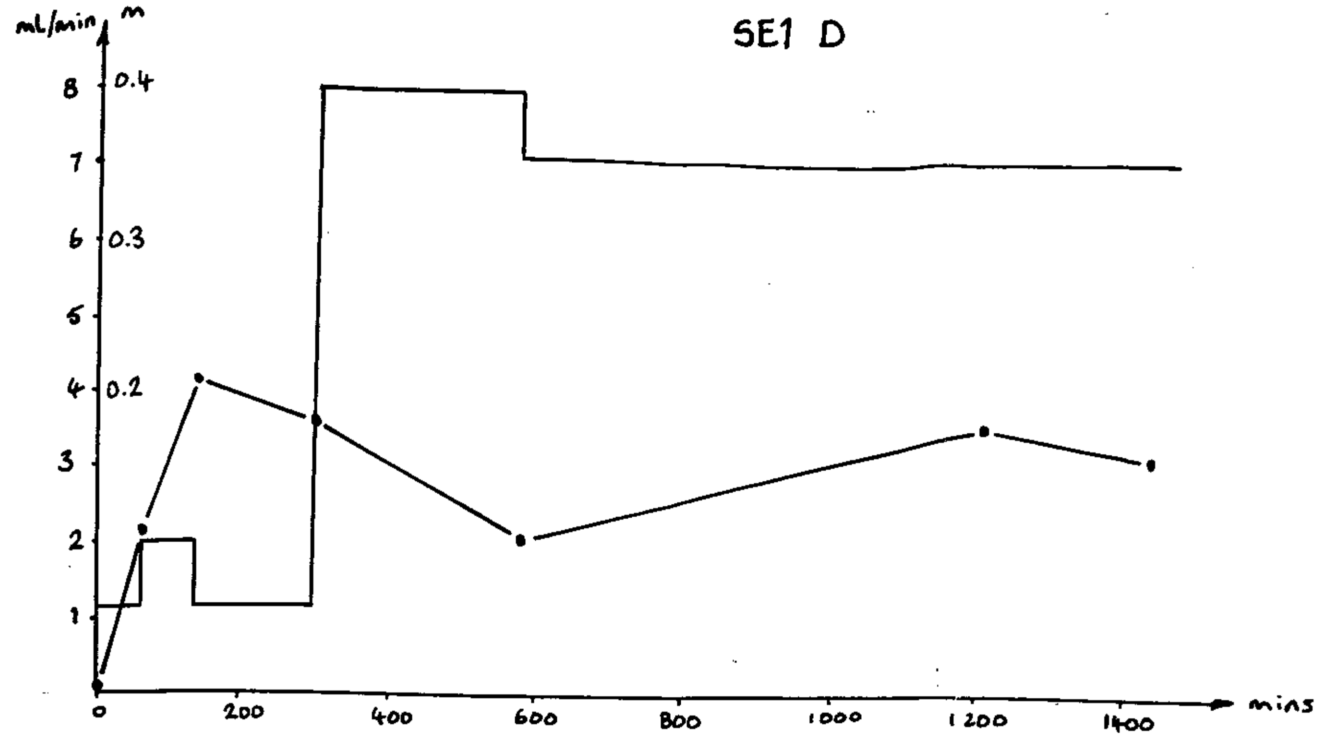
SUMMARY OF WATER CONTENT AND DENSITY MEASUREMENTS

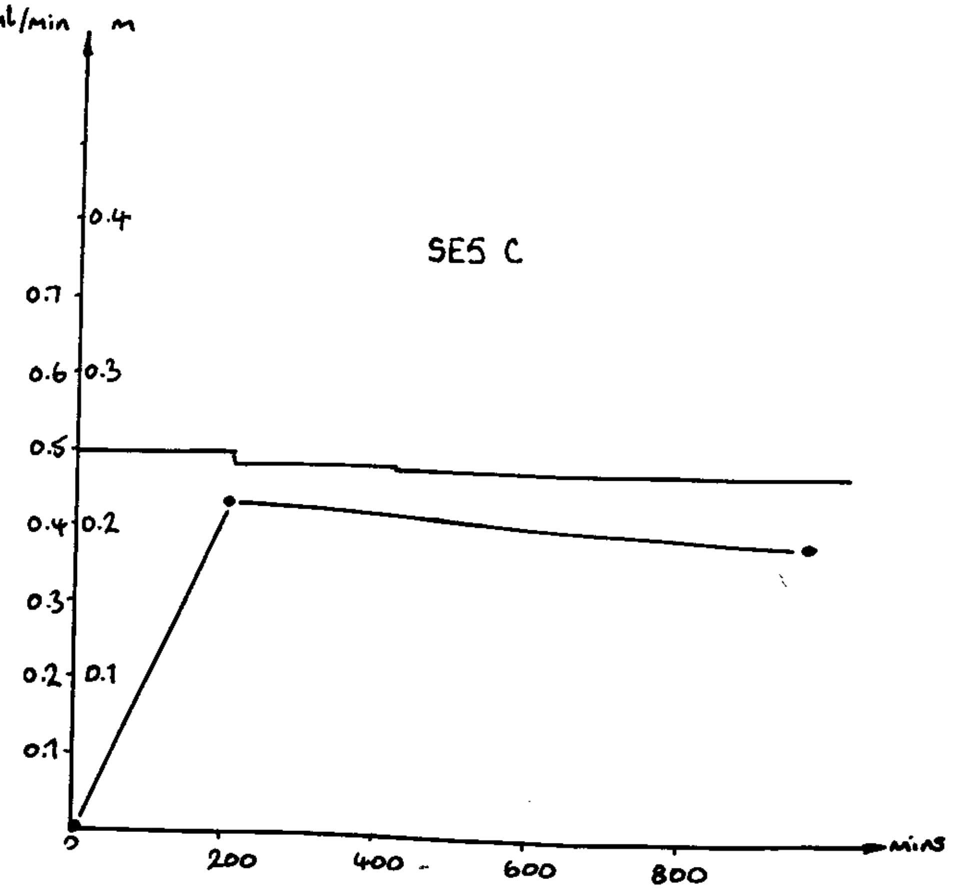
SAMPLE	Mw/Ms	DENSITY
113 2M	34.00	0.83
113 3M	24.68	0.97
113 5M	19.94	0.95
113 7M	13.18	0.74
113 9M	15.26	0.75
SE1 2M	20.24	1.04
SE1 5M	28.48	1.00
SE1 8M	16.48	0.77
SE2 2M	18.46	0.97
SE2 5M	14.38	0.97
SE3 2M	11.12	1.03
SE3 3M	10.60	0.91
SE4 2M	9.76	0.78
SE4 3M	12.64	0.91
SE5 1M	6.60	0.96
SE5 2M	7.30	0.96
SE5 3M	7.52	0.79
108 2M	30.90	1.11
108 3M	28.32	1.05
108 5M	23.98	0.98
108 7M	14.52	1.05
NE1 1M	16.57	1.08
NE1 3M	15.70	0.96
NE1 5M	16.47	1.01
NE1 8M	12.05	0.97
NE2 1M	17.49	1.02
NE2 3M	19.27	0.92
NE2 5M	11.59	0.87
NE2 7M	9.88	1.03
NE3 1M	15.46	
NE3 2M	14.90	
NE3 3M	13.59	
NE3 5M	9.18	
NE4 1M	14.61	
NE4 2M	12.48	
NE4 4M	10.42	
NE5 1M	6.60	
NE5 2M	9.90	
NE5 3M	11.56	
NE5 4M	10.34	
NE6 1M	9.24	
NE6 2M	8.96	
NE6 3M	9.46	
NW1 2M	39.13	
NW1 5M	18.89	
NW1 8M	7.70	
NW2 2M	32.92	
NW2 5M	22.47	
NW2 7M	18.36	
NW3 2M	21.55	

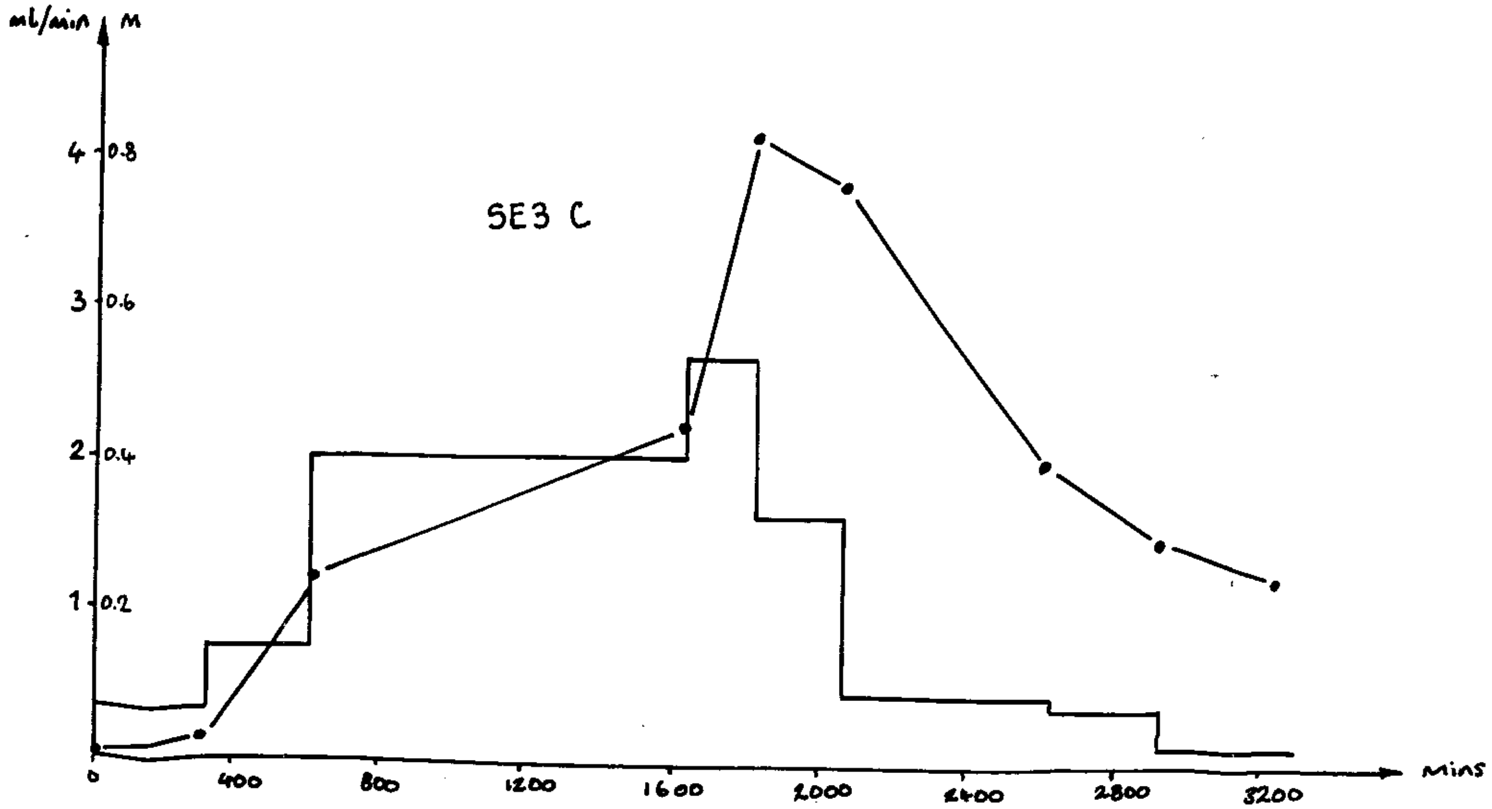
NW3	6M	16.05
NW4	2M	16.62
NW4	4M	17.73
NW5	2M	15.75
NW5	3M	15.30
SW1	2M	23.78
SW1	5M	17.23
SW1	8M	12.49
SW3	1M	15.66
SW3	3M	12.52
SW3	6M	11.58
SW5	1M	9.52
SW5	2M	11.60
SW5	4M	11.95

Original Drawing Size A3









Notes

——————— DISCHARGE

—•———•— APPLIED HEAD

No.	Date	Revision

Clara Bog Project
County Offaly, Ireland

PERMEABILITY TEST DATA ; DISCHARGE & CORRESPONDING APPLIED HEAD WITH TIME. PIEZOS SE5B, SE1 D, SE5 C, SE3 C

Drawn	Date	Checked	Date	Approved	Date

EWRE
Dept. Civil Eng.
Imperial College

Scale AS SHOWN

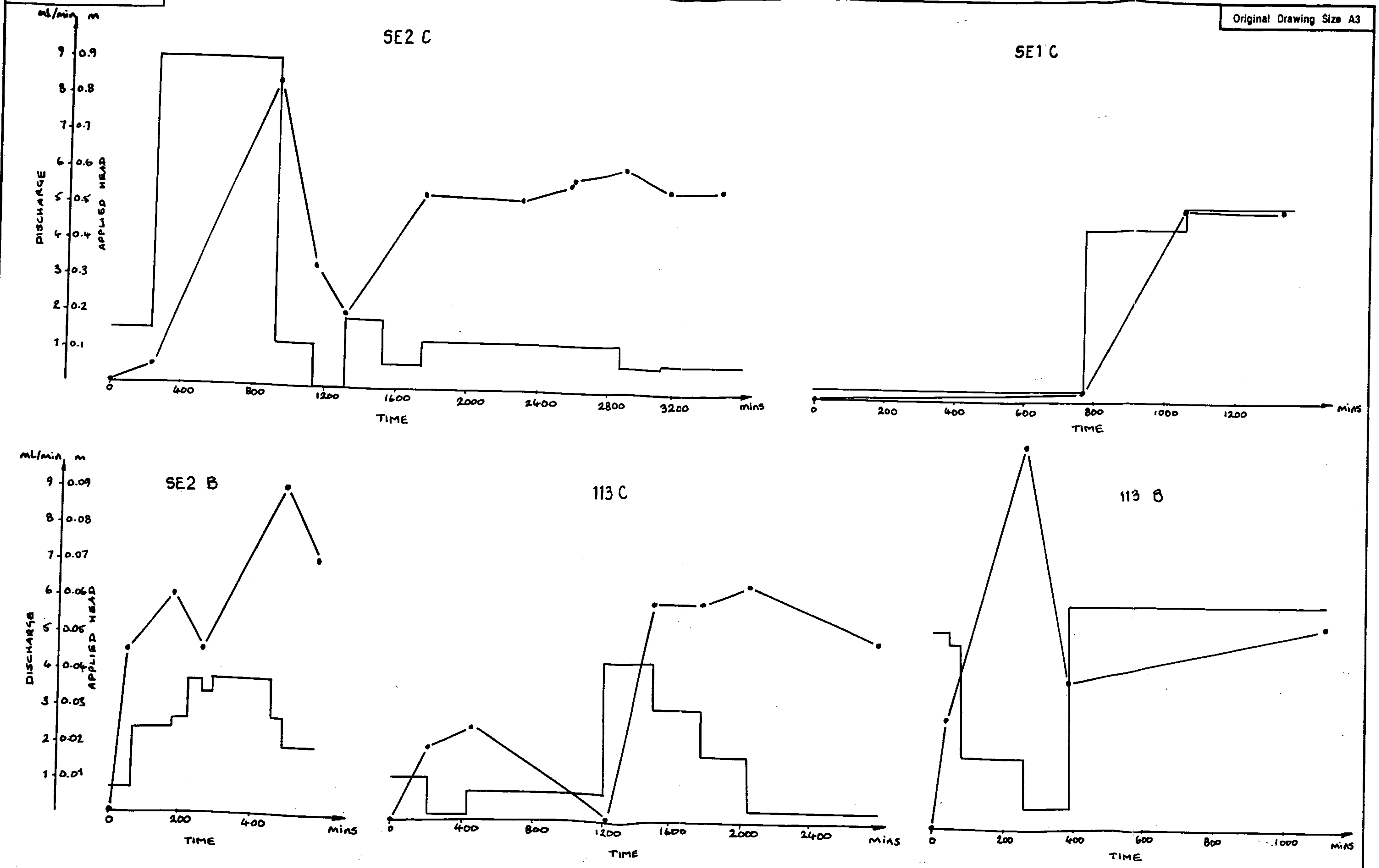
Job No.

Client Drawing No.

Rev.

LGM Drawing No.

A & F Royal Ltd



Notes

——— DISCHARGE

—•——•— APPLIED HEAD

No.	Date	Revision

Clara Bog Project
County Offaly, Ireland

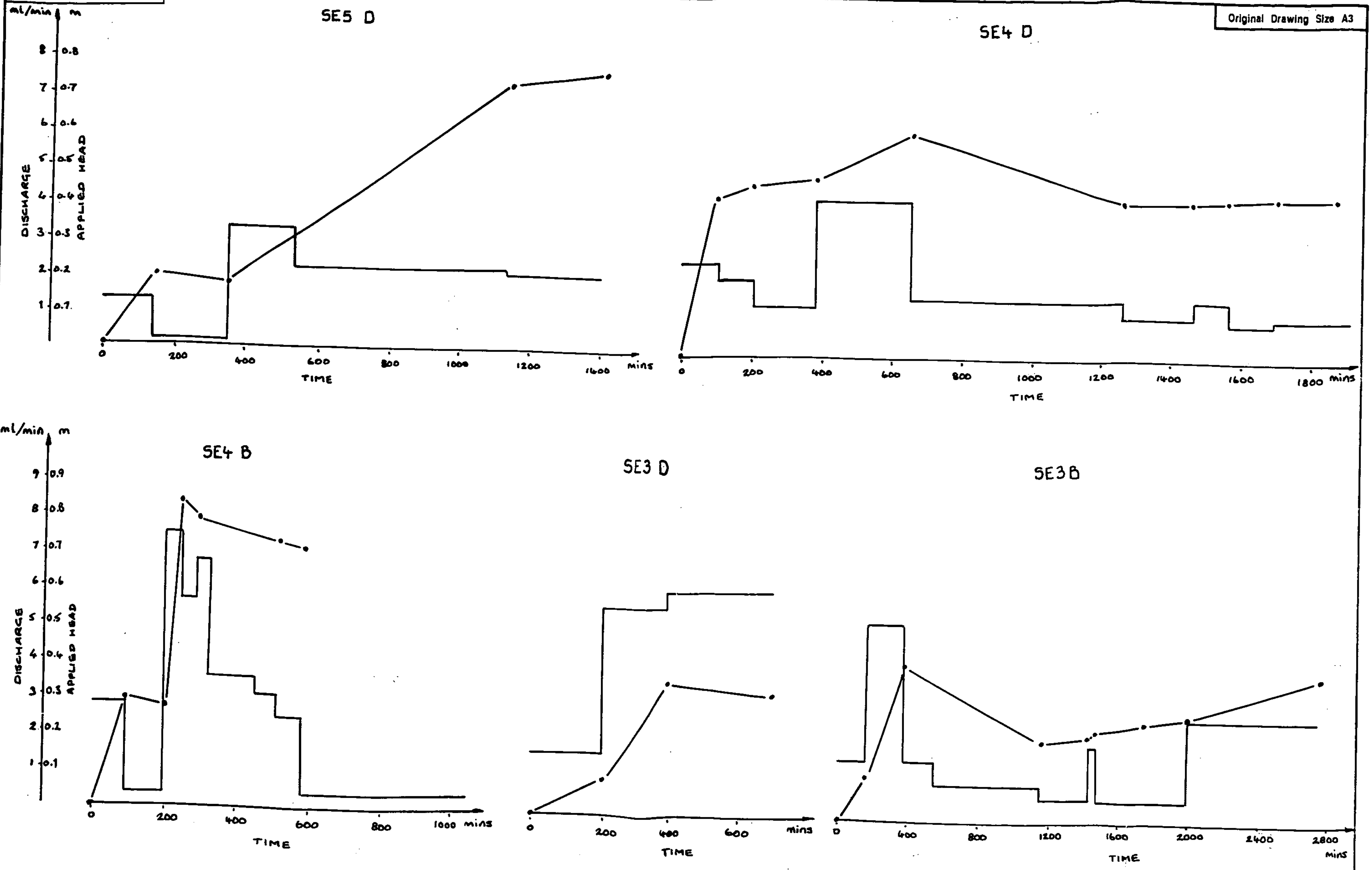
PERMEABILITY TEST DATA; DISCHARGE & CORRESPONDING APPLIED HEAD WITH TIME
PIEZOS SE2C, SE1C, SE2B, 113C, 113B

Drawn	Date	Checked	Date	Approved	Date

EWRE
Dept. Civil Eng.
Imperial College

Scale AS SHOWN
Job No.
Client Drawing No. Rev.
LGM Drawing No.

A & F Royal Ltd



Notes

——— DISCHARGE

—•——•— APPLIED HEAD

No.	Date	Revision

Clara Bog Project
County Offaly, Ireland

PERMEABILITY TEST DATA; DISCHARGE & CORRESPONDING APPLIED HEAD WITH TIME
PIEZOS SE5D, SE4D, SE4B, SE3D, SE3B

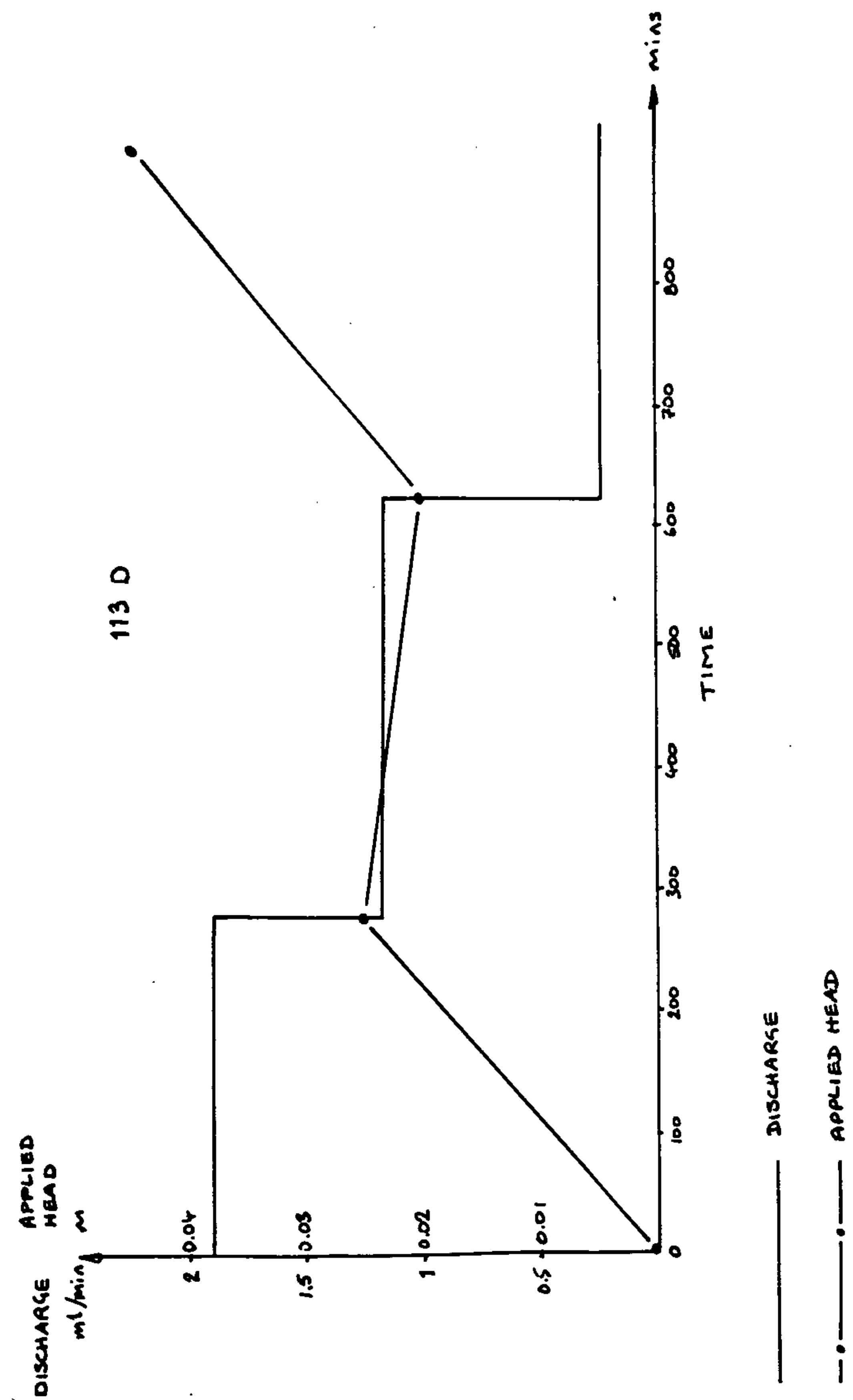
Drawn	Date	Checked	Date	Approved	Date

EWRE
Dept. Civil Eng.
Imperial College

Scale AS SHOWN
Job No.
Client Drawing No.
Rev.
LGM Drawing No.

A&F Royal Ltd

Original Drawing Size A4



Clara Bog Project County Offaly, Ireland	EWRE Dept. Civil Eng. Imperial College	Drawn	Job No.
PERMEABILITY TEST DATA; DISCHARGE & CORRESPONDING APPLIED HEAD WITH TIME PIEZO 113 D		Checked	Date
	Scales AS SHOWN	Drawing No.	Rev.

A&F Royal Ltd

APPENDIX D

Climatological data

```
"Precipitation data at Rossum V-notch, Clara Bog West"
"Data code:" "" "PS"
"Data cat.:" "" "precipitation sums"
"Units:" "" "0.1 mm"

"Date" "Time" "Value" ""
"01-Jan-92" " 1:00"        0. ""
"         " " 2:00"        0. ""
"         " " 3:00"        0. ""
"         " " 4:00"        0. ""
"         " " 5:00"        0. ""
"         " " 6:00"        0. ""
"         " " 7:00"        0. ""
"         " " 8:00"        0. ""
"         " " 9:00"        0. ""
"         " "10:00"        0. ""
"         " "11:00"        0. ""
"         " "12:00"        0. ""
"01-Jan-92" "13:00"        0. ""
"         " "14:00"        0. ""
"         " "15:00"        0. ""
"         " "16:00"        0. ""
"         " "17:00"        0. ""
"         " "18:00"        0. ""
"         " "19:00"        0. ""
"         " "20:00"        0. ""
"         " "21:00"        0. ""
"         " "22:00"        0. ""
"         " "23:00"        0. ""
"         " "24:00"        0. ""
"02-Jan-92" " 1:00"        0. ""
"         " " 2:00"        0. ""
"         " " 3:00"        0. ""
"         " " 4:00"        0. ""
"         " " 5:00"        0. ""
"         " " 6:00"        0. ""
"         " " 7:00"        0. ""
"         " " 8:00"        0. ""
"         " " 9:00"        0. ""
"         " "10:00"        0. ""
"         " "11:00"        0. ""
"         " "12:00"        0. ""
"02-Jan-92" "13:00"        0. ""
"         " "14:00"        0. ""
"         " "15:00"        0. ""
"         " "16:00"        0. ""
"         " "17:00"        0. ""
"         " "18:00"        0. ""
"         " "19:00"        0. ""
"         " "20:00"        0. ""
"         " "21:00"        0. ""
"         " "22:00"        0. ""
"         " "23:00"        0. ""
"         " "24:00"        0. ""
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"         " " 3:00"        0. ""
"         " " 4:00"        0. ""
"         " " 5:00"        8. ""
"         " " 6:00"        0. ""
"         " " 7:00"        0. ""
```

RAINFALL DATA, CLARA BOG WEST
UNITS=0.1MM

DATE	1989	1990	1991	1992
1.01			119	0
2.01			40	0
3.01				85
4.01				25
5.01				339
6.01		9		0
7.01		86		61
8.01		3		32
9.01		0		1
10.01		23		2
11.01		3	1	1
12.01		1	14	0
13.01		5	1	0
14.01			1	0
15.01			1	0
16.01			7	2
17.01			1	0
18.01			63	1
19.01			1	0
20.01			6	1
21.01			29	0
22.01			12	0
23.01			9	0
24.01			1	18
25.01			1	62
26.01			1	3
27.01			0	1
28.01			53	0
29.01			69	0
30.01			0	1
31.01			1	1
1.02			2	1
2.02			2	7
3.02			108	4
4.02			48	0
5.02			0	0
6.02			1	0
7.02			1	0
8.02			1	25
9.02			2	20
10.02			0	11
11.02			28	1
12.02			19	43
13.02			1	16
14.02			50	14
15.02			50	0
16.02			69	0
17.02			24	55
18.02			2	1

19.02		18	0
20.02		31	10
21.02		12	2
22.02	0	80	50
23.02	10	127	0
24.02	103	24	36
25.02	80	8	39
26.02	78	21	2
27.02	29	52	52
28.02	133	2	13
1.03	51	0	8
2.03	0	35	4
3.03	0	27	8
4.03	60	51	0
5.03	0	0	48
6.03	4	38	44
7.03	2	27	47
8.03	12	69	0
9.03	4	1	38
10.03	0	1	30
11.03	15	20	27
12.03	7	0	36
13.03	27	0	6
14.03	4	0	15
15.03	2	33	2
16.03	1	50	4
17.03	0	30	4
18.03	2	81	10
19.03	4	45	6
20.03	5	157	55
21.03	10	8	129
22.03	4	1	55
23.03	17	1	23
24.03	42	0	0
25.03	2	1	20
26.03	0	14	1
27.03	3	3	0
28.03	0	1	7
29.03	0	0	74
30.03	0	0	17
31.03	1	0	48
1.04	74	0	4
2.04	48	62	0
3.04	15	3	0
4.04	0	78	0
5.04	18	94	44
6.04	0	82	31
7.04	0	16	57
8.04	0	8	8
9.04	4	58	0
10.04	1	46	6
11.04	1	56	20
12.04	30	63	21
13.04	8	0	23
14.04	43	0	32
15.04	7	0	0

16.04	29	0	8
17.04	25	0	0
18.04	30	0	1
19.04	4		11
20.04	0		5
21.04	0		1
22.04	0		28
23.04	0		34
24.04	0		92
25.04	2		42
26.04	22		70
27.04	1	3	34
28.04	0	67	16
29.04	1	145	64
30.04	0	8	27
1.05	0	2	12
2.05	0	2	0
3.05	1	5	2
4.05	0	1	69
5.05	0	1	2
6.05	1	6	6
7.05	0	3	5
8.05	98	0	7
9.05	22	8	27
10.05	0	4	49
11.05	0	5	26
12.05	0	5	28
13.05	0	4	1
14.05	14	0	
15.05	46	0	
16.05	36	0	
17.05	1	0	
18.05	1	4	
19.05	0	0	
20.05	0	0	
21.05	0	0	
22.05	0	0	
23.05	0	0	
24.05	1	0	
25.05	0	0	
26.05	0	0	
27.05	1	0	
28.05	0	0	
29.05	46	0	
30.05	2	0	
31.05	8	0	
1.06	47	0	
2.06	5	11	
3.06	12	1	
4.06	16	1	
5.06	17	31	
6.06	24	26	
7.06	29	1	
8.06	16	104	
9.06	0	35	
10.06	0	16	

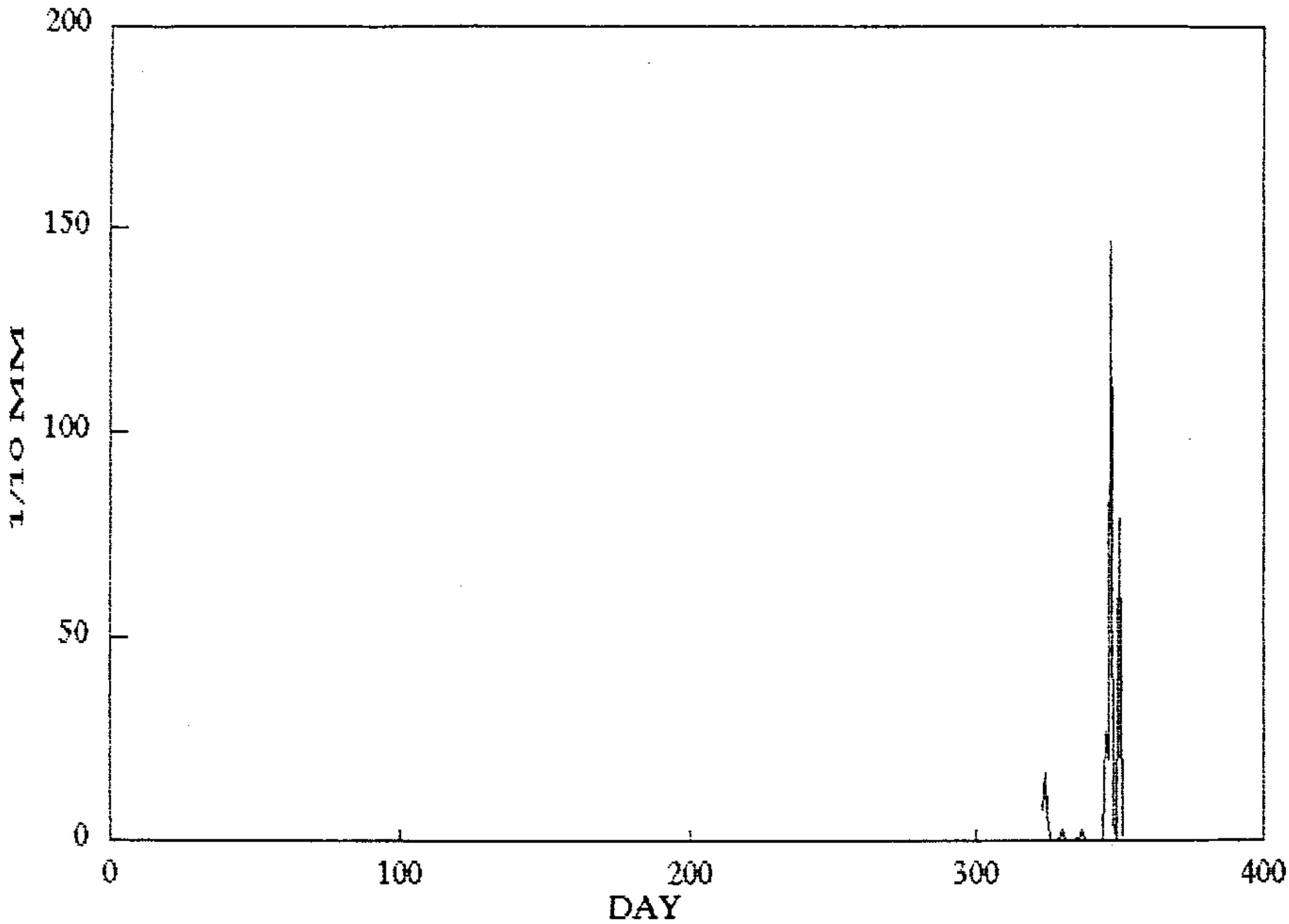
11.06	0	60
12.06	0	41
13.06	1	4
14.06	3	2
15.06	3	78
16.06	3	66
17.06	28	12
18.06	116	4
19.06	20	0
20.06	57	12
21.06	46	47
22.06	2	93
23.06	17	16
24.06	40	8
25.06	1	60
26.06	125	42
27.06	20	66
28.06	24	2
29.06	84	
30.06	28	
1.07	28	
2.07	14	
3.07	29	
4.07	251	
5.07	8	
6.07	45	
7.07	3	
8.07	6	
9.07	1	
10.07	1	
11.07	2	73
12.07	1	9
13.07	0	42
14.07	0	5
15.07	31	34
16.07	1	13
17.07	0	1
18.07	0	35
19.07	0	
20.07	0	
21.07	0	
22.07	0	
23.07	0	
24.07	0	
25.07	0	
26.07	3	0
27.07	73	0
28.07	4	0
29.07	29	0
30.07	7	10
31.07	0	165
1.08	0	17
2.08	0	0
3.08	0	29
4.08	0	13
5.08	0	35

6.08	0	121
7.08	0	18
8.08	4	1
9.08	24	48
10.08	2	40
11.08	16	1
12.08	13	0
13.08	1	0
14.08	69	1
15.08	54	0
16.08	15	16
17.08	60	2
18.08	28	2
19.08	108	41
20.08	10	0
21.08	2	10
22.08	2	3
23.08	174	2
24.08	34	9
25.08	24	1
26.08	16	5
27.08	36	0
28.08	1	0
29.08	52	0
30.08	24	0
31.08	28	0
1.09	0	0
2.09	0	0
3.09	4	0
4.09	13	0
5.09	36	1
6.09	14	1
7.09	4	1
8.09	2	1
9.09	0	2
10.09	0	0
11.09	0	0
12.09	2	0
13.09	0	12
14.09	0	37
15.09	0	131
16.09	9	13
17.09	9	3
18.09	49	9
19.09	22	7
20.09	3	0
21.09	11	55
22.09	39	11
23.09	3	67
24.09	2	12
25.09	1	3
26.09	2	3
27.09	1	29
28.09	0	86
29.09	0	0
30.09	0	33

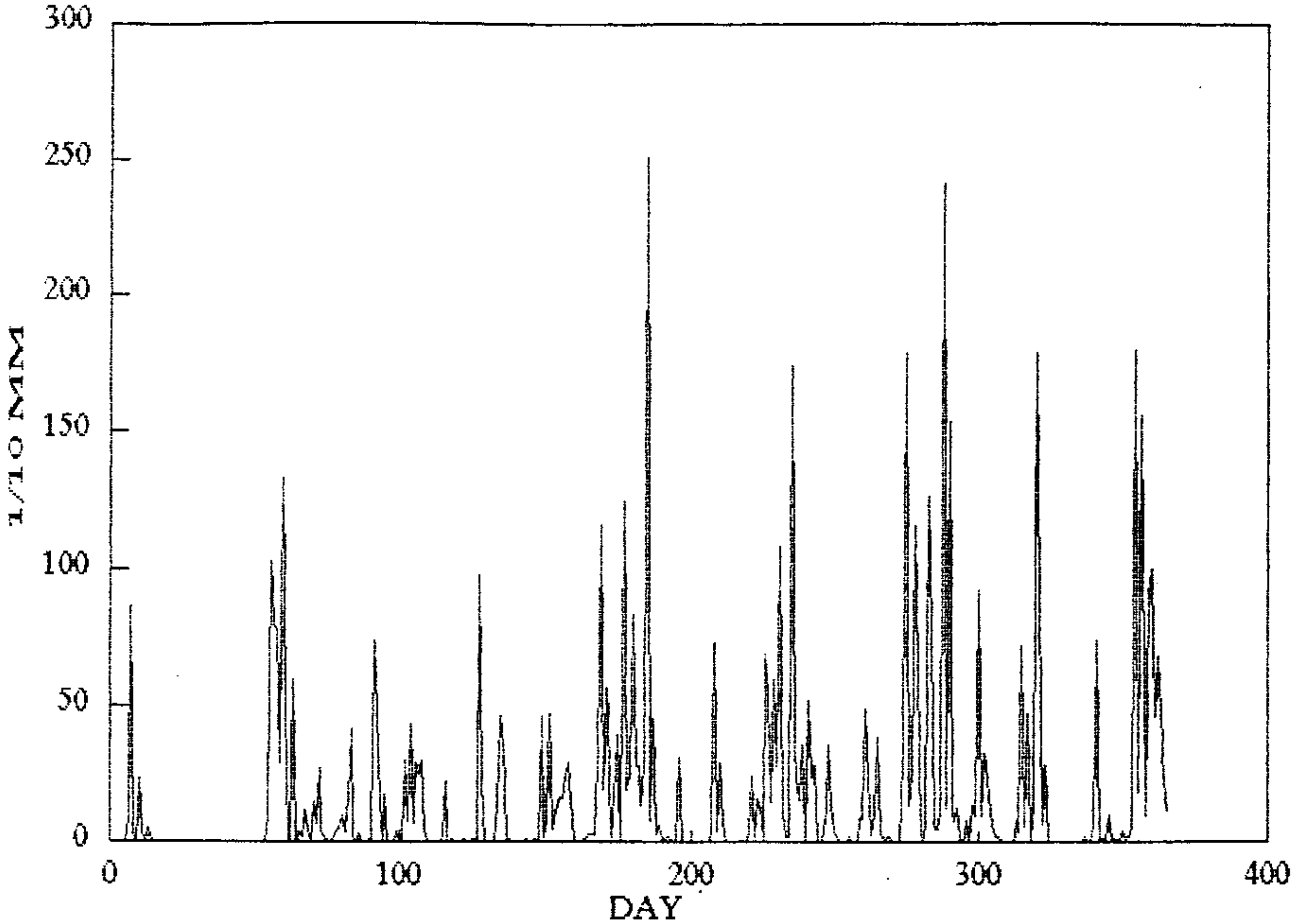
1.10		31	3
2.10		179	50
3.10		14	13
4.10		24	51
5.10		116	11
6.10		64	43
7.10		2	32
8.10		0	1
9.10		6	32
10.10		127	66
11.10		77	1
12.10		6	20
13.10		5	104
14.10		11	0
15.10		241	0
16.10		13	26
17.10		154	12
18.10		10	11
19.10		8	1
20.10		13	0
21.10		1	2
22.10		0	5
23.10		8	0
24.10		0	3
25.10		14	0
26.10		10	0
27.10		92	3
28.10		10	0
29.10		33	89
30.10		28	80
31.10		17	113
1.11		7	25
2.11		2	94
3.11		2	38
4.11		1	2
5.11		0	7
6.11		0	7
7.11		0	63
8.11		0	9
9.11		8	0
10.11		4	95
11.11		72	3
12.11		6	100
13.11		47	49
14.11		1	9
15.11		14	0
16.11		179	18
17.11		89	102
18.11		7	16
19.11	8	28	0
20.11	17	0	0
21.11	6	0	0
22.11	1	0	
23.11	0	0	
24.11	0	0	
25.11	1	0	

26.11	3	0	
27.11	0	0	
28.11	0	0	
29.11	0	0	16
30.11	0	0	8
1.12	1	0	0
2.12	1	0	0
3.12	3	2	0
4.12	0	0	0
5.12	0	0	0
6.12	0	6	2
7.12	0	74	0
8.12	0	1	0
9.12	0	1	4
10.12	0	1	0
11.12	27	10	0
12.12	20	1	0
13.12	147	1	0
14.12	5	1	0
15.12	1	1	21
16.12	79	4	21
17.12	1	1	72
18.12		2	85
19.12		5	66
20.12		180	110
21.12		19	61
22.12		156	25
23.12		62	67
24.12		10	0
25.12		92	0
26.12		100	11
27.12		46	4
28.12		68	0
29.12		48	0
30.12		22	0
31.12		11	6

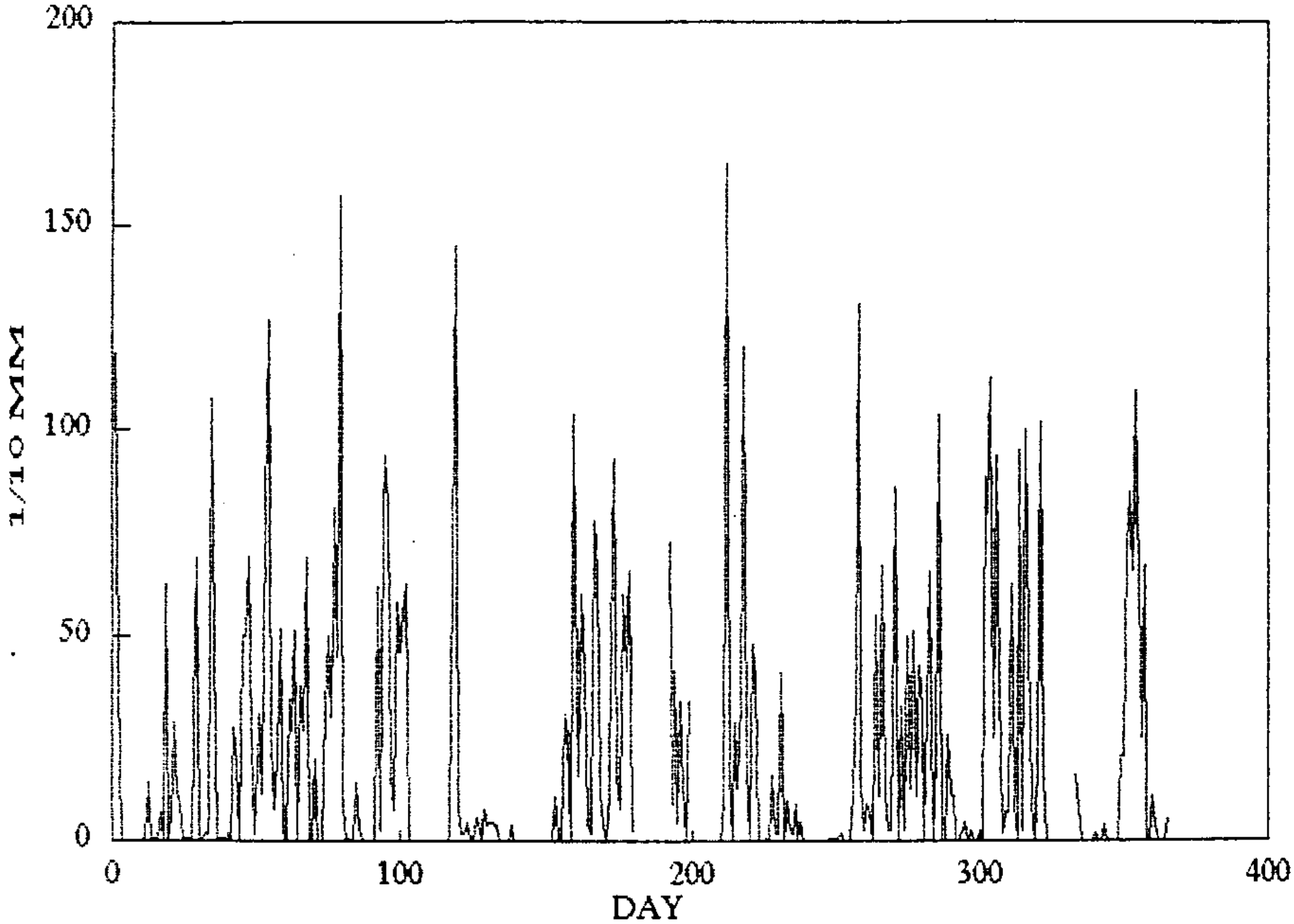
1989 RAINFALL

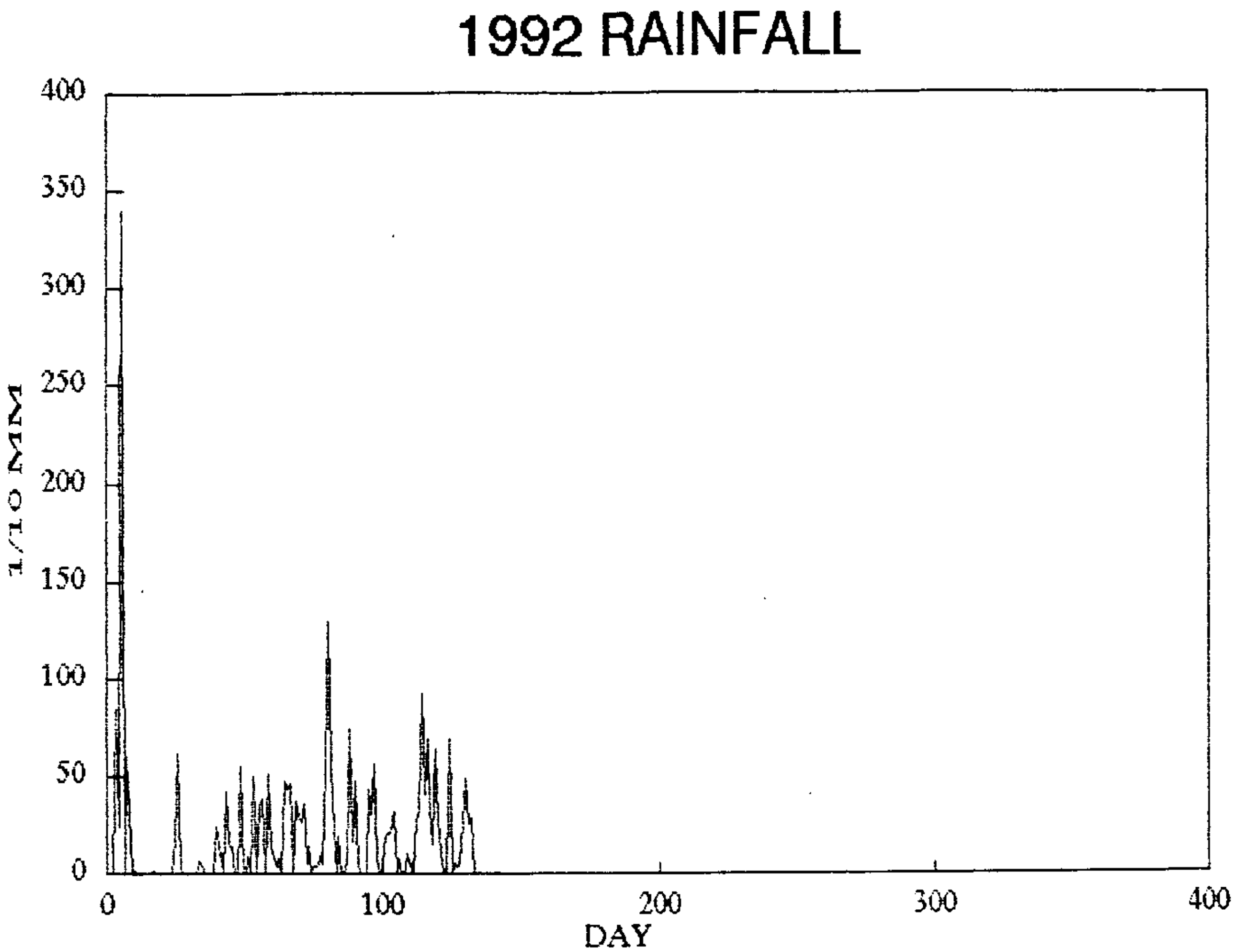


1990 RAINFALL



1991 RAINFALL




1992 RAINFALL
1/10 MM
DAY
0
50
100
150
200
250
300
350
400
0
100
200
300
400

PENMAN POTENTIAL EVAPORATION DATA
FOR BIRR AND MULLINGAR

DATE	BIRR		MULLINGAR		AVERAGE	
	RAIN	P.E.	RAIN	P.E.	RAIN	P.E.
01.91	77.50	1.48	84.80	0.00	81.15	0.74
02.91	60.90	7.52	92.40	6.38	76.65	6.95
03.91	54.60	22.57	91.40	23.03	73.00	22.80
04.91	105.60	45.96	127.10	58.23	116.35	52.10
05.91	4.40	68.26	4.50	76.21	4.45	72.24
06.91	91.20	69.11	78.50	73.82	84.85	71.46
07.91	65.90	66.39	42.10	80.25	54.00	73.32
08.91	74.14	57.74	37.14	61.07	55.64	59.41
09.91	50.10	40.57	50.90	47.39	50.50	43.98
10.91	97.40	15.55	101.10	15.86	99.25	15.71
11.91	88.10	3.79	101.30	2.60	94.70	3.20
12.91	33.20	1.23	70.63	0.00	51.92	0.62
01.92	65.40	1.00	75.90	7.00	70.65	4.00
02.92	41.00	15.00	60.90	14.00	50.95	14.50
03.92	86.80	26.00	90.80	27.00	88.80	26.50

APPENDIX E

Fortran program and datafit plots

```
 PROGRAM DATAFIT
REAL VOID(23),PERM(23),HYDR(23)
REAL ERR,ERRTOT,B,C
INTEGER I,J
OPEN (10,FILE='VOID_1.OUT',STATUS='old')
OPEN (11,FILE='PERM_1.OUT',STATUS='old')
OPEN (12,FILE='HYDR_1.OUT',STATUS='old')
WRITE(6,*) 'ENTER VOID RATIO'
WRITE(6,*)
DO 10 J=1,20
 READ (10,100) VOID(J)
 FORMAT(1X,F8.5)
CONTINUE
WRITE(6,*) 'ENTER PERMEABILITY DATA'
WRITE(6,*)
DO 20 J=1,20
 READ (11,110) PERM(J)
 FORMAT(1X,E12.5)
CONTINUE
WRITE(6,*) 'ENTER HYDRAULIC GRADIENT DATA'
WRITE(6,*)
DO 30 J=1,20
 READ (12,120) HYDR(J)
 FORMAT(1X,F8.3)
CONTINUE
WRITE(6,*) 'ENTER CONSTANT B'
READ (5,*) B
WRITE(6,*) 'ENTER CONSTANT C'
READ (5,*) C
ERRTOT=0.0
DO 40 J=1,20
  ERR=(LOG10(PERM(J))-LOG10((C**(1/VOID(J))*(2.0+B*HYDR(J))))))**2
  ERRTOT=ERRTOT+ERR
CONTINUE
WRITE(6,*) 'ERROR OCCURRING IS',ERRTOT
WRITE(6,*) 'ENTER 0 TO RERUN, 1 TO KEEP VALUE OF B BUT
& CHANGE C,'
WRITE (6,*) 'AND 2 TO QUIT ITERATION'
READ (5,*) I
IF (I.EQ.0) GOTO 35
IF (I.EQ.1) GOTO 36
IF (I.NE.2) GOTO 37
WRITE(6,*) 'THE VALUES OBTAINED FOR THIS FINAL ITERATION'
WRITE(6,*) 'ARE: B=',B
WRITE(6,*) '      C=',C
WRITE(6,*) 'AND SQUARED ERROR =',ERRTOT
CLOSE(10)
CLOSE(11)
CLOSE(12)
STOP
END
```

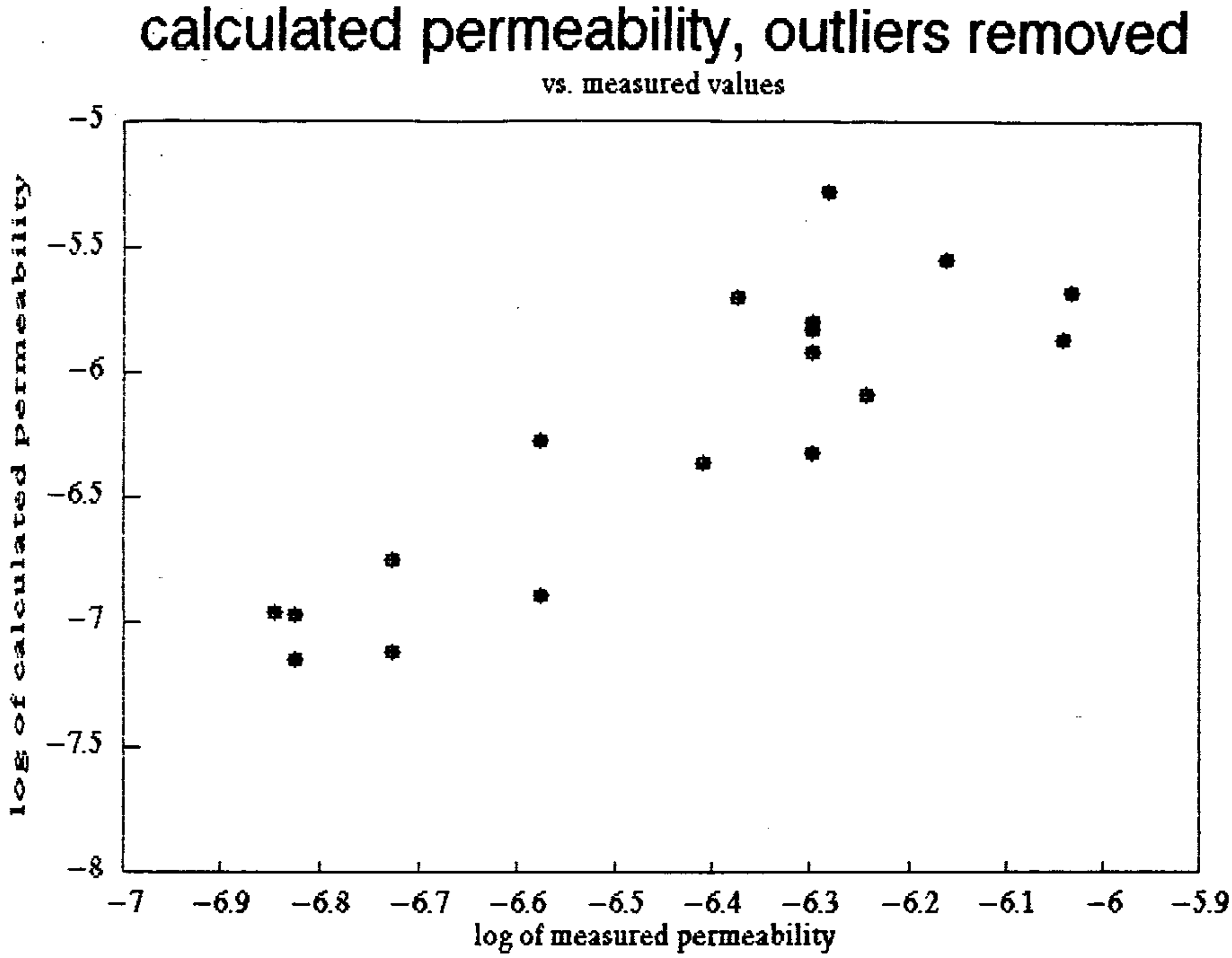
TRIAL DENSITY VS HYDRAULIC CONDUCTIVITY

calculated permeability (log)	field measured permeability (log)
-6.281	-5.282
-6.041	-5.866
-6.161	-5.55
-6.033	-5.678
-6.298	-6.321
-6.373	-5.695
-6.298	-5.801
-6.298	-5.824
-6.298	-5.921
-6.289	-6.951
-6.289	-7.009
-6.409	-6.357
-6.244	-7.157
-6.244	-6.721
-6.244	-6.086
-6.726	-6.745
-6.726	-7.114
-6.575	-6.269
-6.575	-6.886
-6.824	-6.967
-6.824	-7.143
-6.845	-6.959
-6.313	-6.886

Regression Output:

Constant		2.902957
Std Err of Y Est		0.496754
R Squared		0.348787
No. of Observations		23
Degrees of Freedom		21
X Coefficient(s)	1.453427	
Std Err of Coef.	0.433376	

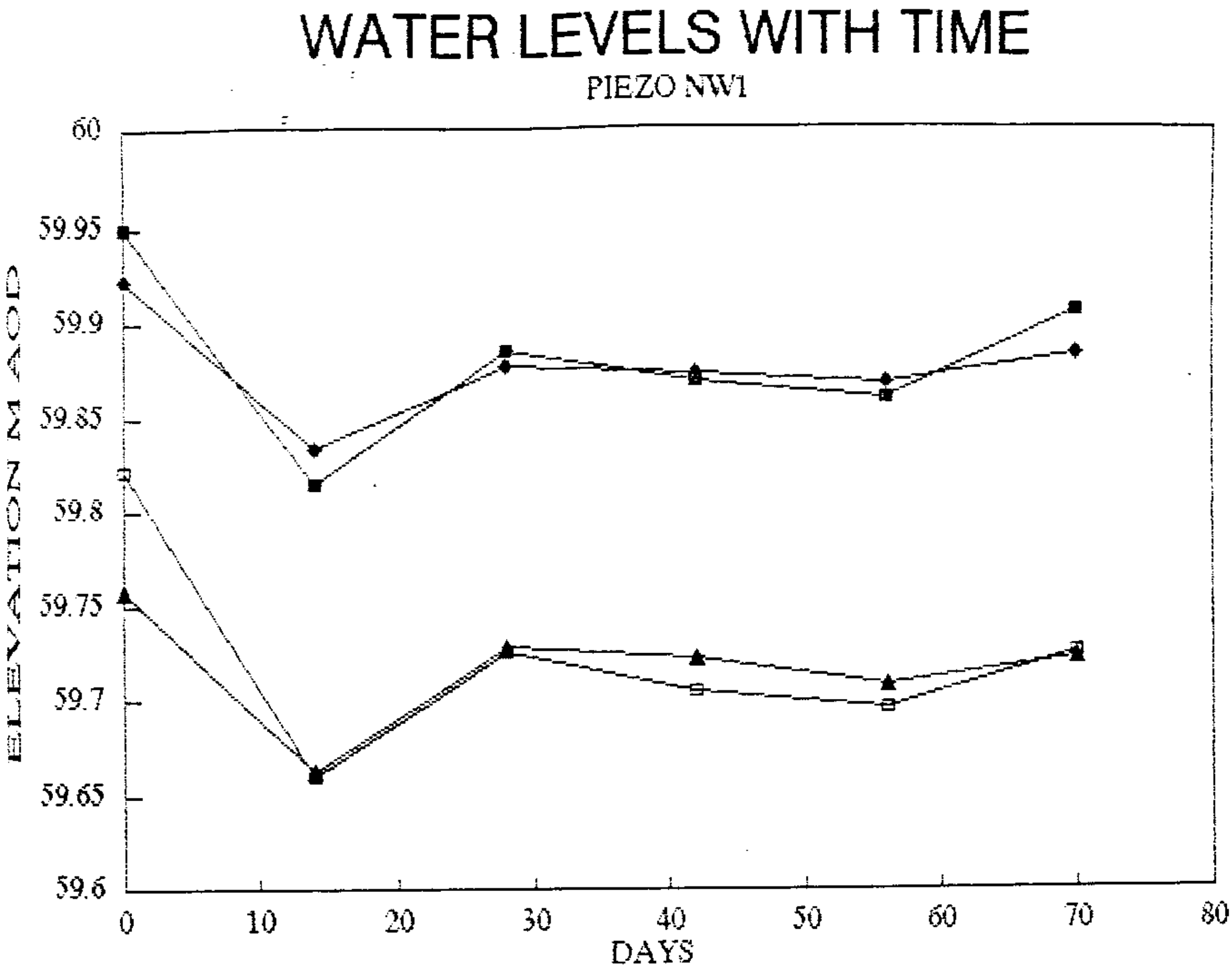
W


calculated permeability, outliers removed
vs. measured values
log of calculated permeability
log of measured permeability
-5
-5.5
-6
-6.5
-7
-7.5
-8
-7
-6.9
-6.8
-6.7
-6.6
-6.5
-6.4
-6.3
-6.2
-6.1
-6
-5.9

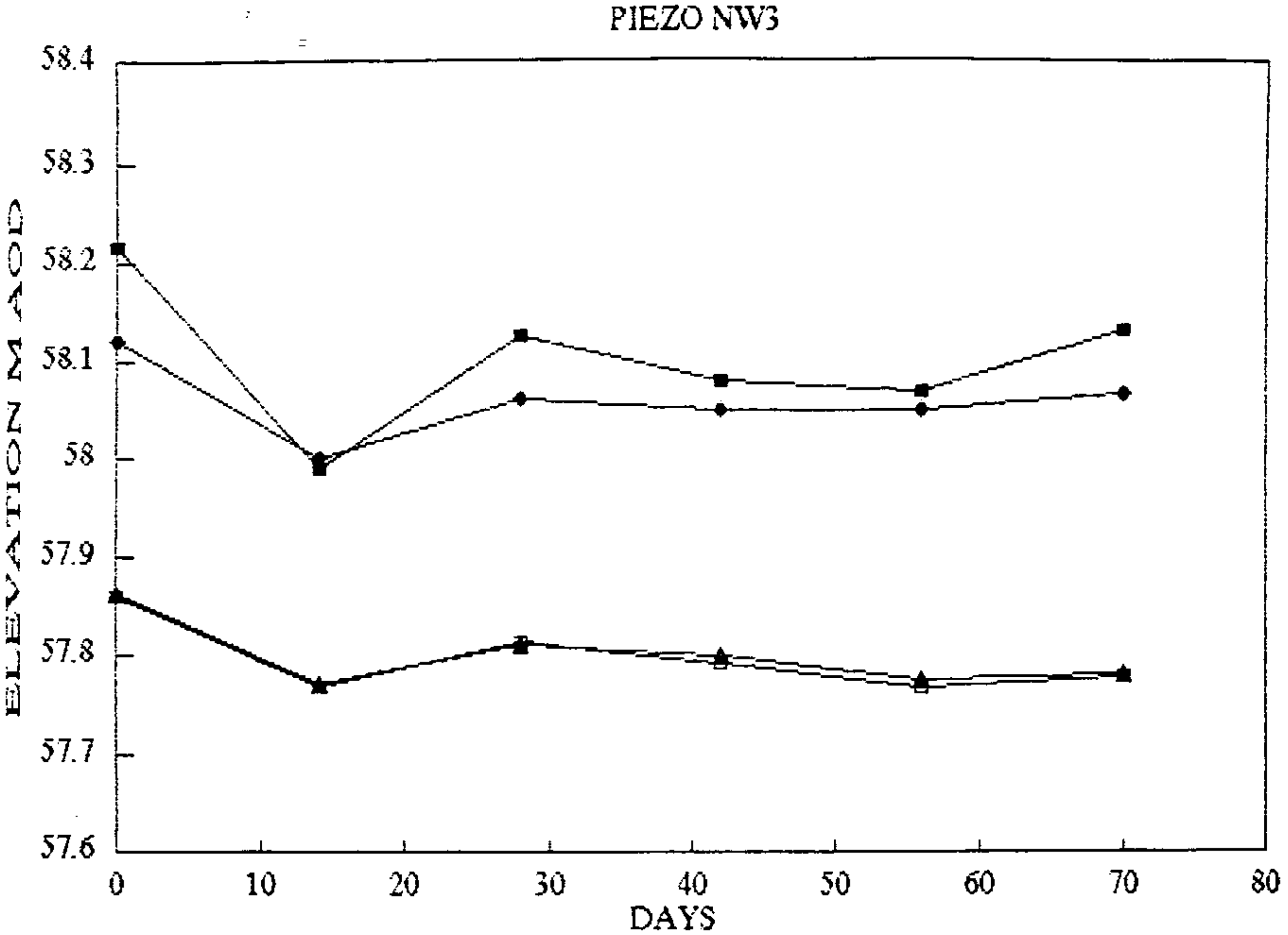
W

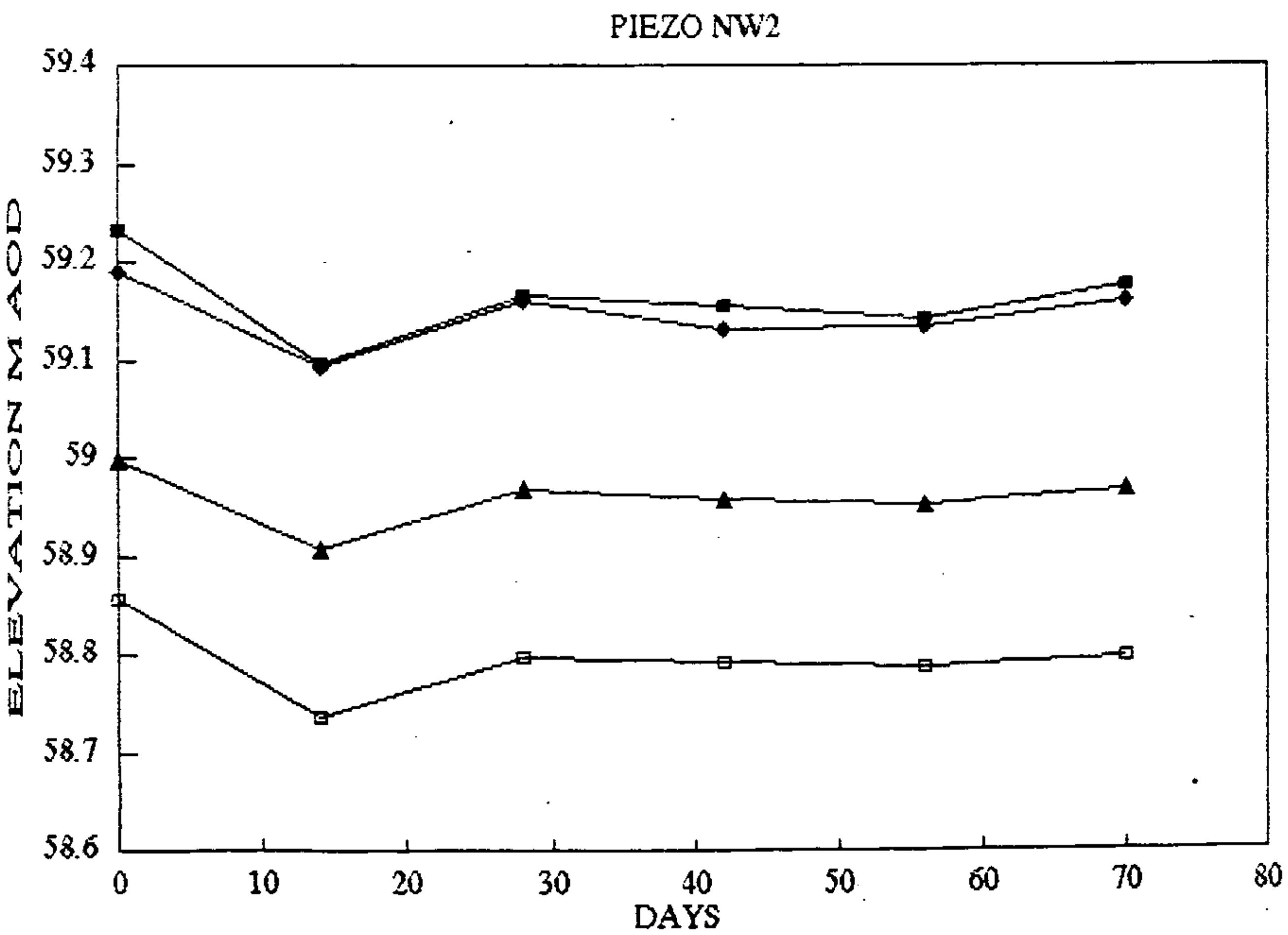
APPENDIX F

Transient piezometer data

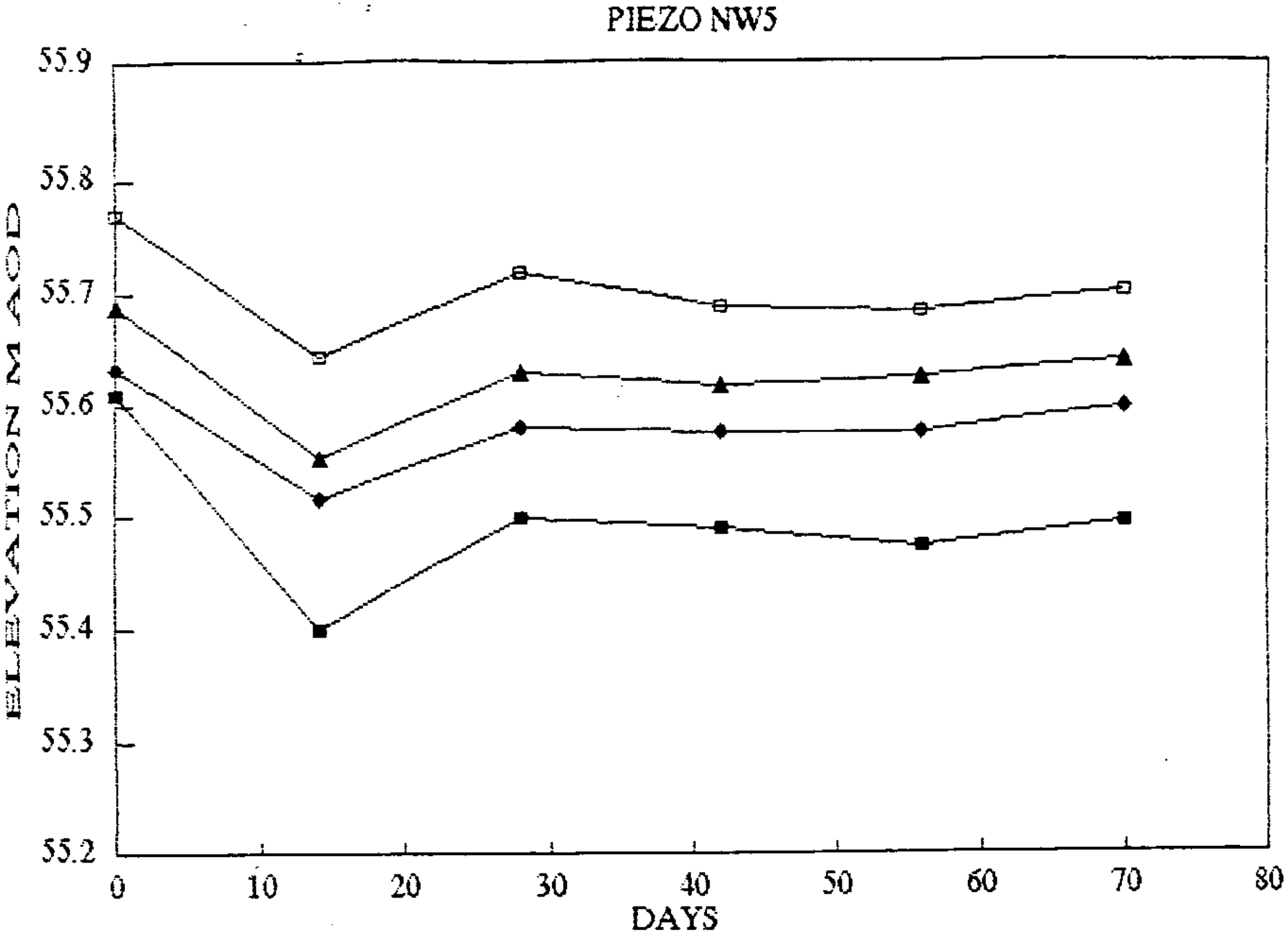

WATER LEVELS WITH TIME
PIEZO NW1
ELEVATION M AOD
60
59.95
59.9
59.85
59.8
59.75
59.7
59.65
59.6
0
10
20
30
40
50
60
70
80
DAYS

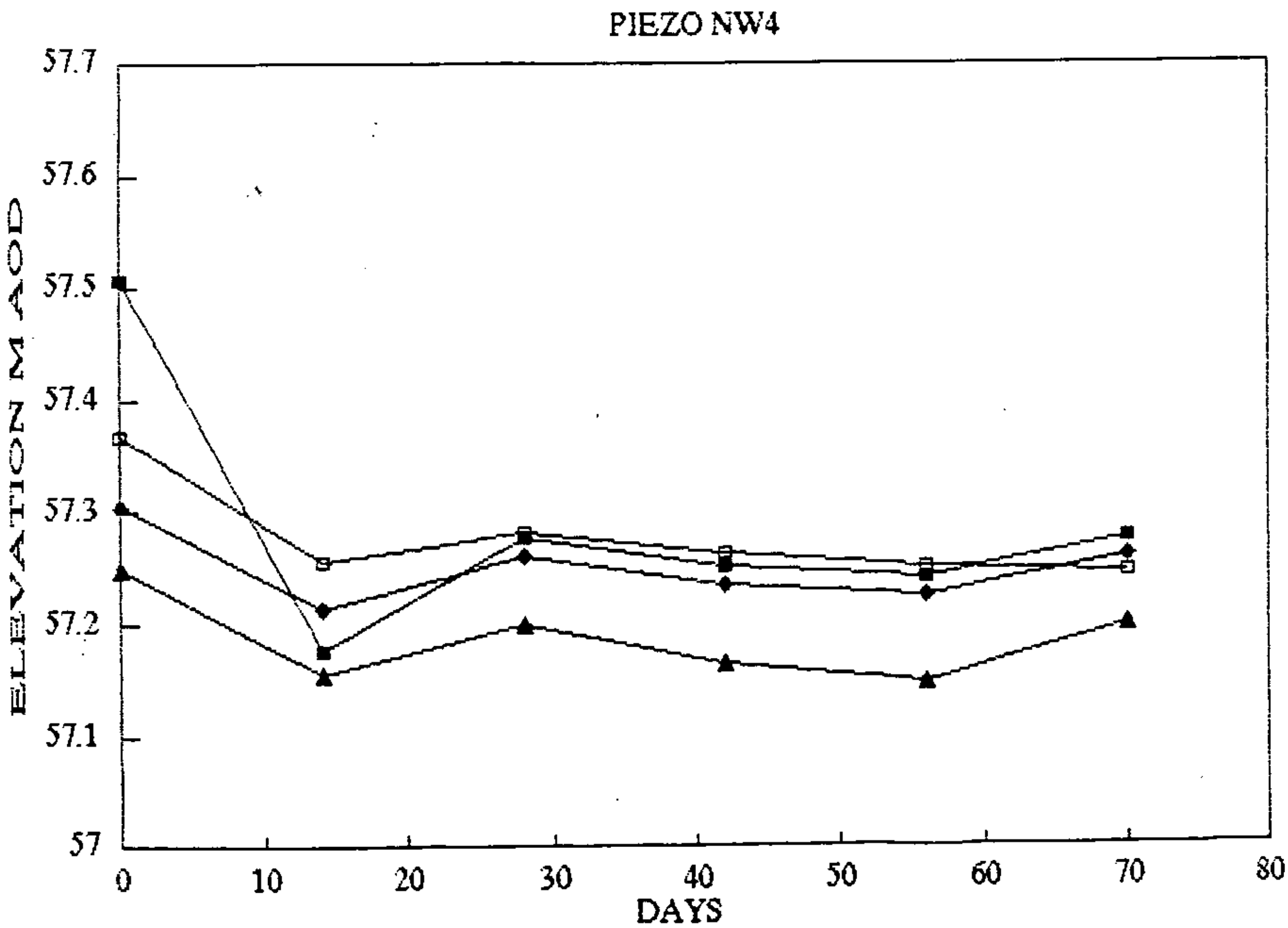
WATER LEVELS WITH TIME



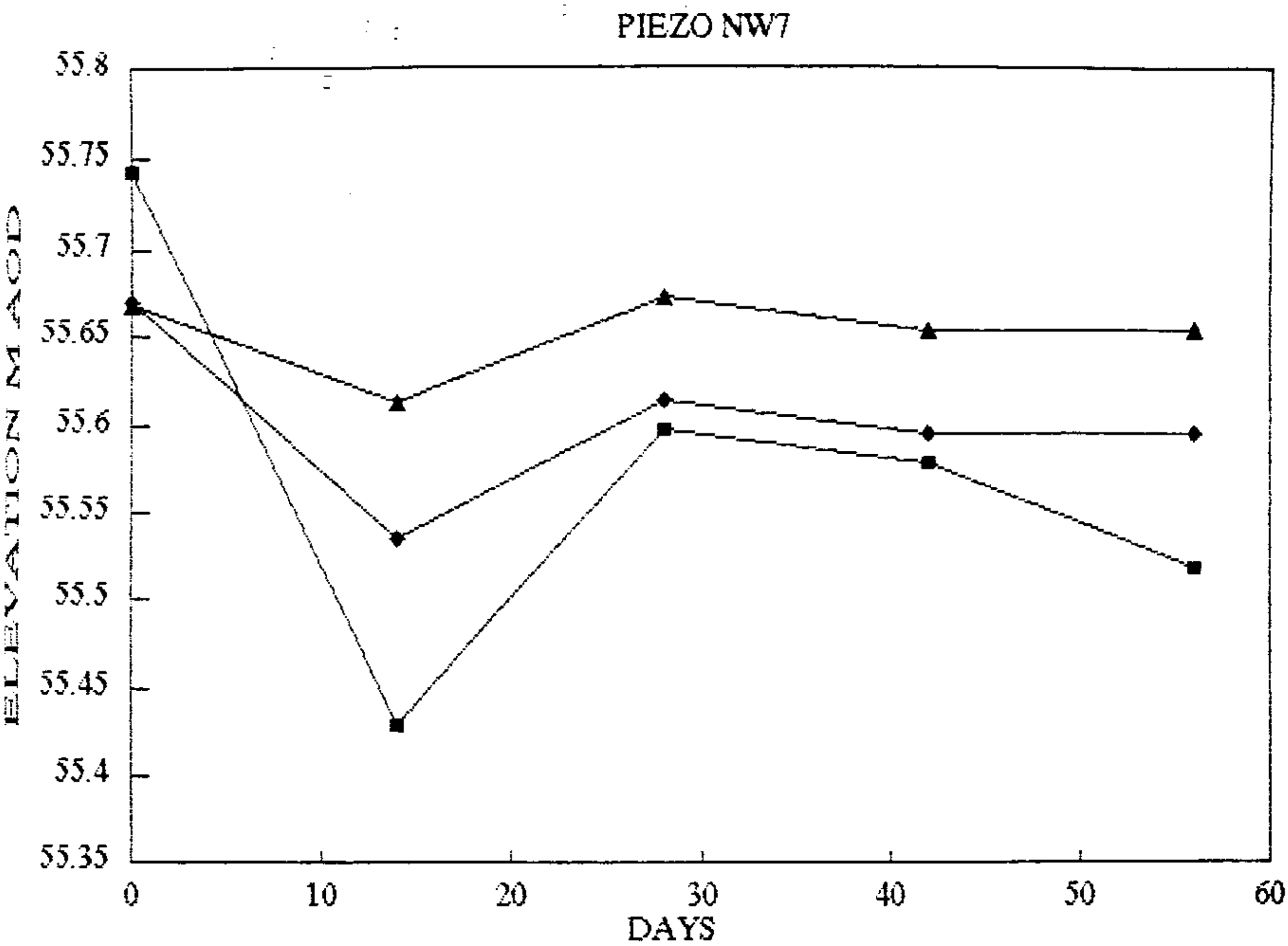


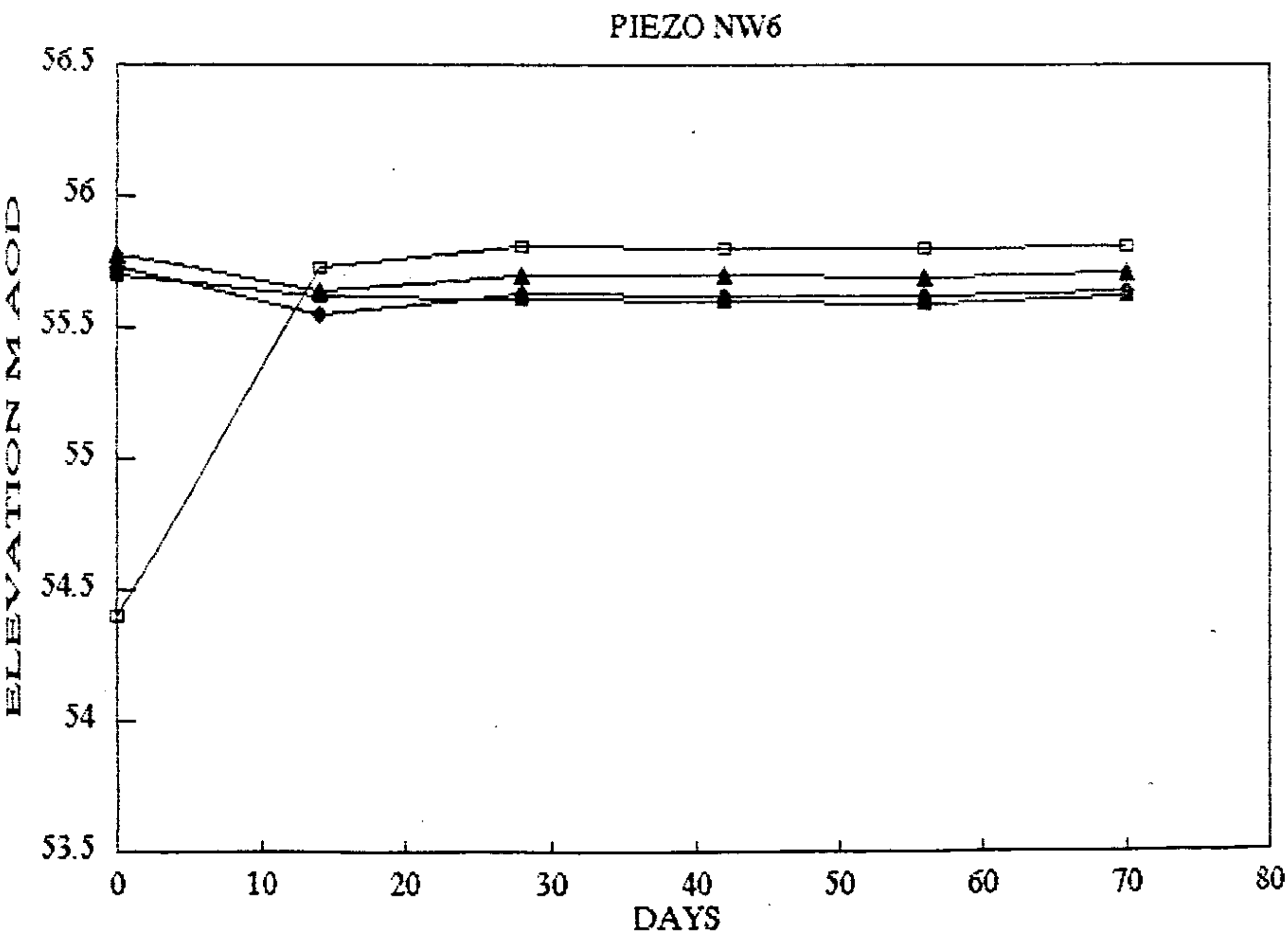
WATER LEVELS WITH TIME



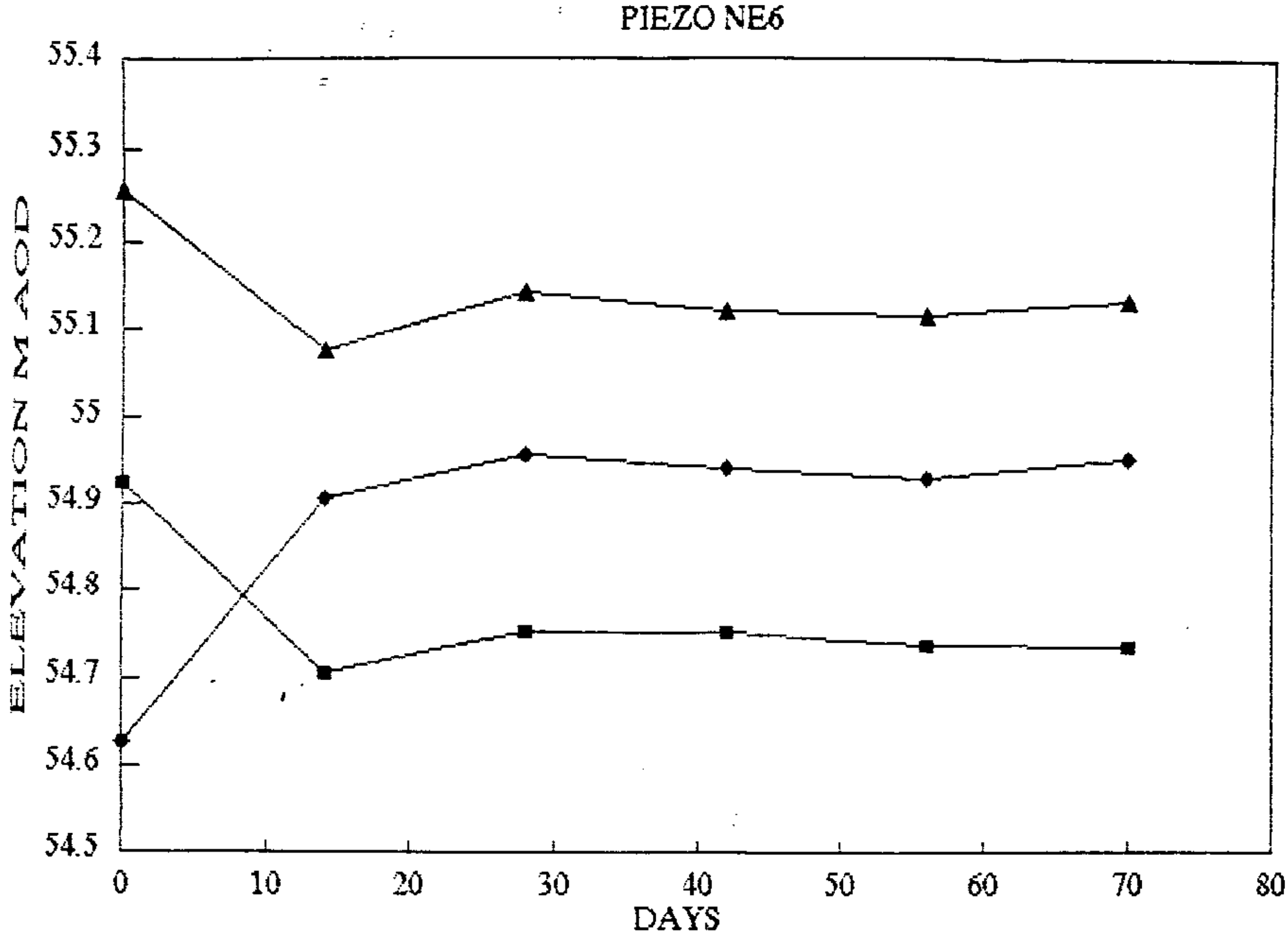


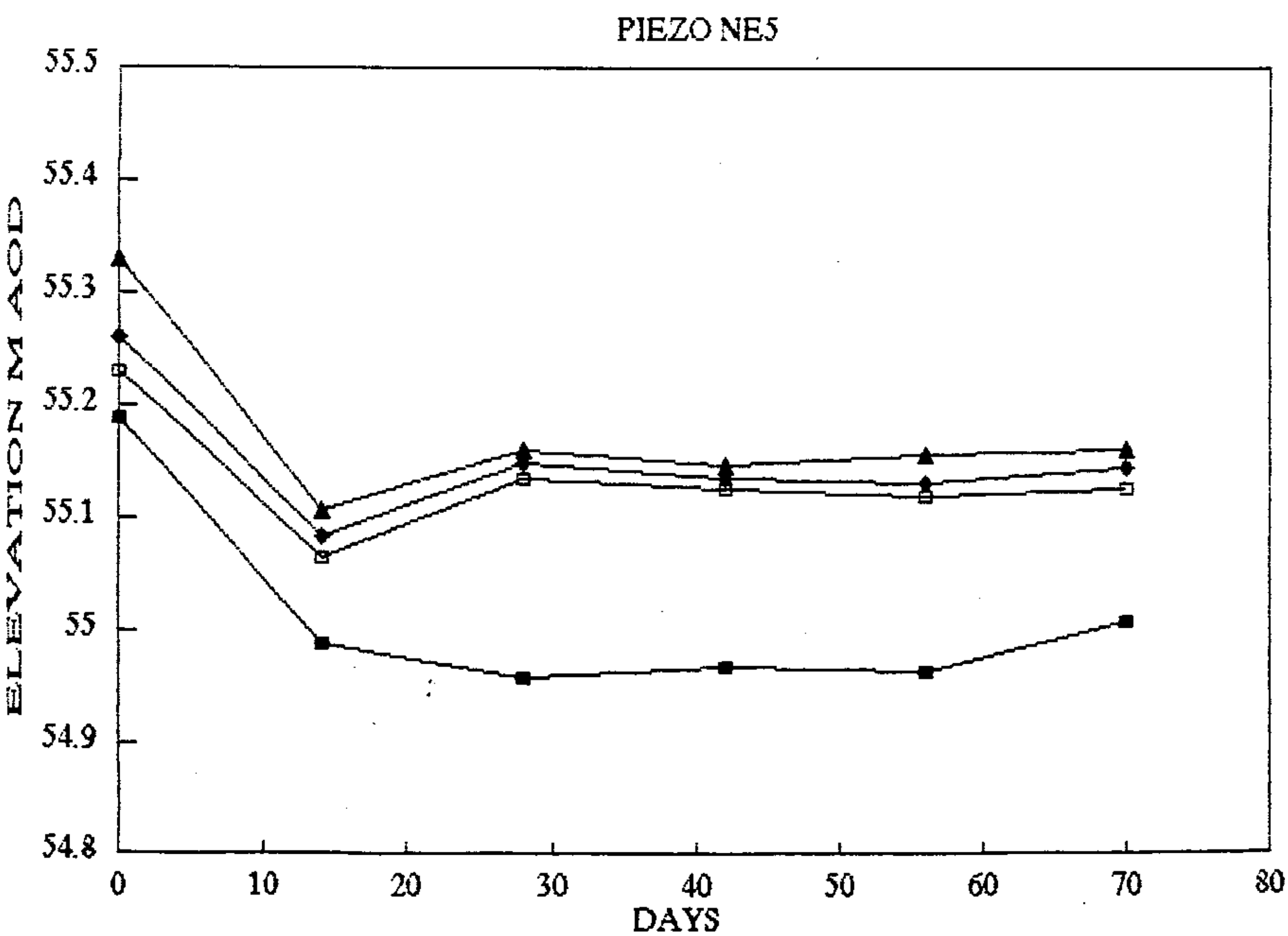
WATER LEVELS WITH TIME



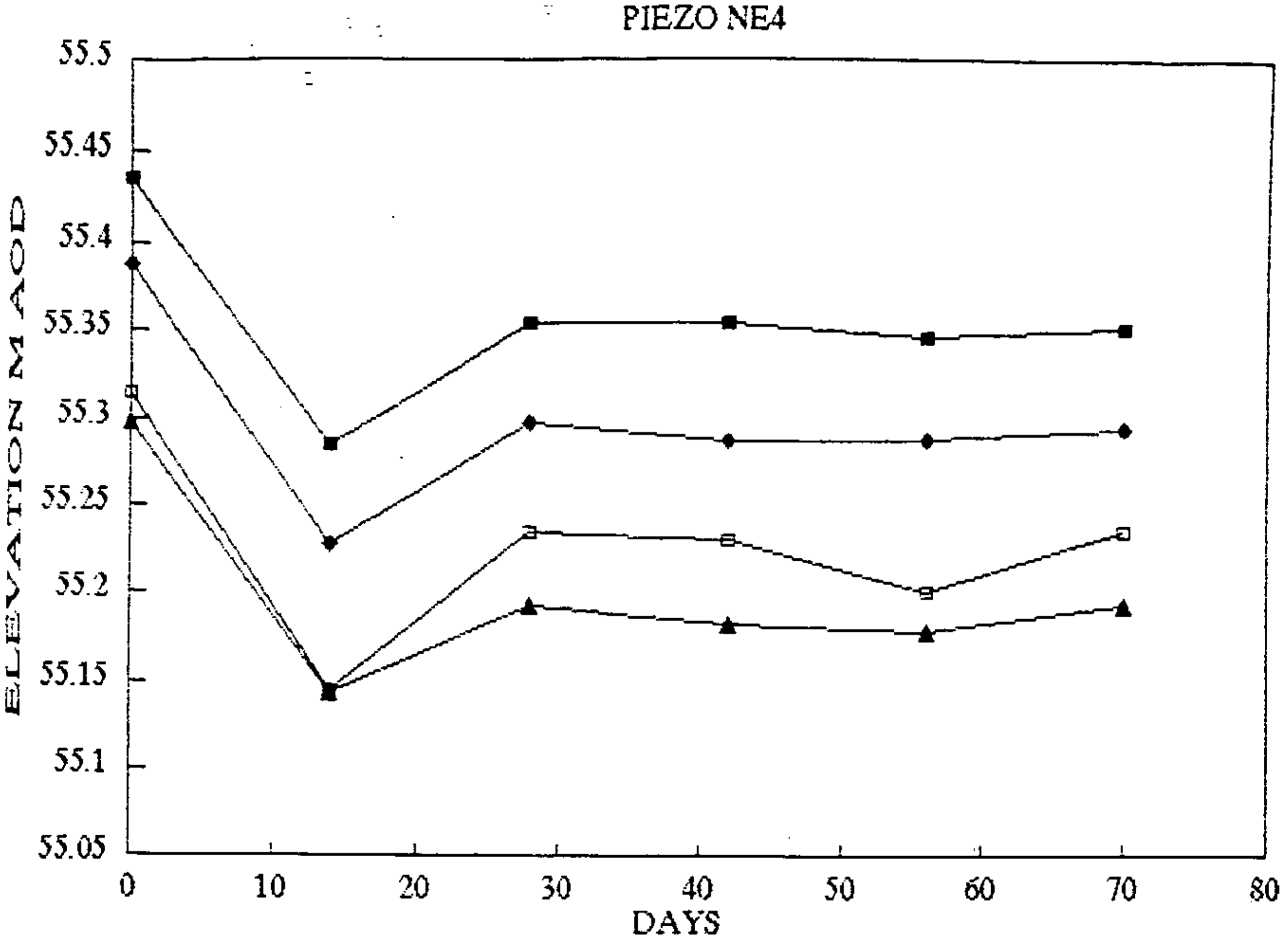


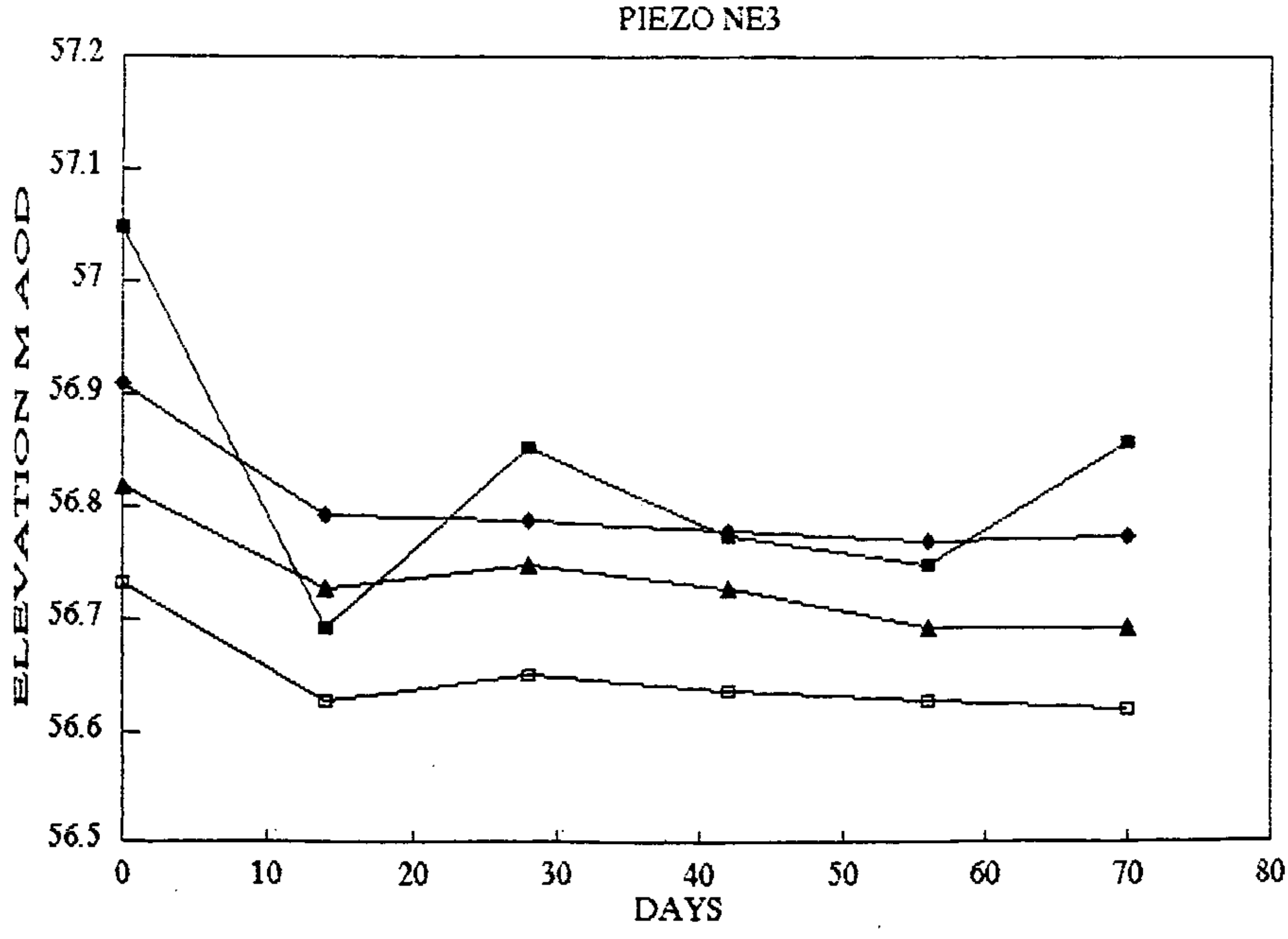
WATER LEVELS WITH TIME



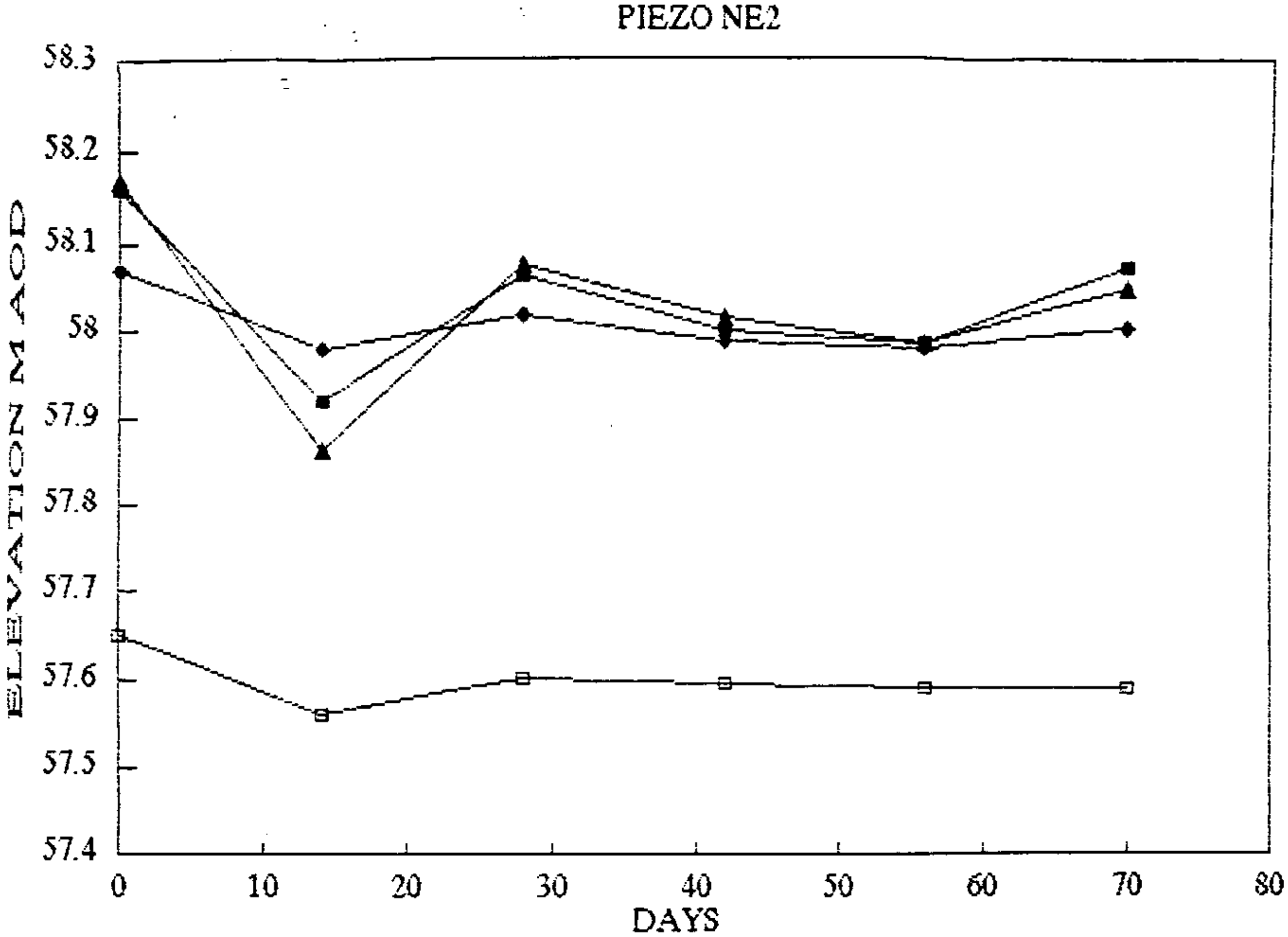


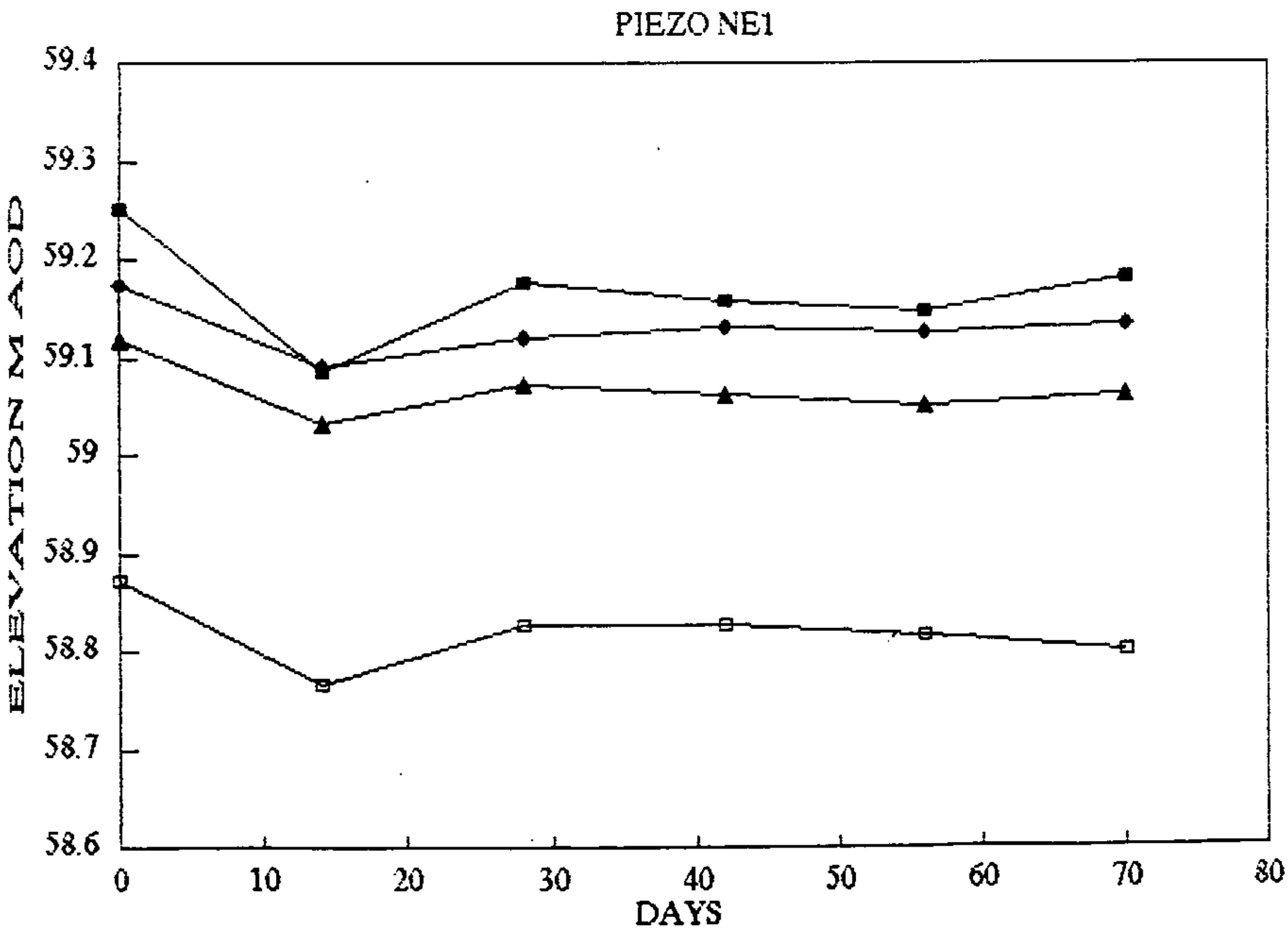
WATER LEVELS WITH TIME





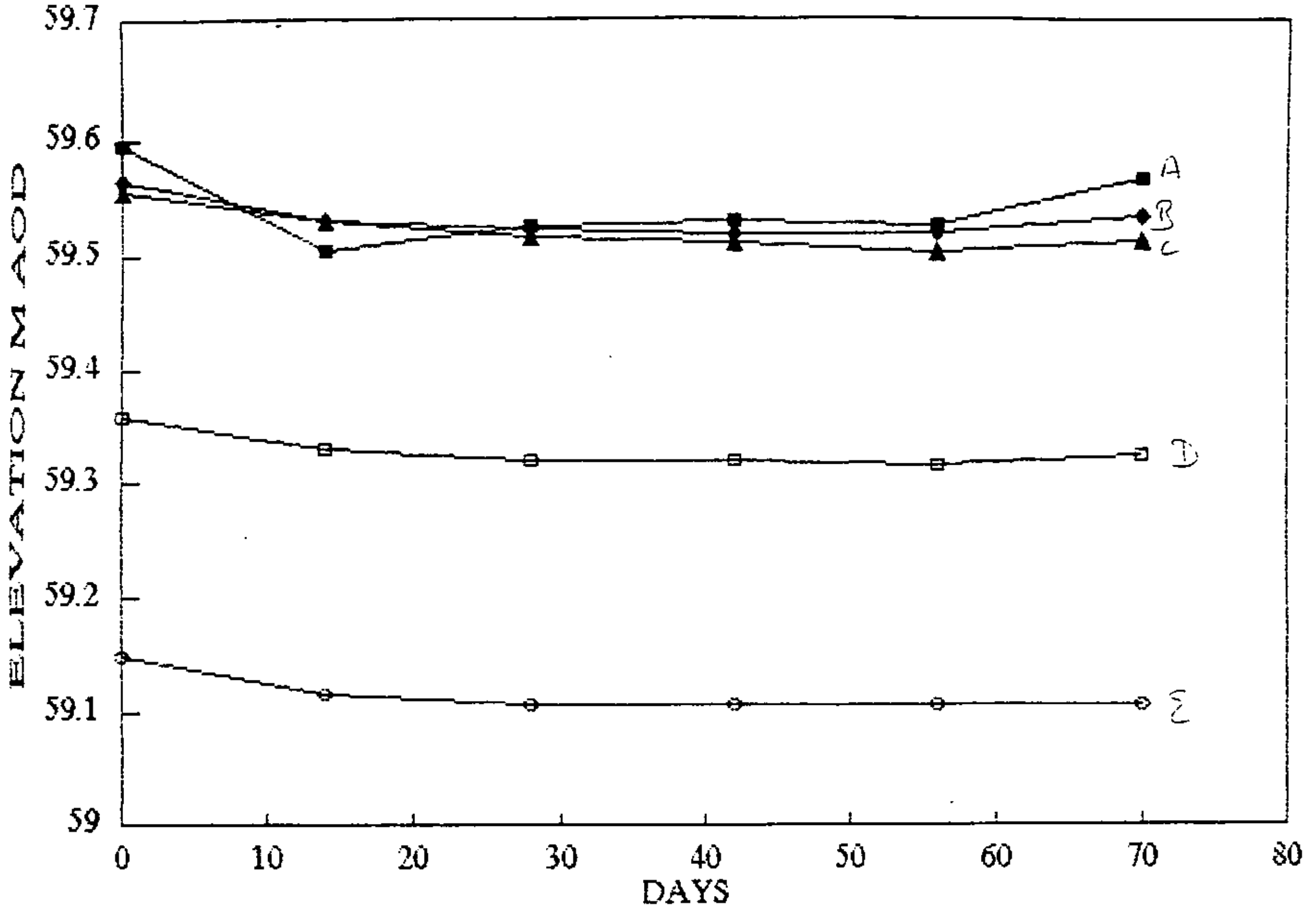
WATER LEVELS WITH TIME





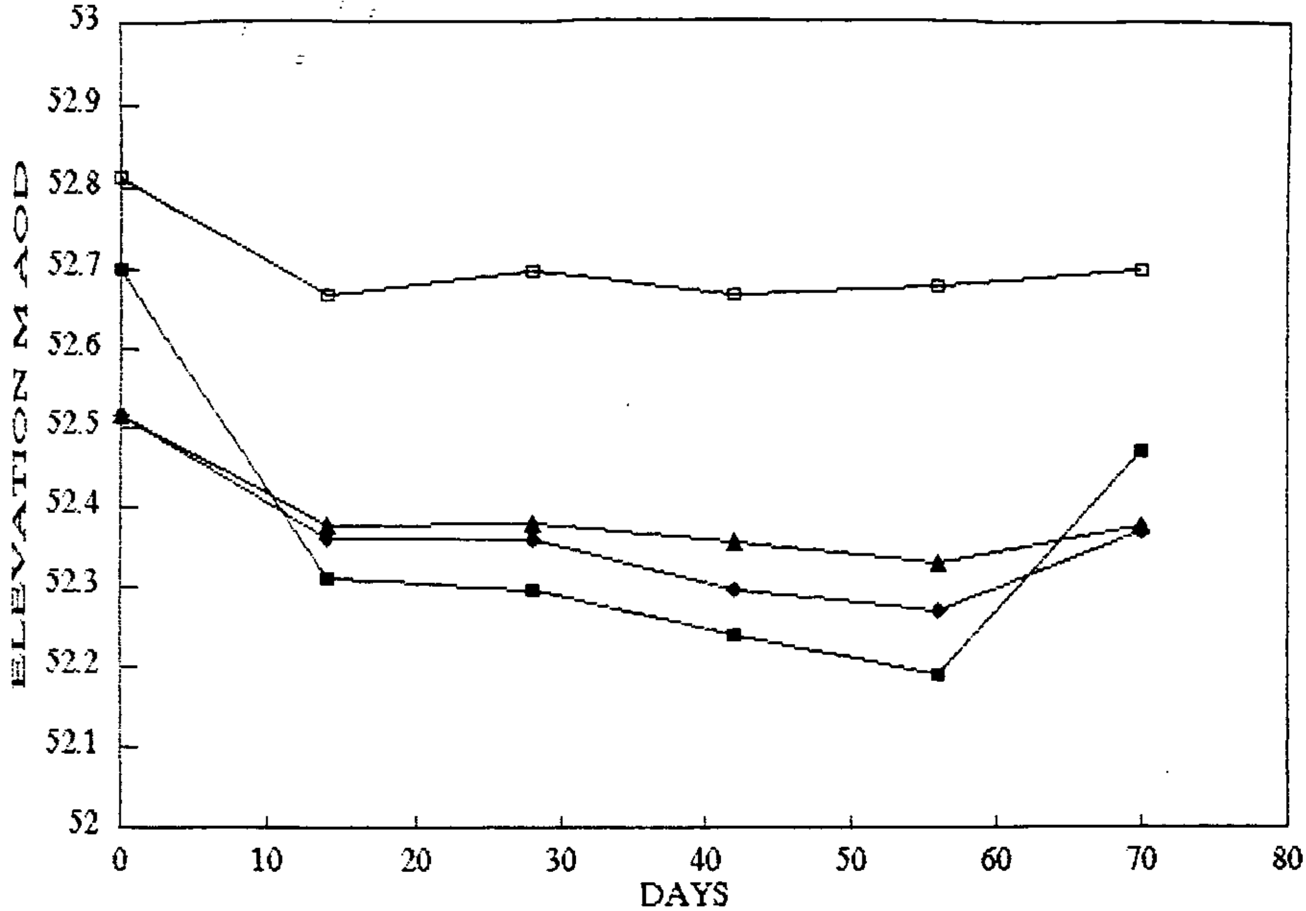
WATER LEVELS WITH TIME

PIEZO 108

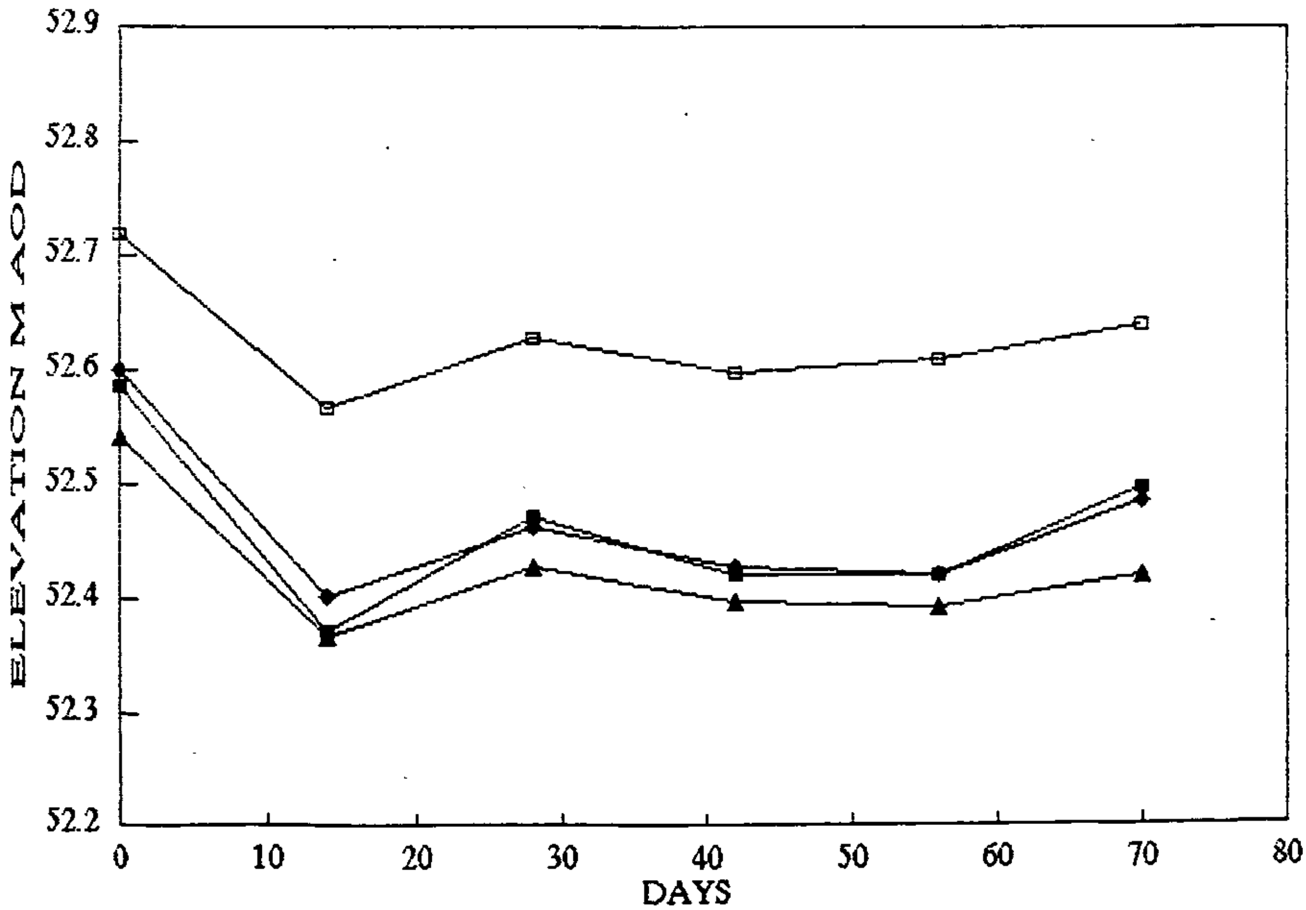


WATER LEVELS WITH TIME

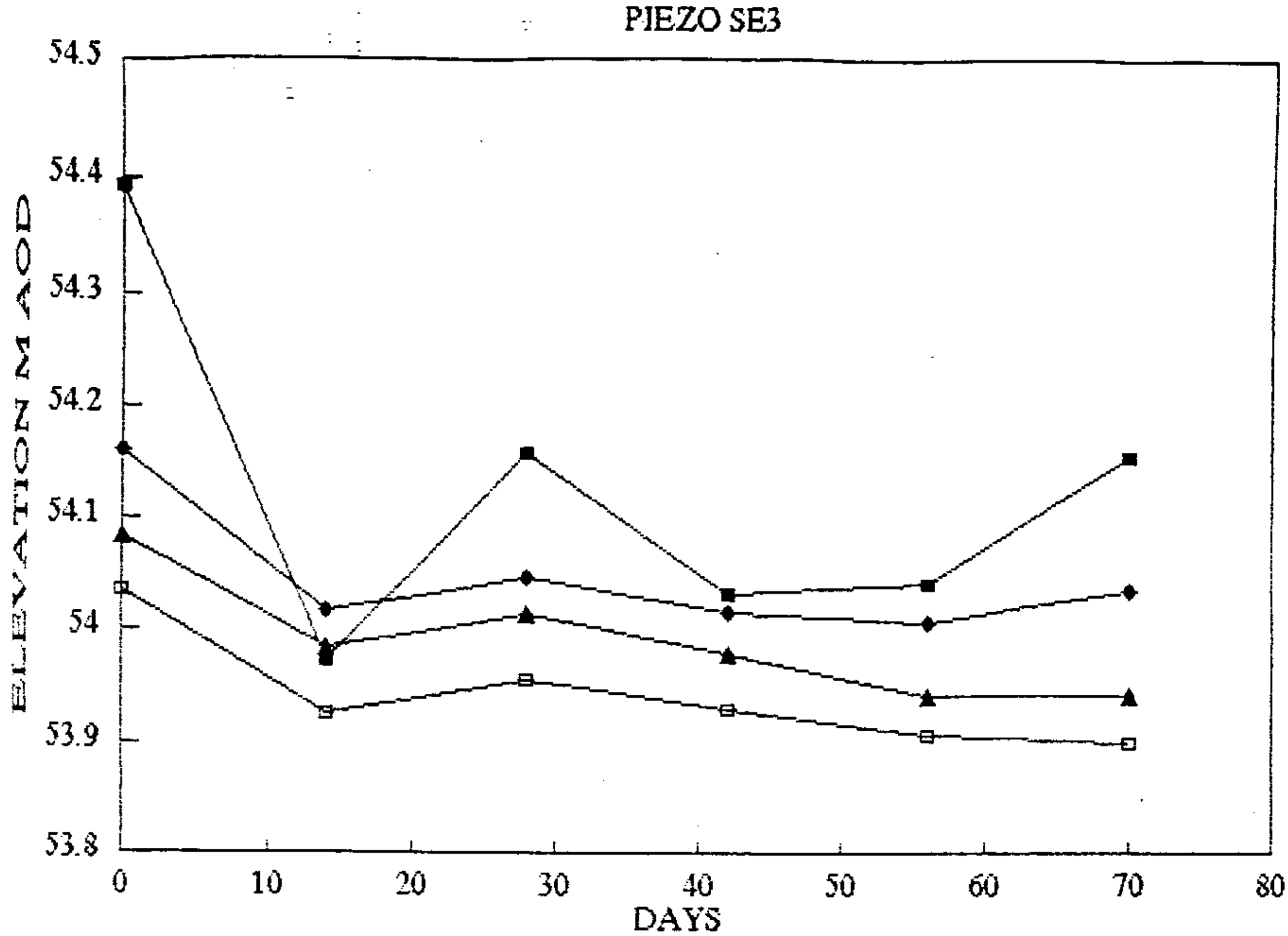
PIEZO SE5

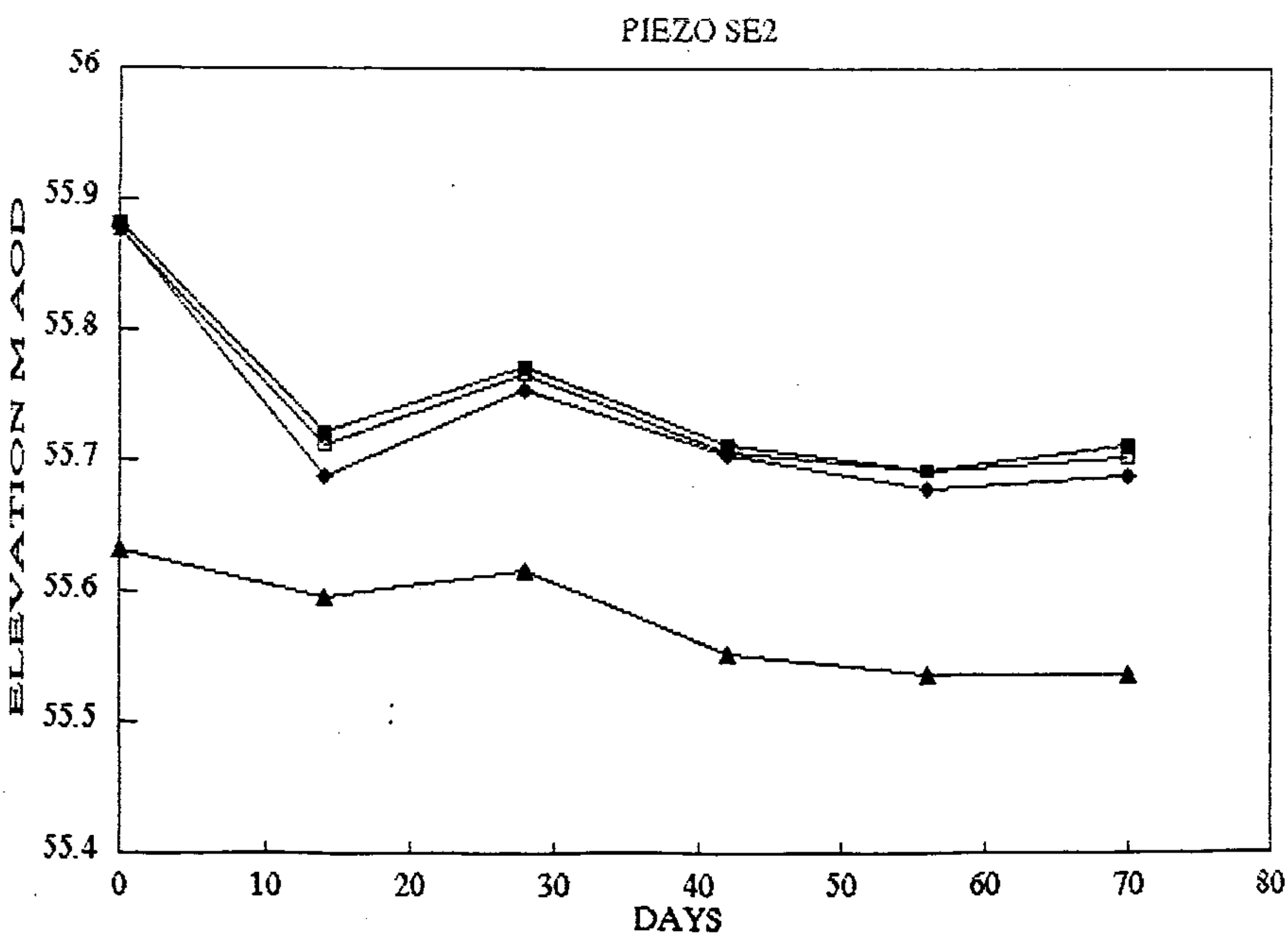


PIEZO SE4

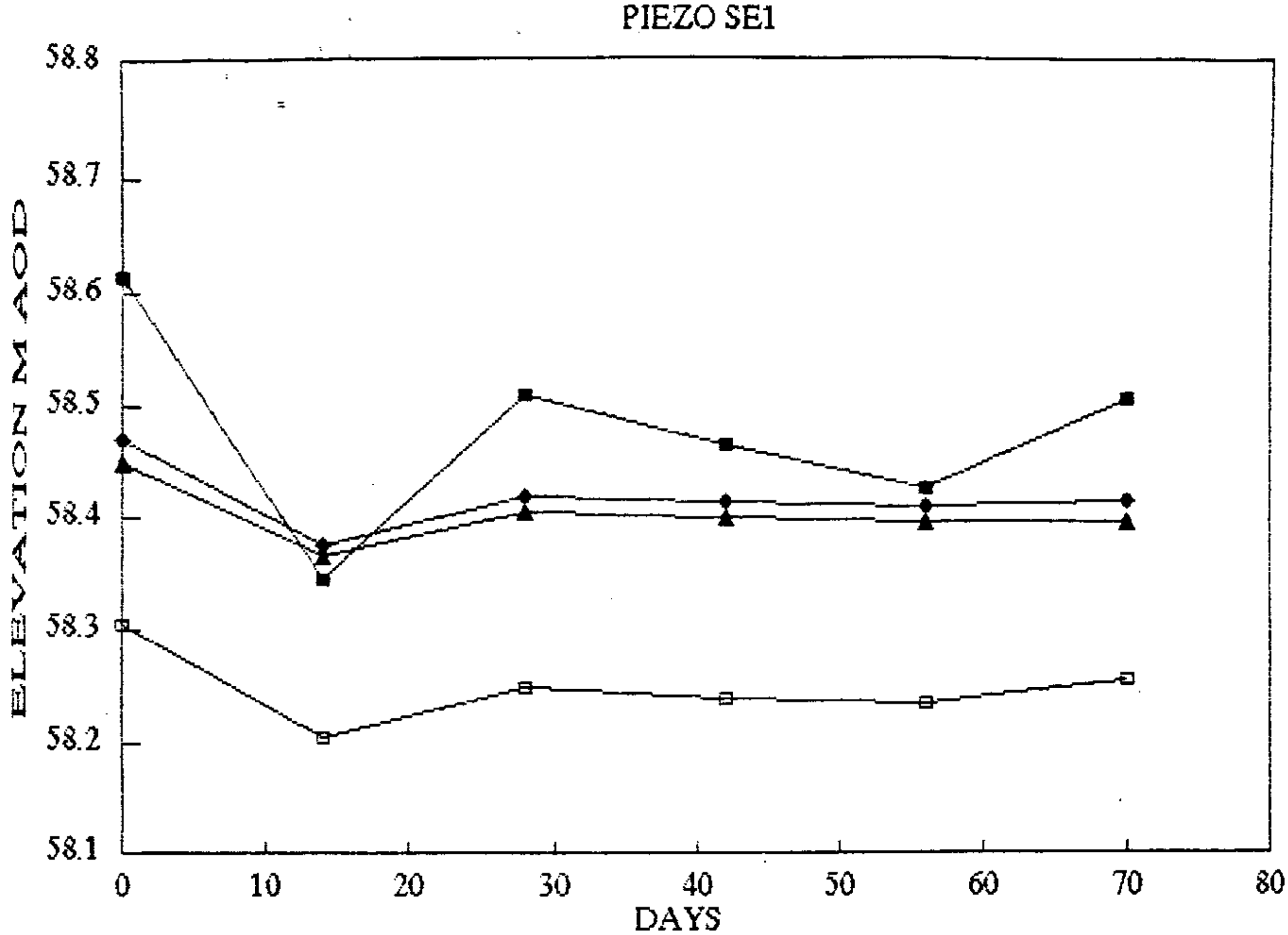


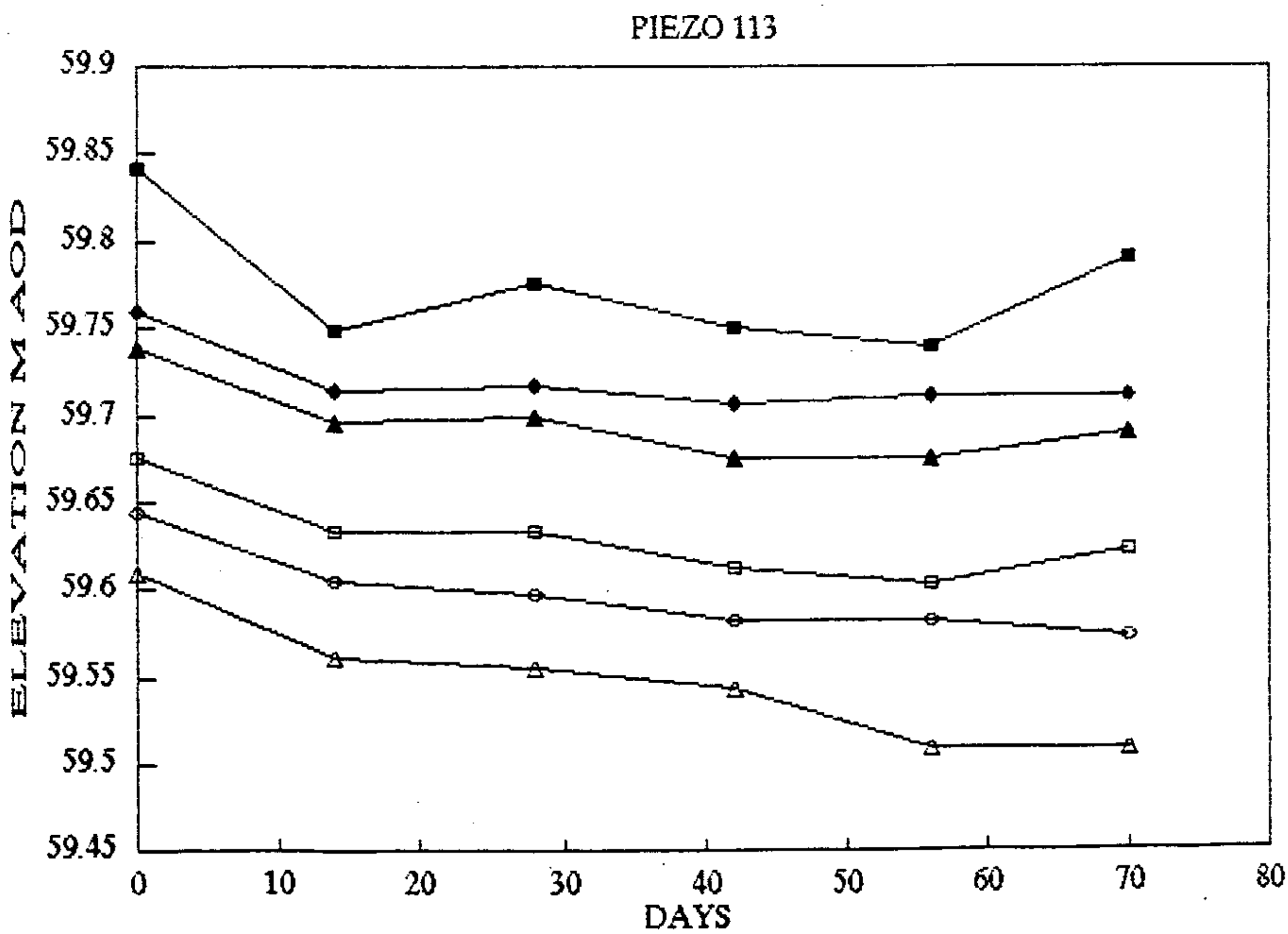
WATER LEVELS WITH TIME



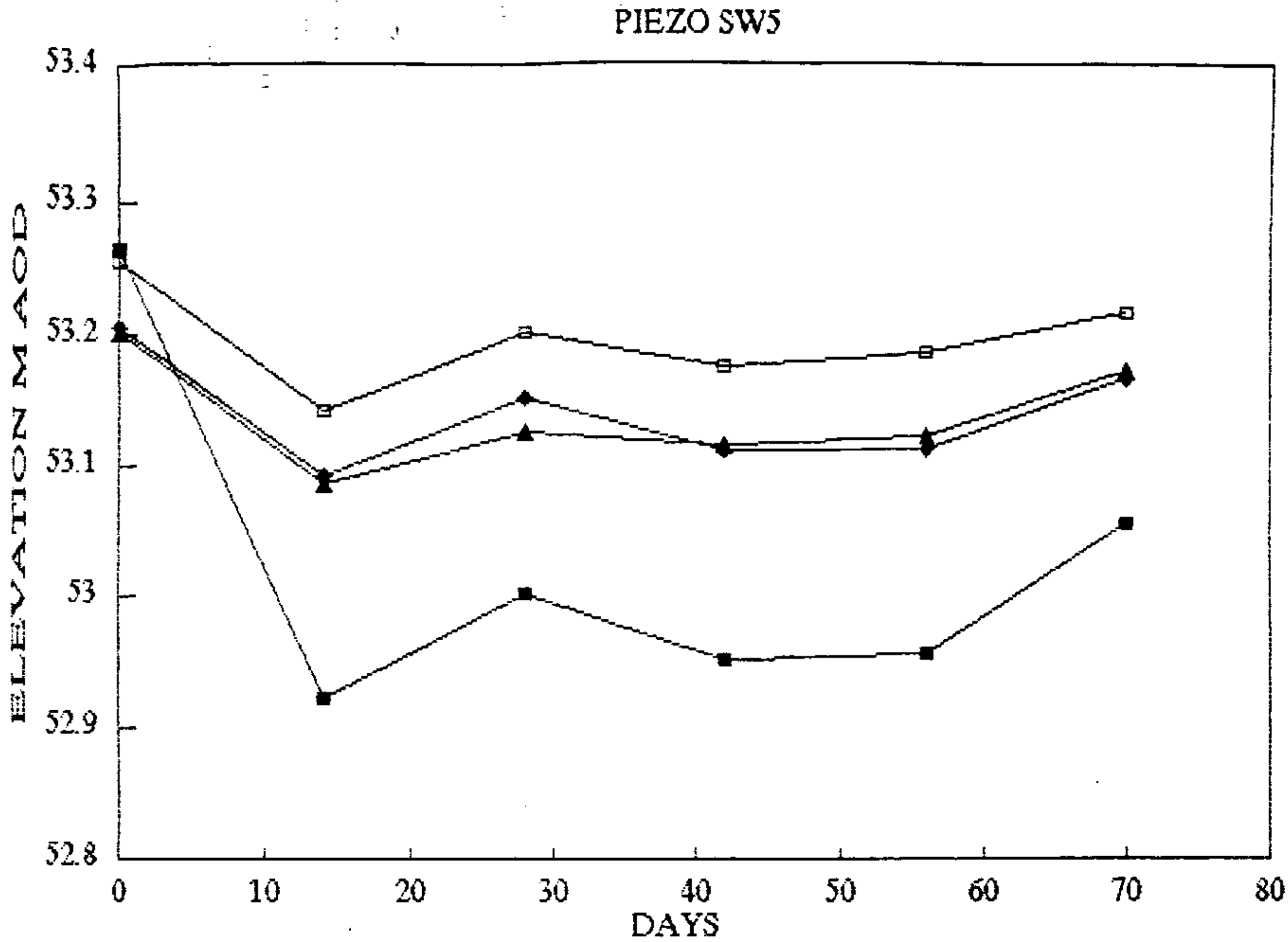


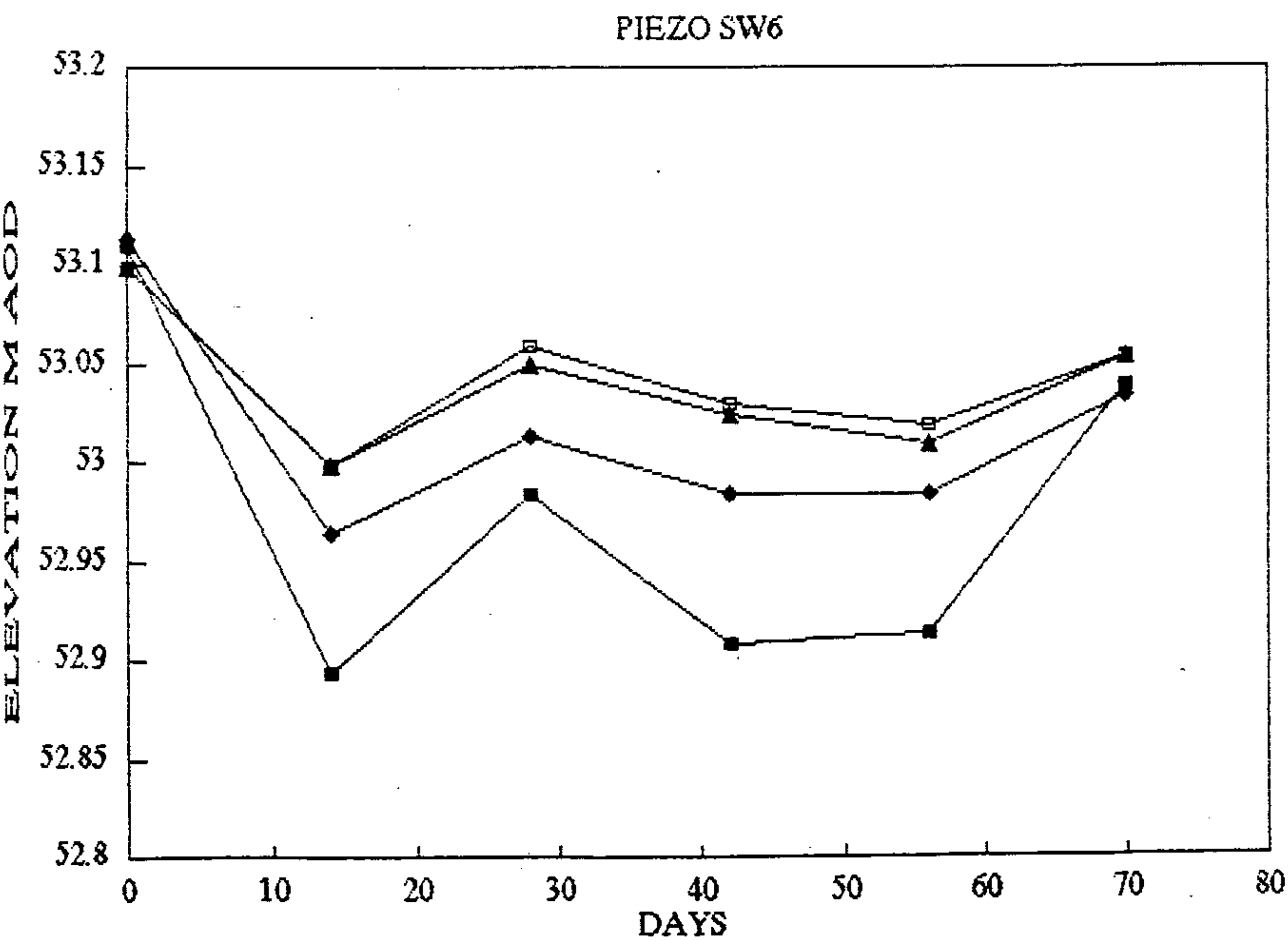
WATER LEVELS WITH TIME



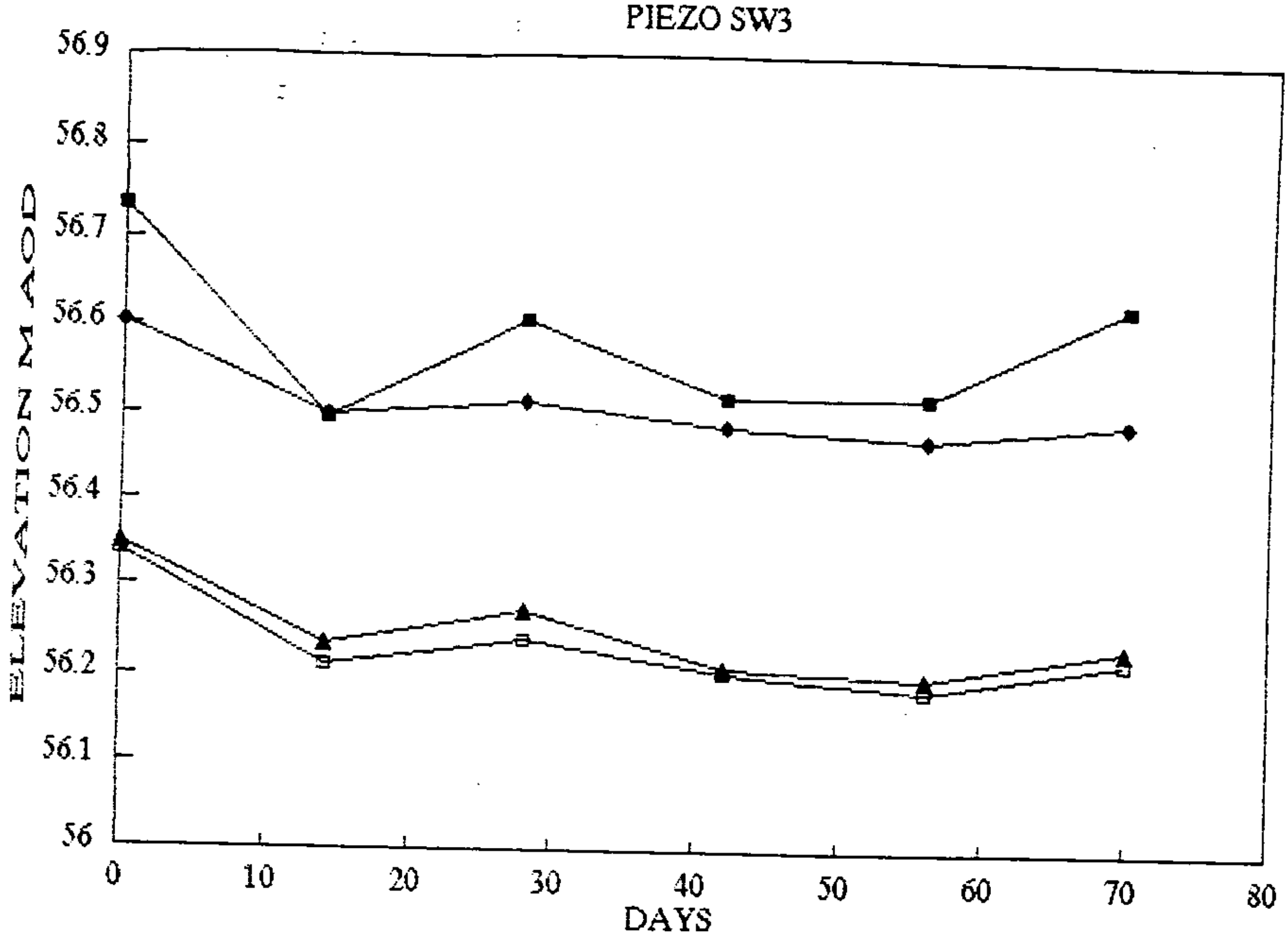


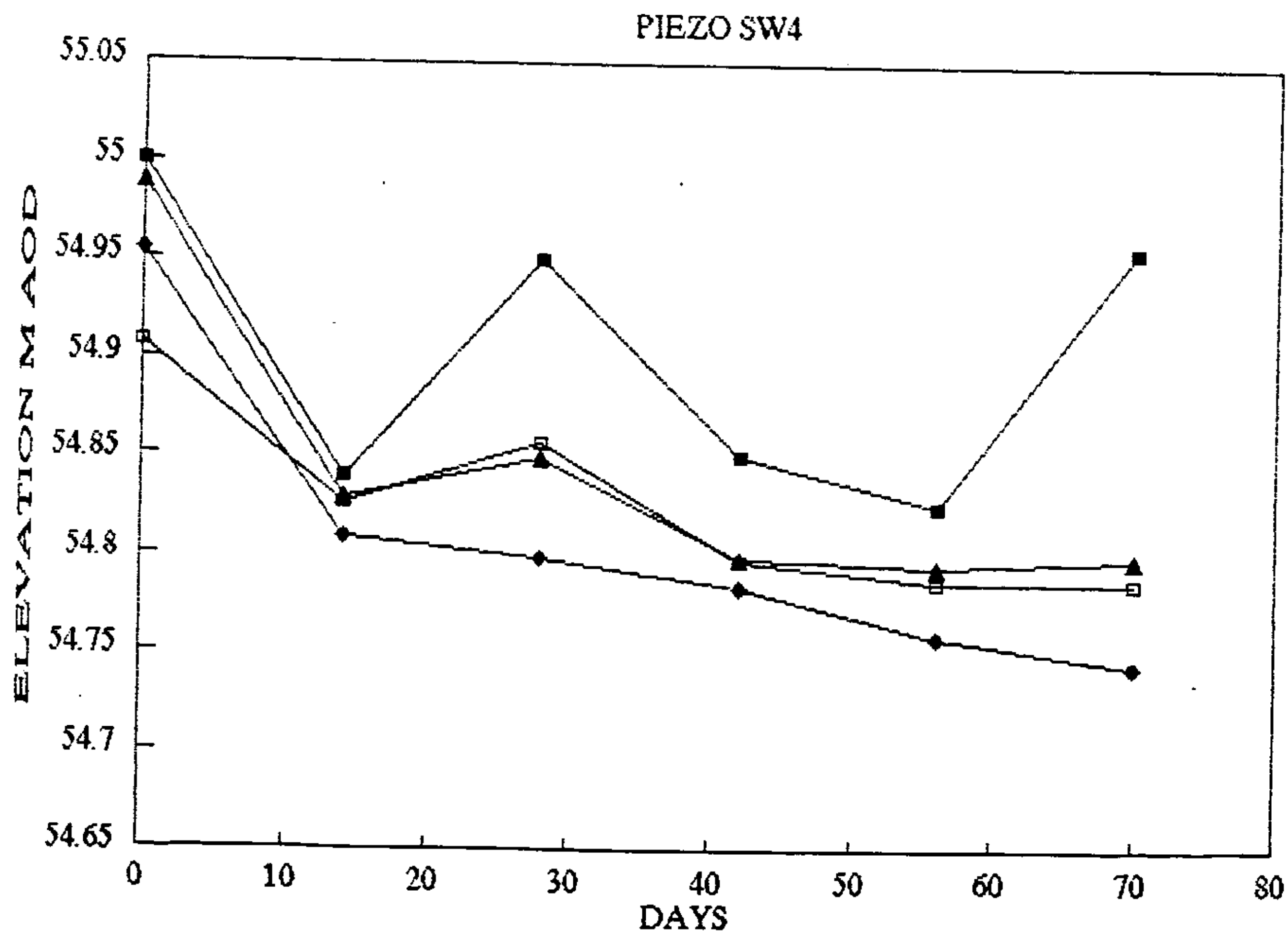
WATER LEVELS WITH TIME



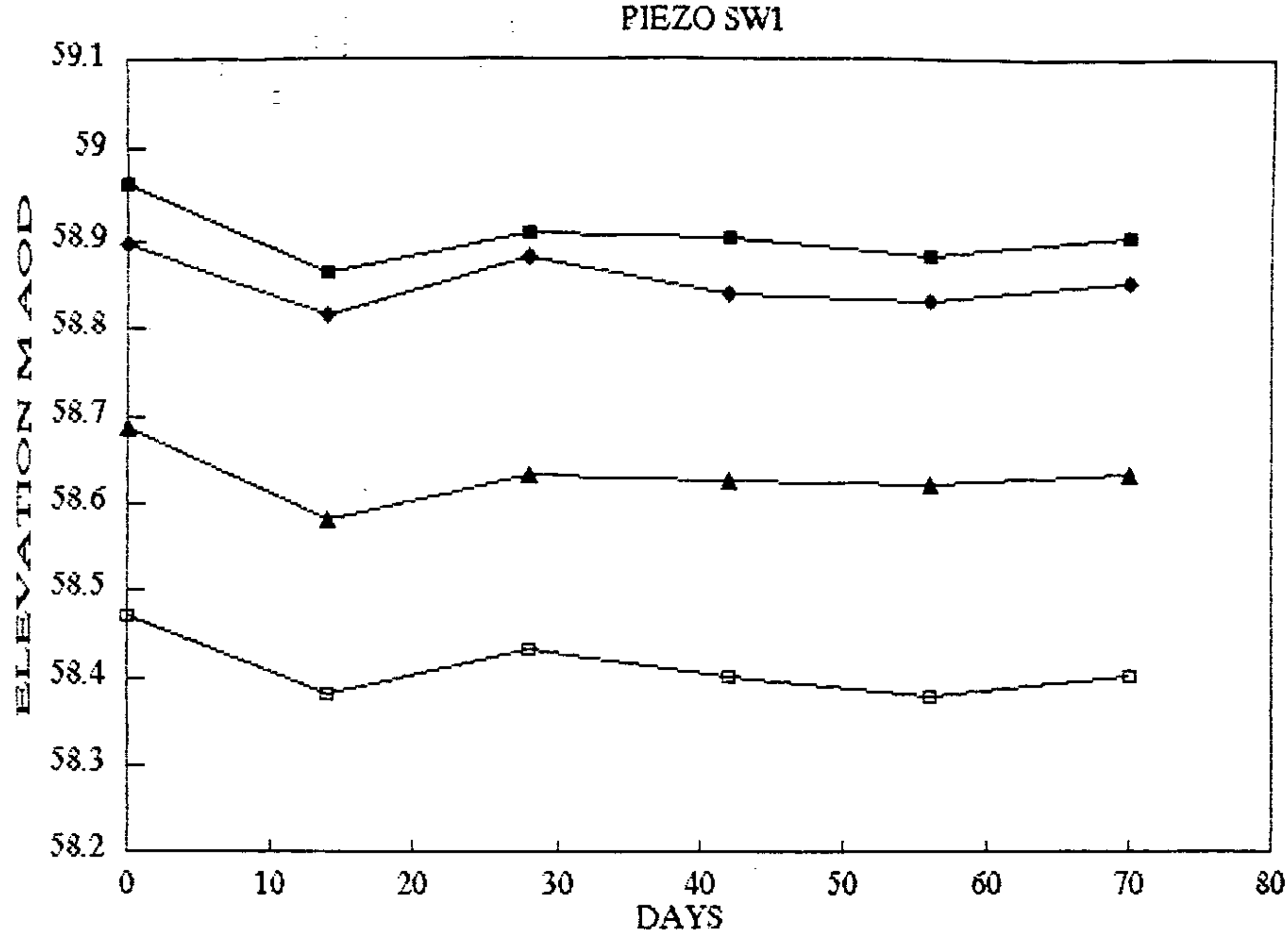


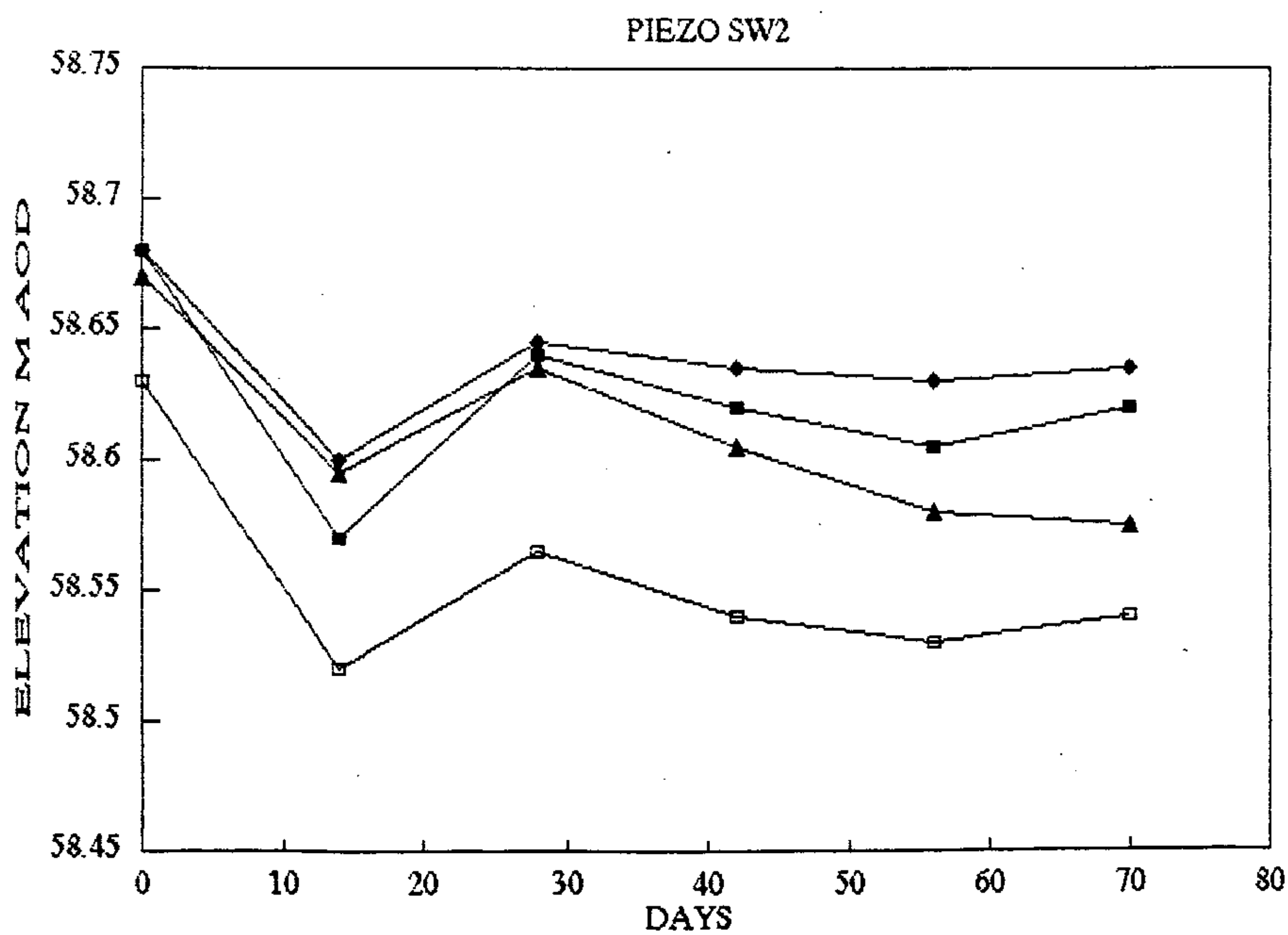
WATER LEVELS WITH TIME





WATER LEVELS WITH TIME





WW

*4/9/92 TRIAL DENSITY VS HYDRAULIC CONDUCTIVITY

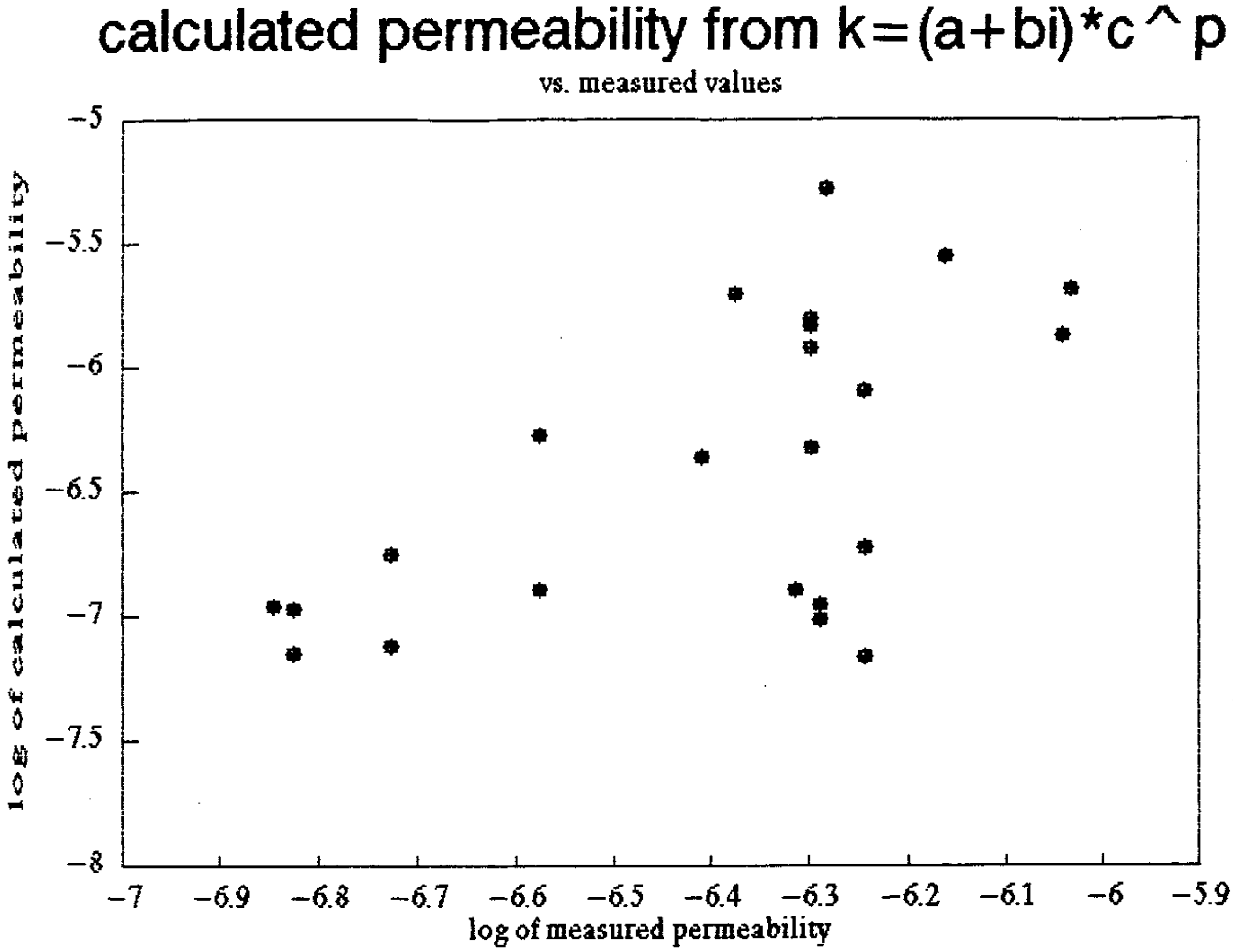
Calculated permeability (log)	Field determined permeability (log)
-6.281	-5.282
-6.041	-5.866
-6.161	-5.550
-6.033	-5.678
-6.298	-6.321
-6.373	-5.695
-6.298	-5.801
-6.298	-5.824
-6.298	-5.921
-6.409	-6.357
-6.244	-6.086
-6.726	-6.745
-6.726	-7.114
-6.575	-6.269
-6.575	-6.886
-6.824	-6.967
-6.824	-7.143
-6.845	-6.959

Regression Output:

Constant		6.209579
Std Err of Y Est		0.297518
R Squared		0.762168
No. of Observations		18
Degrees of Freedom		16
X Coefficient(s)	1.935926	
Std Err of Coef.	0.270358	

W

WWW


calculated permeability from k=(a+bi)*c^p
vs. measured values
log of calculated permeability
log of measured permeability
-5
-5.5
-6
-6.5
-7
-7.5
-8
-7
-6.9
-6.8
-6.7
-6.6
-6.5
-6.4
-6.3
-6.2
-6.1
-6
-5.9

W