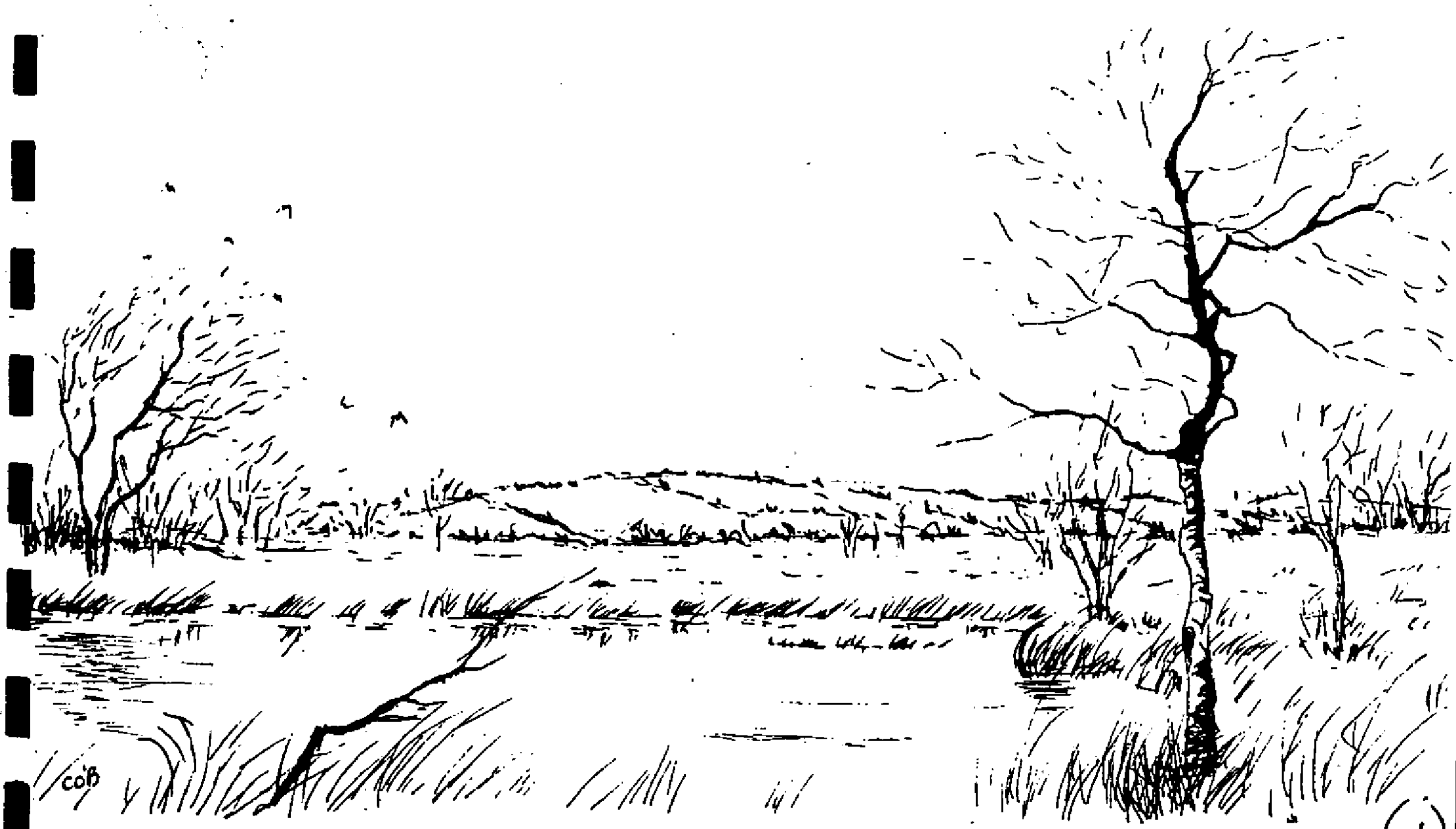
IRISH - DUTCH RAISED BOG STUDY
GEOHYDROLOGY AND ECOLOGY

- National Parks and Wildlife Service of the Office of Public Works, Dublin
- Department of Nature Conservation, Environmental Protection and Wildlife Management, The Hague
- Geological Survey of Ireland, Dublin
- National Forest Service, Driebergen

A HYDROLOGICAL STUDY OF THE LAGG ZONE OF CLARA BOG COUNTY OFFALY, IRELAND

Iain Blackwell
Imperial College, University of London
1992



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

A HYDROLOGICAL STUDY OF THE LAGG ZONE OF CLARA BOG COUNTY OFFALY, IRELAND

Iain Blackwell B.Eng. (Hons)

September 1992

A report submitted in partial fulfilment of the requirement for the degree of Master of Science in the University of London and for the Diploma for Membership of Imperial College.

ABSTRACT

Clara bog has been drained for many years, leading to settlement of the bog along the length of the perimeter drains, and along the road which bisects the bog. This has threatened its future growth, and many of the species which depend on it for their survival. The conservation of the bog is now considered to be important, and it is one of only three raised bogs currently protected by the Irish Wildlife Service. This report describes the field experiments carried out to determine the hydrological significance of one of the major perimeter drains, and makes recommendations for the conservation of the bog.

The source of the water in the drain is investigated by studying the groundwater flow, surface hydrology, and hydrochemistry, in and around the drain. The results of these experiments suggest that to conserve the bog, water levels along the length of the drain need to be raised, to reverse the currently upward hydraulic gradients in the region around the drain. A two-dimensional model of the flow into the drain has been established.

Recommendations are made for future studies, which will help in understanding the significance of the drain in the overall hydrology of the bog.

ACKNOWLEDGEMENTS

I would like to express my thanks to my supervisor, Dr Paul Johnston, for his advice throughout the project. I would also like to thank Manon van der Broogaard for much of the data supplied for the database, and Helen Samuels and Vincent Hussey for help with the levelling on Clara bog. Thanks must also go to Jacob Tomkins and Adrian Butler for help with the modelling aspects of the project.

I wish to thank all the students involved in the project, from University College Dublin, University College Galway, and the Universities of Wageningen and Amsterdam in The Netherlands, without whom, much of the work would neither have been possible, or as enjoyable. Thanks must also go to those involved in the project from The Geological Survey of Ireland and The Irish Wildlife Service.

Finally, I would like to express my deepest thanks to the many people in Clara, especially the Carey family, who made me so welcome, and made my stay there such an enjoyable and memorable one.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 Background to the Project

Ireland ranks third in the world in terms of proportional area of peatland with 17% after Finland and Canada with 34% and 18% respectively (Taylor, 1983). In many European countries, fens and bogs were once commonplace, but drainage for agricultural purposes, and peat cutting for fuel have resulted in their almost total destruction in many countries. In The Netherlands for example, there are no longer any bogs still intact, and Ireland is one of the few countries in western Europe which has any relatively undamaged bogs left (Cross, 1989).

Peat cutting in Ireland, which has been going on for centuries in a small scale manner, has in the last fifty years or so become a much larger commercial activity, led by Bord nà Mona, the Irish Peat Board. Peat cutting on raised bogs has removed about 91% of the original 310,000 ha which once covered much of the Irish Midlands. In addition to this, forests have been planted on about 6,000 ha so that only about 22,000 ha of intact bog remains. At the present rate of decline, it is estimated that by 1997, the only intact raised bogs left in the Midlands, will be those which are currently protected. Figure 1.1 shows the original and present extent of raised bogs in part of the Midlands. Clara Bog may be identified as the 'mostly intact' area about 10 km northwest of Tullamore.

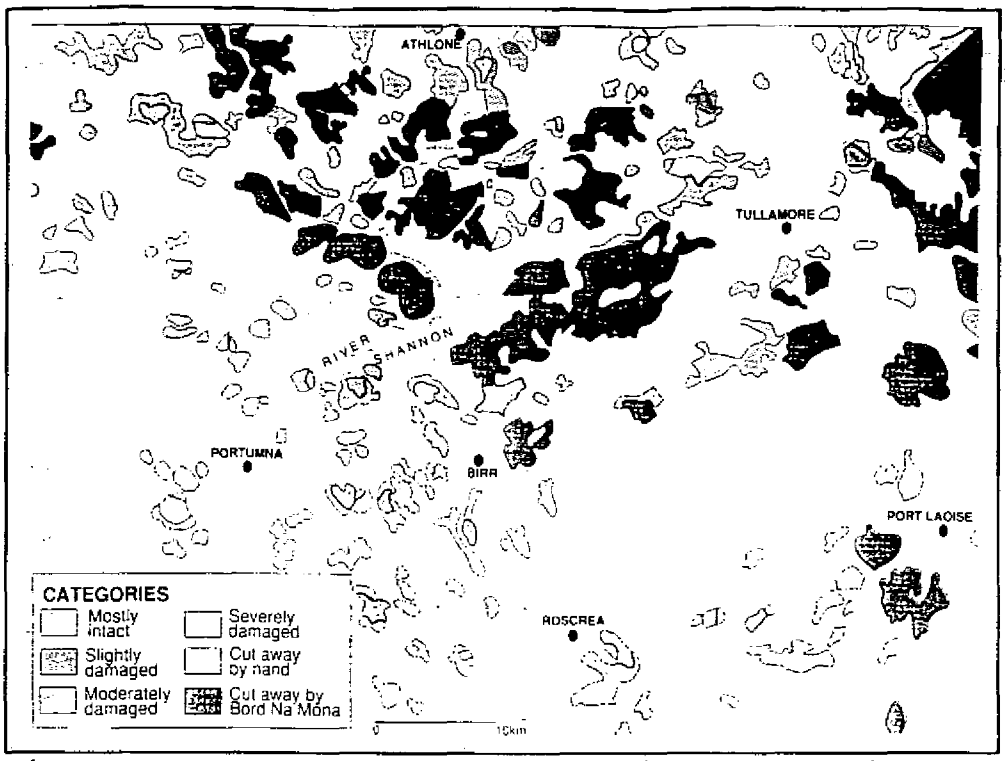


Figure 1.1 Map of part of the midlands showing the original and present extent of raised bogs.

The flora on boglands have to survive acidic, nutrient poor conditions, and have developed in such a way that many species found on bogs are unique to a bog habitat. The threat to the remaining intact bogs was recognised several years ago by the Irish Wildlife Service, who then began a strategic purchase of bog areas in order to conserve this endangered environment. Currently, there are three raised bogs which are protected; Clara Bog, Mongan Bog and Raheenmore Bog, all of which are in County Offaly.

The Irish-Dutch Peatland Geohydrology and Ecology Study was set up in 1989, in order to attain a broader understanding of the interactions between the hydrology, ecology and geology raised bog ecosystems. The aim of the Study is to produce management strategies for the conservation and regeneration of raised bogs in Ireland and The Netherlands. In Ireland, Clara Bog and Raheenmore bog are being studied as part of the project.

1.2 Objectives

The primary objective of this project was to collate and collect existing hydrological and hydrochemical data from the lagg zone of Clara bog, so as to create a model of the hydraulics of the system, and make recommendations for the strategy for conservation and restoration of the bog. The hydrogeology and hydraulics of the lagg zone should be set in the context of the regional hydrological system. This objective may be broken down into three smaller phases as follows:

1.2.1 Data Collection

Much data has already been collected, but as yet, no database has been established. It is proposed that a database be set up, and in areas where there is a significant lack of data, a data collection programme should be implemented. The database should concentrate on three particular aspects concerning the hydrogeology of the area:

1. Water levels in boreholes, wells and piezometers.
2. Hydraulic conductivity measurements.
3. Hydrochemical measurements.

1.2.2 Data Analysis

The data analysis should lead to an overall understanding of the hydrogeology of the lagg zone, within the context of the regional flow pattern. In order to meet this objective, the data analysis should concentrate on four aspects of the hydrogeology:

1. Establishing the pattern of groundwater fluctuation and hydraulic gradients, in particular in the vicinity of the drain.
2. Identifying regions of upwelling mineral water, and correlating with hydrochemical and ecological data.
3. Establishing the nature of the spatial variation of hydraulic conductivity.
4. Constructing a two-dimensional cross-section through the lagg zone, and establishing the hydraulic boundary conditions for use in a two-dimensional model.

1.2.3 Modelling

The aim of the data collection and analysis phases are ultimately for aiding the setting up of a two-dimensional groundwater model of the system. The model is intended to show, firstly, the current hydrological interactions taking place between the bog and the esker, and secondly, to investigate the possible effects of changing the hydraulic boundary conditions. This is intended to aid in the development of a management strategy for conservation of the bog.

1.3 Area of Study

The area of study for the project is primarily in the lagg zone of the northeast margin of Clara Bog. The term 'lagg' is a Swedish word which refers to the area outside the sloping margin at the edge of a raised bog. The lagg zone has fen vegetation, and represents the transition between raised bog peat and mineral soils. Nutrient-rich groundwater influences this region, giving rise to different types of vegetation not found on the rest of the bog. In order to fully understand the hydraulics and hydrochemistry of the lagg zone, the study area is more extensive than just the lagg zone itself, stretching from the esker in the north, to Lough Roe in the south. Figure 1.2 shows a map of Clara Bog, with the study area marked on it.

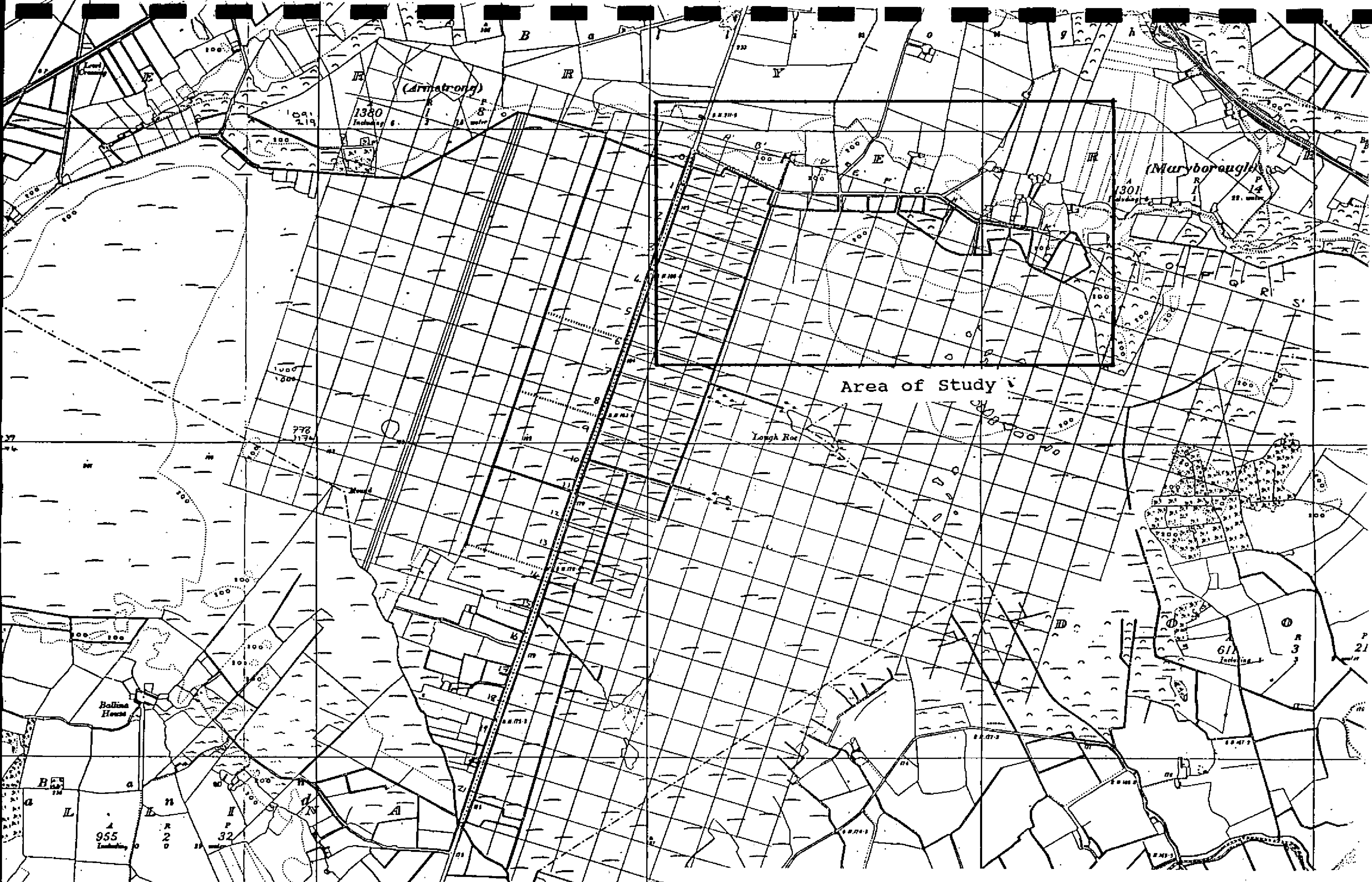


Figure 1.2 Map of Clara bog.

2. HYDROLOGY AND ORIGIN OF RAISED BOGS

2.1 Formation of Raised Bogs

Raised bogs are a typical landform of areas which experience high relative humidity and high precipitation throughout the year. The main stages of development are shown in figure 2.1. Current raised bog formation in Ireland began at the end of the last period of glaciation, about 10,000 ago. As the glaciers retreated to the north, glacial meltwater formed shallow lakes in the depressions between the esker ridges, which impeded free drainage of the meltwater. These lakes were influenced mainly by local flowing, mineral-rich water, which led to the development of reed beds in the lake. As the dead remains of these plants accumulates, terrestrialisation increases, and fen reed peat develops. These species are gradually replaced by a greater diversity of minerotrophic plants, including trees and shrubs. This is the fen stage in the development of the bog. Gradually, the surface of the bog is raised, and is removed from the influence of the mineral-rich groundwater, making it increasingly more difficult for minerotrophic species to maintain their necessary supply of inorganic nutrients. Rainwater then becomes the sole source of moisture and mineral nutrients, and ombrotrophic species such as *Sphagnum* mosses begin to colonise the fen. Minerotrophic species, which are unable to survive in the mineral-poor, acidic environment begin to die, leaving only the ombrotrophic species.

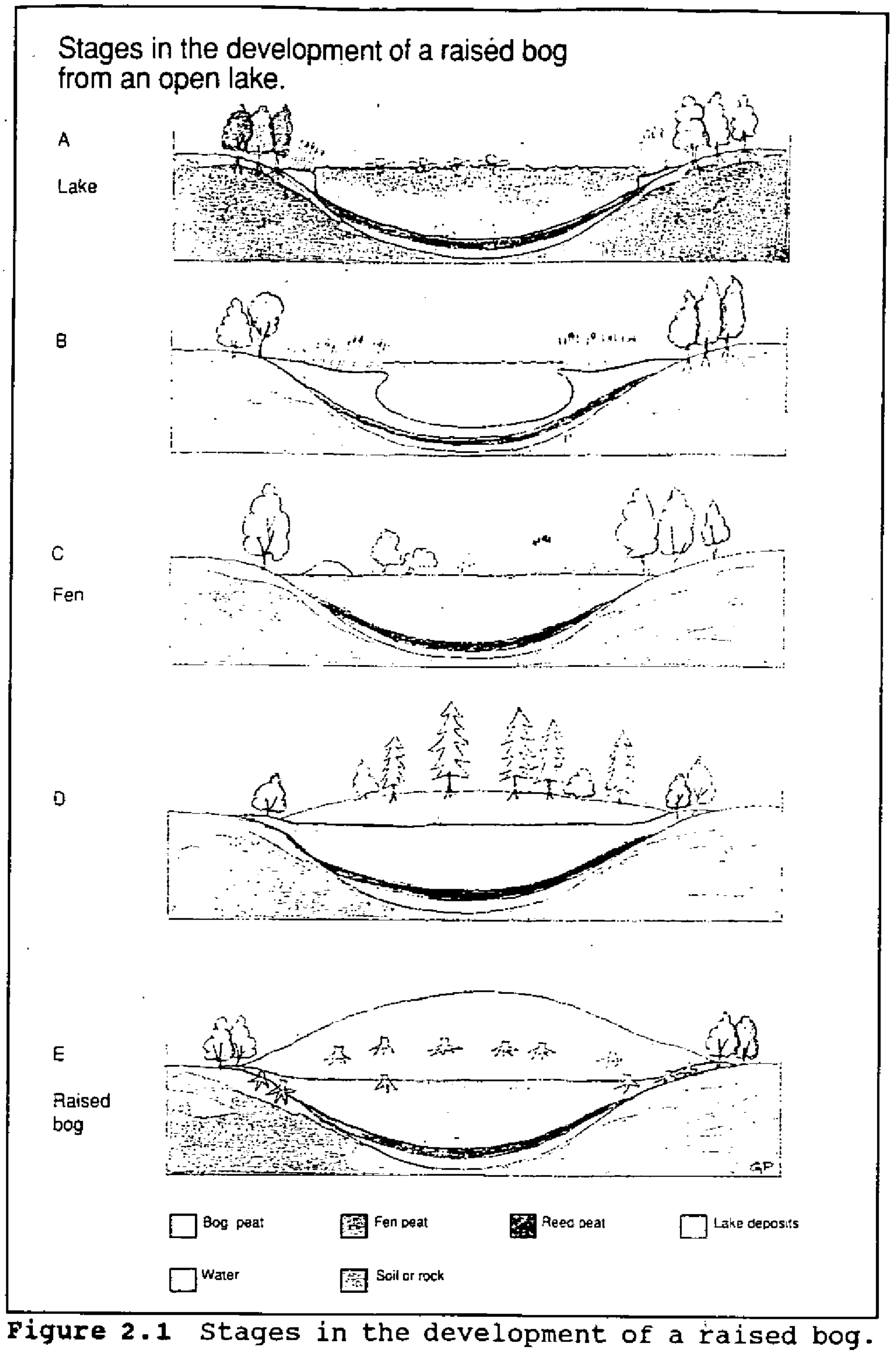


Figure 2.1 Stages in the development of a raised bog.

A represents a lake with open water and marginal reed beds. B shows the lake being infilled with fen reed peat. C is the fen stage. D is the raised bog woodland phase, with minerotrophic species. E is a profile through a present raised bog.

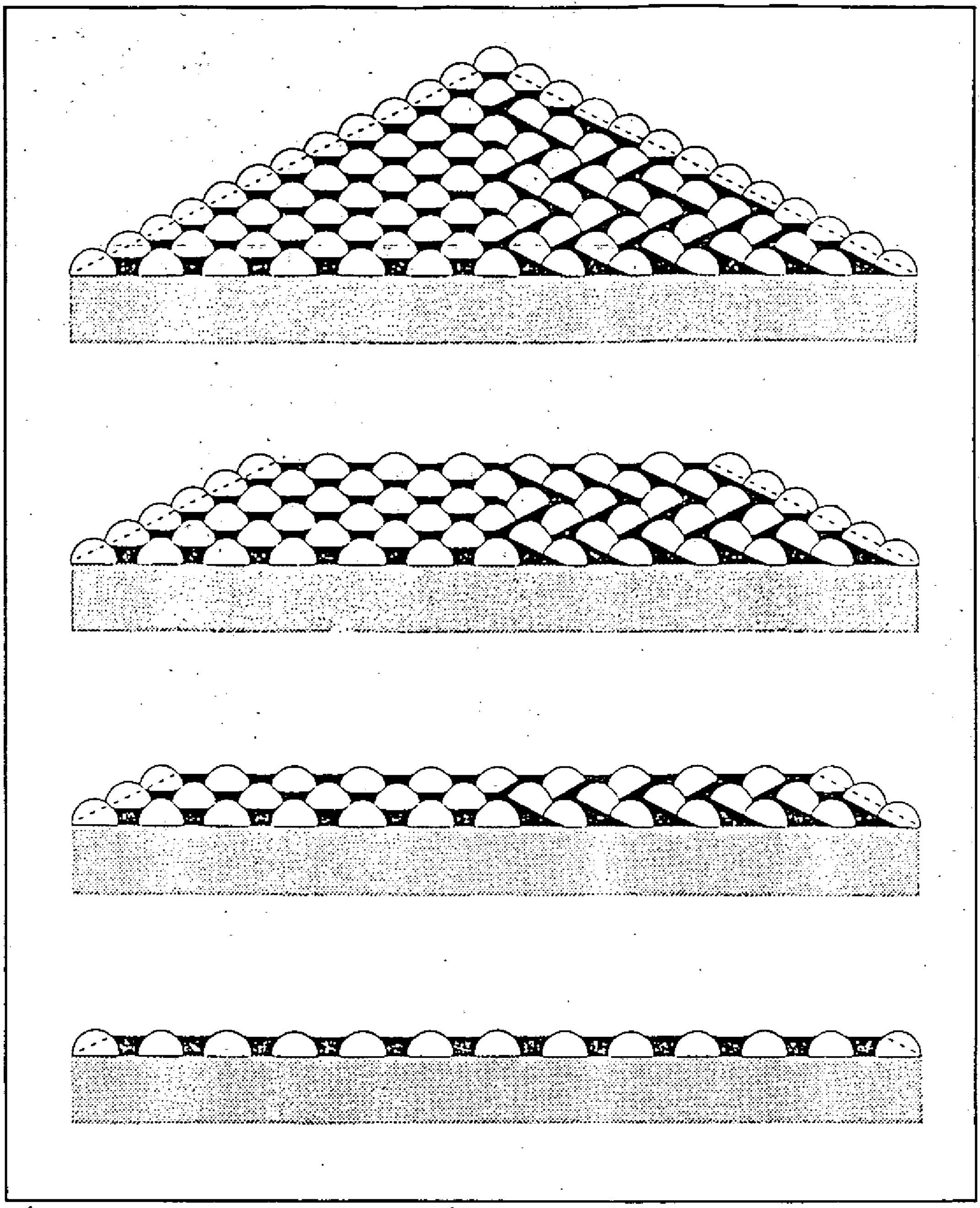


Figure 2.2 Growth of a raised bog (after Bellamy, 1986).

The growth of the bog continues with the development of hummocks and hollows, as shown in figure 2.2. The diagram shows two possible methods by which the peat domes may grow. There is regular regeneration on the left, and sliding growth on the right. The hummock peats are shown in white, and the hollow and pool peats are black. The shaded area represents the fen peat foundation on which the bog grows, and the dotted line is the water table surface. This process has been inferred from the shape of the dome of the bog, which in nature forms an arc not a pyramid, from chemical analyses, and from the presence of extremely ombrotrophic species (Gore, 1983).

The formation of raised bogs is a well documented subject, and for more detailed information, reference should be made to Mitchell (1975), Bellamy (1986), Gore (1983), and Hobbs (1986).

2.2 Hydrology of Raised Bogs

The development of a raised bog is dependent on being fed purely by rainfall, which is low in minerals and nutrients. The amount of precipitation and evapotranspiration are the most important factors in determining the rate of growth of the bog. Higher rainfall, leading to wetter conditions in the bog, leads to a greater availability of water to plants for evapotranspiration. The surplus of precipitation, therefore, determines to a great extent, the rate of growth of the bog (Streefkerk and Casparie, 1989). The water balance for a raised bog may be expressed as:

$$P - E - R - L - V = \Delta S \qquad (2.1)$$

where P is precipitation, E is evapotranspiration, R is the surface runoff, L is lateral seepage, V is downwards vertical seepage, and ΔS is the change in groundwater storage.

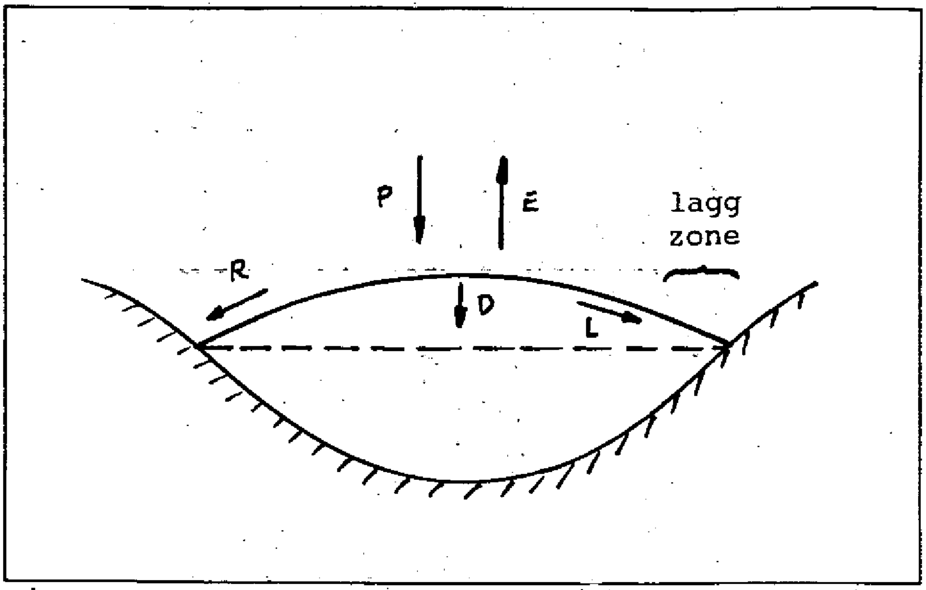


Figure 2.3 Water balance components for a raised bog.

A schematic representation of the water balance for a raised bog with domed relief is shown in figure 2.3. Over a long period of time, the change in storage in the system, ΔS, may be assumed to be zero, and equation 2.1 may be written as:

$$P = E + R + L + V \tag{2.2}$$

If downward seepage, lateral seepage, and surface runoff are a minimum, the water available for evapotranspiration is a maximum, and the rate of growth of the bog will be a maximum. Streefkerk and Casparie (1989) have demonstrated that downward seepage through the layers of humified peat (the catotelm) amounts to approximately 4% of mean annual rainfall, and that lateral seepage is almost entirely confined to the living vegetation layer (the acrotelm). Downward seepage can therefore be assumed to be negligible, and the lateral seepage through the acrotelm can be incorporated into the surface runoff term. With these assumptions, the equation describing the water balance for an intact raised bog may be reduced to:

$$P - E = D \qquad (2.3)$$

where D is the discharge from the bog by surface runoff and lateral seepage through the acrotelm.

2.3 Importance of the Lagg Zone

The hydrological importance of the lagg zone can be seen from figure 2.3. Lateral seepage and surface runoff from the bog ends up in the lagg zone, and it is from here that the water is discharged. The condition of the lagg zone is therefore very important in determining how much, and how quickly, the water drains from the catchment. Natural lagg areas tend to be very wet, with much surface water, due to poor drainage of the area. This affects the rest of the bog, which remains very wet, giving conditions that are ideal for the growth of *Sphagnum* mosses. If the drainage of the lagg zone is disturbed, the water balance may be upset on a long term basis. The result of this may be an increase in discharge from the bog, at the expense of water held in storage. If this is sustained over a long period, the lagg zone will begin to dry out, which in turn will lead to much dryer conditions on the rest of the bog. Such conditions are unfavourable for further development of the bog, and its growth may be seriously affected. Any long term loss of water will result in settlement of the peat, as a result of its extremely high water content.

2.4 Hydrology of the Lagg Zone of Clara Bog

The climate of Clara bog and the surrounding area is typical of most of central Ireland, being temperate and humid all year round. Rainfall measurements taken from tipping bucket rain gauges installed on Clara west indicate an annual rainfall of approximately 850 mm per year. Monthly rainfall data is shown in figure 2.4. Daily values

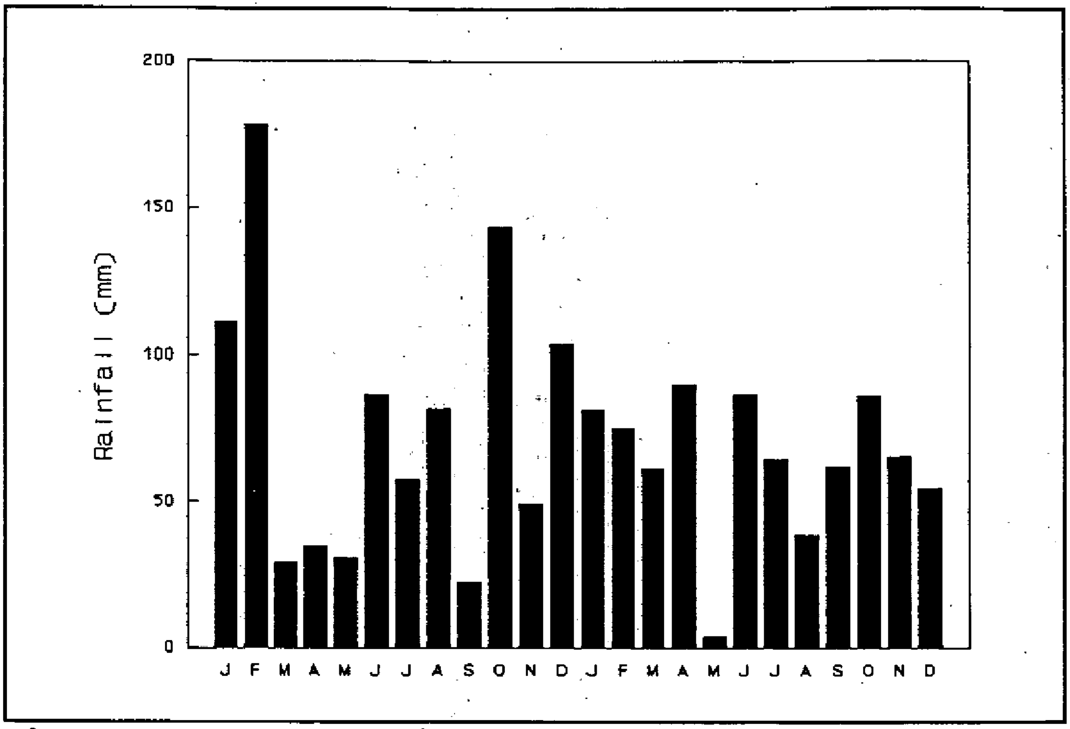


Figure 2.4 Monthly rainfall data for Clara west for 1990 and 1991.

of rainfall show good correlation with data from weather at Mullingar, 15 km north, and Birr, 34 km southwest of Clara. Most of the rain falls in the winter months, although the summer months can also be very wet. Other forms of precipitation are negligible. Assuming the same degree of similarity for other meteorological variables between the two weather stations and Clara bog, potential evapotranspiration is estimated to be 450 mm per year. A slightly higher value may be expected in Clara than at Birr and Mullingar, due to the longer wind fetches on the bog than at the other weather stations. On the assumption that for a raised bog, actual evapotranspiration is approximately equal to potential evapotranspiration (Ingram, 1983), there is, therefore, an annual surplus of precipitation, (P - E) of approximately 400 mm. This must only be considered as a rough estimate. The rainfall record at Clara only extends back to 1989, and as yet, calculations of Penman potential evapotranspiration, from meteorolgical data recorded at the weather station on Clara west, have not been made. Hence, the values quoted should be used with caution. An approximate water balance based on these values, and the work done by Streefkerk and Casparie, is given in Table 2.1. The discharge from the lagg zone on an annual basis is calculated to be 400 mm. However, the assumption on which this is based, i.e. that the bog and

Table 2.1 Approximate Water Balance for Clara Bog, Assuming it to be Intact

	year (mm)	winter (mm)	summer (mm)
Precipitation (P)	850	500	350
Evapotranspiration (E)	450	80	370
(P - E)	400	420	- 20
Discharge (D)	400	340	60
Change in Storage (ΔS)	0	+ 80	- 80

lagg zone are intact, is a questionable one. Extensive peat cutting, and drainage of the area for agricultural purposes has taken place in the past, and is still continuing today. At the end of 1991, the comparatively small drain, which ran along the northeast margin of the bog was enlarged to improve the drainage of the area, primarily to allow for further peat cutting. The newly enlarged drain is approximately 1 m deep, and 1 m wide, cutting right through the catotelm in places, into the underlying clay.

The peat cutting activities have physically removed much of the lagg zone (in its strictest definition), while extensive drainage of the area has led to drying out and compaction of what remains. For the purposes of this project, the area being studied will be referred to as the lagg zone, but it should not be considered to be intact. The value given for discharge in table 2.1 may, therefore, be inaccurate, if for example, actual evapotranspiration is much less than potential evapotranspiration. Also, the lateral drainage through the catotelm, which is assumed to be negligible, may be significant due to the presence of the drain. These two possibilities, and others, may have a significant effect on the various components of the water balance.

A thorough understanding of the hydrology of the lagg zone, and the effect of the drain on the overall water balance, is crucial if the hydrology of the bog as a whole is to be understood. This has important implications in terms of the conservation and restoration of the bog in the long term. The hydrology of the lagg zone is discussed in greater detail in chapters four to seven.

3. GEOLOGY AND HYDROLOGY OF CLARA BOG

3.1 Regional Geology

The geology of North County Offaly is dominated by Pleistocene and recent deposits, the former having a glacial origin (Flynn, 1990). The region is traversed by a series of eskers running from east to west, with subsequent Holocene deposits lying in between the eskers. These deposits are mainly sands, gravels, and clays of alluvial or lacustrine origin, and peat of organic origin. Clara bog itself is located in between two of these esker ridges. The bedrock in the area is Carboniferous limestone.

3.2 Geology of Clara Bog

Much drilling has taken place in and around Clara bog, and in addition to this much geophysical work has been done in order to get information on the geology beneath the bog. A full account of the borehole drilling and geophysical work is covered in reports by Smyth (1991, 1992) and Flynn (1990). The results of this work have shown the general geological succession to be peat (Holocene), lacustrine clay (Holocene), glacial till (Pleistocene), and blue-grey limestone (Carboniferous). The layers of till and clay tend to follow the topography of the limestone surface, but with a smoothing effect. Geophysical data has been used to produce surface contour maps of the limestone, till, and subpeat surfaces (Smyth, 1992).

3.3 Geology of the Study Area

The geology of the study area is fundamentally the same as the that of the rest of the bog, in terms of geological succession. However, there are important geological changes at the edge of the bog which affects the hydrogeology of the region. Figure 3.1 shows a cross-section from the esker to the centre of the bog, in a north-south direction. This shows the important geological features of the area, most notably the transition from the esker to the bog. It can clearly be seen how the peat has formed directly on top of the lacustrine clay, which thins out just beyond the northern edge of the bog. The lagg zone may be identified as this transitional area between the esker and the bog. The section has been compiled from geological and geophysical data by Flynn (1990), and shows only the major geological layers. The actual transition from lacustrine clay to glacial till is a gradual one, with much boulder clay and mixed material between the two layers. The log for borehole 2, CLBH2, gives a much better indication of the precise geological succession in the lagg zone, and is shown in figure 3.2(a). The log for borehole 3, CLBH3, which is located higher up on the esker, is given in figure 3.2(b).

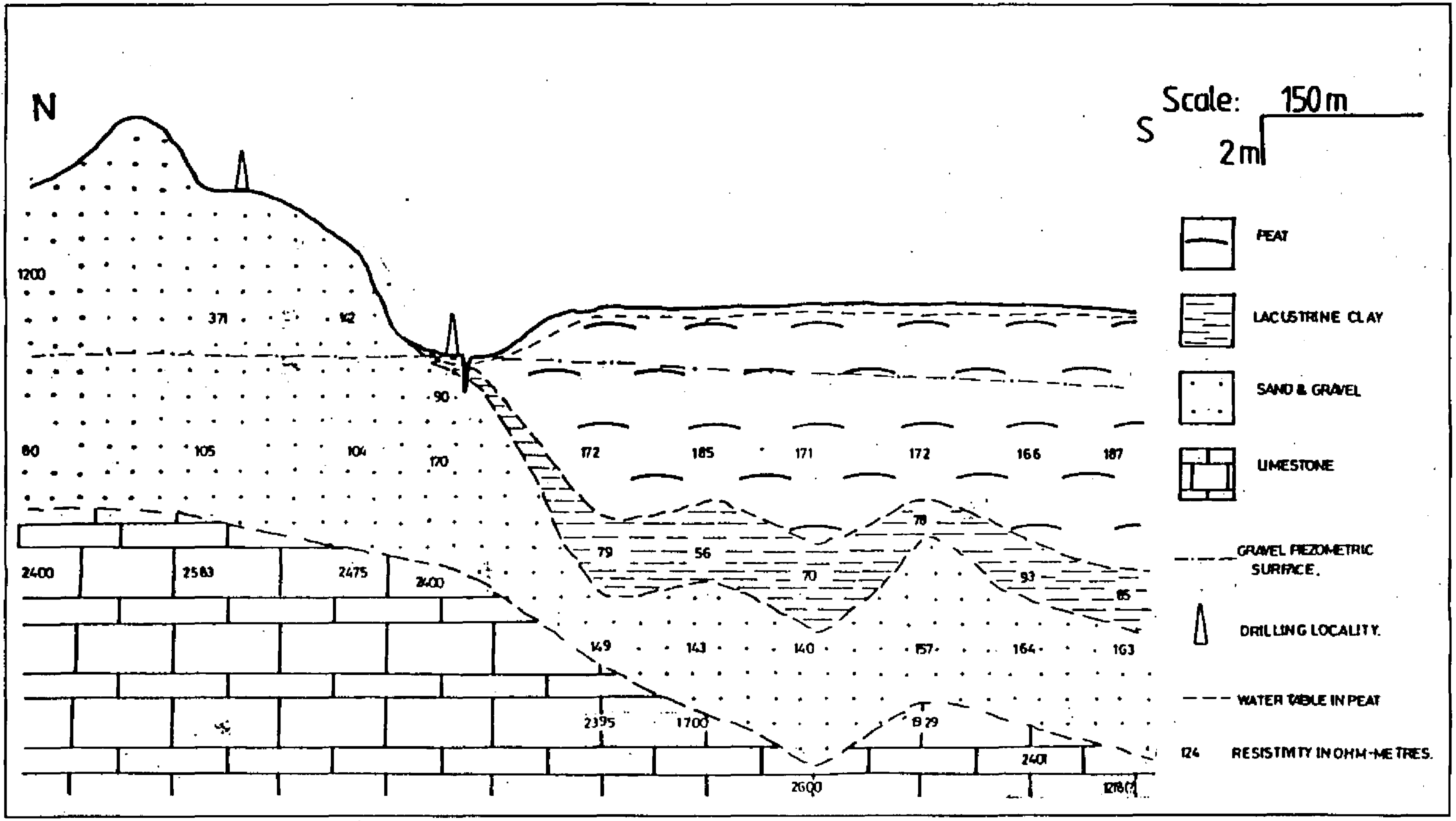


Figure 3.1 Cross-section of Clara bog and adjacent esker.

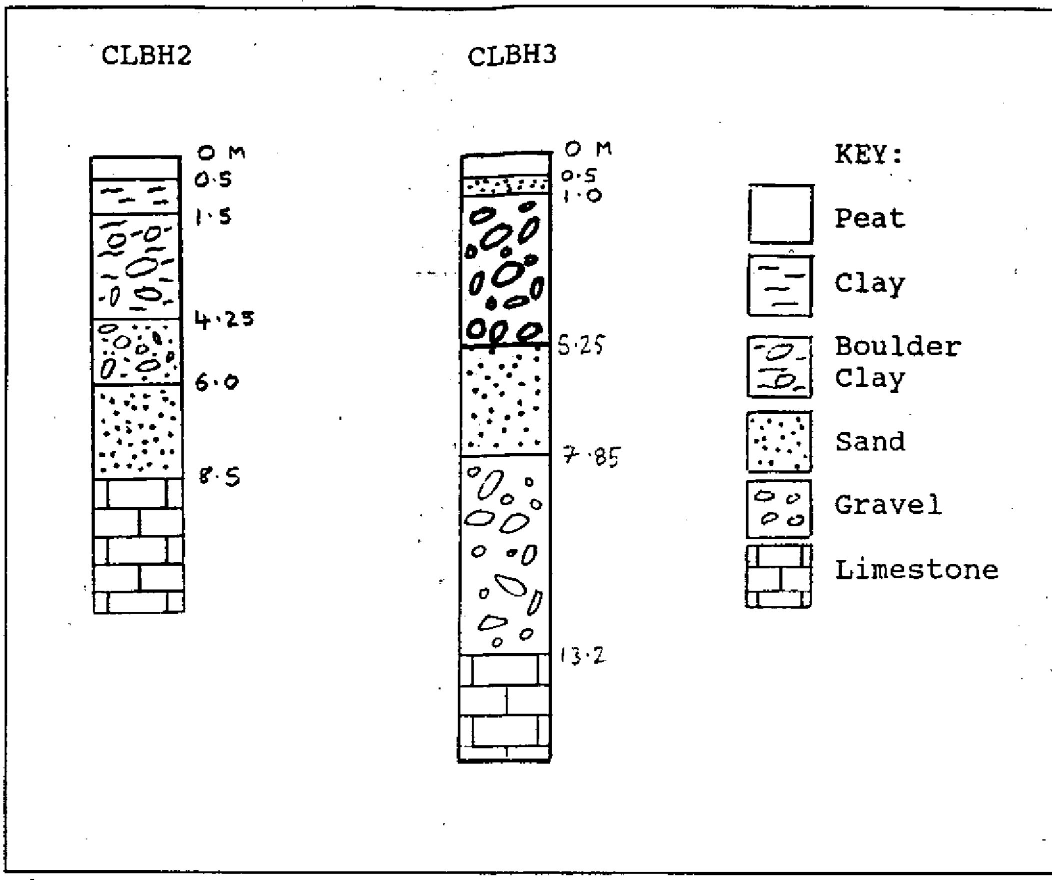


Figure 3.2 Borehole logs for (a) CLBH2 and (b) CLBH3.

4. GROUNDWATER HYDROLOGY

To understand the hydrogeology of the system, the interactions between the glacial till, the clay and the peat need to be known. The two most important parameters governing the flow pattern within the system are hydraulic conductivity and total head. Measurements of these variables should lead to an understanding of the hydrogeology, and enable the system to be represented by a two-dimensional model.

4.1 Two-Dimensional Flowline

In order to model the system in two dimensions, a flow line from the bog, across the lagg zone to the esker needs to be identified, along which measurements of permeability and head may be made. In the bog itself, the water table is generally very close to the ground surface, so it is reasonable to assume that the phreatic surface is similar to the topographic surface. Thus, a flow line may be identified from a surface contour map. On this basis, the flow line can be drawn, and is shown in figure 4.1. On the esker side of the drain, the groundwater flow is assumed to be in a line from CLBH3 to CLBH2. The flow line, from the centre of the bog to the esker passes through a total of 12 piezometer nests, and two boreholes.

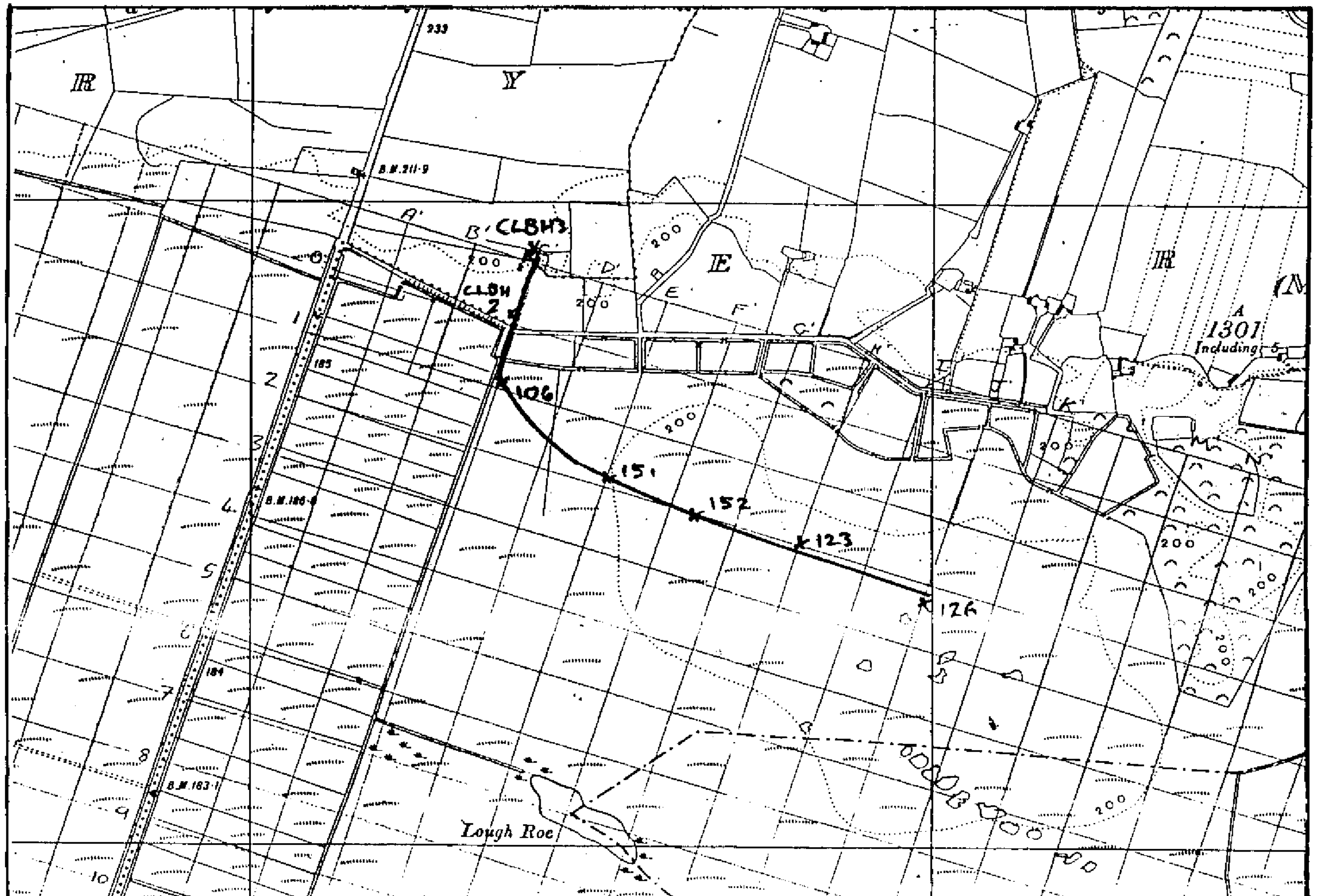


Figure 4.1 Two-dimensional flowline across the lagg zone and esker.

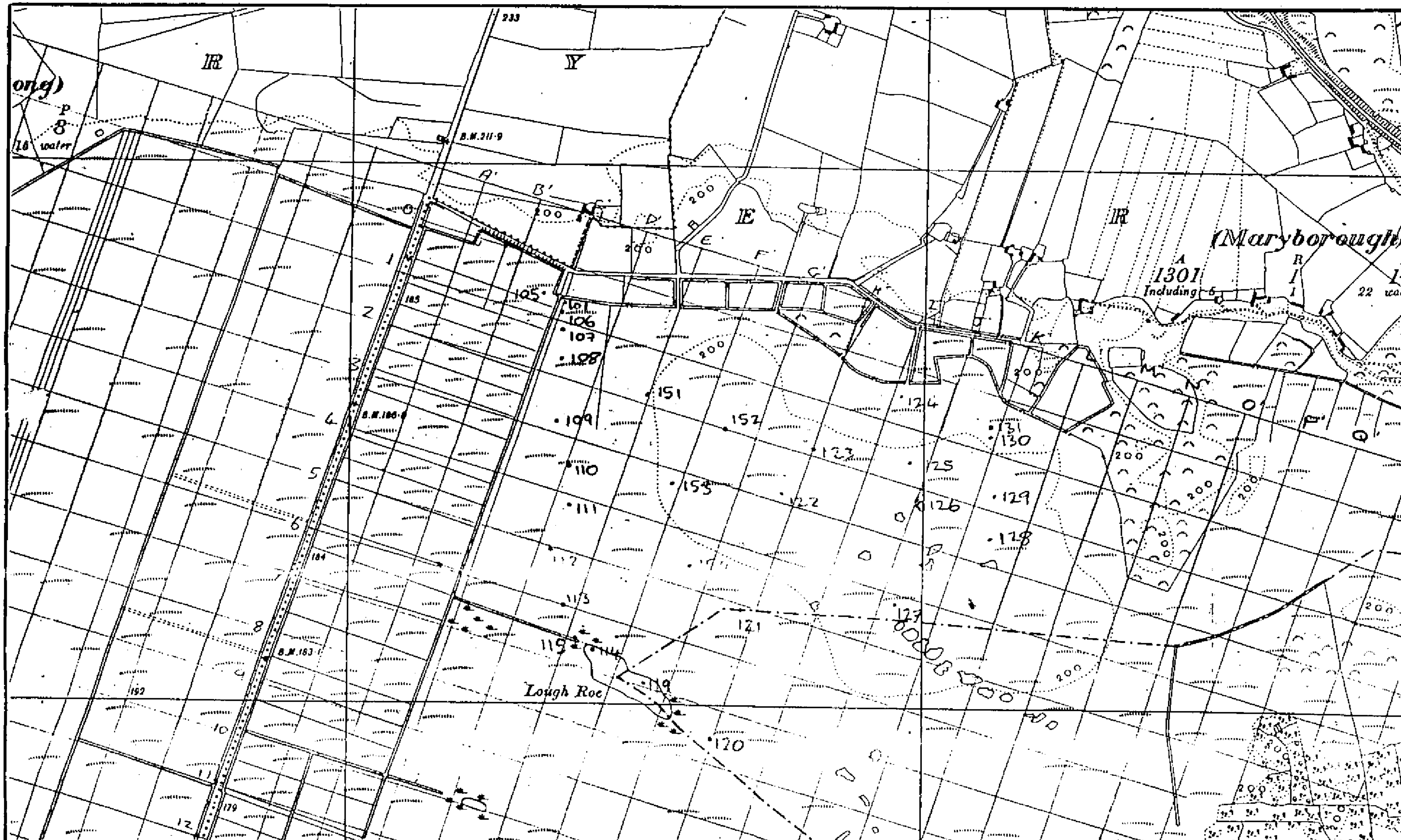


Figure 4.2 Map showing the location of piezometer nests on Clara east.

4.2 Head Measurement

An extensive network of piezometers has been installed on Clara east since the start of the Peatland Study. A map showing the locations of all these piezometers is given in figure 4.2. Each piezometer site has between three and five tubes, depending on the total peat thickness. These are positioned at different depths at approximately 1.5 to 2.0 metre intervals. In addition to these, there is also a phreatic tube at each site, from which the water table elevation may be found.

Despite the large number of piezometers installed on the bog, there were very few in the lagg zone, close to the drain. The nature of groundwater flow in the lagg zone is different from that in the rest of the bog, due to the presence of the drain, so several new sets of piezometers were installed in order to gain information on the nature of flow in the area, and the influence of the drain. A series of six new piezometer nests were installed in the lagg zone, and are shown in figure 4.3. Sites 101, 102 and 103 previously had two piezometers at each location, but some of these were blocked and needed to be replaced. The new nests, 101 to 103, and 141 to 143, each had a total of four piezometers, one of which was a phreatic. Where possible, the deepest piezometer was positioned in the clay by making a hole for it with a Hiller borer. In many instances, especially very close to the drain, the peat is much drier than the rest of the bog, and consequently it is

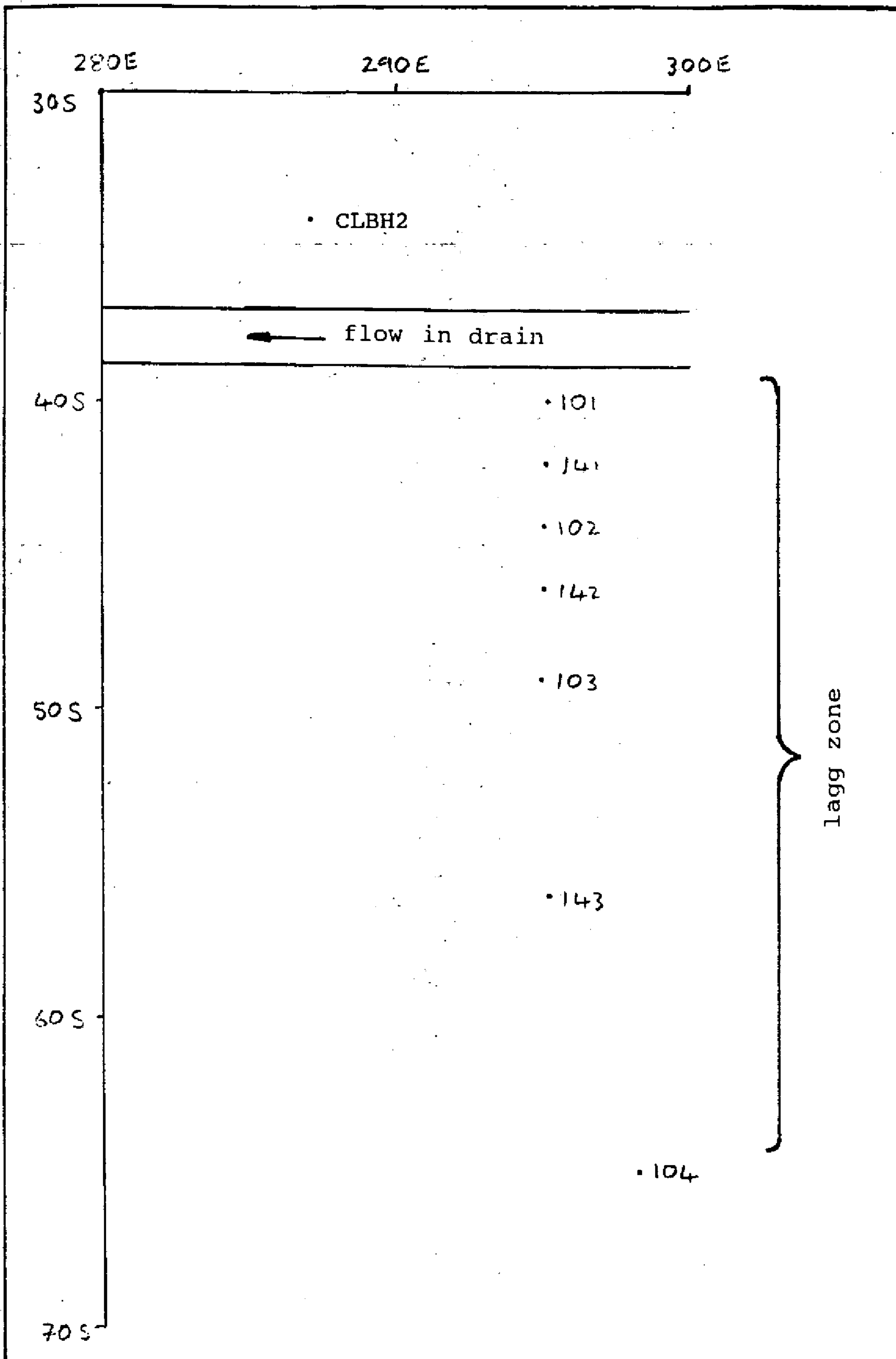


Figure 4.3 Map of the lagg zone showing the location of the new piezometer nests.

much more compact. This makes it more difficult to push the piezometers into place, and so the borer again had to be used.

Along the flow line from the centre of the bog, two new piezometer nests, 151 and 152, were installed in order to fill in the gap between nests 123 and 106. In addition to these, two other nests, 153 and 154, were installed to give better coverage of the bog, although they are not part of the flow line to be modelled. Each of the four new locations, 151 to 154, had a set of five piezometers, one of which was a phreatic. These are shown in figure 4.2.

For details of all the piezometers on Clara east in the area of study, reference should be made to the Clara east database.

4.3 Groundwater Flow in the Peat

From measurements of water levels in the piezometers, the total head may be calculated, from which the flow pattern may be drawn. The data used to construct the equipotential lines is given in appendix A, and is plotted in figures 4.4 and 4.5.

Figure 4.4 shows the regional flow along the cross-section, from the centre of the bog to the esker. Piezometer nest 126 is located at the groundwater divide on the bog, and hence, all equipotential lines cross this boundary at right angles. Away from the centre of the bog, the flow tends towards being horizontal, as demonstrated by the almost vertical equipotential lines. However, the difference between the vertical and horizontal scales should be noted, which gives the impression that the flow is closer to being horizontal than it actually is. A lack of head data in the sands and gravels on the esker side of the drain, and beneath the clay leads to difficulty in constructing the equipotentials.

Figure 4.5 shows equipotentials in the region around the drain. Head measurements in this region indicate upward flowing water from the esker sands and gravels, through the clay, and into the peat. The drain can be seen to influence the groundwater flow up to piezometer nest 143, approximately 18 m from the drain. The flow pattern is complicated by the heterogeneous nature of the peat, and the difference in permeabilities between the peat, clay, and esker materials. For this reason, flow lines are not drawn, as they will not be orthogonal to the equipotentials.

The two flow figures clearly show the influence of the drain on the groundwater flow to be significant. However, it should be noted that the piezometers in the lagg zone were installed only a few weeks before the water level data was collected. In view of the very low permeability of the peat and clay, it is possible that the equilibrium levels had not been established, and that this observed flow pattern may change when equilibrium is reached. In view of this, and the difficulties mentioned above, the figures should be considered more as a qualitative, rather than a exact quantative assessment of the flow.

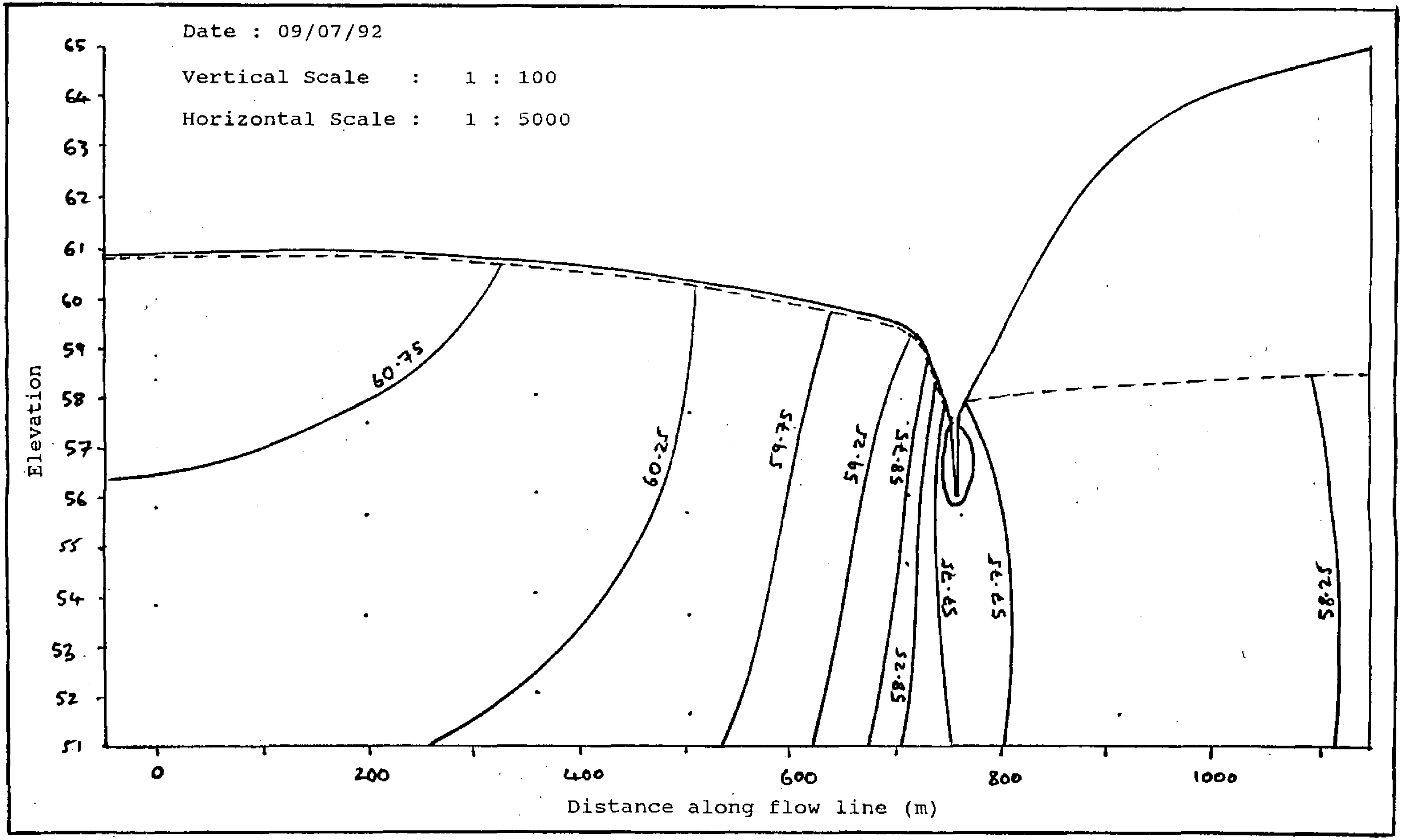


Figure 4.4 Equipotentials for the two-dimensional section across the lagg zone and esker.

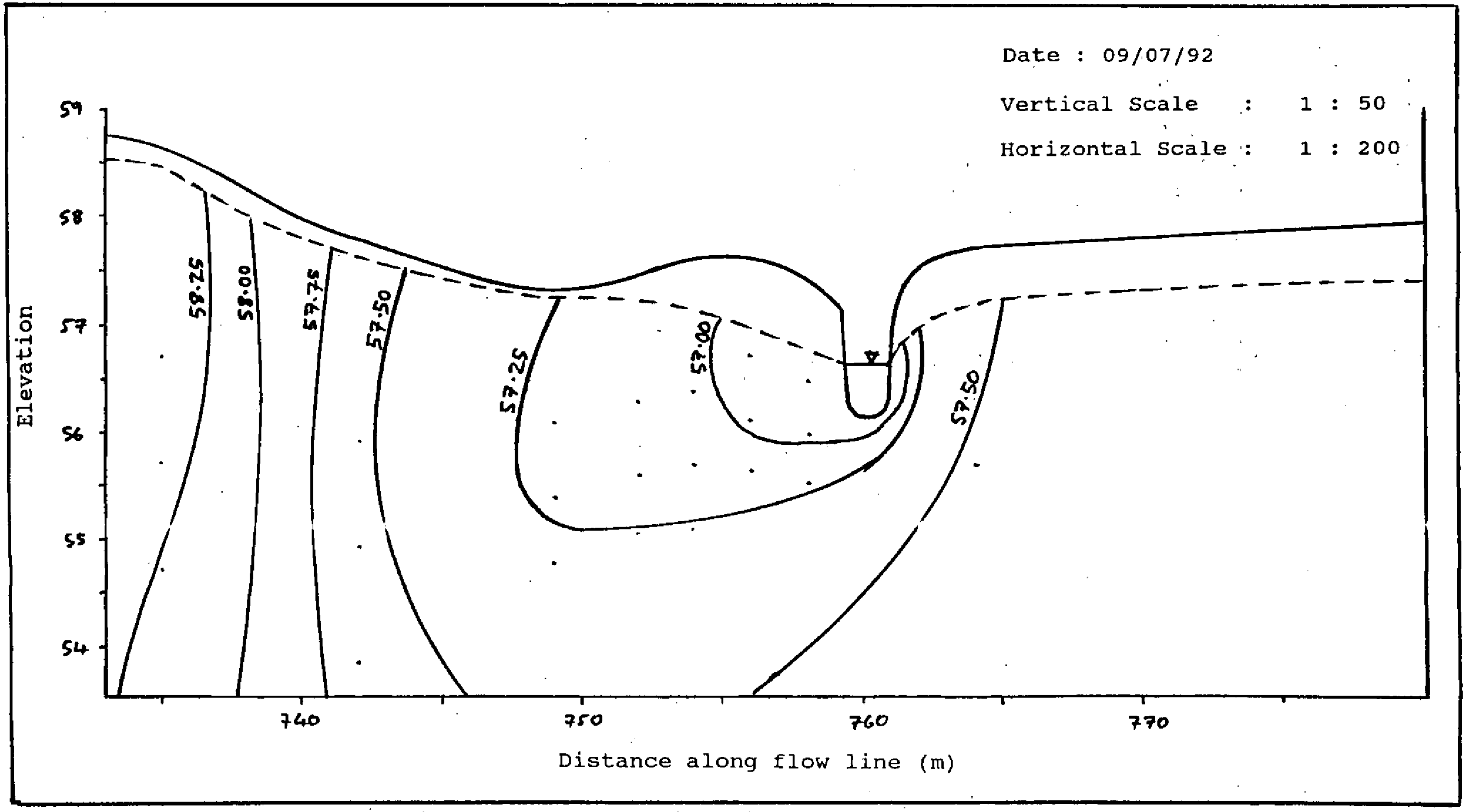


Figure 4.5 Equipotentials for the two-dimensional section in the region close to the drain.

4.4 Hydraulic Conductivity of Peat

Peat is well known to be highly heterogenous, and Ingram (1983) quotes values for hydraulic conductivity in the range 10^{-5} to 10^{2} m/day. This heterogeneity is attributable to the many factors which affect hydraulic conductivity. Ingram (1983) stated that the permeability of peat depends on seven factors:

1. Botanical composition - *Sphagnum* least permeable; sedges most permeable.
2. Degree of humification - the least humified peats are the most permeable.
3. Bulk Density - permeability varies inversely with bulk density.
4. Fibre content - hydraulic conductivity is positively correlated with fibre content.
5. Porosity - higher porosity leads to higher permeability.
6. Drainable porosity - the most readily drainable pores present the least resistance to water movement, and hence are more permeable.
7. Surface loading - increasing surface loading results in an increase in bulk density, and hence a reduction in permeability.

The peat in a raised bog may very broadly be split into two regions. The acrotelm, which is the active surface layer, composed primarily of growing *Sphagnum* mosses, about 50 cm deep, and the catotelm, which comprises the rest of the peat layers, with varying degrees of humification, and different botanical composition. Thus, the catotelm is the broad term describing the reed peat, fen peat and bog peat layers mentioned in section 2.2. These three layers, because of their differences in composition can show a significant variation in hydraulic conductivity.

4.5 Permeability Tests

Darcy's Law states that the flow rate of water through a porous media is proportional to the head loss, h, and inversely proportional to the length of the flow path, l. Thus:

$$v \propto \frac{\Delta h}{\Delta l} \qquad \text{or} \qquad v \propto \frac{dh}{dl} \tag{4.1}$$

Introducing a constant of proportionality K, the hydraulic conductivity gives:

$$v = -K\frac{dh}{dl} \tag{4.2}$$

However, the hydraulic conductivity of humified peat has been shown by several people, notably Waine et al (1985), and Ingram et al (1974), to be a function of the applied hydraulic gradient. This leads to many experimental difficulties in finding field values for K, as the methods normally employed assume that the flow is Darcian. By definition, if the flow rate is a function of the hydraulic gradient, then the flow is non-Darcian, and the hydraulic conductivity term in equation 4.2 is then a function of the hydraulic gradient, such that:

$$v = -K(i)\, i \tag{4.3}$$

where i is the hydraulic gradient, dh/dl.

Three commonly used methods to measure hydraulic conductivity in the field are constant head, falling head and rising head tests.

4.5.1 Constant Head Test

By maintaining a constant water level in the piezometer by means of a constant head device such as a Mariotte vessel, Kirkham (1945) stated that the hydraulic conductivity K is given by:

$$K = \frac{q}{Sh} \qquad (4.4)$$

where q is the discharge from the Mariotte vessel, S is an empirical shape factor, and h is the constant level displacement in the piezometer, i.e. the applied head. Ingram et al (1974) carried out such tests in a raised bog in Scotland, applying different, but constant heads to a number of piezometers. Typical results for experiments carried out on the same day are shown in figure 4.6(a).

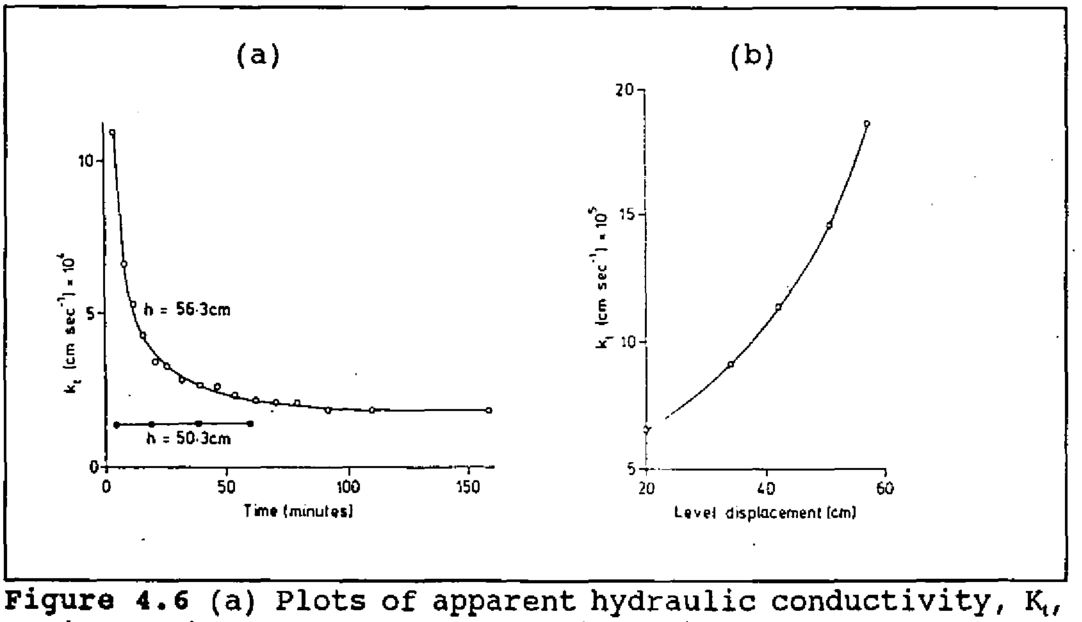


Figure 4.6 (a) Plots of apparent hydraulic conductivity, K_t, against time for two tests with different water level displacement, h. (b) Variation of K_t with displacement h, after allowing for time-dependent effects.

This result suggests that when an artificial gradient is first imposed within the peat, some time elapses before the conductivity becomes constant. After allowing for a period of adjustment, a series of values of conductivity were obtained which showed an increase as the imposed head increased, as shown in figure 4.6(b). These results show that hydraulic conductivity varies with the potential gradient under which it is measured. This variation clearly contradicts Darcy's law, and has important implications in terms of determining a single value of hydraulic conductivity for modelling purposes.

4.5.2 Rising and Falling Head Tests

Kirkham (1945) derived an analytical solution to the Laplace equation, which gives the relationship between the movement of the water level in a piezometer, and the hydraulic conductivity, K, of a Darcian medium:

$$K = \frac{A \ln \frac{y_0}{y}}{S(t - t_0)} \qquad (4.5)$$

where A is the internal cross-sectional area of the tube, S is a shape factor, and y_0 and y are the displacements of the water level from equilibrium at times t_0 and t respectively. Figure 4.7 shows a schematic representation of the test. If the bottom of the tube is sealed, then the flow into (or out of) the tube is approximately horizontal, and hence it is the horizontal hydraulic conductivity that is measured.

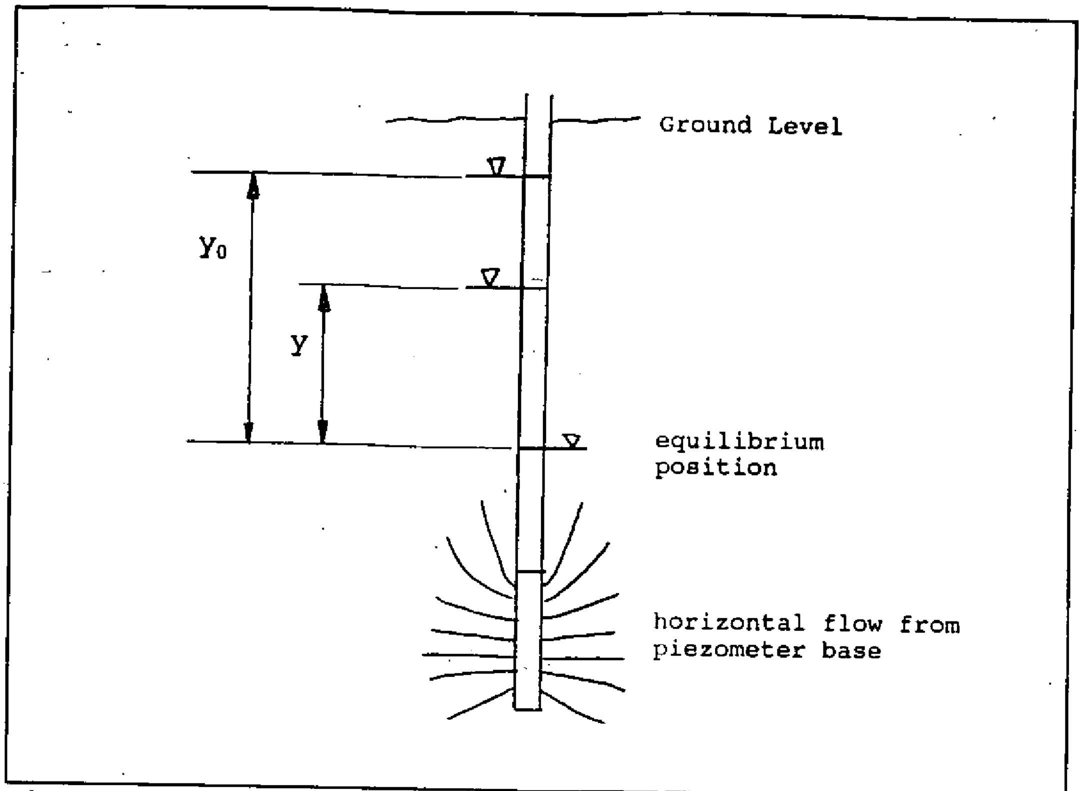


Figure 4.7 Schematic set up of the falling head test.

According to Hvorslev (1951), the shape factor, S, for this arrangement is given by:

$$S = \frac{2\pi l}{\ln\left(l/d + (1 + (l/d)^2)^{\frac{1}{2}}\right)} \qquad (4.6)$$

Rearranging equation 4.5 gives:

$$\ln\left(\frac{y_0}{y}\right) = \frac{KS}{A}\,(t - t_0) \qquad (4.7)$$

which has the equation of a straight line. If $\ln(y_0/y)$ is plotted against $(t - t_0)$, a straight line should be obtained with gradient KS/A. Hence the (constant) hydraulic conductivity may be found. For peat, as has already been discussed, K is a function of the imposed head, and consequently, as the water level in the tube changes, so does the hydraulic conductivity. For a falling head test carried out in peat, a plot of $\ln(y_0/y)$ against $(t - t_0)$ produces an asymptotic curve, as shown in figure 4.8. Initially the gradient of the curve is steep, as the large head disturbs the structure of the peat, leading to a higher value of hydraulic conductivity. As the water level in the tube falls, the head is reduced, and the permeability decreases. At the end of the test when storage effects may be ignored, i.e when the peat structure is no longer adjusting to the increased head, the gradient is constant, and a value for hydraulic conductivity may be found.

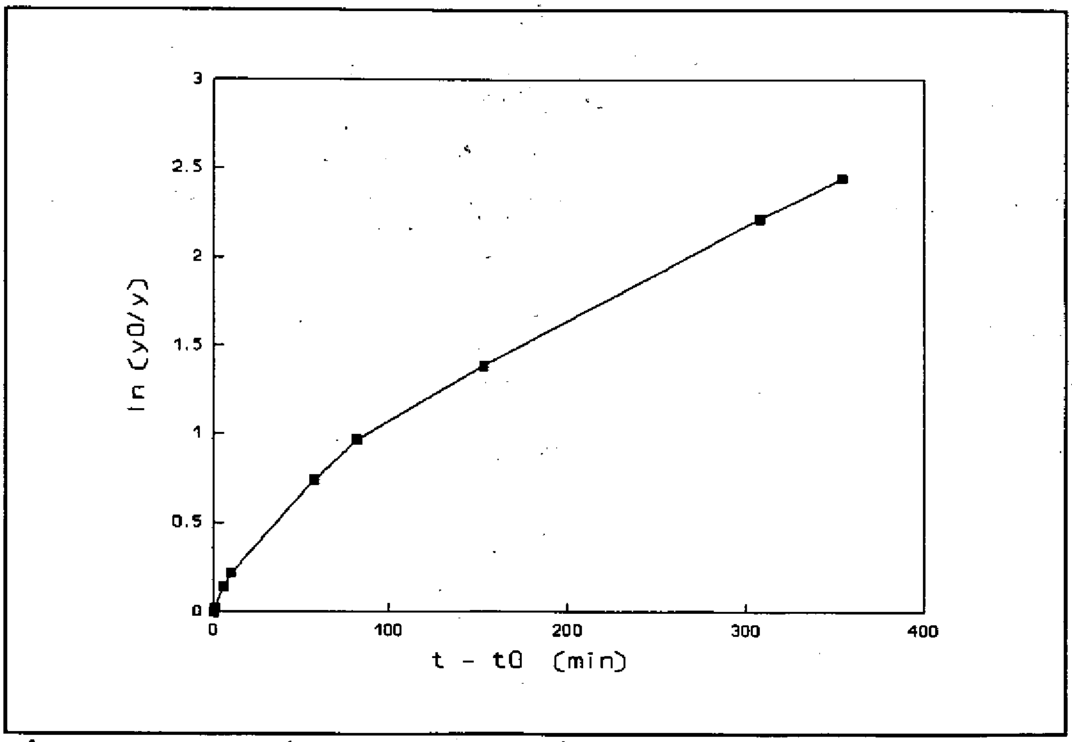


Figure 4.8 Typical graph obtained for a falling head test in peat.

4.5.3 Field Permeability Tests

Much practical and statistical work has been carried out by Sijtsma (1992) on a series of piezometers, located at a relatively homogeneous site on Raheenmore bog, using each of the three methods discussed. The main conclusions of the study, as far as suitability of method is concerned, were as follows:

1. The rising head test tended to give excessively high values for hydraulic conductivity at the start of the test, due to the imposed head being higher than the prevailing head in the peat.
2. In the constant head test, the imposed heads using Mariotte vessels were high (of the order of 50 cm), thus disturbing the soil matrix, leading to artificially high values for K being obtained.
3. In the falling head method, there is a small head imposed at the end of the test, when the water level displacement from the equilibrium position is very small. Storage effects are no longer evident, as the peat matrix has adjusted as a result of the increased head, and is no longer changing. A straight line should then be obtained when $\ln(y_0/y)$ is plotted against $(t - t_0)$ from which K may be found.
4. The statistical analysis showed a much greater spread of values of hydraulic conductivity for the rising head and constant head tests than for the falling head test. In the rising head tests, this may be due to

vacuums present in the peat, as pores are emptied when water moves from the peat into the piezometer. In the constant head tests, it is difficult to maintain a constant discharge from the Mariotte vessel, which will lead to greater uncertainty in the values obtained.

5. In practical terms, the falling head test is easier to set up and monitor than either of the other methods.

For the above reasons, the falling head test was chosen as the recommended method for determining hydraulic conductivity. Nevertheless, it is felt that this method is unsatisfactory for a number of reasons:

1. The fundamental flaw in the theory remains. That is, K is a function of imposed head, which changes with respect to time.
2. Statistical precision is not necessarily a good indicator of accuracy. Although the site was *relatively* homogeneous - in peat terms - it is still likely that significant heterogeneities exist within the plot, due to the factors listed in section 4.4.
3. Storage effects are often only eliminated very near the end of the test, if at all. Consequently a straight line is obtained for only a very small portion of the test. This leads to difficulties in drawing the asymptote accurately, or even determining whether or not it has been reached.

4. At very small displacements from the equilibrium position, large errors for $\ln(y_0/y)$ can easily be incurred, as the accuracy of measuring water levels is approximately 1 mm. For example:

Displacement at t_0 : $y_0 = 80$ mm

1.	At time t :	y = 7 mm	$\ln(y_0/y) = 2.44$
2.	At time t :	y = 8 mm	$\ln(y_0/y) = 2.30$
3.	At time t :	y = 9 mm	$\ln(y_0/y) = 2.18$

Hence, an error of 1 mm in the measured displacement at the end of the test can have a significant effect on the gradient of the end portion of the line, and hence the permeability. This error may be reduced if the initial displacement, y_0, is increased, but the duration of the test then increases which is a disadvantage.

Despite these disadvantages, the method has been used successfully in many instances, although for some of the tests, identifying a straight line portion of the graph is not possible, and an estimate of the gradient of the asymptote has to be made. Examples of a good and bad test result are shown in figures 4.9 and 4.10. In figure 4.9, the last four points form a straight line, giving the gradient of the asymptote. From this, a value for hydraulic conductivity can easily be found, given that the

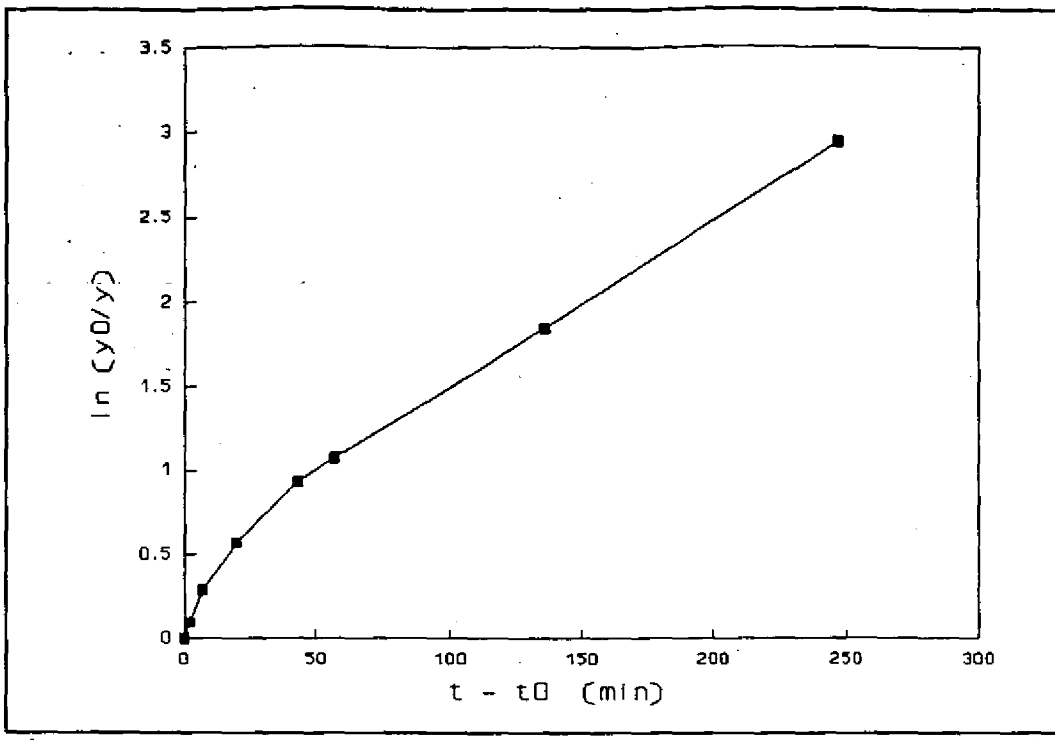


Figure 4.9 Example of a good falling head test result, in which the gradient of the asymptote is easily estimated; piezometer 152.3.

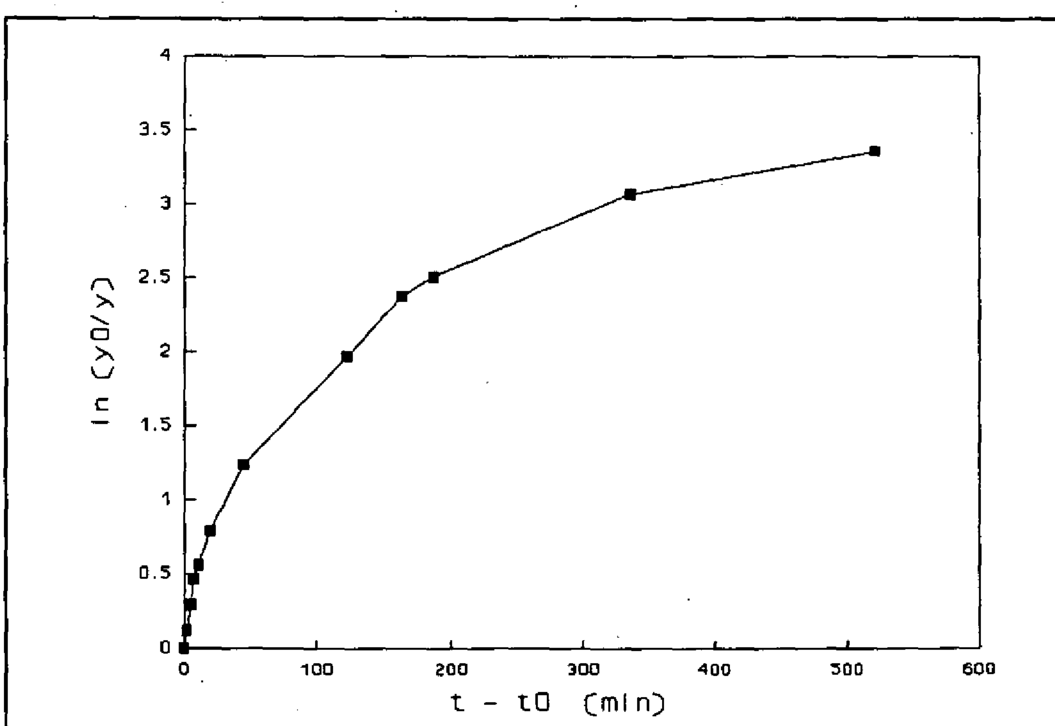


Figure 4.10 Example of a poor falling head test result, in which storage effects are still prevalent and K is still varying; piezometer 106.2.

internal cross-sectional area of the tube and the shape factor are known. In figure 4.10, K is still varying with time, and the gradient of the asymptote cannot be established from the graph. In such cases, an estimate of the asymptotic gradient must be made, from which the hydraulic conductivity is calculated. There is much room for error in doing this, in view of the problems already discussed.

Due to the time restrictions, permeability tests were only carried out in selected piezometers along the flow line described in section 4.2. The permeability values obtained from the tests are given in table 4.1. A full set of data and graphs for all the tests is given in appendix B.

Table 4.1 Permeability Values for Piezometers Along the Flow Line, from Falling Head Tests

Piezometer Nest	Piezometer Number 1	2	3	4
	Hydraulic Conductivity (m/day)			
CLBH2	-	-	0.0181	-
101	0.0002	0.0002	0.0055	-
141	0.0244	0.0043	0.0067	-
102	0.0004	0.0035	0.0116	-
142	0.0042	-	0.0039	-
103	-	0.0235	0.0547	-
143	0.0009	0.0322	0.0025	-
104	0.0764	0.0009	0.0013	-
106	0.0059	0.0034	0.0069	-
151	0.0007	-	0.0319	-
152	-	-	0.0115	0.0063
123	0.0007	0.0226	-	-
126	0.0341	-	0.0376	0.0452

4.5.4 Previous Permeability Tests

Permeability tests have been carried out by Flynn (1990), using the rising head and constant head methods. In total, 22 rising head tests, and 19 constant head tests have been carried out at piezometer nests 104 to 113.

The rising head tests lasted for 30 minutes, with an initial displacement from equilibrium, Y_0, of around 25 cm. At the end of the test, the displacement from equilibrium was in many cases, about half the initial displacement. At this point, storage effects are still prevalent, and the apparently straight line that is observed on the plots of $\ln(Y_0/Y)$ against $(t - t_0)$ is deceptive. If more readings were taken over the next few hours, the graph would deviate substantially from the assumed straight line, giving much lower values of permeability, in a similar manner to that seen in the falling head test in figure 4.10. In tests in which the final displacement is small, and hence Y_0/Y is large, the characteristic asymptotic curve is observed. In these tests, permeability values have been obtained by fitting a straight line to the data at the start of the test, passing through the origin. This gives much higher values of permeability than may actually exist. As has already been discussed, the straight line should be fitted to the last few data points, when storage effects are negligible, and the imposed head is small. Thus, for all the rising head tests, the permeability values obtained are probably artificially large.

In the constant head tests, Mariotte vessels were used as constant head devices, but the applied head was relatively large, in the range 23 to 66 cm. Such values of head disturb the peat matrix from its natural state, giving excessively high values of permeability as described earlier. Plots of permeability as a function of time show a similar shape to those in figure 4.6(a), in which K is initially large, and then reduces to a constant value after a period of adjustment.

For details of all the rising head and constant head tests, reference should be made to the hydrogeological study carried out by Flynn (1990).

4.5.5 Recommendations

Further falling head tests should be carried out on other piezometers to give a fuller picture of the spatial variability of hydraulic conductivity. In addition to this, constant head tests should be carried out in which the imposed head is much smaller than that which has previously been used. If a Mariotte vessel is used as a constant discharge device, rather than a constant head device, smaller heads of the order of 5 cm, could be applied, which should give more accurate values for hydraulic conductivity. This may be very time consuming, but it would give a good indication as to whether or not the falling head test can reliably be used to obtain accurate measurements of permeability.

4.6 Pumping Tests

Pumping tests were carried out for two of the three piezometers located at CLBH2. These were intended to give values of transmissivity for the layer of glacial till, composed of sand and gravels, and the limestone bedrock. The values obtained for transmissivity can be converted to permeability values which may be used in the modelling of the system. The two piezometers in which pumping tests were carried out were CLBH2.1 and CLBH2.2 which have their filters located in the limestone and gravel respectively.

4.6.1 Pumping Test Design

The pump used for the tests was a large diesel suction pump, positioned next to the borehole at ground level. Although the rate at which the pump operates is adjustable, in practise, a small throttle adjustment leads to a large change in engine speed, which may significantly affect the pumping rate, and therefore, the throttle should not be adjusted during the test. The pumping rate is partially governed by the depth to water; the limit being when the water level is 10 metres below ground, at which point cavitation occurs. The pumping rate should, therefore, be set such that the maximum depth of the water below ground is no more than about 9 m. The discharge from the well was monitored using a 5 gallon drum, from which the water was then discharged into the drain, about 50 m downstream. Recharge to the aquifer from the drain is considered unlikely, due to the very low permeability of the clay.

4.6.2 Pumping Test Analysis

The analysis used for the pumping phase of each of the pumping tests is the Cooper-Jacob method (Cooper and Jacob, 1946). The non-equilibrium Theis equation for pumping test analysis is given by:

$$s = \frac{Q}{4\pi T}\int_u^\infty \frac{e^{-u}}{u}du \tag{4.8}$$

or:

$$s = \frac{Q}{4\pi T}W(u) \tag{4.9}$$

where s is the drawdown in the well, Q is the discharge, T is the aquifer transmissivity, and W(u) is the Theis well function, with u expressed as:

$$u = \frac{Sr^2}{4Tt} \tag{4.10}$$

where S is the storage coefficient, r is the distance from the pumped well to the observation well, and t is the time since pumping started. The Theis well function, W(u), may be expressed by the series:

$$W(u) = -0.5772 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!}\ldots \tag{4.11}$$

from which the Jacob solution may be derived. For $u<0.01$, the well function may be approximated by the first two terms of equation 4.11, such that the drawdown, s, is given by:

$$s = \frac{Q}{4\pi T}\left(\ln\frac{1}{u} - 0.5772\right) \tag{4.12}$$

Rearranging equation 4.12 gives:

$$s = \frac{2.30Q}{4\pi T}\log\left(\frac{2.25T}{r^2S}\right) + \frac{2.30Q}{4\pi T}\log t \qquad (4.13)$$

Hence, a plot of s against log t, should give a straight line with gradient 2.30Q/4πT. If Δs is the drawdown per log cycle of time, then the transmissivity, T, may be calculated from:

$$T = \frac{2.30Q}{4\pi \Delta s} \qquad (4.14)$$

No observation wells were logged during the pumping tests, so the storage coefficient, S, can not be evaluated.

The Theis recovery method is used for the analysis of the recovery phase of the tests. It is based on the fact that the curve for *residual* drawdown, s', is the same shape as the drawdown curve, from which it may be shown that:

$$s' = \frac{Q}{4\pi T}[W(u) - W(u')] \qquad (4.15)$$

where:

$$u = \frac{r^2S}{4Tt} \quad \text{and} \quad u' = \frac{r^2S}{4Tt'} \qquad (4.16)$$

where t is the time since pumping started, and t' is the time since pumping stopped. For small r and large t', the Jacob approximation may be applied, so that:

$$s' = \frac{2.30Q}{4\pi T}\log\frac{t}{t'} \qquad (4.17)$$

Thus, a plot of residual drawdown, s', against log(t/t') gives a straight line. The gradient of the line is $2.30Q/4\pi T$, which is equal to $\Delta s'$, the residual drawdown per log cycle of t/t'. The transmissivity is then given by:

$$T = \frac{2.30Q}{4\pi \Delta s'} \qquad (4.18)$$

The main assumptions on which each of the tests are based are as follows:

1. The aquifer is isotropic, homogeneous, of uniform thickness, and infinite areal extent.
2. Before pumping, the piezometric surface is horizontal.
3. The well is pumped at a constant discharge rate.
4. The pumped well penetrates the entire aquifer, and the flow to the well is horizontal.
5. The well diameter is small, so that storage within the well can be neglected.

In each of the tests, a straight line has been fitted to the data by a linear regression, from which the transmissivity is calculated. The data for each of the four tests carried out is given in appendix C.

4.6.3 Pumping Test Results and Discussion

1. CLBH1.1 - Limestone

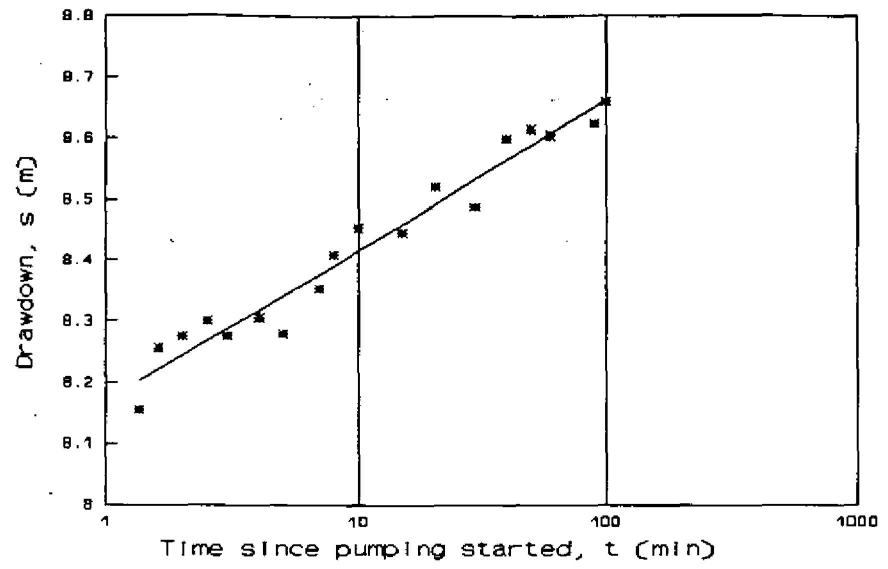


Figure 4.11 Plot of drawdown against time for pumping test at CLBH2.1.

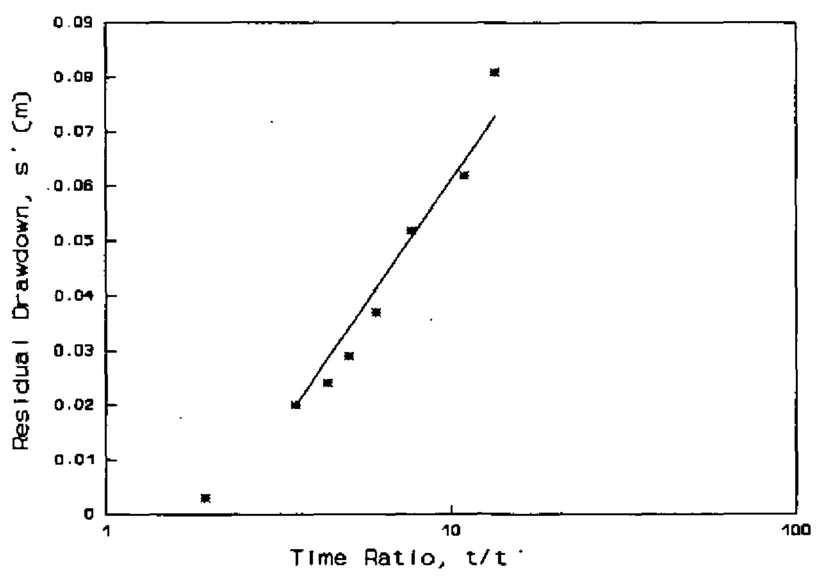


Figure 4.12 Plot of residual drawdown against time ratio for recovery test at CLBH2.1.

Figures 4.11 and 4.12 show the semi-logarithmic plots of the data obtained in each of the tests for the limestone. The values of transmissivity obtained for each of the tests are converted to permeability values by dividing by the aquifer thickness. The thickness of the bedrock at CLBH2 is unknown, so an estimate of the thickness of the active layer, through which all flow takes place, must be made. In the absence of any other evidence, a value of 15 m is considered to be reasonable as a first estimate. The analysis of the graphs, and the results obtained are shown in table 4.2.

Table 4.2 Analysis of Pumping Test and Recovery Test Data for the Limestone, CLBH2.1

		Pumping Test	Recovery Test
Pumping rate Q (m3/day)	:	12.925	12.925
Drawdown Δs (or Δs') (m)	:	0.246	0.900
Transmissivity T (m2/day)	:	9.61	26.29
Permeability K (m/day)	:	0.64	1.75
Data range of t (or t') (min)	:	1.35 - 100	8 - 110

The values for transmissivity (and permeability) of the limestone are uncertain for a number of reasons. Firstly, the two tests give values which differ by about 170%, which casts doubt on the validity of one or other of the tests. Secondly, the graphs do not give good straight lines. The plot for the pumping phase shows a large spread of points, with many fluctuations in drawdown over the duration of the test due to variations in the pumping rate. However, a straight line may fitted to the data, if the points at the very start of the test (up to 1 minute) are ignored. The data points for the recovery phase are much more difficult to fit a straight line to, as they tend to form a curve for the first part of the recovery phase, until t' is approximately 10 minutes. For t'>10 minutes, such that t/t'<10, a straight line may be fitted to the data.

These characteristics are linked to the fissured nature of the limestone. During the first part of the pumping test, the water storage in the well is removed, and the fissures are dewatered very quickly, resulting in the very rapid drawdown, up to 8 m in the first minute of pumping. From then on, there is little water readily available to be removed, and hence the drawdown increases very slowly. Similarly, at the end of the pumping phase, when the pump is switched off, the fissures fill with water very quickly in the first few minutes of recovery, while the remaining recovery is slow. The validity of each of these tests needs to be considered in relation to the assumptions on which the analysis is based.

The fissured nature of the limestone implies a degree of anisotropy and heterogeneity, and hence the first assumption is dubious. The value for transmissivity obtained from the analysis, depends very much on whether or not the filter is located in a fissure. The assumptions of uniform thickness and infinite areal extent are reasonable, although the actual thickness of the active layer is unknown. The piezometric surface around the borehole is actually at a very shallow angle, dipping roughly from north to south, but the effect that this has on the results is minimal.

During the pumping phase, the discharge from the well was very variable and intermittent over short periods of time, i.e. a few seconds, with the water coming out in short bursts. Over a period of a few minutes, the discharge was approximately constant, with variations up to about 5% of the mean value. During the recovery phase, the recharge to the aquifer may be taken as being constant.

It has already been noted that the active thickness of the aquifer is unknown, and therefore, there is uncertainty in whether or not the well fully penetrates the active layer. If the well is partially penetrating, the flow to it will be radial, resulting in a longer average length of flow line, and greater resistance to flow. The drawdown will therefore be greater than if the well is fully penetrating, and the value calculated for transmissivity will be underestimated. In practice, if the well has 85 percent or more, open or screened hole in the saturated thickness, it may be considered as fully penetrating (Todd, 1980).

However, the screened length of the hole is only 4 m, and with an assumed saturated thickness of 15 m, the well the well only partially penetrates the aquifer.

The storage in the well can be shown to have a significant effect on the data at the start of the test. With a tube diameter of 2 inches, and a drawdown of about 8 m, the volume of water in the well, removed at the start of the test is about 16 litres. At an initial pumping rate of 0.175 l/s, the time taken to remove this water is about 90 seconds. Beyond this point, water is removed from storage in the aquifer. For this reason, the straight line has been fitted to the data after the initial removal of water stored in the well, and for this part of the test, the storage in the well can be neglected.

Clearly then, there are many uncertainties in the analyses used, which may go some way to explaining the large difference between the values obtained by each method. Indeed, the violations of many of the main assumptions may suggest that the methods used may not even be appropriate. In view of this, it may be unwise to suggest which value for transmissivity is more accurate. However, if the assumption that the flow in the aquifer takes place in the top 15 m is reasonable, then it is felt that the value of 26 m^2/day obtained in the recovery test is more reasonable, as the permeability value of 1.7 m/day is more representative of fissured limestone than the 0.6 m/day obtained from the pumping test. It should also be noted that the active thickness may be much less than the assumed 15 m.

In view of the violations of some of the assumptions of the analyses, it may be appropriate to carry out different analyses of the data which are more applicable to a partially penetrating well in a fissured aquifer.

2. CLBH2.2 - Glacial Sands and Gravels

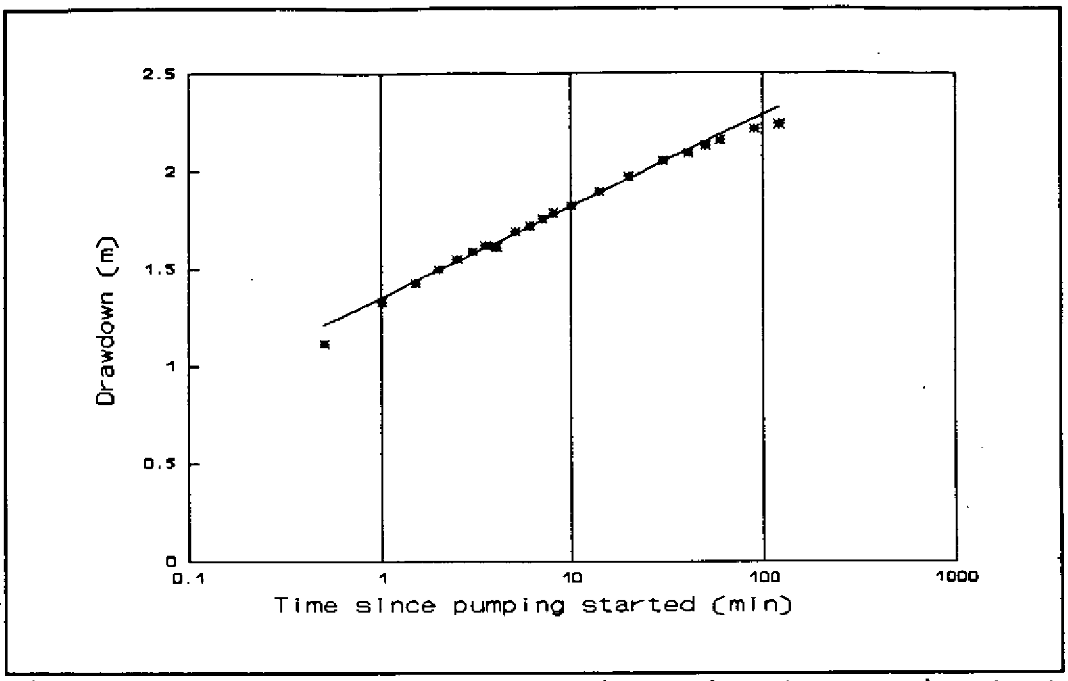


Figure 4.13 Plot of drawdown against time for pumping test at CLBH2.2.

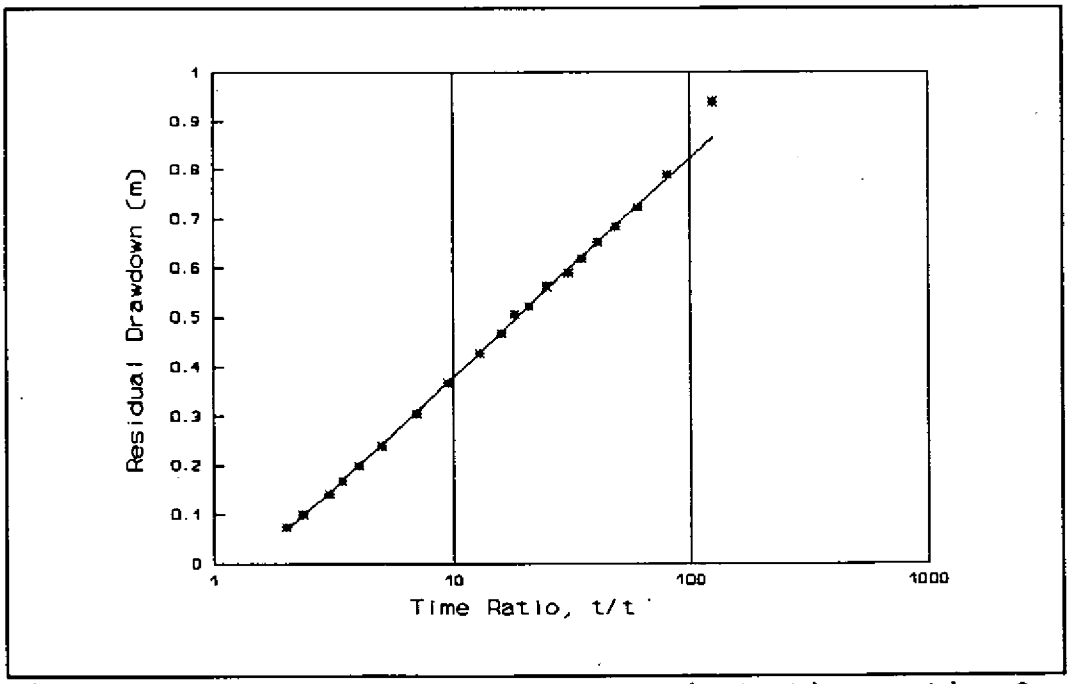


Figure 4.14 Plot of drawdown against time ratio for recovery test at CLBH2.2.

Figures 4.13 and 4.14 show the semi-logarithmic plots obtained for the tests carried out in the glacial sands and gravels. The thickness of the layer is taken as 4.25 m, from the borehole log, shown in figure 4.6. The analysis and results of the tests are shown in table 4.3. The two tests give very similar values for transmissivity, which suggests that the analyses used are more appropriate in this case. Again, consideration must be given to the assumptions on which the analysis is based.

Table 4.3 Analysis of Pumping Test and Recovery Test Data for the Sands and Gravels, CLBH2.2

		Pumping Test	Recovery Test
Pumping rate Q (m3/day)	:	76.1	76.1
Drawdown Δs (or $\Delta s'$) (m)	:	0.467	0.445
Transmissivity T (m2/day)	:	29.9	31.3
Permeability K (m/day)	:	7.04	7.36
Data range of t (or t') (min)	:	0.5 - 120	1 - 120

The glacial till, being made of mixed material, although it is not homogeneous on a small scale, on a larger scale, the assumption is reasonable. Anisotropy is likely to be evident, with the horizontal permeability being greater than the vertical permeability. The assumptions of uniform thickness, a horizontal piezometric surface, and infinite areal extent of the aquifer are also reasonable in this case. The discharge rate during pumping varied very slightly, with a marginally higher value at the start of the test.

The screened length of the hole is 1 m, and the total thickness of the sand and gravel layer is 4.25 m. This effectively makes it a partially penetrating well, with water being drawn from above and below the screened length, and consequently, the transmissivity may be underestimated. Storage in the well may be neglected after the first half minute of pumping, beyond which, a straight line may be fitted to the data.

The values obtained for transmissivity of the gravels are considered to be fairly accurate. Values of hydraulic conductivity have been obtained by dividing the transmissivity by the thickness of the sand and gravel layer. It is felt that both the hydraulic conductivity and the transmissivity may be underestimated due to the well being partially penetrating, rather than fully penetrating.

5. SURFACE HYDROLOGY

The surface hydrology of the lagg zone is an important aspect in the general hydrology of the bog as a whole. The drain which runs along the northern boundary affects the groundwater flow, in the vicinity of the drain, giving rise to upward hydraulic gradients, as discussed in section 4.3. The drain also plays an important role in removing water entering the drain as surface runoff, during storm events. During a storm event, a higher proportion of water from direct runoff may be in the drain, which will affect the hydrochemistry. In order to understand the effect that such runoff has on the hydrochemistry and hydrology of the drain, a runoff coefficient is required. This will also provide valuable information on the surface runoff component of the water balance for the bog.

The runoff coefficient itself will be dependent on many factors, particularly the antecedant conditions and the storm intensity. For example, in winter, when wetter conditions prevail, a greater proportion of runoff may occur, than that which occurs in summer for a similar rainfall event. Thus, the evaluation of a single runoff coefficient is inadequate for a detailed analysis of the surface hydrology, but it may give an indication, on which future studies may be based.

5.1 Flow Gauging in Road Drains

The runoff coefficient may be calculated by analysing rainfall data, and discharge data from two weirs on the east side of the road drain. These weirs, and another on the west side of the drain were installed after recommendations by Bell (1991). However, various problems with both of the weirs on the east side led to them being modified and relocated at more suitable sites. The new locations are shown in figure 5.1. The more northerly one, DEH923, was moved about 30 m downstream, while the southerly one, DEH922, was moved 10 m downstream. The third weir, DEH921, can be seen on the west side of the road.

5.1.1 Weir Modification and Installation

The three weirs in the road drains are V-notch weirs, with an angle of about 30 degrees. The small angle of the V-notch allows very low flows to be gauged accurately, which may be important during the summer months. The disadvantage of having such a small angle is the greater backwater effect which occurs. However, this can not be avoided if flows are to be gauged over the full range of head, due to the shape of the drains, which are in general, narrow and deep.

The initial location of the northerly weir was such that during a significant rainfall event, the large change in head, (due partly to the small V-notch angle), gave rise to

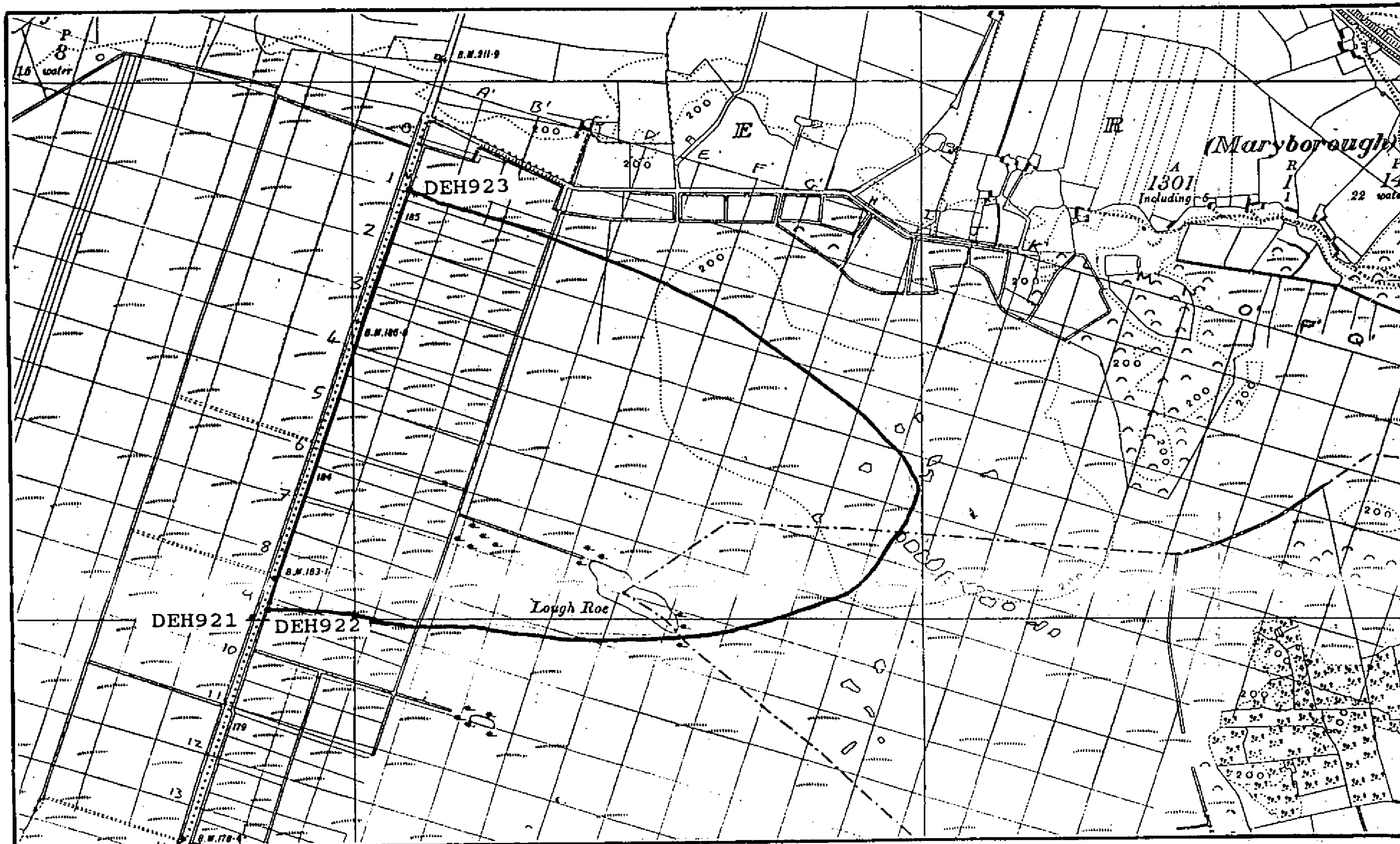


Figure 5.1 Map showing location of the road drain weirs, and the catchment drained by weirs DEH922 and DEH923.

a significant backwater effect which affected local farmland. This was considered to be unacceptable, so a new location had to be found, downstream of the old location. The width of the drain at the new site was greater than the width of the weir itself, so extensions to the weir had to be added before it could be relocated. In repositioning the weir, it was important that the bottom of the V-notch was not too high, as this would again lead to raised water levels on the farmland. At the same time, the level of the V-notch could not be too low, as this would cause the weir to be drowned during high flows. A compromise between these two constraints led to the weir being positioned such that the downstream water level would just reach the bottom of the V-notch, at the same time as the upstream water level to affect the farmland. The stage value at which this occurs is estimated to be around 0.2 m, which corresponds to a flow rate of about 7 l/s. This flow is expected to be reached regularly during the winter months. If this is the case, it may be necessary to modify the weir further, converting it to a sharp-crested Cipolletti weir. This will allow for much larger flows, at a much smaller increase in head, and hence, a smaller backwater effect.

The southerly weir, DEH922, needed to be repositioned due to erosion around the sides, through which water was leaking. Repairing the damaged areas, with the weir *in situ* was considered, but this option would only have been a temporary measure, so a new site was selected downstream of the original location. At the new location, the drain was deeper, and consequently, the bottom of the weir was extended by 30 cm, to allow the V-notch to be positioned so that during high flows the weir did not become drowned. The weir was installed by hammering it into position using sledge hammers, although this proved to be difficult, due to the compact nature of the peat.

5.1.2 Rating Curves for the Weirs

Rating curves were established by measuring the stage at the weir, and recording the time taken to fill a container of known volume. The summer of 1992 was particularly dry, and therefore, the flow in the drain was low for much of the duration of the field study. As a result, the number of points used to establish the rating curve is limited, and these are concentrated at the lower end of the flow range. The rating curve may therefore not be very accurate, outside of the gauged range. In order to improve the accuracy of the stage-discharge relationship, further flow measurements should be carried out at higher flows. The flow range of all three weirs, and the range that has been gauged is given in table 5.1. The stage-discharge relationship for a V-notch weir is:

$$Q = K \tan\frac{\theta}{2} H^{5/2} \qquad (5.1)$$

where Q is the discharge, θ is the V-notch angle, H is the stage, and K is a coefficient with dimensions $m^{1/2}/s$. From the weir geometry, and the recorded stage and discharge,

Table 5.1 Estimated Flow Range and Gauged Flow Range for Road Drain Weirs

Weir No.	Estimated maximum stage (m)	Estimated maximum discharge (m^3/s)	Maximum gauged stage (m)	Maximum gauged discharge (m^3/s)
DEH921	0.6	0.13	0.136	0.003
DEH922	0.9	0.29	0.202	0.007
DEH923	0.9	0.26	0.211	0.007

rating equations for each of the weirs can be evaluated. A plot of discharge, Q, against $\tan(\theta/2)H^{5/2}$ gives a straight line, the gradient of which is K, the weir coefficient. A least squares regression has been used to fit a line to the data. The constant, K, and the V-notch angle, θ, may be incorporated into a single constant, C, so that the stage-discharge relationship becomes:

$$Q = CH^{5/2} \tag{5.2}$$

Table 5.2 shows the calculation of the constant, C, for each of the weirs. The data from which these results were obtained, and the rating curves, are given in appendix D.

Table 5.2 Evaluation of Rating Equation Constants

Weir No.	No. of data points	Weir coeff. K	V-notch angle θ	$\tan(\theta/2)$	Rating equation constant C
DEH921	7	1.837	27.9	0.248	0.456
DEH922	6	1.508	28.2	0.251	0.379
DEH923	4	1.347	28.1	0.250	0.337

5.1.3 Data Recording

Automatic data recorders were installed at the two weirs on the eastern side of the road, at the start of July 1992. This should ensure continuous recording of water levels, at 15 minute intervals, allowing storm hydrographs to be constructed, from which a runoff coefficient may be calculated. A third data recorder should be in place at weir DEH921 by the end of 1992. The recorders are

Figure 5.2 Gauging station at weir DEH922.

basically 'black boxes' with a pulley wheel on the side, from which a float and counterweight are suspended, on a stainless steel band. The recorder itself is housed in a box, beneath which, the float and counterweight are suspended, in a stilling well, and a dry tube respectively. This gauging station at weir DEH922 is shown in figure 5.2.

5.2 Evaluation of Runoff Coefficient

Evaluation of a runoff coefficient requires knowledge of the catchment area between the two weirs. This is estimated by Samuels (1992) to be 1.178 x 10^6 m^2, and is marked on figure 5.1. In addition to this, the hyetograph, and the resulting hydrographs for the weirs, must be known for the rainfall event under consideration. Data from the tipping bucket rain gauge located on Clara west gives hourly rainfall measurements, and the water level recorders give stage readings at 15 minute intervals. In the period from the start of July, when the recorders were installed, until the end of July, there were only two storm events which could be considered to be 'significant'. The first of these occured on July 3rd, at which point only the recorder at weir DEH922 was working, and consequently, this event could not be used. The second event, occuring on July 23rd, amounting to a total of 10 mm rainfall, produced storm hydrographs at both weirs, which could then be analysed to give a runoff coefficient. The water level data first had to be converted into discharge using the appropriate constant in equation 5.2.

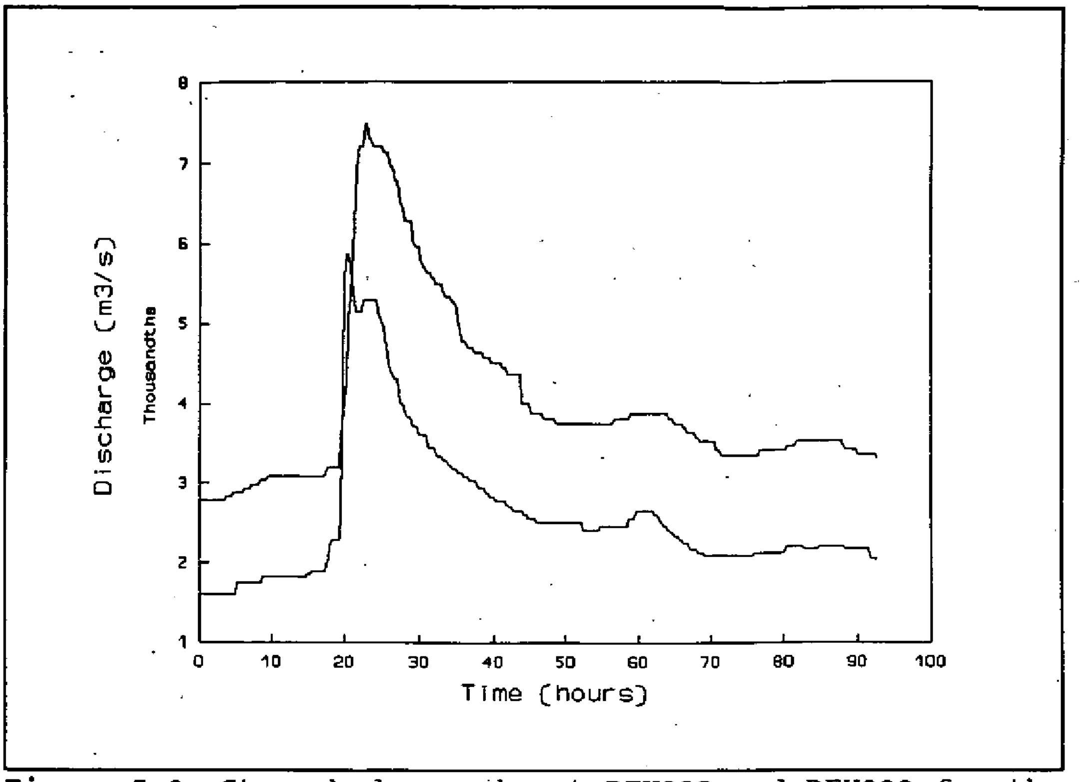


Figure 5.3 Storm hydrographs at DEH922 and DEH923 for the rainfall event on 23/07/92. Time datum 00:00 hrs 23/07/92.

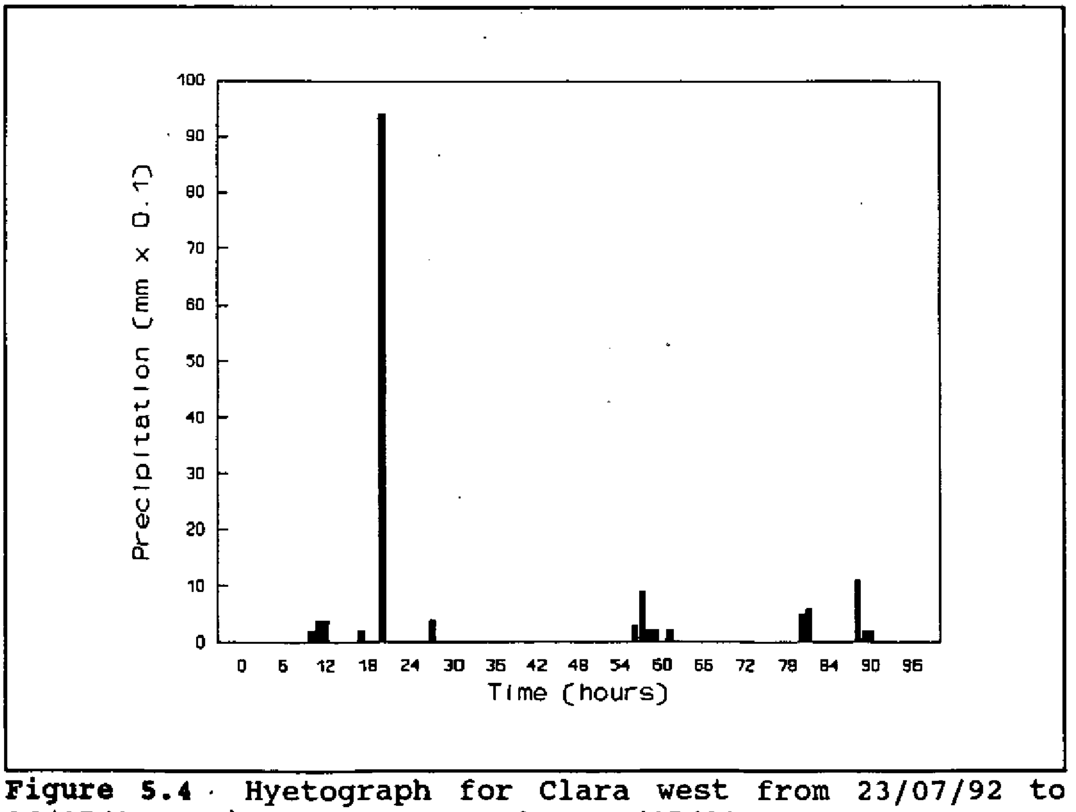


Figure 5.4 Hyetograph for Clara west from 23/07/92 to 26/07/92. Time datum 00:00 hrs 23/07/92.

The storm hydrographs for the two weirs, and the rainfall for Clara west are shown in figures 5.3 and 5.4. The upstream weir, DEH923, shows an earlier, but smaller peak than the downstream weir, DEH922. The duration over which stormflow is evident is approximately 32 hours, and it is on this basis that the volume of stormflow from each of the weirs is calculated, using the trapezium rule:

$$\int_a^b f(x)\,dx \approx \frac{h}{2}((y_0 + y_n) + 2(y_1 + y_2 + \ldots + y_{n-1})) \qquad (5.3)$$

where h is the width of the strip, given by (b - a)/n, and n is the number of strips. Baseflow separation is by a straight line from the start of the rise of the hydrograph, to the point where discharge appears to be approaching a constant, before the next rainfall event has an effect. Allowance must be made for the extra area calculated between the baseflow separation line, and the horizontal datum from which the ordinates, y_n, are measured. The data used for the calculations is given in appendix E, and a summary of the results is shown in table 5.3.

Table 5.3 Calculation of Stormflow Volume At each Weir

		DEH922	DEH923
(b - a)/n		0.25	0.25
$y_0 + y_n$		2.43	2.49
$y_1 + y_2 + \ldots + y_{n-1}$		945.3	32.6
Total volume	(m^3) :	236.6	183.5
Volume between datum and baseflow line	(m^3) :	38.8	39.8
Stormflow Volume	(m^3) :	197.8	143.6

Calculation of the runoff coefficient for the given storm is now possible:

Rainfall	:	0.01 m
Catchment area	:	1178000 m^2
Total rainfall volume	:	11780 m^3
Total runoff volume	:	54.2 m^3
$\frac{\text{Total outflow}}{\text{Total inflow}}$	:	0.005

The runoff coefficient for the storm event is therefore 0.5%. This is extremely low, and is due mainly to the very dry antecedant conditions, and the relatively small size of the storm, in which much of the rainfall is likely to have been taken up by depression storage.

In view of this, it is considered that the above value is not representative of a 'typical' runoff coefficient. The exceptionally dry conditions which prevailed throughout the summer of 1992 have led to lower groundwater levels on the bog, and a generally dryer bog surface. Consequently, much rainfall will be needed to replenish groundwater supplies, before a significant proportion of runoff can be expected. It is proposed that a similar analysis is carried out for a number of storms, with different antecedant conditions, in order to get a better picture of the surface hydrology of the bog.

5.3 Surface Hydrology of the Lagg Zone

The surface hydrology of bog area of the lagg zone may be assumed to be similar to that of the rest of the bog. The use of runoff coefficients calculated for the gauged catchment, as above, is therefore reasonable. Given that the bog area of the catchment draining through weir DEH923 (the northerly weir) is known, the total runoff volume from the bog area can be found, for a given event. The remaining stormflow must come from a different source. A knowledge of the relative proportions of runoff coming from the bog, and that coming from elsewhere is important if the effects of drainage in the lagg zone are to be understood. Measurements of electrical conductivity taken along the drain will provide valuable information on the source of the water in the drain, leading to a better understanding of the lagg zone hydrology.

6. HYDROCHEMISTRY AND ECOLOGY

The hydrochemical and ecological aspects of this project are limited, but they act as useful indicators of groundwater and surface water hydrology. The hydrochemical aspect is restricted to measurements of electrical conductivity, which gives an indication of the mineral content of the water. This can be a key indicator in identifying areas of upwelling mineral water, as these will show a much higher EC than more typical bog areas, which have a very low EC. The only ecological consideration is in terms of the plant species present in the lagg zone, which differ greatly from those found on the rest of the bog. This is a reflection of the mineral content of the water, which affects acidity, and hence the species which are able to survive.

6.1 Hydrochemistry of the Lagg Zone

Measurements of EC were taken in all the piezometers in the lagg zone, and in several others further into the bog to try and identify areas in the peat where mineral water is present. High values of EC indicate a high total dissolved solids content, TDS. In general, groundwater contains a variety of ionic and undissociated species, and consequently, there is no unique relationship between EC and TDS, as it will depend on the species present in the water. However, for most natural water, with conductivity in the range 100 to 5000 μS/cm, an approximate relationship

Table 6.1 EC and TDS of Selected Bog Piezometers

	EC µS/cm				TDS mg/l			
Piezometer Number	4	3	2	1	4	3	2	1
101	479	423	664	772	307	271	426	495
141	379	131	504	665	243	84	323	426
102	170	412	494	796	109	264	317	510
142	100	148	493	751	64	95	316	481
103	68	100	132	699	44	64	85	448
143	73	99	125	-	47	63	80	-
104	76	87	110	115	49	56	71	74
106	73	68	76	84	47	44	49	54
107	84	77	108	112	54	49	69	72

may be used, where 1 mg/l is equivalent to 1.56 µS/cm (Logan, 1961). The results obtained are given in table 6.1. They show conductivity and TDS to be higher in the deeper piezometers, and in those which are closest to the drain. It should be noted that the deepest pizometers (number one) at locations 101, 102, 103, 141 and 143, are in the clay. This gives a good indication of the mineral content of the water entering the peat layers from the clay. The dilution of this water can be seen in the reduction of EC and TDS higher up the peat profile. It should also be noted that there is a natural increase in EC with depth, and this should be considered when assessing the extent to which the mineral-rich water from the clay layer affects the EC of the bog water. From these results, it would appear that the upwelling mineral-rich water extends approximately to the area around piezometer 143, which is on the edge of the lagg zone.

6.2 Ecology of the Lagg Zone

The plant ecology of the lagg zone is significantly different from that of the rest of the bog due to the presence of minerals from the clay layer below the peat. This gives rise to a less harsh environment in which other plant species are able to survive such as bracken and silver birch. There is also an absence of typical bog vegetation such as cotton grasses, bogbean, sundew, and *Sphagnum* mosses which are the main component of raised bog vegetation. Figure 6.1 clearly shows the transition from the bog, which is very brown in appearance, to the lagg zone which is more verdant.

Figure 6.1 Transition from bog vegetation (foreground) to lagg zone vegetation (background).

6.3 Hydrochemistry of the Drain

An analysis of the hydrochemistry of the drain should give an indication of the catchment drained by it. It has already been noted that there is a difference in EC between water coming from the bog, and that coming from the esker of about one order of magnitude. The mixing of waters in the drain and the resulting EC should indicate, the relative contribution of each source to flow in the drain. Figure 6.2 shows a map of the drain, and the points at which conductivity was measured. In order to make sense of these measurements, they must be related to the flow rate in the drain. Simple float gauging experiments were undertaken to obtain an estimate of the flow in the drain at two locations, corresponding to points 2 and 16a in figure 6.2. The calculation of these flow rates is given in appendix F. The conductivity measurements taken along the length of the drain, and in the tributaries to it, are shown in table 6.2. A plot of conductivity as a function of distance along the drain shows a general trend of increasing conductivity downstream, as shown in figure 6.3. The only obvious exception to this trend occurs at point 15, where the conductivity is considerably lower than would perhaps be expected. This may be the result of a very localised, low conductivity outflow from the bog, a short distance upstream of the sampling point. From this data, a straight line may be fitted, (ignoring point 15,) from which estimates of conductivity may be obtained at any point along the drain. The justification for using a

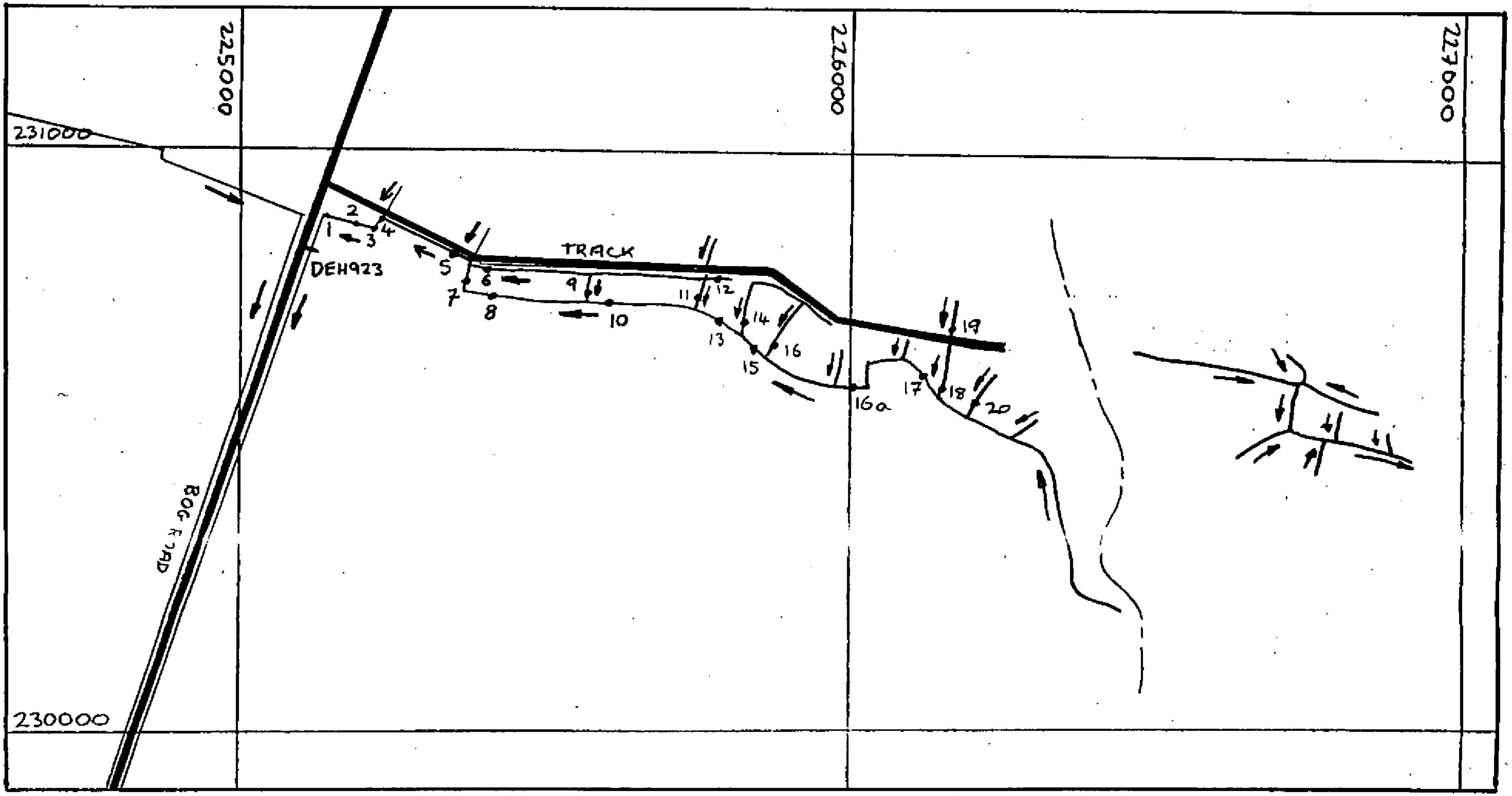


Figure 6.2 Map of the northeast drain showing sampling and gauging locations.

Table 6.2 Conductivity Measurements at Selected Points Along the Northeast Drain, 15/06/92

Measurements along main drain			Tributary Measurements	
Location	Distance along drain (m)	EC (uS/cm)	Location	EC (uS/cm)
1	0	525	6	756
2	50	521	9	486
3	80	527	11	752
4	100	524	12	758
5	230	510	14	716
7	300	484	16	703
8	370	486	18	543
10	570	490	19	686
13	750	465	20	758
15	820	381		
17	1210	444		

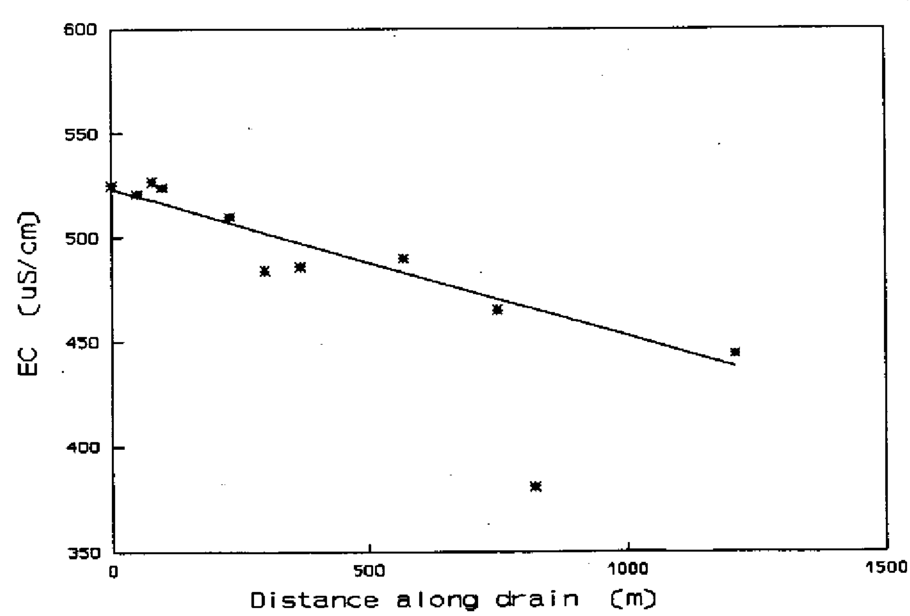


Figure 6.3 Plot of EC as a function of distance along the main drain from the data in table 6.2.

linear relationship lies in its simplicity, and the absence of any other data to suggest otherwise. For the current purposes, this approximation is reasonable. The solute fluxes, F, at the two gauged points may then be calculated as in table 6.3. The solute flux, F, is calculated from:

$$F = Q \times TDS \tag{6.1}$$

where Q is the discharge, and TDS is the salts concentration at the sampling point.

Table 6.3 Calculation of Solute Fluxes at Two Gauged Locations

Location	Flow rate Q (l/s)	EC (μS/cm)	TDS (mg/l)	Solute Flux F (mg/s)
2	1.11	520	333	370
16a	0.55	452	290	159

Thus, the solute mass flux out of the drain increases further downstream. Using this result, and taking approximate values of EC of 700 and 80 μS/cm, (equivalent to 449 and 51 mg/l TDS) for water coming from the esker and the bog respectively, the relative contribution of each source may be estimated. (The estimates of EC have been chosen on the basis of conductivity measurements of water in the tributaries to the drain on the esker side, and in bog piezometers away from the lagg zone). By solving two simultaneous equations for each location, one referring to the solute concentration and the other to discharge, the flow from the esker and the bog can be calculated.

For point 2 : $449\ Q_e + 51\ Q_b = 370$ (6.2a)

$Q_e + Q_b = 1.11$ (6.2b)

For point 16a : $449\ Q_e + 51\ Q_b = 159$ (6.3a)

$Q_e + Q_b = 0.55$ (6.3b)

where Q_b and Q_e are the discharges from the bog side, and the esker side of the drain. Solution to equations 6.2 and 6.3 gives the flow rate for each contributing source, from which the proportion of water in the drain originating in the esker and the bog may be found. These results are summarised in table 6.4.

Table 6.4 Contribution to Flow in the Drain from Bog and Esker

Gauged Location	Contribution of Source to Flow in the Drain			
	Flow from Bog		Flow from Esker	
	l/s	%	l/s	%
2	0.32	(29)	0.79	(71)
16a	0.22	(40)	0.33	(60)

It should be stressed that these calculations are approximate due to the uncertainty in the values obtained for the flow at each of the two gauged points. The method used to measure the flow was a simple float gauging technique. A coefficient of 0.8 has been applied to the float velocity to give a mean value for the stream velocity. The estimated uncertainty in the values obtained for discharge at point 2 and 16a are about 25% and 15%

respectively. It should be noted that the conductivity of the water changes with time as the contributing sources become larger or smaller with respect to each other. The measurements described above took place after a dry spell, in which there had been no rainfall for the previous five days, and a total of about 50 mm in the previous month. It is likely that the relative contribution of water to the drain from each source changes during and after a storm event. This will be dependent on the runoff coefficient for the bog area of the catchment, which may be very variable, as discussed in chapter five. Due to a lack of significant rainfall events, it was not possible to carry out any further hydrochemical analyses to ascertain how the hydrochemistry of the drain is affected during a storm event.

From the above analysis, under the conditions described, it may be concluded that the majority of the flow in the drain is from water originating in the esker. The most important processes by which the water enters the drain are by throughflow from the esker, into the tributaries which feed the drain, and groundwater recharge from the till and clay. However, this situation is likely to change in wetter periods, when runoff from the bog side of the drain may be significant.

The flow of water into the drain from the bog may be more significant than has been suggested. The assumed value of conductivity for the bog water of 80 μS/cm may be too low, and consequently, the contribution it makes, may be underestimated. The high conductivities recorded in the piezometers in the lagg zone close to the drain would certainly confirm this. However, although this water has entered the drain via the peat, i.e. from the bog side of the drain, much of it has originated as groundwater from the till and clay and has entered the peat as a result of the upward hydraulic gradients around the drain. Hence, the source of this water is actually the esker side of the drain.

In summary, the water in the drain at the time of sampling, may be from one of three sources:

1. Water from the esker side of the drain, of high conductivity, by groundwater recharge.
2. Water from the bog side of the drain, of very low conductivity, by groundwater recharge.
3. Groundwater recharge from the bogside of the drain by water originating in the esker, and flowing upwards through the clay, into the peat. The conductivity of this water is somewhere between that of natural bog water and esker water.

In general, water may also enter the drain via throughflow from the esker, during, and shortly after a storm event. Overland flow from the esker side is unlikely, due to the very permeable nature of the topsoil and glacial till. From the bog side, both throughflow and overland flow are possible processes by which water may enter the drain. All of these processes may occur during much wetter periods, especially shortly after a heavy storm. A detailed analysis of a number of storm hydrographs, as described in chapter five, is required before any firmer conclusions can be made. Measurements of EC and discharge should also be taken, at a few points along the drain, after storm events with different antecedant conditions. This should lead to a better understanding of the contribution of each source, to the flow in the drain.

7. WATER BALANCE FOR CLARA BOG

7.1 Water Balance for an Intact Raised Bog

The concept of a water balance for an intact raised bog was introduced in chapter two. It will be recalled that the equation governing the water balance may be expressed as:

$$P - E = D \tag{7.1}$$

where P is the precipitation, E is the evapotranspiration, and D is the discharge from the bog by surface runoff, and lateral seepage through the acrotelm. The water balance for Clara bog assuming it to be intact, as developed in chapter two, is given in table 7.1.

Table 7.1 Approximate Water Balance for Clara Bog, Assuming it to be Intact

	year (mm)	winter (mm)	summer (mm)
Precipitation (P)	850	500	350
Evapotranspiration (E)	450	80	370
(P - E)	400	420	- 20
Discharge (D)	400	340	60
Change in Storage (ΔS)	0	+ 80	- 80

The preceding chapters on groundwater hydrology, surface hydrology, and hydrochemistry, clearly demonstrate that the flow from the bog through the catotelm is significant, and this component of the water balance can not be ignored. No evapotranspiration data for the bog is available, although it may be assumed that evapotranspiration continues at the potential rate. The groundwater flow in the bog, away from the lagg zone, has been shown to be predominantly horizontal. Hence, the assumption that downward vertical seepage through the catotelm into the clay layer is negligible, is a reasonable one.

7.2 Water Balance for Clara Bog

From the analysis of the preceding chapters, the water balance for a raised bog in which marginal drainage is significant may be expressed as:

$$P - E - R - L = \Delta S \qquad (7.2)$$

where R is the surface runoff (including lateral seepage through the acrotelm), L is lateral seepage through the catotelm into the drain, and ΔS is the change in storage. Thus, the drainage term, D, of equation 7.1 is now expressed as two separate terms, R and L. Over a period of a few years, the change in storage may be assumed to be zero, so that equation 7.2 becomes:

$$P - E = R + L \qquad (7.3)$$

From flow measurements taken in the northeast drain, it was shown in chapter six, that the drainage from the bog due to the presence of the drain may be estimated as 0.32 l/s. The bog area of the catchment at the gauged location is estimated to be 17 ha, from which the lateral drainage through the catotelm is calculated to be the equivalent of 30 mm rainfall, for the summer period of six months. From time series plots of groundwater level data, the change in storage during the summer is estimated to be 80 mm. From these values, a water balance for the bog may be defined, which includes lateral drainage through the catotelm, and surface runoff from the bog. This is shown in table 7.2.

Table 7.2 Conceptual Water Balance for Clara Bog

	year (mm)	winter (mm)	summer (mm)
Precipitation (P)	850	500	350
Evapotranspiration (E)	450	80	370
(P - E)	400	420	- 20
Surface Runoff (R)	330	300	30
Lateral Seepage (L)	70	40	30
(R + L)	400	340	60
Change in Storage (ΔS)	0	+ 80	- 80

The lateral seepage term is assumed to be reasonably constant throughout the year, although it may be slightly higher in winter, due to higher groundwater levels. The surface runoff component is small during the summer due to the generally dryer conditions on the bog, although it is significantly higher than the value of 0.5%, calculated in chapter five. In the winter months, surface runoff is likely to be much greater, as a result of wetter conditions on the bog, and heavier rainfall. It should be stressed that the values quoted are not considered to be representative of the actual water balance, due to the many uncertainties in the analyses used. The model should only be considered as a conceptual model, on which further investigations may be based. In order to gain a fuller understanding of how the water balance has been affected by marginal drainage, regular monitoring of each of the water balance components is required.

The surface runoff term may be evaluated by analysing many storm hydrographs, as in section 5.2, throughout the year, at the weirs located in the road drains. A mean seasonal surface runoff coefficient may then be estimated, and used in the water balance. Lateral seepage through the catotelm should also be monitored on a regular basis, although the seasonal variation in this term is likely to be relatively small. The hydrochemical analysis used in section 6.3 may be used to derive this term. Rainfall is monitored on Clara west, and hence, the only unknown term is the evapotranspiration. Lysimeter data, and meteorological data from the weather station on Clara west should be available from the autumn of 1992, from which estimates of evapotranspiration may be made.

Knowledge of all of the terms in equation 7.3 will allow appropriate adjustments to be made to each of the components of the water balance, depending on the uncertainty of each estimate. This should lead to a quantative assessment of the hydrological significance of the drain.

7.3 Long Term Water Balance for Clara Bog

Bell (1991) has shown that the road which bisects the bog has dramatically affected the water balance, such that the drainage term is much more significant than in an undisturbed bog. Since the building of the bog road, approximately 200 years ago, the bog has been drained, and settlement has been taking place, giving Clara bog its two-domed appearance. Over such a long period of time, the change in storage can not be assumed to be zero, as it is this which leads to the settlement of the bog. For a long term water balance, equation 7.2 must be used:

$$P - E - R - L = \Delta S$$

In order to assess the importance of each of these components in the long term, detailed studies of the settlement of the bog, and the short term water balance, as outlined in the previous section, are required. For the purposes of this project, it may be sufficient to conclude that the annual change in storage in the short term may be very small, but over long periods of time it is a crucial component of the water balance, and can not be ignored.

8. MODELLING

8.1 Two-Dimensional Model

It has been shown in the previous four chapters, that the drain on the northern margin of Clara east, and the road drains, are important factors in the drainage of the bog. Controlling the water flow from these drains is, therefore, important for conservation. In order to investigate the current hydrological situation, the system is modelled as a two-dimensional section. The section which is modelled is that described in section 4.1, from the centre of the bog, across the lagg zone, to the adjacent esker.

The model used is a Modular Three-Dimensional Finite Difference Groundwater Flow Model, MODFLOW, produced by the United States Geological Survey. The modular structure consists of a main program, and a series of independent subroutines, which are grouped together into packages. Two of these packages must be specified for all model simulations. These are the Basic Package, which contains information on the model structure and solution procedure, and the Block-Centred Flow Package, which is needed in solving the finite difference equation. All the other packages deal with a specific feature of the hydrological cycle, and may be used as required in any simulation. Flow associated with external stresses such as recharge, rivers and drains, are modelled using these stress packages.

8.2 MODFLOW Packages

8.2.1 Basic Package

The Basic Package is required for all model simulations. It contains information on the basic model structure, and the other packages which are to be used in the simulation. The main information which is required is as follows:

1. Specification of which stress packages are to be used in the simulation.
2. Number of layers, rows and columns in the model.
3. Number and length of stress periods, and the number of time steps within each stress period. The time units for the simulation must also be specified.
4. Boundary conditions for each cell; either constant head, variable head or no flow cells.
5. Starting heads for each cell.
6. Solution procedure.

In modelling the flow line across the bog, the stress packages used are the Drain Package and the Recharge Package. The system is represented as a two-dimensional section, with 23 columns, six layers, and one row giving a total of 138 nodes. The simulated stress period is one year, with 365 one day time steps. The boundary conditions for the model consist of a mixture of constant head, variable head, and no flow cells. These will shortly be discussed in greater detail.

8.2.2 Block-Centred Flow Package

The Block-Centred Flow (BCF) Package calculates the terms required in the finite difference equation, which determine flow between adjacent cells. To make these calculations, it is assumed that a node is located at the centre of each cell. The data required by the BCF Package is as follows:

1. Steady-state or transient simulation.
2. Layer type; confined or unconfined.
3. Transmissivity and/or hydraulic conductivity. Storage coefficients are also required for a confined layer in a transient solution.
4. Cell width along each row and column.
5. Anisotropy factors for each layer, and the vertical conductivity between layers.
6. Elevation of the top and bottom of each layer, from which the layer thickness is found.

The system is modelled in steady-state conditions, and hence storage coefficients for each of the model layers are not required. Each of layers, apart from the top layer are modelled as confined layers, with hydraulic conductivities and transmissivities specified using the results of the falling head tests and the pumping tests, discussed in chapter four. The hydraulic conductivities used will shortly be discussed in greater detail. As the model is two-dimensional, the cell width along the single row is chosen arbitrarily as 1 m. The cell width of each column is variable, from 100 m at one of the model boundaries to 2 m in the vicinity of the drain. The anisotropy factor for all layers is taken as one, as there is no information on the vertical hydraulic conductivity of each layer.

8.2.3 Drain Package

The Drain Package allows the effect of agricultural drains to be modelled. The drain on Clara northeast is modelled as two separate drains, one located in the peat, the other in the underlying clay. The data required by this package is as follows:

1. Specification of the cell in which the drain is located.
2. Elevation and hydraulic conductivity of the base and sides of the drain.

8.2.4 Recharge Package

The Recharge Package simulates areally disributed recharge by one of three options. For this model, the recharge is applied to the uppermost active cell in each column. Recharge to constant head cells has no effect.

The data required by this package is simply the recharge applied to each cell. In this case, the recharge is the precipitation surplus minus an allowance for surface runoff. As there is only one stress period, the recharge is distributed evenly throughout the year.

8.3 Model Requirements

8.3.1 Geometry of Section and Model Structure

The geometry of the section has been established from a number of augerings on both the esker, and bog sides of the drain, and from geophysical soundings on and around the bog (Smyth, 1991). The geological section along the flow line is shown in figure 8.1, in which each of the geological layers can be identified.

The discretisation of the system into a series of blocks is an important aspect of the model, if it is to accurately represent the hydrogeological system. Consideration must be given to the way in which the geological layers are represented, as some of them thin out to zero thickness. In modelling terms, the layer cannot be specified as having zero thickness, and in such cases, the layer is incorporated into one of the other model layers, with the hydraulic conductivities and layer thicknesses being changed as required. This can lead to confusion as to which of the model layers represents a geological layer, and which ones exist simply in order to make the model function properly. In broad terms, layers one, two, and three represent the peat, while layers four, five, and six represent the clay, glacial sands and gravels, and the limestone bedrock respectively. Table 8.1 gives an indication of the basic model structure, and the geological layers represented by each of the model cells.

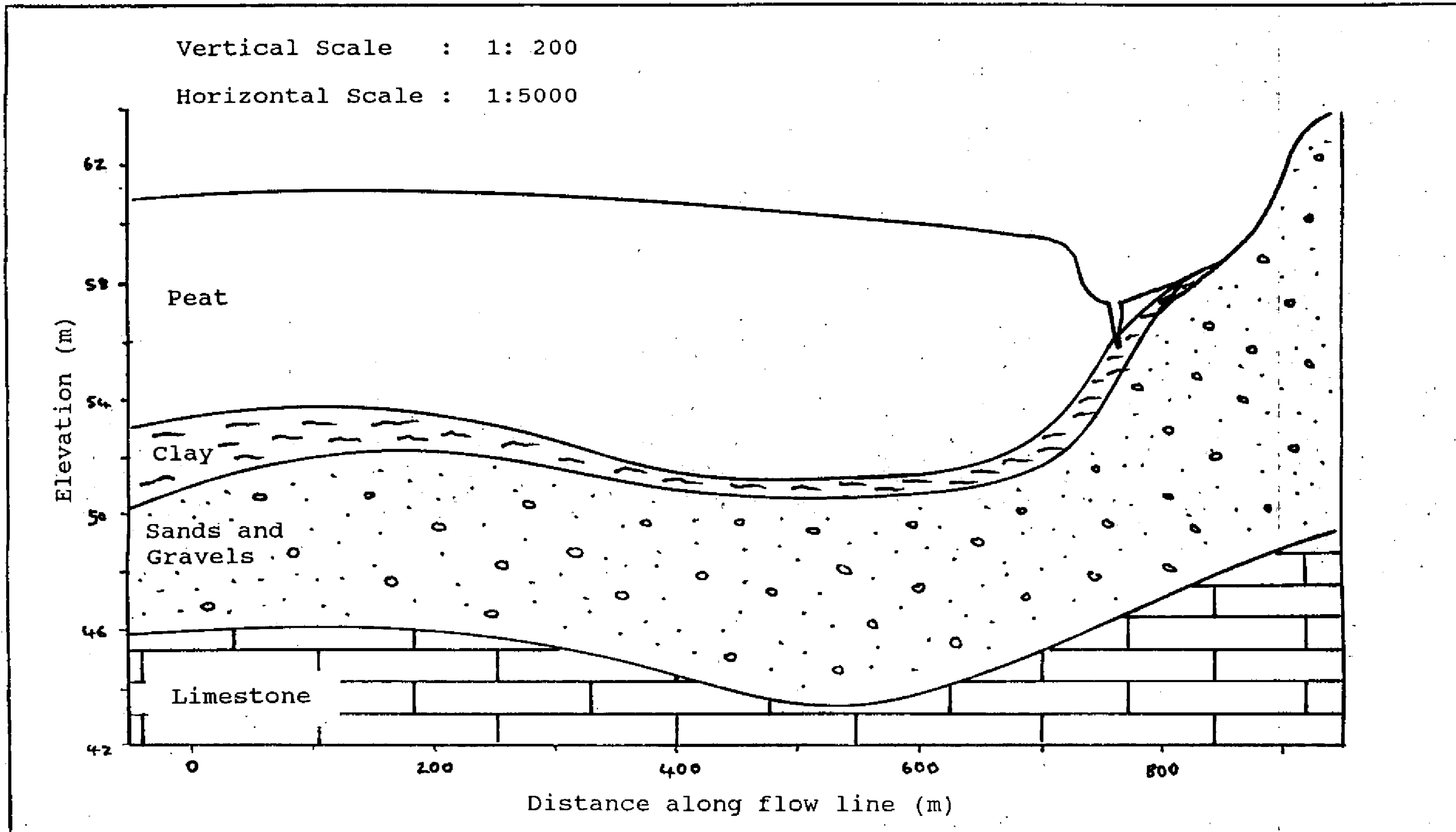


Figure 8.1 Geological section along the modelled flow line.

Table 8.1 Model Structure Showing Geological and Model Layers

Column Number	Cell Width	Layer 1	2	3	4	5	6
1	100	P1	P2	P3	C	S	L
2	100	P1	P2	P3	C	S	L
3	100	P1	P2	P3	C	S	L
4	100	P1	P2	P3	C	S	L
5	100	P1	P2	P3	C	S	L
6	100	P1	P2	P3	C	S	L
7	100	P1	P2	P3	C	S	L
8	25	P1	P2	P3	C	S	L
9	10	P1	P2	P3	C	S	L
10	6	P1	P2	P3	C	S	L
11	5	-	P2	P3	C	S	L
12	5	-	P2	P3	C	S	L
13	2	-	P2	P3	C	S	L
14	2	-	P2	P3	C	S	L
15	2	-	P2	P3	C	S	L
16	2	-	P2	P3	C	S	L
17	2	-	D	D	C	S	L
18	2	-	P2	P3	C	S	L
19	2	-	P2	P3	C	S	L
20	14	-	P2/S	P3/S	C/S	S	L
21	40	-	S	S	S	S	L
22	50	-	S	S	S	S	L
23	45	-	S	S	S	S	L

P : Peat layers 1, 2 and 3
S : Sand and Gravel
D : Drain
C : Clay
L : Limestone

It should be noted that the three peat layers are intended to represent the bog peat, fen peat and reed peat, as described in chapter one, although the boundaries between the layers are not well defined. In general, the upper layers of peat are more permeable than the lower layers. In the model, the difference between peat layers two and three is minimal.

8.3.2 Hydraulic Conductivity

The hydraulic conductivity values for the peat layers of the model have been based on the results of the falling head tests. Because of the highly heterogeneous nature of the peat, there is much approximation and interpolation involved in assigning values to the cells which represent the peat. As a result, significant differences exist between the model values, and those obtained in the field tests, as the value used in the model must be representative of the permeability on a much larger scale. In the falling head tests, hydraulic conductivity is measured at a point, which does not give a good indication of the 'regional' permeability. It would be misleading to assign such a value to a cell representing a 100 x 3 x 1 m section of the bog. On a macro scale, the hydraulic conductivity may be of the order of a few mm/day, as demonstated by the falling head tests, but on a larger scale, it may be two or three orders of magnitude higher. This is due to the preferential flow paths within the peat. In layer one, a value of 0.5 m/day has been assigned to the cells in which flow takes place, due to the flow in the acrotelm being considerably greater than that in the rest of the layer. In layers two and three, the permeability is generally lower, of the order of 0.05 m/day, except in the vicinity of the drain, where it is about an order of magnitude higher. Peat cutting and drainage in the area, has led to subsidence, and the development of macropores in the peat, up to about 20 m from the drain.

In the clay layer, a value of 0.003 m/day has been used for the clay beneath most of the bog, up to about 50 m from the drain. At this point the permeability is gradually increased, from column 8 to 17, to about 0.01 m/day beneath the drain. The clay in the region close to the drain is more permeable than that beneath the rest of the bog, due to the presence of cracks in the clay. In the area north of the drain where the clay thins out, the model permeability values are higher by up to two orders of magnitude. In reality, the clay does not form a continuous homogeneous layer, as it is mixed with sand and gravel. Assigning much higher permeabilities to the clay in this area is, therefore, reasonable.

The glacial sands and gravels are represented by a single layer in the model, and have a permeability value based on the results of the pumping and recovery tests, carried out at CLBH2.2. A slight decrease in permeability with increasing depth may be expected, and hence, lower values around 5 m/day are assigned to the sand and gravel cells beneath the bog. Further north towards the esker, the permeability is increased to 10 m/day. The peat and clay layers which do not physically exist on the esker side of the drain, but still exist in the model, are incorporated into this layer. The permeability of these layers is increased to about 10 m/day, (the same as that of the sand and gravel layer) with a change of around three orders of magnitude between columns 18 and 21.

The limestone bedrock is considered as a single layer, with a permeability based on the pumping and recovery test analyses. There is a degree of uncertainty in this value, which has been discussed in detail in chapter four. In order to improve the performance of the model, the permeability of the limestone has been taken as 2 m/day, which is slightly above the value obtained in the pumping tests. However, in view of the uncertainties already discussed, it is felt such a small adjustment is reasonable. The thickness of the layer (which represents the active layer of the limestone) is variable, but in general, it is around 15 m. The base of the layer is specified as constant elevation, and is considered to be impermeable.

8.3.3 Boundary Conditions

Boundary conditions must be specified for each of the cells, as constant head, variable head, or no flow cells. In column one, each of the six cells are specified as constant head boundaries. In column 23, the cells in layers four, five and six are also constant head boundaries. The values used have been established from water table elevation, and piezometric surfaces in the peat, clay, glacial till and limestone. In layer one, cells 11 to 23 are specified as no flow cells as these are above ground level. All other cells in the model are variable head cells.

8.4 Model Results

The MODFLOW Package data files used in the simulation are given in appendix G. Table 8.2 shows the resulting heads in each cell at the end of the last time step. From this data, equipotential contours may be constructed showing the nature of the modelled groundwater flow.

Figure 8.2 shows the regional flow, and figure 8.3 shows the flow in the vicinity of the drain. These may be compared with the equipotentials constructed from observed field data, given in chapter four. Fundamentally, the results of the modelling, and the field observations show the same flow pattern. Figure 8.2 shows the flow to be predominantly vertically downwards in the middle of the bog, gradually shifting towards being horizontal at the edge of the bog, in the vicinity of the drain. Figure 8.3 shows the shape of the equipotentials to be similar to those of figure 4.5, with a relatively large vertical hydraulic gradient across the sand and gravel, and clay layers, giving rise to upwelling mineral-rich water into the peat, up to about 20 m from the drain.

One of the advantages of using the model is that it allows equipotentials to be constructed in the sand and gravel, and limestone layers. A general lack of field data for both these layers makes it impossible to construct the actual flow pattern under the bog.

Table 8.2 Heads in Each Model Cell at the End of the Model Simulation

MODEL CELL (specified by column and layer)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	60.5	59.7	59.8	59.8	59.8	59.6	59.3	58.7	58.3	58.0	99.0	99.0	99.0	99.0	99.0	99.0	99.0	99.0	99.0	99.0	99.0	99.0	99.0
2	60.1	59.7	59.8	59.8	59.8	59.6	59.3	58.7	58.2	58.0	57.9	57.7	57.6	57.5	57.4	57.1	56.5	57.3	57.7	58.1	+	+	+
3	59.7	59.7	59.7	59.7	59.7	59.6	59.3	58.6	58.2	58.0	57.9	57.7	57.6	57.5	57.4	57.1	56.6	57.3	57.7	58.1	58.1	+	+
4	58.7	59.7	59.7	59.7	59.7	59.6	59.3	58.6	58.2	58.0	57.9	57.7	57.6	57.5	57.4	57.1	56.6	57.3	57.7	58.1	58.1	+	+
5	58.5	58.7	58.9	58.9	58.9	58.7	58.5	58.3	58.3	58.2	58.2	58.2	58.2	58.2	58.2	58.2	58.2	58.2	58.2	58.1	58.1	58.0	58.0
6	58.2	58.7	58.9	58.9	58.9	58.7	58.5	58.3	58.3	58.2	58.2	58.2	58.2	58.2	58.2	58.2	58.2	58.2	58.2	58.2	58.1	58.0	58.0

99.0 indicates a no-flow cell
\+ indicates cell went dry during the simulation

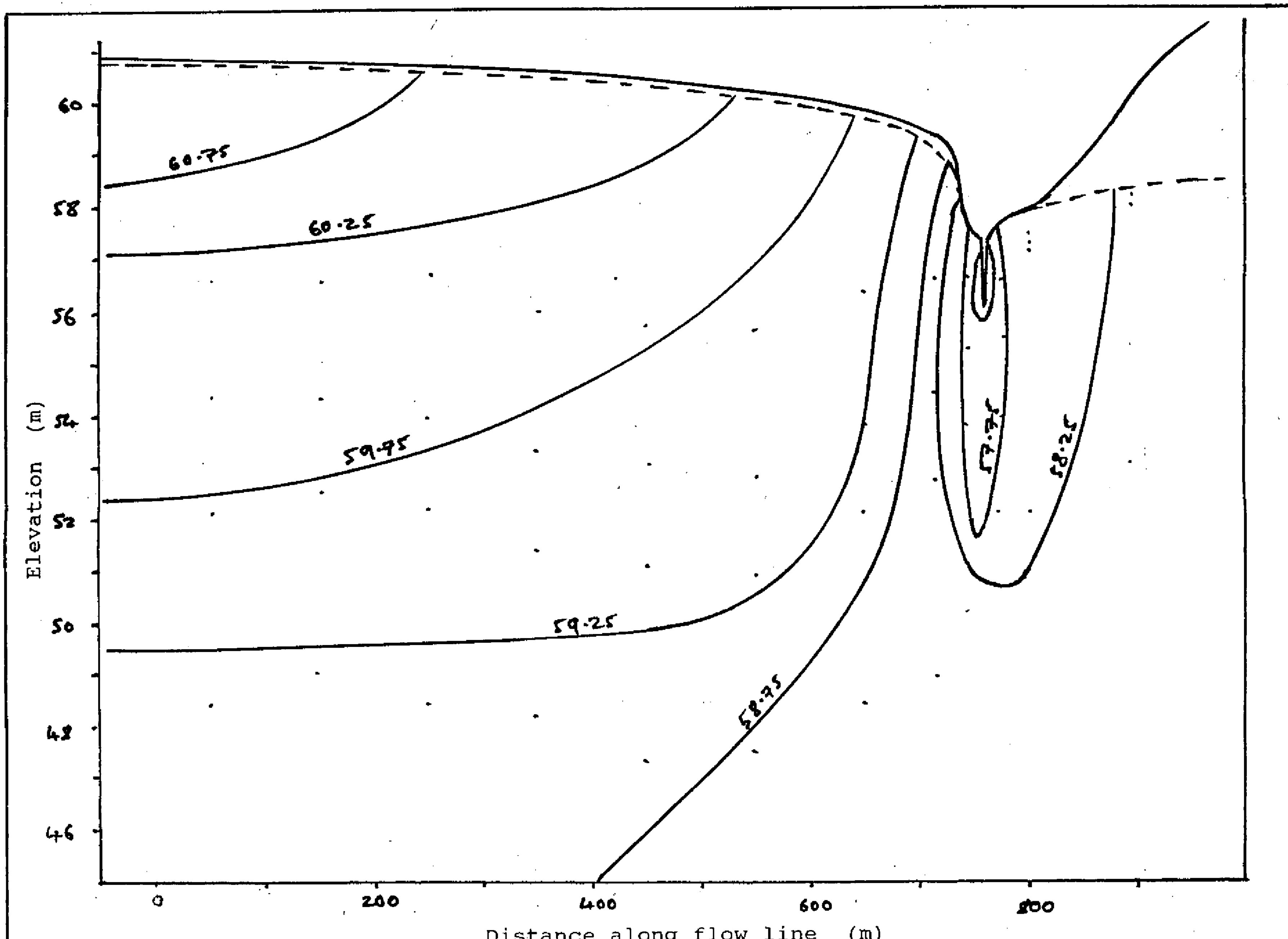


Figure 8.2 Equipotentials across bog and esker, constructed from model simulation output.

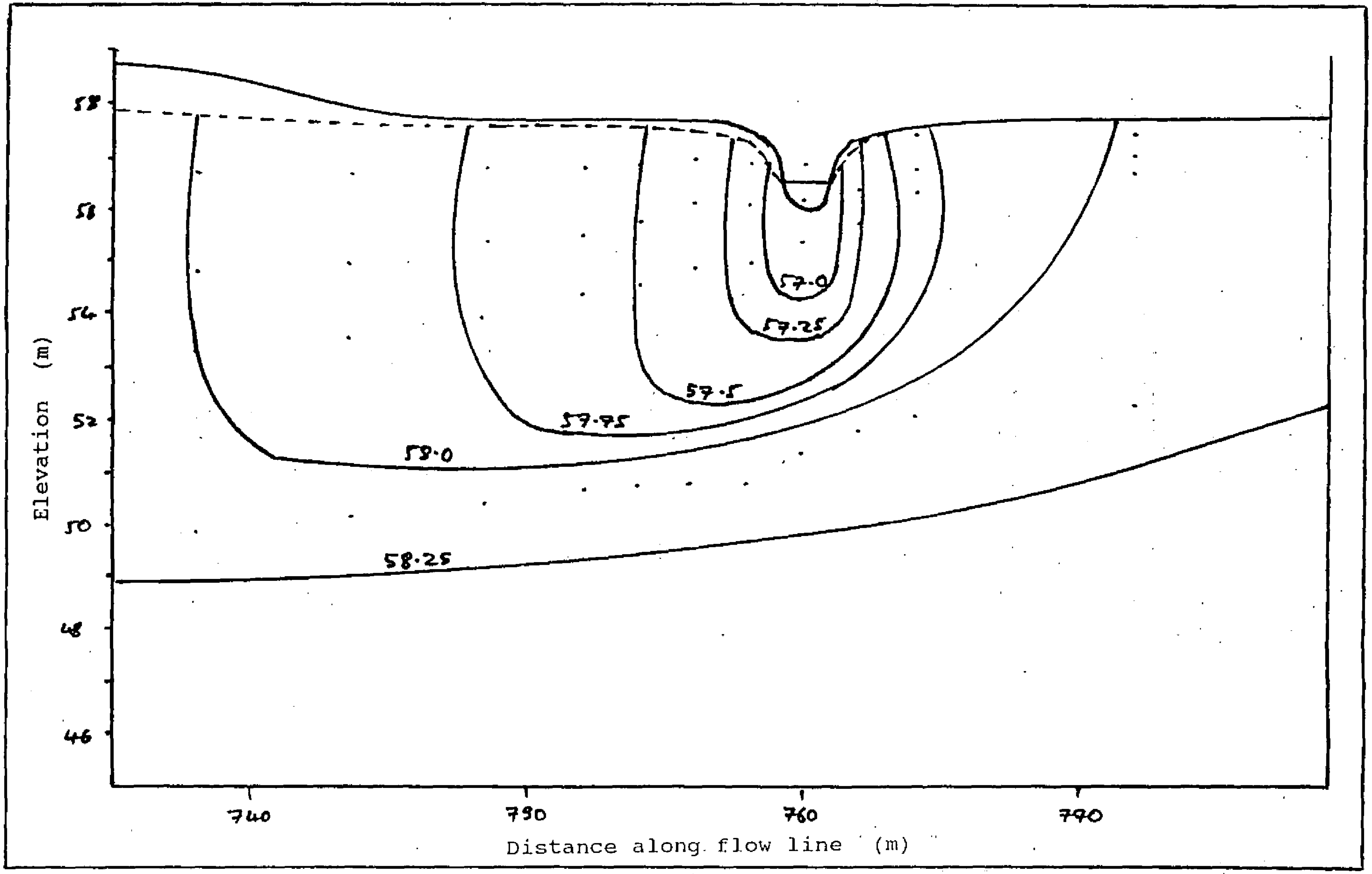


Figure 8.3 Equipotentials in the vicinity of the drain, constructed from model simulation output.

Despite the similarities between the observed and modelled flow, care must be taken in interpreting the model results, as there are some important differences between the observed head data, and the results from the model simulation. The main areas of concern are as follows:

1. Heads in peat layers one and two.
2. Heads in the sand and gravel layer, columns 19 to 21.

In peat layers one and two, the heads in columns one to 10 are lower than the observed heads, such that the water table in the model is between about 0.3 and 0.9 m below the observed water table. The error is more significant in the centre of the bog, so a certain amount of discretion is used when drawing the equipotentials in order to make the flow pattern more sensible. The reason for this error may be the boundary conditions being incorrect for column one, or, more likely, the hydraulic conductivity being too low. It should also be noted that in layer two, the head in columns 11 to 13 is about 0.2 m too high. This may be due to the hydraulic conductivity being too low, and the very abrupt change in topography between columns 10 and 11.

In the sand and gravel layer, on the esker side of the drain, the heads suggest that the water table is at, or slightly above ground level in columns 19 to 21. This error is a combination of several factors. The discretisation of the model in this area may be too coarse, such that the column width is too great, and the hydraulic conductivities and ground levels may be too low.

The water balance for the bog suggests that the model is a reasonable representation of the system. The output from the simulation shows the total recharge to the system to be 196 m^3, and the total discharge via the drain to be 53 m^3. From the flow gauging carried out in the drain, discussed in chapter six, the flow per unit length of drain may be estimated as 18 m^3 per year. It should be taken into consideration that the flow gauging experiments were carried out in summer, and also that the flow measurement was fairly crude. Hence, the difference between the discharge via the drain in the model, and the actual discharge, may not be as large as these figures suggest.

Part of the difficulty in obtaining a good correlation between the observed, and the actual flow pattern, lies in the fact that the model is a two-dimensional representation of a three-dimensional system. The modelled flow line was established on the basis of topgraphic data, and groundwater flow in the peat, as discussed in chapter four. However, it has since been discovered that the regional groundwater flow, in the sands and gravels, and the limestone, is quite different to that in the peat. A contour map of groundwater levels shows there to be a groundwater mound extending underneath the bog, such that the flow in the sands and gravels, and the limestone, may actually be perpendicular to the assumed flow line. The results of the model must be interpreted in the light of this, and this may go some way to explain some of the discrepancies between the model results and the observed field data. It should also be noted that the system has been modelled using only one stress period, with recharge being distributed evenly throughout the year. This assumption is clearly not a true representation of reality. In winter, evapotranspiration is low, and rainfall is relatively high, while in summer, evapotranspiration may exceed rainfall, such that the nett recharge is negative.

These factors underline the need to interpret model results in relation to the assumptions on which the model is based. It should also be remembered that much interpretation of field data is required, in order to make the model function sensibly. The model as it stands at present, is one of many ways in which to represent the system, and shows one possible regional groundwater flow regime, which would give rise to the observed flow in the bog and esker. It is possible that the flow in the bog may be modelled using a different model structure, producing a different regional groundwater flow regime.

8.5 Sensitivity Analysis

The sensitivity analysis for the model is restricted to a broad qualitative assessment of some of the model parameters.

The permeability of the two drains, located in layers two and three of column 17, is a major control on the groundwater flow, both in terms of the discharge from the drain, and the heads in the surrounding model cells. Controlling the water level in the drain is most effectively done by changing the drain permeability. It is this parameter which should be adjusted in order to assess the effects of different conservation measures. Raising the water level in the drain and the surrounding area, should lead to a reversal of the currently upward hydraulic gradients, such that the groundwater movement is downwards, thus preventing the mineral-rich water from the glacial sands and gravels entering the bog.

The permeability of clay has a significant effect on the head in the clay and peat layers of the model. This may be an important control in increasing the head in the peat layers in columns one to 10, and reducing the head in columns 11 to 13. The permeability of the sands and gravels and the limestone, control the heads throughout the model, but in general, have a less significant effect than the permeability of the clay.

It should be noted that there are many unknowns in the model, especially the hydraulic conductivities of most of the layers. The permeability of the peat, although many measurements have been taken at specific points, is unknown on a much larger scale. In the case of the clay, little is known about its permeability, both on a macro, and a large scale. The uncertainty in the permeability of the sands and gravels, and the limestone has already been discussed.

There is also uncertainty in the recharge applied to the system. At present, the recharge to the uppermost active cell in each column is 0.7 mm. The actual recharge figure may be up to 50 percent higher, but the effect that this has on the heads throughout the system is relatively small.

8.6 Future Modelling

At present, the model is a reasonable representation of the current hydrological regime, although further calibration of the model is required, before it can reliably be used for investigating the effects of raising the water level in the drain. Small adjustments to some of the model parameters, particularly the permeabilities of the clay and peat layers around the drain, should lead to a better model of the system. Consideration should be given to using two or more stress periods, in which the recharge to the system changes seasonally. It may also be useful to use the MODFLOW Evapotranspiration Package, so that recharge and evapotranspiration are modelled separately, rather than applying a nett recharge to the system. More field data concerning the hydraulic conductivity of each of the layers, especially the clay layer, and piezometric levels in the clay, sand and gravel, and limestome layers would also be useful. The effectiveness of various conservation options, may then be assessed with greater certainty, and recommendations for conservation of the bog may be made.

9. CONSERVATION OF CLARA BOG

9.1 Drainage of Clara East

The drains along the northeast margin of the bog, and the drains along the road have been shown to have a significant effect on the drainage of the bog. This has caused the centre of the bog to sink, leaving two domes (Bell, 1991), which changes the position of the groundwater divide. As the groundwater divide moves eastwards, further from the road, so the area of bog being drained increases, causing the bog to dry out further. In the same way, the drain on the northeast margin, will cause the groundwater divide to move further south, away from the drain. If this drainage continues, the bog may become too dry for the necessary *Sphagnum* species to survive, and the growth of the bog will cease.

In addition to these major drains, a series of drainage ditches were dug by Bord nà Mona in 1983, to increase the drainage of the bog for peat cutting purposes. When the bog was bought by the Irish Wildlife Service in 1987, these ditches were blocked to prevent further drainage, and since then, *Sphagnum* mosses have started to grow in the ditches, thus initiating the peat forming process.

The primary aim for conservation of the bog, is to keep as much water in the bog as possible, by slowing down the rate of drainage, and encouraging the regrowth of *Sphagnum*.

9.2 Prevention of Drainage

The key to the conservation and regeneration of Clara bog may be identified as the prevention of drainage of the bog, and encouraging conditions which will aid the regrowth of *Sphagnum* mosses. One way of doing this would be to dam the drains at the southern edge of the bog, which would lead to a rise in water levels on the bog. This may have a significant effect on the overall hydrology of the bog. Slowing down the drainage process would reduce the change in storage in the bog, in the long term. This has been identified as one of the most important long term factors in the conservation of the bog.

Much of the lagg zone of the northeast margin of the bog is currently fed by mineral-rich water, due to the presence of the drain which gives rise to upward hydraulic gradients in the area. The rise in water level, if it is large enough, may lead to the reversal of the hydraulic gradients, such that the water movement is downwards through the clay, into the glacial till and limestone. If this were the case, the present lagg zone would become a small lake, fed predominantly by rainwater, low in mineral content. This would encourage the growth of *Sphagnum* mosses in a similar way as blocking the drainage ditches on Clara east has, although the timespan is likely to be considerably greater.

The rise in water level will also lead to flooding of large areas on and around the bog. The amount of land that is flooded depends on the rise in water level required to reverse the hydraulic gradients on the notheast margin. Currently, the elevation of the piezometric surface in the clay, glacial till, and limestone at CLBH2 is approximately 57.7 m, with slightly lower values as the depth increases. Reversing the hydraulic gradients in this area will require a rise in the surface water level to at least 57.7 m, although the rise should be more, if any significant downward water movement is required. The effects of raising the water level may be seen by constructing cross-sections across the drain. Four cross-sections have been used, the locations of which are shown in figure 9.1. Figures 9.2 to 9.5 show each of the cross-sections, from which the location of the drain, and the track north of the drain can easily be identified. By superimposing different water levels on the sections, the flooded area may be estimated in each case. The effects of raising the water to three different levels are shown in figure 9.6, and the estimated flooded area for each option is given in table 9.1.

Table 9.1 Effects of Flooding Under Different Water Level Rises

Option	Water Level (m)	Flooded Area (ha)
1	57.7	12
2	58.2	5
3	59.0	1.3

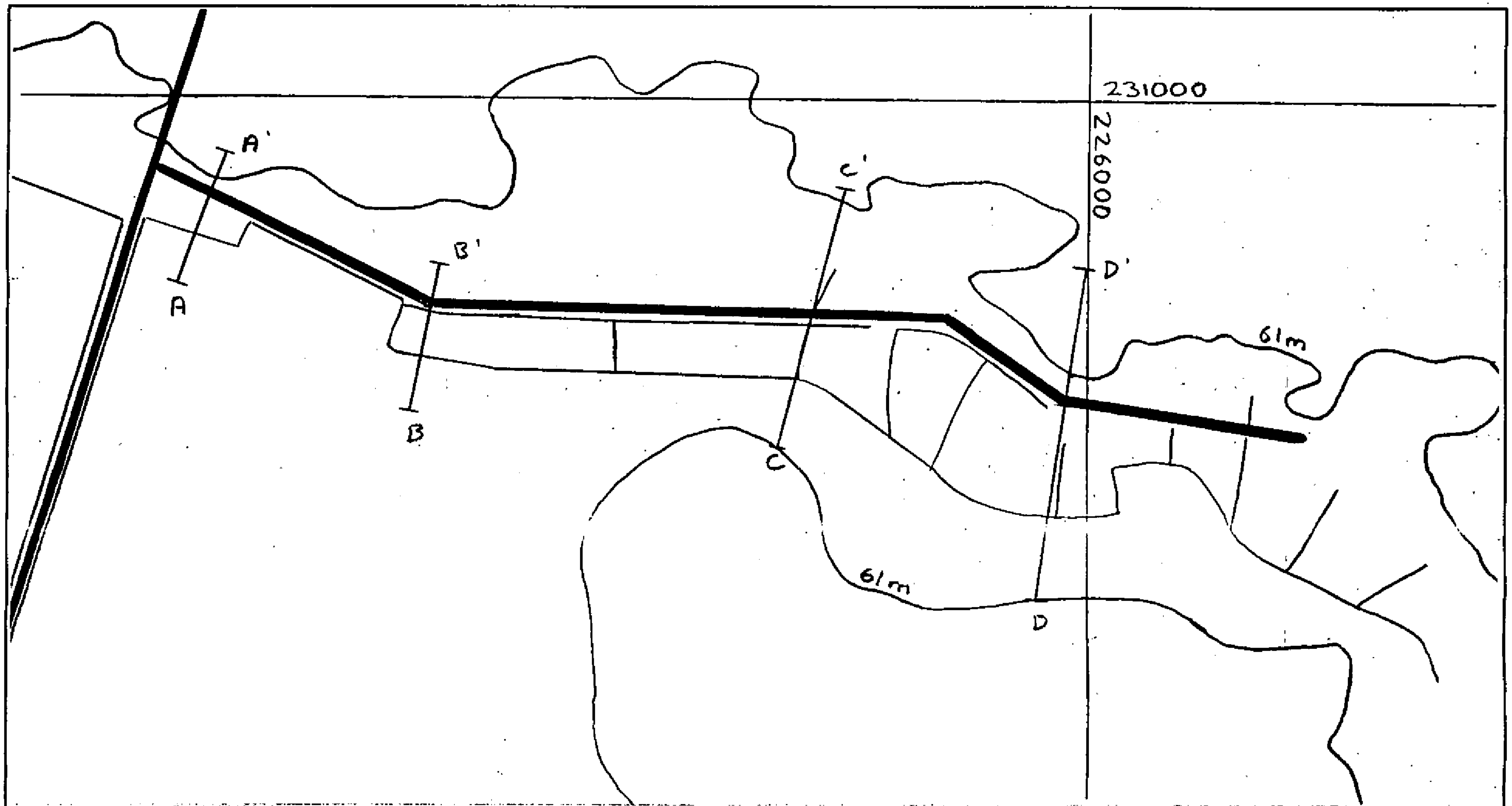


Figure 9.1 Cross-sections across the lagg zone used for estimating flooded areas.

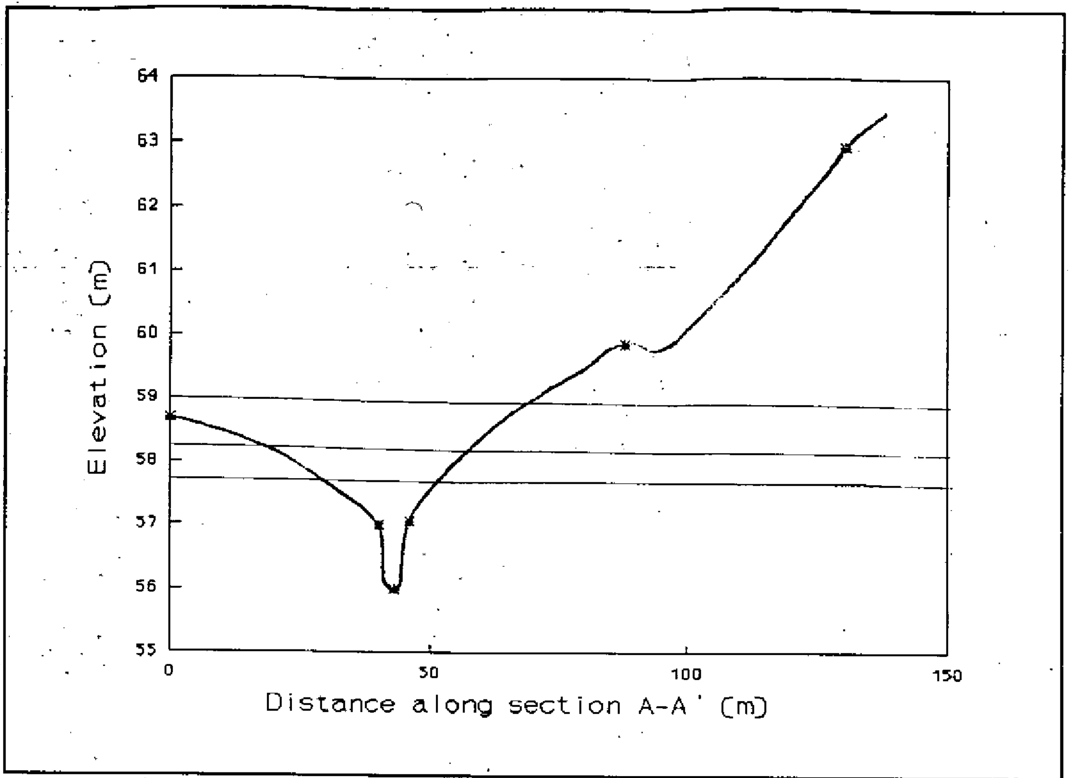


Figure 9.2 Cross-section A-A' across the lagg zone.

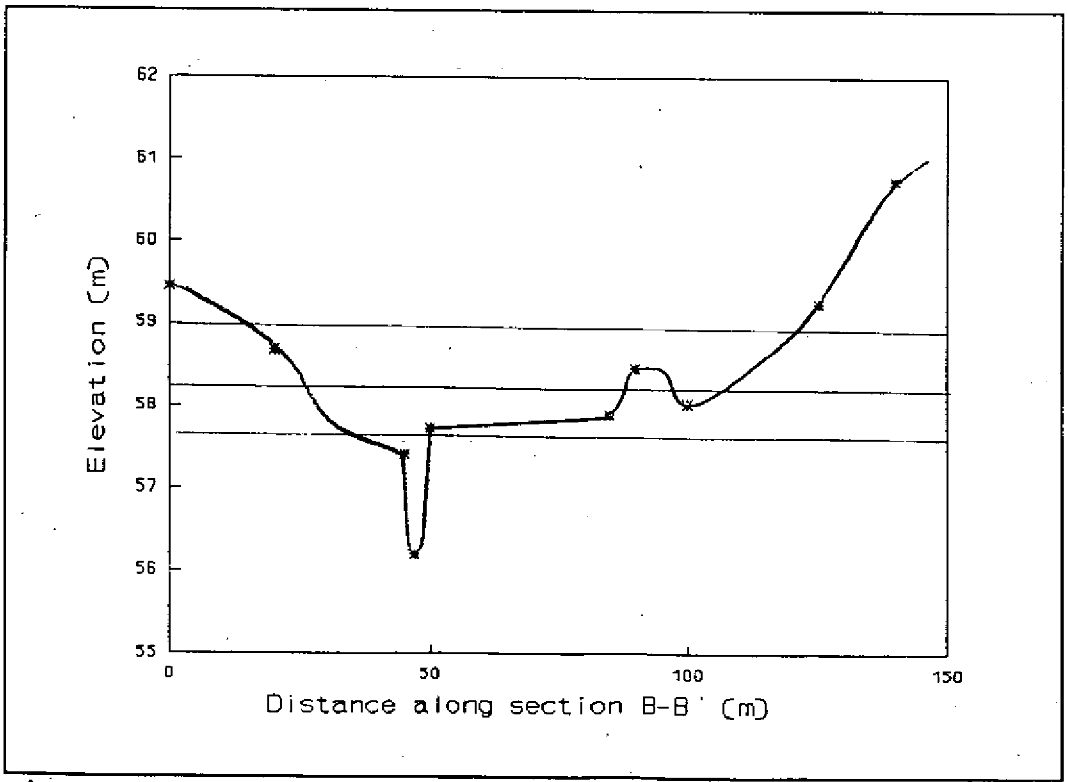


Figure 9.3 Cross-section B-B' across the lagg zone.

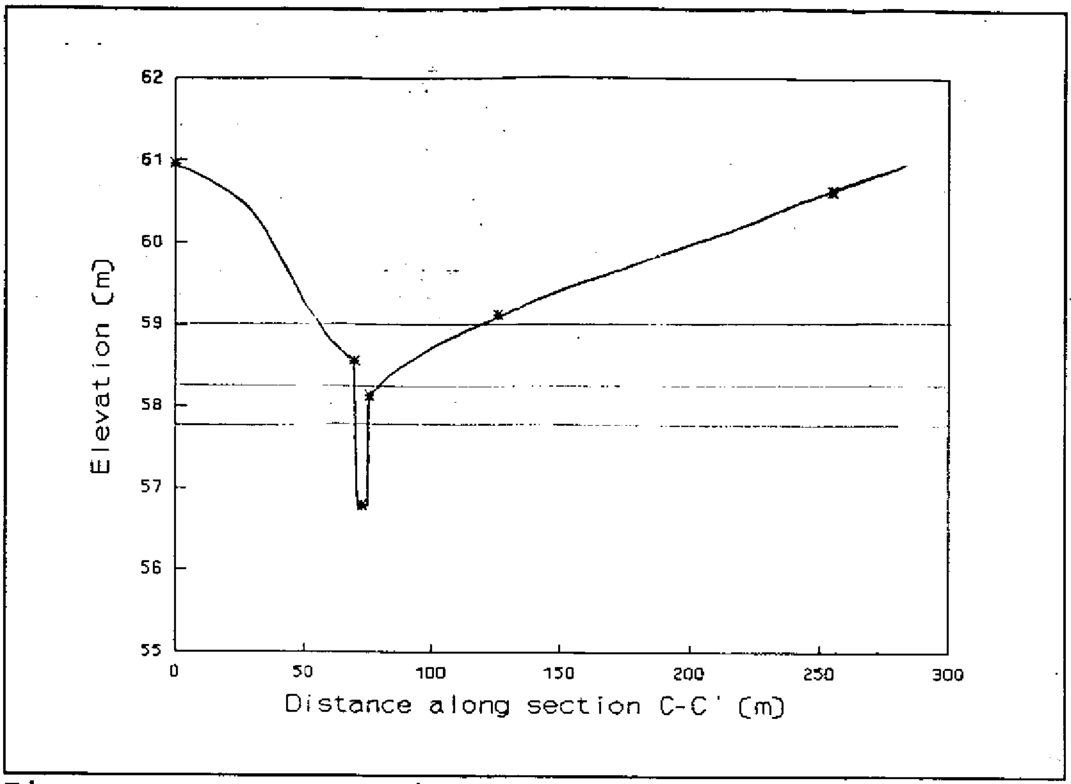


Figure 9.4 Cross-section C-C' across the lagg zone.

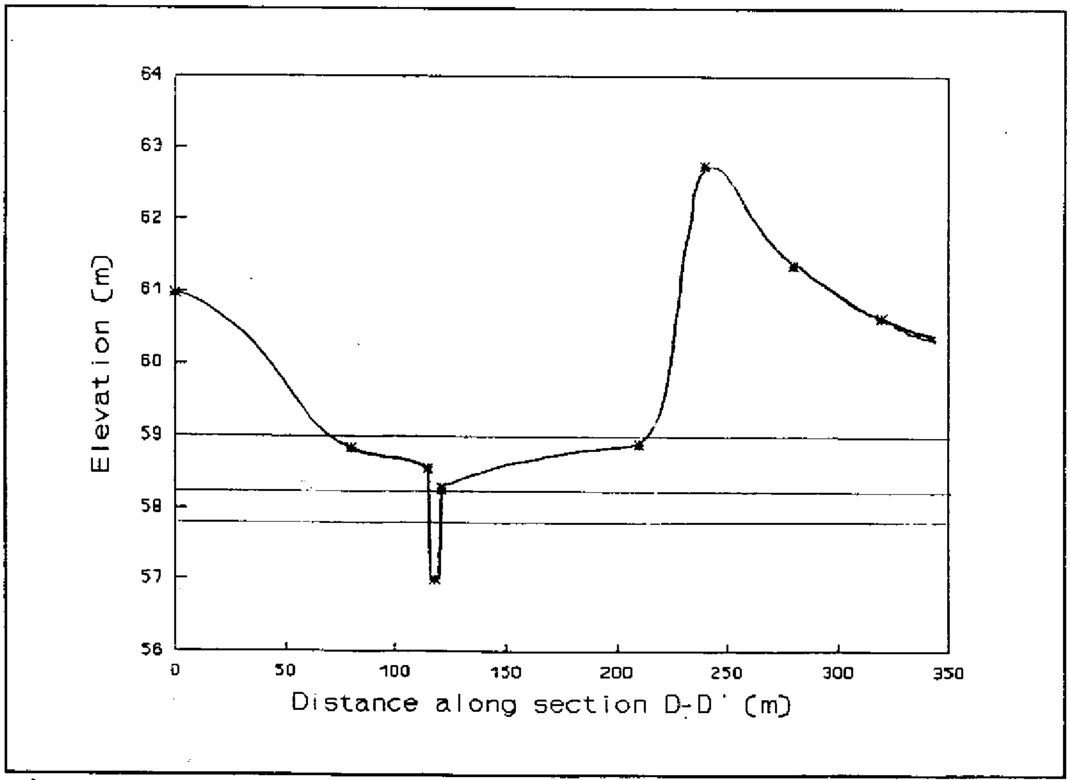


Figure 9.5 Cross-section D-D' across the lagg zone.

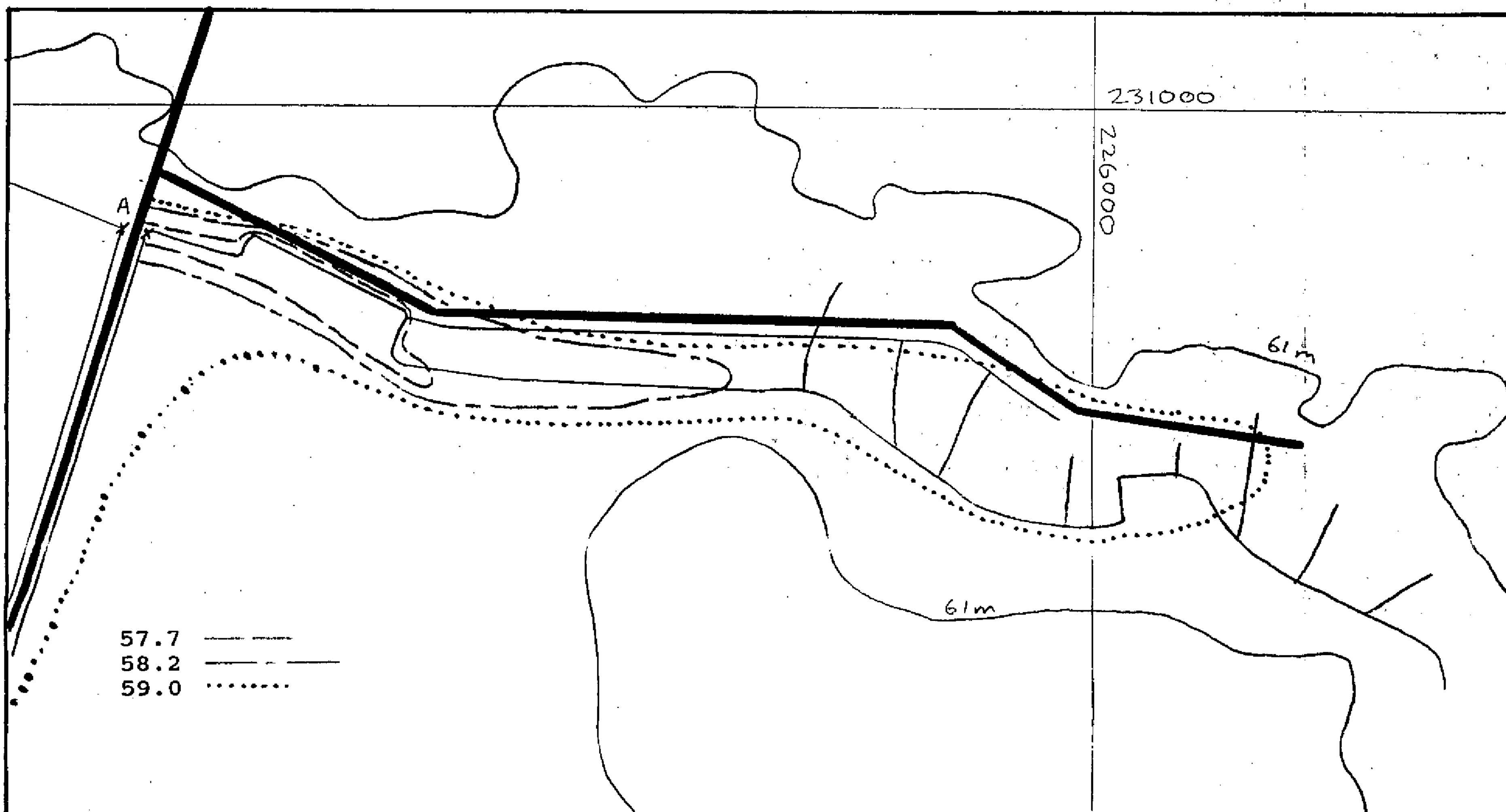


Figure 9.6 Estimated flooded areas on Clara east around the lagg zone under different water level rises.

Damming the drains at the southern end of the bog, thus raising the water level to a point where the hydraulic gradients will be reversed, will clearly have a major impact on the bog, in terms of the area which may be flooded. It should be noted that the estimates given in table 8.1 refer to the flooded area in the northeast part of the bog. As this is the highest side of the bog, the flooding in other areas will be more severe, in particular on the south side of the bog.

With the water level at 59.0 m, the bog road would be completely flooded, even at the northern end of the bog. If this option is adopted as a conservation measure, the road would need to be closed, and much farmland to the north of the bog would have to be purchased, as this too, would be flooded. Raising the water level to a point below the current piezometric surface at CLBH2 (57.7 m), in order to reduce the effects of flooding, would not significantly aid the conservation of the bog, as the newly formed lake would be filled with mineral-rich water, in which *Sphagnum* species would not be able to establish themselves. However, the rise in water level would help to slow down the drainage of the bog.

An alternative option to damming the drains at the southern end of the bog would be to dam the northeast drain, at the junction with the road drain, at the northern end of the bog, corresponding to point A in figure 9.6. This would not have such a drastic effect, in terms of flooding the whole bog. The flooding of the farmland to the north of the bog would still be as severe, but the effect on the road would be much less. This may be advantageous in economic terms, and for convenience, but in terms of conservation of the bog, the effect would be minimal. Although the northeast drain plays a significant role in the drainage of the bog, it has a smaller effect than the two road drains. Any engineering measures taken, to prevent drainage of the northern part of the bog, would not significantly aid the conservation of the bog in the long term. For any significant impact on conservation, efforts should be concentrated on preventing drainage at the southern end of the two road drains.

10. HYDROMETRIC DATABASE FOR CLARA EAST

The requirements of the database for Clara east have briefly been mentioned in section 1.2. The main focus of the database is the northeastern part of the bog, but data outside this area is also included. The structure of the database may be broken down into the following components:

1. Piezometer, Borehole, Cobra Drilling and Domestic Well Basic Information.
2. Groundwater Level Data.
3. Rainfall and Evapotranspiration Data.
4. Weir Water Level Data.
5. Hydraulic Conductivity Data.
6. Topographic Data.

All the data files are Lotus 1-2-3 spreadsheets with **.WK3** extensions. These will need to be updated regularly, and may require currently missing data to be entered.

A sample of each of the database files is given in appendices H1 to H8.

10.1 Piezometer Basic Information - TUBEDAT1.WK3

The piezometer database gives details of piezometers on the northern part of Clara east. For each piezometer, the following information is given:

1. Elevation of the top of the tube, and the height above ground level.
2. Ground level.
3. Tube length.
4. Elevation of the mid-point of the filter.
5. Co-ordinates of the piezometer on the OPW grid.

10.2 Borehole/Cobra Basic Information - BCWDAT1.WK3

The borehole and Cobra drilling database gives information on the piezometers, in each of the boreholes and Cobra drillings around Clara bog, up to July 1992. The information contained in the data file is as follows:

1. Elevation of the top of the borehole casing or cobra drilling tube.
2. Elevation of the mid-point of the filter of each piezometer.
3. Filter length of each piezometer.
4. Co-ordinates of the borehole, or Cobra drilling, on the OPW grid.

10.3 Domestic Well Basic Information - BCWDAT1.WK3

The domestic well database gives information on all domestic wells in the area as follows:

1. Elevation of the top of the well, from which water levels are measured.
2. Elevation of the bottom of the well.
3. Co-ordinates of the well on the OPW grid.

10.4 Groundwater Level Data - WATLEV*.WK3

Groundwater level data has been recorded since June 1990, in piezometers, domestic wells and boreholes. The frequency of recording varies, but is generally fortnightly or monthly. However, there are many gaps in this data, most notably from January to April 1992. From April 1992, water levels have been recorded fortnightly in the cobra drillings, boreholes, and selected domestic wells and piezometers. The **WATLEV*.WK3** files contain the following water level data:

WATLEV1.WK3	Piezometers 101 to 107
WATLEV2.WK3	Piezometers 108 to 111
WATLEV3.WK3	Piezometers 112 to 114, 119 to 120
WATLEV4.WK3	Piezometers 121 to 125
WATLEV5.WK3	Piezometers 126 to 131
WATLEV6.WK3	Piezometers 141 to 143, 151 to 154
WATLEV7.WK3	Domestic wells, Cobra drillings and boreholes

10.5 Rainfall Data - CWR*.WK3

Rainfall data has been recorded by a tipping bucket raingauge on Clara west on an hourly basis since 1989. The data record is continuous, apart from a few days each month due to technical problems with the recording equipment. The Clara West Rainfall, **CWR*.WK3** files contain the following rainfall data:

CWR89A.WK3	18/11/89 to 31/12/89
CWR90A.WK3	01/01/90 to 31/03/90
CWR90B.WK3	01/04/90 to 30/06/90
CWR90C.WK3	01/07/90 to 30/09/90
CWR90D.WK3	01/10/90 to 31/12/90
CWR91A.WK3	01/01/91 to 31/03/91
CWR91B.WK3	01/04/91 to 30/06/91
CWR91C.WK3	01/07/91 to 30/09/91
CWR91D.WK3	01/10/91 to 31/12/91
CWR92A.WK3	01/01/92 to 31/03/92
CWR92B.WK3	01/04/92 to 15/05/92

10.6 Evapotranspiration Data

As yet no evapotranspiration data has been collected for Clara bog, but by the end of 1992, lysimeter data and Penman evapotranspiration data should be available. Currently, the only evapotranspiration data which may be used is from weather stations at Birr and Mullingar. This data is in **PE_PNMAN.WK3**.

10.7 Weir Water Level Data - CEW*.WK3

Stage data at weirs DEH922 and DEH923 has been recorded at 15 minute intervals since the start of July 1992. Weir DEH921 should have an automatic data recorder installed in the autumn of 1992. The period covered by each data file should correspond to the rainfall records. The Clara East Weir, **CEW*.WK3** files contain the following stage data:

CEW592B.WK3	Weir DEH922:	29/06/92 to 26/07/92
CEW692B.WK3	Weir DEH923:	03/07/92 to 26/07/92

10.8 Hydraulic Conductivity Data - KCE.WK3

Hydraulic conductivity values have been calculated for selected piezometers on Clara east, from falling head tests. This data is given in **KCE.WK3**. The experimental data from which the hydraulic conductivity is calculated is given in **FALLHEAD.WK3**.

10.9 Topographic Data - GRNDLEV.WK3

Topographic data from the levelling of the bog carried out in September 1991 is given in **GRNDLEV.WK3**. This gives the ground level elevation above ordnance datum, every 100 m from the OPW grid datum on the bog road. The levels of the bolts on the bog road, on which the OPW grid is based, is given in **GRIDLEV.WK3**.

CONCLUSIONS AND RECOMMENDATIONS

The main conclusion of the project is that the drain on the northeast margin of the bog has a significant effect on the overall hydrology of the bog. Other drains around the bog are likely to have a similar effect. The source of the water in the drain has been shown to be partly from the bog and partly from the esker. Further analysis needs to be done in order to assess fully, how the influence of the drain changes seasonally. This will require further hydrochemical analysis at regular intervals, and the analysis of many storm hydrographs at the weirs in the east drain of the bog road.

The water balance of the bog has been upset by the presence of the drains, such that over a long period of time, the change in storage is significant, leading to settlement of the bog. If this drainage continues, the bog will eventually dry out to a point where further development of the bog is impossible. In order to assess the effects of the drain on the water balance, further studies must be made of the hydrochemistry, surface hydrology, and groundwater flow in the region around the drain.

Conservation of the bog depends very much on preventing flow from the bog. This will require the drains to be blocked, leading to large areas of bog and farmland being flooded. A thorough investigation of the effects of blocking the drains should be made. As an alternative to blocking the main drains from the bog, the northeast drain, and others, may be blocked, so that flooding would be less of a problem. However, it is unlikely that this would aid the conservation of the bog in the long term, as these smaller perimeter drains have less impact than the road drains on the overall hydrology.

The analysis of the drain for this project has been concentrated on one cross-section. It is proposed that other sections across the lagg zone are studied, in order to get a more complete picture of lagg zone hydrology. It would also be useful to look at different lagg zones, on other parts of Clara bog in order to understand how the hydrology of the bog is affected on a larger scale.

Currently, the model of the lagg zone is a reasonable representation of the hydrogeological system. Future modelling should concentrate on developing the model to a stage where the current situation is more accurately simulated. The boundary condition in the drain may then be changed, allowing the effectiveness of various conservation measures to be assessed. Recommendations for the conservation of Clara bog may then be made, with a greater degree of certainty than at present.

BIBLIOGRAPHY

Bell, J., *A Study of the Hydrological Effects of a Bog Road, Clara Bog, County Offaly,* Department of Civil Engineering, Imperial College London, 1991.

Bellamy, D.J., *Bellamy's Ireland - The Wild Boglands,* Country House, Dublin, 1986.

Cooper, H.H. and Jacob, C.E., *A Generalised Graphical Method for Evaluating Formation Constants and Summarising Wellfield History,* Trans. Amer. Geophysical Union, 27, 1946.

Cross, J.R., *Peatlands: Wasteland or Heritage,* Wildlife Service Ireland, 1989.

Flynn, R., *Clara Bog: A hydrogeological study,* Department of Geological Sciences, University of Birmingham, 1990.

Gore, A.J.P., *Ecosystems of the World 4A; Mires: Swamp, Bog, Fen and Moor - Introduction,* Elsevier Scientific Publishing Company, Oxford, 1983.

Hobbs, N.B., *Mire Morphology and the Properties and Behaviour of some British and Foreign Peats,* Quarterly Journal of Engineering Hydrology, 19, 1986.

Ingram, H.A.P., *Ecosystems of the World 4A; Mires: Swamp, Bog, Fen and Moor - Hydrology,* Elsevier Scientific Publishing Company, Oxford, 1983.

Ingram, H.A.P., Rycroft, D.W., and Williams, D.J.A., *Anomalous Transmission of Water Through Certain Peats,* Journal of Hydrology, Amsterdam, 22, 1974.

Kirkham, D., *Proposed Method for Field Measurement of Permeability of Soil Below the Water Table,* Proc. Soil Sci. Soc. Am., 10, 1945.

Logan, J., *Estimation of Electrical Conductivity from Chemical Analysis of Natural Waters,* Journal of Geophysical Research, 66, 1961.

Mitchell, F., *Reading the Irish Landscape,* Collins, London, 1975.

Shaw, E.M., *Hydrology in Practice,* 2nd edition, Chapman and Hall, London, 1988.

Samuels, H., *Settlement and Drainage of a Raised Bog,* Department of Civil Engineering, Imperial College London, 1992.

Sijtsma, B., Chapter six, *Piezometer Tests,* Draft report, University of Wageningen, The Netherlands, 1992.

Smyth, M., *A preliminary 3-Dimensional Space Form Model of Clara Bog, Co. Offaly,* University College Galway, 1991.

Smyth, M., *Geophysical Mapping Techniques to Investigate the Geological Structure of two Raised Bogs, Clara and Raheenmore, Co. Offaly,* University College Galway, 1992.

Taylor, J.A., *Ecosystems of the World 4B; Mires: Swamp, Bog, Fen and Moor - The Peatlands of Great Britain and Ireland*, Elsevier Scientific Publishing Company, Oxford, 1983.

Todd, D.K., *Groundwater Hydrology,* 2nd edition, John Wiley & Sons, New York, 1980.

Waine, J., Brown, J.M.B., and Ingram, H.A.P., *Non-Darcian Transmission of Water in Certain Humified Peats,* Journal of Hydrology, Amsterdam, 82, 1985.

LIST OF APPENDICES

APPENDIX A

Head Data used in Equipotential Construction

EQUIPOTENTIAL HEAD DATA: Section across drain, 09/07/92

Distance along flow line (m)	Piezo nest	Piezo no.	Tube elev. (m)	Water level (m)	Piezo. level (m)	filter elev. (m)	Ground level (m)
735	104	1	59.09	0.85	58.24	54.70	58.68
		2	59.09	0.74	58.35	55.69	
		3	59.09	0.63	58.46	56.70	
		4	59.10	0.64	58.46	WT	
742	143	1	57.98	0.34	57.64	53.78	57.79
		2	57.99	0.37	57.63	54.89	
		3	57.99	0.48	57.52	55.89	
		4	58.23	0.62	57.61	WT	
749	103	1	57.46	-	-	54.76	57.27
		2	57.46	0.24	57.22	55.36	
		3	57.46	0.25	57.21	56.06	
		4	57.73	0.49	57.24	WT	
752	142	1	57.67	-	57.67	54.97	57.51
		2	57.67	0.49	57.18	55.57	
		3	57.67	0.52	57.14	56.27	
		4	57.97	0.80	57.18	WT	
754	102	1	57.77	0.48	57.29	55.07	57.57
		2	57.77	0.60	57.17	55.67	
		3	57.77	0.65	57.12	56.37	
		4	57.97	0.87	57.10	WT	
756	141	1	57.79	0.53	57.26	55.59	57.64
		2	57.79	0.92	56.87	56.09	
		3	57.79	0.91	56.88	56.69	
		4	58.11	1.23	56.88	WT	
758	101	1	57.59	0.26	57.33	55.49	57.39
		2	57.53	0.54	56.99	55.93	
		3	57.53	0.77	56.76	56.43	
		4	57.75	0.99	56.77	WT	
760	Drain		56.10	-0.50	56.60		56.10
764	CLBH2	1	58.35	0.63	57.72	46.73	57.72
		2	58.35	0.76	57.59	52.48	
		3	58.35	0.77	57.58	55.63	
914	CLBH3	1	64.32	6.48	57.84	51.63	63.85

EQUIPOTENTIAL HEAD DATA: Section across bog and esker, 09/07/92

Distance along flow line (m)	Piezo nest	Piezo no.	Tube elev. (m)	Water level (m)	Piezo. level (m)	filter elev. (m)	Ground level (m)
0	126	1	61.25	0.67	60.58	53.93	60.93
		2	61.29	0.48	60.81	58.43	
		3	61.24	0.51	60.73	55.84	
		4	61.28	0.47	60.81	58.91	
		5	61.34	0.50	60.84	WT	
200	123	1	60.89	0.73	60.16	53.74	60.89
		2	60.89	0.36	60.53	55.68	
		3	60.91	0.21	60.70	57.52	
		4	60.94	0.22	60.72	WT	
360	152	1	60.97	0.77	60.20	52.07	60.7
		2	60.97	0.60	60.37	54.07	
		3	60.97	0.47	60.50	56.07	
		4	60.97	0.36	60.61	58.07	
		5	61.11	0.48	60.63	WT	
505	151	1	60.60	0.75	59.85	51.70	60.33
		2	60.60	0.74	59.86	53.70	
		3	60.60	0.50	60.10	55.70	
		4	60.60	0.36	60.24	57.70	
		5	60.78	0.52	60.26	WT	
715	106	1	59.87	0.79	59.08	55.03	59.46
		2	59.88	0.70	59.18	56.52	
		3	59.88	0.69	59.19	57.46	
		4	59.89	0.66	59.23	WT	
754	102	1	57.77	0.48	57.29	55.07	57.57
		2	57.77	0.60	57.17	55.67	
		3	57.77	0.65	57.12	56.37	
		4	57.97	0.87	57.10	WT	
760	Drain		56.10	-0.40	56.50	Drain W	56.10
764	CLBH2	1	58.35	0.63	57.72	46.73	57.72
		2	58.35	0.76	57.59	52.48	
		3	58.35	0.77	57.58	55.63	
914	CLBH3	1	64.32	6.48	57.84	51.63	63.85

APPENDIX B

Falling Head Test Data and Graphs

PIEZOMETER TEST : 101.1

t0 : 36 min   y0 : 8.8 cm
start WL: 25.8 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
36	0	17.0	8.8	0.0000
37	1	17.1	8.7	0.0114
44	8	17.2	8.6	0.0230
54	18	17.4	8.4	0.0465
100	64	17.7	8.1	0.0829
203	167	18.0	7.8	0.1206
280	244	18.3	7.5	0.1598
399	363	18.5	7.3	0.1869
1100	1064	19.8	6.0	0.3830
1515	1479	20.2	5.6	0.4520
1863	1827	20.7	5.1	0.5455
2655	2619	21.2	4.6	0.6487

Regression Output:

Constant	0.204622
Std Err of Y Est	0.020016
R Squared	0.97995
No. of Observations	4
Degrees of Freedom	2

X Coefficient(s) 0.000173
Std Err of Coef. 0.000018

PIEZOMETER TEST : 101.2

t0 : 1 min   y0 : 19.5 cm
start WL: 54 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
1	0	34.5	19.5	0.0000
6	5	34.5	19.5	0.0000
17	16	34.5	19.5	0.0000
38	37	34.5	19.5	0.0000
60	59	34.7	19.3	0.0103
120	119	34.8	19.2	0.0155
200	199	35.0	19.0	0.0260
297	296	35.2	18.8	0.0366
387	386	35.4	18.6	0.0473
615	614	36.1	17.9	0.0856
738	737	36.6	17.4	0.1139
1546	1545	38.3	15.7	0.2168
1877	1876	38.8	15.2	0.2491
2773	2772	40.7	13.3	0.3827
8605	8604	48.2	5.8	1.2126
9235	9234	48.9	5.1	1.3412

Regression Output:

Constant	-0.00831
Std Err of Y Est	0.01743
R Squared	0.999177
No. of Observations	6
Degrees of Freedom	4

X Coefficient(s)	0.000144
Std Err of Coef.	2.1E-06

PIEZOMETER TEST : 101.3

t0 : 2 min   y0 : 9.8 cm
start WL: 79.5 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
2	0	69.7	9.8	0.0000
4	2	69.8	9.7	0.0103
13	11	70.2	9.3	0.0524
31	29	70.9	8.6	0.1306
77	75	72.1	7.4	0.2809
113	111	73.0	6.5	0.4106
177	175	74.4	5.1	0.6531
303	301	76.8	2.7	1.2891
383	381	78.0	1.5	1.8769

Regression Output:

Constant	-0.05063
Std Err of Y Est	0.091122
R Squared	0.983995
No. of Observations	8
Degrees of Freedom	6

X Coefficient(s)	0.004709
Std Err of Coef.	0.000245

PIEZOMETER TEST : 102.1

t0 :	47 min	y0 :	18.1 cm
start WL:	48 cm		

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
47	0	29.9	18.1	0.0000
49	2	30.2	17.8	0.0167
55	8	30.2	17.8	0.0167
68	21	30.4	17.6	0.0280
95	48	30.8	17.2	0.0510
205	158	31.6	16.4	0.0986
282	235	32.1	15.9	0.1296
401	354	32.8	15.2	0.1746
1100	1053	37.0	11.0	0.4980
1225	1178	37.5	10.5	0.5445
1515	1468	38.6	9.4	0.6552
1730	1683	39.4	8.6	0.7441
1862	1815	39.7	8.3	0.7797
2657	2610	41.2	6.8	0.9790

Regression Output:

Constant	0.101097
Std Err of Y Est	0.005916
R Squared	0.998243
No. of Observations	5
Degrees of Freedom	3
X Coefficient(s)	0.000377
Std Err of Coef.	9.1E-06

PIEZOMETER TEST : 102.2

t0 : 10 min y0 : 10.5 cm
start WL: 61 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
10	0	50.5	10.5	0.0000
20	10	51.5	9.5	0.1001
37	27	53.3	7.7	0.3102
64	54	54.9	6.1	0.5431
98	88	56.4	4.6	0.8253
123	113	57.5	3.5	1.0986
203	193	59.0	2.0	1.6582
260	250	59.9	1.1	2.2561
299	289	60.0	1.0	2.3514
389	379	60.3	0.7	2.7081
601	591	60.6	0.4	3.2677

Regression Output:

Constant	1.516252
Std Err of Y Est	0.047784
R Squared	0.992742
No. of Observations	4
Degrees of Freedom	2

X Coefficient(s)	0.002994
Std Err of Coef.	0.000181

PIEZOMETER TEST : 102.3

t0 : 6 min   y0 : 9 cm
start WL: 68.8 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
6	0	59.8	9.0	0.0000
14	8	60.5	8.3	0.0810
32	26	61.8	7.0	0.2513
78	72	64.1	4.7	0.6497
114	108	65.4	3.4	0.9734
178	172	66.9	1.9	1.5554
305	299	68.3	0.5	2.8904

Regression Output:

Constant	-0.0946
Std Err of Y Est	0.046899
R Squared	0.998501
No. of Observations	4
Degrees of Freedom	2
X Coefficient(s)	0.009904
Std Err of Coef.	0.000271

PIEZOMETER TEST : 103.2

t0 : 25 min   y0 : 8.4 cm
start WL: 24.8 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y)
25	0	16.4	8.4	0.0000
33	8	19.4	5.4	0.4418
40	15	20.7	4.1	0.7172
50	25	22.0	2.8	1.0986
55	30	22.3	2.5	1.2119
66	41	23.2	1.6	1.6582
77	52	23.5	1.3	1.8659
92	67	23.8	1.0	2.1282
124	99	24.3	0.5	2.8214

Regression Output:

Constant	0.818225
Std Err of Y Est	0.02978
R Squared	0.997696
No. of Observations	4
Degrees of Freedom	2

X Coefficient(s) 0.02008
Std Err of Coef. 0.000682

PIEZOMETER TEST : 103.3

t0 : 220 min   y0 : 6 cm
start WL: 24.9 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
220	0	18.9	6.0	0.0000
221	1	19.2	5.7	0.0513
225	5	20.8	4.1	0.3808
228	8	21.7	3.2	0.6286
232	12	22.4	2.5	0.8755
240	20	23.5	1.4	1.4553
252	32	24.1	0.8	2.0149
273	53	24.6	0.3	2.9957

Regression Output:

Constant	0.521399
Std Err of Y Est	0.00044
R Squared	1
No. of Observations	3
Degrees of Freedom	1

X Coefficient(s)	0.046683
Std Err of Coef.	0.000019

PIEZOMETER TEST : 104.1

t0 : 11 min y0 : 5.9 cm
start WL: 85.3 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
11	0	79.4	5.9	0.0000
15	4	82.4	2.9	0.7102
20	9	83.9	1.4	1.4385
27	16	84.5	0.8	1.9981
30	19	84.7	0.6	2.2858
35	24	84.8	0.5	2.4681

Regression Output:

Constant	1.139956
Std Err of Y Est	0.09005
R Squared	0.927793
No. of Observations	3
Degrees of Freedom	1

X Coefficient(s)	0.056476
Std Err of Coef.	0.015755

PIEZOMETER TEST : 104.2

t0 : 73 min   y0 : 11.6 cm
start WL: 73.6 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
73	0	62.0	11.6	0.0000
75	2	62.0	11.6	0.0000
80	7	62.3	11.3	0.0262
95	22	62.7	10.9	0.0622
126	53	63.1	10.5	0.0996
205	132	64.2	9.4	0.2103
248	175	64.9	8.7	0.2877
300	227	65.2	8.4	0.3228
392	319	66.2	7.4	0.4495
490	417	66.9	6.7	0.5489
600	527	67.9	5.7	0.7105
743	670	68.5	5.1	0.8218
1256	1183	70.4	3.2	1.2879
1530	1457	70.8	2.8	1.4214
1888	1815	71.4	2.2	1.6625
2038	1965	71.7	1.9	1.8092

Regression Output:

Constant	0.486125
Std Err of Y Est	0.033745
R Squared	0.986197
No. of Observations	4
Degrees of Freedom	2

X Coefficient(s) 0.00066
Std Err of Coef. 0.000055

PIEZOMETER TEST : 104.3

t0 : 5 min y0 : 6.8 cm
start WL: 63.1 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
5	0	56.3	6.8	0.0000
8	3	56.3	6.8	0.0000
27	22	56.4	6.7	0.0148
155	150	57.5	5.6	0.1942
250	245	57.9	5.2	0.2683
391	386	58.8	4.3	0.4583
453	448	59.0	4.1	0.5059
542	537	59.4	3.7	0.6086
1335	1330	61.4	1.7	1.3863
1680	1675	61.9	1.2	1.7346

Regression Output:

Constant	0.066607
Std Err of Y Est	0.007586
R Squared	0.999893
No. of Observations	4
Degrees of Freedom	2

X Coefficient(s) 0.000995
Std Err of Coef. 7.3E-06

PIEZOMETER TEST : 106.1

t0 : 266 min y0 : 7.9 cm
start WL: 79.8 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
266	0	71.9	7.9	0.0000
268	2	72.4	7.4	0.0654
271	5	72.6	7.2	0.0928
282	16	73.6	6.2	0.2423
305	39	75.5	4.3	0.6082
397	131	78.2	1.6	1.5969
492	226	78.9	0.9	2.1722
605	339	79.3	0.5	2.7600
744	478	79.5	0.3	3.2708

Regression Output:

Constant	1.227676
Std Err of Y Est	0.077556
R Squared	0.990049
No. of Observations	3
Degrees of Freedom	1

X Coefficient(s)	0.004334
Std Err of Coef.	0.000434

PIEZOMETER TEST : 106.2

t0 : 83 min y0 : 8.6 cm
start WL: 70.2 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
83	0	61.6	8.6	0.0000
85	2	62.6	7.6	0.1236
88	5	63.8	6.4	0.2955
90	7	64.8	5.4	0.4654
94	11	65.3	4.9	0.5625
103	20	66.3	3.9	0.7908
128	45	67.7	2.5	1.2355
206	123	69.0	1.2	1.9694
246	163	69.4	0.8	2.3749
270	187	69.5	0.7	2.5084
420	337	69.8	0.4	3.0681
604	521	69.9	0.3	3.3557

Regression Output:

Constant	2.106381
Std Err of Y Est	0.145977
R Squared	0.942606
No. of Observations	3
Degrees of Freedom	1

X Coefficient(s)	0.002501
Std Err of Coef.	0.000617

PIEZOMETER TEST : 106.3

t0 : 5 min   y0 : 22.9 cm
start WL: 70.5 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
5	0	47.6	22.9	0.0000
5.5	0.5	48.0	22.5	0.0176
6	1	48.5	22.0	0.0401
7	2	49.1	21.4	0.0677
8	3	49.7	20.8	0.0962
9	4	50.4	20.1	0.1304
10	5	50.9	19.6	0.1556
12	7	51.5	19.0	0.1867
15	10	52.7	17.8	0.2519
20	15	54.0	16.5	0.3278
25	20	55.6	14.9	0.4298
42	37	58.4	12.1	0.6379
64	59	60.6	9.9	0.8386
91	86	62.5	8.0	1.0517
112	107	63.8	6.7	1.2290
201	196	66.8	3.7	1.8228
286	281	67.9	2.6	2.1756
398	393	69.0	1.5	2.7257

Regression Output:

Constant	0.73667
Std Err of Y Est	0.07223
R Squared	0.991177
No. of Observations	4
Degrees of Freedom	2

X Coefficient(s)	0.005124
Std Err of Coef.	0.000342

PIEZOMETER TEST : 123.1

t0 : 223 min y0 : 6.5 cm
start WL: 72.8 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
223	0	66.3	6.5	0.0000
231	8	66.3	6.5	0.0000
441	218	67.9	4.9	0.2826
550	327	68.6	4.2	0.4367
1012	789	70.0	2.8	0.8422
1348	1125	70.5	2.3	1.0389
1653	1430	70.8	2.0	1.1787

Regression Output:

Constant	0.433663
Std Err of Y Est	0.016599
R Squared	0.995178
No. of Observations	3
Degrees of Freedom	1

X Coefficient(s)	0.000526
Std Err of Coef.	0.000037

PIEZOMETER TEST : 123.2

t0 : 107 min y0 : 7.1 cm
start WL: 36.4 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
107	0	29.3	7.1	0.0000
108	1	29.8	6.6	0.0730
110	3	30.6	5.8	0.2022
114	7	31.8	4.6	0.4340
135	28	34.1	2.3	1.1272
144	37	34.8	1.6	1.4901
175	68	35.5	0.9	2.0655
194	87	35.7	0.7	2.3168

Regression Output:

Constant	0.886666
Std Err of Y Est	0.05081
R Squared	0.992813
No. of Observations	3
Degrees of Freedom	1

X Coefficient(s)	0.016731
Std Err of Coef.	0.001424

PIEZOMETER TEST : 126.1

t0 : 0 min y0 : 12.5 cm

Time t (min)	t - t0 (min)	y (cm)	ln(y0/y) -
0	0	12.5	0.0000
0.8	0.8	10.4	0.1839
1.6	1.6	9.2	0.3065
2.3	2.3	8.5	0.3857
3	3	7.7	0.4845
4	4	6.9	0.5942
5.5	5.5	5.7	0.7853
6.4	6.4	5.1	0.8965
8	8	4.4	1.0441
10	10	3.6	1.2448
12	12	3.2	1.3626
15	15	2.3	1.6928
19	19	1.9	1.8839
24	24	1.4	2.1893
31	31	1.0	2.5257
41	41	0.8	2.7489
56	56	0.6	3.0366

Regression Output:

Constant	1.666891
Std Err of Y Est	0.091995
R Squared	0.955972
No. of Observations	4
Degrees of Freedom	2
X Coefficient(s)	0.025216
Std Err of Coef.	0.003827

PIEZOMETER TEST : 126.3

t0 : 185 min   y0 : 6.4 cm
start WL: 51.4 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
185	0	45.0	6.4	0.0000
187	2	46.0	5.4	0.1699
190	5	46.9	4.5	0.3522
198	13	48.4	3.0	0.7577
214	29	49.7	1.7	1.3257
237	52	50.4	1.0	1.8563

Regression Output:

Constant	0.441726
Std Err of Y Est	0.095242
R Squared	0.984975
No. of Observations	3
Degrees of Freedom	1

X Coefficient(s) 0.027814
Std Err of Coef. 0.003435

PIEZOMETER TEST : 126.4

t0 : 122 min y0 : 6.3 cm
start WL: 46.9 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
122	0	40.6	6.3	0.0000
124	2	42.0	4.9	0.2513
126	4	42.8	4.1	0.4296
131	9	44.0	2.9	0.7758
140	18	45.0	1.9	1.1987
164	42	46.1	0.8	2.0637
180	58	46.4	0.5	2.5337

Regression Output:

Constant	0.610997
Std Err of Y Est	0.051908
R Squared	0.997062
No. of Observations	3
Degrees of Freedom	1

X Coefficient(s)	0.033586
Std Err of Coef.	0.001823

PIEZOMETER TEST : 141.1

t0 : 38 min y0 : 15.2 cm
start WL: 53.1 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
38	0	37.9	15.2	0.0000
39	1	38.5	14.6	0.0403
40	2	38.8	14.3	0.0610
45	7	40.4	12.7	0.1797
51	13	42.0	11.1	0.3144
69	31	45.1	8.0	0.6419
98	60	48.7	4.4	1.2397
113	75	49.9	3.2	1.5581
204	166	53.1	0.0	ERR
281	243	54.0	-0.9	ERR

Regression Output:

Constant	0
Std Err of Y Est	0.023695
R Squared	0.998414
No. of Observations	8
Degrees of Freedom	7
X Coefficient(s)	0.020813
Std Err of Coef.	0.000232

PIEZOMETER TEST : 141.2

t0 : 5 min   y0 : 11.7 cm
start WL: 92 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
5	0	80.3	11.7	0.0000
7	2	80.4	11.6	0.0086
18	13	81.2	10.8	0.0800
36	31	82.4	9.6	0.1978
61	56	83.8	8.2	0.3555
100	95	85.4	6.6	0.5725
122	117	86.0	6.0	0.6678
201	196	88.0	4.0	1.0733
259	254	88.9	3.1	1.3282
298	293	89.4	2.6	1.5041
390	385	90.2	1.8	1.8718
486	481	90.7	1.3	2.1972
600	595	91.1	0.9	2.5649
739	734	91.5	0.5	3.1527

Regression Output:

Constant	0.435805
Std Err of Y Est	0.036613
R Squared	0.997511
No. of Observations	5
Degrees of Freedom	3

X Coefficient(s)	0.003662
Std Err of Coef.	0.000106

PIEZOMETER TEST : 141.3

t0 : 0 min y0 : 12.1 cm
start WL: 91.4 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
0	0	79.3	12.1	0.0000
2	2	79.7	11.7	0.0336
6	6	80.3	11.1	0.0863
10	10	80.7	10.7	0.1230
16	16	81.3	10.1	0.1807
26	26	81.9	9.5	0.2419
52	52	83.9	7.5	0.4783
69	69	84.7	6.7	0.5911
156	156	87.7	3.7	1.1849
251	251	89.2	2.2	1.7047
382	382	90.4	1.0	2.4932
451	451	90.7	0.7	2.8499

Regression Output:

Constant	0.288804
Std Err of Y Est	0.023033
R Squared	0.999377
No. of Observations	4
Degrees of Freedom	2

X Coefficient(s) 0.005708
Std Err of Coef. 0.000101

PIEZOMETER TEST : 142.1

t0 : 48 min y0 : 13.8 cm
start WL: 29.8 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
48	0	16.0	13.8	0.0000
50	2	16.4	13.4	0.0294
52	4	16.8	13.0	0.0597
67	19	17.8	12.0	0.1398
94	46	19.0	10.8	0.2451
206	158	22.9	6.9	0.6931
283	235	24.6	5.2	0.9760
402	354	26.2	3.6	1.3437

Regression Output:

Constant	0.106843
Std Err of Y Est	0.037441
R Squared	0.995654
No. of Observations	4
Degrees of Freedom	2

X Coefficient(s) 0.00357
Std Err of Coef. 0.000167

PIEZOMETER TEST : 142.3

t0 : 216 min   y0 : 15.6 cm
start WL: 54 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
216	0	38.4	15.6	0.0000
218	2	38.9	15.1	0.0326
222	6	39.4	14.6	0.0662
226	10	39.9	14.1	0.1011
235	19	41.0	13.0	0.1823
253	37	42.6	11.4	0.3137
302	86	45.4	8.6	0.5955
393	177	48.9	5.1	1.1180
488	272	50.7	3.3	1.5533
609	393	51.8	2.2	1.9588
741	525	52.4	1.6	2.2773
900	684	52.9	1.1	2.6520

Regression Output:

Constant	1.02451
Std Err of Y Est	0.003291
R Squared	0.999955
No. of Observations	3
Degrees of Freedom	1

X Coefficient(s)	0.002381
Std Err of Coef.	0.000016

PIEZOMETER TEST : 143.1

t0 : 8 min y0 : 5.1 cm
start WL: 34.1 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
8	0	29.0	5.1	0.0000
33	25	29.1	5.0	0.0198
80	72	29.4	4.7	0.0817
180	172	29.7	4.4	0.1476
305	297	30.2	3.9	0.2683
386	378	30.5	3.6	0.3483
627	619	31.0	3.1	0.4978

Regression Output:

Constant	0.016621
Std Err of Y Est	0.019903
R Squared	0.990105
No. of Observations	6
Degrees of Freedom	4

X Coefficient(s) 0.000809
Std Err of Coef. 0.00004

PIEZOMETER TEST : 143.2

t0 : 29 min y0 : 12.2 cm
start WL: 37.5 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
29	0	25.3	12.2	0.0000
30	1	26.8	10.7	0.1312
32	3	28.6	8.9	0.3154
34	5	30.4	7.1	0.5413
41	12	33.3	4.2	1.0664
46	17	34.5	3.0	1.4028
52	23	35.0	2.5	1.5851
58	29	35.6	1.9	1.8596
67	38	36.4	1.1	2.4061
76	47	36.9	0.6	3.0123
86	57	37.2	0.3	3.7054
97	68	37.3	0.2	4.1109
125	96	37.4	0.1	4.8040

Regression Output:

Constant	2.180961
Std Err of Y Est	0.075697
R Squared	0.990717
No. of Observations	3
Degrees of Freedom	1

X Coefficient(s) 0.0275
Std Err of Coef. 0.002662

PIEZOMETER TEST : 143.3

t0 : 224 min y0 : 12.5 cm
start WL: 47.5 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
224	0	35.0	12.5	0.0000
227	3	35.1	12.4	0.0080
237	13	35.4	12.1	0.0325
251	27	35.8	11.7	0.0661
301	77	37.3	10.2	0.2033
394	170	38.9	8.6	0.3740
490	266	40.0	7.5	0.5108
607	383	42.0	5.5	0.8210
742	518	43.4	4.1	1.1147
1255	1031	46.0	1.5	2.1203
1528	1304	46.8	0.7	2.8824
1655	1431	46.9	0.6	3.0366

Regression Output:

Constant	-0.02987
Std Err of Y Est	0.090004
R Squared	0.993012
No. of Observations	4
Degrees of Freedom	2

X Coefficient(s)	0.002165
Std Err of Coef.	0.000128

PIEZOMETER TEST : 151.1

t0 : 84 min y0 : 8 cm
start WL: 75.3 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
84	0	67.3	8.0	0.0000
86	2	67.3	8.0	0.0000
94	10	67.5	7.8	0.0253
150	66	68.5	6.8	0.1625
246	162	69.6	5.7	0.3390
395	311	70.9	4.4	0.5978
447	363	71.1	4.2	0.6444
546	462	71.8	3.5	0.8267
1342	1258	73.2	2.1	1.3375
1682	1598	73.6	1.7	1.5488

Regression Output:

Constant	0.533409
Std Err of Y Est	0.003836
R Squared	0.999947
No. of Observations	3
Degrees of Freedom	1

X Coefficient(s)	0.000637
Std Err of Coef.	4.7E-06

PIEZOMETER TEST : 151.3

t0 : 41 min y0 : 7.1 cm
start WL: 51.1 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
41	0	44.0	7.1	0.0000
43	2	45.1	6.0	0.1683
45	4	45.8	5.3	0.2924
54	13	47.8	3.3	0.7662
72	31	49.5	1.6	1.4901
90	49	50.2	0.9	2.0655
108	67	50.5	0.6	2.4709

Regression Output:

Constant	0.673805
Std Err of Y Est	0.069361
R Squared	0.990097
No. of Observations	3
Degrees of Freedom	1
X Coefficient(s)	0.027245
Std Err of Coef.	0.002725

PIEZOMETER TEST : 151.4

t0 : 76 min y0 : 5.5 cm
start WL: 36 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
76	0	30.5	5.5	0.0000
77	1	32.4	3.6	0.4238
78	2	33.4	2.6	0.7492
80	4	34.7	1.3	1.4424
81	5	34.9	1.1	1.6094
82	6	35.0	1.0	1.7047
85	9	35.7	0.3	2.9087

PIEZOMETER TEST : 152.1

t0 : 0 min y0 : 8.3 cm

Time t (min)	t - t0 (min)	y (cm)	ln(y0/y) -
0	0	8.3	0.0000
21	21	7.8	0.0621
47	47	7.5	0.1014
163	163	6.8	0.1993
281	281	6.5	0.2445
1569	1569	6.3	0.2757

PIEZOMETER TEST : 152.3

t0 : 49 min y0 : 7.6 cm
start WL: 47.8 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
49	0	40.2	7.6	0.0000
51	2	40.9	6.9	0.0966
56	7	42.1	5.7	0.2877
69	20	43.5	4.3	0.5695
92	43	44.8	3.0	0.9295
106	57	45.2	2.6	1.0726
185	136	46.6	1.2	1.8458
296	247	47.4	0.4	2.9444

Regression Output:

Constant	0.507036
Std Err of Y Est	0.003341
R Squared	0.999991
No. of Observations	4
Degrees of Freedom	2

X Coefficient(s)	0.009864
Std Err of Coef.	0.000021

PIEZOMETER TEST : 152.4

t0 : 90 min   y0 : 9.2 cm
start WL: 36 cm

Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y)
90	0	26.8	9.2	0.0000
91	1	27.0	9.0	0.0220
96	6	28.0	8.0	0.1398
100	10	28.6	7.4	0.2177
147	57	31.6	4.4	0.7376
172	82	32.5	3.5	0.9664
243	153	33.7	2.3	1.3863
398	308	35.0	1.0	2.2192
444	354	35.2	0.8	2.4423

Regression Output:

Constant	0.5379
Std Err of Y Est	0.021953
R Squared	0.999333
No. of Observations	4
Degrees of Freedom	2

X Coefficient(s) 0.005421
Std Err of Coef. 0.000099

PIEZOMETER TEST : CLBH2.3

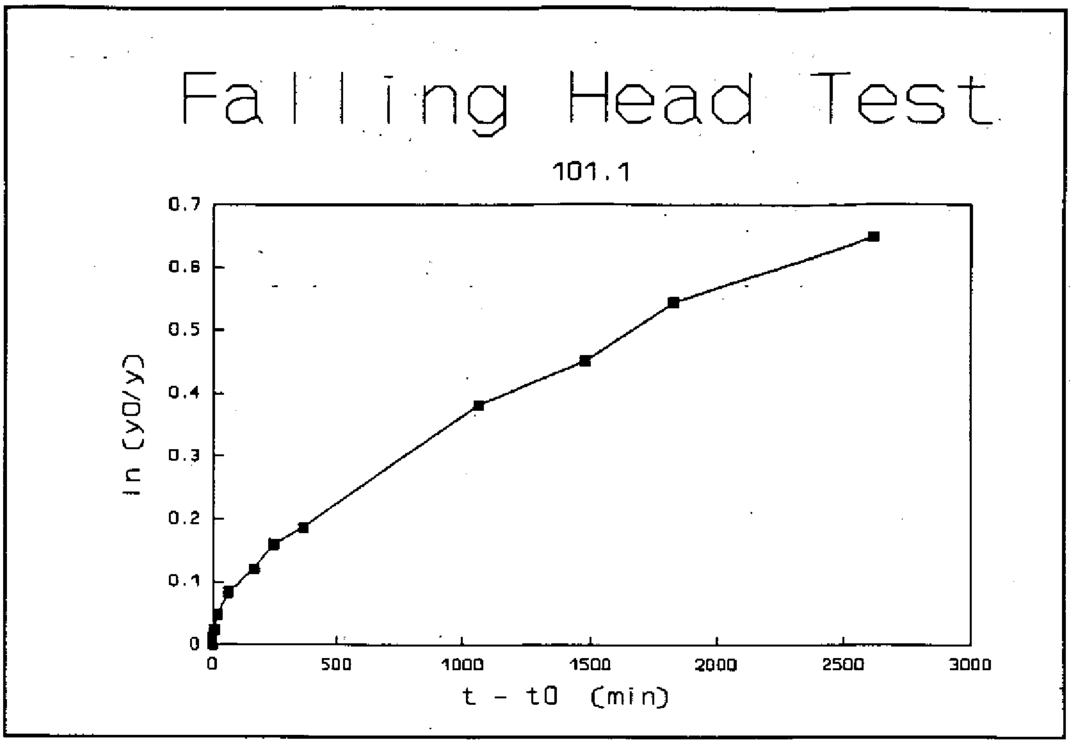
t0 : 83 min y0 : 21.5
start WL: 73.5 cm

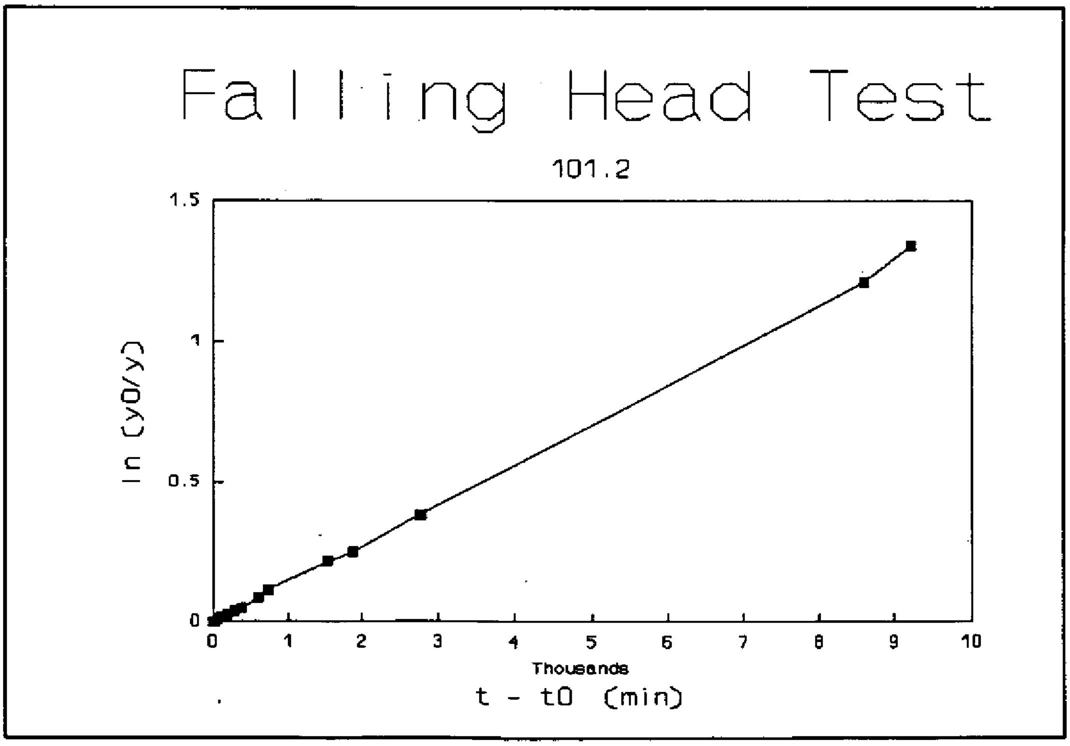
Time t (min)	t - t0 (min)	Water Level (cm)	y (cm)	ln(y0/y) -
83	0	52.0	21.5	0.0000
84	1	52.4	21.1	0.0188
87	4	53.4	20.1	0.0673
96	13	55.8	17.7	0.1945
108	25	58.4	15.1	0.3534
208	125	69.6	3.9	1.7071
289	206	72.0	1.5	2.6626
404	321	73.4	0.1	5.3706

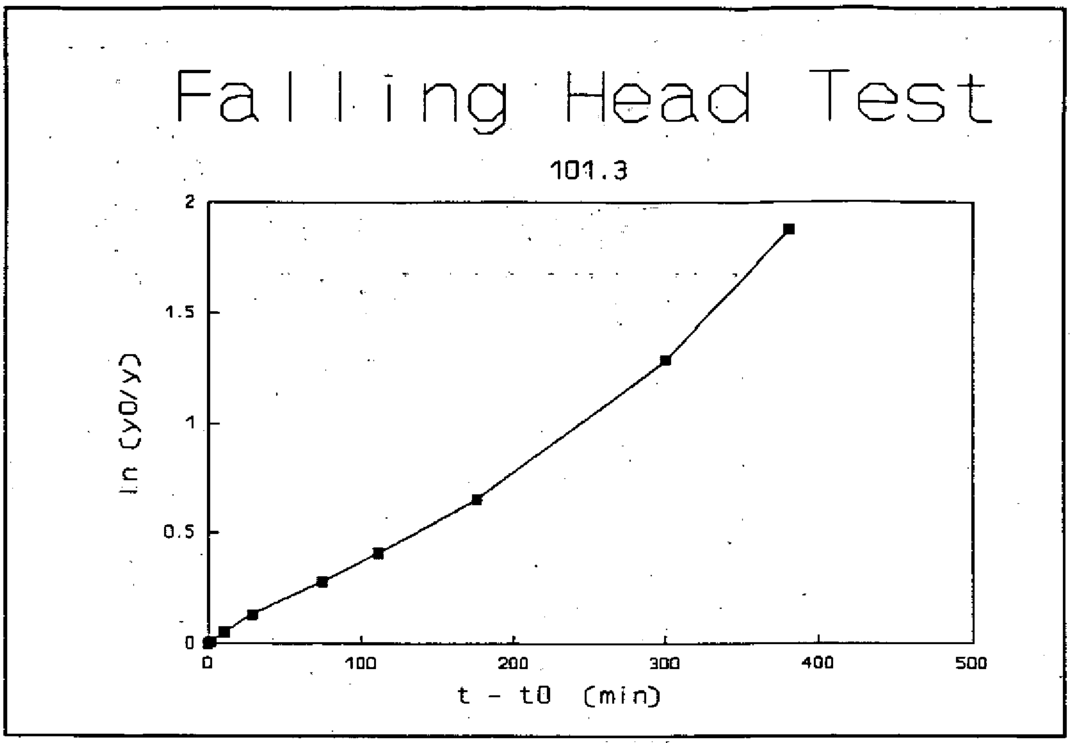
Regression Output:

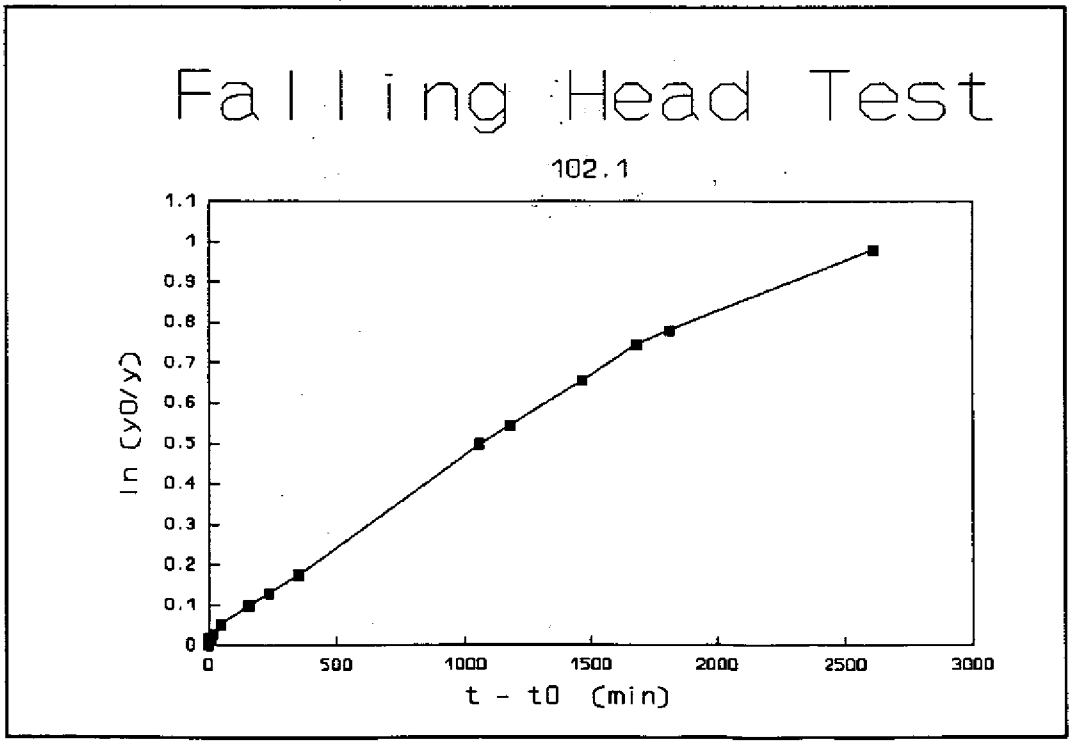
Constant	0.019373
Std Err of Y Est	0.03412
R Squared	0.999117
No. of Observations	7
Degrees of Freedom	5

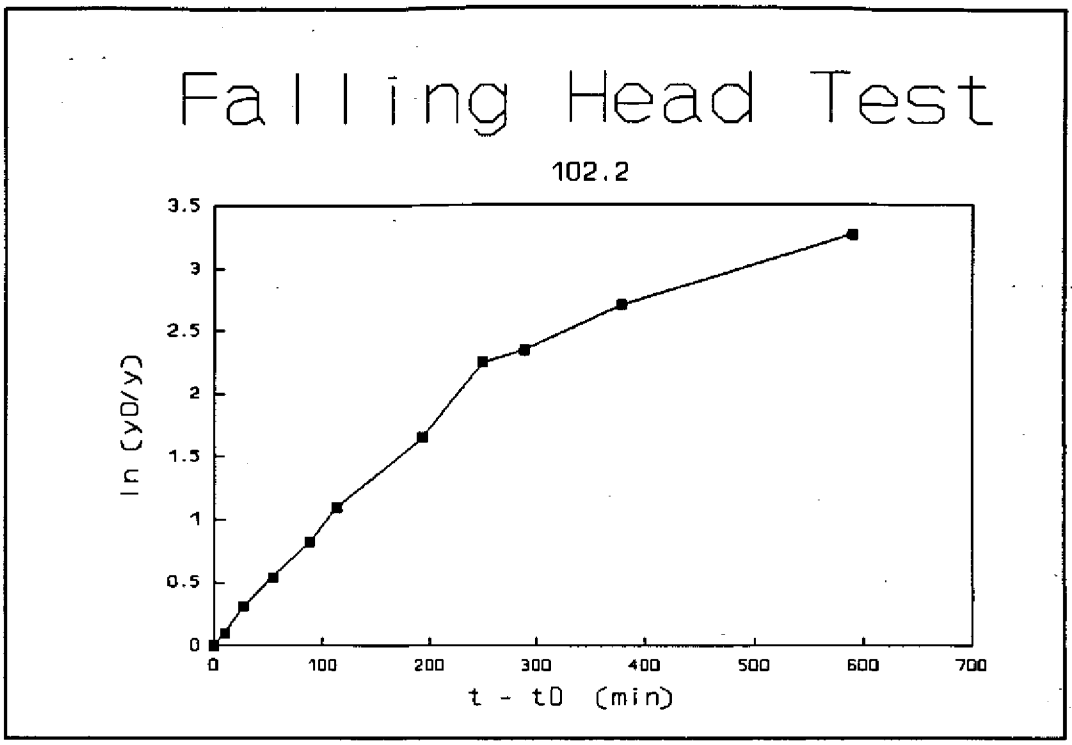
X Coefficient(s)	0.013016
Std Err of Coef.	0.000173

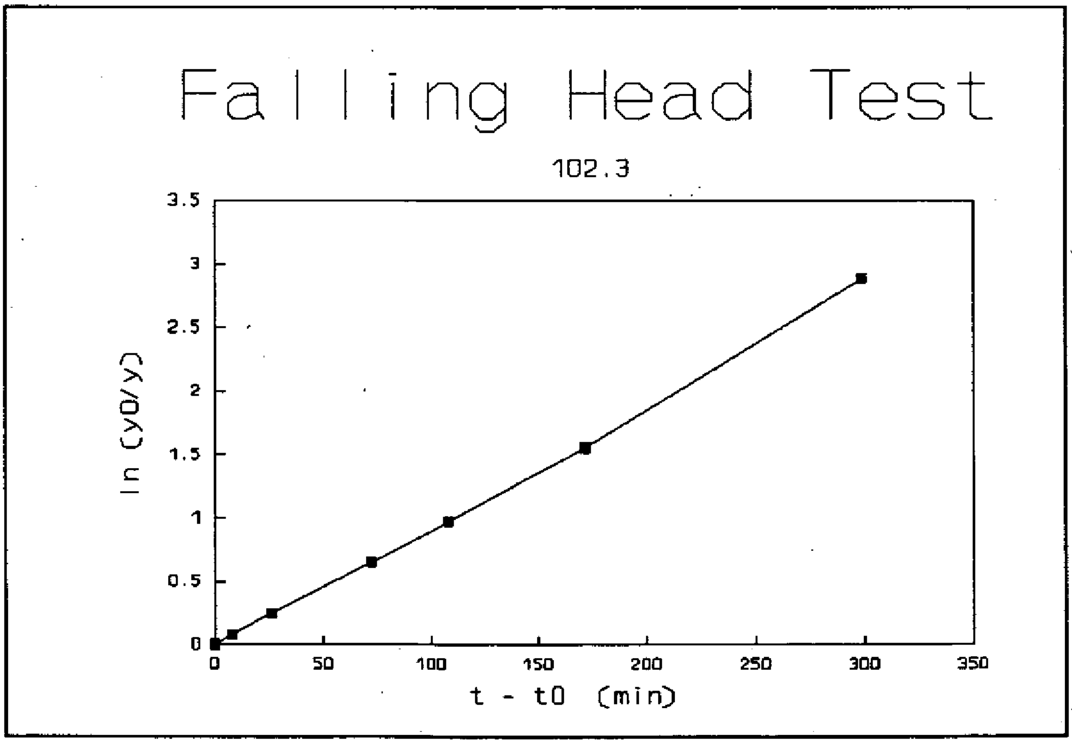

Falling Head Test
101.1
ln (y0/y)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
500
1000
1500
2000
2500
3000
t - t0 (min)

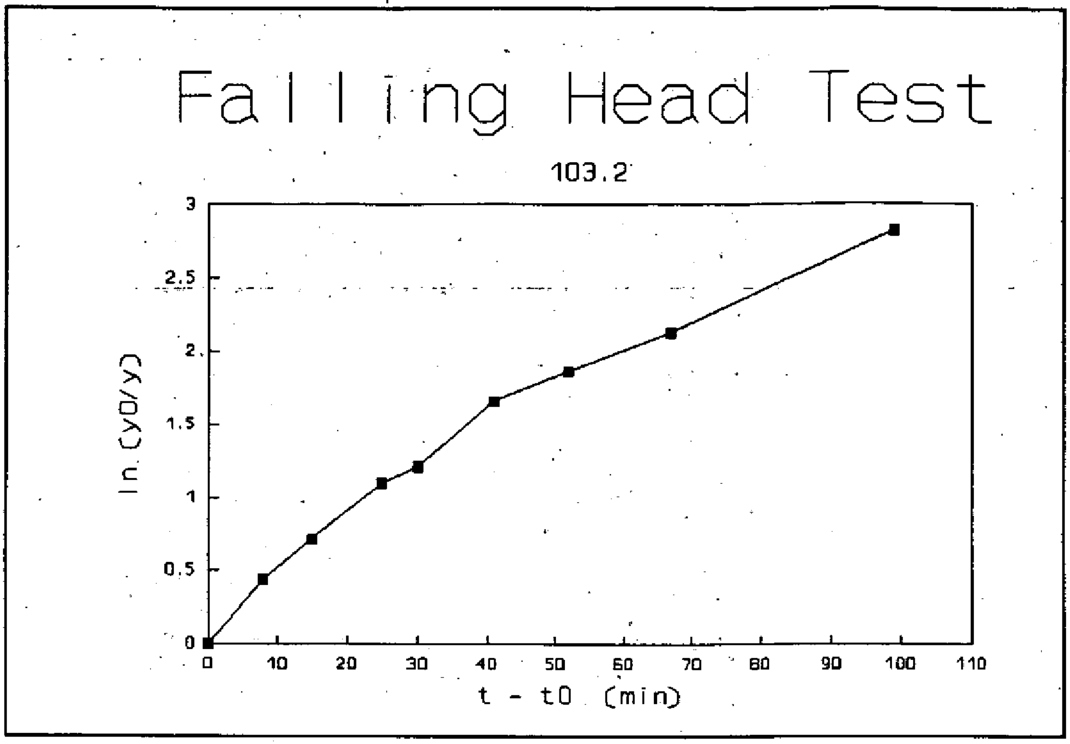

Falling Head Test
101.2
ln (y0/y)
0
0.5
1
1.5
0
1
2
3
4
5
6
7
8
9
10
Thousands
t - t0 (min)

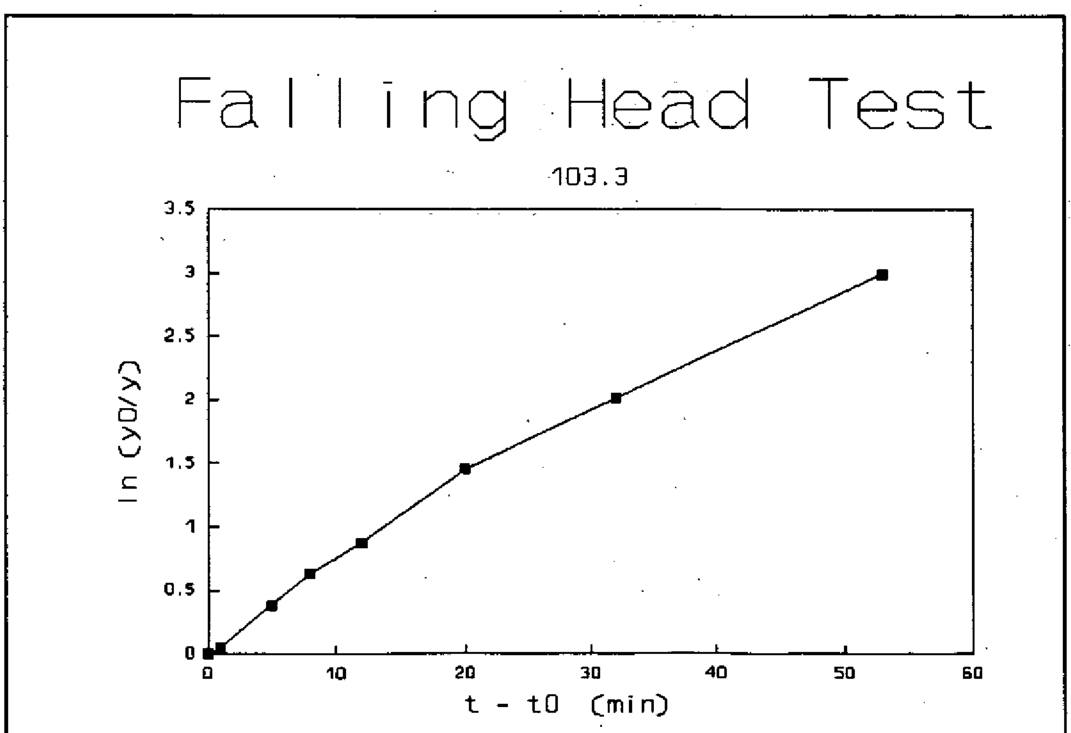

Falling Head Test
101.3
ln (y0/y)
t - t0 (min)
0
0.5
1
1.5
2
0
100
200
300
400
500

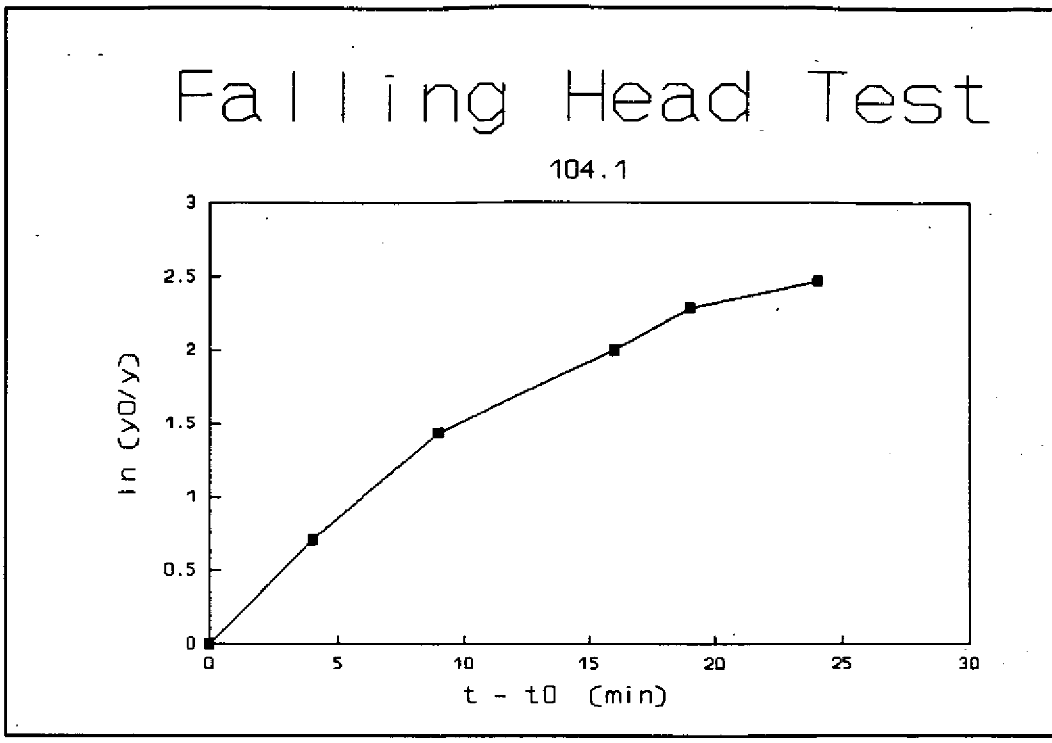

Falling Head Test
102.1
ln (y0/y)
t - t0 (min)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
0
500
1000
1500
2000
2500
3000


Falling Head Test
102.2
ln (y0/y)
t - t0 (min)
0
0.5
1
1.5
2
2.5
3
3.5
0
100
200
300
400
500
600
700

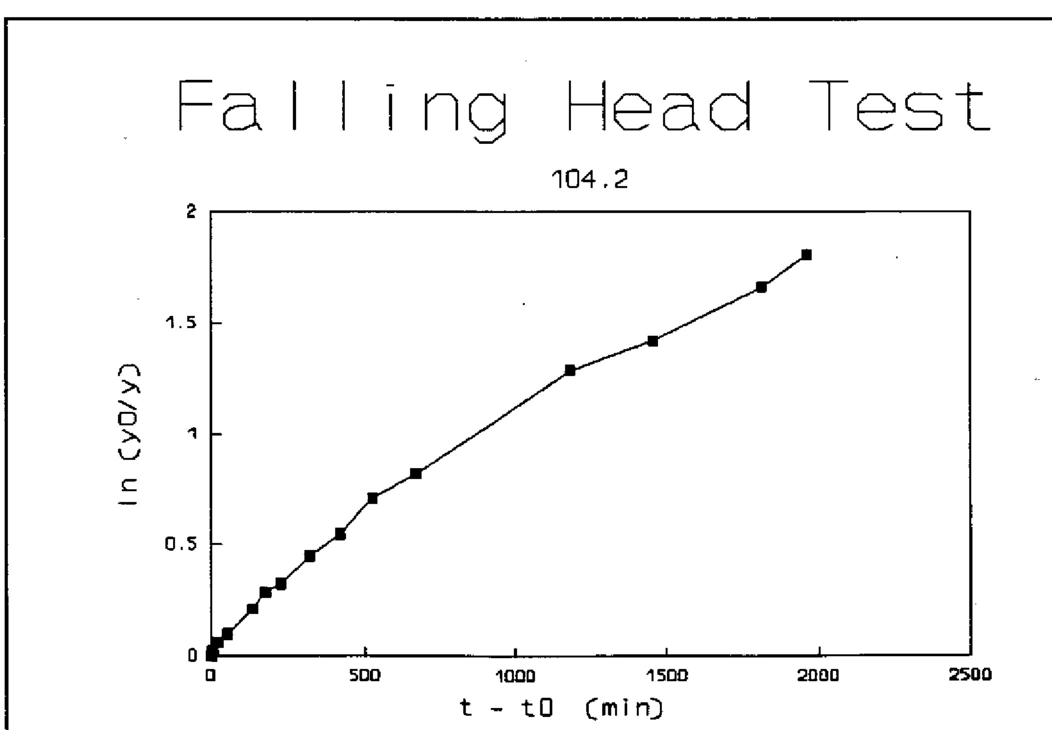

Falling Head Test
102.3
ln (y0/y)
t - t0 (min)
0
0.5
1
1.5
2
2.5
3
3.5
0
50
100
150
200
250
300
350


Falling Head Test
103.2
ln (y0/y)
t - t0 (min)
0
0.5
1
1.5
2
2.5
3
10
20
30
40
50
60
70
80
90
100
110

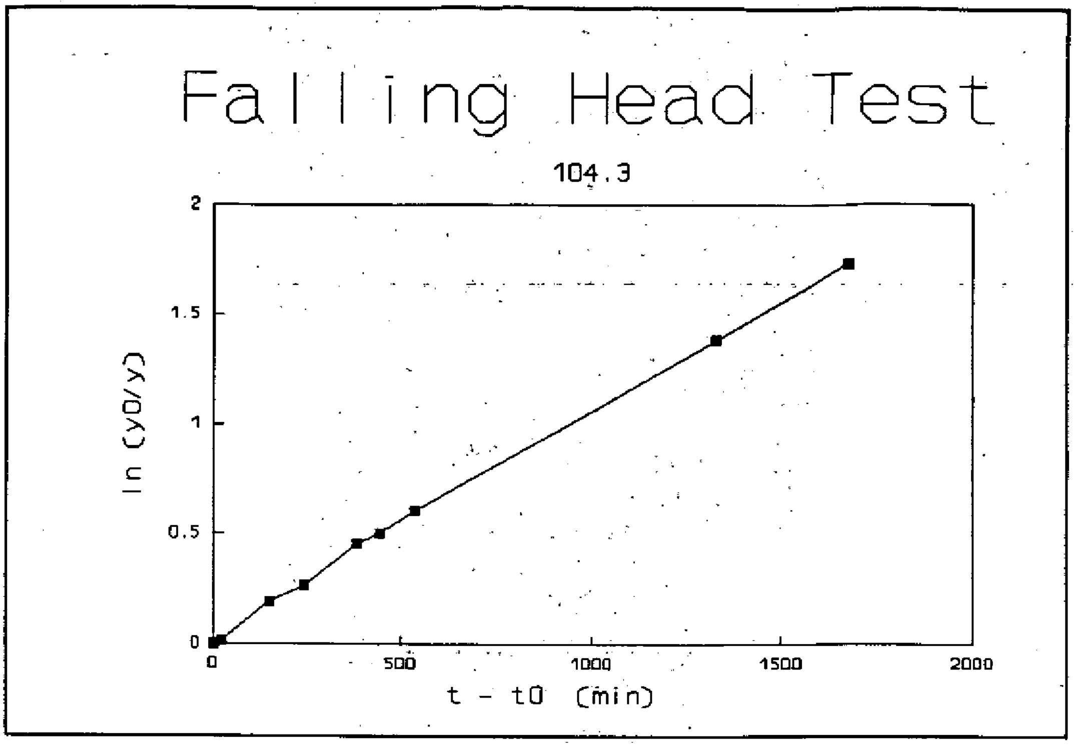

Falling Head Test
103.3
ln (y0/y)
t - t0 (min)
0
0.5
1
1.5
2
2.5
3
3.5
10
20
30
40
50
60

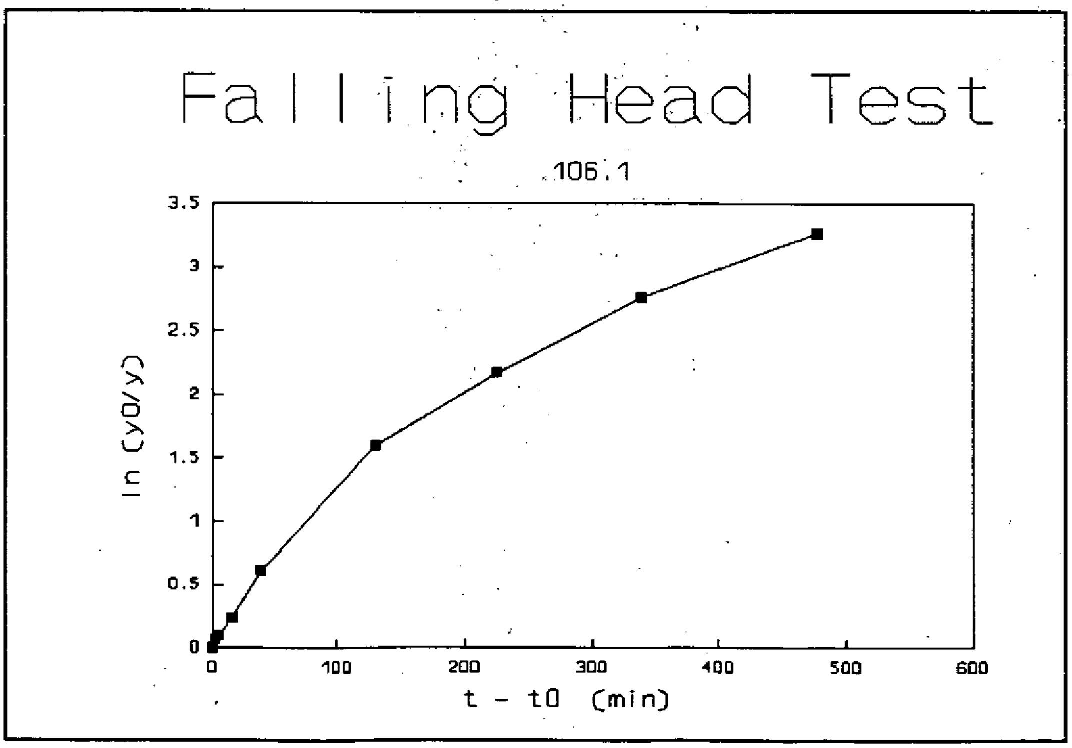


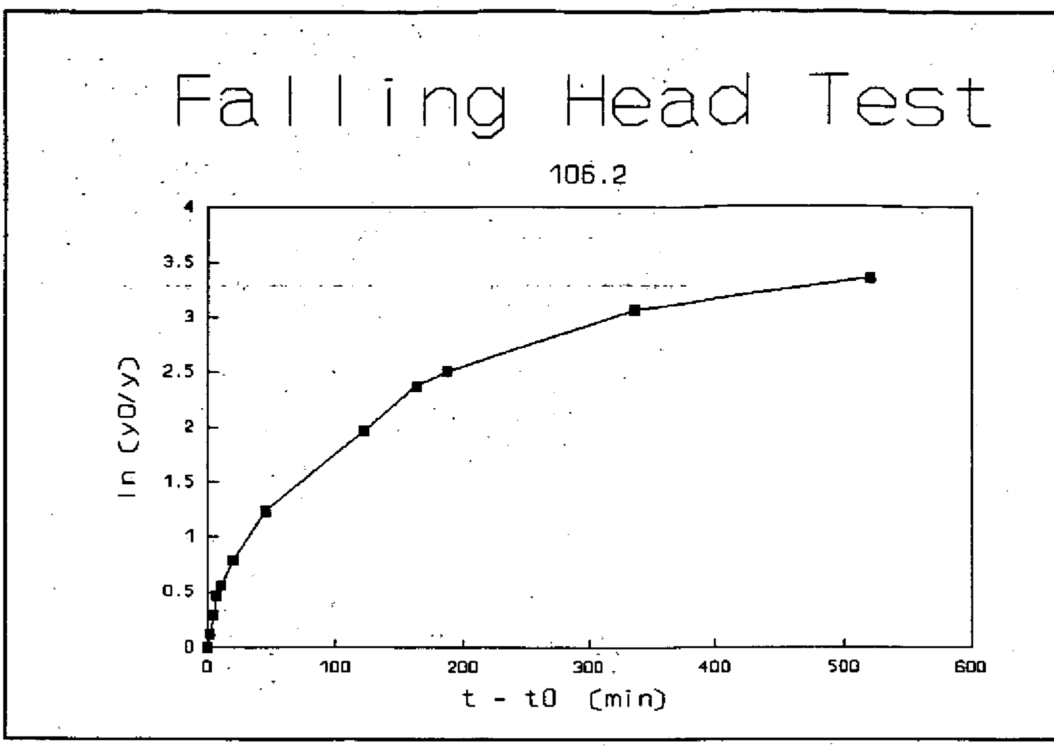
Falling Head Test
104.1
3
2.5
2
1.5
1
0.5
0
0
5
10
15
20
25
30
ln (y0/y)
t - t0 (min)

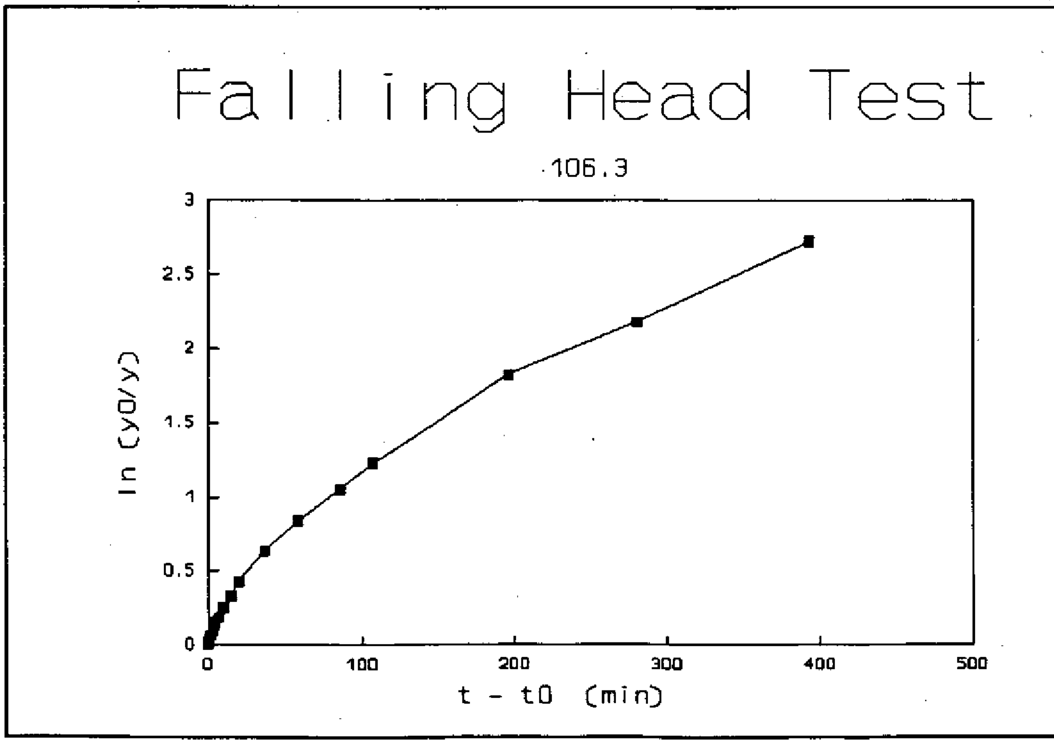


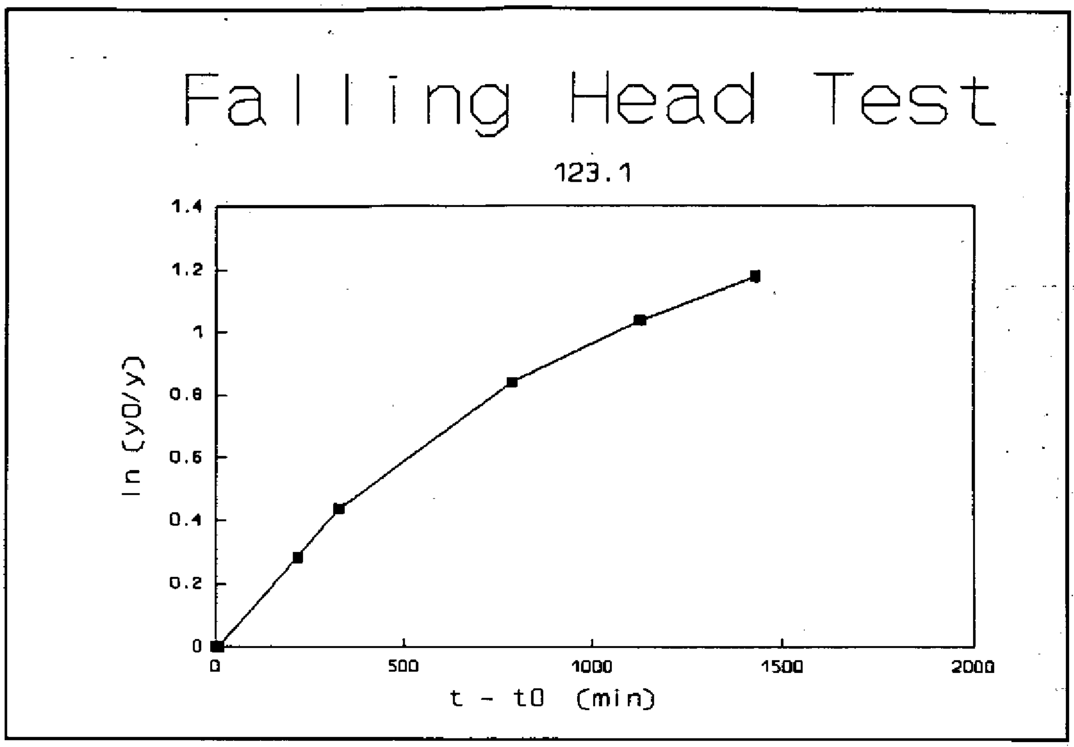
Falling Head Test
104.2
2
1.5
1
0.5
0
0
500
1000
1500
2000
2500
ln (y0/y)
t - t0 (min)

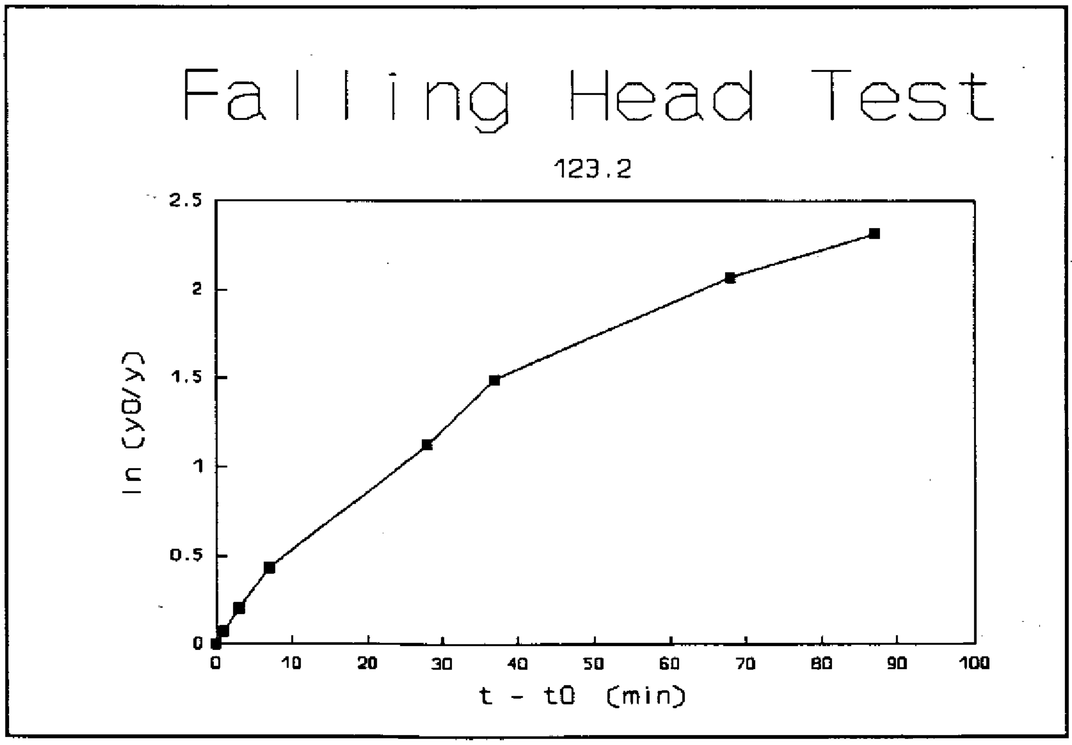

Falling Head Test
104.3
ln (y0/y)
t - t0 (min)
0
0.5
1
1.5
2
500
1000
1500
2000

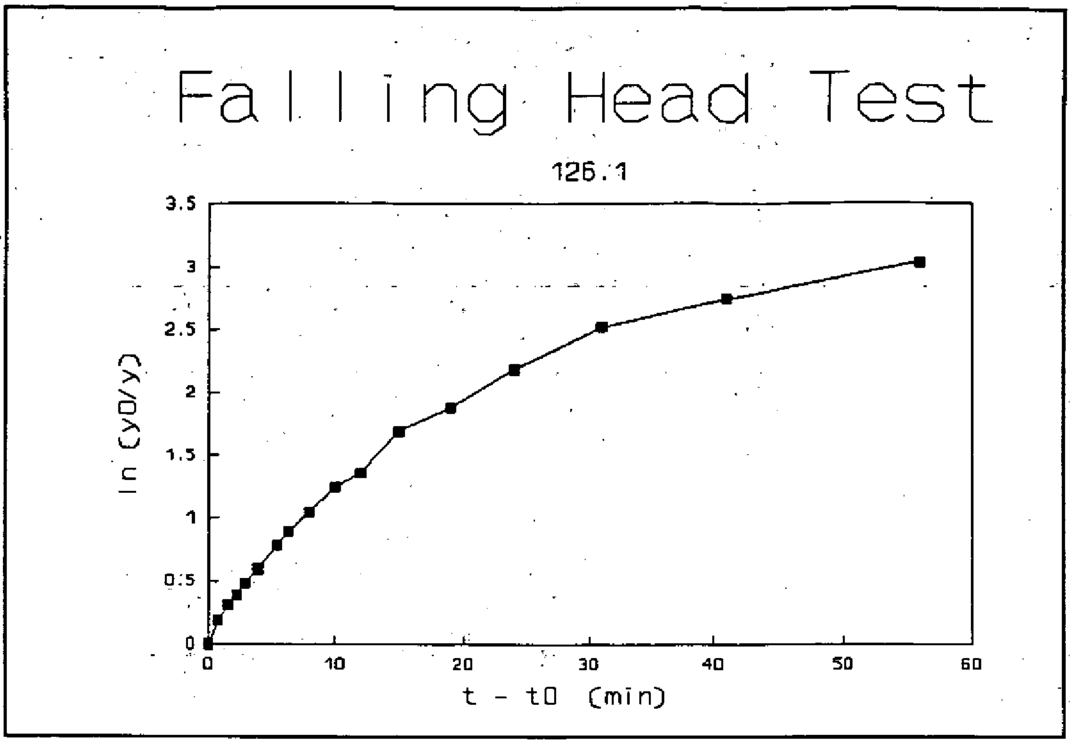

Falling Head Test
106.1
ln (y0/y)
t - t0 (min)
0
0.5
1
1.5
2
2.5
3
3.5
100
200
300
400
500
600

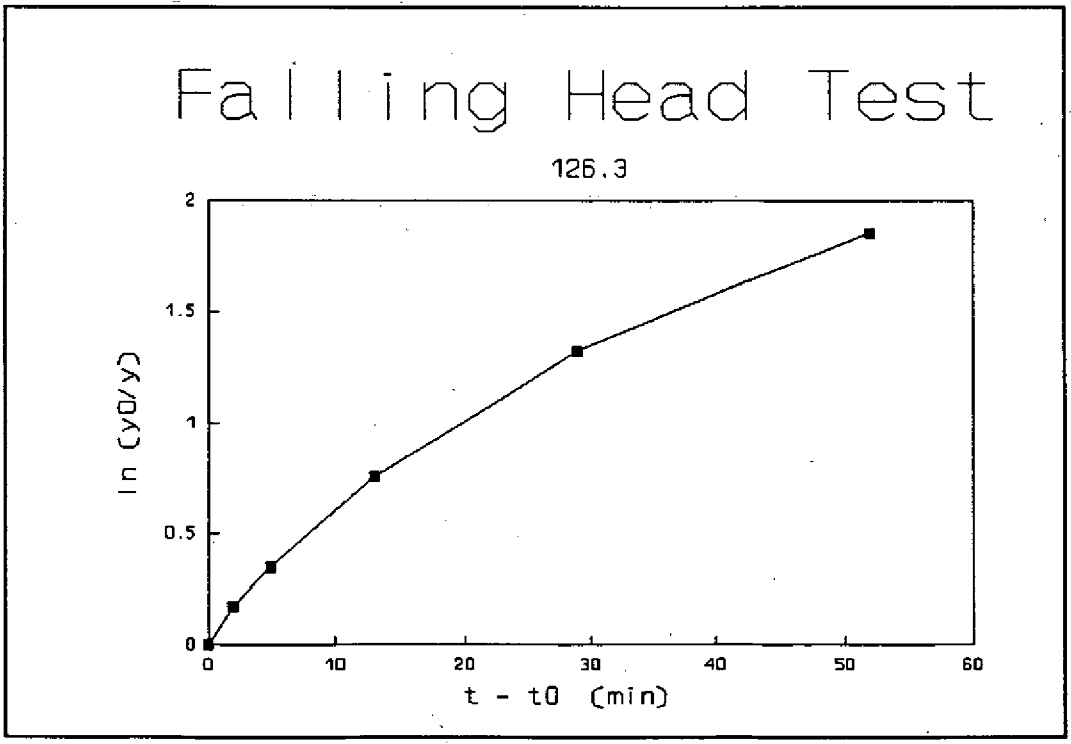

Falling Head Test
106.2
ln (y0/y)
t - t0 (min)
0
0.5
1
1.5
2
2.5
3
3.5
4
100
200
300
400
500
600

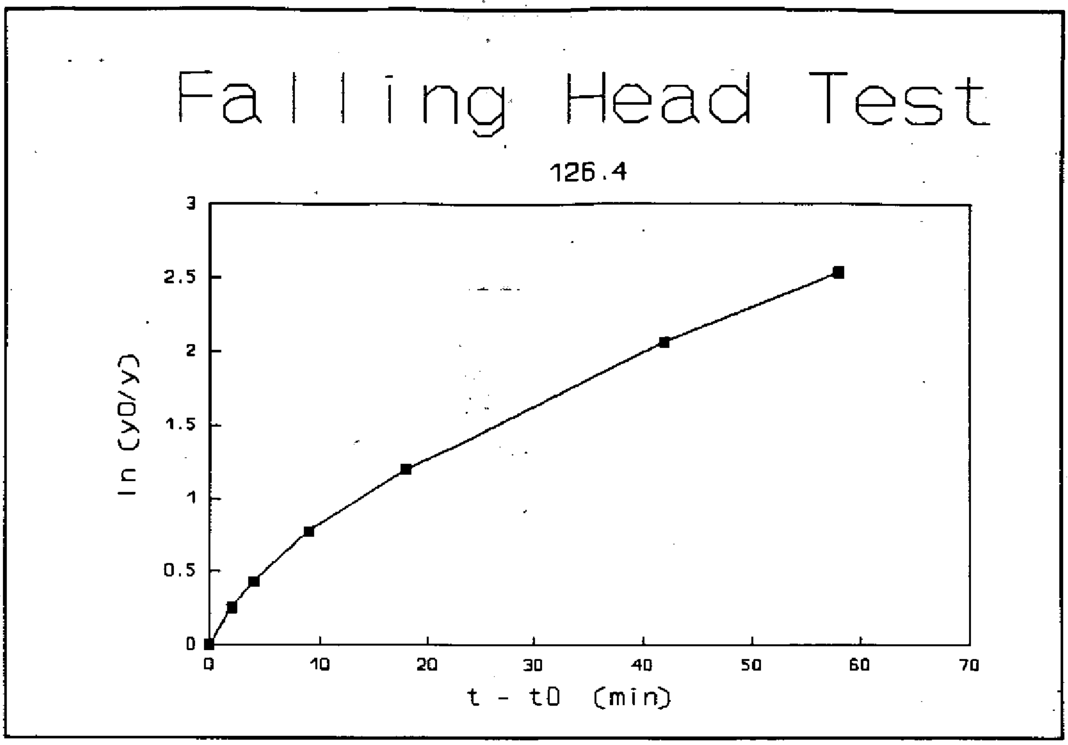

Falling Head Test
106.3
ln (y0/y)
t - t0 (min)
0
0.5
1
1.5
2
2.5
3
100
200
300
400
500

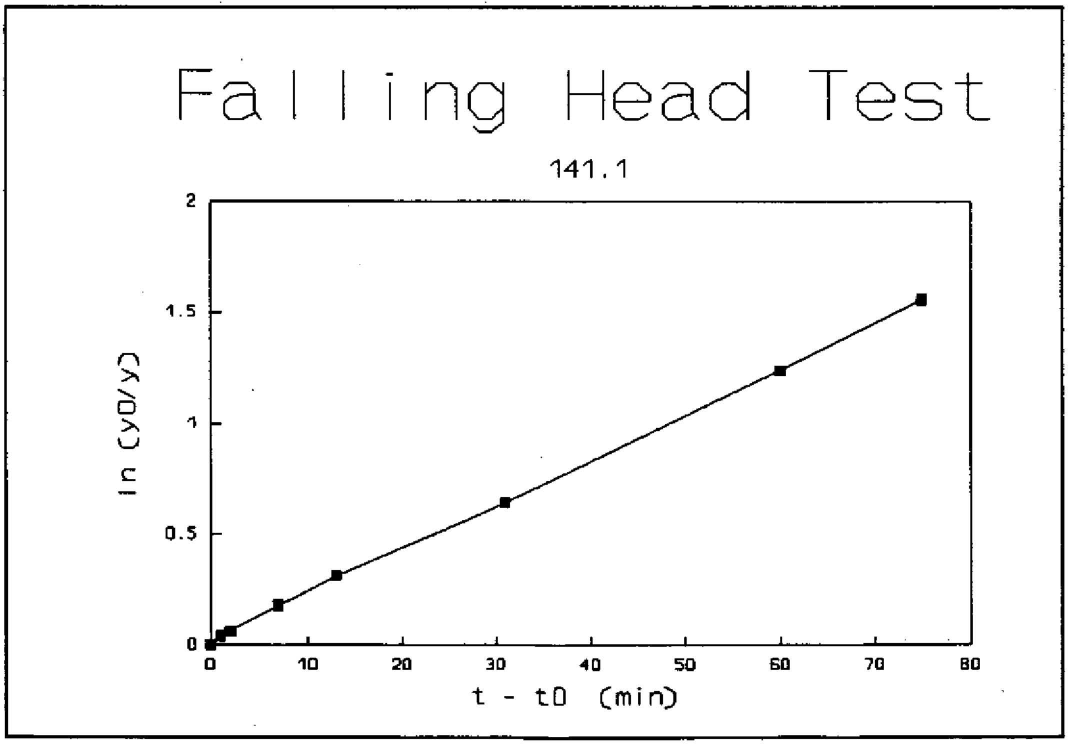

Falling Head Test
123.1
1.4
1.2
1
0.8
0.6
0.4
0.2
0
ln (y0/y)
0
500
1000
1500
2000
t - t0 (min)

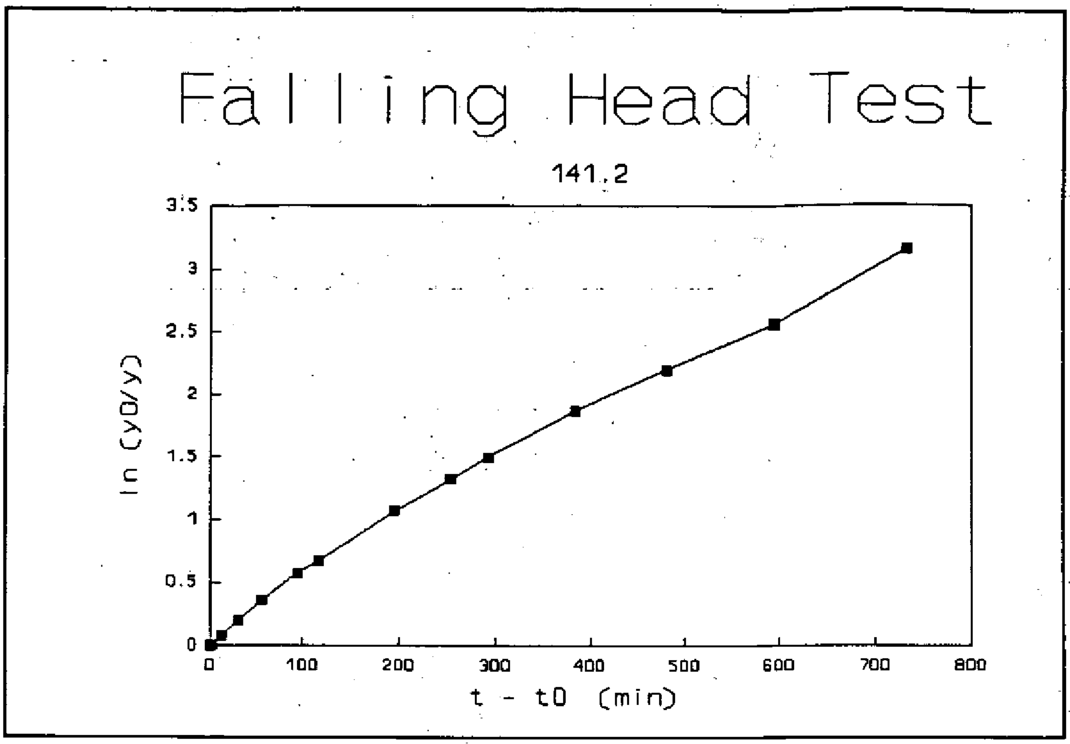

Falling Head Test
123.2
2.5
2
1.5
1
0.5
0
ln (y0/y)
0
10
20
30
40
50
60
70
80
90
100
t - t0 (min)


Falling Head Test
126.1
ln (y0/y)
t - t0 (min)
0
0.5
1
1.5
2
2.5
3
3.5
10
20
30
40
50
60

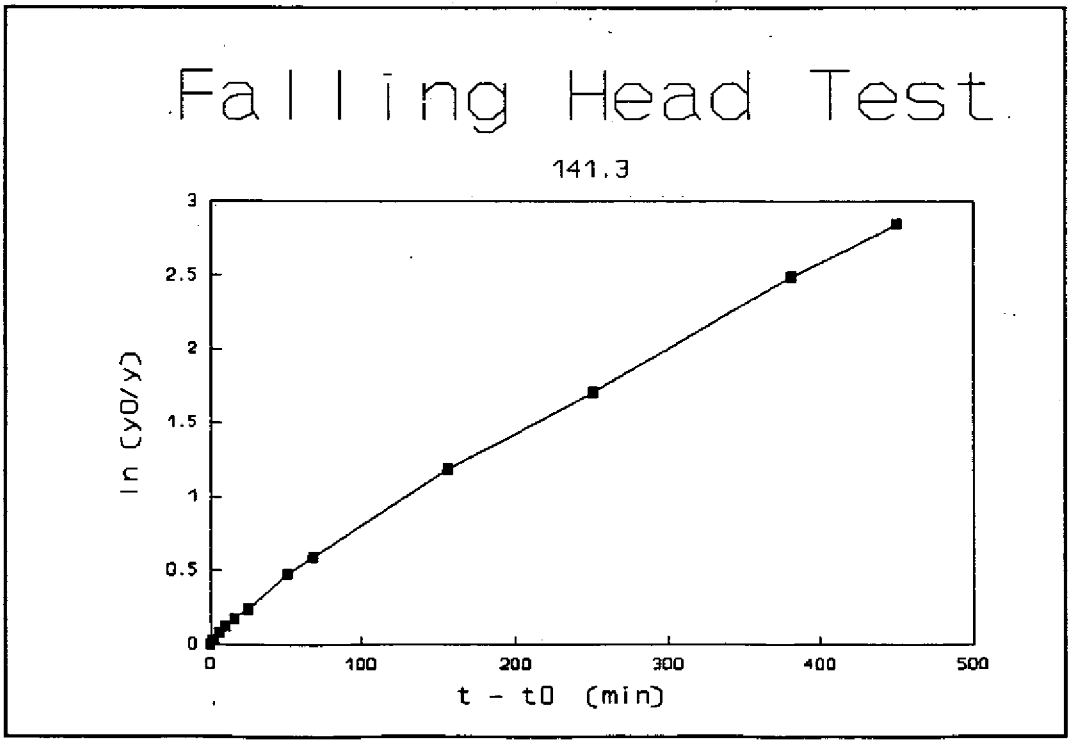

Falling Head Test
126.3
ln (y0/y)
t - t0 (min)
0
0.5
1
1.5
2
10
20
30
40
50
60


Falling Head Test
126.4
ln (y0/y)
t - t0 (min)
0
0.5
1
1.5
2
2.5
3
0
10
20
30
40
50
60
70

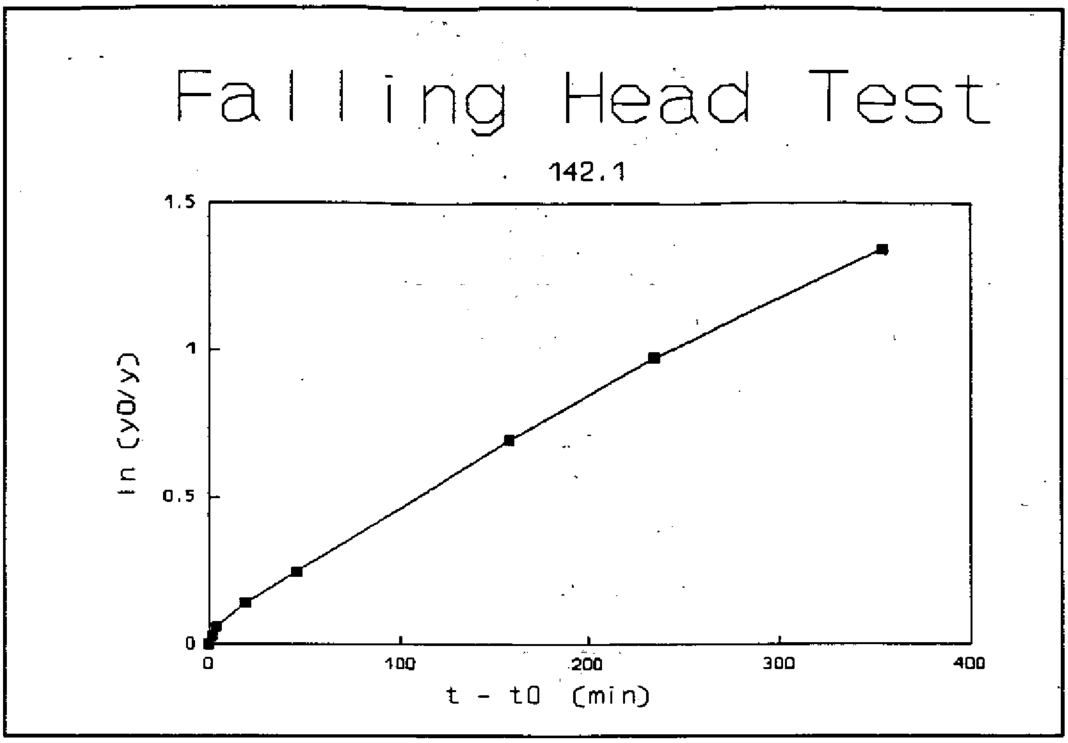

Falling Head Test
141.1
ln (y0/y)
t - t0 (min)
0
0.5
1
1.5
2
0
10
20
30
40
50
60
70
80



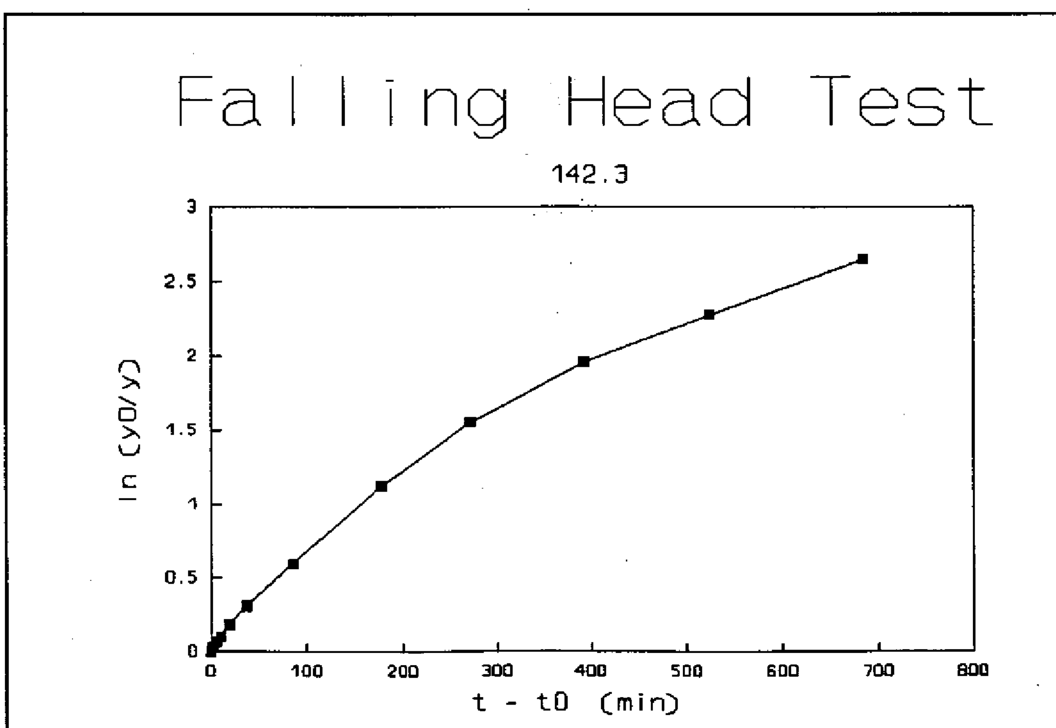
Falling Head Test
141.2
ln (y0/y)
t - t0 (min)
0
0.5
1
1.5
2
2.5
3
3.5
100
200
300
400
500
600
700
800



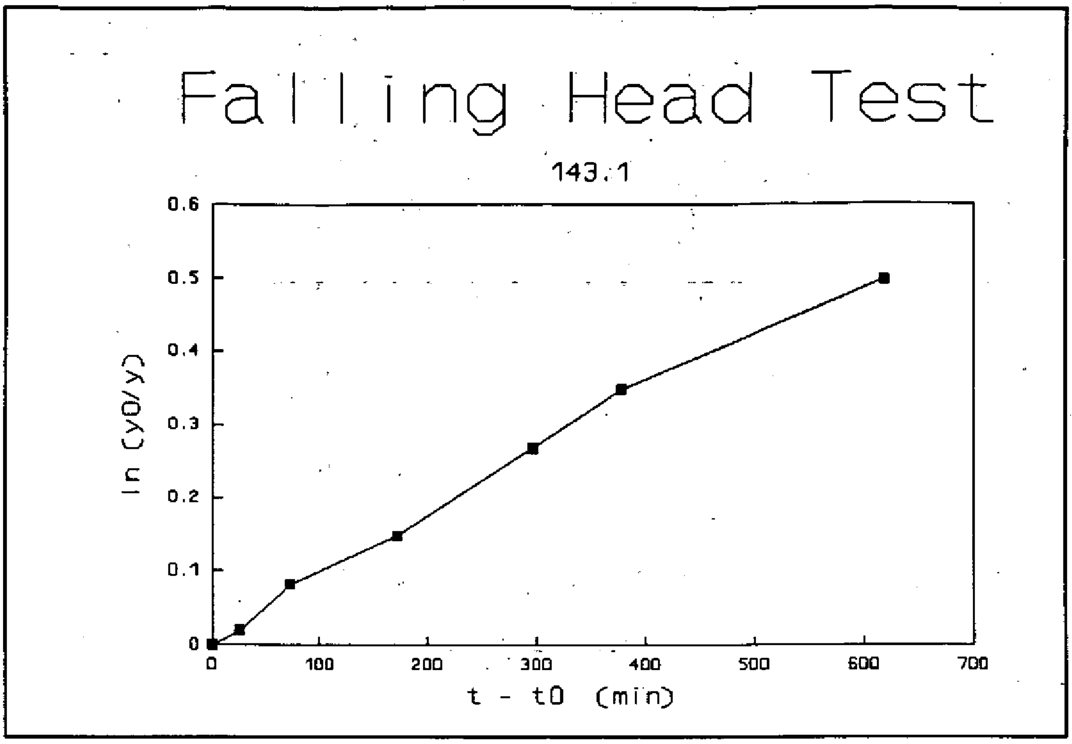
Falling Head Test
141.3
ln (y0/y)
t - t0 (min)
0
0.5
1
1.5
2
2.5
3
100
200
300
400
500

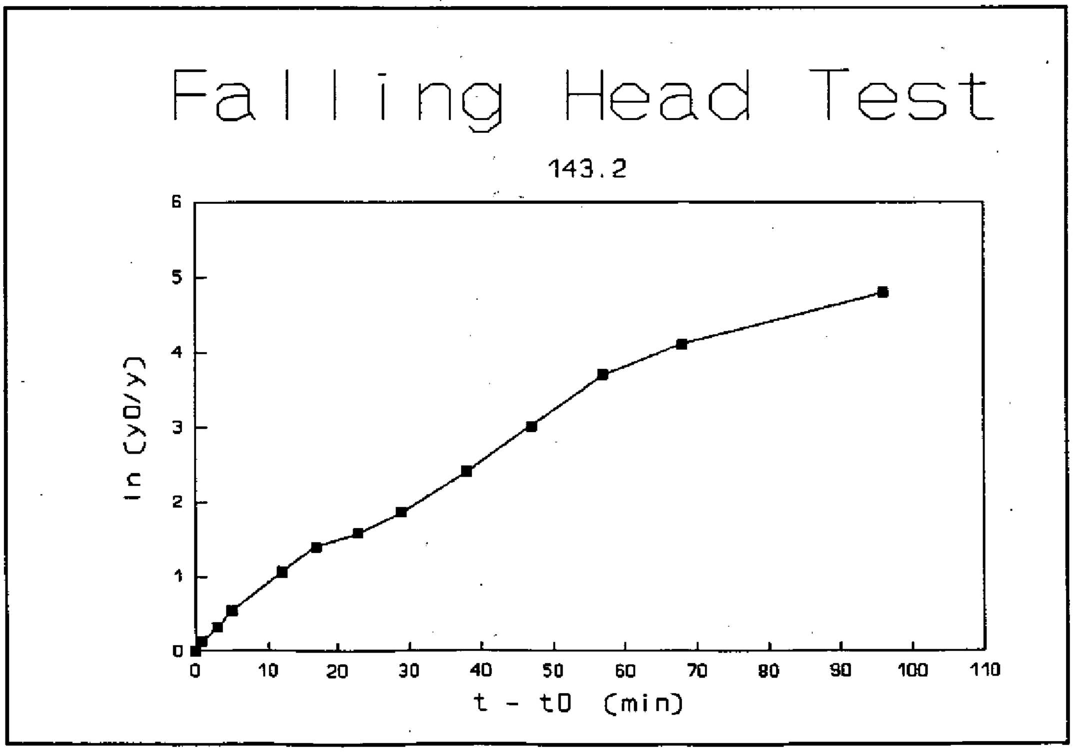


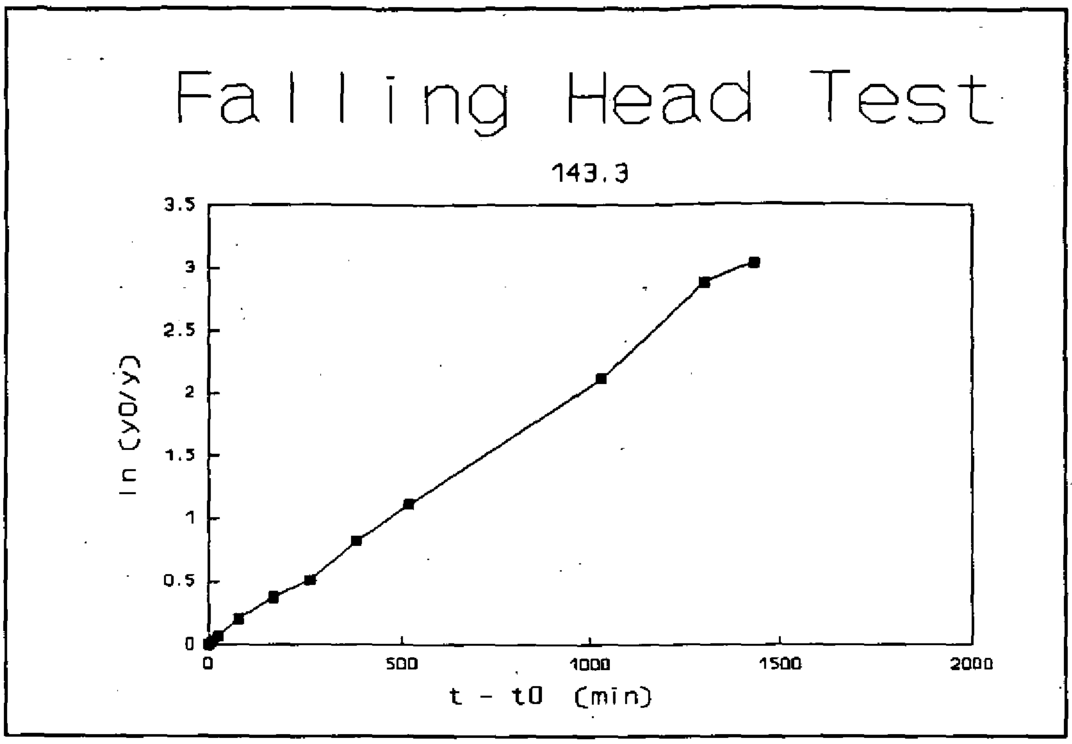
Falling Head Test
142.1
1.5
1
0.5
0
ln (y0/y)
0
100
200
300
400
t - t0 (min)

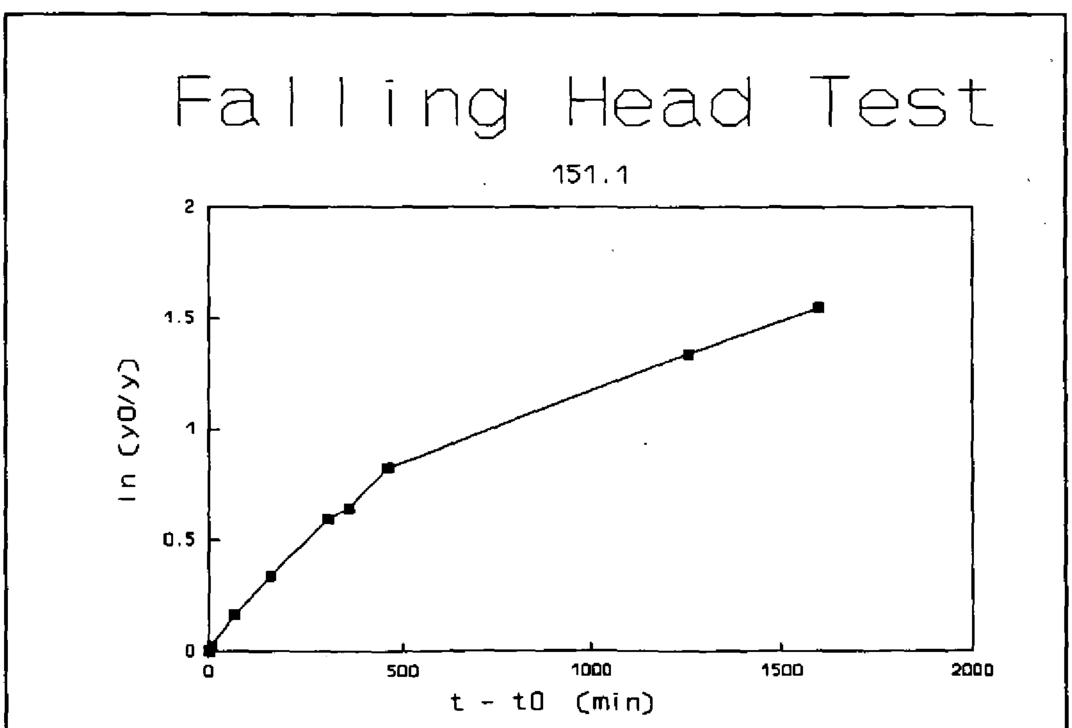


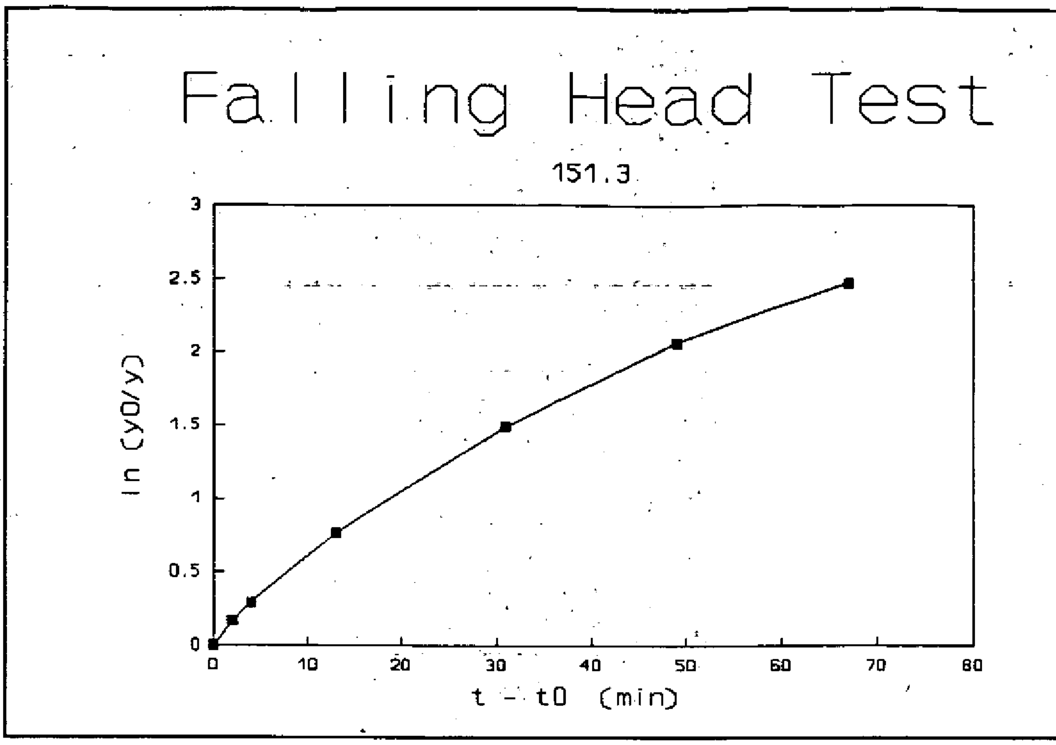
Falling Head Test
142.3
3
2.5
2
1.5
1
0.5
0
ln (y0/y)
0
100
200
300
400
500
600
700
800
t - t0 (min)


Falling Head Test
143.1
ln (y0/y)
t - t0 (min)
0
0.1
0.2
0.3
0.4
0.5
0.6
100
200
300
400
500
600
700

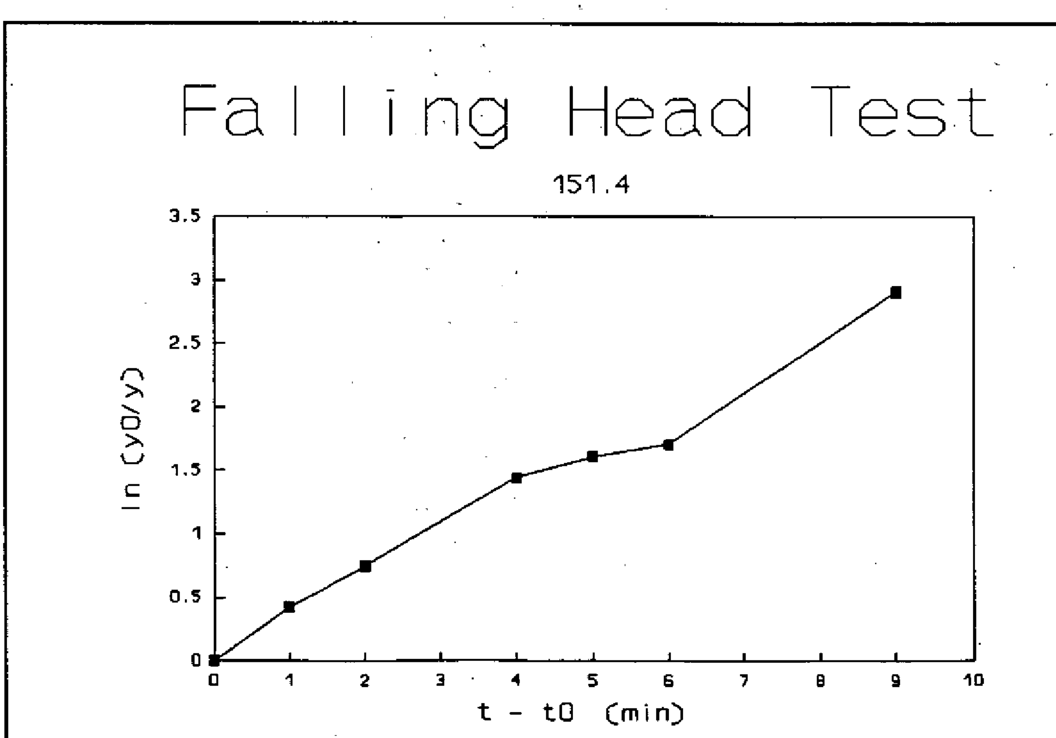

Falling Head Test
143.2
ln (y0/y)
t - t0 (min)
0
1
2
3
4
5
6
10
20
30
40
50
60
70
80
90
100
110


Falling Head Test
143.3
3.5
3
2.5
2
1.5
1
0.5
0
ln (y0/y)
0
500
1000
1500
2000
t - t0 (min)

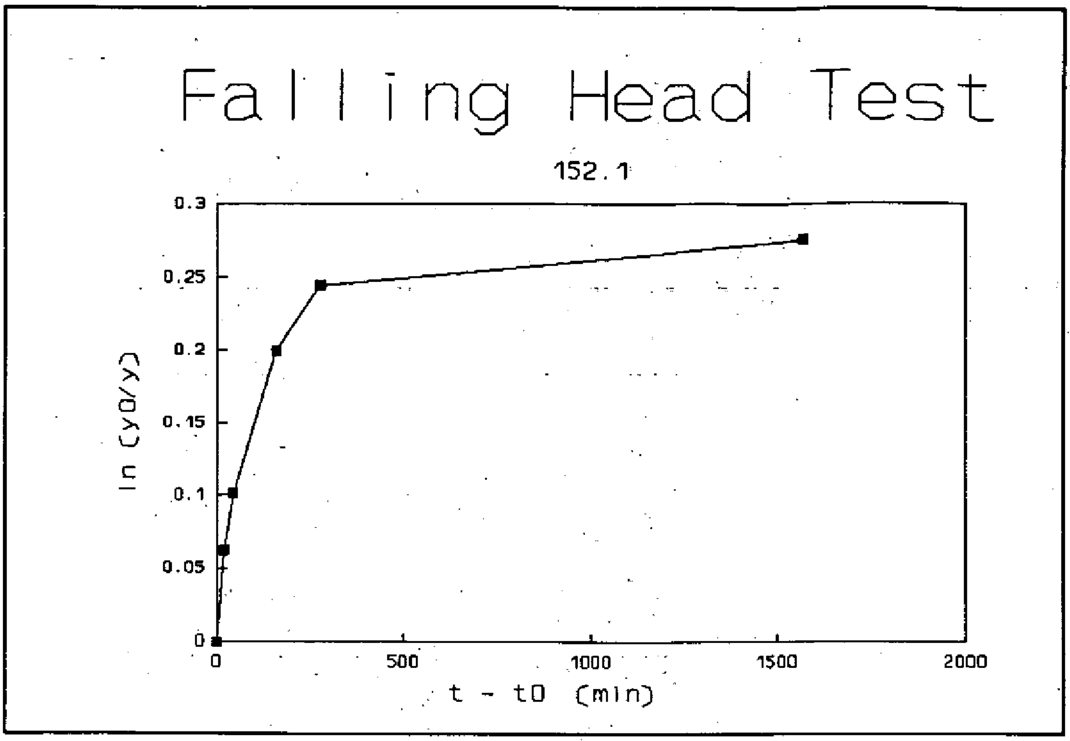

Falling Head Test
151.1
2
1.5
1
0.5
0
ln (y0/y)
0
500
1000
1500
2000
t - t0 (min)

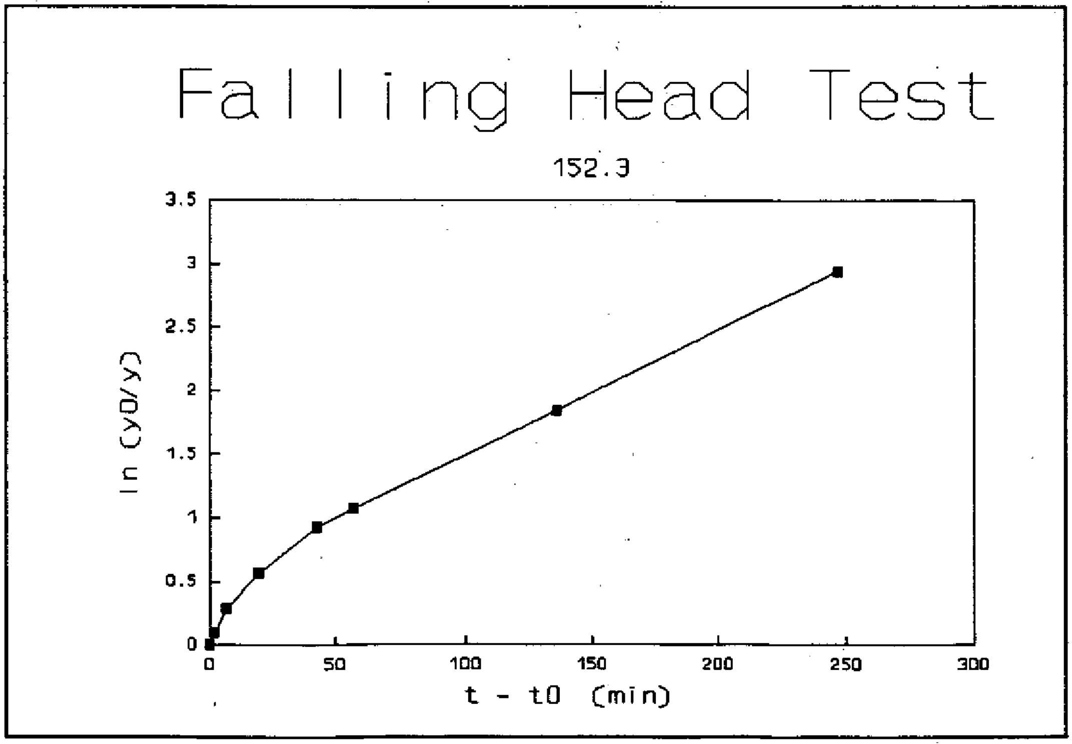


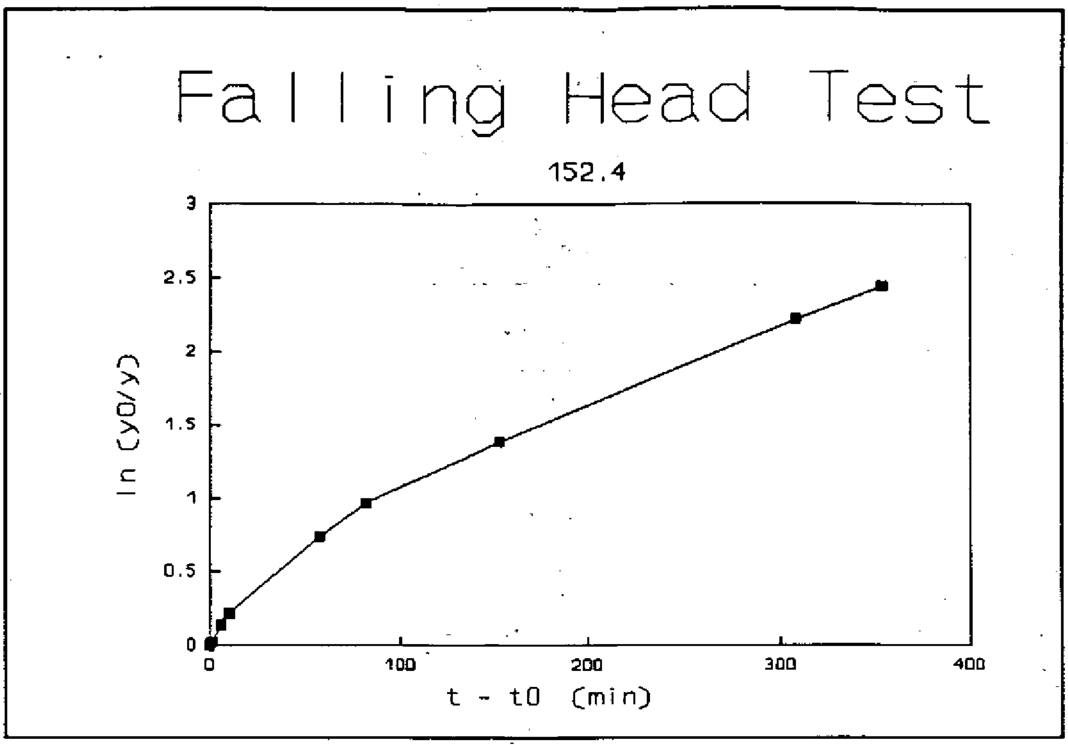
Falling Head Test
151.3
ln (y0/y)
t - t0 (min)

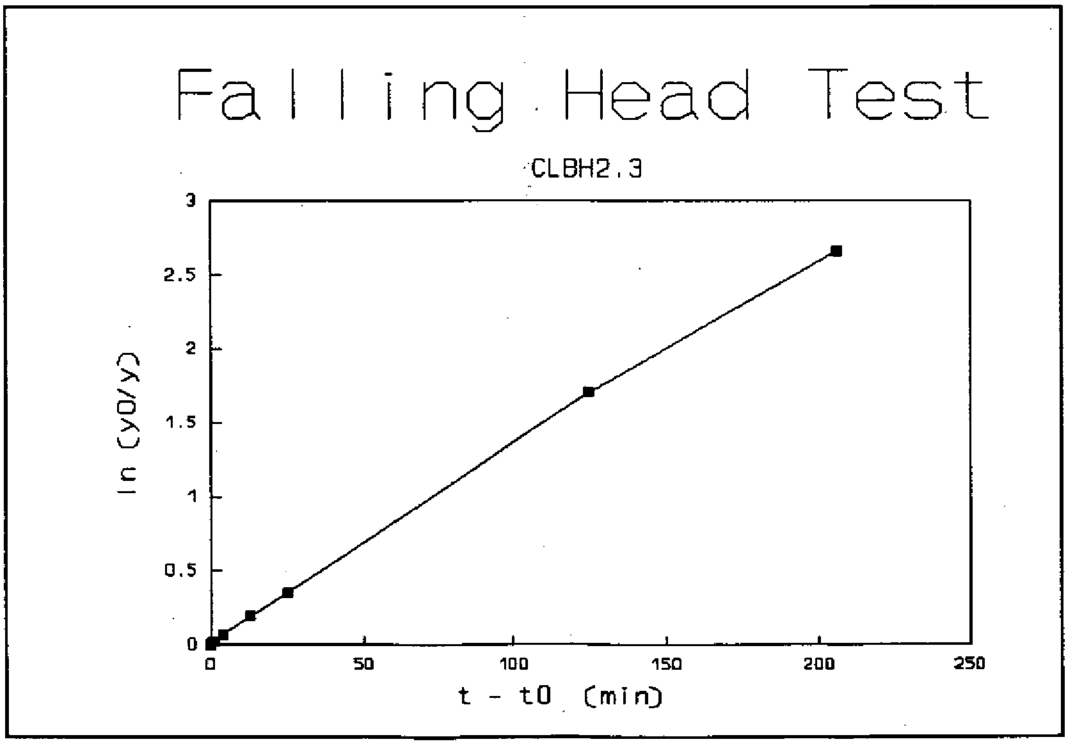


Falling Head Test
151.4
ln (y0/y)
t - t0 (min)


Falling Head Test
152.1
ln (y0/y)
t - t0 (min)
0
0.05
0.1
0.15
0.2
0.25
0.3
500
1000
1500
2000


Falling Head Test
152.3
ln (y0/y)
t - t0 (min)
0
0.5
1
1.5
2
2.5
3
3.5
50
100
150
200
250
300


Falling Head Test
152.4
ln (y0/y)
t - t0 (min)
0
0.5
1
1.5
2
2.5
3
0
100
200
300
400


Falling Head Test
CLBH2.3
ln (y0/y)
t - t0 (min)
0
0.5
1
1.5
2
2.5
3
0
50
100
150
200
250

APPENDIX C

Pumping Test Data

PUMPING TEST DATA: CLBH2.1 (Limestone), 02/07/92

Initial Water Level: 0.644 m
Mean Pumping Rate : 0.150 l/s
12.925 m3/day

Time since pumping started t (min)	log(t) (min)	Water Level (m)	Drawdown s (m)	Pumping rate Q (l/s)	Comments
0.00	-	0.644	0.000	-	
0.22	-0.664	3.000	2.356	-	
0.53	-0.273	6.000	5.356	-	
0.88	-0.054	8.000	7.356	-	
1.35	0.130	8.800	8.156	-	
1.62	0.209	8.900	8.256	-	
2.0	0.301	8.920	8.276	-	
2.5	0.398	8.945	8.301	-	
3.0	0.477	8.920	8.276	0.175	
4.0	0.602	8.950	8.306	0.175	
5.0	0.699	8.925	8.281	0.175	Adjusted pump
7.0	0.845	9.000	8.356	0.157	at 6 min
8.0	0.903	9.055	8.411	0.157	
10.0	1.000	9.098	8.454	0.151	
15.0	1.176	9.091	8.447	0.151	
20.5	1.312	9.165	8.521	0.151	
30.0	1.477	9.132	8.488	0.151	
40.0	1.602	9.245	8.601	0.151	
50.0	1.699	9.260	8.616	0.146	
60.0	1.778	9.250	8.606	0.146	
90.0	1.954	9.270	8.626	0.146	
100.0	2.000	9.305	8.661	0.146	

Regression Output:

Constant	8.170423
Std Err of Y Est	0.033049
R Squared	0.957519
No. of Observations	18
Degrees of Freedom	16
X Coefficient(s)	0.246268
Std Err of Coef.	0.012968

Mean pump rate:

4 min @ 0.175 :	0.700 l/s
3 min @ 0.157 :	0.471 l/s
40 min @ 0.151 :	6.040 l/s
50 min @ 0.146 :	7.300 l/s

Mean pump rate: 0.150 l/s

RECOVERY TEST DATA: CLBH2.1 (limestone), 02/07/92

Initial Water Level: 0.644 m
Mean Recharge Rate : 0.150 l/s
12.925 m3/day

Pump shut down at t = 100 min

Time since pumping started t (min)	Time since pumping stopped t' (min)	Time Ratio t/t' -	log(t/t') -	Water Level (m)	Residual Drawdown s' (m)
100.00	0.00	-	-	9.305	8.661
100.25	0.25	401.0	2.603	7.000	6.356
100.47	0.47	215.3	2.333	6.000	5.356
101.00	1.00	101.0	2.004	4.000	3.356
101.42	1.42	71.6	1.855	3.000	2.356
101.88	1.88	54.1	1.733	2.200	1.556
102.72	2.72	37.8	1.578	1.430	0.786
103.50	3.50	29.6	1.471	0.950	0.306
104.0	4.0	26.0	1.415	0.920	0.276
105.0	5.0	21.0	1.322	0.800	0.156
106.0	6.0	17.7	1.247	0.763	0.119
107.0	7.0	15.3	1.184	0.737	0.093
108.0	8.0	13.5	1.130	0.725	0.081
110.0	10.0	11.0	1.041	0.706	0.062
115.0	15.0	7.7	0.885	0.696	0.052
120.0	20.0	6.0	0.778	0.681	0.037
125.0	25.0	5.0	0.699	0.673	0.029
130.0	30.0	4.3	0.637	0.668	0.024
140.0	40.0	3.5	0.544	0.664	0.020
210.0	110.0	1.9	0.281	0.647	0.003

Regression Output:

Constant	-0.02895
Std Err of Y Est	0.005506
R Squared	0.959084
No. of Observations	8
Degrees of Freedom	6
X Coefficient(s)	0.090001
Std Err of Coef.	0.007589

PUMPING TEST DATA: CLBH2.2 (Gravel), 01/07/92

Initial Water Level: 0.780 m
Mean Pumping Rate : 0.881 l/s
76.119 m3/day

Time since pumping started t (min)	log(t) (min)	Water Level (m)	Drawdown s (m)	Pumping rate Q (l/s)	Comments
0.0	-	0.780	0.000	-	
0.5	-0.301	1.900	1.120	-	
1.0	0.000	2.115	1.335	0.84	
1.5	0.176	2.210	1.430	0.84	
2.0	0.301	2.278	1.498	0.88	
2.5	0.398	2.332	1.552	0.88	
3.0	0.477	2.371	1.591	0.88	
3.5	0.544	2.405	1.625	0.81	Engine revs
4.0	0.602	2.395	1.615	0.84	dropped
5.0	0.699	2.475	1.695	0.88	
6.0	0.778	2.505	1.725	0.81	
7.0	0.845	2.541	1.761	0.88	
8.0	0.903	2.570	1.790	0.88	
10.0	1.000	2.607	1.827	0.88	
14.0	1.146	2.678	1.898	0.88	
20.0	1.301	2.753	1.973	0.88	
30.0	1.477	2.833	2.053	0.88	
41.0	1.613	2.875	2.095	0.91	
50.0	1.699	2.911	2.131	0.88	
60.0	1.778	2.936	2.156	0.88	
90.0	1.954	2.997	2.217	0.88	
120.0	2.079	3.020	2.240	0.88	

Regression Output:

Constant	1.357697
Std Err of Y Est	0.013251
R Squared	0.996986
No. of Observations	17
Degrees of Freedom	15
X Coefficient(s)	0.46657
Std Err of Coef.	0.006623

Mean pump rate:

2 min @ 0.84	1.68 l/s
107 min @ 0.88	94.16 l/s
1 min @ 0.81	0.81 l/s
9 min @ 0.91	8.19 l/s
Mean pump rate:	0.881 l/s

RECOVERY TEST DATA: CLBH2.2 (Gravel), 01/07/92

Initial Water Level: 0.780 m
Mean Recharge Rate : 0.881 l/s
76.119 m3/day

Pump shut down at t = 120 min

Time since pumping started t (min)	Time since pumping stopped t' (min)	Time Ratio t/t' -	log(t/t') -	Water Level (m)	Residual Drawdown s' (m)
120.0	0.0	-	-	3.020	2.240
120.6	0.6	219.2	2.341	2.505	1.725
121.0	1.0	125.1	2.097	1.720	0.940
121.5	1.5	81.0	1.908	1.570	0.790
122.0	2.0	61.0	1.785	1.502	0.722
122.5	2.5	49.0	1.690	1.464	0.684
123.0	3.0	41.0	1.613	1.433	0.653
123.5	3.5	35.3	1.548	1.398	0.618
124.0	4.0	31.0	1.491	1.370	0.590
125.0	5.0	25.0	1.398	1.343	0.563
126.0	6.0	21.0	1.322	1.303	0.523
127.0	7.0	18.1	1.259	1.286	0.506
128.0	8.0	16.0	1.204	1.247	0.467
130.0	10.0	13.0	1.114	1.209	0.429
134.0	14.0	9.6	0.981	1.148	0.368
140.0	20.0	7.0	0.845	1.087	0.307
150.0	30.0	5.0	0.699	1.020	0.240
160.0	40.0	4.0	0.602	0.980	0.200
170.0	50.0	3.4	0.531	0.948	0.168
180.0	60.0	3.0	0.477	0.923	0.143
210.0	90.0	2.3	0.368	0.880	0.100
240.0	120.0	2.0	0.301	0.855	0.075

Regression Output:

Constant	-0.06619
Std Err of Y Est	0.00535
R Squared	0.99947
No. of Observations	19
Degrees of Freedom	17
X Coefficient(s)	0.444882
Std Err of Coef.	0.002485

APPENDIX D

Road Drain Weir Rating Curves and Data

WEIR RATING CURVE DATA: Weir DEH921

Date	Depth (m)	Stage (m)	Volume (m3)	Time (s)	Discharge (m3/s)	H^5/2	Rated Q (m3/s)
		0.000			0.00000	0.00000	0.00000
28.05.92	1.018	0.088	0.01400	13.20	0.00106	0.00230	0.00105
29.05.92	1.017	0.089	0.01400	12.50	0.00112	0.00236	0.00108
09.06.92	1.016	0.090	0.01400	11.10	0.00126	0.00243	0.00111
21.05.92	1.010	0.096	0.01400	9.90	0.00141	0.00286	0.00130
16.05.92	0.997	0.109	0.01012	5.00	0.00202	0.00392	0.00179
04.06.92	0.970	0.136	0.01400	4.90	0.00286	0.00682	0.00311

Height of datum above V-notch: 1.106 m

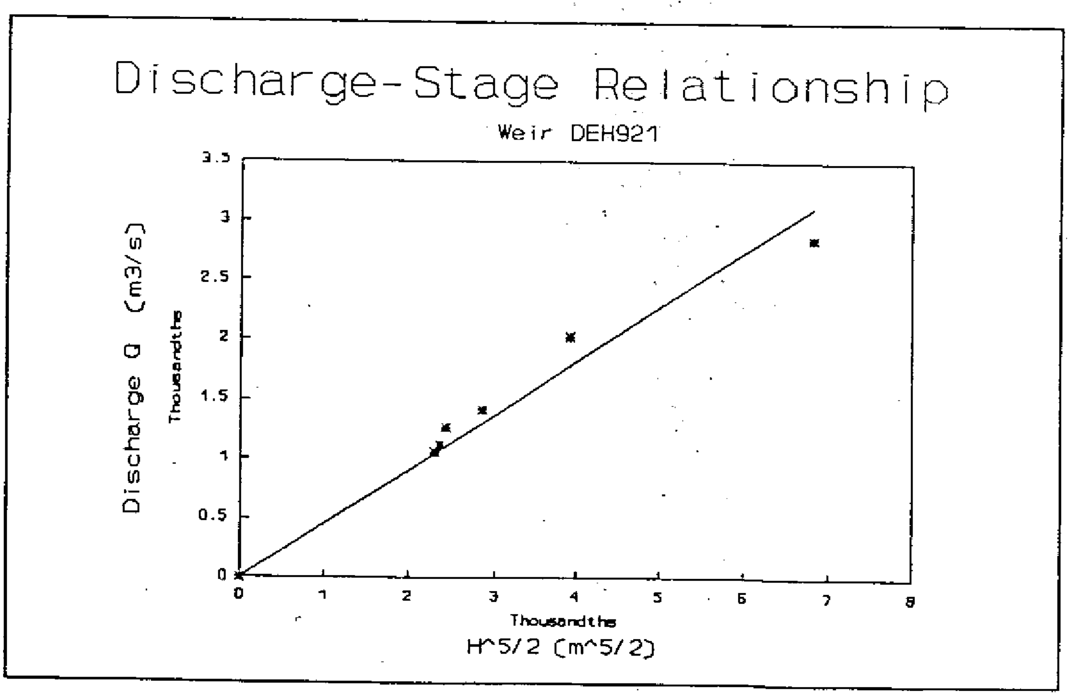
V-notch angle, 027.900 degrees tan(O/2 0.248
0.487 radians

Regression Output:

Constant	0.000
Std Err of Y Est	0.000
R Squared	0.966
No. of Observations	7
Degrees of Freedom	6
X Coefficient(s)	0.456
Std Err of Coef.	0.017

Rating Curve Equation:

Q = 0.456 H^5/2



WEIR RATING CURVE DATA: Weir DEH922

Date	Depth (m)	Stage (m)	Volume (m3)	Time (s)	Discharge (m3/s)	H^5/2	Rated Q (m3/s)
		0.000			0.00000	0.00000	0.00000
28.05.92	0.881	0.141	0.01400	4.30	0.00326	0.00747	0.00283
29.05.92	0.878	0.144	0.01400	4.10	0.00341	0.00787	0.00298
21.05.92	0.860	0.162	0.01400	3.00	0.00467	0.01056	0.00400
09.06.92	0.856	0.166	0.01400	3.00	0.00467	0.01123	0.00425
16.05.92	0.820	0.202	0.01012	1.70	0.00595	0.01834	0.00695

Height of datum above V-notch: 1.022 m

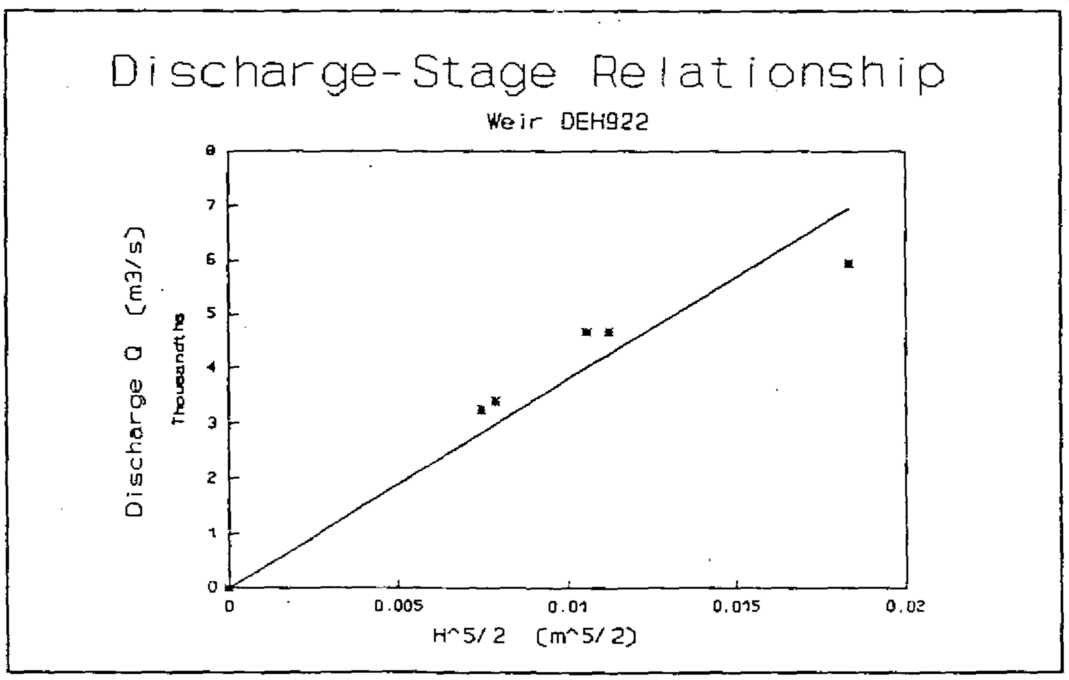
V-notch angle, 028.200 degrees tan(O/2 0.251
0.492 radians

Regression Output:

Constant	0.000
Std Err of Y Est	0.001
R Squared	0.906
No. of Observations	6
Degrees of Freedom	5
X Coefficient(s)	0.379
Std Err of Coef.	0.024

Rating Curve Equation:

Q = 0.379 H^5/2



WEIR RATING CURVE DATA: Weir DEH923

Date	Stage (m)	H (m)	Volume (m3)	Time (s)	Discharge (m3/s)	H^5/2	Rated Q (m3/s)
		0.000			0.00000	0.00000	0.00000
02.07.92	0.540	0.121	0.01400	6.65	0.00211	0.00509	0.00172
09.06.92	0.573	0.154	0.01400	4.10	0.00341	0.00931	0.00314
04.06.92	0.630	0.211	0.01400	2.10	0.00667	0.02045	0.00689

Height of datum below V-notch: 0.419 m

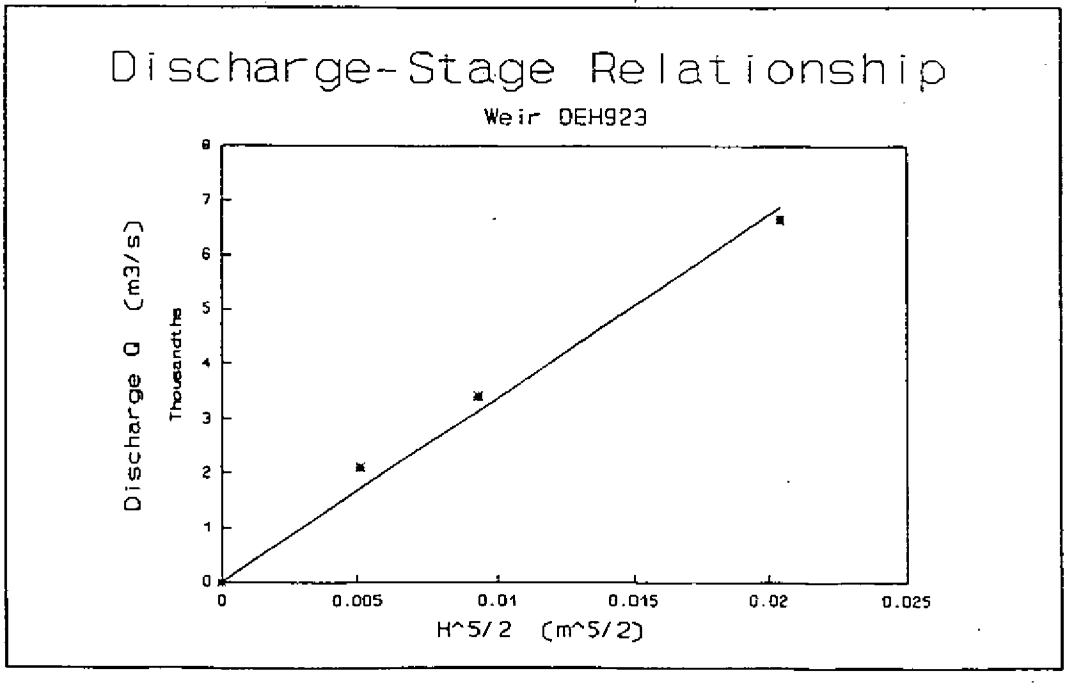
V-notch angle, 028.090 degrees tan(O/2 0.250
0.490 radians

Regression Output:

Constant	0.000
Std Err of Y Est	0.000
R Squared	0.988
No. of Observations	4
Degrees of Freedom	3
X Coefficient(s)	0.337
Std Err of Coef.	0.013

Rating Curve Equation:

Q = 0.337 H^5/2



APPENDIX E

Data used in Runoff Coefficient Evaluation

STORMFLOW VOLUME EVALUATION : Weir DEH922

From the storm hydrograph, total stormflow volume is calculated using the Trapezium rule, to find the area under the curve representing stormflow. Baseflow separation is by a straight line.

Date	Time	Time (hours)	Q 922 (m3/s)	Q 922 (m3/h)	Integration Ordinates
	1400	14.00	0.00309	11.1128	
	1415	14.25	0.00309	11.1128	
	1430	14.50	0.00309	11.1128	
	1445	14.75	0.00309	11.1128	
920723	1500	15.00	0.00309	11.1128	
	1515	15.25	0.00309	11.1128	
	1530	15.50	0.00309	11.1128	
	1545	15.75	0.00309	11.1128	
	1600	16.00	0.00309	11.1128	
	1615	16.25	0.00309	11.1128	
	1630	16.50	0.00309	11.1128	
	1645	16.75	0.00309	11.1128	
	1700	17.00	0.00309	11.1128	
	1715	17.25	0.00309	11.1128	0.000000
	1730	17.50	0.00314	11.3041	0.191266
	1745	17.75	0.00319	11.4973	0.384495
920723	1800	18.00	0.00319	11.4973	0.384495
	1815	18.25	0.00319	11.4973	0.384495
	1830	18.50	0.00319	11.4973	0.384495
	1845	18.75	0.00319	11.4973	0.384495
	1900	19.00	0.00319	11.4973	0.384495
	1915	19.25	0.00319	11.4973	0.384495
	1930	19.50	0.00358	12.9054	1.792576
	1945	19.75	0.00388	13.9715	2.858647
	2000	20.00	0.00407	14.6356	3.522797
	2015	20.25	0.00426	15.3183	4.205539
	2030	20.50	0.00507	18.2386	7.125800
	2045	20.75	0.00536	19.2806	8.167775
920723	2100	21.00	0.00565	20.3575	9.244674
	2115	21.25	0.00620	22.3272	11.214428
	2130	21.50	0.00661	23.8015	12.688711
	2145	21.75	0.00712	25.6459	14.533043
	2200	22.00	0.00721	25.9613	14.848487
	2215	22.25	0.00721	25.9613	14.848487
	2230	22.50	0.00721	25.9613	14.848487
	2245	22.75	0.00748	26.9215	15.808740
	2300	23.00	0.00748	26.9215	15.808740
	2315	23.25	0.00730	26.2791	15.166247
	2330	23.50	0.00730	26.2791	15.166247
	2345	23.75	0.00721	25.9613	14.848487
920724	0	24.00	0.00721	25.9613	14.848487
	15	24.25	0.00721	25.9613	14.848487
	30	24.50	0.00721	25.9613	14.848487
	45	24.75	0.00721	25.9613	14.848487
	100	25.00	0.00721	25.9613	14.848487
	115	25.25	0.00712	25.6459	14.533043
	130	25.50	0.00712	25.6459	14.533043

	145	25.75	0.00712	25.6459	14.533043
	200	26.00	0.00704	25.3327	14.219910
	215	26.25	0.00695	25.0219	13.909082
	230	26.50	0.00695	25.0219	13.909082
	245	26.75	0.00678	24.4071	13.294320
920724	300	27.00	0.00678	24.4071	13.294320
	315	27.25	0.00678	24.4071	13.294320
	330	27.50	0.00653	23.5021	12.389324
	345	27.75	0.00645	23.2050	12.092208
	400	28.00	0.00636	22.9102	11.797357
	415	28.25	0.00628	22.6176	11.504766
	430	28.50	0.00628	22.6176	11.504766
	445	28.75	0.00628	22.6176	11.504766
	500	29.00	0.00628	22.6176	11.504766
	515	29.25	0.00604	21.7533	10.640490
	530	29.50	0.00596	21.4697	10.356878
	545	29.75	0.00596	21.4697	10.356878
920724	600	30.00	0.00596	21.4697	10.356878
	615	30.25	0.00581	20.9091	9.796339
	630	30.50	0.00573	20.6322	9.519400
	645	30.75	0.00573	20.6322	9.519400
	700	31.00	0.00565	20.3575	9.244674
	715	31.25	0.00565	20.3575	9.244674
	730	31.50	0.00565	20.3575	9.244674
	745	31.75	0.00558	20.0850	8.972154
	800	32.00	0.00558	20.0850	8.972154
	815	32.25	0.00550	19.8146	8.701835
	830	32.50	0.00550	19.8146	8.701835
	845	32.75	0.00550	19.8146	8.701835
920724	900	33.00	0.00550	19.8146	8.701835
	915	33.25	0.00543	19.5465	8.433710
	930	33.50	0.00536	19.2806	8.167775
	945	33.75	0.00536	19.2806	8.167775
	1000	34.00	0.00536	19.2806	8.167775
	1015	34.25	0.00536	19.2806	8.167775
	1030	34.50	0.00528	19.0168	7.904022
	1045	34.75	0.00528	19.0168	7.904022
	1100	35.00	0.00521	18.7553	7.642446
	1115	35.25	0.00507	18.2386	7.125800
	1130	35.50	0.00493	17.7306	6.617789
	1145	35.75	0.00479	17.2312	6.118364
920724	1200	36.00	0.00479	17.2312	6.118364
	1215	36.25	0.00479	17.2312	6.118364
	1230	36.50	0.00472	16.9847	5.871855
	1245	36.75	0.00472	16.9847	5.871855
	1300	37.00	0.00472	16.9847	5.871855
	1315	37.25	0.00472	16.9847	5.871855
	1330	37.50	0.00465	16.7403	5.627475
	1345	37.75	0.00465	16.7403	5.627475
	1400	38.00	0.00465	16.7403	5.627475
	1415	38.25	0.00465	16.7403	5.627475
	1430	38.50	0.00465	16.7403	5.627475
	1445	38.75	0.00458	16.4980	5.385217
920724	1500	39.00	0.00458	16.4980	5.385217
	1515	39.25	0.00458	16.4980	5.385217
	1530	39.50	0.00458	16.4980	5.385217
	1545	39.75	0.00452	16.2579	5.145075
	1600	40.00	0.00452	16.2579	5.145075

	1615	40.25	0.00452	16.2579	5.145075
	1630	40.50	0.00452	16.2579	5.145075
	1645	40.75	0.00452	16.2579	5.145075
	1700	41.00	0.00452	16.2579	5.145075
	1715	41.25	0.00445	16.0199	4.907042
	1730	41.50	0.00445	16.0199	4.907042
	1745	41.75	0.00445	16.0199	4.907042
920724	1800	42.00	0.00438	15.7839	4.671113
	1815	42.25	0.00438	15.7839	4.671113
	1830	42.50	0.00438	15.7839	4.671113
	1845	42.75	0.00438	15.7839	4.671113
	1900	43.00	0.00438	15.7839	4.671113
	1915	43.25	0.00438	15.7839	4.671113
	1930	43.50	0.00438	15.7839	4.671113
	1945	43.75	0.00438	15.7839	4.671113
	2000	44.00	0.00400	14.4122	3.299357
	2015	44.25	0.00400	14.4122	3.299357
	2030	44.50	0.00400	14.4122	3.299357
	2045	44.75	0.00400	14.4122	3.299357
920724	2100	45.00	0.00400	14.4122	3.299357
	2115	45.25	0.00388	13.9715	2.858647
	2130	45.50	0.00388	13.9715	2.858647
	2145	45.75	0.00388	13.9715	2.858647
	2200	46.00	0.00388	13.9715	2.858647
	2215	46.25	0.00388	13.9715	2.858647
	2230	46.50	0.00388	13.9715	2.858647
	2245	46.75	0.00388	13.9715	2.858647
	2300	47.00	0.00382	13.7542	2.641365
	2315	47.25	0.00382	13.7542	2.641365
	2330	47.50	0.00382	13.7542	2.641365
	2345	47.75	0.00382	13.7542	2.641365
920725	0	48.00	0.00382	13.7542	2.641365
	15	48.25	0.00382	13.7542	2.641365
	30	48.50	0.00382	13.7542	2.641365
	45	48.75	0.00376	13.5389	2.426124
	100	49.00	0.00376	13.5389	2.426124
	115	49.25	0.00376	13.5389	2.426124
	130	49.50	0.00376	13.5389	
	145	49.75	0.00376	13.5389	
	200	50.00	0.00376	13.5389	
	215	50.25	0.00376	13.5389	
	230	50.50	0.00376	13.5389	
	245	50.75	0.00376	13.5389	
920725	300	51.00	0.00376	13.5389	
	315	51.25	0.00376	13.5389	
	330	51.50	0.00376	13.5389	
	345	51.75	0.00376	13.5389	
	400	52.00	0.00376	13.5389	

Trapezium rule:

y0 + y128	2.426
y1 + y2 +...+ yn-1	945.302
h = (b - a)/n	0.250

Area between curve and horizontal datum :	236.629
Area between baseflow and horizontal datum:	38.818
Total stormflow volume through weir :	197.811 m3

STORMFLOW VOLUME EVALUATION : Weir DEH923

From the storm hydrograph, total stormflow volume is calculated using the Trapezium rule, to find the area under the curve representing stormflow. Baseflow separation is by a straight line.

Date	Time	Time (hours)	Q 923 (m3/s)	Q 923 (m3/h)	Integration Ordinates
	1400	14.00	0.00182	6.5688	
	1415	14.25	0.00182	6.5688	
	1430	14.50	0.00182	6.5688	
	1445	14.75	0.00182	6.5688	0.000000
920723	1500	15.00	0.00186	6.7020	0.133238
	1515	15.25	0.00186	6.7020	0.133238
	1530	15.50	0.00190	6.8369	0.268084
	1545	15.75	0.00190	6.8369	0.268084
	1600	16.00	0.00190	6.8369	0.268084
	1615	16.25	0.00190	6.8369	0.268084
	1630	16.50	0.00190	6.8369	0.268084
	1645	16.75	0.00190	6.8369	0.268084
	1700	17.00	0.00190	6.8369	0.268084
	1715	17.25	0.00190	6.8369	0.268084
	1730	17.50	0.00198	7.1114	0.542628
	1745	17.75	0.00205	7.3925	0.823682
920723	1800	18.00	0.00222	7.9743	1.405525
	1815	18.25	0.00230	8.2752	1.706414
	1830	18.50	0.00230	8.2752	1.706414
	1845	18.75	0.00230	8.2752	1.706414
	1900	19.00	0.00230	8.2752	1.706414
	1915	19.25	0.00230	8.2752	1.706414
	1930	19.50	0.00265	9.5464	2.977569
	1945	19.75	0.00426	15.3216	8.752841
	2000	20.00	0.00559	20.1111	13.542333
	2015	20.25	0.00588	21.1639	14.595076
	2030	20.50	0.00588	21.1639	14.595076
	2045	20.75	0.00573	20.6335	14.064676
920723	2100	21.00	0.00551	19.8530	13.284170
	2115	21.25	0.00530	19.0905	12.521652
	2130	21.50	0.00516	18.5920	12.023230
	2145	21.75	0.00516	18.5920	12.023230
	2200	22.00	0.00516	18.5920	12.023230
	2215	22.25	0.00516	18.5920	12.023230
	2230	22.50	0.00530	19.0905	12.521652
	2245	22.75	0.00530	19.0905	12.521652
	2300	23.00	0.00530	19.0905	12.521652
	2315	23.25	0.00530	19.0905	12.521652
	2330	23.50	0.00530	19.0905	12.521652
	2345	23.75	0.00530	19.0905	12.521652
920724	0	24.00	0.00530	19.0905	12.521652
	15	24.25	0.00530	19.0905	12.521652
	30	24.50	0.00516	18.5920	12.023230
	45	24.75	0.00510	18.3458	11.776981
	100	25.00	0.00503	18.1015	11.532700
	115	25.25	0.00496	17.8592	11.290380
	130	25.50	0.00483	17.3804	10.811606

	145	25.75	0.00463	16.6768	10.108028
	200	26.00	0.00450	16.2174	9.648635
	215	26.25	0.00444	15.9906	9.421821
	230	26.50	0.00438	15.7657	9.196921
	245	26.75	0.00432	15.5427	8.973929
920724	300	27.00	0.00432	15.5427	8.973929
	315	27.25	0.00432	15.5427	8.973929
	330	27.50	0.00402	14.4562	7.887410
	345	27.75	0.00402	14.4562	7.887410
	400	28.00	0.00396	14.2446	7.675755
	415	28.25	0.00390	14.0348	7.465971
	430	28.50	0.00384	13.8269	7.258052
	445	28.75	0.00384	13.8269	7.258052
	500	29.00	0.00378	13.6208	7.051991
	515	29.25	0.00373	13.4166	6.847785
	530	29.50	0.00373	13.4166	6.847785
	545	29.75	0.00373	13.4166	6.847785
920724	600	30.00	0.00361	13.0137	6.444910
	615	30.25	0.00361	13.0137	6.444910
	630	30.50	0.00361	13.0137	6.444910
	645	30.75	0.00361	13.0137	6.444910
	700	31.00	0.00361	13.0137	6.444910
	715	31.25	0.00345	12.4232	5.854359
	730	31.50	0.00345	12.4232	5.854359
	745	31.75	0.00345	12.4232	5.854359
	800	32.00	0.00345	12.4232	5.854359
	815	32.25	0.00340	12.2300	5.661156
	830	32.50	0.00334	12.0386	5.469767
	845	32.75	0.00334	12.0386	5.469767
920724	900	33.00	0.00334	12.0386	5.469767
	915	33.25	0.00329	11.8490	5.280187
	930	33.50	0.00329	11.8490	5.280187
	945	33.75	0.00329	11.8490	5.280187
	1000	34.00	0.00324	11.6612	5.092409
	1015	34.25	0.00324	11.6612	5.092409
	1030	34.50	0.00319	11.4752	4.906428
	1045	34.75	0.00319	11.4752	4.906428
	1100	35.00	0.00319	11.4752	4.906428
	1115	35.25	0.00314	11.2910	4.722238
	1130	35.50	0.00314	11.2910	4.722238
	1145	35.75	0.00314	11.2910	4.722238
920724	1200	36.00	0.00309	11.1086	4.539833
	1215	36.25	0.00309	11.1086	4.539833
	1230	36.50	0.00309	11.1086	4.539833
	1245	36.75	0.00304	10.9280	4.359209
	1300	37.00	0.00304	10.9280	4.359209
	1315	37.25	0.00304	10.9280	4.359209
	1330	37.50	0.00304	10.9280	4.359209
	1345	37.75	0.00299	10.7492	4.180357
	1400	38.00	0.00294	10.5721	4.003274
	1415	38.25	0.00294	10.5721	4.003274
	1430	38.50	0.00294	10.5721	4.003274
	1445	38.75	0.00294	10.5721	4.003274
920724	1500	39.00	0.00289	10.3968	3.827953
	1515	39.25	0.00289	10.3968	3.827953
	1530	39.50	0.00284	10.2232	3.654387
	1545	39.75	0.00284	10.2232	3.654387
	1600	40.00	0.00284	10.2232	3.654387

	1615	40.25	0.00279	10.0514	3.482572
	1630	40.50	0.00279	10.0514	3.482572
	1645	40.75	0.00279	10.0514	3.482572
	1700	41.00	0.00279	10.0514	3.482572
	1715	41.25	0.00279	10.0514	3.482572
	1730	41.50	0.00279	10.0514	3.482572
	1745	41.75	0.00274	9.8813	3.312502
920724	1800	42.00	0.00274	9.8813	3.312502
	1815	42.25	0.00270	9.7130	3.144169
	1830	42.50	0.00270	9.7130	3.144169
	1845	42.75	0.00265	9.5464	2.977569
	1900	43.00	0.00265	9.5464	2.977569
	1915	43.25	0.00265	9.5464	2.977569
	1930	43.50	0.00265	9.5464	2.977569
	1945	43.75	0.00265	9.5464	2.977569
	2000	44.00	0.00265	9.5464	2.977569
	2015	44.25	0.00261	9.3815	2.812696
	2030	44.50	0.00261	9.3815	2.812696
	2045	44.75	0.00256	9.2184	2.649543
920724	2100	45.00	0.00256	9.2184	2.649543
	2115	45.25	0.00256	9.2184	2.649543
	2130	45.50	0.00256	9.2184	2.649543
	2145	45.75	0.00256	9.2184	2.649543
	2200	46.00	0.00252	9.0569	2.488104
	2215	46.25	0.00252	9.0569	2.488104
	2230	46.50	0.00252	9.0569	2.488104
	2245	46.75	0.00252	9.0569	2.488104
	2300	47.00	0.00252	9.0569	
	2315	47.25	0.00252	9.0569	
	2330	47.50	0.00252	9.0569	
	2345	47.75	0.00252	9.0569	
920725	0	48.00	0.00252	9.0569	
	15	48.25	0.00252	9.0569	
	30	48.50	0.00252	9.0569	
	45	48.75	0.00252	9.0569	
	100	49.00	0.00252	9.0569	
	115	49.25	0.00252	9.0569	
	130	49.50	0.00252	9.0569	
	145	49.75	0.00252	9.0569	
	200	50.00	0.00252	9.0569	
	215	50.25	0.00252	9.0569	
	230	50.50	0.00252	9.0569	
	245	50.75	0.00252	9.0569	
920725	300	51.00	0.00252	9.0569	
	315	51.25	0.00252	9.0569	
	330	51.50	0.00252	9.0569	
	345	51.75	0.00252	9.0569	
	400	52.00	0.00252	9.0569	

Trapezium rule:

y0 + y128	2.488
y1 + y2 +...+ yn-1	732.579
h = (b - a)/n	0.250

Area between curve and horizontal datum	:	183.456
Area between baseflow and horizontal datum	:	39.810
Total stormflow volume through weir	:	143.646 m3

APPENDIX F

Calculation of Flow Rates in Northeast Drain

FLOW GAUGING IN NORTHEAST DRAIN: 14/07/92

Two points were selected in the drain at convenient sites for measuring discharge. These were at sampling point 2, and at point 16a, between sampling points 16 and 17.

Point 2: 50 m along drain

Length of reach	:	0.25 m
Time of float travel	:	0.90 s
Float coefficient	:	0.80
Float Velocity	:	0.28 m/s
Mean Velocity	:	0.22 m/s
Cross-sectional Area	:	0.005 m2
Mean Discharge	:	0.0011 m3/s 1.11 l/s

Point 16a: 1010 m along drain

Length of reach	:	1.30 m
Time of float travel	:	18.90 s
Float coefficient	:	0.80
Float Velocity	:	0.07 m/s
Mean Velocity	:	0.06 m/s
Cross-sectional Area	:	0.01 m2
Mean Discharge	:	0.0006 m3/s 0.55 l/s

APPENDIX G

MODFLOW Data Files

BCF Data File

```
          1          0
 1 3 3 3 3 3
          0          1
          2          1(23F5.0)
 100. 100. 100. 100. 100. 100. 100.  25.  10.   6.   5.   5.   2.   2.
   2.   2.   2.   2.   2.  14.  40.  50.  45.
          0          1
          2          1(23F6.3)
 0.500 0.500 0.500 0.500 0.500 0.500 0.500 0.500 0.500 0.50098.50098.5
0098.50098.50098.50098.50098.500 7.000 7.000 7.000 7.000 7.000 7.000
          2          1(23F5.1)
 57.8 57.8 57.8 57.2 57.2 57.2 57.8 57.8 57.8 57.8 57.8 57.6 57.6 57.6
 57.6 57.5 57.5 57.5 57.7 57.8 57.9 58.8 60.0
          2          1(23F6.3)
 0.150 0.150 0.150 0.140 0.130 0.130 0.140 0.150 0.150 0.15030.30831.2
7031.27032.29533.39033.39033.390 3.571 3.922 4.000 4.167 5.263 5.263
          2          1(23F6.3)
 0.050 0.050 0.050 0.050 0.050 0.050 0.050 0.070 0.150 0.200 0.400 0.6
00 0.600 0.400 0.300 0.200 0.200 0.200 0.200 1.00010.00010.00010.000
          2          1(23F5.1)
 55.5 55.5 55.5 55.0 54.5 54.5 55.0 55.5 55.5 55.8 55.8 56.0 56.0 56.2
 56.4 56.4 56.4 56.7 57.2 57.3 57.5 58.5 58.5
          2          1(23F7.4)
 0.0233 0.0233 0.0204 0.0185 0.0179 0.0172 0.0208 0.0333 0.0714 0.1026
 0.2222 0.4286 0.4800 0.3636 0.3529 0.2500 0.2857 0.2857 0.3333 2.2222
33.333357.000012.9032
          2          1(23F5.1)
 57.8 57.8 57.8 57.2 57.2 57.2 57.8 57.8 57.8 57.8 57.8 57.6 57.6 57.6
 57.6 57.5 57.5 57.5 57.7 57.8 57.9 58.8 60.0
          2          1(23F6.3)
 0.050 0.050 0.050 0.050 0.050 0.050 0.050 0.070 0.150 0.200 0.400 0.4
00 0.400 0.400 0.400 0.400 0.400 0.400 0.400 1.00010.00010.00010.000
          2          1(23F6.2)
 53.40 53.40 52.80 51.80 51.60 51.40 52.90 53.50 53.50 53.80 54.10 54.
80 55.10 55.40 55.90 55.90 56.10 56.10 56.50 56.90 57.30 58.45 58.45
          2          1(23F8.4)
  0.0217  0.0286  0.0256  0.0250  0.0263  0.0250  0.0286  0.0400  0.09
38  0.1290  0.2857  0.2759  0.3478  0.3333  0.3200  0.3333  0.4706  0.
6667  0.8000  2.8571 66.6667200.0000200.0000
          2          1(23F5.1)
 55.5 55.5 55.5 55.0 54.5 54.5 55.0 55.5 55.5 55.8 55.8 56.0 56.0 56.2
 56.4 56.4 56.4 56.7 57.2 57.3 57.5 58.5 58.5
          2          1(23F6.3)
 0.003 0.003 0.003 0.003 0.003 0.003 0.003 0.005 0.005 0.005 0.005 0.0
05 0.005 0.005 0.005 0.010 0.010 0.010 0.100 1.000 7.000 7.000 7.000
          2          1(23F5.1)
 50.9 52.0 51.6 51.0 50.7 50.5 51.5 52.0 52.3 52.7 53.0 53.1 53.7 53.8
 53.9 54.0 54.7 55.5 56.2 56.6 57.2 58.4 58.4
          2          1(23F7.4)
 0.0008 0.0008 0.0008 0.0009 0.0008 0.0008 0.0008 0.0013 0.0015 0.0015
 0.0015 0.0014 0.0014 0.0013 0.0013 0.0025 0.0025 0.0025 0.0235 0.2273
 2.2222 2.0513 2.1164
          2          1(23F6.2)
 53.40 53.40 52.80 51.80 51.60 51.40 52.90 53.50 53.50 53.80 54.10 54.
80 55.10 55.40 55.90 55.90 56.10 56.10 56.50 56.90 57.30 58.45 58.45
          2          1(23F4.1)
 4.0 5.0 5.0 6.0 7.0 8.0 9.010.010.010.010.010.010.010.010.010.010.010
.010.010.010.010.010.0

          2          1(23F5.1)
 46.0 46.0 45.5 44.9 44.0 44.3 45.0 45.7 46.7 47.1 47.3 47.6 47.7 47.8
 47.9 48.0 48.0 48.0 48.0 48.1 48.3 48.7 49.0
          2          1(23F5.2)
 0.42 0.50 0.51 0.63 0.75 0.86 0.92 1.00 0.99 0.97 0.95 0.95 0.92 0.92
 0.91 0.91 0.88 0.85 0.83 0.81 0.79 0.76 0.76
          2          1(23F5.1)
 50.9 52.0 51.6 51.0 50.7 50.5 51.5 52.0 52.3 52.7 53.0 53.1 53.7 53.8
 53.9 54.0 54.7 55.5 56.2 56.6 57.2 58.4 58.4
          2          1(23F4.1)
 2.0 2.0 2.0 2.0 2.0 2.0 2.0 2.0 2.0 2.0 2.0 2.0 2.0 2.0 2.0 2.0 2.0 2
.0 2.0 2.0 2.0 2.0 2.0
          2          1(23F5.1)
 32.0 32.0 32.0 32.0 32.0 32.0 32.0 32.0 32.0 32.0 32.0 32.0 32.0 32.0
 32.0 32.0 32.0 32.0 32.0 32.0 32.0 32.0 32.0
          2          1(23F5.1)
 46.0 46.0 45.5 44.9 44.0 44.3 45.0 45.7 46.7 47.1 47.3 47.6 47.7 47.8
 47.9 48.0 48.0 48.0 48.0 48.1 48.3 48.7 49.0
```

BAS Data File

```
Bog/Drain/Esker 2d model with
6 layers, recharge and drain, 1 stress period.
           6          1          23          1          4
  2  0 10  0  0  0  0  8  0  0  0 12 13  0
           0          1
           1          1(23I2)                           2
-1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0
           1          1(23I2)                           2
-2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
           1          1(23I2)                           2
-3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3
           1          1(23I2)                           2
-4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4-4
           1          1(23I2)                           2
-5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5-5
           1          1(23I2)                           2
-6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6-6
         99.
           1          1(23F6.2)                         1
 60.50 60.80 60.70 60.70 60.00 60.00 60.00 60.00 60.00 60.00 99.    99.
   99.    99.    99.    99.    99.    99.    99.    99.    99.    99.    99.
           1          1(23f6.2)                         1
 60.10 60.00 60.00 60.00 60.00 60.00 59.00 59.00 59.00 58.00 58.00 57.
00 57.00 57.00 57.00 57.00 57.00 57.00 57.50 57.50 57.50 57.50 57.50
           1          1(23f6.2)                         1
 59.70 60.00 60.00 60.00 60.00 60.00 59.00 59.00 58.00 58.00 58.00 57.
00 57.00 57.00 57.00 57.50 57.50 57.50 57.50 57.50 57.50 57.50
           1          1(23f6.2)                         1
 58.70 57.50 57.50 57.50 57.50 57.50 57.50 57.50 57.50 57.50 57.50 57.
50 57.50 57.50 57.50 57.50 57.50 57.50 57.50 57.50 57.50 57.50 57.90
           1          1(23f6.2)                         1
 58.50 57.50 57.50 57.50 57.50 57.50 57.50 57.50 57.50 57.50 57.50 57.
50 57.50 57.50 57.50 57.50 57.50 57.50 57.50 57.50 57.50 57.50 57.95
           1          1(23f6.2)                         1
 58.20 57.50 57.50 57.50 57.50 57.50 57.80 57.80 57.80 57.80 57.80 57.
80 57.80 57.80 57.80 57.80 57.80 57.80 57.80 57.80 57.80 57.80 58.00
        365.        365          1.
```

DRN Data File

```
           2          0
           2
           2          1          17          56.4          0.4000
           3          1          17          56.1          0.2000
```

RCH Data File

```
           3          0
           1
           8          1(23F8.5)
 0.00070 0.00070 0.00070 0.00070 0.00070 0.00070 0.00070 0.00070 0.000
70 0.00070 0.00070 0.00070 0.00070 0.00070 0.00070 0.00070 0.00070 0.0
0070 0.00070 0.00070 0.00070 0.00070 0.00070
```

APPENDIX H1

Piezometer Basic Information - TUBEDAT1.WK3

APPENDIX H2

Borehole, Cobra Drilling and Domestic Well Basic Information - BCWDAT1.WK3

BOREHOLE DATA: Basic Information

Borehole No.	Casing Elevation (m)	Filter 1 Elevation (middle) (m)	Filter 2 Elevation (middle) (m)	Filter 3 Elevation (middle) (m)	Co-ords. S (m)	OPW Grid E (m)	Comment
CLBH2	58.35	46.73	52.48	55.63			
CLBH3	64.32	51.63	-	-			
CLBH4	59.52	47.77	54.12	56.22			
CLBH5	56.21	51.04	49.84	-			
CLBH6	56.21	35.45	41.78	43.80			
CLBH7	50.79	44.27	46.43	-			
CLBH8							

COBRA DRILLING DATA: Basic Information

Cobra Drill No.	Tube Elevation (m)	Filter Elevation (middle) (m)	Co-ords. S (m)	OPW Grid E (m)	Comment
CLCD1	55.615	43.425			Before 18/05/92
CLCD1	54.225	43.425			After 18/05/92
CLCD2_N	51.805	46.705			
CLCD2_S	51.718	47.818			
CLCD3	58.893	49.263			

DOMESTIC WELL DATA: Basic Information

Well No.	Top Elevation (m)	Bottom Elevation (m)	Co-ords. OPW Grid S (m)	E (m)	Comment
0	67.00	32.96			
1	60.12	56.32			
2	58.53	55.58			
3	57.71	53.98			
4	53.98				Depth unknown
5	60.42	56.02			
6	60.26	56.61			
7	60.51	55.41			
8	60.89	56.64			
9	60.04	56.54			
12	56.09	51.36			
13	62.75				Depth unknown
14					Depth 3.80 m
15	54.07	37.97			
16	51.15	47.38			
17	61.26				Depth unknown
18	64.86	46.56			
19	70.27	57.37			
20	54.03	49.78			
21	60.04	46.09			
22	55.41				Depth unknown
23	57.85				Depth unknown

APPENDIX H3

Groundwater Level Data - WATLEV1.WK3

GROUNDWATER LEVEL DATA: Piezometer Stations 101 to 107

Site ID No.	Piezo No.	Date	Water Level (m)	Collar Elev. (m)	Water Elev. (m)	Date Number
2023SEH0101	1	16/01/91	0.580	57.69	57.11	33254
2023SEH0101	1	29/01/91	0.550	57.69	57.14	33267
2023SEH0101	1	28/02/91	0.545	57.69	57.14	33297
2023SEH0101	1	13/03/91	0.550	57.69	57.14	33310
2023SEH0101	1	25/03/91	0.550	57.69	57.14	33322
2023SEH0101	1	10/04/91	0.570	57.69	57.12	33338
2023SEH0101	1	24/04/91	0.560	57.69	57.13	33352
2023SEH0101	1	22/05/91	0.550	57.69	57.14	33380
2023SEH0101	1	12/06/91	0.494	57.69	57.20	33401
2023SEH0101	1	24/07/91	0.756	57.69	56.93	33443
2023SEH0101	1	07/08/91	0.712	57.69	56.98	33457
2023SEH0101	1	21/08/91	0.792	57.69	56.90	33471
2023SEH0101	1	04/09/91	0.890	57.69	56.80	33485
2023SEH0101	1	21/10/91	0.820	57.69	56.87	33532
2023SEH0101	1	14/11/91	0.870	57.69	56.82	33556
2023SEH0101	1	22/12/91	0.790	57.69	56.90	33594
2023SEH0101	2	16/01/91	0.710	57.69	56.98	33254
2023SEH0101	2	29/01/91	0.720	57.69	56.97	33267
2023SEH0101	2	28/02/91	0.690	57.69	57.00	33297
2023SEH0101	2	13/03/91	0.700	57.69	56.99	33310
2023SEH0101	2	25/03/91	0.726	57.69	56.96	33322
2023SEH0101	2	10/04/91	0.762	57.69	56.93	33338
2023SEH0101	2	24/04/91	0.772	57.69	56.92	33352
2023SEH0101	2	22/05/91	0.752	57.69	56.94	33380
2023SEH0101	2	12/06/91	0.746	57.69	56.94	33401
2023SEH0101	2	10/07/91	0.492	57.69	57.20	33429
2023SEH0101	2	24/07/91	0.422	57.69	57.27	33443
2023SEH0101	2	07/08/91	0.383	57.69	57.31	33457
2023SEH0101	2	21/08/91	0.383	57.69	57.31	33471
2023SEH0101	2	04/09/91	0.440	57.69	57.25	33485
2023SEH0101	2	21/10/91	0.430	57.69	57.26	33532
2023SEH0101	2	14/11/91	0.400	57.69	57.29	33556
2023SEH0101	2	22/12/91	0.350	57.69	57.34	33594
2023SEH0102	1	10/07/91	0.597	57.72	57.12	33429
2023SEH0102	1	24/07/91	0.545	57.72	57.18	33443
2023SEH0102	1	07/08/91	0.544	57.72	57.18	33457
2023SEH0102	1	21/08/91	0.565	57.72	57.16	33471
2023SEH0102	1	04/09/91	0.640	57.72	57.08	33485
2023SEH0102	1	14/11/91	0.610	57.72	57.11	33556
2023SEH0102	1	22/12/91	0.580	57.72	57.14	33594
2023SEH0102	2	16/01/91	0.240	57.72	57.48	33254
2023SEH0102	2	29/01/91	0.230	57.72	57.49	33267
2023SEH0102	2	28/02/91	0.215	57.72	57.51	33297
2023SEH0102	2	13/03/91	0.225	57.72	57.50	33310
2023SEH0102	2	25/03/91	0.210	57.72	57.51	33322

2023SEH0102	2	10/04/91	0.250	57.72	57.47	33338
2023SEH0102	2	24/04/91	0.240	57.72	57.48	33352
2023SEH0102	2	22/05/91	0.350	57.72	57.37	33380
2023SEH0102	2	12/06/91	0.587	57.72	57.13	33401
2023SEH0102	2	10/07/91	0.563	57.72	57.16	33429
2023SEH0102	2	24/07/91	0.513	57.72	57.21	33443
2023SEH0102	2	07/08/91	0.468	57.72	57.25	33457
2023SEH0102	2	21/08/91	0.555	57.72	57.17	33471
2023SEH0102	2	04/09/91	0.710	57.72	57.01	33485
2023SEH0102	2	21/10/91	0.890	57.72	56.83	33532
2023SEH0102	2	14/11/91	0.790	57.72	56.93	33556
2023SEH0102	2	22/12/91	0.740	57.72	56.98	33594
2023SEH0103	1	16/01/91	0.250	57.50	57.25	33254
2023SEH0103	1	29/01/91	0.260	57.50	57.24	33267
2023SEH0103	1	28/02/91	0.230	57.50	57.27	33297
2023SEH0103	1	13/03/91	0.245	57.50	57.25	33310
2023SEH0103	1	25/03/91	0.225	57.50	57.27	33322
2023SEH0103	1	10/04/91	0.250	57.50	57.25	33338
2023SEH0103	1	24/04/91	0.235	57.50	57.26	33352
2023SEH0103	1	22/05/91	0.230	57.50	57.27	33380
2023SEH0103	1	12/06/91	0.261	57.50	57.24	33401
2023SEH0103	1	10/07/91	0.303	57.50	57.19	33429
2023SEH0103	1	24/07/91	0.231	57.50	57.27	33443
2023SEH0103	1	07/08/91	0.195	57.50	57.30	33457
2023SEH0103	1	21/08/91	0.274	57.50	57.22	33471
2023SEH0103	1	04/09/91	0.370	57.50	57.13	33485
2023SEH0103	1	21/10/91	0.380	57.50	57.12	33532
2023SEH0103	1	14/11/91	0.360	57.50	57.14	33556
2023SEH0103	1	22/12/91	0.320	57.50	57.18	33594
2023SEH0104	1	28/06/90	0.860	59.09	58.23	33052
2023SEH0104	1	16/07/90	0.920	59.09	58.17	33070
2023SEH0104	1	02/08/90	0.900	59.09	58.19	33087
2023SEH0104	1	22/08/90	0.930	59.09	58.16	33107
2023SEH0104	1	05/09/90	0.940	59.09	58.15	33121
2023SEH0104	1	19/09/90	0.935	59.09	58.16	33135
2023SEH0104	1	17/10/90	0.845	59.09	58.25	33163
2023SEH0104	1	14/11/90	0.940	59.09	58.15	33191
2023SEH0104	1	12/12/90	0.896	59.09	58.19	33219
2023SEH0104	1	16/01/91	0.805	59.09	58.29	33254
2023SEH0104	1	29/01/91	0.838	59.09	58.25	33267
2023SEH0104	1	28/02/91	0.840	59.09	58.25	33297
2023SEH0104	1	13/03/91	0.845	59.09	58.25	33310
2023SEH0104	1	25/03/91	0.835	59.09	58.26	33322
2023SEH0104	1	10/04/91	0.845	59.09	58.25	33338
2023SEH0104	1	24/04/91	0.830	59.09	58.26	33352
2023SEH0104	1	22/05/91	0.840	59.09	58.25	33380
2023SEH0104	1	12/06/91	0.832	59.09	58.26	33401
2023SEH0104	1	10/07/91	0.899	59.09	58.19	33429
2023SEH0104	1	24/07/91	0.838	59.09	58.25	33443
2023SEH0104	1	07/08/91	0.839	59.09	58.25	33457
2023SEH0104	1	21/08/91	0.752	59.09	58.34	33471
2023SEH0104	1	04/09/91	0.960	59.09	58.13	33485
2023SEH0104	1	21/10/91	0.960	59.09	58.13	33532
2023SEH0104	1	14/11/91	0.960	59.09	58.13	33556
2023SEH0104	1	22/12/91	0.870	59.09	58.22	33594
2023SEH0104	1	28/05/92	0.820	59.09	58.27	33752

APPENDIX H4

Clara West Rainfall Data - CWR92A.WK3

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

03-Jan-92	1:00	0
	2:00	0
	3:00	0
	4:00	0
	5:00	8
	6:00	0
	7:00	0
	8:00	1
	9:00	6
	10:00	17
	11:00	10
	12:00	10
03-Jan-92	13:00	9
	14:00	9
	15:00	7
	16:00	6
	17:00	1
	18:00	0
	19:00	1
	20:00	0
	21:00	0
	22:00	0
	23:00	0
	24:00	0
04-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
04-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	4
	22:00	4
	23:00	4
	24:00	13

APPENDIX H5

Evapotranspiration Data - PE_PNMAN.WK3

PENMAN POTENTIAL EVAPOTRANSPIRATION DATA

Data obtained from Birr and Mullingar weather stations.

Year	Month	BIRR P.E. (mm)	BIRR Rainfall (mm)	MULLINGAR P.E. (mm)	MULLINGAR Rainfall (mm)
1991	Jan	1.5	77.5	0.0	84.8
	Feb	7.5	60.9	6.4	92.4
	Mar	22.6	54.6	23.0	91.4
	Apr	46.0	105.6	58.2	127.1
	May	68.3	4.4	76.2	4.5
	Jun	69.1	91.2	73.8	78.5
	Jul	66.4	63.9	80.3	42.1
	Aug	57.7	74.1	61.1	37.1
	Sep	40.6	50.1	47.4	50.9
	Oct	15.6	37.4	15.9	101.1
	Nov	3.8	88.1	2.6	101.3
	Dec	1.2	33.2	0.0	70.6
1991	Tot	400.2	741.0	444.8	881.9
1992	Jan	1.0	65.4	7.0	75.9
	Feb	15.0	41.0	14.0	60.9
	Mar	26.0	86.8	27.0	90.8

APPENDIX H6

Weir Water Level Data - CEW592B.WK3

APPENDIX H7

Hydraulic Conductivity Data - KCE.WK3

HYDRAULIC CONDUCTIVITY DATA: Clara East

Hydraulic Conductivity calculated from falling head test data.

Piezo No.	Grad. of asymptote (/min)	Open Length (cm)	l/d -	Shape Factor (cm)	Area (cm2)	Hydraulic Conductivity (cm/min)	Hydraulic Conductivity (m/day)
BH2.3	0.0154	20	9.524	42.602	3.464	0.001254	0.0181
101.1	0.0002	20	9.524	42.602	3.464	0.000014	0.0002
101.2	0.0001	20	9.524	42.602	3.464	0.000012	0.0002
101.3	0.0047	20	9.524	42.602	3.464	0.000383	0.0055
141.1	0.0208	20	9.524	42.602	3.464	0.001692	0.0244
141.2	0.0037	20	9.524	42.602	3.464	0.000298	0.0043
141.3	0.0057	20	9.524	42.602	3.464	0.000464	0.0067
102.1	0.0004	20	9.524	42.602	3.464	0.000031	0.0004
102.2	0.0030	20	9.524	42.602	3.464	0.000243	0.0035
102.3	0.0099	20	9.524	42.602	3.464	0.000805	0.0116
142.1	0.0036	20	9.524	42.602	3.464	0.000290	0.0042
142.3	0.0033	20	9.524	42.602	3.464	0.000268	0.0039
103.2	0.0201	20	9.524	42.602	3.464	0.001633	0.0235
103.3	0.0467	20	9.524	42.602	3.464	0.003795	0.0547
143.1	0.0008	20	9.524	42.602	3.464	0.000066	0.0009
143.2	0.0275	20	9.524	42.602	3.464	0.002236	0.0322
143.3	0.0022	20	9.524	42.602	3.464	0.000176	0.0025
104.1	0.0565	16	7.619	36.850	3.464	0.005308	0.0764
104.2	0.0007	16	7.619	36.850	3.464	0.000062	0.0009
104.3	0.0010	16	7.619	36.850	3.464	0.000094	0.0013

Piezo No.	Grad. of asymptote (/min)	Open Length (cm)	1/d -	Shape Factor (cm)	Area (cm2)	Hydraulic Conductivity (cm/min)	Hydraulic Conductivity (m/day)
106.1	0.0043	16	7.619	36.850	3.464	0.000407	0.0059
106.2	0.0025	16	7.619	36.850	3.464	0.000235	0.0034
106.3	0.0051	16	7.619	36.850	3.464	0.000482	0.0069
151.1	0.0006	20	9.524	42.602	3.464	0.000052	0.0007
151.3	0.0272	20	9.524	42.602	3.464	0.002215	0.0319
152.3	0.0099	20	9.524	42.602	3.464	0.000802	0.0115
152.4	0.0054	20	9.524	42.602	3.464	0.000441	0.0063
123.1	0.0005	16	7.619	36.850	3.464	0.000049	0.0007
123.2	0.0167	16	7.619	36.850	3.464	0.001573	0.0226
126.1	0.0252	16	7.619	36.850	3.464	0.002370	0.0341
126.3	0.0278	16	7.619	36.850	3.464	0.002614	0.0376
126.4	0.0334	16	7.619	36.850	3.464	0.003139	0.0452

Piezometer tube diameter, d : 2.1 cm

Piezometer tube area, A : 3.464 cm2

APPENDIX H8

Topographic Data - GRNDLEV.WK3 and GRIDLEV.WK3

TOPOGRAPHIC DATA: Clara East

Ground levels at OPW Grid points

	a	b	c	d	e	f	g	h
1	58.59	59.29	59.36	59.66	60.11	60.47		60.13
2	58.44	59.22	59.56	59.88	60.30	60.71	60.72	60.74
3	57.92	59.15	59.32	59.73	60.23	60.55	60.59	60.62
4			59.26	59.71	60.18	60.31	60.51	60.61
5	57.78	58.57	59.05	59.44	59.82	60.01	60.21	60.26
6	57.04	57.76	58.55	59.35	59.72	59.84	59.97	60.00
7	56.97	58.17	58.36	59.26		59.73	59.83	
8	56.52	58.02	58.41		59.42	59.69	59.85	60.00
9	56.03	57.36	58.06		59.24	59.46	59.64	59.84
10			58.07		59.21	59.42	59.48	59.53
11				58.61	58.95	59.42	59.27	59.30

	i	j	k	l	m	n	o	p
1								
2	60.79	60.79	60.78	60.30		60.06	59.34	59.84
3		60.90	60.47	60.60	60.38	60.14	59.66	58.82
4	60.62	60.47	60.28	60.05	59.86	59.84	59.98	59.48
5	60.27	60.25	60.03	59.59	59.40	59.39	59.56	59.45
6	59.84	59.86	59.55	59.19	59.16	59.26	59.31	
7	59.81	59.60	59.19	58.83	59.13	59.30	59.08	
8	59.60	59.19	58.82		58.05	59.28	58.37	
9	59.38	58.84	58.29	58.06	57.40			
10	59.30	58.67	57.98	56.85				
11	59.19	59.78	55.95					

TOPOGRAPHIC DATA: OPW Grid, Bog road

Station Number	Bolt level (m)
0	57.62
1	56.47
2	56.22
3	56.14
4	56.13
5	55.35
6	55.20
7	54.82
8	54.53
9	54.41
10	54.29
11	54.22
12	53.96
13	53.89
14	53.87