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A BRIEF REPORT OUTLINING FIELDWORK UNDERTAKEN AT STUDLAND BAY FROM 1982 -1986 AND PRESENTING PROPOSALS FOR 1987

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1. Introduction

This short report outlines briefly the subject of saline intrusion in coastal groundwater aquifers. It then goes on to discuss the investigative work undertaken by members of the Institute of Hydrology (Wallingford) and Imperial College (London) into the behaviour of fresh and saline waters on a section of beach at Studland Bay on the Isle of Purbeck. In particular, how over the last year, results obtained from the field site have revealed that the hydrological processes in the beach area are different to those originally thought to be occurring and initially indicated by the early studies. Finally the report then presents the proposals for the next phase of field work experiments to be conducted during the period January - April 1987.

2. The classical saline intrusion problem

Figure 1 shows the 'classical' saline intrusion problem. Fresh groundwater in a coastal aquifer is draining into the sea from an inland source (eg rainfall or river recharge). At the shore the groundwater then comes into contact with a body a water about 2% more dense by virtue of the high concentration of saline ions dissolved in it. The result of this density difference is that the sea water seeks to intrude inland by undercutting the fresh water. The limit to which this body of saline water can progress to is governed by two factors: the first is the density difference between the two types of water (the larger the difference the further inland the salt water enchroaches), the second is magnitude of the outflow f the fresh water from the aquifer (the higher the outflow the less the amount of saline intrusion). In the situation described above the two different water types are assumed to be immiscible and under these circumstances the body of saline water in the aquifer is static and the postion of the saline/fresh water interface is given by the following equation:

$$z = \frac{pf}{ps - pf} h$$

where: z is the depth of the interface below sea level
h is the height of the water table above sea level
pf is the density of the fresh water
ps is the density of the salt water

3. The problem of dispersion

In the case given above the assumption was made that the saline and fresh waters were immiscible. This is not true, however, in real situations. Instead of a sharp boundary between the fresh

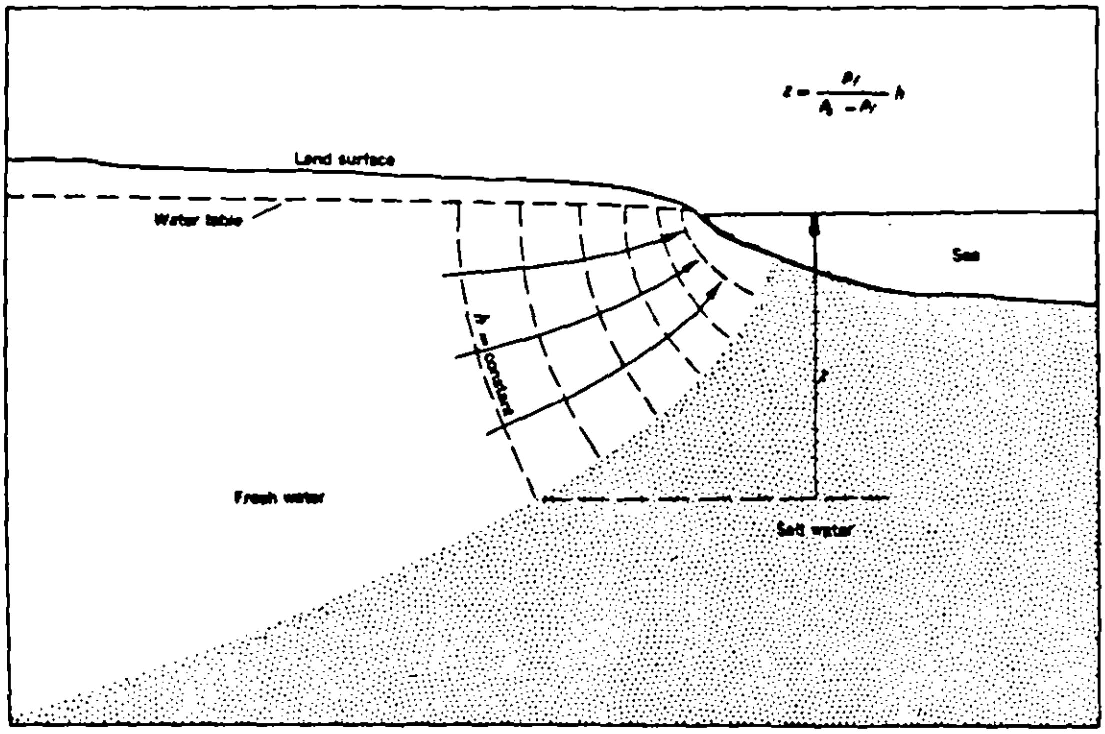


FIGURE 1.—Balance between fresh water and salt water in a coastal aquifer in which the salt water is static.

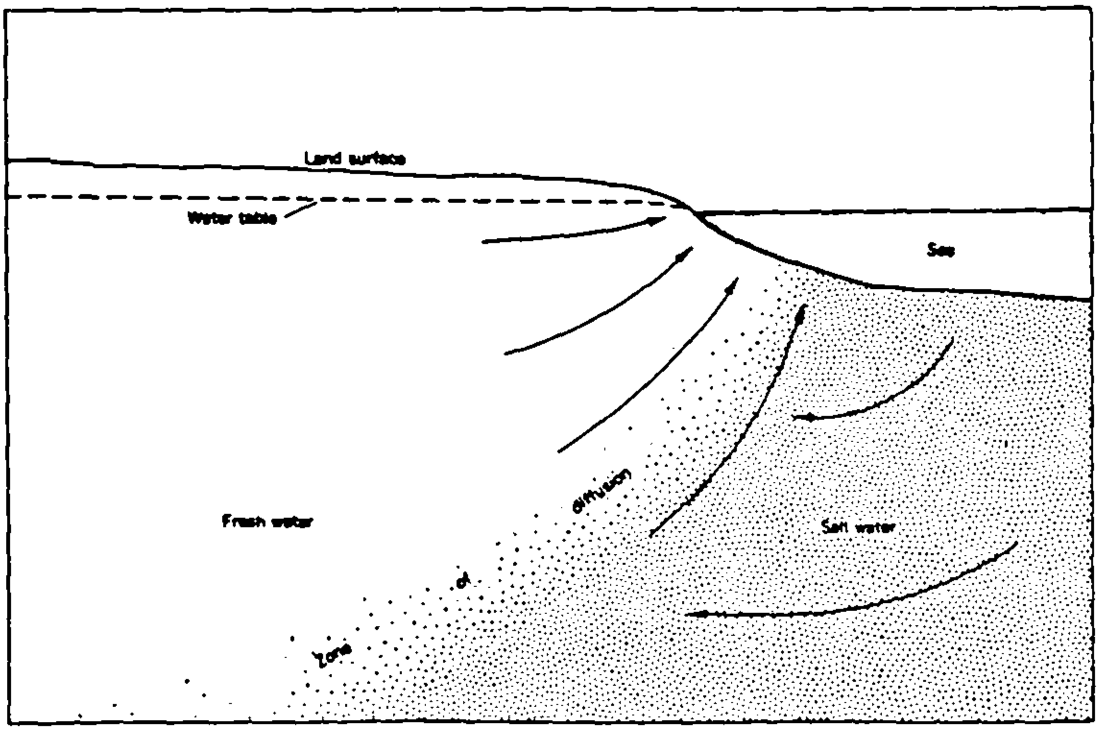


FIGURE 2.—Circulation of salt water from the sea to the zone of diffusion and back to the sea.

and salt waters there exists a transition zone of brackish water. This zone is formed by the mixing processes which take place along the interface and is called either a zone of diffusion or a dispersion zone (figure 2). Its existence has a number of important consequences. The first is that there is a seaward flow taking place through the transition zone removing saline ions from it. Hence if the postion of the interface is to remain constant there must be a supply of new saline ions into the transition zone to replace those lost. This implies that there exists within the body of saline water a slow circulation bringing salt ions into the interface region. A second consequence of the mixing process is that effects of the salt water extend further inland than in the previous example. This has important ramifications on the potential use of the water since a chloride concentration of 100 mg/l imparts a salty taste and the recommended limit for drinking water is 250 mg/l whereas the typical chloride concentration for sea water is 19,000 mg/l. Therefore when seeking to manage a coastal aquifer properly it is important to take into account the salinity distribution.

The problem of aquifer management involves the use of mathematical representations of the main physical processes occurring within the aquifer and are known as groundwater models. These representations take the form of equations which are then usually solved using a computer. The main difficulty is that often the representations used in these models are inadequate due to our lack of knowledge of the physical processes. A notable example of which is the problem of dispersion along a saline interface. As the Institute of Hydrology had during the late seventies and early eighties developed an interest in the problem of dispersion in coastal aquifers and because of the difficulties involved it was decided that it should conduct its own experimental research work into this area.

4. Studland Bay fieldwork

The previous section described the reason why the Institute of Hydrology was interested in studying the problem of dispersion. The main drawback however was that in general, saline intrusion problems occur on large spatial scales (eg tens of kilometers) and the result is that investigations made on thse scales are extremely expensive. In addition they also suffer from the fact that accurate aquifer measurements of groundwater salinities are difficult to obtain. Instead the Institute decided that an alternative approach would be to investigate the problem on a much smaller scale (ie meters). One set of conditions which satisfies this requirement are to be found on a shallow beach environment. A number of beach sites were considered as candidates for the experimental work and finally Studland Bay was chosen as the one which seemed to be most suited for the purpose.

4.1 Salinity measurements

It was mentioned above that there are difficulties when seeking to obtain values of groundwater salinity contents. The usual methods the involve the use of either borehole logs or surface resistivity suveys. Both of these methods however have serious drawbacks. The problem with drilling a borehole is that it represents a major disturbance to the aquifer and can therfore lead to unrepresentative results especially in unconsolidated material. Whilst surface resistivity surveys are unable to provide a detailed resolution of the subsurface features. Instead a new technique for studying groundwater salinities in unconsolidated conditions was developed by the Institute. This involved the use of an electrical probe which could be drilled down into the aquifer formation. The probe, shown in figure 3, consists of 4 ring electrodes mounted on a plastic sheath covering a steel rod with a drive point at the end. The outermost electrodes pass an electrical current (I) through the formation, the potential difference (V) is then measured between the inner two electrodes. These provide a resistance value (V/I) and hence enable the resistivity of the aquifer material immediately surrounding the probe to be calculated. It is then possible to relate this local measurement of resistivity to groundwater conductances and salinities. This method has a number of attractive features. They are that the drilling of the probe causes minimal disturbance to the original formation, a continuous profile of salinities can be made during drilling and the probe can be left in the ground in order to enable localised time-varying readings to be obtained.

4.2 Initial field results

The initial investigations undertaken by the Institute in 1982 using a surface resistivity measuring technique seemed to indicate that there was saline/freshwater interface at a depth varying between 2m at the mean high tide mark to 8m at a distance of 100m inland. The following year a major site investigation at the location shown in figure 4 was conducted in order to test the newly developed resistivity probe. The probe was used to build up a 2-dimensional picture of the groundwater conductivities below a section of beach (figure 5). The results showed there to be a layer of saline water 4 - 5m below the beach surface along with a transition zone to freshwater over a depth of about 1m. One interesting feature of these results were that the lines of equal conductance seemed to be quite shallow - a marked contrast to the steep gradients produced in the 'classical' picture of saline intrusion. In addition measurements the position of the water table in the beach area were made, water quality samples taken and the lithology of the beach environment investigated. The results obtained from this period of field work showed that there existed a number of interesting features in the area which were thought to require further study before the field data could be used as a basis for testing and validating computer models.

Figure 3.

Diagram showing construction of resistivity probe

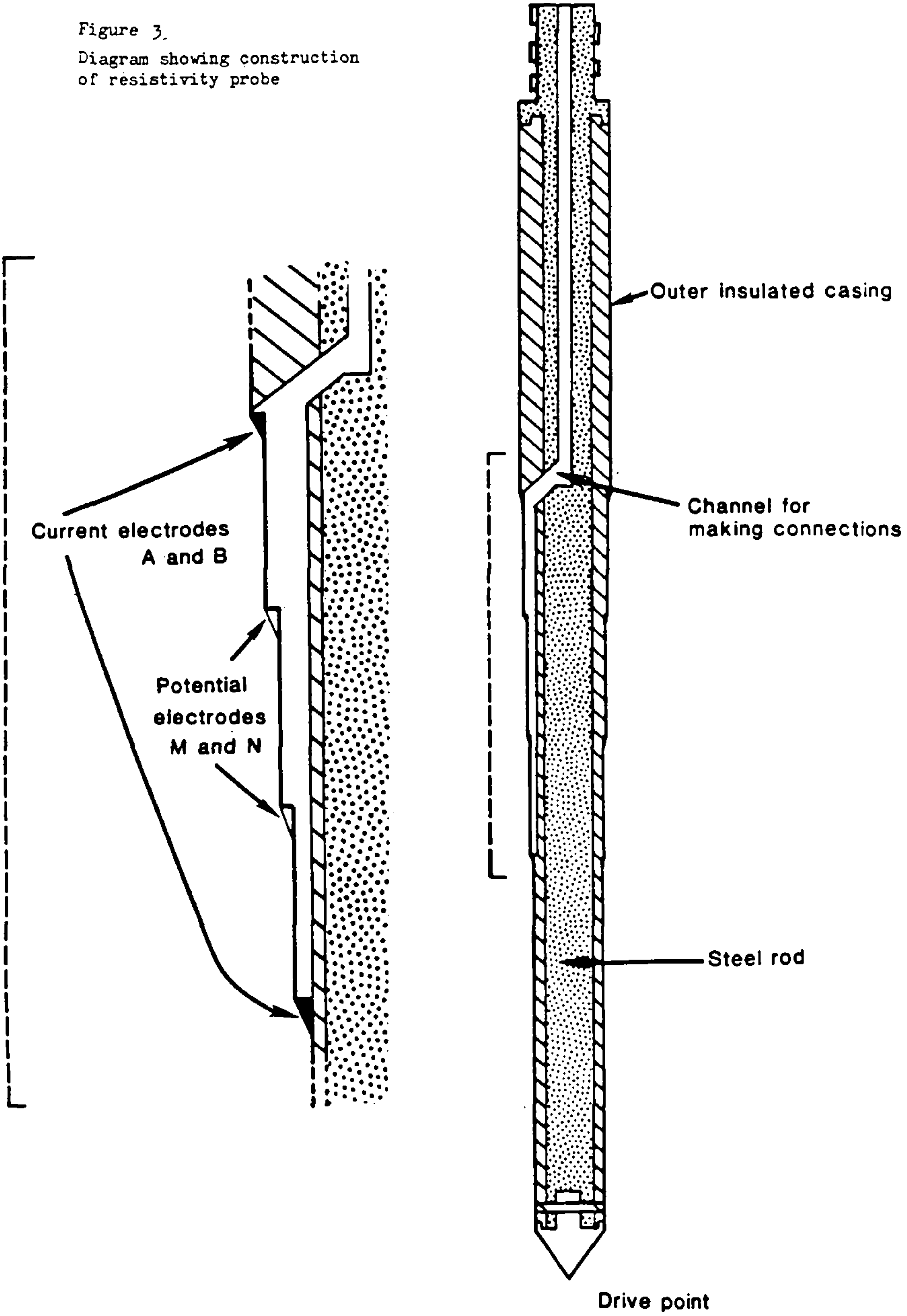
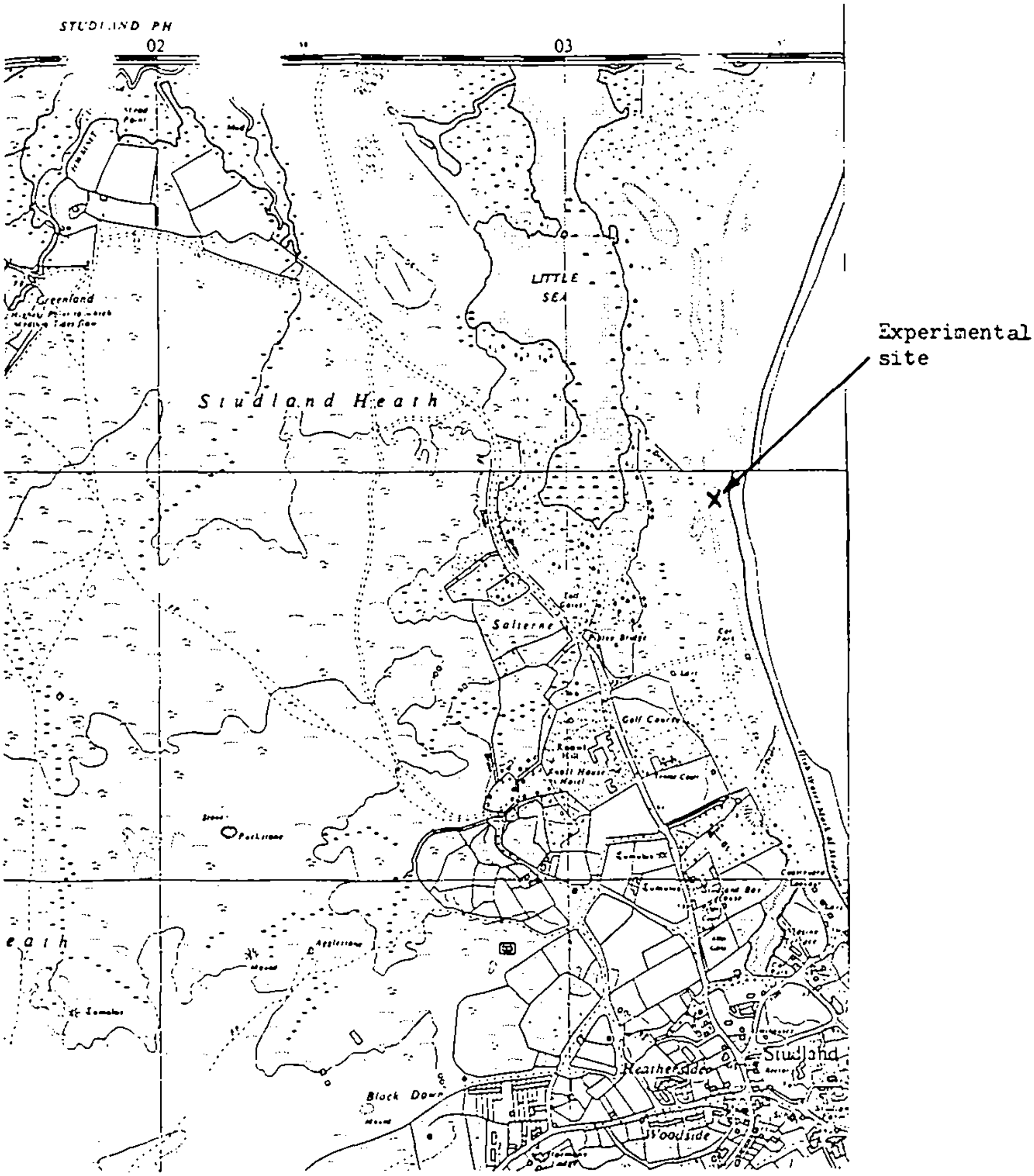


Figure 4

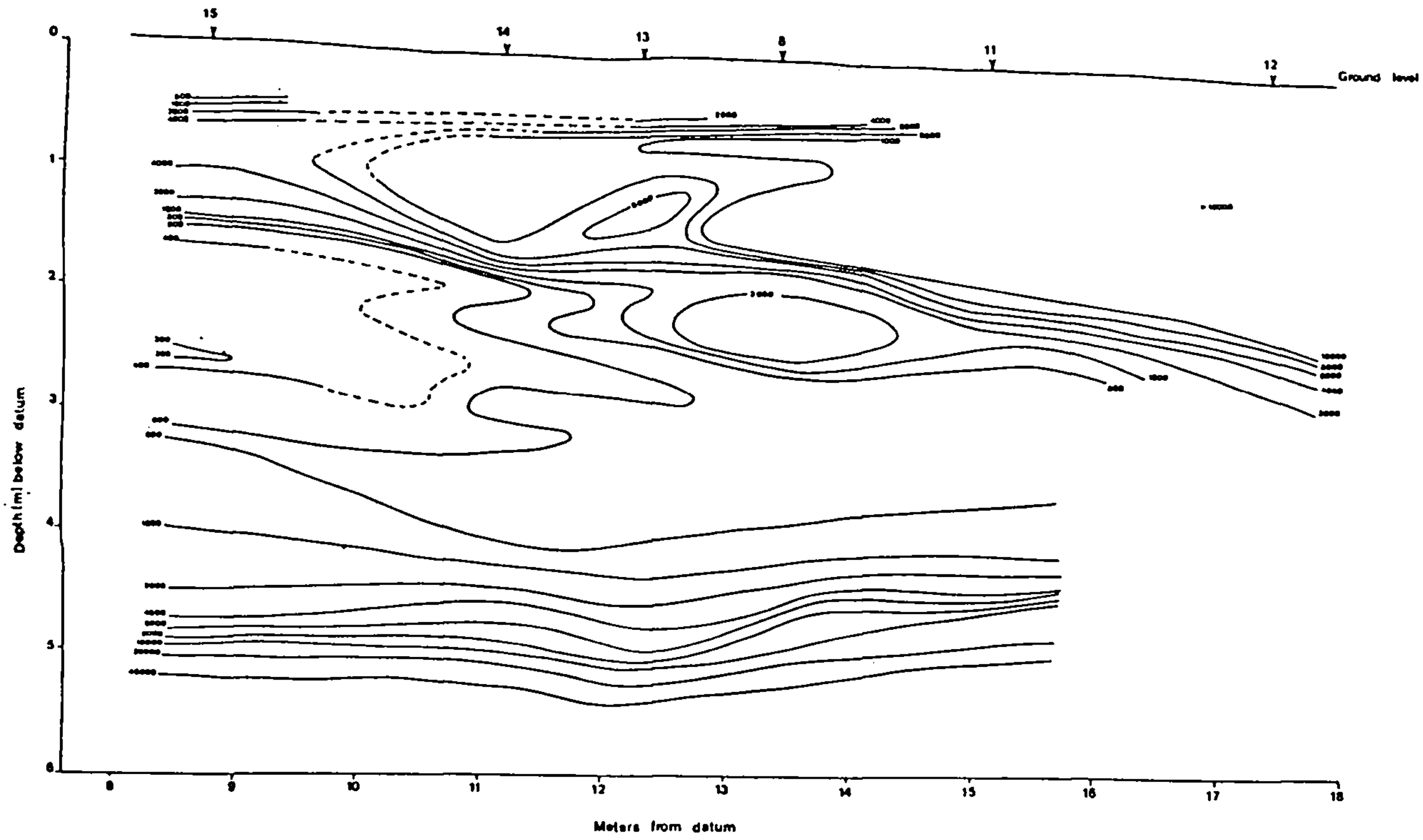
Location of experimental site



Experimental site

Figure 5

Section showing contours of interpreted pore water conductivity



4.3 1985/6 Studland field work

Once the decision had been taken to continue with the field work at Studland it was decided that the project should become ajoint one between the Institute and Imperial College. The research work forming the basis for a PhD studentship.

The next period of field work was then undertaken between November 1985 to May 1986. During this time a detailed study of the behaviour of the groundwater at the same site under the beach was made. The study involved the use of about 20 resistivity probes, 15 of which were left installed in the beach during the study period. In addition a number of piezometers, a tidal recorder and a raingauge were also employed on the site. The positions of these items of equipment are shown in figures 6a,b,c. All these instruments were then connected to automatic loggers recording at 10 minute intervals. The results obtained from this investigation revealed a number of interesting features.

1. The resistivity profiles obtained during installation along with the long period measurments at specific locations indicated that in general the saline/freshwater interface was extremely stable. Also core samples extracted from the beach at various locations showed that the base of the aquifer consisted of an organic clay layer about 5m below the beach surface which meant that the thickness of the saline water layer was approximately 40cm.

2. The only major disturbances which occurred to the system was during very high tides which were able to overwash the study area. In these cases the result was an input of saline water from the surface which then permeated downwards causing a disturbance to the resistance profile in the upper layers. Figure 7 shows an example of disturbed and undisturbed resistivity profiles.

3. Once a disturbance to the system had taken place it was found that the original resistivity profile was restored by 'flushing' of the aquifer due to increased flow from rainfall rechgarge and/or a reduction in the seaward water table as the tides changed from springs to neaps.

4. The three resistivity profiles taken at sites 5m apart again showed that the groundwater salinities were very uniform along a horizontal plane. Since the flow is predominantly horizontal this meant that there did not seem to be any response of the interface to tidal oscillatins. Although the effects of the tides could be clearly seen at the piezometer sites with a noticeable

Figure 6a

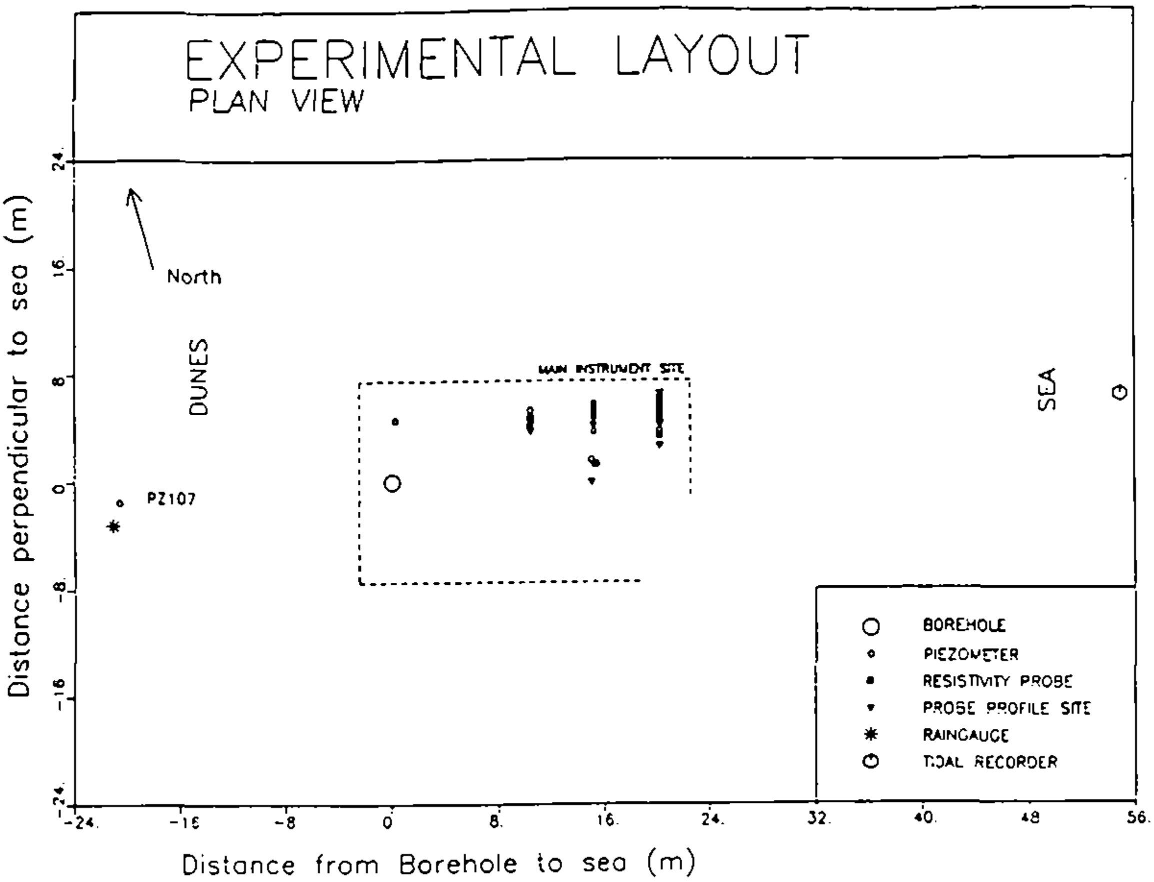


Figure 6b

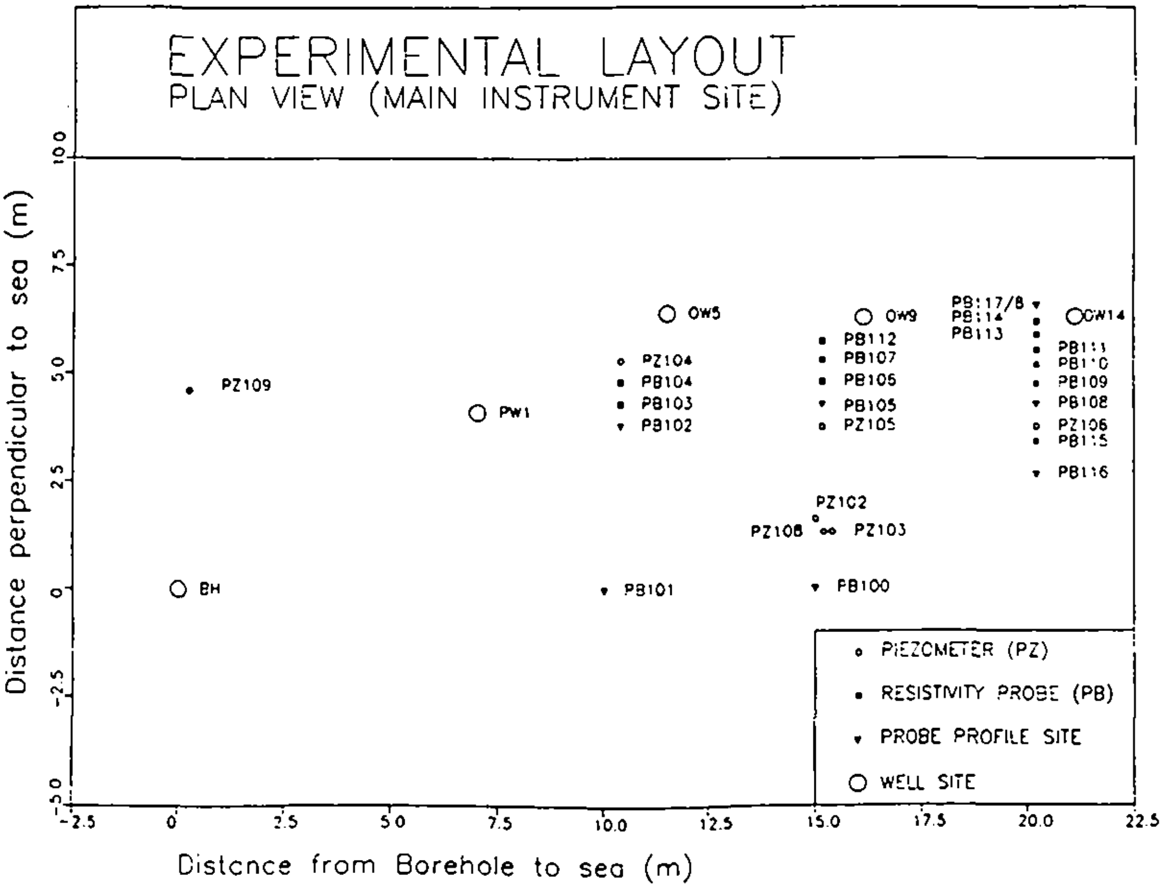


Figure 6c

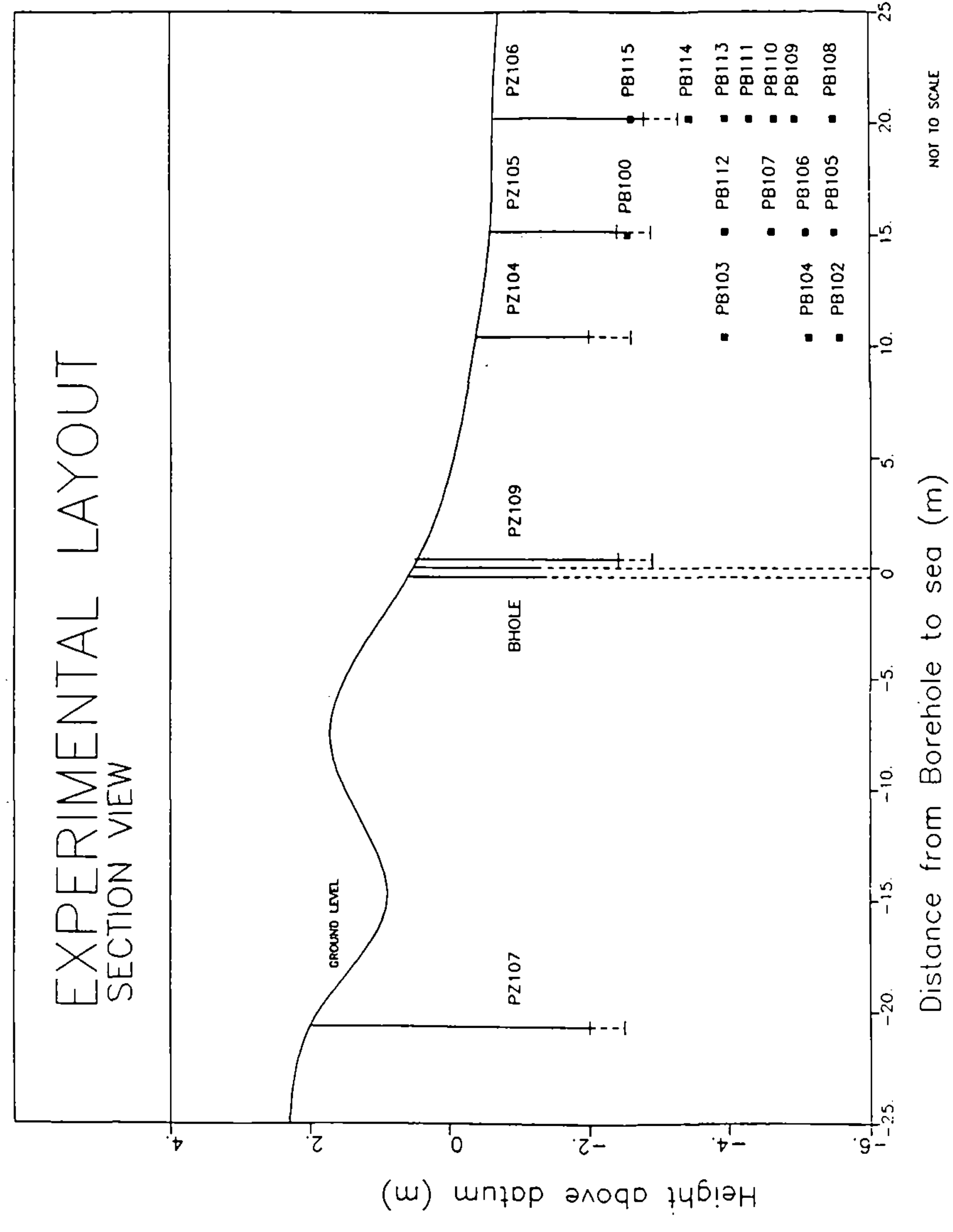
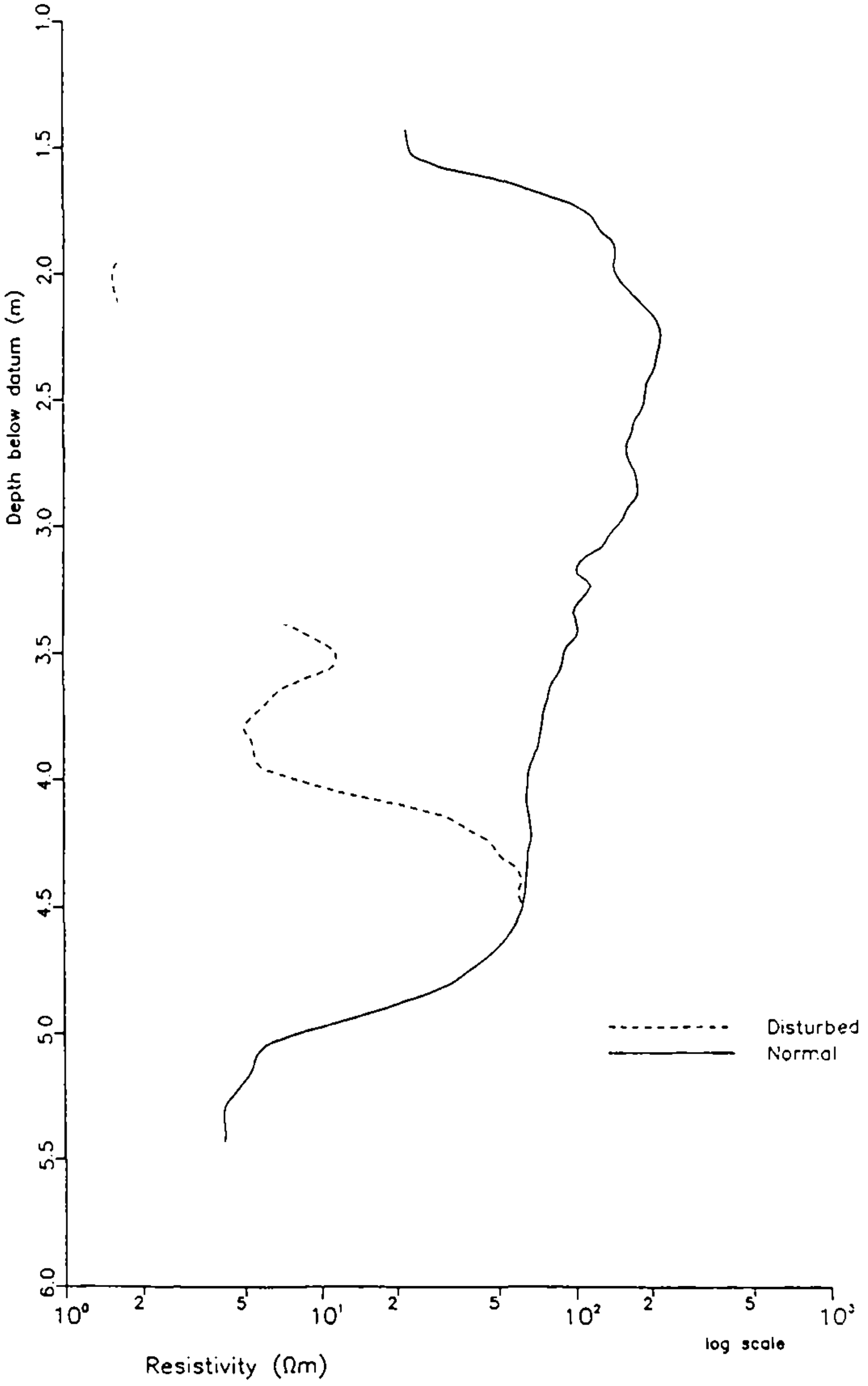

EXPERIMENTAL LAYOUT
SECTION VIEW
GROUND LEVEL
PZ107
BHOLE
PZ109
PZ104
PZ105
PZ106
PB100
PB115
PB114
PB103
PB112
PB113
PB111
PB107
PB110
PB104
PB106
PB109
PB102
PB105
PB108
NOT TO SCALE
Height above datum (m)
4.
2.
0
-2.
-4.
-6.
Distance from Borehole to sea (m)
-25.
-20.
-15.
-10.
-5.
0
5.
10.
15.
20.
25.

Figure 7



PLOT OF NORMAL AND DISTURBED RESISTIVITY PROFILES time lag and amplitude attenuation of the head fluctuations as one progressed inland.

5. The only exception to the above was during the period 10/12 18/12/85. Prior to the start of this period the system had been disturbed by a tidal overwash, as a result the isochlors were no longer horizontal, instead there was quite a steep gradient to them. During the above period a transition from spring to neap tides occurred (shown from the piezometric data given in figure 8) and this resulted in the disturbed section of groundwater being 'flushed' pass one of the probes (PB110). The measurements logged from this probe during the period clearly show the return to the normal state by the rise in resistance, but also show on top of this a semi-diurnal oscillation resulting from the effects of the tide (figure 9).

4.4 Interpretation of 1985/6 field data

Items 1 - 6 above briefly summarise the major observations which were produced by the 1985/6 field work programme. The main problem was that these results when considered together did not tarry with those expected from the type of saline intrusion situations outlined in sections 2 and 3 (ie that the saline water was acting as a virtually static body of water with a slow circulation within it in order to replenish saline ions in the interface region). Instead the conclusion drawn was that in addition to the fresh water zone originating from inland the saline water was also flowing towards the sea. If this indeed was the case then this represented a major change in our understanding of the hydrological processes in the area.

The next step therefore was to test this result in order to establish whether or not it was true. This was achieved by a last period of field work which was undertaken during December 1986.

4.5 December 1986 field work

Two types of experiments were conducted during this period of field study. The first involved placing at each of the three sites used previously (see figure 6b) two observation wells. One measuring the hydraulic head at a depth of roughly 1m below the water table in the fresh water zone, the second measuring the head over a distance of 30cm above the aquifer base in the saline water zone. After installation the water levels in these wells were dipped over a three day period. The measurements are shown in figure 10. The graphs show two main features. In the first case there is a clear reduction of hydraulic head seawards at both levels indicating flow from inland. Secondly the hydraulic heads in the shallow wells at each site are greater than the corresponding heads in the deeper wells. This effect can be largely explained by the fact that the waters in

Figure 8

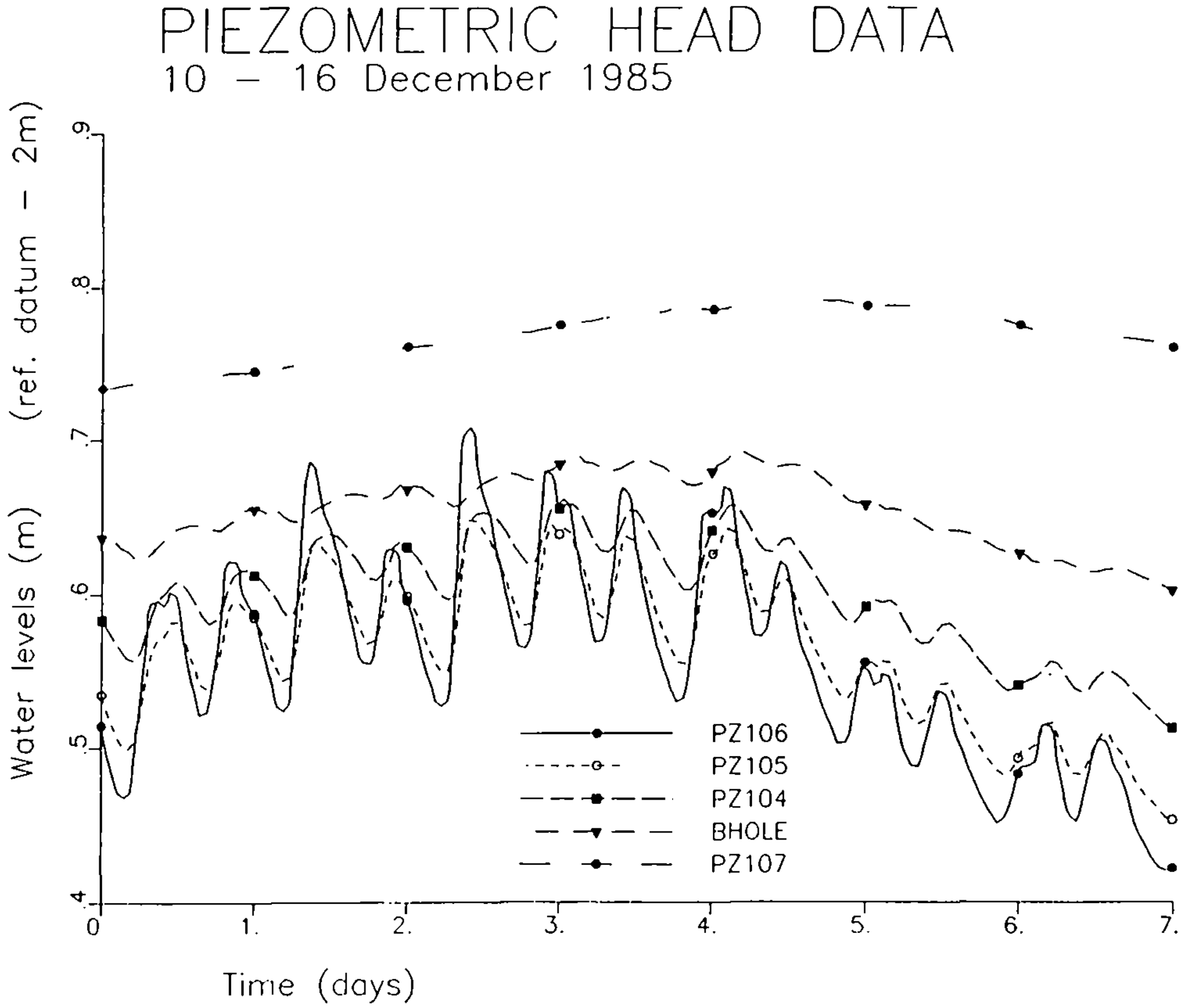

PIEZOMETRIC HEAD DATA
10 – 16 December 1985
Water levels (m) (ref. datum – 2m)
9.
8.
7.
6.
5.
4.
0
1.
2.
3.
4.
5.
6.
7.
Time (days)
PZ106
PZ105
PZ104
BHOLE
PZ107

Figure 9

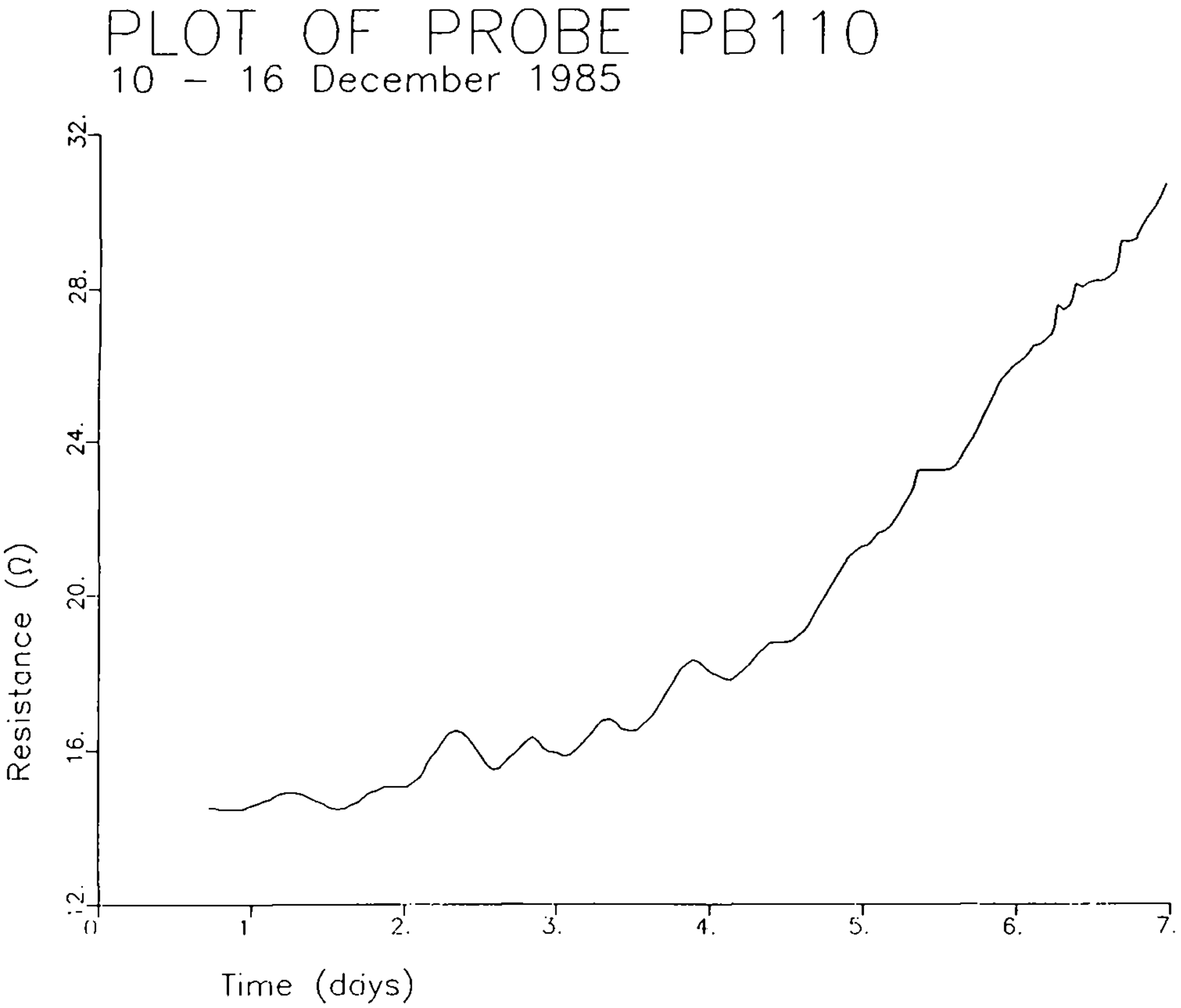
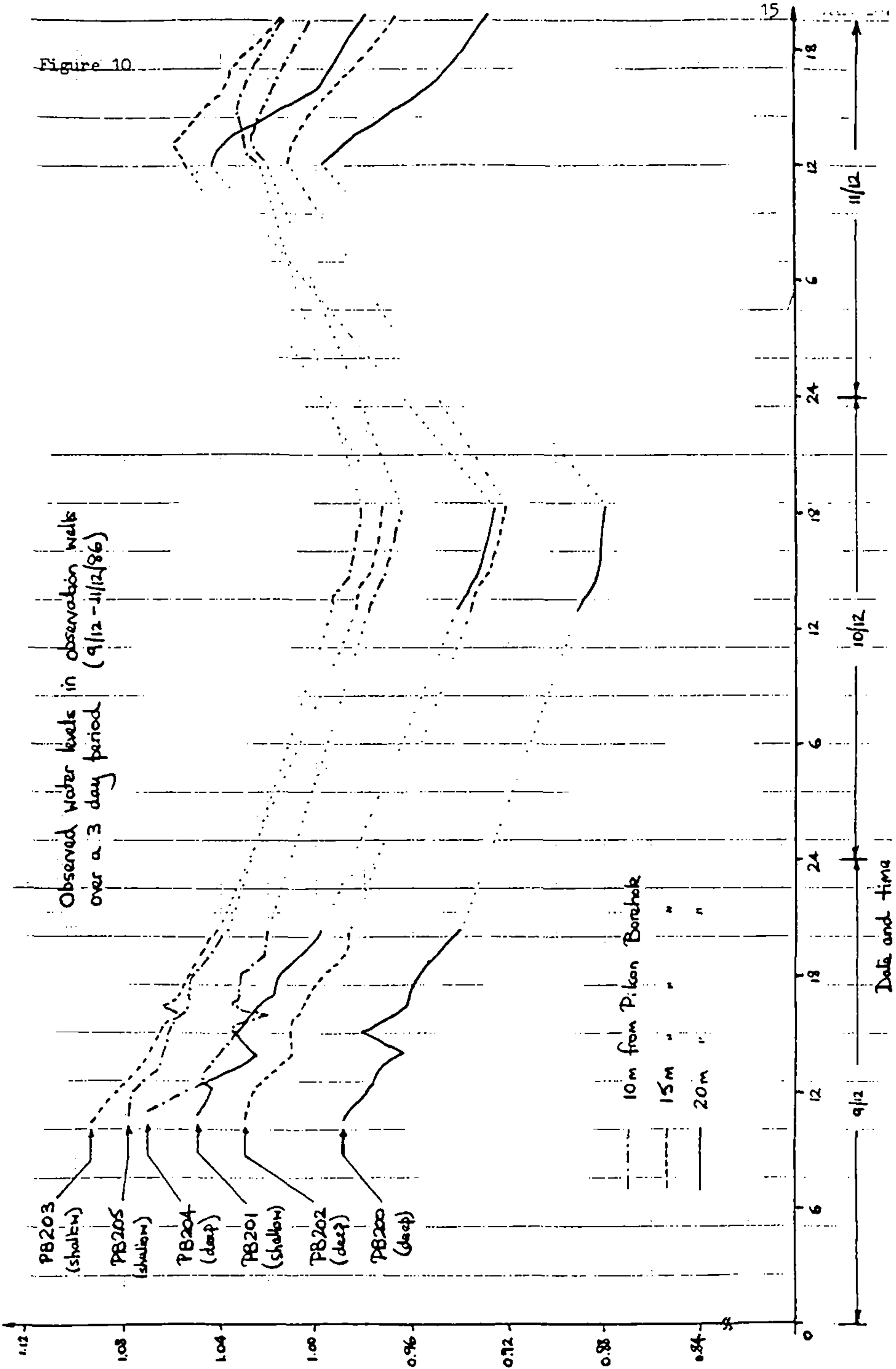

PLOT OF PROBE PB110
10 – 16 December 1985
Resistance (Ω)
32.
28.
24.
20.
16.
12.
0
1
2.
3.
4.
5.
6.
7.
Time (days)

Figure 10



Observed water levels in observation wells over a 3 day period (9/12 - 11/12/86) the deep wells are saline and hence more dense than those in the shallow wells.

The second experiment which was performed sort to obtain measurements of the postion of the sand/clay interface (the aquifer base) and accompanying resistance profiles in the area immediately behind the experimental site. Altogether 4 sets of results were taken the final set at a distance of 44m inland from the deep borehole. In figure 11 the positions of the 10, 50, 100 and 200 ohm measurements are plotted along with the position of the aquifer base. The plot seems to indicate that the saline water zone extends inland with a uniform thickness and follows the topography of the sand/clay boundary.

4.6 Implications from December 1986 field data

The results described in section 4.4 confirm that the phenomenon being observed below the beach site at Studland is not saline intrusion in the normal sense. In fact it could almost be called saline extrusion. This therefore raises a number of important questions which need to be answered concerning the hydrology of the area before the data can be properly used for detailed modelling studies. These questions may be summarised as follows:

1. What is the areal extent of the saline water layer ?

2. What effect does the Little Sea have on the problem ?

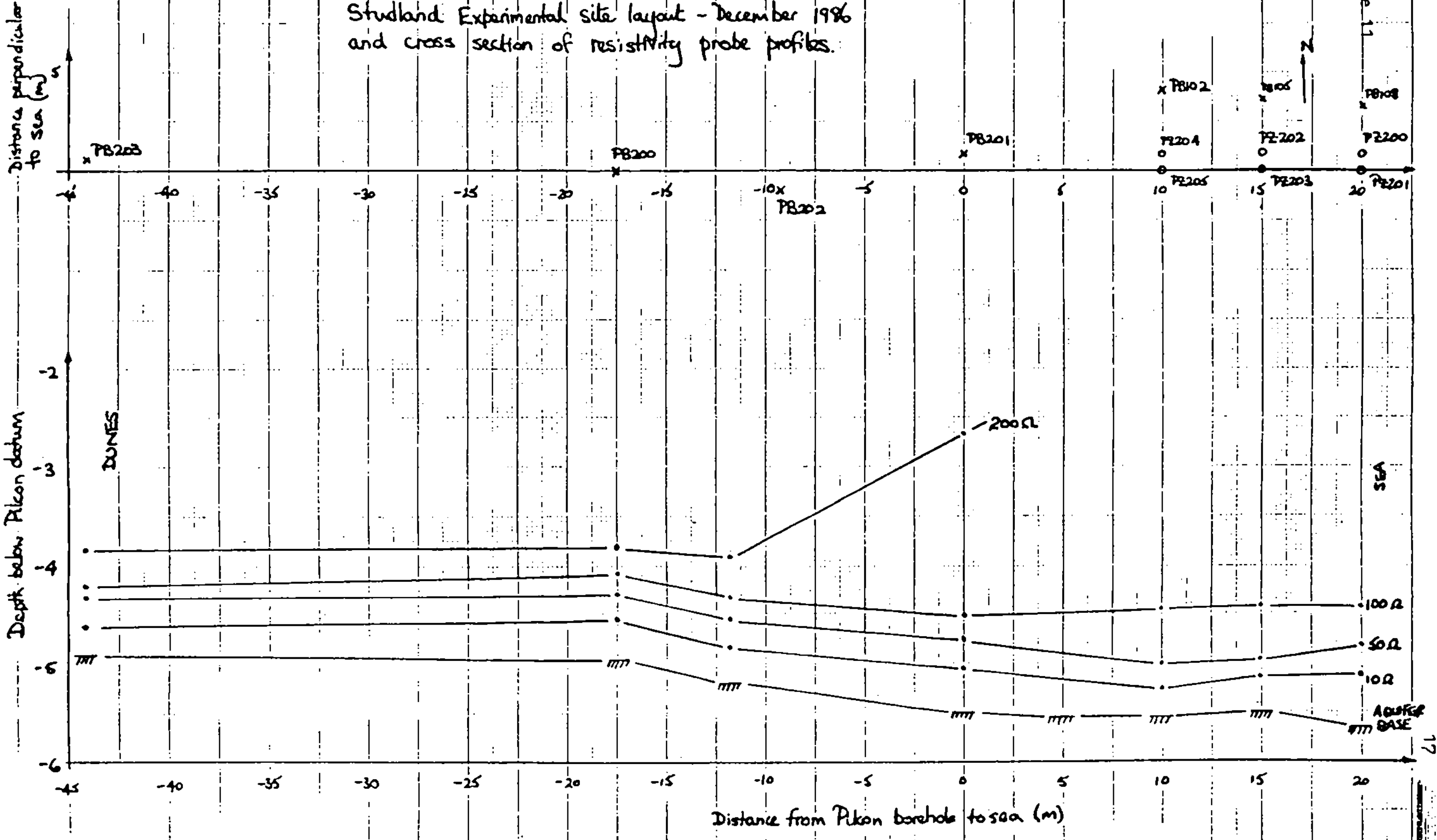
3. Where has the saline water originated from ?

4. How has the hydrology of the area developed into its current state ?

At present the best theory which has been put forward to explain how current situaton might have arisen is as follows. The saline layer observed is in fact remnant water from the time when the peninsular was in the process of being developed by the deposition from the sea. At that time (probably from 1000 to 500 years BP) sea water covered much of the whole area. In fact only as far back as a hundred years ago the Little Sea (which originally formed part of Poole harbour estuary) was still being occasionally washed by the sea as high spring tides were able to breach the intervening dunes. During the subsequent time period there has been a gradual drainage of the saline water from the area and the zone of water observed represents the current remains of the original deposits. Although at first it may appear surprising that after such a time period any remnant water should be found .If however one takes into account rainfall recharge occurring in the area then the situation does not seem so far fetched. Considering a few simple calculations: the average annual rainfall over the area is about 800mm. If it is assumed that roughly a third of this

Figure 11

Studland Experimental site layout - December 1986
and cross section of resistivity probe profiles.



is lost in evaporation then about 530mm reaches the water table. Considering a one meter strip along the distance between the Little Sea and the shore (about 375m) this represents an average annual recharge of about 200 m3/a/m. Now measurments of the hydraulic head gradient along with aquifer permeabilities give an estimated annual outflow to the sea of about 220 m3/a/m. Thus it would appear from these rough calculations that the outflow is primarily from rainfall recharge from the dunes area. This in fact is not ureasonable since it is to be expected that the area will, in general, be in hydrological balance. Any recharge which supplies the Little Sea is controlled by the drainage channels connecting it to Poole harbour estuary thereby keeping the water level of the lake fairly constant (a fact observed during the 85/86 field season when measurements of the water level of the lake were made). Thus it can be argued that the loss of saline water is not as great as at first thought. Although the above reasoning does seem to present a possible explanation for the hydrological state of the field site currently observed there many aspects to it which need to be supported before any real confidence could be placed in such a theory. It is with this purpose in mind that the next stage of the Studland Bay field work has been planned. However the main problem which arises is that the thrust of the project has now taken a direction which was not originally expected. In the next section the proposals for the future field work in the area are outlined.

5. Proposals for future field work at Studland

In the preceding section the results obtained from the field work at Studland were briefly presented. It was shown that although a definite saline/freshwater interface had been discovered below the beach surface further results had shown that this had not resulted from saline intrusion directly from the sea but rather from fresh and saline waters which had both originated from inland. At the end of the previous section four questions were asked. The object of the next proposed set of field work experiments due to take place during the January - April 1987 are intended to try to produce some answers to those questions. The drawback however is that in order to do this field experiments will have to be made further inland and here there may be some problems due to the fact that the dunes area behind the beach has been designated as a national nature reserve which is owned by the National Trust and managed by the Nature Concervency Council. Since it is not the intention of the members of this project to cause unnecessary disturbance to this area of outstanding natural beauty a general outline of the field work requirements is presented in this section.

The data requirements for the proposed field work period can be divided into 4 types. These will be discussed saparately giving the reasons why the data is required, the general area over which the information would like to be collected and the method of data collection.

1. Resistivity profile survey

It has already been described in section 4.1 how the resistivity probe is able to give an interpreted measurement of the salinity profile with depth. Therefore by obtaining a number of these profiles further inland an indication could be obtained as to the areal extent to which the saline water extends. Particularly of interest is the area around the Little Sea since at present the influence that this body of water has on the groundwater quality is uncertain. Initially profiles would be required on either side of the longitudinal axis of the southern section of the lake. The method for installing the probes is to use percussive hammers. The main tool for this purpose is a hydraulic jack hammer. Although well suited for the job it has the drawback of limited portability and therefore generally needs to be driven to the drilling site by Land Rover. The second method for installing probes is with a petrol driven rock drill. This drill lacks the power of the first tool and as a result is more time consuming when being used for profiling also in some cases it may be unable to provide deep enough penetration into the ground. However with its weight at 25 kg it does have the advantage of being hand portable over reasonable distances.

2. Groundwater observation wells

In order to conclusively show the existence of saline water (given that this has already been indicated by a resistivity profile) some further deep observation wells should be installed in order to enable the probe readings to be calibrated. The wells would also enable water samples from the saline layer to be taken so that water quality analyses could be made. These might provide an insight into the historical nature of the water. The proposed location for these wells would be in the vicinity of the western and eastern shores of the Little Sea. The method of installation is with a small cable tool drilling rig. This has the problem that access is limited to well defined tracks (suitable for Land Rovers) which do not have sharp bends in them. The envisaged drilling depths required for the wells would not be any greater than 10m.

3. Piezometric survey

An important aspect needed for understanding the groundwater hydraulics of the problem is the general shape of the water table in the area. This would enable the general flow patterns of the groundwater to be determined. The measurements of the height of the water table would be made by installing temporary piezometers. These would consist of a driving a series of rods connected to a well point into the sand using either of the tools described in item 1 to a depth of about 1m below the water table. The general sites areas for these piezometers is in the dunes area between the shore and the Little Sea and in the area behind the Little Sea. It is hoped that up to 12 installations could be made.

4. Stratigraphic analyses

When seeking to develop model of groundwater aquifers an important requirement is an accurate understanding of the properties of the material which constitutes the aquifer and where the aquifer base is located. This information can be gained from lithological samples of the area being considered. The method used to obtain this data is a 'flow through' sampler. This type of sampler is driven into the ground, again using the methods outlined in item 1, and has the ability to allow the aquifer formation to flow through the sample barrel as it is driven into the material. Once the required depth is reached the sampler is retrieved and the barrel split open to reveal the original formation. By taking successive samples at progressivly deeper depths a complete picture of the stucture and composition of the material below the ground surface can be obtained. It is hoped that stratigraphic logs will be made at most of sites where resistivity profiles are made and observation wells installed.

5. Analyses of the Little Sea

In section 4.5 the question of what extent the Little Sea has on groundwater quality was asked. In order to answer this, it is proposed that a number a measurments of the Little Sea should be made. These would include taking water samples at various depths for laboratory analysis and also taking conductivity depth profiles at a number of sites on the lake. Although these measurements are not inherently difficult they do require the use of some form of boat in order to gain access on to the middle of the lake.