HYDROGEOLOGY OF THREE HARD ROCK CATCHMENTS IN BRITAIN

by

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ABSTRACT

The groundwater regimes of three small, undisturbed (natural) and accessible hard rock catchments representing the South, Midlands and the North of Great Britain have been hydrogeologically investigated and compared.

There is a dearth of hydrogeological information on hard rock areas in Britain. This is because the general availability of surface water and extensive sedimentary aquifers has not encouraged groundwater prospecting in hard rock areas. In view of this, low flow study was considered essential since geology exerts a great influence on its characteristics. This was carried out using baseflow recession analysis.

From a combination of practical, empirical and theoretical considerations aided by statistical analysis on a computer, baseflow recession constants which dynamically reflect the physiographic and geologic controls within a catchment were derived for the catchments investigated. These were used to characterise the behaviour of the low flows. A new method which is free of random selection of data for baseflow recession analysis is presented and a model for the curve fitting both by computer and manual methods are fully discussed and its application is also presented.

Water balance computations for each of the three catchments is presented in chapter 2.

Lithological units were identified by a detailed geological study. These were further investigated using resistivity and electromagnetic methods of geophysical survey. Hydrogeological properties of the aquifers were investigated by pumping test analysis and subsequent comparison of hydraulic conductivities from soils and baseflow studies.

A water chemistry investigation of spring, river and rain waters has been carried out to try and define flow paths of the groundwater and this is presented in chapter 7.

From these investigations, this research concludes that large community water supplies through boreholes can be economical only in one of the catchments (East Dart catchment). In the other two catchments (Blackbrook and Calder catchments), small community and household supplies are possible through boreholes (in some areas) and large diameter wells.

DECLARATION

No portion of the research referred to in this thesis has been submitted in support of an application for another degree or qualification at this or any other University or other institutions of learning.

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Chapter 1
INTRODUCTION

1.1 Aims

To compare the groundwater regimes of three selected hard rock catchments. A hard rock catchment is defined as one in which the majority of groundwater is expected to exist in the weathered zones and joints and not in primary intergrannular spaces.

1.2 Objectives

1. To quantify the hydrogeologic parameter of each catchment.

2. To obtain a baseflow recession constant and relate them to catchment characteristics.

3. To assess the groundwater potential of each catchment and relate it to all the catchment parameters.

4. To determine if water chemistry can be used to locate the flow paths and origin of the groundwater.

1.3 Catchment Selection

The three catchments selected are

1. East Dart at Bellever (NGR SX657775) on Dartmoor Forest, South West England.
2. Blackbrook at One Barrow (NGR SK466171) on the Charnwood Forest, the East Midlands, England.
3. Calder at Muirshiel (NGR NS309638) near the Muirshiel Country park, west of Glasgow in Scotland.

These were selected because

1. they have higher groundwater potentials than other catchments within the same region. This choice is based on the baseflow recession results which is fully discussed in chapter 8.

2. their geology is different; petrologically East Dart is granitic, Blackbrook is Precambrian volcanic rocks and the Calder consists of basaltic rocks.

3. they represent the South, Midlands and the North of Britain.

4. climatologically, they differ slightly due to differences in latitude and altitude.

5. historically, the north is the most affected by the glacier of the ice age (Pleistocene), the Midlands were also affected but not on the same scale as the north while the south was periglacial. Therefore, the weathered material may have been affected by the moving glacier differently.

6. they represent small and natural catchments -unaffected by regulation either for water supply or recreational purposes.

7. accessibility was considered important because property is owned by individuals or organisations as such permission was needed for any survey to be carried out.

8. the catchments are not urbanised either in the form of village or town. The only form of settlement are farm houses.

In Britain, because of an abundance of surface water and extensive sedimentary aquifers (chalk and Bunter sandstone), little attention has been paid to groundwater in hard rock areas (of the types considered limestones are covered by the definition but not used). This is simply because hard rock areas are thought not to contain any aquifers of economic significance. This assumption may be true in some cases. In any case, it is worthwhile investigating the hard rock catchments as some areas may contain groundwater which could be easily exploited and used for domestic supply and irrigation; to supplement supplies from surface sources in times of drought, accidental pollution or even in times of war. In developing countries, groundwater is the preferred type of resource for small scale supplies in the rural and urban environment. This is because of the nature of the geology (basement complex in most cases) coupled with the climate (lack of rain -drought). But even in the developed areas of the world, as the demand for water increases, and opposition to construction of new reservoirs mounts, the development of groundwater is likely to assume importance in future.

Baseflow recession when properly analysed, provides a useful tool in hydrogeological investigation especially in areas with inadequate hydrogeological data. From the analysis,

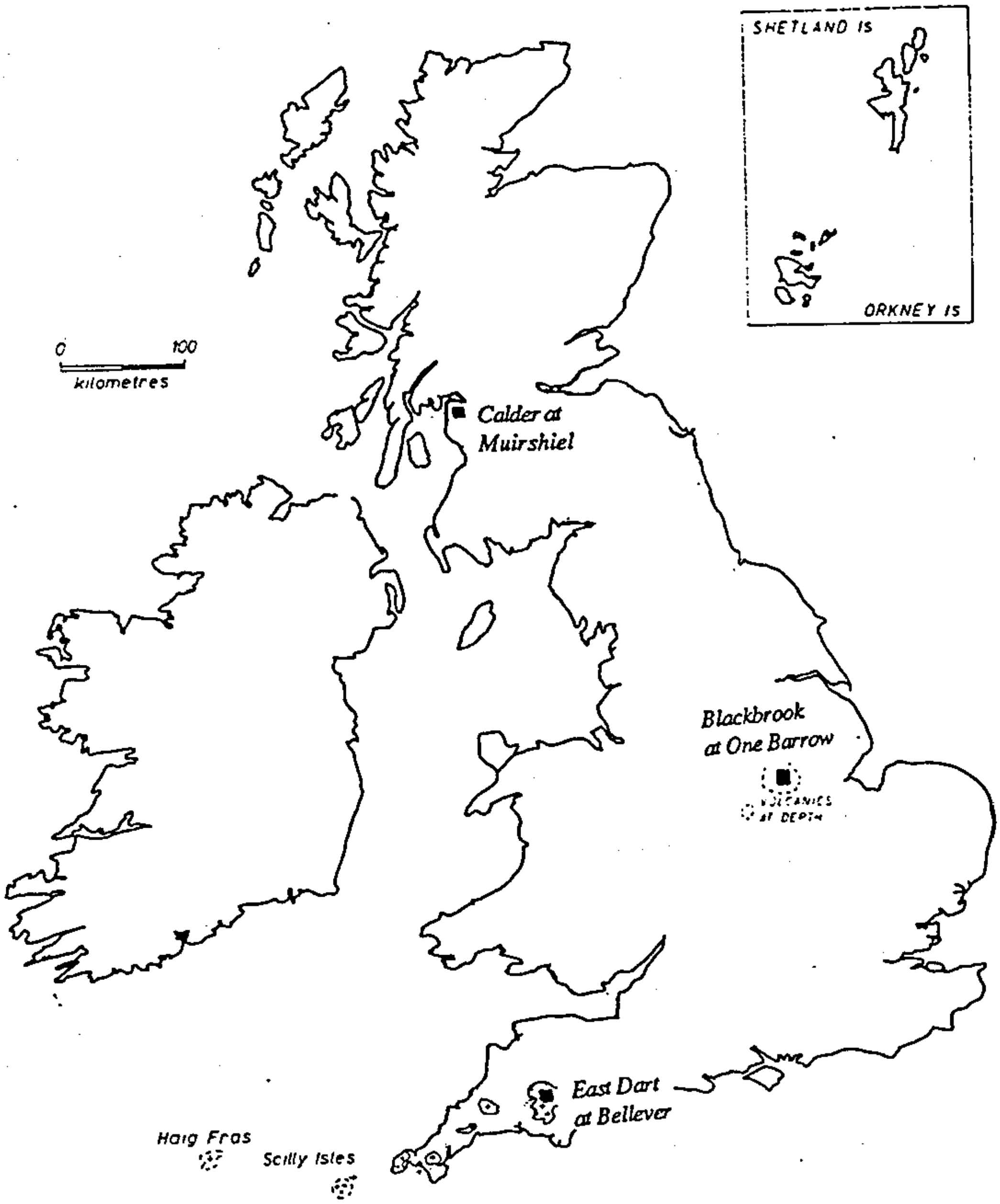


Figure 1.1 Catchment Location Map

estimates can be made of the volume of water released from storage at any time and it also enables the calculation of the specific yield or coefficient of storage (in the case of confined aquifers) of a catchment. Among other things, baseflow recession analysis has also found application in the water industry for flow forecasts and the prescription of the absolute minimum flows. Because of its applicability in an hydrogeological investigation, it constitutes an important aspect of this research.

A new method for baseflow recession analysis is presented in chapter 8 and a model for the curve fitting both by computer and manual methods are fully discussed with the application to hydrogeological investigation.

1.4 Location

The three selected catchments for detailed investigation are indicated in figure 1. Their relative positions are represented on Dartmoor Forest in South West England, Charnwood Forest in the East Midlands and the Renfrewshire Hills, west of Glasgow in Scotland as earlier mentioned. For simplicity, these catchments will be referred to as East Dart, Blackbrook and Calder in the text.

1.5 Method of Study Adopted

The methods adopted for this study include:-

(a) a study of the British climate in general with specific reference to the selected catchments and their water balance.

(b) determination of the relationship between geology and baseflow for river catchments within and outside the study areas with an aim to quantifying geology in terms of groundwater potentials of the catchments.

(c) infiltration as a means of recharge to the groundwater regime was used for correlation purposes with the recession constants derived.

(d) on the basis of the reasons for catchment selection and site accessibility, geophysical methods were employed during the field survey. Resistivity and electromagnetic (EM34-3) surveys were employed to estimate the depth and extent of the weathered profile and also the thickness of the various lithologic units or the overburden.

(e) Pumping test of open wells and boreholes (where existent) were carried out with a view to analysing the data for the determination of formation constants. On the basis of the geology and hydrogeology, groundwater abstraction methods will be recommended for each of the catchments.

(f) Spring, rain and river water have been chemically analysed to try and determine the flow paths and the origin of the groundwater and also for the completeness of the investigation. From the quality and quantity its use for domestic and industrial supply are discussed.

1.6 Water Use

In this section a review of water use is made of the two sources readily available; springs and wells. Thus:

1.6.1 Blackbrook Catchment

In the early days, the rural water supply was from springs and wells (Richardson, 1931). Loughborough, Nanpantan and Thorpe Acre were supplied from the catch waters of the Charnwood Forest (through the Nanpantan reservoir) while other parts of the district of Loughborough had their supplies mostly from wells.

From the author's field survey, records collected from the British Geological Survey (BGS) and the farmers, it is found that open wells, boreholes and springs have been used for rural supplies. The open wells extend only into the superficials. Some of the boreholes were drilled into the Precambrian rocks of the Charnwood Forest. The rate of success was low due to the fact that primitive methods were used in groundwater location -dowsing by "water diviners". The wells and springs were effectively used during the world wars due to fear of poisoning of reservoirs. Field evidences of spring development and exploitation exist at the Charnwood Lodge and Charley Mill farm where most of the springs are concentrated and are found to have been connected by pipes to form two major supply points.

The monastery at Mt. Saint Bernard Abbey still uses hand dug wells for their water supply. From personal discussions with the monks responsible for water supply, the source is found to be reliable and has withstood droughts in the past. A borehole drilled by the monks in 1964 is not being used.

A farmer at the edge of the catchment still has a borehole in use for irrigation purposes. The borehole is drilled into the bed rock and the supply is very adequate. Borehole records on the Charnwood Forest are rare.

Today, all the rural and urban supplies in the district of Loughborough comes from Blackbrook, Nanpantan reservoirs and River Dove. All the farmers except the monastery are supplied with pipe borne water through the mains.

1.6.2 East Dart Catchment

The East Dart catchment is blessed with many springs. The earlier settlements utilised the springs and the river water for industrial and domestic supplies. Some of the wells act as reservoirs for spring water storage.

From the literature (Edmonds et al, 1968), it is strongly believed that the area was occupied in the bronze age by the Celtic race and later in the 10th century by the Celtic and the Saxon races because of the presence of stone circles and avenues, hut circles etc. which are common on Dartmoor. The spring and river waters may have served as sources of water supply considering that both sources are perennial.

1.6.3 Calder Catchment

Today the catchment is sparsely populated although in the past there had been settlements scattered all over the area. This is evidenced by abandoned settlements, a well and developed springs. Some of the springs are indicated on the Ordnance Survey map whereas others were located with the help of the older farmers who also confirmed the fact that the catchment had settlements in the past (personal communication). All the settlements were near the springs and these are said to be very reliable sources of supply. Some three houses near the catchment (downstream) still use springs for their supplies. The reason for not having mains connection could be due to the rugged terrain and also the remoteness of the area coupled with the small number of houses which makes it uneconomical.

However, there existed a dam along the Calder river but this has been dismantled. The purpose of the dam is unknown (Strathclyde Regional Council, 1980). Part of the water from the river is being diverted to a nearby dam. Recently, the Strathclyde Regional Council has made some feasibility studies for the construction of a dam downstream of the catchment (Lower Clyde Water Board, 1975; and Strathclyde Regional Council, 1980). The aim is to supply water to the two counties in the area.

From what has been discussed above, it is evident that spring and well water have served for domestic supplies and still do in some areas when the need arises. Whether these are groundwater or surface water, it is yet to be proved. Chapter 8 deals with this topic in detail.

At the time of writing this thesis, it is the intention of the government of the day to privatise the water authorities. If this comes to be, the farmers may find it uneconomical to irrigate their lands from public supplies. As a result there may be the need to resort to groundwater sources through open dug wells, open-cum-dug wells or boreholes for irrigation and domestic use. This obviously will depend on the quality and economics as labour is very expensive.

Chapter 2
HYDROMETEOROLOGY

2.1 Climate - A Review

Climate is an important factor in a hydrogeological investigation because it has a fundamental influence upon the way of life of inhabitants, animals and vegetation. In this section, climate is discussed in general terms for Britain because variability in the climatic factors are local and are due to topography. Some of the catchment climatic factors are shown in Table 2.1 (see figure 1.1 for locations). Catchment water balances have been carried out in section 2.2.

Rainfall, the most important parameter in the hydrologic cycle, is relatively uniformly distributed at any particular time and place over lowland areas, although the western side of mainland Britain is generally wetter than the eastern side all times of the year. The long term predictability of the British climate is evident by the lack of extremes of drought, heat and flood. In the west of Britain, rainfall is found to greatly exceed evaporation and in the east, the rainfall just marginally exceeds evaporation (Aldwell et al, 1978).

On a daily basis rainfall is very reliable in Britain because of its frequency when compared with semi - arid areas. This does not seem to give any variety in the weather because there is no clear demarcation between the four seasons however, there is some variation from year to year as a response to the changes in atmospheric circulation and in particular to the location, intensity and duration of the main centres of cyclonic activity. The regulating effect being the Atlantic ocean, English Channel and the North Sea.

Britain lies between the continent of Europe to the east and Atlantic to the west. Westerly drifting winds are normally modified by encounters with differing atmospheric systems originating from the continental landmass. It is this effect that causes rapid changes in the weather which at times occur regardless of season. This sometimes makes it difficult to distinguish the four seasons.

Other micro-climatic factors such as temperature, humidity and solar radiation are mild compared with the tropics. Relative humidity generally increases with altitude and decreases inland. The amount of sunshine hours, decreases from south to north, but for any given latitude, the amounts are found to be higher in the west than in the east as is also the solar radiation (Chandler and Gregory, 1976).

The temperature is modified by gulf streams from the Atlantic (Mexico) as it drifts towards the coast of Britain; this effect also occurs in winter. The Welsh mountains however, prevent this effect on Charnwood Forest and in particular the Blackbrook Catchment. However, it should be noted that temperature drops significantly with height in winter while this is not the case with latitude. Wind speeds can easily turn to gale force and this is strongest along the coastal areas. The recent storm (October, 1987) which caused damage to property in the south coast is a rarity.

Precipitation and evaporation and evapotranspiration which are very important elements of the water balance are discussed in the following subsections; while a water balance of the three catchments is presented in section 2.2.

2.1.1 Precipitation

This is the most appropriate term especially in temperate climate as it encompasses all forms of atmospheric moisture reaching the ground in form of snow, hail, dew and condensation drips although rainfall is by far the most important of all. Precipitation is important because it is the initial input into the hydrologic cycle. Its distribution in space and time is essential for the baseflow recession analysis in order to isolate periods in which streamflow was diminishing with no significant input and also for the water balance computations.

In the west, cyclonic rainfall predominates although this is sometimes modified by topography (hills and mountains). The rainfall over north west Britain is due to frontal systems while the south east of Britain has a combination of cyclonic and convective storms. It is this convective rainfall that give rise to localised storm cells. The rainfall pattern in the temperate environment is usually fairly uniformly distributed over a wide area; whereas in a tropical environment, high net radiation creates localised storm cells which are normally characterised by very high intensity rainfall over limited areas. Because of the uniformity of rainfall in Britain and the temperate environment in general, only one station is found to be adequate for sorting out dry days per catchment in chapter 8 and also the water balance computations in section 2.2.

In Britain, rainfall tends to increase with altitude. The annual average shows similar patterns for most years with the highlands of Wales, Scotland, the English Lake District, Dartmoor and Devon having the highest totals. This is governed by the frontal depressions in the northern westerly circulations which gives these areas the highest mean annual totals and the leeward the lowest.

Generally, the winter months (October - March) are wetter than the summer (April - September) months. As such the ground is fully saturated in winter and most of the groundwater in storage is released in summer. This however, may not always be the case as maximum rainfall can occur locally in summer due to convective storm cells. Using the meteorological office (met. office, 1952) definition of drought,

> 'it is a period of at least 15 consecutive days to none of which is credited 0.25mm or more of rainfall'.

Britain has encountered only one such period; in 1975/76.

The average monthly rainfall over a standard period (1941 -1970) for East Dart, Blackbrook and Calder catchments are given in section 2.2.1.

2.1.2 Evaporation and Evapotranspiration

In Britain, evaporation is measured using the evaporation pan or a simple irrigated evapotranspirometer. There are several methods available for the evaluation of evapotranspiration. Some of the methods are mentioned in section 2.2. The choice of method for the evaluation depends on the availability of data both in space and time and the ultimate result presentation.

The annual potential evapotranspiration (PE) is found to decrease from south to north and also away from the coast (Chandler and Gregory, 1976). These characteristics reflect the availability of net radiation although higher coastal values are probably also a reflection of the additional drying power associated with higher wind speeds in coastal areas than inland. Reduced PE in the highlands is associated with low radiation availability.

Table 2.1 Catchment Characteristics

Area	A	B	C	D	E
Av. Height above Sea Level (m)	460	200	350		
Av. Annual Rainfall (mm)*	2042	750	2314	508	991
Mean Annual PE (mm)+	516	625	575	4052	1669
Mean Annual AE (mm)+	516	583	575		
Av. Daily bright~ Sunshine Hours	<4	4	3.5		
Av. daily total ~ of global solar radiation (MJm^{-2}) for the year	11	9	8		

Remarks: Data is the average of the period 1941 - 1970 (for the catchments).
D and E are from Nigerian Data

Sources: * Institute of Hydrology, Wallingford.
+ Calculated in section 2.2
~ Chandler and Gregory, 1976

A = East Dart at Bellever, B = Blackbrook at One Barrow, C = Calder at Muirshiel,
D = Maiduguri (Kida, 1984) and E = Bauchi (Acworth, 1981).

2.2 Water Balance

Introduction

In this section, a water balance has been carried out for the three selected catchments with a view to finding instantaneous and long term moisture relationships. The deficits, surplus' and recharge are the most important in the water balance computations.

The simple water balance equation is given as

$$P = ET + RO + I + DS \quad \text{.............................(2.1)}$$

where

P = precipitation

ET = evapotranspiration

RO = Runoff or total streamflow

I = Infiltration

and DS = change in storage

Equation 2.1 can also be simply written as

$$P = ET + RO + DS \text{ ....(2.2)}$$

whereby the runoff term includes the infiltration since this component cannot be accurately measured in the field. From the two equations above, only precipitation and runoff can be measured accurately in the field. The other components cannot be measured accurately in the field hence they are normally calculated from meteorological data. Of the measured data, rainfall which represents the P term, is obtained from areal computations since only one or few raingauge(s) is / are normally installed per catchment. For the catchments in question, only one raingauge has been installed per catchment.

There are several methods used for the computation of evapotranspiration (ET) and the water balance components in general. The methods include standard meteorological formulae such as the aerodynamic, energy budget, combination methods (Penman, 1948, or its modified version by Monteith, 1965) and temperature formulae (Blaney - Criddle, Thornthwaite and Budyko formulae). The most widely used of them is the Penman equation or its refined version by Monteith. In reality, the choice of method to be used depends on the type of data and its availability both in space and time.

Although Penman's equation has been found to give good results for measured field data from open water (Raghunath, 1982), it is limited by its complexity and the fact that it utilises several parameters which are not available in published weather data. Given this condition, the empirical method of Thornthwaite (Boucher, 1981) has been adopted for the purpose of computation of the water balance parameters of the three catchments. The data needed for the computation of the water balance parameters are precipitation, temperature and runoff and these are readily available for all British catchments. Other reasons include the fact that the method has been found to produce reasonable results for monthly computations of the water balance (Mather, 1974 and Oliver, 1973). The equation is also found to provide good results since it is the ultimate comparison of P and ET that is of importance rather than the particular method applied.

Thornthwaite's equation is given as

$$ET = 1.6(10T/I)^a \quad \text{..............................(2.3)}$$

where

ET = the monthly unadjusted potential evapotranspiration (PE)

t = mean monthly temperatures in degrees C

I = annual heat index. This is the sum of 12 monthly values of i where $i = (t/5)^{1.514}$

and a = a constant which is a function of I and is obtained from tables.

The main deficiency of this method is that temperature is considered to be the energy input responsible for water evaporational losses. The method is empirical and its results tested on 13000 localities (Harry, P et al, 1972) have been found to accord closely with measured field data for open water. However, the calculations are found to fall within reasonable expectations only in mid-latitudes (45^0 - 60^0) although a modified version has been applied by Thornthwaite in Sudan. The success of Thornthwaite's water balance computation has been attributed to the nature of energy transfer at the surface of the earth. This is true based on the argument that the energy input is given by the relationship

$$Rn = H + LE \quad \text{..............................(2.4)}$$

where

Rn = the net radiation received by the surface

H = the sensible heat transfer from the surface to air

LE = the heat used in converting liquid into vapour.

and for practical purposes the ratio H/LE which is known as the Bowen ratio approximates to 0.5; which in turn means that the energy is equally divided between heating the air (sensible heat) and evaporating water (latent heat). Considering that this assumption is substantially correct, then it becomes possible to assess latent heat and sensible heat. Sensible heat is measured as temperature whilst latent heat is difficult to measure. Therefore, taking the Bowen's ratio (0.5) into consideration, it is possible to assess the energy requirements for sensible heat assuming that this also applies to the latent heat; and Thornthwaite's equation suffices for the computation of the water balance for the three catchments being investigated.

2.2.1 Procedure

The procedure for computing the various components of the water balance has been explained by Thornthwaite and Mather (1957). Their procedure and tables have been adopted to calculate the parameters in tables 2.2, 2.3 and 2.4.

Monthly mean temperatures and rainfall representing the period 1941 to 1970 have been used for the computation. The early stages of the computation involves using the temperature values to obtain heat indices for each month. The total heat index was used with a nomogram (figure 1 of Mather, 1972) to obtain the values of unadjusted PE. Daylength correction factors were obtained to take account of the mean possible monthly duration of sunlight hours in the northern hemisphere. The values obtained for the respective latitudes were divided by the number of days in the month. The correction factors were subsequently multiplied by the unadjusted PE to obtain monthly adjusted PE.

Table 2.2. Average Monthly Climatic Water Budget (1941-1970) for East Dart at Bellever Catchment.

	J	F	M	A	M	J	J	A	S	O	N	D
PE (mm)	12	11	24	29	56	73	81	77	63	48	26	16
Precipitation (P; mm)	241	176	153	127	133	102	127	153	172	182	231	245
P - PE	229	165	129	98	77	29	46	76	109	134	205	229
Storage (S)	110	110	110	110	110	110	110	110	110	110	110	110
DS	-	-	-	-	-	-	-	-	-	-	-	-
AE	12	11	24	29	56	73	81	77	63	48	26	16
Deficit (D)	-	-	-	-	-	-	-	-	-	-	-	-
Surplus (Sp)	229	165	129	98	77	29	46	76	109	134	205	229

The new values obtained for the adjusted PE were entered in whole in row 1 of the respective catchments (tables 2.2 - 2.4) for computations of the average climatic water balance. The mean monthly precipitation was entered in row 2. Row 3 was filled in by subtracting row 1 from row 2 (P - PE). Row 4 which represents storage was obtained from a table specially extracted from Thornthwaite and Mather (op. cit.) by Boucher (1981) using a maximum soil moisture retention of 110mm as the water holding capacity of the soils. The table represents

Table 2.3. Average Monthly Climatic Water Budget (1941-1970) for Blackbrook at One Barrow Catchment.

	J	F	M	A	M	J	J	A	S	O	N	D
PE (mm)	11	15	28	49	71	95	102	92	74	49	25	14
Precipitation (P; mm)	64	55	47	52	63	57	70	88	62	58	79	55
P - PE	53	40	19	3	-8	-38	-32	-4	-12	9	54	41
Storage (S)	110	110	110	110	104	81	65	63	58	67	121	162
DS	-	-	-	-	-6	-23	-16	-2	-5	9	54	41
AE	11	15	28	49	69	80	86	90	67	49	25	14
Deficit (D)	-	-	-	-	2	15	16	2	7	-	-	-
Surplus (Sp)	53	40	19	3	-	-	-	-	-	Recharge		

Table 2.4. Average Monthly Climatic Water Budget (1941-1970) for Calder at Muirshiel Catchment.

	J	F	M	A	M	J	J	A	S	O	N	D
PE (mm)	10	12	26	43	68	91	99	85	65	42	21	13
Precipitation (P; mm)	228	169	155	156	138	141	183	194	236	249	221	244
P - PE	218	157	129	113	70	50	84	109	171	209	200	231
Storage (S)	110	110	110	110	110	110	110	110	110	110	110	110
DS	-	-	-	-	-	-	-	-	-	-	-	-
AE	10	12	26	43	68	91	99	85	65	42	21	13
Deficit (D)	-	-	-	-	-	-	-	-	-	-	-	-
Surplus (Sp)	218	157	129	113	70	50	84	109	171	209	204	231

soil moisture retained after different amounts of potential loss of water from the soil have occurred. It also takes into consideration the different combination of vegetation and soils. Because row 3 adds up as a positive figure for each of the catchments being investigated, the maximum soil moisture retention was used for the first value in row 4. There was no change in storage for East Dart and Calder catchments since precipitation exceeds PE (Tables 2.2 and 2.4). In the Blackbrook catchment (Table 2.2) there was a change in storage between the months of May and September inclusive. For those months, the moisture retention value was obtained from the main body of the table adopted from Boucher (1981). This was done by counting down the number of negative values of P -

PE and at the end of the negative values, the positive values of P - PE were added as moisture coming into storage. Row 5 (change in storage) was obtained from the difference between soil moisture from one month to the next. The actual ET (row 6, AE) was calculated on the basis that when precipitation exceeds the PE, the soil moisture remains full of water and therefore, AE = PE. For the converse however, the soil begins to dry up and AE becomes less than is potentially possible. Under this condition, the AE equals the precipitation plus the amount of water drawn from soil moisture storage disregarding the signs. Moisture deficit (row 7) is the amount by which the actual ET and PE differ in any month. The moisture surplus (row 8) is the excess precipitation which runs off after the moisture storage reaches the water holding capacity. Therefore, the values for the P - PE were considered for this purpose.

There are exceptions for temperatures below -1^{0}C. This was not considered as the mean temperatures for the respective catchments are positive.

2.2.2 Result and Discussion

The result of the water balance is presented in tables 2.2, 2.3 and 2.4. Graphs of the water balance (precipitation and PE) are presented in figures 2.1, 2.2 and 2.3 for the catchments being investigated.

Fig. 2.1 Mean monthly water balance of East Dart at Bellever Catchment

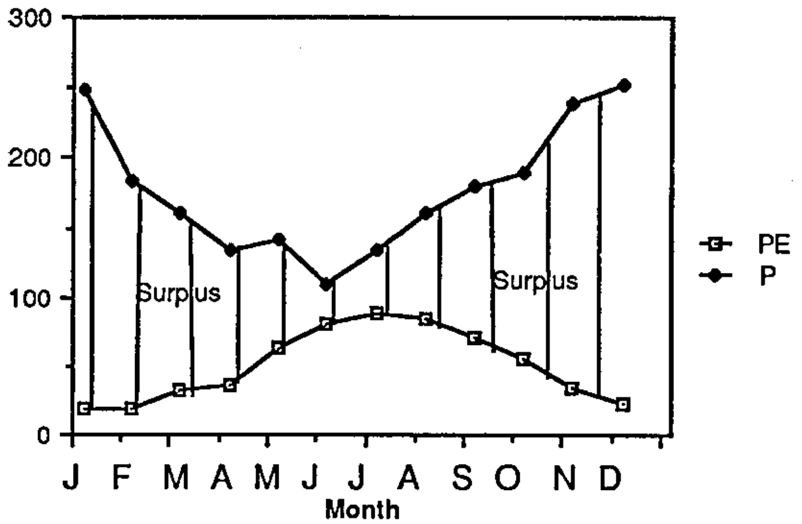


Fig. 2.2. Mean monthly water balance of Blackbrook at One Barrow Catchment

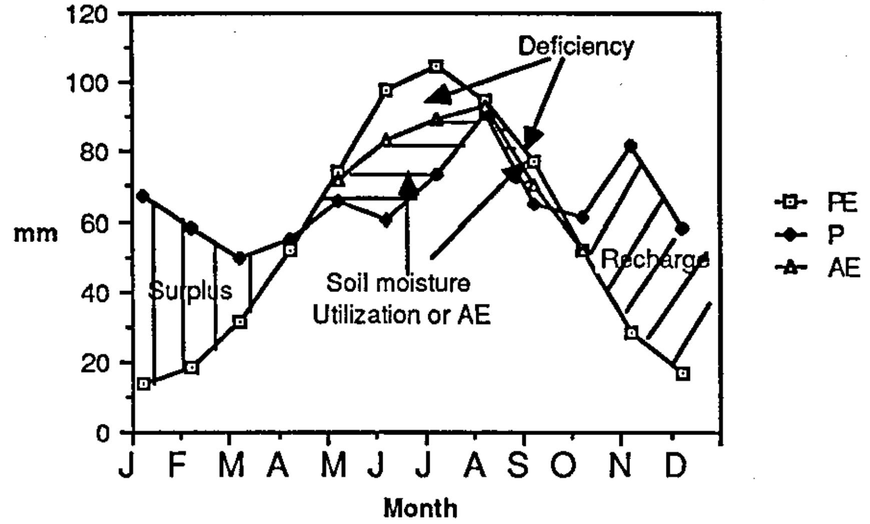
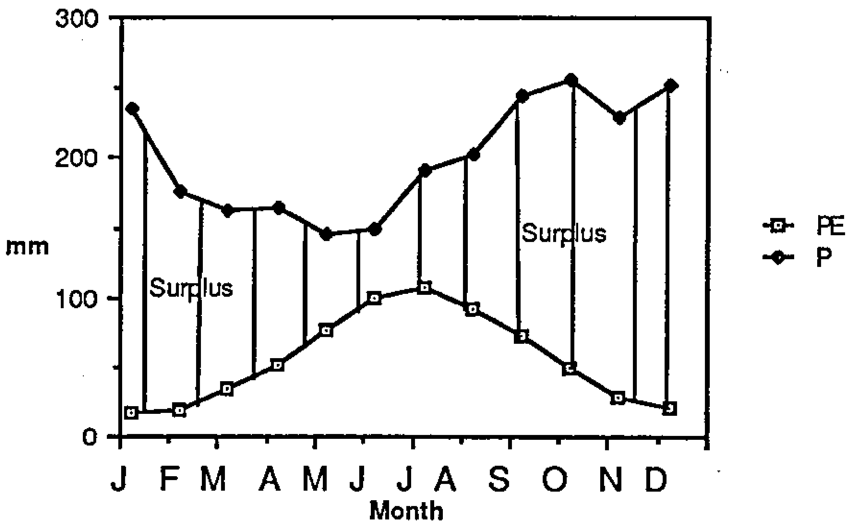


Fig. 2.3. Mean monthly water balance of Calder at Muirshiel Catchment



Comparing the three catchments, East Dart and Calder catchments are not deficient of water during the period for which the water balance has been computed. They in fact had surplus of water throughout the year indicating permanent saturation (tables 2.1 and 2.3). Unlike the two catchments mentioned above, Blackbrook catchment had water deficiency in the months of May to September (part of summer). As a result, AE exceeds the precipitation. Although this is the case, there is no severity as the maximum value of the deficit is only 16mm (Table 2.4). In practice, the winter surplus fully saturates the soils in winter. A study of daily evaporation and evapotranspiration was undertaken by Hill (1966) in the Blackbrook catchment. Hill's result revealed lower evaporation rates for winter compared to summer which is no surprise as the dynamic factors, solar radiation and temperature, are at their minimum.

Although this calculations indicate permanent saturation for East Dart and Calder catchments, in reality this is not the case since there are dry spells especially in summer months. This situation has occurred because average monthly values have been used thereby averaging out the effects of dry spells. This confirms the findings of Chandler and Gregory (1976), that the water deficits that do occur locally during rainless periods could be easily "smoothed out" when monthly or annual values of precipitation and potential evaporation are used.

2.3 Summary

A study of the British climate in general shows that differences in climatic factors from one area to another are due mainly to geographical location and topography. Precipitation is found to be uniformly distributed over a particular area at any given time, the use of one rain gauge station per catchment for the water balance and sorting out dry days in chapter 8 is therefore justified. There is no severity (extremes) in the climatic factors and it has been reported by Chandler and Gregory (1976) that ET amounts to less than 20% of the precipitation in mountainous areas, while elsewhere in England, over 50% is lost. Thus the remaining precipitation either runs off as streamflow or infiltrates to form soil moisture or groundwater.

The water balance of the three catchments reveals that potential ET for East Dart, Blackbrook and Calder catchments are 25%, 83% and 24.8% of the average annual rainfall respectively. Although the potential value for Blackbrook catchment is high, the actual ET is just over 70%. This percentages are not far from the findings of Chandler and Gregory (op. cit.).

The results of the water balance is compared with some results of tropical areas in Nigeria to have a feel of the extremes in the climatic factors in the tropics (see Table 2.1). Acworth (1981), in a hydrogeological study of the basement complex in Northern Nigeria, quoted values of evaporation from open water which approximately doubles the annual rainfall.

The annual evaporation and evapotranspiration estimates as given by Acworth are 2093mm and 1669mm respectively for data from Bauchi in the Savannah of Nigeria. The total annual rainfall for the Bauchi data being 739mm and 991mm for 1973 and 1979 respectively. In another study, Kida (1984) computed total annual potential evaporation from a class 'A' pan for Maiduguri, Nigeria; a value of 4052mm with a total of 2176mm for the rainy season (April - October) was calculated. The total rainfall for the same period is between 508mm and 762mm. Taking the highest rainfall value in the rainy season, evaporation is almost three times the total rainfall.

It is this imbalance that necessitates detailed study of the water balance of an area for any reasonable assessment of the potential recharge. In a temperate environment such as Britain, with surplus rainfall coupled with the availability of data; this has enabled the computation of the climatic water balance.

Chapter 3

GEOLOGY

3.1 Introduction

Recent studies indicate a great deal of geological work has been undertaken on granitic and similar rocks in Britain (Alexander, 1983, Black, 1979, Moseley and Ford, 1985, Heath and Durrance,1985, and Glending, 1980); of all the works, the one most related to this study is that of Alexander (op. cit.). Others (Heath and Durrance, 1985 and Black, 1979) are more concerned with repository site investigation for nuclear waste disposal. The rest are concerned purely with the solid geology.

The geology of the study catchments are Precambrian igneous rocks in Blackbrook, granitic rocks in the East Dart and basaltic rocks in Calder. In this study, the discussion of geology is restricted to the distribution of the different lithological units which either directly or indirectly affect groundwater occurrence, movement and chemistry. Therefore, an account of the geology will be restricted to features considered relevant to subsequent sections. A summary contrasting major important features within the three catchments which affect groundwater occurrence and movement is given in section 3.4. (see Table 3.6).

3.2 General Geology

A detailed field work of the three catchments was undertaken in the summers and early part of winter of 1987 (alongside geophysical survey) and 1988 with prior reconnaissance surveys. The geology of the catchments in question are discussed below with respect to the area within which they are located as the catchments are a small part of a geologic environment. For each catchment, a general description is given followed by a detailed description from field observation (measurements) substantiated by work of others for a better understanding of the geology since the bedrock are covered in most places by superficials and weathered rock material.

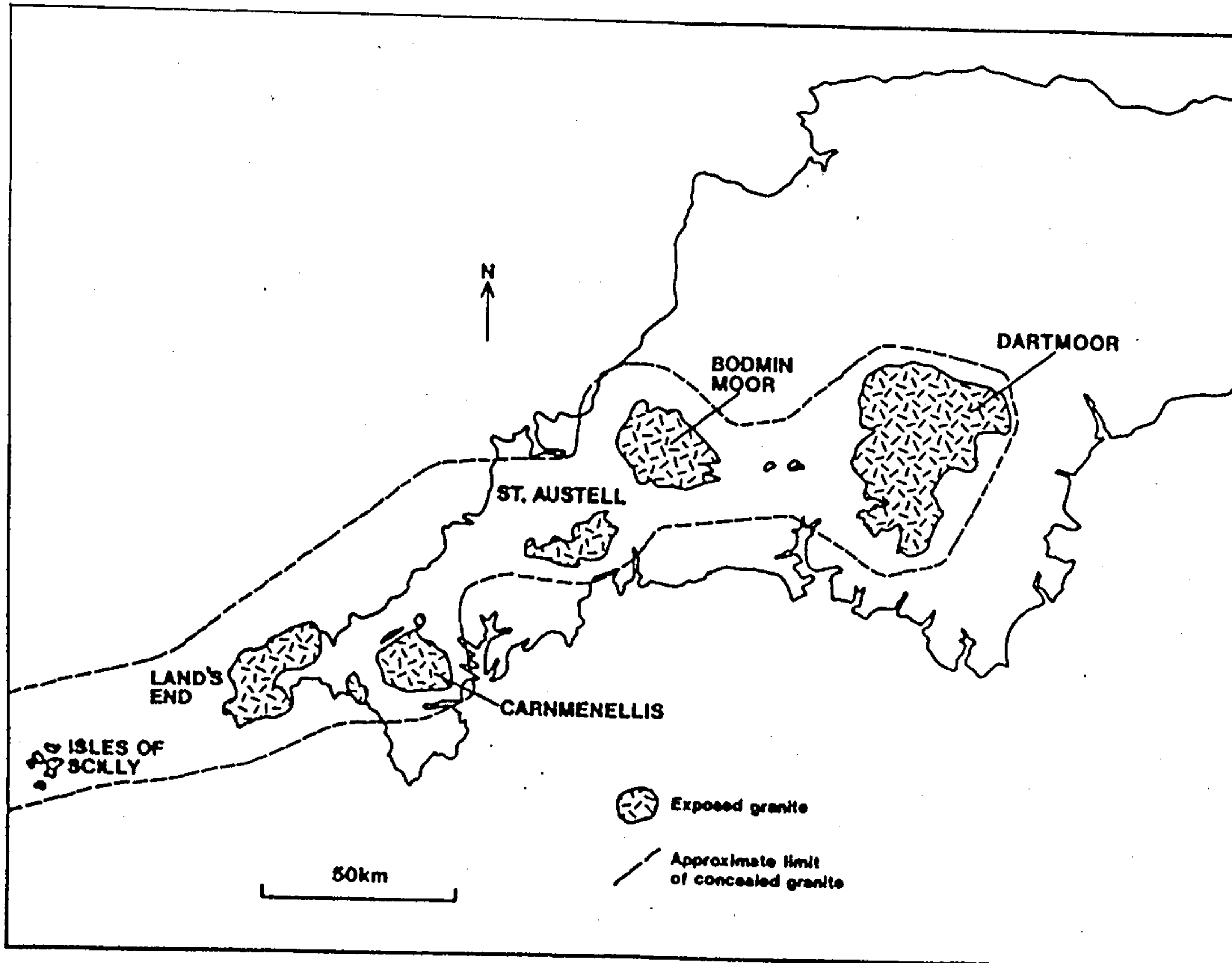


Figure 3.1 Simplified Geological map of S.W. England indicating Dartmoor.

3.2.1 East Dart Catchment

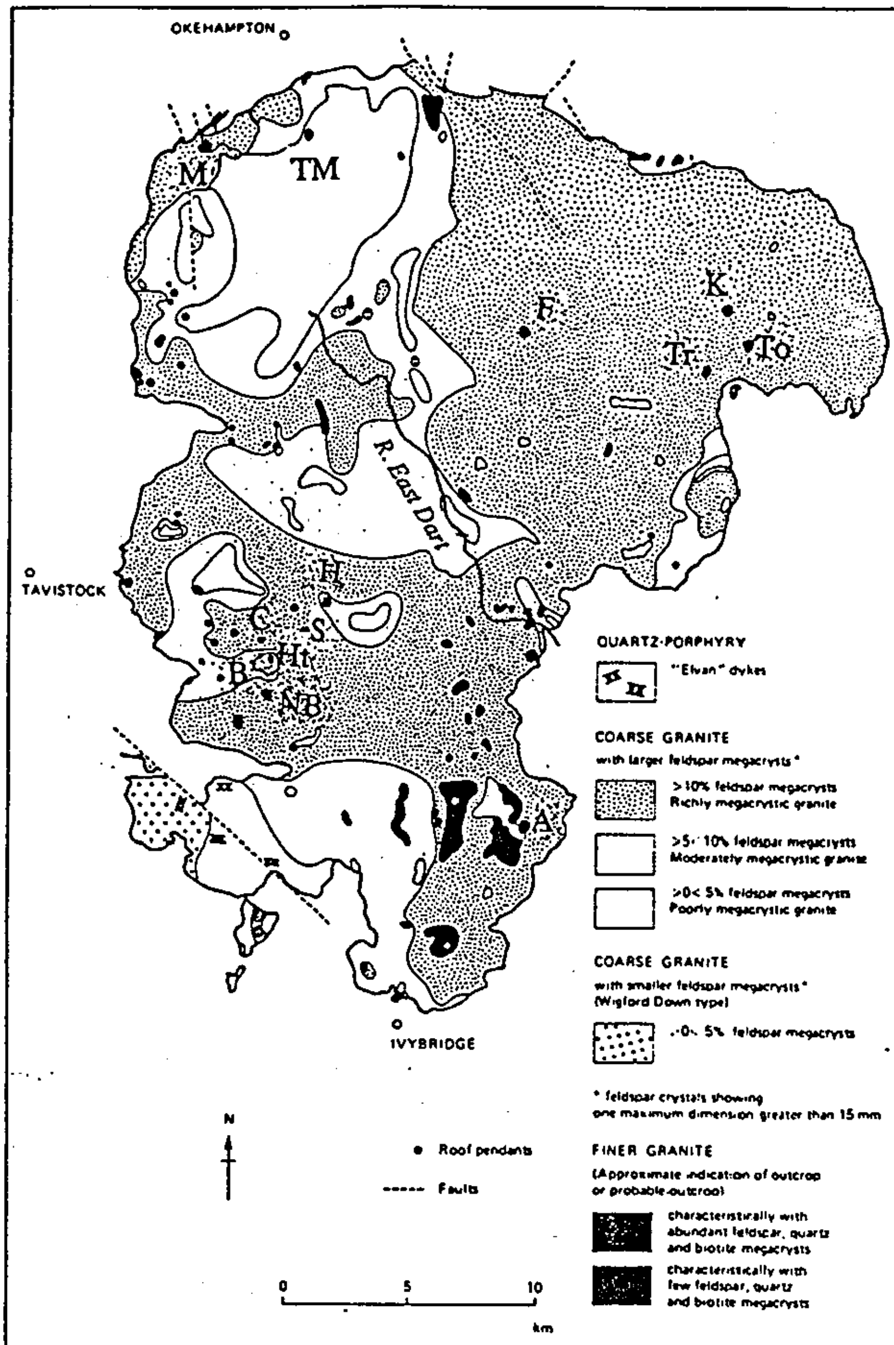
Outcrops are not common on the East Dart catchment. In areas where they occur, they are either found on hill tops or valley sides and bottoms. These areas include Hartland Tor, Sittaford Tor, Gawler Brook, the river valley near the water falls on the major river, Braddon Brook and Stannon hill. Most of the bedrock is covered with peaty soils and superficials (see Plate 3.1). Rock boulders are scattered on flat areas or near exposures. Some of the boulders especially those covered by thin sediments could easily be mistaken for an exposure. However, this mistake did not occur because their existence was picked up by geophysical methods used (as in chapter 6). There are no exposures for the upper reaches of the catchment (1/5th) after Broadmarsh.

Plate 3.1 Rock Outcrop covered by thin soil. Notice Bracken on Hill side

The Dartmoor granite is part of the granitic intrusion during the late Carboniferous period (Edmond et al, 1968, Brunsden and Gerrard,1971, Perkins, 1972, and Heath and Durrance, 1985) which stretches from the edge of Dartmoor to the Isles of Scilly (figure 3.1). They comprise of six large plutons which are linked at depth to form one huge South West England batholith. The six plutons appear on the surface although they are a part of a continuous body of rock 200km long and up to 50km wide. From geophysical, (gravity and seismic) evidence the depth of the batholith is given as between 10 -15kms (Heath and Durrance, 1985). In an earlier work, Alexander (1983) gave the depth of the batholith to be between 16 - 19kms.

The granite is adamellite or quartz monzonite which is approximately of equal proportions of orthoclase and plagioclase feldspars with quartz constituting about 30%. The granites are classified into three kinds (Perkins, 1972, Edmonds et al,1968, Dearman,1964, Hawkes, 1982 and Heath and Durrance, 1985) viz 'Tor or Giant Granite' characterised by large opaque white feldspars known as megacrysts which range in length between 10mm - 170mm and give a porphrytic look. 'Quarry or Blue Granite,' which has a smaller grain size, is still classed as a porphyritic rock with fewer feldspar megacrysts. This variety has more Muscovite than biotite. The giant and blue granites are classified as coarse granite by Hawkes, (1982). The third are known as aplites; these are fine-grained sheet-like masses. They are minor features compared to the whole granite area.

The order of abundance of the granite matrix are feldspars forming up to 65% of the rocks, quartz about 30% and biotite between 5 and 7% while accessories amount to less than 15% by volume (Hawkes, 1982). Muscovite, tourmaline and chlorite are the most conspicuous of numerous accessory species; tourmaline being the most conspicuous in the coarse granite. Some of the minerals of the granite are of economic value (Brunsden and Gerrard, 1971). The geochemical analyses of the Dartmoor granite is summarised in Table 3.1 (Al-Saleh Fuge et al and Rea, 1977). The East Dart river drains the coarse grain granite (see figure 3.2; indicating locations of depth of incoherent granite, with values in Table 3.6). As defined from the ordnance survey map of Great Britain (1:50000; sheet 388), about one fifth of the upper reaches of the East Dart river drains the fewer k-feldspar megacrysts while the remaining four fifths of the river drains the abundant k-feldspar megacrysts.



Key:

A	Avon	Ht	Hart Tor	TM	Taw Marsh
B	Burrator	K	Kennick	To	Tottiford
C	Cowsic	M	Meldon	Tr	Trenchford
F	Fernworthy	NB	Narrator Brook		
H	Huccaby	S	Swincombe		

Figure 3.2 Dartmoor: megacryst granite distribution also indicating East Dart River.

Table 3.1 Average Chemical Composition of Dartmoor Granites

Ions	Big Feldspar	Giant Granite	Poorly Megacrystic	Blue Granite
SiO_2	72.30	71.56	74.60	74.77
Al_2O_3	13.60	14.08	12.7	13.33
Fe_2O_3	1.17	0.55	0.67	0.44
FeO	1.74	2.21	1.11	1.38
MnO	0.06	0.06	0.05	0.08
MgO	0.50	0.60	0.22	0.47
CaO	0.92	1.55	0.50	0.63
Na_2O	2.91	3.01	3.24	2.87
K_2O	5.49	4.87	4.79	4.75
Li_2O	0.06	-	0.10	-
TiO_2	0.40	0.42	0.17	0.20
P_2O_5	0.19	0.21	0.20	0.18
H_2O	1.23	0.88	0.95	0.90
Total	100.57	100.00	99.30	100.00

3.2.1.1 Structures

The Dartmoor granite on the East Dart catchment is found to have many joints and cracks, some of which are quite open. The jointing pattern falls into three sets two of which are well developed (see Plate 3.2). The first two consist of those that are inclined at high angles or vertical and the third set which are sub-horizontal and usually termed floor joints. This group control the shape of the Tors (blocky). The third group is less well developed and is inclined at angles between 15 and 80 degrees. This group has been referred to as pseudo - bedding or dilation features (Alexander, 1983). The general feature of the joints is that their number decrease with depth. In an excavation site south east of Dartmoor Forest, 25m was recorded as the depth of jointing (Alexander, op. cit.). There was no such site on the East Dart catchment.

The giant granite has well developed divisional planes and widely spaced vertical and horizontal, joints, often up to 3m and 1.5m apart respectively. The pseudo-bedding planes are usually not more than 1.5m apart and they are minor features because they do not penetrate far into the rock. The blue granite is divided by several sets of closely spaced vertical joints.

The jointing patterns are thought to be produced by field stress (Hawkes, 1982) as a result of later faulting or gravitationally induced vertical compression within the rocks during its

Plate 3.2 Tor: showing 2 major sets of jointing

formation. In fact it is believed to be a phenomenon produced in response to stored stress in the rock when it was formed and the upward increase in the number of open partings as an expression of the hydrostatic relief due to denuded overlying rock. However, Hawkes (1982) observed that the jointing is an expression of an extremely complex and changing web of stress fields which has acted on the granite over a long period of time. The rivers are formed in areas weakened by fractures in the granite.

Faulting is restricted to the granite boundary and two faults have been identified in the north and south but it is thought that many more are yet to be discovered (Hawkes, op. cit).

3.2.2 Blackbrook Catchment

The geology is discussed in conjunction with the Blackbrook Reservoir catchment which is approximately a third of the Blackbrook catchment and is of similar geology.

The Charnwood Forest area of Leicestershire is quadrilateral, having corners at Leicester, Ashby-de-la-Zouch, Loughborough and Market Bosworth. The Charnwood Forest forms the most easterly of a number of older rocks called "inliers" by Watts (1947) that stretch from Wrekin and Malvern Hills into Warwickshire and Leicestershire. These rocks rise above the Midland plain of England which is underlain by the Triassic Bunter Sandstone. The rock exposures are found in a small area bounded by the lines Leicester - Coleorton - Loughborough - Leicester forming a triangular area of 110 km^2.

The area of exposure has been of great interest to the British geological survey, Leicester, Loughborough and Nottingham universities. The interest shown is due to the age of the rocks, their mode of origin, mineralogy, the effect of glaciation on them and their proximity to these institutions. Some of the recent geological works by Watts (1947), Evans (1968) and Moseley and Ford (1985), have enabled the detailed study of the geology of the Blackbrook and reservoir catchments.

The Charnwood Forest occurs as a ridge caused by an anticlinal fold (Watts, 1947, and Moseley and Ford, 1985) trending North-west to south-east with some structural faults. The major rock groups of the Charnwood Forest are given by Watts (1947) in descending sequence and this is given below as

CLASTIC ROCKS

Post-Glacial	Alluvial River Terraces	
Glacial	Boulder Clay Sands and Gravels	
Trias	Keuper Marl Keuper Sandstone	
Carboniferous	Carboniferous Limestone	
Charnian System Precambrian	C. The Brand Series	3. Swithland Slates 2. Trachose Grit and Quartzite 1. Hanging Rocks Conglomerate

B. The Maplewell Series	
	4. Woodhouse and Bradgate Beds
	3. Slate-agglomerate
	2. Beacon Hill Beds
	1. Felsitic Agglomerate
A. The Blackbrook Series	Blackbrook Beds.

IGNEOUS ROCKS

Basalt and Dolerite dykes
Diorite of Brazil Wood
Granite and related rocks of Mountsorrel
Microgranite of Lubcloud
Syenite (Northern type)
Syenite (Southern type)
Porphyroids and related rocks.

The systems and series have been renamed (or redefined) by Moseley and Ford (1985) as supergroups and groups respectively. This is thought to be adequate as former divisions were of limited local value for correlation. The redefinition of the clastic rocks into the Charnian Supergroup is divided into Blackbrook, Maplewell and Brand Groups with two volcanic complexes. The Charnian Supergroup which is not well exposed is overlain unconformably by Triassic and Pleistocene sediments. The area however, represents a zone of active volcanic and earthquake activity which is now extinct or dormant. The geology of the catchment is represented on the modified maps of Moseley and Ford (1985) in figure 3.3.

The geology of the Blackbrook and Reservoir catchments consists of the Blackbrook, part of the Maplewell groups, the Triassic Keuper Marl and the igneous complexes of Whitwick and Northern Diorites as given by Moseley and Ford (op. cit.). The Blackbrook Group is further divided into formations which is given by Moseley and Ford as

The Stratigraphic division of the Blackbrook Group

	Members	Lithologies
		c. 370m of tuffaceous pelites dust tuffs and subordinate coarse-grained tuffs
Blackbrook tuffs		c. 30m of very weathered coarse-grained
Reservoir c. 610m	None	with subordinate tuffaceous pelites
		c. 210m of tuffaceous pelites, dust tuffs and pelites and subordinate coarse-grained tuffs

	South Quarry Slump Breccia Member c. 32m	Slump breccia, coarse-grained tuffs and dust tuffs
Ives Head Formation at least 820m	Lubcloud Greywackes Member c. 550m	Medium- to very fine-grained greywackes are dominant. Some greywackes are tuffaceous. Subordinate coarse-grained greywackes and tuffaceous pelites
	Morley Lane Tuffs Member at least 238m	Coarse-grained tuffs with subordinate dust tuffs and tuffaceous pelites

The Charnwood Lodge Member of the Maplewell group also falls within the catchments. Outcrops in the Blackbrook and Reservoir catchments are found on the major hills such as Ives Head, Peldar Tor, Mould Hill, Collier Hill and others. The striking difference between Blackbrook catchment and the other catchments being investigated is that bed rock is seen to outcrop in broad valleys such as near Rock Farm and the Reservoir. Their occurrences is discussed in Chapter 5 in relation to well siting in a hard rock catchment. The geology consist of Precambrian igneous rocks and Mercian Mudstones sometimes referred to as Keuper Marl. An account of the geology and specifically the petrology is as follows:-

(a) The Blackbrook Group

The Blackbrook and Maplewell groups are predominantly pyroclastic and volcaniclastic. The Brand Group are dominantly sedimentary, including greywackes with conglomerates, sandstone (including quartz - arenites), and siltstone (now slates).

The Blackbrook Group is rich in pyroclastic detritus forming thick sequences of dust tuffs, pelites and tuffaceous pelites. This has been divided into the Reservoir and Ives head formation and the Blackbrook group is found to be the thickest of the groups. The thickness of the different lithologies are as indicated above; they are found to be coarser and thin out due to increasing distance from a volcanic centre.

The rocks are compact and can be flinty. Their colour is greenish, buff and creamy grey. Bedding planes, cleavage and joints are found and in most cases, they are stained by red marl. Joint planes break the grits into blocks which are not rectangular. The jointing has prevented quarrying for slate.

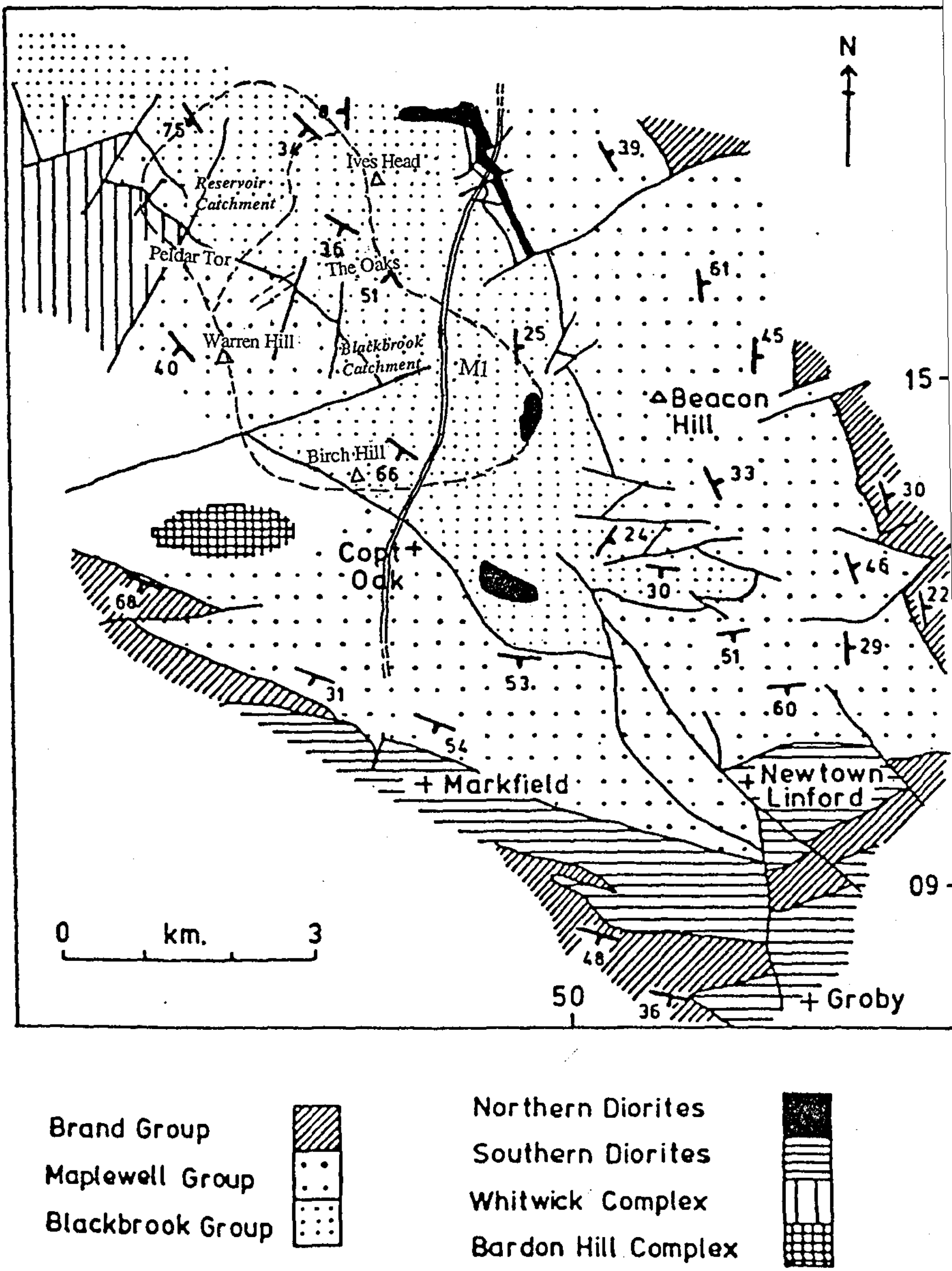


Figure 3.3 The outcrop pattern of the Blackbrook, Mapplewell and Brand groups indicating Blackbrook and Reservoir catchments.

The Ives Head formation is divided into Morley Lane Tuffs, Lubcloud Greywackes and the South quarry slump Breccia members where they are exposed. The Morley lane tuffs are predominantly coarse-grained rhyolitic crystal tuffs and dust tuffs. The Lubcloud Greywackes are of lithic grains and of arid igneous origin. The south quarry slump Breccia consists of clasts of rhyolitic dust-tuffs in a matrix of weathered coarse grained rhyolitic tuffs.

The Blackbrook reservoir formation consists mainly of tuffaceous pelites and rhyolitic dust-tuffs. Some thin coarse-grained rhyolitic tuffs do occur and also 30m of very weathered, coarse grain tuffs.

b) Charnwood Lodge member of Maplewell Group.
This is found in the north western part of the catchments. The top and base is not exposed (Morley and Ford, op. cit.). This member is confined to the area around Charnwood Lodge and the Mt. St. Bernard Abbey. A type section in a Nature Reserve between Flat hill and Warren Hill indicate a thickness of about 1286m with about 980m being volcanic breccias, lapilli tuffs and subordinate coarse - grained tuffs; 306m is coarse-grained andesitic tuffs with thin dust tuffs and tuffaceous pelites with a very thin slump breccia. This member is seen to be faulted against the Blackbrook Group and Whitwick complex (Moseley and Ford, op. cit.).

c) Igneous complexes.
The igneous complexes found within the catchment are the Whitwick and the Northern diorites.

i) Whitwick Complex.
Their origin is thought to be from explosive volcanics. They are in contact with the Blackbrook and Maplewell groups against which they are faulted. The Peldar-type or Whitwick complex is well developed at Peldar Tor, High Sharpley and Houghton Hill. The rocks are massive and show no bedding or layering. This is why they are probably quarried for construction purposes. Thorpe (1982) carried out a petrological analysis of the rocks. His result gave a rock of intermediate-to-acid lavas known as porphyroids, locally corresponding to andesites and dacites respectively. Earlier work by Evans (1968) had suggested only dacites. The porphyries are generally porphyritic, with phenocrysts of plagioclase and quartz in a fine-grained or cryptocrystalline quartzo-feldspathic matrix. The group is Na_2O-rich and K_2O poor.

The colouration of the quartz-phenocrysts are thought to be due to secondary haematite impregnation while the zoning of plagioclase is due to mixing. The rocks are usually green with dark weathered surface and are rarely nodular. Cleaved and crushed zones are seen in places.

ii) Diorites

The Charnian diorites are found in the north and south of the forest. The northern diorites intrude part of the Blackbrook group and thus the catchment. They are grey in colour and basic in composition. The rocks are quarried for construction purposes. The geochemical analysis of Thorpe (op. cit.) suggested that the rocks are of the theolitic basalt percentage. This confirms the suggestion of Evans (1968) of plagioclase dominance (andesite - labradorite) with a little potash feldspar.

Alteration has been observed as augite and hornblende are chloritised (Sylvester-Bradley and Ford, 1968).

It is worth noting that the breccias, tuffs, agglomerates, greywackes, and conglomerates mentioned above are not permeable. This is because they are compact and massive except in areas where they have been affected by faulting and folding resulting in fractures or fissures.

Keuper Marls (Mercian Mudstone)

The valley of the catchment is for the most part covered by an almost impervious layer of Triassic Keuper Marl. Boulder clay, sand, sand and gravel which are glacial deposits (Pleistocene) also occur in isolated patches. These overly the Charnian rocks uncomformably. The Pleistocene sediments are a subject of the superficials in chapter 4.

The Keuper marls are clastic rocks and constitute part of the solid geology although hydrogeologically they possess almost the same properties as clay in terms of water absorption and transmission. They are discussed in general terms.

The Charnian rocks became covered by the marls in the Triassic period. They rest on the Charnian rocks as well as in joints. The marls are filled with angular breccias and occasional wind-fretted boulders of fresh igneous rocks. An intensive study of the marls was undertaken by Bosworth (1912). He however, noticed some isolated patches of sandstone within the catchment but this may have been mistaken for pockets of sandy gravel found locally. Some sand of considerable proportion was found in the marl.

From quarry observations, Bosworth (op. cit.) divided the marls into three viz:

1. coarser material of breccia with evidence of exfoliation. This in most cases is found to overly the bed rock directly in areas where the three types are observed. This suggests some form of segregation during deposition.

2. Breccia and grit which seldom exceeds 1m thickness.

3. Stones in the marl both large and small with grit in abundance.

A major structure observed in the marls is the jointing pattern which can be curvilinear, cubic, ball and loose earthy texture. Bosworth observed several varieties of the marl ranging from compact fine to coarse breccia and gritty compact marls. In the stratified coarse sandy variety, the sand fraction may be anything up to 100% with some pebbles.

Apart from the red marls, grey marls are also in abundance. The grey marls are a transition of the red marls when bleached by weak carbonic acid from rain-water and organic acid. Thus, the red marl is mottled with the grey marls in places.

Table 3.2 Average Chemical Composition of the Charnian Rocks

Ions	Acid Dust Tuffs	Blackbrook Reservoir	Beacon Hill	Newhurst Quarry
SiO_2	70.83	83.36	79.81	76.79
TiO_2	0.42	0.21	0.29	0.20
Al_2O_3	13.81	7.94	10.45	11.85
Fe_2O_3	Fe as FeO	1.61	2.07	4.71
FeO	2.77	Fe as	Fe2O3	
MgO	0.85	0.64	0.68	1.79
CaO	1.76	0.51	1.29	0.34
Na_2O	6.84	3.52	1.84	5.90
K_2O	0.76	1.03	2.88	0.81
P_2O_5	-	0.02	0.04	0.02
H_2O	-	-	-	-
CO_2	-	-	-	-
MnO	-	0.04	0.15	0.15
Total	98.04	98.88	99.50	102.56

The chemical composition of some of the rocks in Blackbrook and Reservoir catchments as given by Moseley (1979) is given in table 3.2.

3.2.2.1 Structures

The Precambrian rocks have three sets of joint pattern (see Plate 3.3) thus:

1. vertical or near vertical joints
2. high angle joints and
3. low angle joints

Plate 3.3 The 3 sets of joints as seen in Whitwick Quarry

The high and low angle joints are very tight and measurable only in few millimetres as in the Calder catchment. The vertical joints can also be very tight but they are found to be open in places. The open joints are often occupied by clay, marl or weathered rock material (photos). The rocks dip away from the centre of extrusion. The high and low angle joints dip at about 12^0 - 40^0 and 10^0 from the horizontal respectively. Generally, outcrops appear shattered because of the high degree or numerous jointing. The number of joints decrease with depth as evident at the Whitwick quarry.

Plate 3.4 Precambrian Outcrop

The shattered and rugged looking outcrops is due to the fact that the Charnwood rocks were subjected to severe earth movements after their formation (see Plate 3.4). The movement has resulted in major structures such as a fold, cleavage and faults. The structures have been thoroughly discussed in Watts (1947), especially faulting, and Evans (1968).

The main structure in the Charnwood Forest is an anticlinal fold trending NW-SE referred to as the 'Charnoid trend' by Evans (op. cit.). Other minor synclinal and anticlinal folds which vary in wavelengths between a few metres to more than a kilometre are observed. However, inferences from bedding and horizons of different beds have suggested that no inversion has occurred (Evans, 1968).

Cleavage is seen to affect all the rocks of the Charnian supergroup (Evans, op. cit.). They vary from a perfect slaty cleavage in slates to fracture cleavage in the volcanic breccias. Faulting and dyke intrusion have caused planes of crushing, cleavage and foliation.

Faulting is anticlinal and reversed, normal and transverse. Transverse faults are known to cross the entire anticline from side to side. From fig. 2 of Evans (op. cit.) and figs.1 and 4 of Moseley and Ford (1985), three sets of faults are observed in the Blackbrook and reservoir catchments. Their orientation is NE-SW, E-W and NW-SE with some other minor faults emanating from the major ones. These sets of faults can be seen on figure 3.3 which is a modification of maps 1 and 4 of Moseley and Ford (op. cit.).

A Study of the crustal and upper mantle structure of the rocks of the central Midlands has been undertaken by the geophysics group of Leicester University (Maguire et al, 1981) and Whitcombe and Maguire, (1981). This study revealed a major fault within the Charnwood Forest and some other minor faults in the vicinity of the Forest.

3.2.3 Calder Catchment

Calder catchment is situated on the Renfrewshire hills which is part of the Clyde plateau volcanics, consisting largely of lavas. Rock outcrops are rare on the Calder catchment. Most of the area is covered with peat and morainic sediments. The only rock exposures are found at the disused baryte quarry, beside the road leading to the quarry near the sheep fold and along the river valley. The lack of many exposures has made it difficult to observe most of the structures that would otherwise have been seen. The rocks consist of basaltic and rhyolitic varieties.

The igneous succession is Dinantian (Lower Carboniferous: Richleyet al, 1930, Cameron and Stephen, 1985, Sutherland, 1982, Craig, 1965, McGregor, 1925 and Bluck, 1973) in the calciferous sandstone series. The thickness is thought to be 800m (Cameron and Stephen, op. cit.). It consists largely of alternating sequence of markle-type hawaiites and mugearites. The basal units comprise of basaltic tuffs, ankaramites and micropophyritic basalts while the upper series are macropophrytic, Dunsapie and Dalmeny type basalts. Thick trachyte and rhyolite lavas are found to form in the middle of the main series. Individual lava thicknesses are in the region of 5m - 30m (Sutherland, op. cit).

The bulk of the lavas are olivine-basalts; Richley et al (op. cit.) and Craig (op. cit.) have given a classification of the rocks in the catchment as:

1. Markle type: macropophyritic basalts with phenocrysts of labradorite and olivine. Feldspar is in abundance (>2mm grain size)

2. Dunsapie type: macropophyritic basalts with phenocrysts of labradorite, olivine and augite. Feldspar, augite and olivine are in abundance (>2mm grain size).

3. Dalmeny type: micropophyritic basalts with phenocrysts of olivine and sometimes sporadic labradorites and augites. Olivine is in abundance (>2mm grain size).

The main groundmass constituents are labradorite, augite and iron ore. Intermediate and acid members of the alkaline lavas include trachybasalts, trachyandesites, felsite and rhyolite. The trachybasalt lavas include mugearite. Mugearites constituents are a little oligoclase laths together with varying degree of olivine, augite and iron ore and often a little of late-formed biotite and hornblende. A sketch of the simplified geology is represented in figure 3.4. The geochemical analysis of some representative rocks as given by Richley (1930) is given in Table 3.3.

Two intersecting dykes trending E-W and NNE-SSW of late Carboniferous and Tertiary respectively are found. Its simple geology is basalt, dolerite and allied types. Veins of barytes ($BaSo_4$) occupy several fracture directions in the dykes. It is worth noting that the barytes were mined from the 18th century to the late 1960's (Hobson, 1959).

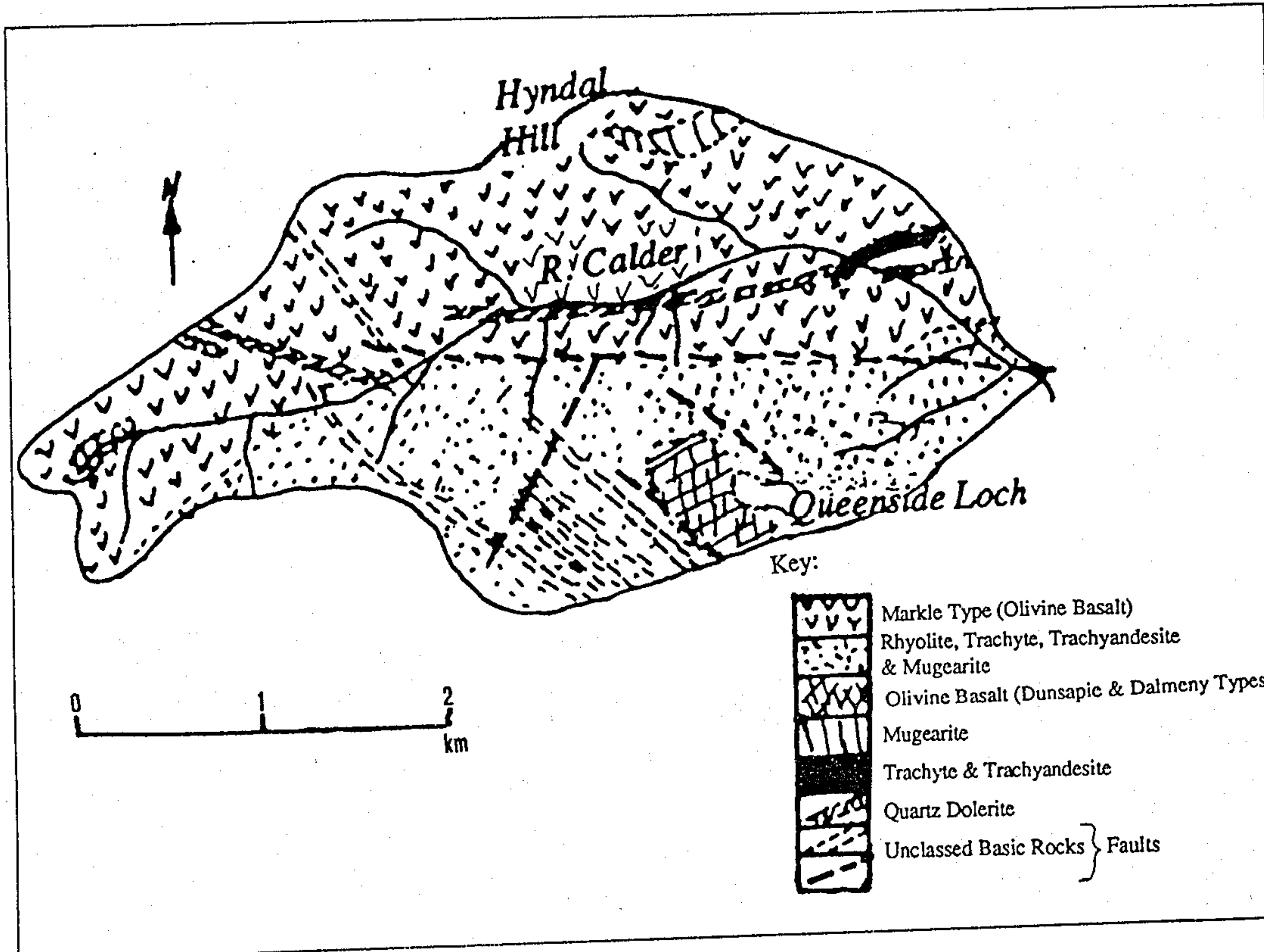


Figure 3.4 Simplified Geology of the Calder Catchment.

Table 3.3 Average Chemical Composition of Mugearites, Trachyandesite & Olivine Basalts

Ions	Mugearite	Trachy-andesite	Olivine Basalt Markle Type	Olivine Basalt Dunsapie Type
SiO_2	50.06	58.30	49.54	46.01
TiO_2	2.46	1.40	-	-
Al_2O_3	15.72	18.13	22.23	19.19
Fe_2O_3	3.94	3.59	9.55	5.91
FeO	7.63	0.90	1.12	6.75
MnO	0.30	0.23	0.08	0.19
MgO	3.82	2.36	2.80	6.81
CaO	5.90	3.11	7.19	8.68
Na_2O	4.55	5.83	4.56	3.27
K_2O	2.16	3.72	1.81	1.20
P_2O_5	0.64	0.40	-	-
H_2O	2.03	2.13	2.42	3.07
CO_2	1.08	0.06	-	-
CL	0.04	-	-	-
Total	100.33	100.16	101.30	101.08

Six boreholes drilled at the dam site indicate a depth to bed rock of between 1m to 16m with a silty clay overburden (Lower Clyde Water Dept; 1975). Hobson (op. cit.) reported the thickness of peat and glacial drift to vary within wide margins and very rapidly. In the dam site feasibility report of the Water Dept, the rock is found to comprise of a succession of basaltic lava flows which dips downstream. However, during the field work, the rocks are found to dip northwards (20^0) in most cases. The rocks were found to dip downstream only at the exposure upstream of the foot bridge; in fact, they are found to dip northwards downstream of the foot bridge. Weathering and jointing is found within the basaltic rock and this is discussed below.

3.2.3.1 Structures

There are two major joint patterns in the rocks (see Plate 3.5). There are those that are sub-horizontal or dipping and the other set are vertical or near vertical. The vertical set are numerous and this results in wedge - shaped rock fragments on breakage. The rocks within the catchment are found to dip northwards in most cases as earlier mentioned. The only exception are the outcrops upstream of the foot bridge. The separation of the horizontal blocks is between 0.25m - 2m. The joint widths vary between 0.5mm - 2mm. The joints are obviously very tight compared to East Dart catchment. Water seeps out only in areas where superficials cover the rock. There are other minor fissure found within the rock with no

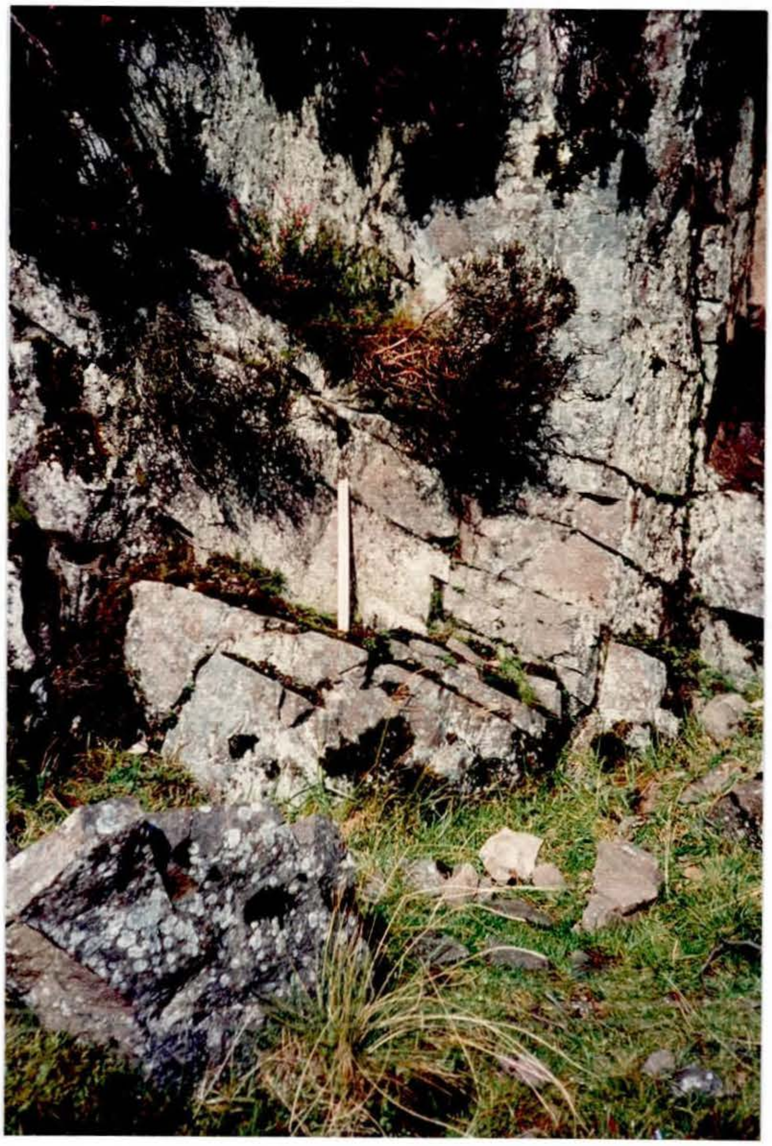


Plate 3.5 Jointing as seen at the Baryte Quarry

particular orientation. Typical columnar jointing was not seen. Richley et al, (1930) noticed fissured lava tops under the weathered rock material. The jointing is thought to be due to contraction during cooling and not as a result of weathering.

From the Lower Clyde Water department feasibility report, it is thought that some faults or fractures may be found in the area. These however, could be minor fractures associated with the main highland boundary fault. Cameron and Stephenson (1985) traced a parallel structure that runs NNE into the Renfrewshire Hills and this may be related to the minor fractures (see fig. 3.3).

3.3 Weathering: General

3.3.1 Introduction

The study of the solid geology and structures certainly aid in the understanding of weathering processes of the hard rock which consequently increase its water transmitting properties. In this introductory part, an attempt will be made to explain the elementary terms, the chemical decomposition of some of the minerals in the rocks and also the structures as they serve as weak points for alteration and subsequent decomposition. No attempt however, is made for the breakdown of the crystal lattice of the minerals as this is beyond the scope of this investigation.

The processes of weathering includes physical or mechanical, chemical and biological. These processes go on simultaneously in all climatic environments but the physical is considered dominant in cold and arid climates. Chemical weathering on the other hand is more dominant in warm and humid climates (UNESCO, 1984). However, the physical weathering in the cold climates aid the chemical weathering by opening up joints and exposing the less weathered material to chemical attack. Weathering including that of hard rocks, is fully explained by Ollier (1969).

Some simplified processes of rock chemical decomposition are explained and presented below. The actual process is very complex. The process starts by the formation of weak carbonic acid from rain water coming in contact with CO_2 in the air in the presence of oxygen and later with vegetation roots. The weak carbonic acid under favourable conditions dissociates to release hydrogen ions. The breakdown of the primary hard rock minerals is enhanced by the hydrogen ions as they travel downwards. This is simply represented as:

$$H_2O + CO_2 = H_2CO_3^-$$

$$H_2CO_3^- = H^+ + HCO_3^-$$

Thus for the alteration of albite (sodium-rich plagioclase)

$$2NaAlsi_3O_8 + 2H^+ + 9H_2O \dashrightarrow Al_2Si_2O_5(OH)_4 + 4H_4SiO_4 + 2Na$$
(Albite) (Kaolinite) (Silicic acid)

and also for the calcium-rich plagioclase such as anorthite which are unstable under low pH conditions can be represented as:

$$CaAl_2Si_2O_8 + CO_2 + 2H_2O \dashrightarrow CaCO_3 + Al_2Si_2O_5(OH)_4$$
(Anorthite) (Calcite) (Kaolinite)

In the presence of CO_2, the calcite is dissolved by the reaction

$$CaCO_3 + H_2O + CO_2 \dashrightarrow Ca_2^+ + 2HCO_3^-$$
(Calcite)

Similarly the hydrolysis reaction by alteration of forsterite (Olivine) as found in basalt or other ultrabasic and basic igneous rocks can be illustrated as:

$$Mg_2SiO_4 + 4H^+ \dashrightarrow 2Mg_2^+ + H_4SiO_4$$

These reactions confirm the fact that most groundwater from crystalline rock areas is predominantly calcium carbonate type with high quantities of dissolved silica. Calcite is often deposited as pH increases.

A weathering profile of fresh crystalline rock into soil, forming zones as the case may be is presented in Acworth (1987) and this is illustrated in figure 3.5 (compare this with figure 3.6).

It is often thought that in Britain all the weathered materials of hard rocks were removed in the Pleistocene by the movement of glacier with decreased intensity from north to south. This however is not the case as recent studies (Glending 1980, Moore and Gribble, 1980, and Alexander, 1983) have revealed depths of 40m to 60m for the Altna Breac and Peterhead Granite respectively in Scotland.

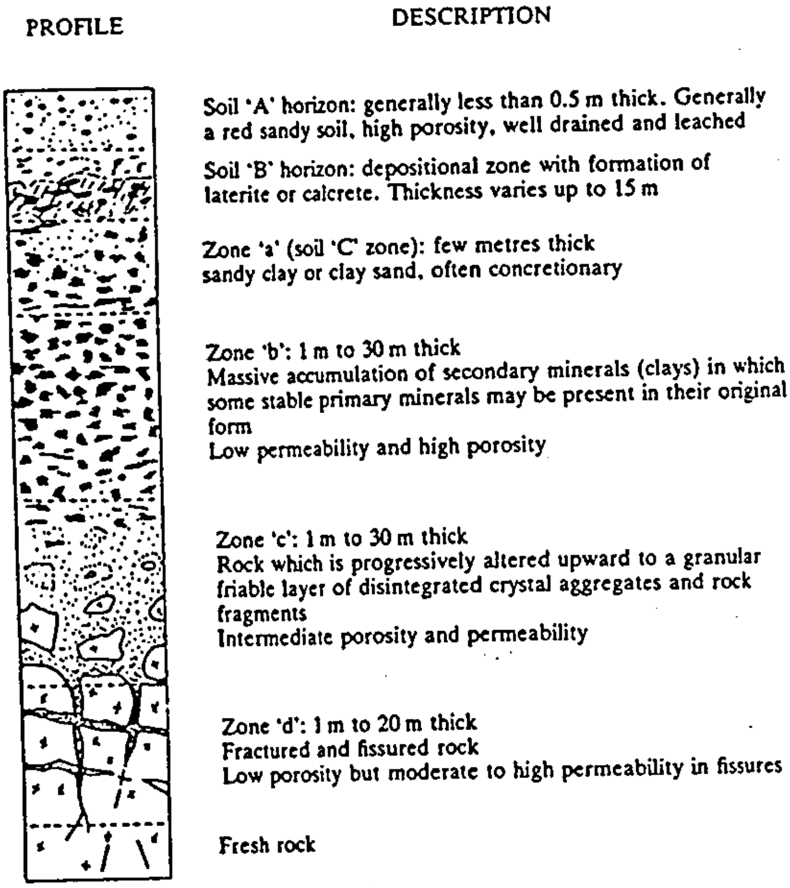


Fig. 3.5 Typical weathering profile developed upon crystalline basement rocks.

Weathering is also noticed from basaltic areas by Richley et al (1930) in their mapping of North Ayrshire also in Scotland. The process of weathering, as it affects the hard rock of the three catchments, is presented below.

3.3.2 East Dart Catchment

Weathering on Dartmoor has been reported by many workers and some of the most recent include the works of Alexander (op. cit.) and Heath and Durrance (op. cit.). During the late stages in the magma, pneumatolytic processes of alteration were reported in the granite. This process was also observed in the Carnmenellis granite by Heath and Durrance (1985) in which periodic hydrothermal circulation of groundwater in the granite resulted in the alteration of some minerals in the form of tourmalinisation (replacement of tourmaline by biotite), chloritisation and kaolinisation. These processes are also reported on Dartmoor granite in the earlier works of Brunsden (1964), Eden and Green (1971) and Perkins (1972). Acid water circulated in the rock during the late stages of the granitic formation causing chemical replacement of feldspars by muscovite, aided by boron gases, while tourmalisation followed as the temperature dropped. Kaolinisation followed as cooling continued i.e. yielding kaolin or China clay in some areas.

After intrusion and deposition, other processes of weathering started acting on the granite as noted by Brunsden (op. cit), Perkins (op. cit), Fookes (1971), Eden and Green (op. cit.), Dearman (1978) and Alexander (op. cit). The processes are explained in detail in Brunsden, Dearman, Eden and Green and Alexander.

Brunsden (op. cit.) concentrated his studies on chemical and physical weathering although some of the work is contested by some authors (Alexander, 1983) which they think of weathering from top to bottom coupled with hydrothermal processes has resulted in such thickness of weathered material. In the East Dart catchment, weathering is noticed from top to bottom and an account of the process is presented below.

The chemical weathering starts from the surface where weak carbonic acid and oxygen and organic acids derived from the soil and surface peat penetrate downward. From the minerallogic composition of the granite (biotite, plagioclase, orthoclase and quartz) and also considering the degree of their susceptibility to weathering, in which biotite is first to be affected (bleached to chlorite) although the rate of weathering is slower than the feldspars eventually with plagioclase being the least susceptible of the feldspars. Oxidation leads to the formation of reddish-brown soil material and stains which

Table 3.4. Weathering zones on Dartmoor

Zone		Section	Characteristics
Migratory layer		Beardown	Disturbed, structureless layer consisting of quartz sand and coarse granite fragments. Often red-brown in colour. Involutions and frost -wedges often present.
Zone 1		Lakemoor	Undisturbed, structureless. High proportion of quartz. Yellow-red-brown in colour.
PALLID ZONE	Zone 2a	Two Bridges Lakemoor Widecombe	Well rotted and incoherent. Granite structure retained. Well leached. Crumbles in hand.
	Zone 2b	Two Bridges	Well rotted but coherent. Little leaching. Tends to break into rotted joint blocks. Some rounded core-stones. Clay minerals on joints.
Zone 3		Two Bridges Burrator Lakemoor	Partial decomposition along joints. Spheroidal scaling and formation of grus. Core-stones angular and locked. Angularity increases with depth.
		Merrivale Lucky Tor	Merges downward into solid rock that shows brown staining. No decomposed rock in joints.

constitute the iron-pan found especially in weathered insitu granitic material (see Plate 3.6). The carbonate from feldspars and silica goes into solution followed by leaching of the clay minerals. Quartz is untouched by chemical weathering and this remains as part of the weathered rock forming about 90% of the residue in places. The decomposed granite on Dartmoor is locally referred to as 'growan'. It is worth noting that the chemical decomposition starts at the joints. A schematic diagram is represented by Brunsden (1964) and this is illustrated in Table 3.5 and figure 3.6.

Physical weathering, which is the in-situ fragmentation of rock without chemical changes is also reported by Brunsden (op. cit.) on Dartmoor. The most common are expansion and unloading, frost action and organic activity. This is evident by the boulders on valley sides and bottom and near exposures on the catchment. Although these do not produce growan, they are however important in that they make the granitic rocks more susceptible to chemical decomposition.

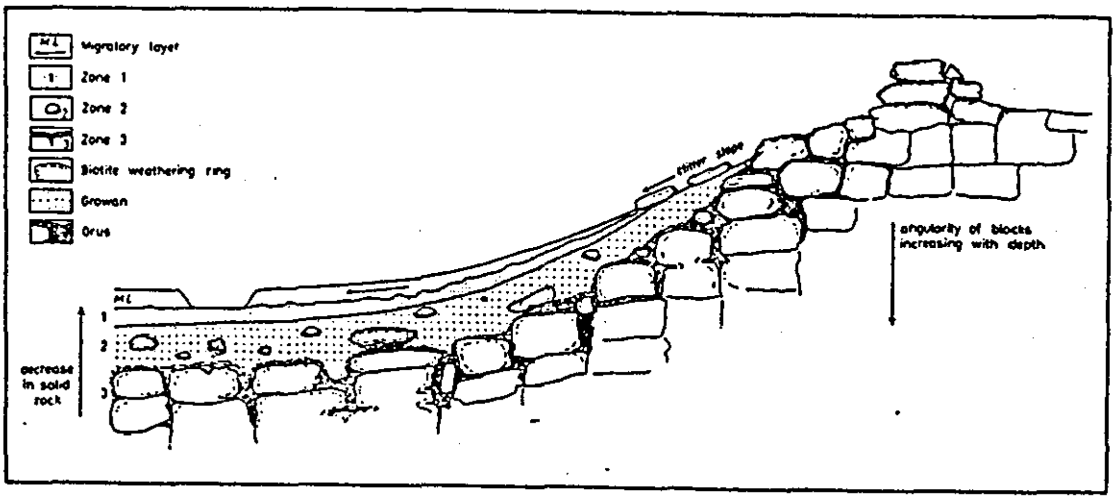


Fig. 3.6. Schematic representation of a weathering profile in the Dartmoor granite (Brunsden, 1964).

Kaolinisation is a process resulting from decomposition of feldspar as noted above. Quartz forms the bulk of the sand fraction, with some mica and tourmaline. Except in superficial layers close to the rock boundary, 'core stones' or boulders are found in the China clay. Its colour is brown to reddish brown even though some whitish or greyish varieties are noted by Brunsden (1964). The growan is found to retain a crystalline rock texture but can be broken by hand. The growan grades into the fresh granite. A typical section at a quarry just outside the catchment (S.E. of Wala Brook) comprises from top to bottom of:

1. Peaty top soil (0.2m)
2. Unsorted sandy soil with rock fragments (0.5m; superficials)
3. weathered granite (0.7m)
4. Weathered insitu granite which retains the parent rock structure (growan) with some red banding (>1m).

Plate 3.6 Weathered granite in-situ (growan).
Notice the brownish stains which often results in iron-pan

It is the red banding that often results in the formation of iron pan in the weathered rock material. This phenomenon can be seen in plate 3.6.

The weathering zones as given by Brunsden (1964) is presented in table 3.5. Some examples of depth of weathered or incoherent granite as given in Alexander (op. cit.) and from field mapping carried out by the author is presented in table 3.6 (also see figure 3.1).

Table 3.5. Depth of Incoherent Granitic Material in S.W. England

Sites	Location	Depth to Solid Granite
Burrator	W. Dartmoor	0.60 -12.19m
Sheepstor	W. Dartmoor	4.26 - 30.48m
Harttor	3km N. of Burrator	4.87 - 20.11m
Coswic	7.5km N.E. of Burrator	12.19 - 36.57m
Taw Marsh+	5km S.E. of Okehampton	2.43 - 46.93m
Drift Dam	Lands end Granite	20.00m
Stithians Dam	N.W.of Falmouth Cornwall	1.50 - 24.00m
Swincombe	4.5km N.E. Burrator	1.27 - 15.24m
Huccaby	8km N.E. of Burrator	8.14 - 34.23m
Sibbley	Bodmin Moor, N. of Liskeard	21.33m
Two Bridges+	Two Bridges	>18m
Broadmarsh*	East Dart River	>5m

* Inside catchment
\+ Near catchment

3.3.3 Blackbrook Catchment

The weathered rock material is greenish grey and the products are clayey. Weathering seems to persist in shattered zones and not necessarily from top to bottom as is always assume to be the case (see Plate 3.7). Over 20m of weathered zone was seen between fresh rocks at the Whitwick quarry. Water was not seen to seep through the joints although weathered zones look wet. However, the lack of seepages along the joints is attributed to the fact that the joints dip away from the centre of extrusion hence water flows outwards. The solid bed rock is overlain either by superficials, clay or marl. Marl of over 30m thickness was observed in the quarry.

Ford (1967) discussed deep weathering in the Charnwood Forest and nearby south Leicestershire diorites. Most of the study was based on observations from quarry sites. He inferred that weathering only took place in areas of rock exposures not covered by Keuper marl or glacial deposits except in areas where the marl is permeable. In general, the marl acts as an impermeable seal preventing deep weathering. His major contention is that deep weathering is post Triassic when glaciers that deposited the boulder clay removed some of the marl cover and most of the rotted materials. At Bardon Hill quarry, little patchy deep weathering was seen in a zone of structural disturbance in the northern diorites.

The weathered surface of the Whitwick Complex was noticed by Watts (1947). Chloritisation of augite and hornblende is noticed in the diorites (Evans, 1968). In a recent study, Moseley and Ford (op. cit.) observed weathered coarse-grain tuffs in the Blackbrook reservoir formation to a depth of 30m.

Plate 3.7 Weathered joints (centre of photograph) as seen at Whitwick Quarry

3.3.4 Calder Catchment

The weathering of the basaltic rocks starts by the replacement of olivine by red-brown pseudomorphs or iddingsite followed by albitisation, chloritisation, oxidation, hydration and replacement by carbonate. Another process include the formation of amygdaloidal material (chlorite, haematite, calcite, quartz and chalcedony), autobrecciated and / or hydrothermally altered rubble and zeolites. Silicification is the most common process of weathering in the rhyolites.

Plate 3.8 Peat and thin soil over weathered basaltic rock: brownish grey

Weathering of the basaltic lava has been reported by Richley et al (1930), Craig (1965), and Cameron and Stephenson (1985). Contemporaneous rotting of lava-flows is found throughout the volcanic suite within the Renfrewshire hills. Tropical weathering between eruptions in some areas are found to produced redden flow tops or red-brown lateritic boles. In some areas, the rotted basalt is well developed and this forms a peculiar subsidence stratification (Richley, et al, op. cit.). The subsidence is caused by reduction in volume consequent on rotting coupled with pressure from overlying deposits. Weathered basaltic rock materials were seen near the baryte quarry and upstream of the foot bridge. The weathered material consist of red or greyish blue clay (see Plate 3.8). The thicknesses of the weathered rock materials are a few centimetres (<30cm). Rock fragments found within the moraine or boulder clay are either weathered completely or shows signs of weathering. The difference in colour is due to the presence of ferrous and ferric iron in the rock. The rotted material is reported to be of considerable depth in places (Richley et al, 1930) although no figures are given. The rotted material rests on relatively unaltered basalt. Some of the red boles are seen to penetrate the fissured joints.

3.4 Summary

It is apparent from this chapter that the main geological units that may be of hydrogeological importance are the weathered material (regolith), structure, glacial and superficial deposits. The structures which have been formed either through faulting, dyke formation or pressure release may contain groundwater depending on their width, degree of jointing and the permeability of the overlying material. The weathered material, glacial and superficial deposits may contain groundwater depending on their thickness and lateral extent. A considerable amount of clay fraction may impede permeability. The overlying material also controls their degree of saturation and recharge.

A summary of the most important geological parameters contrasting the three catchments is given in Table 3.7. The important hydrogeological parameters are given in the remarks column. From the table of summary, it is apparent that East Dart catchment is likely to have deeper aquifer units and also higher permeability than the other two catchments due to lithological differences and texture. The localised sand and gravel in Blackbrook and Calder catchments are the important hydrogeological parameters. Structures such as faults and dykes found in Blackbrook and Calder catchments could also be important hydrogeological features since they could act as subsurface water dams. The nature and kind of alluvium and superficials found in the three catchments are discussed in chapter 4. However, deep

Table 3.6 A Summary of Important Geological Parameters

Catchment

Parameter	East Dart	Blackbrook	Calder
Geology	Granite	Precambrian (Igneous) & Mercian Mudstones	Basaltic & Rhyolitic rocks
Weathered Products	Sandy (>18m depth recorded)	Clayey (>20m weathered zone inbetween fresh rock) marl >30m at Peldar Tor	Clayey
Structures: Joints	3 sets, vertical can be quite open (up to 0.4m width)	3 sets but very tight (as in Calder)	2 sets but very tight (max. 2mm)
Fault(s)	None	3 major sets with other minor sets emanating from the major ones. Have caused planes of crushing, cleavage and foliation in bed rock	minor faults associated with main highland boundary fault. Quartz dolerite dykes are found.
Fold(s)	None	One major anticlinal & other minor synclinal & anticlinal folds of short wavelength	None
Typical lithology	Peaty soil, sandy superficials with rock fragments, weathered sandy overburden, insitu weathered granite (growan) and solid bed rock.	Fine loamy soils, clay, marl an solid bed rock. Some sand and sandy gravels are found locally	Peat and blanket peat, peaty soils, moraine, boulder clay and bed rock. Moundy sand and gravel are found locally in the glacial till.
Remarks	Valley gravel, alluvium, superficials and weathered granite are of hydrogeological importance.	Sand, gravels and the structures are of hydrogeological importance	Moundy sandy gravel and faults are importan hydrogeologically.

weathering, structures, glacial sands and gravels and the superficials are not a reliable surface indication for ground water resources. Hence, considerable geophysical effort is required to accurately site boreholes and open wells. This process is presented in chapter 5.

Chapter 4
GEOMORPHOLOGY, LAND USE AND VEGETATION

4.1 Topography

4.1.1 East Dart Catchment

Dartmoor is an upland plateau with rounded hills forming rolling scenery; basin like valleys and also narrow gorges.

The East Dart catchment starts at the highest point on the northern part of Dartmoor near Okement Hill at a height of 568m O.D. and is generally 320m O.D.

Rocky tors stand out as bold rounded grey masses, commonly cut by two major sets of joints. The catchment is characterised by many rounded and oblong hills (figure 4.1). The East Dart river runs through broad valleys and very steep gorges in places. The average stream channel slope measured between two points, 10% upstream and 85% downstream (10/85) of the stream length from the head of the river is 22.6m/km (pers. comm; Institute of Hydrology, Wallingford).

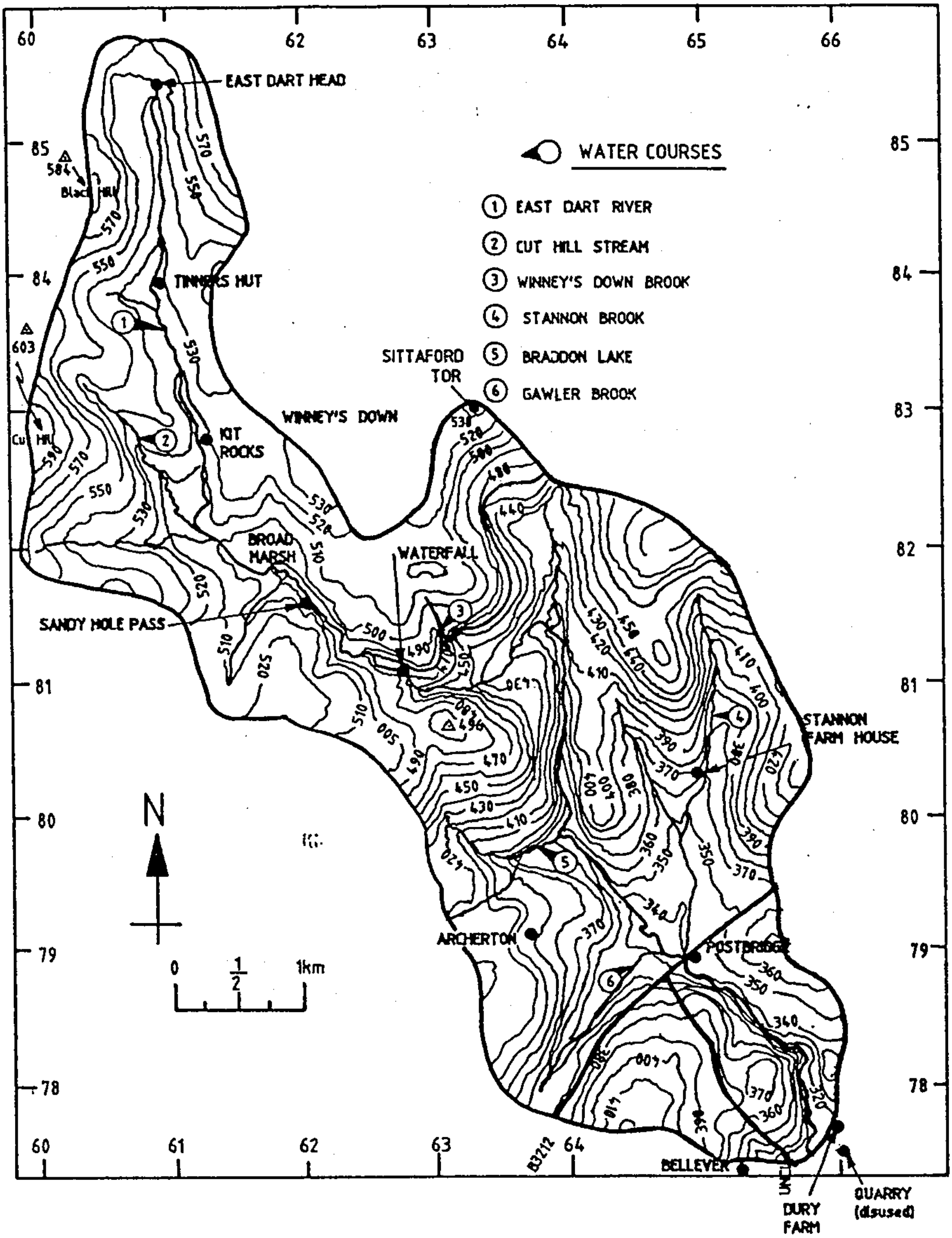
4.1.2 Blackbrook Catchment

The Charnwood Forest on which Blackbrook catchment is found, rises above the Midland plain to a maximum height of 280m O.D. at Bardon Hill. Quite a number of hills are found within and outside the catchment. It is bounded by Ives Head Hill (201m O.D.) in the north, Birch Hill (251m O.D.) in the south, Whittle Hill (183m O.D.) and Warren Hills (243m O.D.) to the east and west respectively (see figure 4.2). The 10/85 slope of the river is 10.09m/km.

Unlike the other catchments, Blackbrook has no gorges although it is an upland catchment. The valley is relatively wide in most places. Where rock exposures occur, they are ragged and jagged. The ground is generally 130m O.D. One major feature in the catchment is the M1 motorway that cuts through its eastern part.

4.1.3 Calder Catchment

The catchment is moorland country on the slopes of the Hill of Stake, close to the boundary between Renfrewshire and Ayrshire on the Clyde Plateau.



EAST DART AT BELLEVER CATCHMENT

Figure 4.1 Topography and Drainage System on the East Dart catchment.

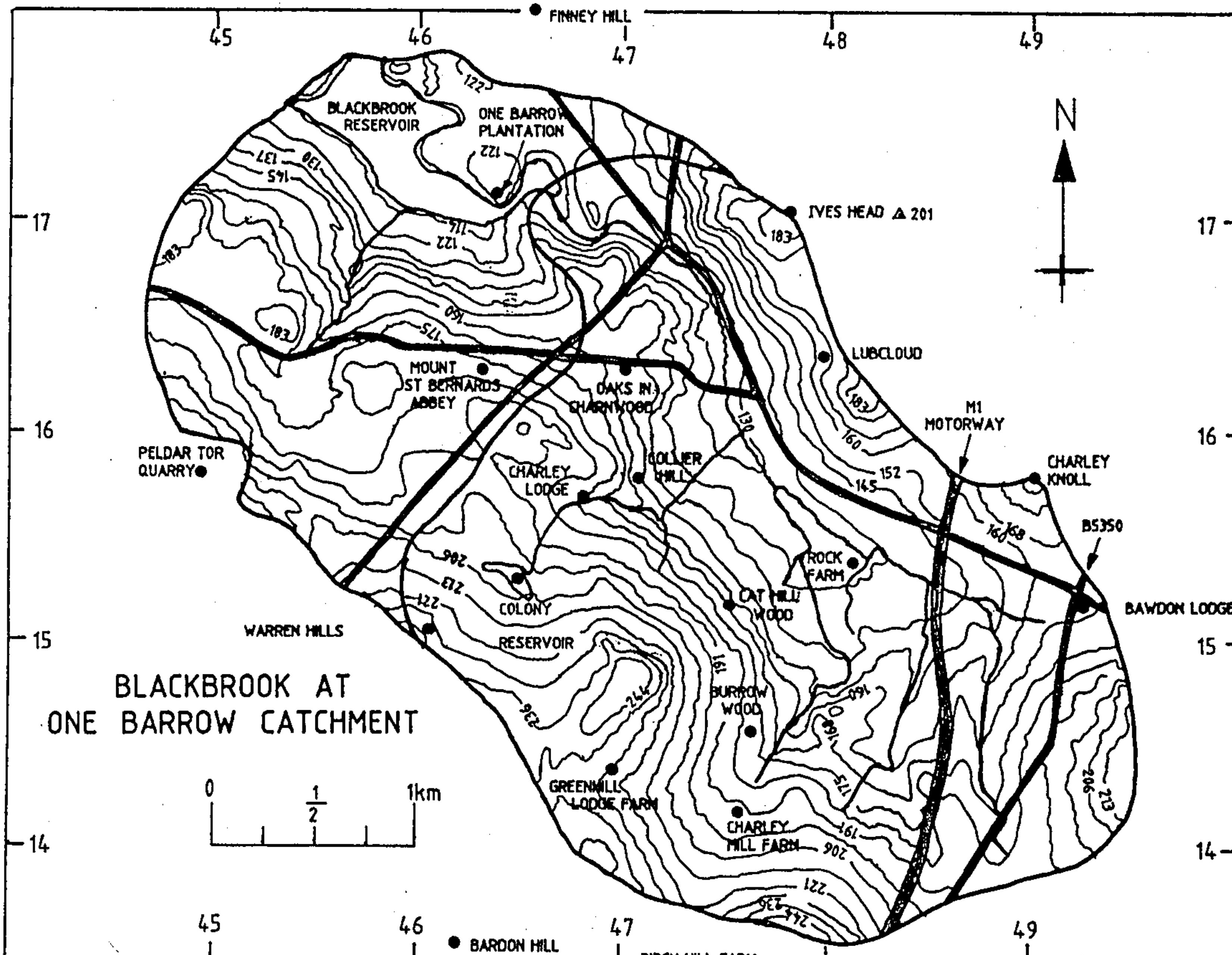
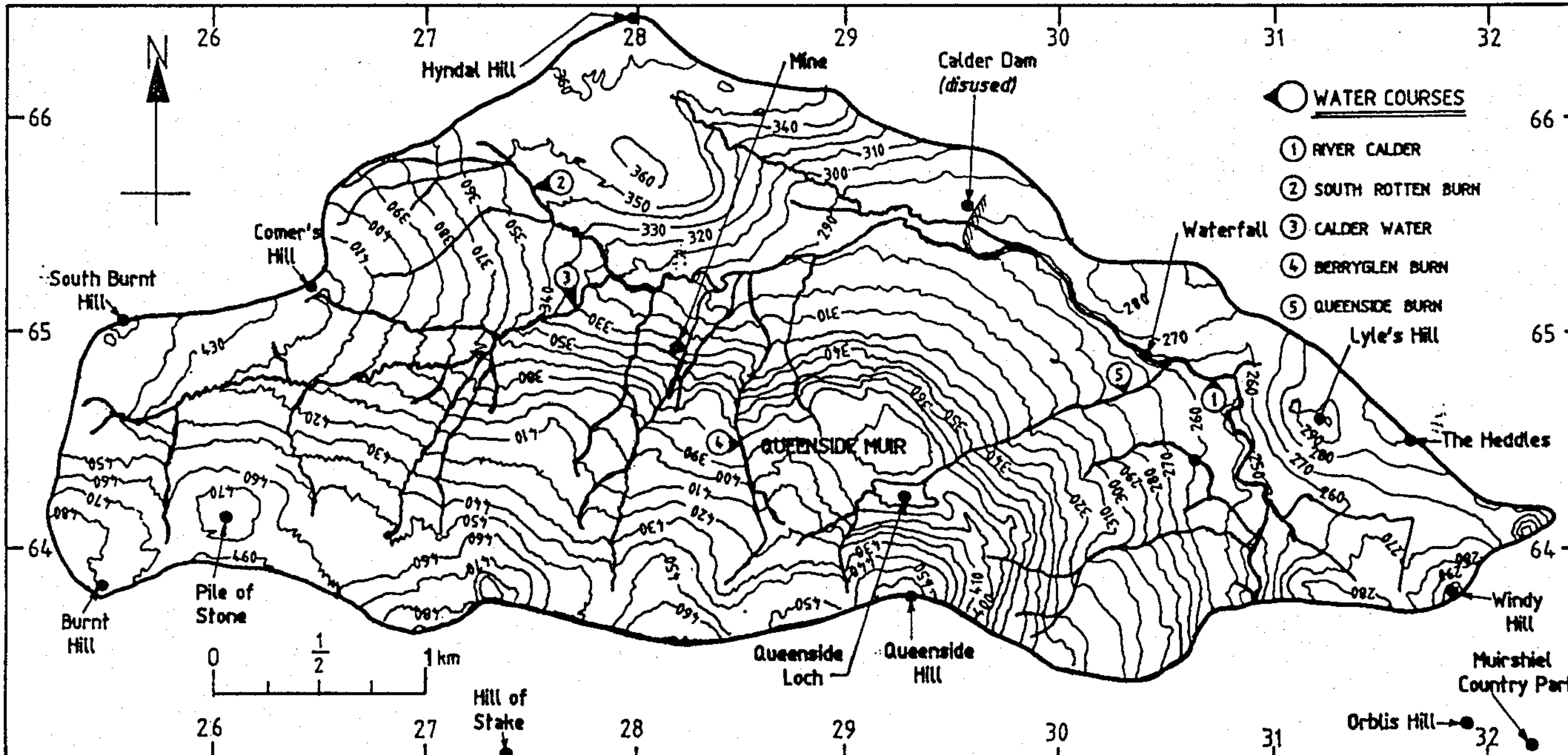


Figure 4.2 Topography and Drainage System on the Blackbrook and



CALDER AT MUIRSHIEL CATCHMENT.

Figure 4.3 Topography and Drainage System on the Calder catchment.

Topographically it consists of part of the glaciated plateau of the Renfrewshire heights incised by the Calder. The highest point being 489m O.D. at Burnt hill but generally the catchment is 250m O.D. (See figure 4.3). It is also an upland catchment.

Deep gorges are found at the upper reaches of the catchment and the valley becomes broader towards the disused dam forming humocky ground in places. The 10/85 slope of the river course is given as 28.78m/km.

Discussion

The general slope (10/85) can sometimes give an indication of the rate of water flow in areas of similar geological conditions. The slope quoted for East Dart, Blackbrook and Calder catchments are 22.6m/km, 10.09m/km and 28.78m/km respectively. This indicates that the rate of water outflow is supposed to be highest in the Calder catchment compared to the other two catchments while Blackbrook catchment is the lowest of the three. This however, is not always the case since the three catchments differ considerably in many respects such as the geology, superficials and weathered rock material as discussed in chapter 3. This shows clearly one of the restrictions of the applicability of some of the morphometric features in the description of a complex phenomenon operating in drainage basins of different geologic environment.

4.2 Drainage

Drainage is discussed from the 1:25000 ordnance survey map of Great Britain.

4.2.1 East Dart Catchment

The East Dart catchment drains an area of $21.5km^2$. It has the highest average altitude of the three catchments that are being investigated. East Dart is the main stream within the catchment. It runs NE-SE and has many tributaries. The stream order is seven. Sand, gravel, pebbles and boulders are found along the river bed downstream of Broadmarsh.

The South West Water Authority in conjunction with the author, carried out two surveys of the flow contributed to the major streamflow by its tributaries in a dry period (representative of the baseflow). The survey was carried out to determine which tributary contribute most to the flow, and also the possible reasons for this. This is dealt with in chapter 5. The first part was a 3-day period between 11th and 13th of July, 1987 after a 13 days dry period. The result of this study is presented in figure 4.4. The flow values were steady throughout the period indicating the most sustained source of the streamflow (baseflow).

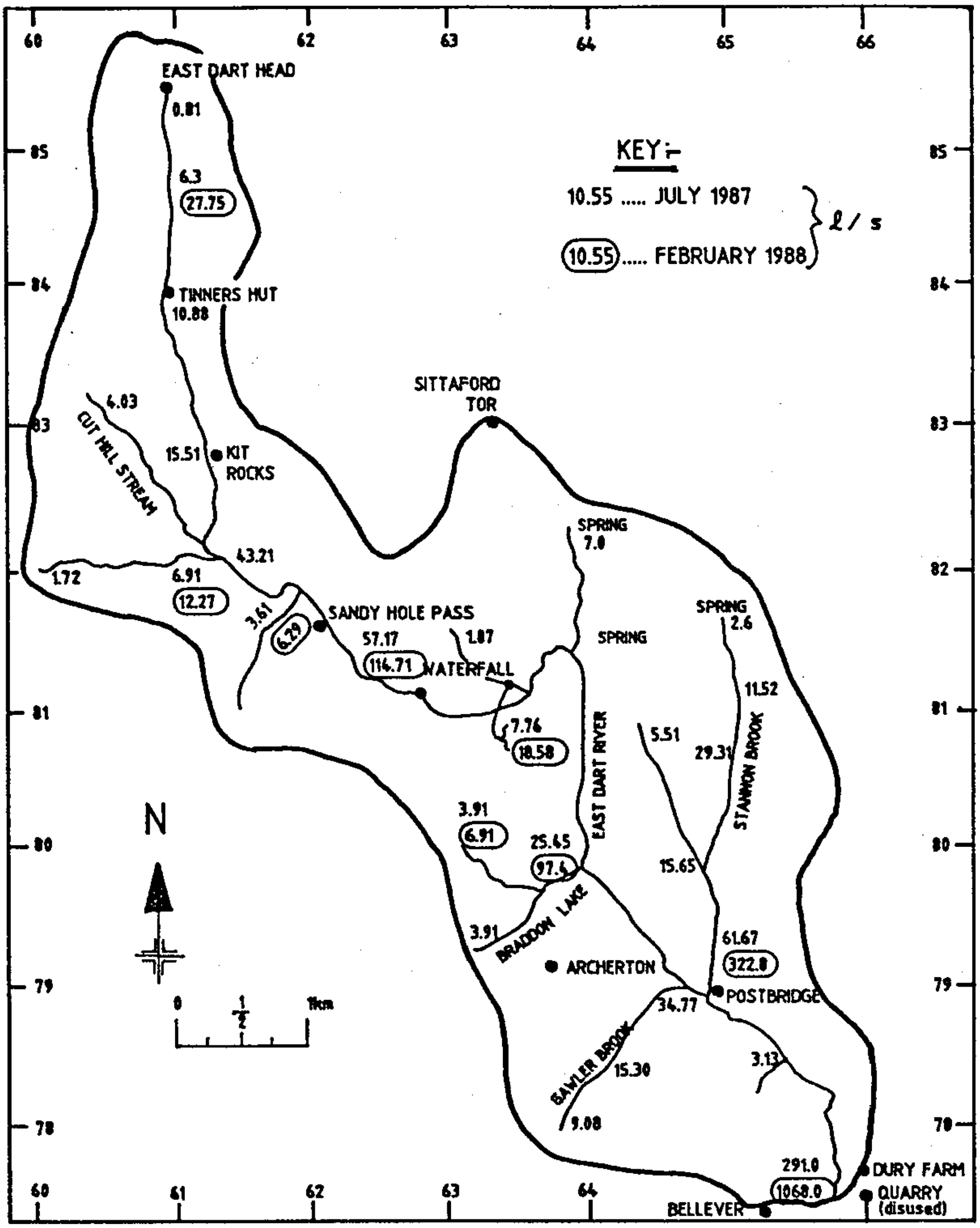


Figure 4.4 East Dart catchment: Drainage indicating spot flow values for July, 1987 and February, 1988.

On the 20^{th} of February, 1988, a similar survey was carried out after a 7-day dry period in a very wet winter. The result is presented in figure 4.4 along with the July '87 values. A comparison of the two values indicate that the area drained by the peat bog holds a small proportion of the riverflow. The most important tributary in relation to flow is Stannon Brook.

During the field survey (flow measurement, geophysical and geological field mapping), it was found that the drainage falls into two categories. In the upper part from the head of East Dart river to Sandyhole (near the Waterfalls), the river drains upland peat with greyish dirty water and no springs or seepages were seen. The first half mile of the East Dart is completely lost in peat bog, rough grass and reed. The second part of the river course has clear water, many springs and seepages both from the side of the stream and its tributaries. Probably it is these that dilute the dirty water and make it clearer.

4.2.2 Blackbrook Catchment

The Blackbrook catchment drains an area of 8.36km^2. The stream runs SE-NW and flows into the Blackbrook Reservoir which has a separate catchment area. The stream order is four. Most of the tributaries are confined to the western side of the main stream and so are the springs.

The brook drains an almost impervious layer of Triassic red marls of the Keupar series and isolated patches of boulder clay. Alluvium borders the stream for most of its course. Blackbrook water is clear for most of the year except during heavy storms.

4.2.3 Calder Catchment

The Calder catchment drains an area of 12.04 km^2. The stream runs west to east for most of its course and then turns southwards at Lyle Hill near the abandoned dam. The stream order is 19 and the catchment can be said to be highly dissected by many tributaries compared to the other two catchments.

The alluvium within the river bed consists of sand, gravel, pebbles, boulders and silty clay sediments. No seepages or springs were located along the course of the river. The water is brownish and is thought to be due to peat and/or iron ore.

Discussion

The dissection of the catchment is represented by the stream order using Strahler's method (Gregory and Walling, 1973) of classifying streams. The values obtained are 7, 4 and 19 for East Dart, Blackbrook and Calder catchments respectively. Calder catchment is highly dissected by many tributaries although it is not the largest catchment. The high degree of dissection can be directly related to the slope, geology and historical events. The high slope results in fast flowing water courses and this was seen to hack the peat cover in places resulting in the formation numerous water courses. The glacial till forms small rolling hills whose valley give rise to small and large water courses.

The morphometric features of the basins have been considered but it has been decided that they are not of any importance to this investigation for reasons given below. The most important morphometric feature in a geomorphological study is drainage density. The drainage density can be a valuable measure of an index of drainage processes and can also be used to subsequently estimate permeability. However, the estimation of permeability in this manner has major drawbacks in its application. Most important of all is the fact that drainage density is a dynamic factor rather than a static phenomenon. Therefore, time has to be taken into account, which drainage density does not. Other problems include differences in scale and dates of maps. Differences in scale for the same catchment results in differences in the value of drainage density; and so also is the date of publication and season. With the season, however, is whether the drainage network of a catchment as define by contour crenulations or blue lines reflect current processes, also winter drainage may differ from summer. The difficulties outlined above have made it unrealistic to try and estimate permeability by using the relationship between lithology and drainage density as portrayed on published maps. Therefore, a more reliable method which takes into consideration the time factor, baseflow, has been applied for this purpose in chapter 8.

4.3 Soils and Superficials

4.3.1 Soils

The catchments being studied are relatively small and therefore recharge to groundwater is local. The soils have a considerable depth and their study will aid the understanding of infiltration capabilities and subsequent recharge to the groundwater regime in each catchment.

Soil survey maps of England and Wales; and Scotland (1: 250,000) and their accompanying hand books were used to summarise the soil types and their characteristics for each of the catchments being investigated (see Table 4.1). Wet sieve analysis was also carried out for some soils and weathered granitic material for comparison with the deductions made from Table 4.1. Welsh catchments have been included for comparisons with Table 5.6. The average depth of soil sampling is about 1.5 metres.

The parent material referred to in Scotland is the source of the weatherable material which could be the superficial deposits or the bedrock.

Peat forms part of the soil profile. It is found to form from decaying plant residues where there are insufficient soil organisms to decompose and incorporate them into the soil. They normally form in upland areas of altitude in excess of 350m above sea level with very high rainfall; in excess of 2000mm.

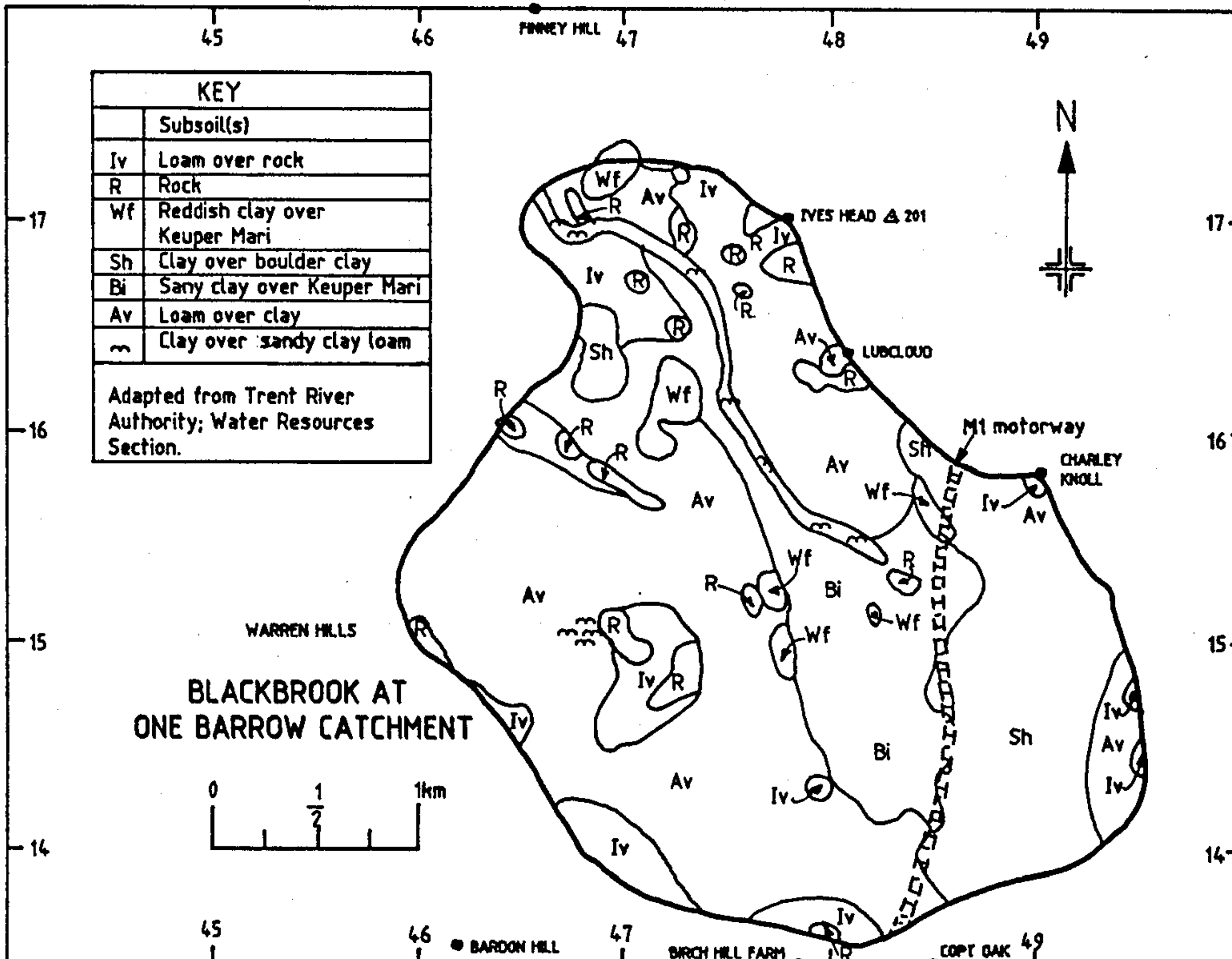
A detailed study of the soils of the Blackbrook catchment has been carried out by the Water Resources section of the Severn Trent River Authority (see figure 4.5). The soils are divided into slowly and moderately permeable.

A summary of the soils of the catchments studied including those used for baseflow recession analysis is given in Table 4.1. This is deemed necessary in order to compare their hydraulic conductivity to the recession constants derived in chapter 8.

A study of the hydraulic conductivity (permeability: average of lateral and vertical) of the soil profile is presented in Thomasson (1975, p. 20); and the values relevant to this study have been adopted. This is presented below alongside the soils. The values are given in ranges because the hydraulic conductivity frequently differs between vertical and horizontal directions (anisotropy). It is also found to change markedly with depth in most soils.

For simplicity, the summary of each locality and the K (m/day) is given in Table 4.1. From the table, it is possible to discuss in depth the infiltration capabilities of the various localities. Cornwall and Dartmoor Catchments are well drained and also very permeable except for some localised ironpans and peat. The Welsh catchments are reserved for subsequent comparison in chapter 8 as earlier mentioned. In the Blackbrook catchment, the soil is slowly to moderately permeable. Peat is absent and some well drained soils are found on brows and hill slopes. Soil texture is fine to loam over clay. The parent material in the Scottish catchments are drifts or morainic sediments of the glacial age. Some alluvium and organic soils are found in some river beds and are generally limited in areal extent. The soils

Figure 4.5 Soil groups of the Blackbrook catchment.



are peaty. Peat, blanket peat and some rankers are found. Infiltration is generally from slowly to very slowly (Thomasson, 1975) and in some cases the soil is only moist.

Table 4.1 Soils and their Hydraulic Conductivities

Locality	Summary of Soils (and Superficials)	Remark
Cornwall & Dartmoor	Well drained coarse to very coarse sandy soils	Permeable. Except for localised peat and ironpan which impedes water infiltration. $1 \leq K < 10$
Wales	Well drained fine and silty soils	Permeable to slowly permeable. Ironpan and peat found on higher grounds in places. Peat is thick in places $0.01 < K \leq 10$
Blackbrook	Fine loam over clay. Well drained on brows and steep slopes locally. Peat is absent.	Slowly to moderately permeable. $0.01 < K \leq 0.3$
Scotland	The parent materials are drifts in most cases. Alluvium and Organic soils form parent materials in some places. Soils are peaty. Peat and blanket peat are common. Brown forest soils and rankers are also found in places. Some humus-iron podzols and subalpine soils. Alluvial soils and loam sands overlying gravels in case of catchments with alluvium	Slowly permeable and very slowly permeable to moist. Steep slopes are found in places. $0 < K \leq 0.1$

The characteristics of some of the materials found within some of the catchments are worth commenting on. Peats absorb and hold large quantities of water and hence may be important in terms of their effects on infiltration rates, runoff and groundwater recharge. Alexander (1983) gave the hydraulic conductivity of different kinds of peats and this is represented in Table 4.2.

Those applicable to this study are the last two and are both found in East Dart and Calder catchments. The impermeable layer in some cases may be due to the formation of ironpan and not the parent material as in Cornwall and Dartmoor.

Table 4.2 Hydraulic conductivities of different types of peats.

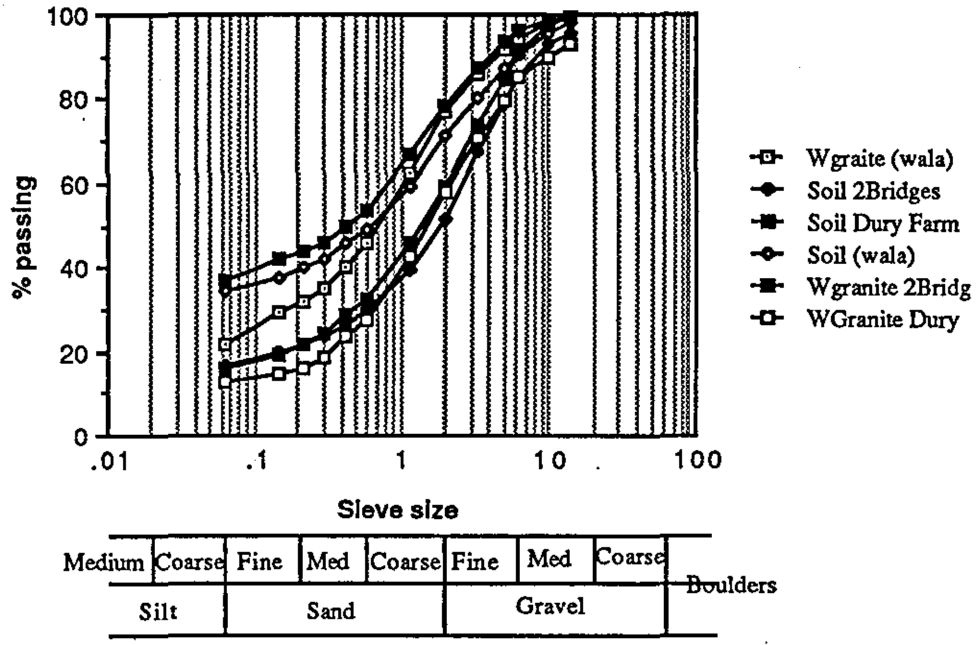
Peat Material	K(m/day)
Undecomposed peat	32.92
Woody peats and deep undecomposed peats	0.48
Dense decomposed and herbaceous peats	0.0065
Blanket peat	0.018 - 0.13

Wet sieving (BS 1377:1975) was carried out on soils, weathered granitic and morainic soil material from East Dart and Calder catchments. The results are presented in figures 4.6 and 4.7. None was carried out for the Blackbrook catchment because the sandy gravel (discussed in chapter 3) are not exposed on the surface. Only boulder clay and marl are seen in most places. Hydrogeologically, boulder clay and marl have low permeabilities and do not usually form aquifers, more so any sieve analysis will indicate high proportions of clay fraction.

It is yet for a relationship to be found between particle size distribution and hydraulic conductivity. However, for general descriptions, the sediment size, slope and shape of curve are taken into consideration. Sediment size is indicated on the horizontal scale (sieve size in millimetres) from silt to gravel fractions. Samples less than 0.063m are not represented and this is in accordance with the code of practice used (BS 1377:1975). The slope is defined by a uniformity coefficient between two points; 90% and 40% passing size of the sample. The average value for East Dart samples is 12 and those of Calder catchment is over 30. According to (Driscoll, 1986), the uniformity coefficients derived are not meaningful since their value has to be less than 5. However, in general terms, East Dart has a lower value. This indicates a more uniform grading of the soils and weathered rock material in East Dart catchment than in the Calder catchment.

East Dart type curves usually represent samples having higher porosity (s-shaped) than ones found in the Calder catchment which are distorted for having a high proportion of gravel at the tail end. This phenomenon is termed as a 'tail configuration'.

Fig. 4.6 Soils & weathred Granite from East Dart Catchment



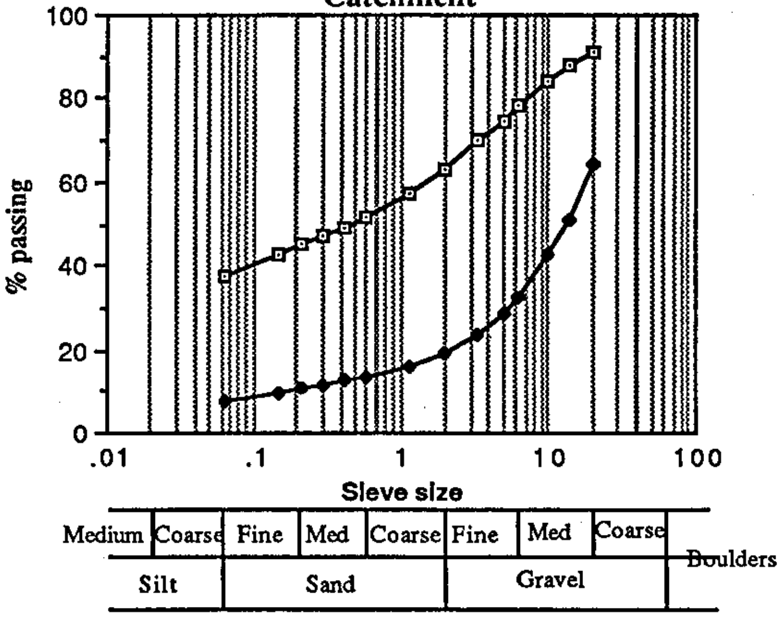
Soils at the South East of the East Dart catchment have silt and clay fraction of 40% or less while that from Two Bridges (West) has less than 20%. The high percentage of silt and clay fraction impedes water infiltration and therefore has a reducing effect on permeability of the soils. The gravels generally have silt and clay fraction of less than 20%. This indicates that they are more permeable than the soils.

The two curves in figure 4.7 for the Calder catchment look quite different. The upper curve has about 40% silt and clay fraction while the lower has less than 20%. This indicate the variability of the constituent of the morainic material and hence the variation in permeability from place to place. Glacial till of boulder clay in addition to peat covers most of the catchment.

From a study of the hydraulic conductivities and the graphs of particle size distribution, East Dart catchment is the most permeable of the three catchments being investigated.

The discussion in this section is necessary because regardless of the permeability of the underlying layers, if the overlying layers are impermeable no recharge takes place, particularly as recharge is local in these catchments. However, at least the three catchments are permeable to some extent and therefore recharge to groundwater does take place.

Fig. 4.7 Morainic Clay from Calder Catchment



The discussion in this section has been possible because of the high rainfall pattern throughout the year in Britain. This conclusion would not have been possible in the desert or arid regions where the soil texture may indicate permeable soils but lack of rainfall makes the term "permeability" meaningless.

4.3.2 Superficials

In most cases, the superficials form the weatherable parent materials of the soils. In hard rock catchments, the regolith or weathered material and the superficials (or alluvium deposits and aeolian sands) form part of the major lithological units in addition to structures. The understanding of their water bearing and transmitting capabilities, depth and lateral extent is of importance in a hydrogeological investigation of this nature. Their occurrence is briefly discussed below.

4.3.2.1 East Dart Catchment

The head of East Dart to the Waterfalls drains hill and basin peat for about a third of the river course. Narrow alluvium borders the river for most of its course except in areas where the river incises steep valleys.

Valley gravel and head occurs at the Gawler brook tributary south of Archerton. Extensive spreads of Hill and basin peat and alluvium borders the Stannon Brook. Other tributaries are bordered by alluvium.

The peat and valley gravels overly the growan or weathered granite.

4.3.2.2 Blackbrook Catchment

The catchment is covered by Triassic Keupar marls for most part. The main superficials are clay, boulder clay, sand and sandy gravels. These are products of glacial erosion of the Pleistocene.

The superficials occur in isolated patches and in some cases they are found either to overly the Keupar marl or the bed rock. The marl and the superficials form the weatherable parent material of the soils. Other superficials of local interest are head and alluvium. The head which occurs in isolated patches, consists of Charnian and diorite derived scree with some variable loam. Alluvium borders the stream from Rock farm to the reservoir.

4.3.2.3 Calder Catchment

Generally, glacial till and peat with some morainic deposits over-lay the basaltic bed rock. From the one inch map of the Geological Survey of Scotland, the main stream is bordered by morainic glacial deposits. They consist of boulder clay, morainic drift and moundy sand and gravel. The boulder clay borders the main stream and its tributaries in the upper reaches with some little river deposits to the junction with South Rotten Burn. A little boulder clay is found below the disused dam. Moundy sand and gravel is found in localised patches in the catchment forming large patches around the dam (disused) and also found in the upper reaches of the major tributary that flows into the dam around Hyndal Hill. Quite substantial mounds of drift are found upstream of the dam and the area around Queenside Muir. The drift is derived mainly from the basaltic bed rock.

Peat is dominant over the catchment forming about 60% of the cover. In the proposed new dam feasibility report (op. cit.) the bed rock is found within a few metres of the ground surface (1m - 6m).

4.4 Land Use and Vegétation

The vegetation of the three catchments was mapped but it was considered not necessary to include a detailed map in the thesis since evapotranspiration is not critical in any of the catchments investigated. The vegetation is artificially controlled either by farmers or by law on moorlands where crop cultivation are prohibited.

4.4.1 East Dart Catchment

The East Dart catchment is situated on the Dartmoor Forest and it is a part of the Dartmoor National Park. Farming practices are open grazing and forestry. Because it is a Park, crops are prohibited from being grown except hay. The forested area is on the lower western side between Postbridge and Bellever. This is planted by the Forestry Commission and forms 8% of the catchment vegetation. The open grazing involves cattle and sheep farming. The sheep are found to wander all over the catchment whereas the cattle are kept near the settlements. Ponies including wild varieties are found on the catchment between Postbridge and Bellever.

The catchment is moorland and the vegetation consists of vast covers of rough grass. Other forms of vegetation are whortleberry, heather, goarse, bracken, cotton grass and reed marshes (see Plate 3.1). The rough grass is short and very thick. Rough grass covers about 75% of the catchment north of Postbridge and forms 60% of the catchment vegetation cover. This is thought to help retain rainwater and thereby aid in the slow processes of its percolation. Goarse, bracken, heather, whortleberry are restricted to the dryer parts of the catchment, especially on hills and hill slopes. Reed is common in bogy (water logged) areas such as at Broad Marsh although they can be found locally on high grounds of similar conditions. Cotton grass is also found in bogy areas although it can also be found on high grounds.

4.4.2 Blackbrook Catchment

In the Blackbrook catchment of the Charnwood Forest, most of the area is suitable for farming. About four fifths of the land is used for mixed farming while the remainder is unsuitable either for cultivation or grazing purposes. Root and vegetables account for only 1% of the catchment area. There is little or no evidence of crop rotation in the catchment. Animals grazed include cattle and sheep which are fenced.

Grassland covers about a third of the farmed area and cereal crops predominate over the arable land. Of the area unsuitable for farming, most of it is covered by woodland while the remainder consists of marsh and moorland covered with long coarse grass, bracken and scrub.

4.4.3 Calder Catchment

The catchment is a moorland and it forms part of the Muirshiel country park. The only commercial activity in the catchment is sheep farming.

Plate 4.1 Vegetation: Heather and Rough grass

A very small proportion of the catchment is wooded by the Forestry commission. Rough grass and heather predominates (see Plate 4.1). The rough grass and heather are also very thick as found in East Dart catchment. Heather constitutes about 60% of the vegetation cover in the catchment. The rough grass forms about 30% while the ramianing vegetation is made up of planted forest, cotton grass, bracken and reed (found in water logged areas).

4.5 Summary

The catchments being investigated are 'upland catchments'. The one most dissected by drainage network is the Calder catchment and this is likened to the slope, geology and historical events.

Average permeability values have been allocated to the different areas within which the catchments are found or for the catchment concerned. From the average permeability values and the results from the particle size distribution from the sieve analysis of soils, weathered granite and morainic sediments, East Dart catchment is the most permeable of the three catchments. The Blackbrook and Calder catchments have low permeability values and that of Calder is confirmed by the result of the particle size distribution of the morainic samples. Permeability study is important because the soils have a great influence on infiltration and subsequent recharge to the groundwater regime of the catchments concerned.

The superficials can be aquifers especially where they are wide spread and of considerable depth. This situation can be found in the valleys of Gawler and Stannon Brooks, tributaries of the East Dart catchment. Vegetation is considered not crucial for the investigation as evapotranspiration does not cause serious water deficits in the catchment as demonstrated in section 2.2. (chapter 2) and for reasons mentioned in section 8.3 (chapter 8).

The permeabilities of the subsoils and the superficials of importance to this investigation are discussed in the subsequent three chapters.

Chapter 5
GEOPHYSICS

5.1 Introduction

The geology including weathered zones and structures, has been discussed in chapter 3. The delineation of the aquifers within the three catchments for groundwater development is obscured since relative positions, thickness and extent are not expressed on the surface. Therefore, geophysical techniques have been used to try and determine their actual existence and extent where possible.

Indirect methods of geophysical survey were applied. The geophysical methods employed were resistivity and electromagnetic. These two methods were found to be adequate in delineating the different lithologies within the catchments and also were convenient in terms of labour requirements.

The only geophysical work that has previously been undertaken on two of the catchments, East Dart and Blackbrook, are gravity and seismic surveys. The gravity and seismic surveys (Exley & Stone, 1982 and Heath and Durrance, 1985) were carried out to map the granitic masses of South West England. Maguire (1987) and Whitcombe and Maguire (1981) carried out two lines of seismic survey across Charnwood Forest to investigate the contact of the Precambrian rocks with the surrounding sediments. Their work is at too large a scale to give any detailed information on Blackbrook catchment. No published geophysical investigations have been undertaken in the Calder catchment that are known to the author.

The geophysical techniques used are discussed in section 5.4.

5.2 Electrical Resistivity Sounding

Electrical resistivity techniques are some of the most successful geophysical methods by which aquifers and different lithologies or strata can be delineated. This method can be successfully employed where a sequence of plane layered homogeneous media is to be resolved into depths and resistivities of the component layers. Due to inhomogeneity this simple situation is rarely found in real life. Apart from information on lithology, the technique provides data on aquifer geometry, properties and water quality.

In the electrical resistivity method, electric current is introduced into the ground and the resulting potential difference measured at the surface. This process depends for its operation on the fact that any subsurface variation in conductivity alters the form of the current flow within the earth and this affects the distribution of electric potential. The degree to which it is affected depends on the size, shape, location and electrical resistivity of the subsurface layers or bodies. Resistivity (r) is measured in ohm-m and the reciprocal is termed conductivity (d). Acworth (1981) gave the relationship between conductivity and a material as

$$d = \underset{\sim}{j}/\underset{\sim}{E} \quad \ldots\ldots\ldots\ldots\ldots (5.1)$$

where

$\underset{\sim}{j}$ = current density ($amp.m^2$)
$\underset{\sim}{E}$ = electric field (Vm^{-1})

Electrical conductivity may be affected directly by degree of saturation of the material, nature of the pore fluids, nature and size of the grains making up the matrix, and degree of consolidation. A high value of conductivity (low resistivity) indicates saturation or a high total dissolved solids (TDS).

With the exception of clays and certain metallic ores the passage of electricity through rocks takes place by way of the groundwater contained in the pores and fissures, the rock matrix being non-conducting. Thus, porosity is the major control of the resistivity of rock and resistivity generally increases as porosity decreases. However, even crystalline rocks with negligible intergranular porosity are conductive along cracks and fissures. In purely intergranular rocks like sandstone the current is carried only by electrolyte and this makes them more tractable. In readily tractable formations, a simple relationship exist between the resistivity of the rocks (ρ) and that of the water (ρ_w) contained therein, thus:

$$F = \rho / \rho_w$$

and this tends to be constant for a particular formation. It is known as the formation factor. The relationship between the formation factor (F) and the porosity (Φ) is given by Griffiths and King (1981) as

$$F = a/\Phi^m \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.2)$$

where a and m are constants, their values being governed by the nature of the formation. Because conduction takes place through clays by way of weakly bonded surface ions, the above equation does not apply to porous rocks containing any appreciable amount of clay minerals.

The principle of measuring electrical resistivity is by passing a known current between two electrodes (A & B) connected to a power source, which may be AC or DC, and measuring the resulting potential difference between two other electrodes (M & N). A number of electrode configuration are in common use. These are illustrated in Acworth (1981), Bako (1985), and Saidu (1987).

The commonly used electrode configurations are the Schlumberger and Wenner arrays. The methods employed for this study was the four electrode array of Schlumberger and the 5-electrode of the modified Wenner array (Barker, 1981). The Wenner and Schlumberger arrays give depths of investigation of 0.11b and 0.125b respectively (Beck, 1981), where b is the current electrode separation. Therefore, the Schlumberger array shows only a little advantage over the Wenner array as regards depth of investigation. Another claimed advantage of the Schlumberger array is that sensitivity to lateral effects is reduced. In practice however, the choice of array is usually a matter of convenience or custom rather than technical merit.

It is often thought that with increased current electrode separation, current penetration increases leading to a greater depth of investigation. This is however not always the case because the existence of a thin horizontal high resistivity layer in an otherwise homogeneous medium, under a single current source and two closely spaced potential electrodes; during resistivity sounding will cause only the potential of the layer above the high resistivity to be measured.

Plotting the results is described in Koefoed (1979), Griffiths and King (1981) and Bako (1985) and the interpretation techniques are described in detail in Koefoed (op. cit.) and Saidu (op. cit.).

5.3 Electromagnetic Profiling

In the EM profiling, the EM34-3 Geonics conductivity meter was used to obtain data over a range of depths. The purpose of this is to determine the frequency of occurrence of fractures (or faults) and also conductive zones which are normally the water bearing zones in hard rock areas. The EM method is alternatively known as induction methods.

This method has been used extensively on basement areas in Nigeria (Acworth, 1981 and de Rooy et al, 1986). de Rooy et al reported a well site location success rate of 91.2% which indicates how useful it can be in a hydrogeologically difficult terrain. The usefulness and rapidity of the EM method in delineating productive zones in the crystalline rocks and alluvium in Northern Nigeria has also been reported in a recent study by Hazell et al (1988).

The equipment consists of a receiver, transmitter and their coils. It is two-man operated. The coils are read in either vertical or horizontal positions or both. The vertical component of the penetrates the ground slightly deeper than the horizontal. The coil separation is varied as required but it is normally 10m, 20, and 60m (McNeill, 1980 and Griffiths and King, 1981)) and the result enables the thickness and conductivity variations in several layers to be monitored.

The readings are in millimhos/m and this can be converted to ohm/m. The interpretation as in other geophysical methods is more of an art than a science.

In principle, a uniform ground gives uniform conductivity but in real life the ground is not uniform. Therefore, anomalies are encountered. The method consists of probing the subsurface by means of an artificially generated magnetic field in search of conductive zones which may represent fracture in hard rock areas. The fractures are possible water conduits. The determination of fractures will also enable a speculation on the frequency of their occurrence in the studied catchments.

The instrument is designed in such a way that when it approaches a structure such as faults, dykes or fractures and passes over them, the current flow in them becomes essentially the same as if they were in free space, thus giving rise to a negative anomaly. Such an anomaly may be sufficiently large to make the meter reading go off-scale below zero. The EM34-3 used incorporates a meter polarity-reversal switch which enables negative measurements to be made.

5.4 Field Procedure

Two main field procedures were employed; vertical electrical sounding (VES) and electromagnetic (EM) methods. Applying VES has revealed the delineation of the different lithological horizons and also the depth to bed rock which has led to the estimation of the various thicknesses of the overburden, aquifers and also the water quality.

The two VES methods employed are the Schlumberger and the Offset Wenner sounding systems. The Schlumberger array was used in the Blackbrook catchment and this was purely for convenience and proximity to Loughborough. The Offset Wenner system, which is relatively the most recent (Barker, 1981) of other systems, was employed in the other two catchments because of some advantages over the Schlumberger array as discussed below. Some of the advantages of the Offset Wenner system includes time saved in moving electrodes, which was considered important, as the equipment uses a multicore cable with a series of connected electrodes and a central control box. The equipment is portable and can be one-man operated and allows for more soundings to be made. Essentially, the Offset Wenner system makes use of 5 electrodes with the central electrode kept in a fixed position at any particular time when a reading is taken. The procedure is fully explained in Barker (1981). Some added advantages are the reduction of lateral effects, the calculation of errors due to lateral effects or equipment malfunction and therefore allows a close check on the accuracy of the result. According to Barker (op. cit.), observational errors between -5% and 5% (due to observation and instrument) are acceptable and root mean square (RMS) values of offset and lateral in excess of 25% and 50% respectively indicates a sounding curve that is strongly influenced by lateral resistivity effects.

For Blackbrook catchment, 43 VES were carried out using the Schlumberger array. East Dart and Calder had 15 and 9 VES carried out respectively using the Offset Wenner array.

5.5 Data Processing

The resistivity program of the Natural Environmental Research Council (NERC) computing services was used for the data processing (Pedley, 1985) with the permission of the Regional Geophysical Research Group of the British Geological Survey (BGS), U.K. The program runs on I.B.M. computers or fully compatibles. From the raw field data, the program calculates the apparent resistivities which are used to construct and display the graph of apparent resistivity against current electrode spacings.

The program can be used for the interpretation of sounding data for Offset Wenner, Schlumberger and Wenner arrays. For this study, the Schlumberger and the Offset Wenner resistivity interpretation program was used. The master curve generating program (RESIST) is based on the methods of Ghosh, Koefoed and Johansen (Smith, I. 1986. pers. comm.). The iterative method is then used to calculate true resistivities and thicknesses of the underlying media and this model is superimposed on the observed plot. The model is then adjusted until it approximates the observed curve. The process of iterative method of resistivity sounding data interpretation is fully discussed in Koefoed (1979).

Other manual methods used for interpretation are curve matching (including partial curve matching) techniques. This technique is discussed in Koefoed (1979) and Saidu (1987) and also the notes on Geoelectric Methods of Resistivity interpretation (McNeill, 1983). The procedure involves the matching of standard curves with known thicknesses and resistivities to the calculated field apparent resistivities.

5.5.1 Result and Discussion

Resistivity values of dry and saturated rocks from Parasnis (1973) and Griffiths and King (1981) were used for the interpretation. The number of layers varied between three and five for the three catchments.

5.5.1.1 Resistivity

5.5.1.1.1 Blackbrook and Reservoir Catchments

The result of the resistivity survey (VES) is presented in Table 5.1
and the location map in figure 5.1. VES 24 and 25 were carried out on Bawdon Castle farm just outside the catchment.

Note:
t = thickness in metres
ρ = reistivity in ohm-metre (Ωm)
α = infinite layer
for Tables 5.1, 5.2 and 5.3

Table 5.1 Blackbrook and Reservoir Catchments Resistivity Data

Station No.	t_1	ρ_1	t_2	ρ_2	t_3	ρ_3	t_4	ρ_4	t_5	ρ_5
1	1.1	220	9.9	75	α	600				
2	0.6	150	4.0	47	α	500				
3	1.2	90	1.8	140	9.0	110	α	1500		
4	1.3	27	8.7	74	16.0	200	4.0	260	α	300
5	1.2	100	14.8	40	α	200				
6	0.6	100	1.2	74	2.2	120	16	22	α	400
7	0.7	270	6.3	40	27.0	24	α	1000		
8	0.8	650	6.0	68	8.2	63	25	22	α	500
9	0.7	260	12.0	22	α	600				
10	0.4	290	0.8	400	1.8	300	2.1	100	α	9000
11	0.75	190	5.0	16	α	1000				
12	0.9	220	4.85	22	α	1000				
13	1.0	190	14.0	34	α	70				
14	0.6	1499	1.6	2000	4.8	1050	α	1700		
15	0.55	220	4.45	34	15	90	α	270		
16	1.1	108	16.9	54	α	400				
17	0.6	690	0.8	1000	9.0	86	α	650		
18	0.7	250	0.4	26	2.0	82	26	31	α	700
19	0.7	240	0.4	20	1.9	78	10	62	α	3000
20	0.5	160	4.5	70	23	23	α	400		
21	6.5	44	15.7	25	α	750				
22	0.8	185	3.0	50	14.2	34	α	280		
23	0.7	140	2.6	190	22	39	α	1000		
24	0.9	450	4.1	270	20	110	α	1500		
25	0.5	160	2.4	140	32.1	24	α	95		
26	0.7	63	7.0	21	14.5	30	18	14	α	1000
27	0.7	110	0.7	65	1.0	120	12.6	83	α	250
28	0.6	335	0.6	400	28.8	28	α	250		
29	1.15	16	4.0	50	10.85	17	α	300		
30	0.8	26	0.4	10	24.8	22	α	30		
31	1.7	80	20.3	28	33.0	60	α	200		
32	1.2	115	5.2	22	16.6	16.5	α	180		
33	0.7	284	2.5	16	41.8	23	α	80		

Table 5.1 Continued

Station No.	t_1	ρ_1	t_2	ρ_2	t_3	ρ_3	t_4	ρ_4	t_5	ρ_5
34	0.6	150	20.4	23	18.0	14	α	400		
35	0.8	110	10.2	18	49.0	25	α	80		
36	0.5	350	2.0	18	12.0	40	14.0	8	α	600
37	0.5	320	24	23	15.5	28	α	110		
38	0.63	240	2.37	52	22	28	α	90		
39	0.7	550	1.5	43	17.8	21	18	45	α	500
40	0.5	180	2.0	46	19.5	22	15	50	α	400
41	0.78	620	3.5	89	23.72	28	α	500		
42	0.4	150	0.5	24	2.0	30	17.1	18	α	400
43	0.3	70	0.3	22	2.0	28	19.4	21	α	200

The interpretation and subsequent delineation of the different strata in the catchments was carried out by correlation with the geology, superficials and well lithological logs (driller's). The wells used are those at the monastery, Oaks in Charnwood and Green Hill Lodge Farm. These are given as

(a) Mt. St. Bernard Abbey (Monastery NGR 4586/1604)

Clay	6.1m
Weathered Rock	15.24m
Gravels (Pebbles)	1.83m
Clay (Marl)	7.32m

(b) Green Hill Lodge Farm (NGR 4690/1440)

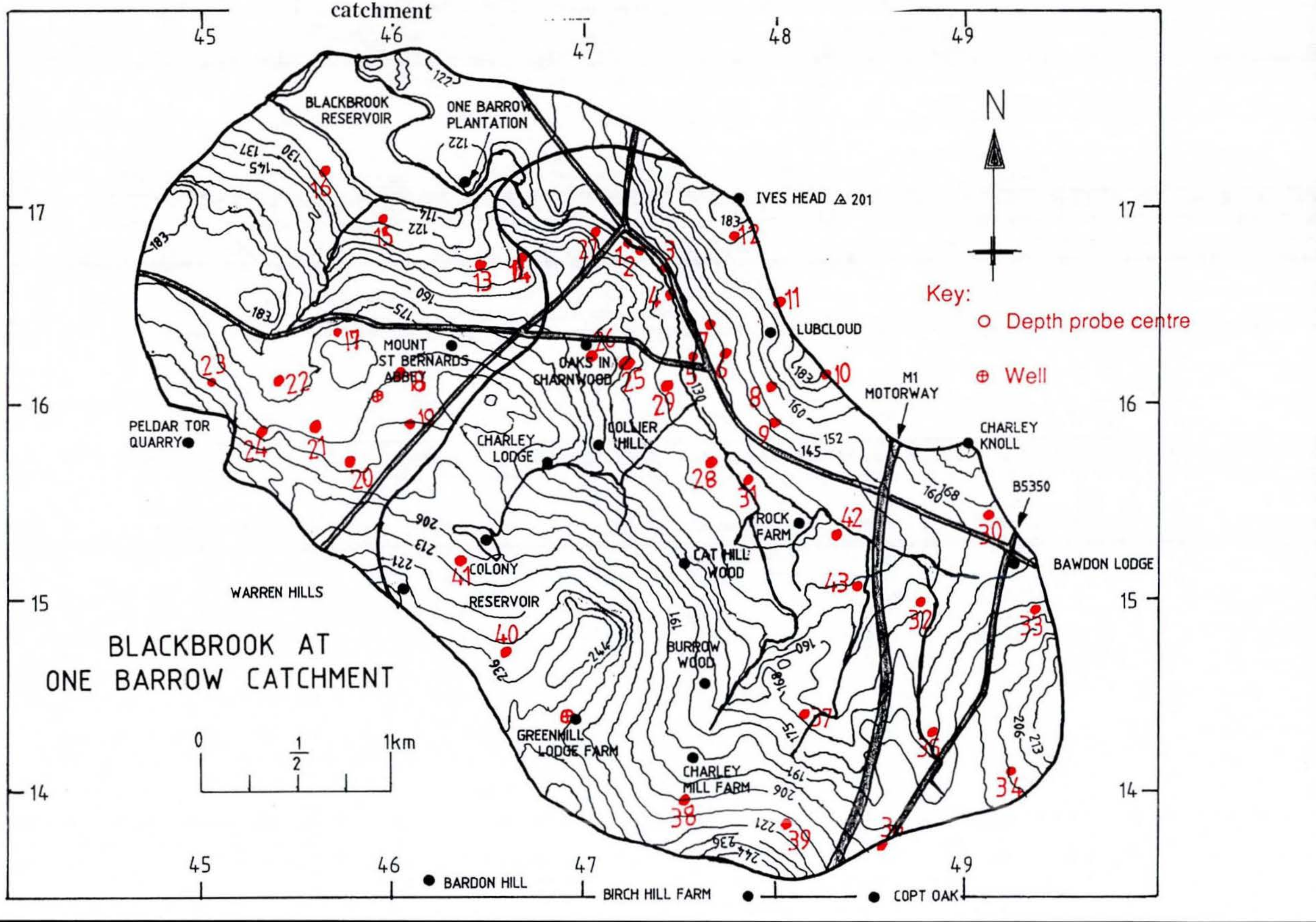
Rock (Scree)	1.2m
Marl	2.13m
Granite (Precambrian)	5.79m

(c) Oaks in Charnwood (NGR 4730/1630)

Hard Red Clay	7.01m
Hard Red Clay	3.66m
Soft Open Clay	1.52m
Hard Red Granite	12.19m

These were compared with stations (VES) 18, 19, 21, 26, 28 and 29. These and type sections seen in quarries have served as a basis for the identification of the different strata. It

Figure 6.1 Resistivity depth probe and well locations in the Blackbrook catchment



has also enabled approximate resistivity ranges to be apportioned to different formations thus

Top Soil	16 - 350 Ωm
Clay and Marl	8 - 69 Ωm
Dirty Sandy Gravel	70 - 100 Ωm
Weathered & Fissured Precambrian	100 - 900 Ωm
Unweathered Precambrian	>1000 Ωm

The thicknesses of clay and marl, dirty sandy gravel are plotted on figures 5.2, 5.3 respectively, while the depth to bed rock where encountered is plotted in figure 5.4. These are discussed in general terms below.

Top Soil

The top soil exhibits extremes in the resistivity values (very low and high). But generally, the top soil is clayey to marley and also water saturated in places giving low resistivity values (16 Ωm). This tallies well with the soils discussed in chapter 4. Some boulders are found locally in the top soil which have values between 450 and 1500 Ωm. On correlation, however, some of the high values are due to scree or head although most are due to the dry nature of the top soil as observed during the survey.

Clay and Marl

The two are treated together because they have the same properties in terms of water transmission even though it has been claimed with some sceptism that marl can be permeable (Saidu, 1987).

The low values indicate a high degree of saturation. The clay and marl are found almost all over the catchments as discussed under soils in chapter 4. The six survey sites (VES 1, 3, 10, 14, 17, and 24) in which they are not found are on hill slopes and in some cases in the alluvium.

From figure 5.2, clay and marl thicknesses vary considerably from place to place between

0.7m to 59.2m; but generally they are thicker from around Peldar Tor Quarry (type section) to behind the Monastery and become thickest in the area south east of Lubcloud Farm and the Colony Reservoir. In this area, the clay and marl are found to overly the dirty sandy gravel.

Dirty Sandy Gravel

The plot is presented in figure 5.3. Due to low resistivity, the sandy gravel is thought to be highly contaminated by saturated clay and, or marl, thus dirty. They occur in isolated patches though some form lenses in places. They are found around the Monastery, Reservoir, Lubcloud Farm and south east of Blackbrook catchment. At the south east of the catchment, the thicknesses were not determined because they form the infinite layer. Around the Monastery, their thickness range between 2m and 20m towards the quarry. The sandy gravel found around the reservoir is thought to be the sandstone identified by Watts (1947) but due to its low resistivity value, it corresponds to the correlation made at the Monastery. At Lubcloud Farm, the thickness is between 2m and 6m.

Water saturated alluvial sandy gravel of considerable thickness (9m - 14m) is found in the river valley between Lubcloud and Little Garendon.

Weathered and Fissured Precambrian

The resistivity values of the weathered Precambrian varies within wide margins and it is thought that the low values (140 - 250Ωm) represent completely weathered material. Since most of the fissures are sandwiched with clay and marl or both, coupled with the clay produced as a result of weathering, the resistivity values are low and in some cases they may be lower than 100Ωm. These values were correlated with (stations 23 and 24) the crushed and fractured top of the Whitwick Complex at the Peldar Tor quarry as discussed in chapter 3. It was not possible to correlate the resistivity result with well data because the only well drilled into the bed rock is outside the catchment. The evidence of fracturing as observed in the quarry by Watts (1947) and also from conductivity survey as mentioned above is discussed below under conductivity result and therefore some resistivity curves (stations 1, 2, 11, & 12) are included in Appendix 1A (figures c - f). The fissured rock form the infinite layer in places.

Unweathered (Solid) Precambrian

The depth to solid bed rock, where encountered, is presented in figure 5.4. The solid rock was encountered in only ten locations, and most are near exposures on hill slopes. The depth

Figure 6.2 Approximate thicknesses of clay and marl in the Blackbrook catchment.

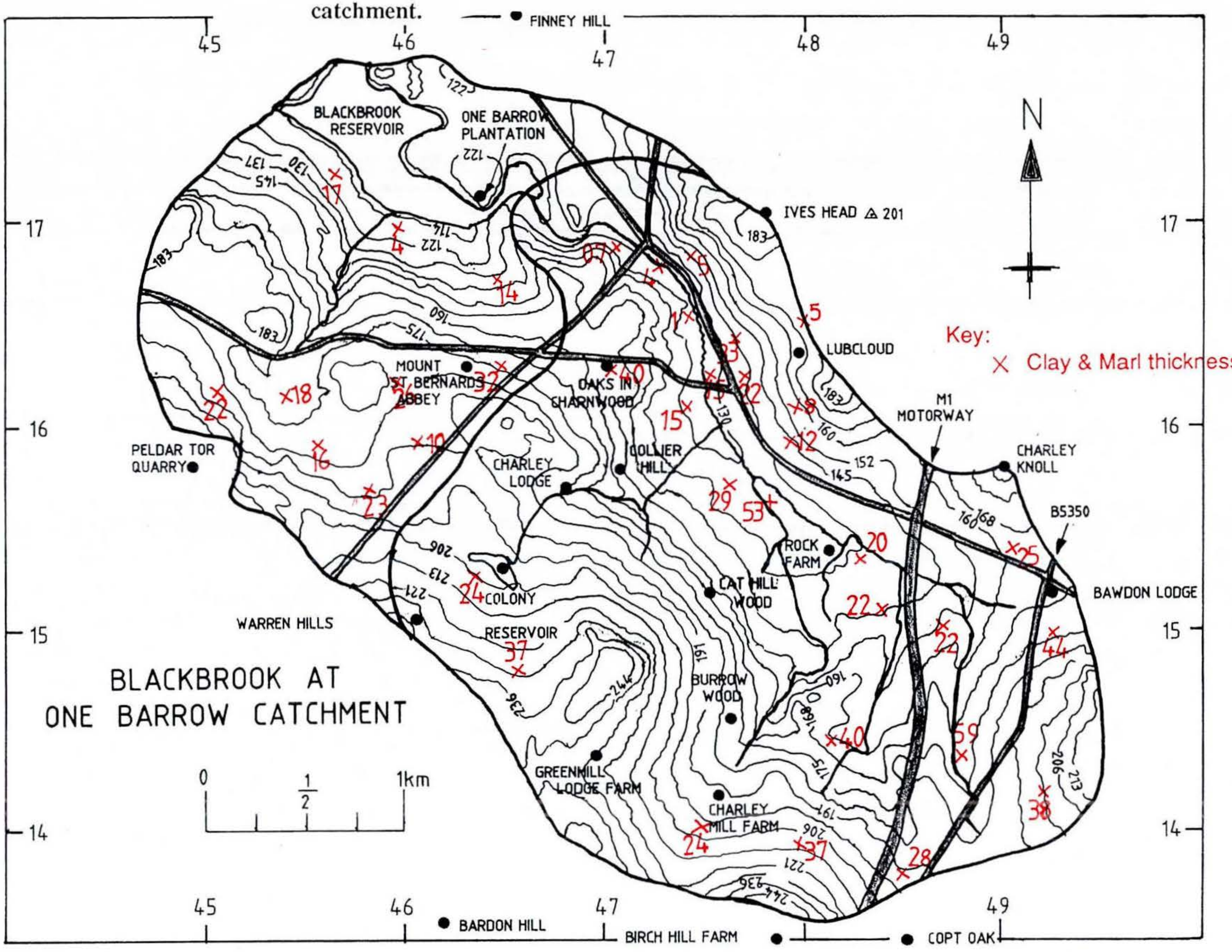


Figure 6.3 Approximate thicknesses of sandy gravel in the Blackbrook catchment.

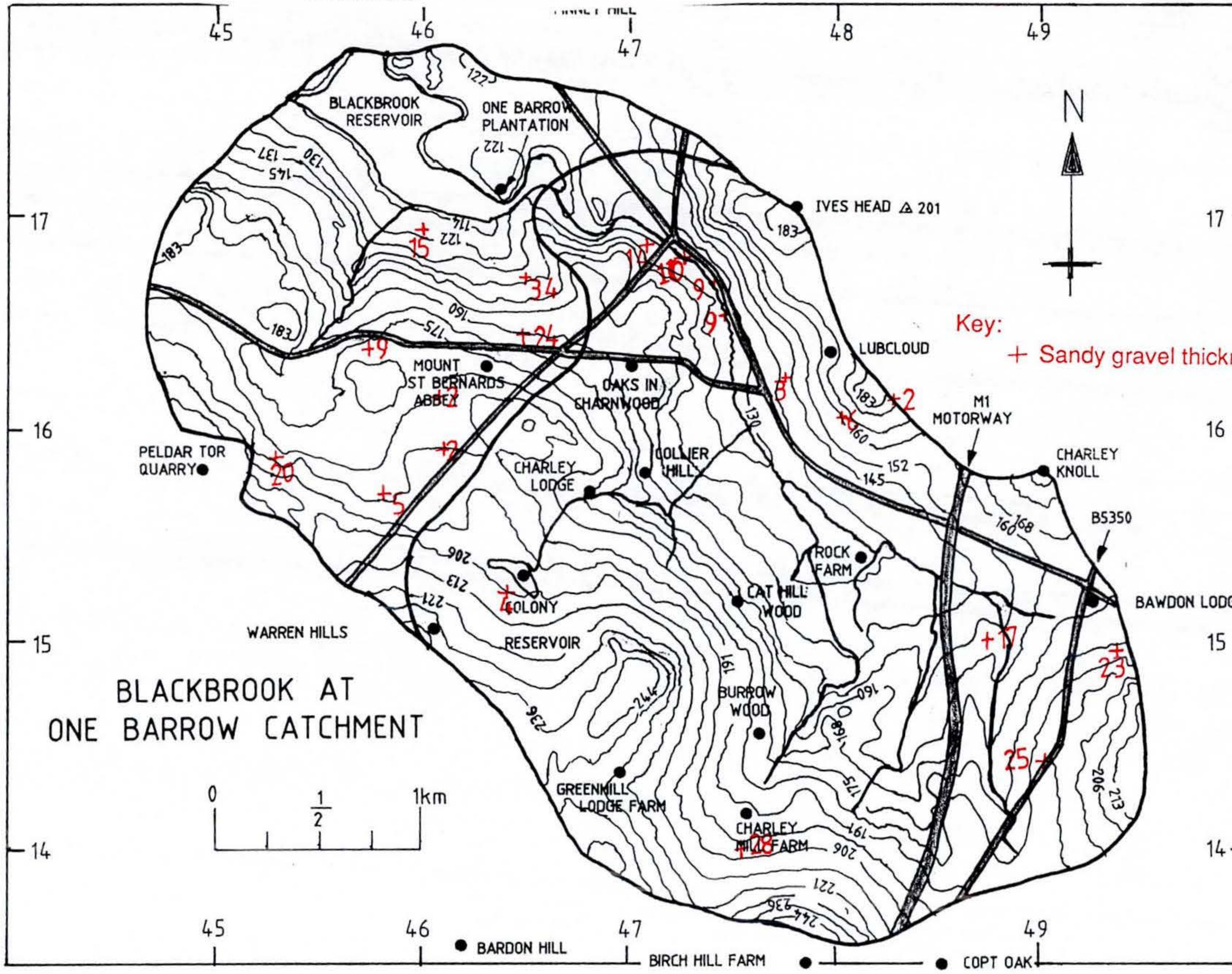
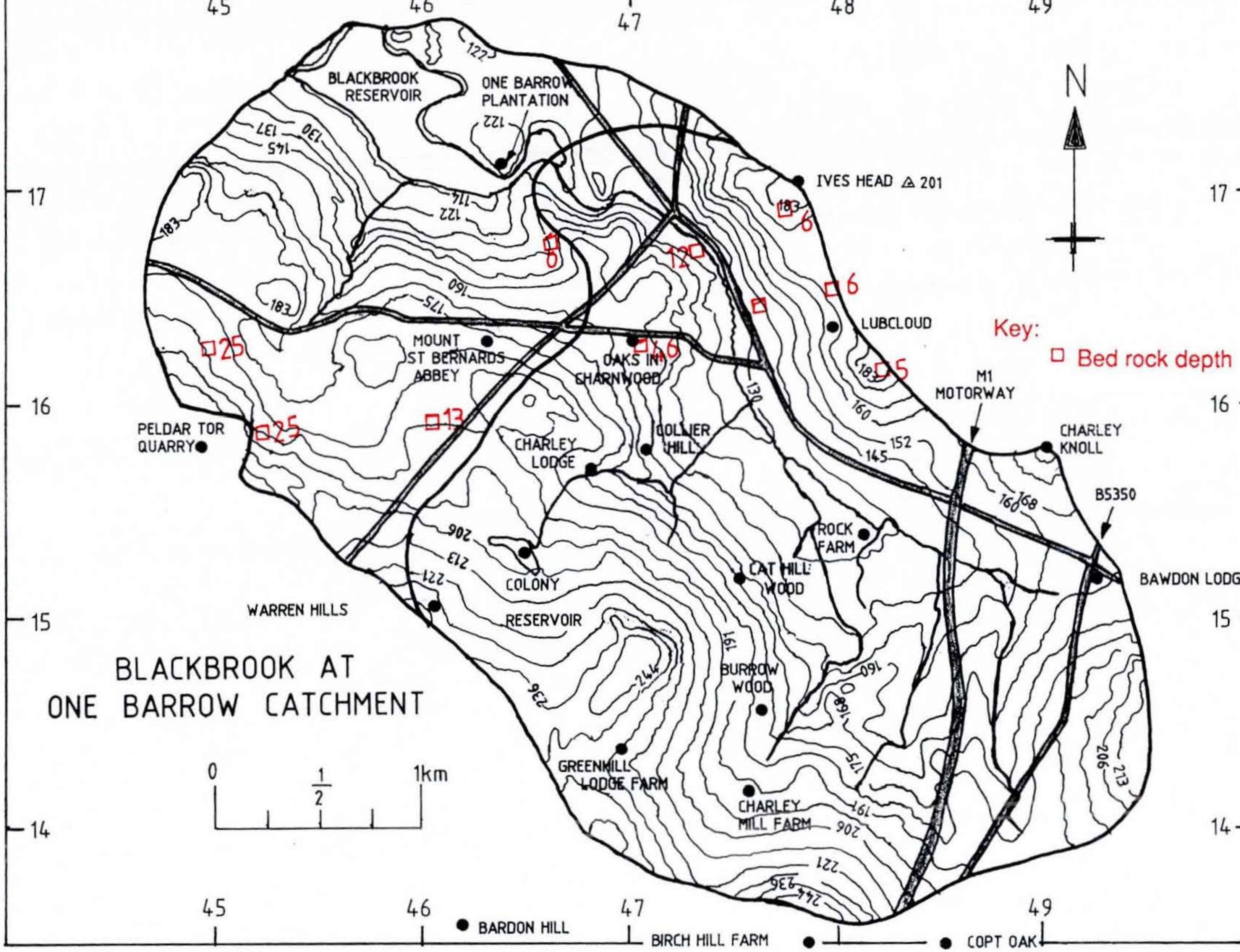


Figure 6.4 Approximate depth to bed rock in the Blackbrook catchment.



to solid rock varies considerably, and ranges between zero and 46m. The areas within which it is found tend to form an alignment from east to west suggesting the possibility that the Precambrian occurs as a ridge within the catchments between Peldar Tor quarry and Lubcloud Farm. Any verification will require some seismic survey for the precise determination of the geometry of the bed rock. However, this is not important in this study.

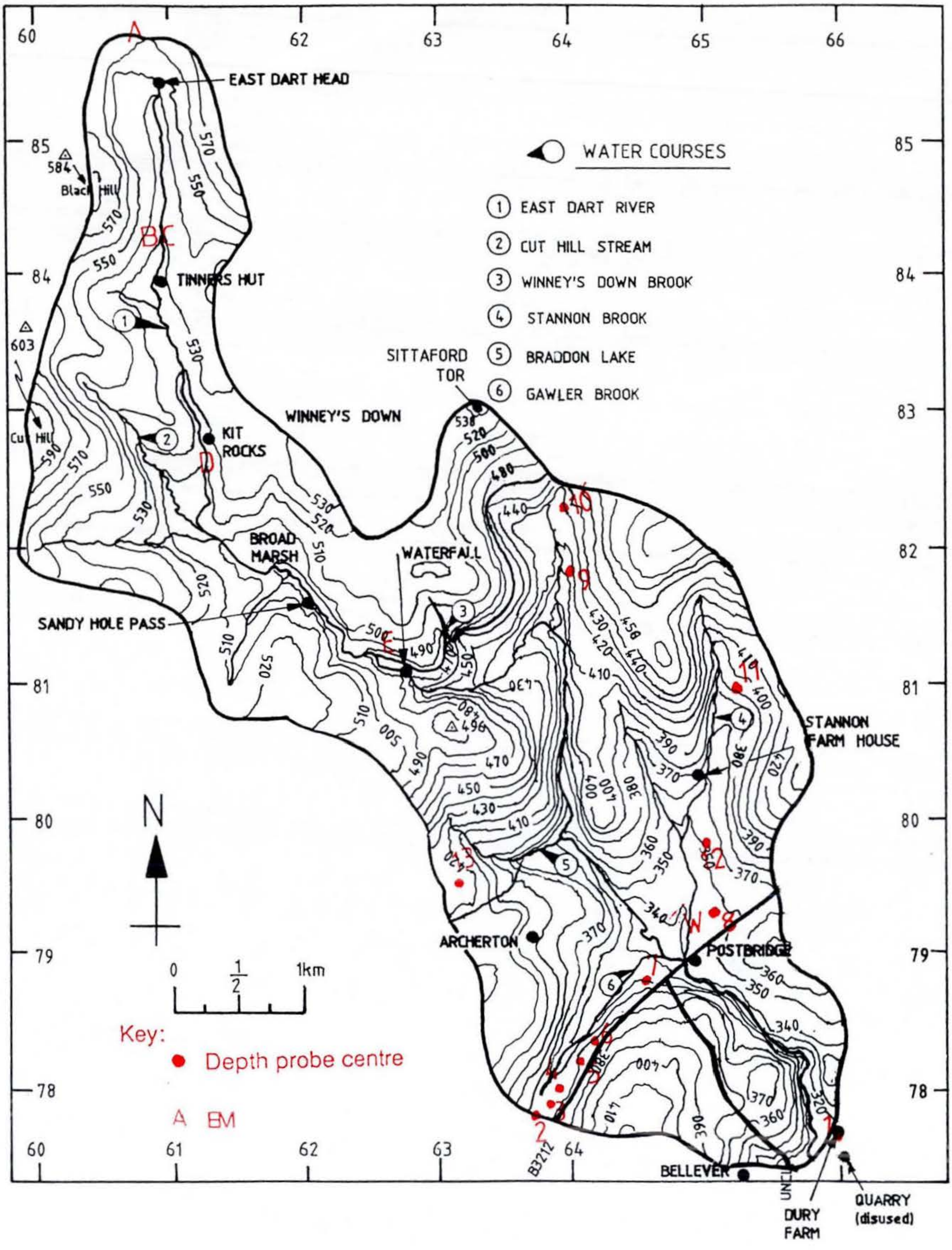
5.5.1.1.2 East Dart Catchment

There is lack of well logs for comparison with resistivity results in the East dart catchment, as such the interpretation is based on knowledge of the geology and superficials and the values of resistivity of rocks as mentioned at the beginning of the chapter. The results are presented in Table 5.2 and their relative positions in figure 5.5. Stations with an A and B indicate same station with B carried out at 90° to A with the same centres.

Table 5.2 East Dart Catchment Resistivity Data

Station No.	t_1	ρ_1	t_2	ρ_2	t_3	ρ_3	t_4	ρ_4	t_5	ρ_5
1	0.6	280	9.4	1200	8.0	700	42	1100	α	550
2	0.66	150	8.34	1500	α	1000				
3	0.7	150	11.0	1600	10.0	700	α	600		
4	0.65	160	5.85	960	23.5	1500	α	300		
5	0.45	170	4.55	800	25.0	950	α	1800		
6	0.35	300	2.15	700	5.5	1200	12.0	1100	α	1500
7	0.6	250	6.2	1200	13.2	1100		1000		
8	0.8	700	2.2	1500	5.0	1000	8.0	650	α	2700
9	0.53	200	3.47	800	36.0	440	α	1000		
10	0.8	180	3.7	700	21.5	360	α	1000		
11	0.85	200	19.15	1450	α	630				
12A	0.6	140	9.4	1000	18.0	340	α	1700		
12B	0.6	140	4.4	1000	13.0	500	12.0	1600	α	360
13A	1.0	130	4.8	600	α	1000				
13B	1.0	130	4.8	600	24.2	900	α	400		

Since fresh granite has a resistivity of over 1000 Ωm, station 1 has a top soil of about 0.6m. This was observed to be saturated (marshy) and boulders are found locally in the top soil. Because of its low resistivity and correlation to a nearby disused quarry, the top soil may be residue of the weathered granite. The 8m of 700 Ωm is thought to be highly weathered



EAST DART AT BELLEVER CATCHMENT

Figure 6.5 Resistivity depth probe and EM survey locations in the East Dart catchment.

granite below a localised overlying fresh rock of high resistivity may be due to difference in jointing. Stations 2 to 7 are within the valley of Gawler Brook. The top soil is also marshy with boulders found locally. The resistivity of the top soil ranges between 150 and 300 Ωm with an assumed thickness of between 0.35 to 0.7m. The weathered rock (Growan) can be said to have a resistivity range of 200 Ωm to 1000 Ωm although the lower limit may merge into weathered granite residue and the upper limit into the less fresh and jointed rock. Stations 4 to 6 have weathered material of about 6m thickness and station 5 about 30m thickness. At station 3, more than 10m of weathered material is found below less weathered or fresh to jointed rock of 11m thickness. It is this weathered material that is probably referred to as valley gravel and head in chapters 3 and 4.

At station 8, about 8m of weathered rock is recorded after 7m of less fresh or jointed granite. At the tributary west of Stannon Brook, Beehive Hut, valley gravel and head forms the top soil followed by about 25m to 40m of growan.

At the Valley of the Stannon brook, the top soil (0.6 -0.85) was observed to consist of peat and sandy soil. It is marshy in places. A section along the river shows unsorted sand, pebbles and boulders. The peat and sandy soil has resistivity ranges of 140 to 200 Ωm. This is followed by less fresh rock of between 4.4m and 9.4m, and weathered saturated rock of 13m to infinity.

Near the Braddon Lake (station 13), peat which was seen during the survey has a resistivity of 130 Ωm with a thickness of 1m. The growan has a thickness of about 24m.

In the East Dart catchment, it can be concluded that the weathered material is not uniform from top to bottom as slightly weathered or fresh granite boulders are found in the top soil and weathered granite in places. A maximum thickness of 40m has been recorded for the weathered granite. The different strata are water saturated as evidenced by springs, marsh and bogs.

5.5.1.1.3 Calder Catchment

The result are presented in Table 5.3 and resistivity points illustrated figure 5.6. In the Calder catchment, there are no well logs for correlation purposes. As such, the interpretation is based on the geology and superficials as discussed in chapters 3 and 4.

Table 5.3 Calder at Muirshiel Catchment Resistivity Data

Station No.	t_1	ρ_1	t_2	ρ_2	t_3	ρ_3	t_4	ρ_4	t_5	ρ_5
1A	0.7	160	4.3	1000	α	400				
2A	0.6	130	3.9	300	10.5	400	α	1200		
4A	0.55	130	3.95	300	10.5	450	21	165	α	1000
5A	0.3	120	1.5	180	5.2	260	13	400	α	700
6A	0.3	120	0.9	170	4.8	400	α	1000		
7A	0.6	130	0.9	220	6.5	80	14	220	α	1000
8A	0.4	140	0.6	200	4.0	1100	α	275		
9A	0.5	120	3.0	170	2.5	370	24	800	α	1000

Peat is found to cover about 60% of the catchment. Its resistivity value ranges between 120 to 300 Ωm and it occurs in all the stations with a thickness of 0.7m to 7m.

Because the basaltic rocks are jointed and weathered at the surface it is difficult to apportion resistivity values but anything above 500Ωm can be considered to be solid rock.

The resistivity values between 400 and 450Ωm is thought to be morainic sediments which may consist of gravely materials. In some places, material of less resistivity is found below the solid rock or moraine. Those found under the solid rock may be weathered clayey material of contemporaneous nature as discussed under weathering in chapter 3. The ones found under the moraine may be weathered top of the basaltic or fractured rocks.

5.5.2 Electromagnetic Results

5.5.2.1 Blackbrook Catchment

In Blackbrook catchment, traverses were carried out between Ives Head and Lubcloud Farm and the river (Resistivity stations 1 & 2). Readings were taken for both the vertical and horizontal components for coil separations of 20m and 40m. The results were plotted on linear scale. A typical curve is illustrated in figure 5.7 (Ives Head - Lubcloud Farm). This was carried out between an area of known exposure to check the accuracy of the result. Another traverse at right angles to it (at the 520m mark on figure 5.7) was carried out towards the residence of Lubcloud Farm. This and a third one in the valley of Blackbrook are in appendix 1A.

In figure 5.7 and figures a, and b of appendix 1A, the horizontal components pick up the fractures in the Precambrian (negative values) better than the vertical components. In figure a, the fractures are approximately 100m apart. In the other two figures, no pattern was established. The conductive zones reach a peak of 36mmhos/m but generally the low conductivity indicates the nearness of the Precambrian to the surface.

The position of resistivity centres along two of the profiles (figures a and b in appendix 1A) are indicated. The result of the model resistivity for these centres were converted to conductivity (mmhos/m) by inputting them in a conversion computer program of the BGS Keyworth (M. G. Raines, 1987; pers. comm). The procedure is fully explained in McNeill (1983). The result listing of EM34-3 response to the VES sites are presented in Table 5.4 (a - d). The results seem to broadly agree with each other although station 11 shows very little comparison between the input and output models. However, on observation, the values fall to low numbers as outcrop is approached (see start and end of fig. a and the start of fig b). Also as the sediments increase towards the valley bottoms, note that all coil configurations show a maximum. The overhead cables in figure c have a very marked effect on the profile and any readings close to them have been discounted in the interpretation.

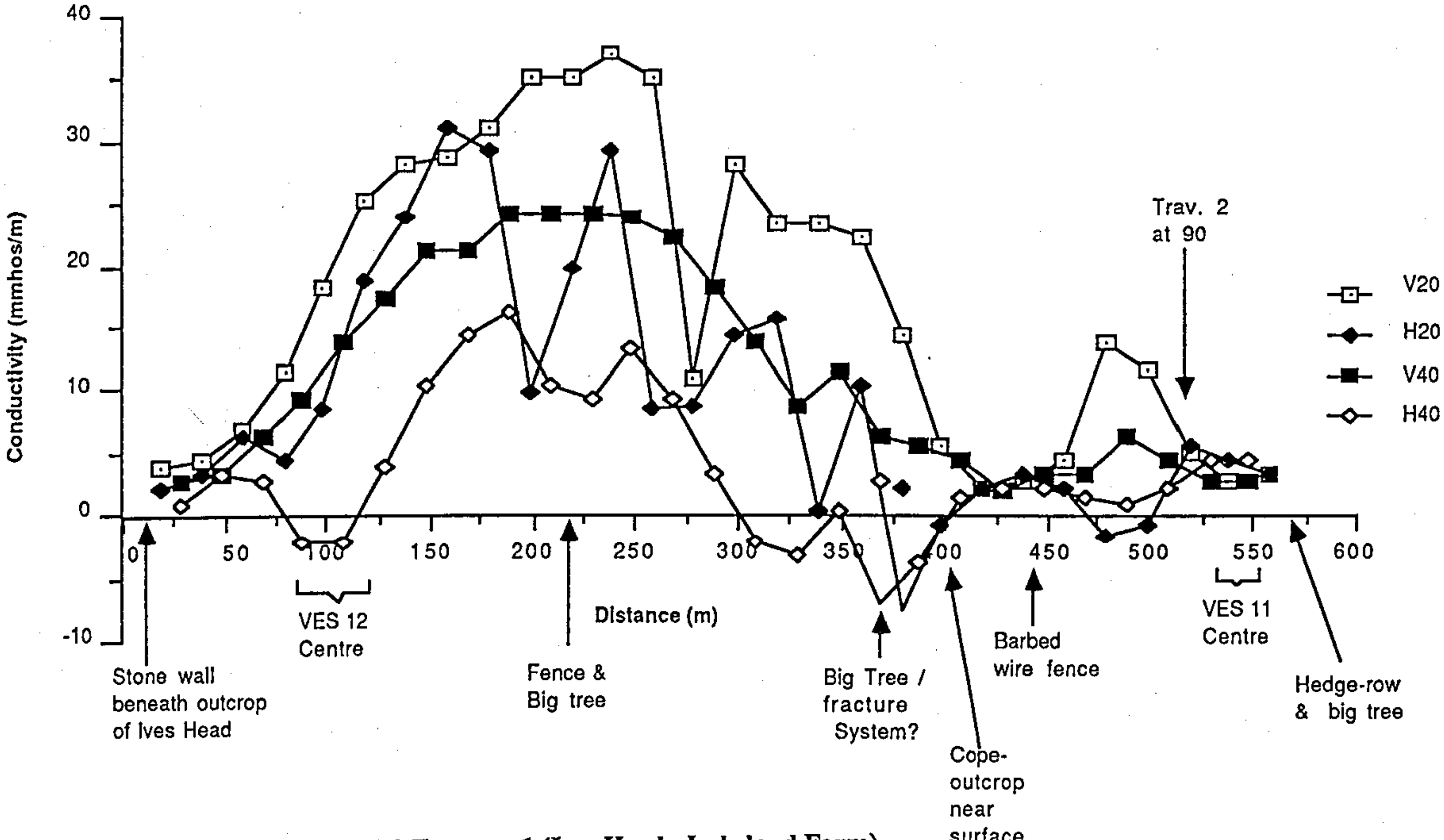


Figure 5.7 EM34-3 Traverse 1 (Ives Head - Lubcloud Farm).

Table 5.4 Output listing of predicted EM34-3 response over a layered Earth.

(a) Input model -VES 1 (Traverse 3)

Layer	Resistivity	Thickness	Depth
1	220.0	1.10	1.10
2	75.0	9.90	11.00
3	600.0	*	*

Calculated Conductivity values (mS/m):

CS:	VC	HC	CVC
10:	9.1	8.3	0.0
20:	7.9	5.4	6.7
40:	6.0	3.1	4.0

(b) Input model -VES 2 (Traverse 3)

Layer	Resistivity	Thickness	Depth
1	150.0	0.60	0.60
2	47.0	4.00	4.60
3	500.0	*	*

Calculated Conductivity values (mS/m):

CS:	VC	HC	CVC
10:	11.2	7.0	0.0
20:	8.1	3.7	5.0
40:	5.5	2.5	2.9

(c) Input model -VES 11 (Traverse 1)

Layer	Resistivity	Thickness	Depth
1	190.0	0.75	0.75
2	16.0	5.00	5.75
3	1000.0	*	*

Calculated Conductivity values (mS/m):

CS:	VC	HC	CVC
10:	31.6	21.5	0.0
20:	22.8	9.0	14.0
40:	14.1	3.4	5.4

(d) Input model -VES 12 (Traverse 1)

Layer	Resistivity	Thickness	Depth
1	220.0	0.90	0.90
2	22.0	4.85	5.75
3	1000.0	*	*

Table 5.4 Continued

Calculated Conductivity values (mS/m):

CS:	VC	HC	CVC
10:	22.1	15.6	0.0
20:	16.2	6.8	10.3
40:	10.2	2.7	4.1

Notes:

CS = coil spacing
VC = vertical coils
HC = horizontal coils
CVC = dual-spacing VC response

5.5.2.2 East Dart & Calder Catchments

For East Dart and Calder catchments, the horizontal components for a coil separation of 10m were used throughout. The horizontal dipole was employed in the survey in the two catchments because this component appeared to detect fractures more easily than the vertical dipole as stated above. Since the bed rock is known to be deep in places, traverses were carried out either near exposures or over them.

In East Dart catchment, eight traverses were carried out with some at right angles to each other. The conductivities are generally low. A maximum of 10mmhos/m was recorded. Negative values were recorded on only three traverses (Stannon Brook and north of the waterfalls at Kits Rocks). This result is no surprise as the top soil is thin and most part of the granite head is weathered as discussed under geology. Two of the graphs (wide valley in Stannon Brook and head of East Dart river) are presented in figures 5.8 and 5.9. It is thought that the rotten rock has masked the fractures such that they are not reflected on the conductivity readings.

In the Calder catchment, five traverses were carried out. The results also indicate low conductivity values (10mmhos/m). The conductivity generally increases away from exposures. No fractures were recorded.

The EM traverse graphs for East Dart and the Calder catchments are presented in appendix 1B and 1C respectively.

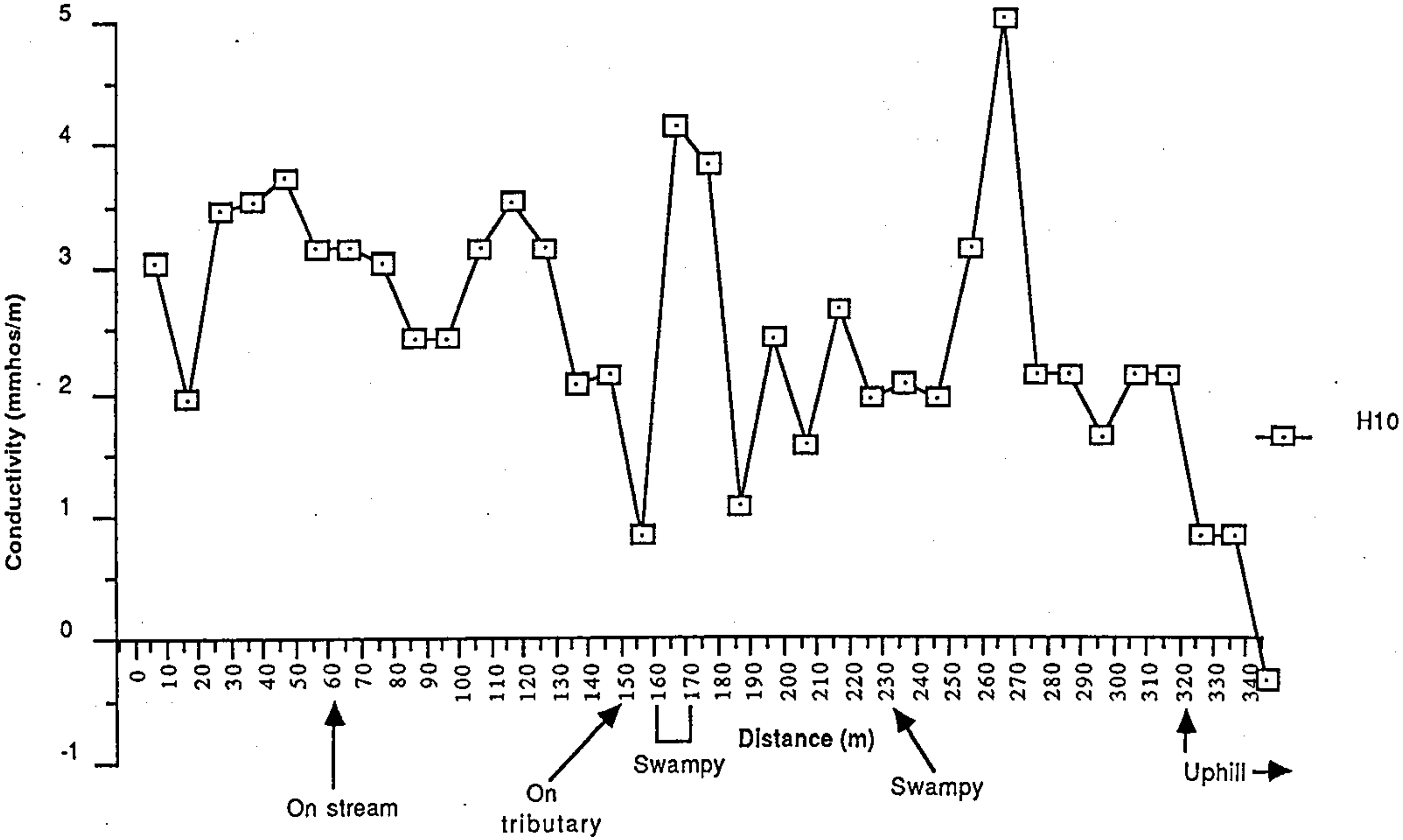


Figure 5.8 EM34-3 Traverse 100m upstream of Farm House (valley of Stannon Brook)

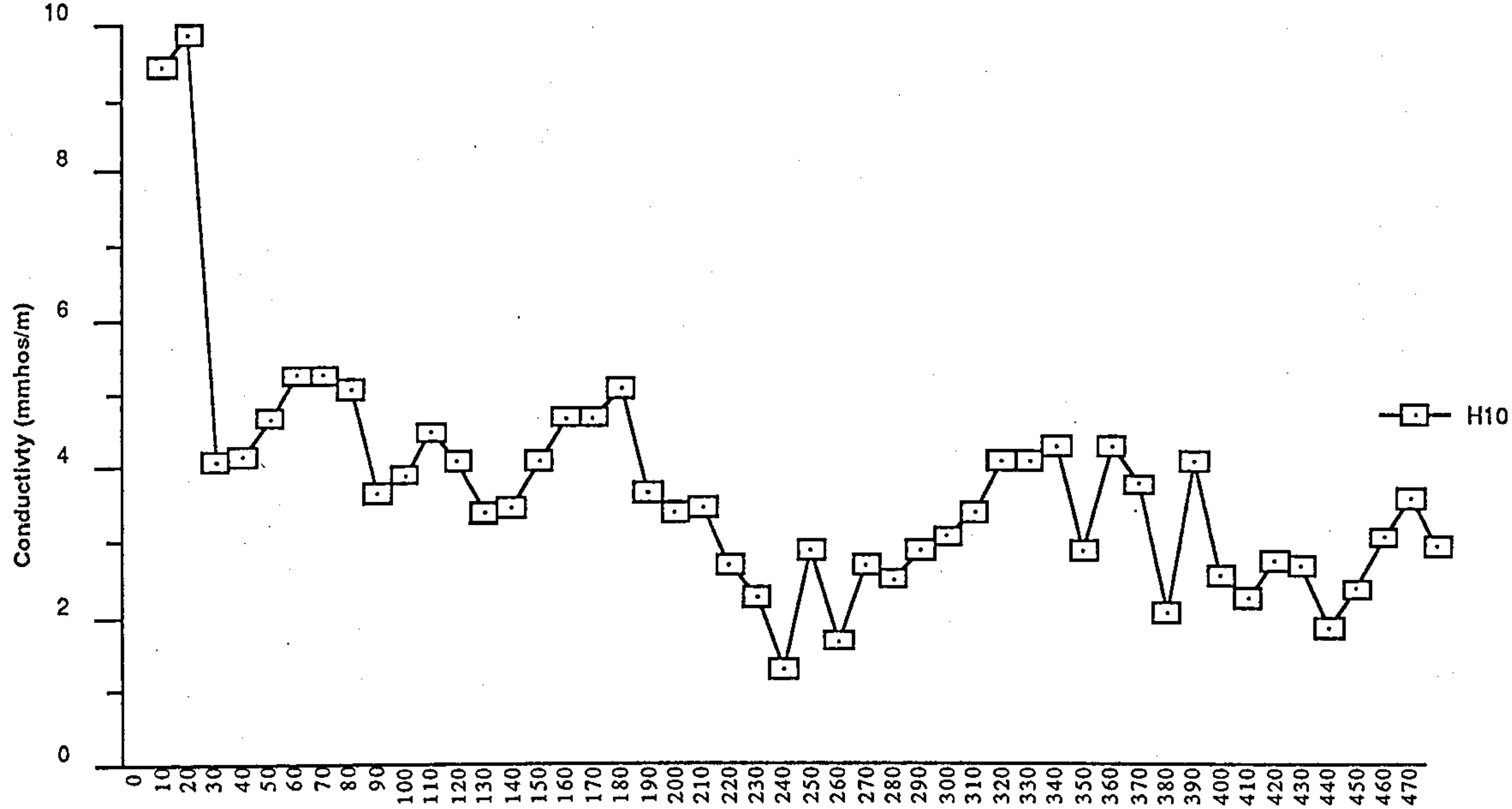


Figure 5.9 EM34-3 Traverse (A) across the head of East Dart River.

5.6 Summary

An investigation of the subsurface strata and bed rock as discussed in chapter 3, has been undertaken in this chapter. Their existence and surface expressions have been proved. A brief account is given below in relation to their water transmitting ability as concluded in chapters 4 and 8.

In the Blackbrook and Reservoir catchments, clay and marl and sandy gravel were located. Clay and marl are found to cover most of the catchment and they thicken towards the South East. Sandy gravel is found to occur in isolated (localised) patches with a maximum thickness of 20m. The thickness of weathered and fissured Precambrian could not be estimated accurately because of lack of well logs into these zones. The existence of an extensive spread of clay and marl with their characteristic low permeability has confirmed the low values for the soil permeability in chapter 4 and also the low infiltration rates in chapter 8.

In the East Dart catchment, the thickness of the weathered granite (growan) varies from place to place ranging between 0.6m to 40m. Fresh boulders are found locally within the growan. The weathered material in Gawler Brook valley consists of granite residue resting on growan. It is this residue that has been referred to as valley gravels and head in chapter 3. At Stannon Brook valley, weathered granitic material of considerable thickness (18m) was found in places. In fact, it is thought that the nearness of the fresh and less fresh rock in places coupled with high degree of saturation gives rise to springs at the head of the valley. The Stannon Brook has the widest valley in compared to other tributaries of the East Dart. The brook west of Stannon, which also has springs, the top soil is followed by weathered rock and evidences of springs are as a result of saturation as well.

Considering the thickness of weathered granitic material and the high degree of saturation, it is no surprise that Stannon brook contributes the greatest flow to the East Dart river compared to other tributaries. The high infiltration rate (calculated in chapter 8), hydraulic conductivity values and particle size distribution analysis is confirmed by the presence of weathered granite material which consists mainly of sands and gravels in the East Dart catchment.

Peat is found to cover most parts of the Calder catchment and varies in thickness between 0.7m and 7m. At times, the peat is found to rest directly on the solid rock. Moraine is also found (below the peat in places) almost all over the catchment. Moundy sand and gravel have not been located for certain because it is thought that either their resistivity values are masked by the moraine or the survey centres were not in areas in which they occur. The morainic sediments consist mainly of boulder clay and a mixture of boulder clay and gravels. Hydrogeologically, boulder clay is known to be virtually impermeable. The particle size distribution result has proved the variability of the composition of the morainic sediments and therefore, the findings of the geophysical investigation in this catchment has confirmed the low infiltration rate calculated in chapter 8.

The result of the geophysical investigation has again confirmed the findings of chapters 4 and 8. Particularly the recession constants, time for flow to half and also the infiltration rates derived in chapter 8. It can be concluded that the soils play a big role in the recharge processes of the catchment subsoils. The findings in the aforementioned chapters is further investigated in the Blackbrook catchment in chapter 6 for reasons later stated in chapter 8.

Chapter 6
HYDROGEOLOGY

6.1 Introduction

The comparison of well lithological logs and type sections has enabled the delineation of the most probable aquifers in Blackbrook and East Dart catchments while the lack of these in the Calder catchment has made it almost impossible. The lack of well lithological logs can be attributed to the availability of pipe borne water supplies and springs which make borehole or well construction uneconomical in Britain considering that a licence is required before groundwater abstraction can be carried out.

Groundwater supplies from wells and springs and evidence of ancient supplies are found from the hard rock catchments as discussed in chapter 1. In most places, the water table is close to the surface and from the findings of previous chapters it can be concluded that this is due to high degree of saturation as a result of high rainfall (and low potential evapotranspiration) or low permeability.

The determination of the depth to bed rock is hydrogeologically meaningful only in the East Dart catchment since the head of the granite is weathered. In the other two catchments, aquifer units are localised and sometimes their presence is masked by impermeable layers.

6.2 Lithological Units

On the basis of the geology, soils and superficials substantiated by subsurface geophysical result as discussed in chapters 3, 4 and 5, the different combination of lithological units that can be found in each of the three catchments are as follows:-

<u>Blackbrook</u>
Alluvium
Clay and Marl
Sandy Gravel
Weathered (clayey) and fissured Precambrian

East Dart
Peat
Alluvium
Valley Gravel and Head
Weathered Granite Residue (Sandy Gravel)
Weathered Granite in situ (Growan)
Fractured Granite

Calder
Peat
Boulder Clay
Glacial till (Moraine)
Moundy Sand and Gravel
Weathered Basaltic material (clayey)

The lithological units of hydrogeological interest are those capable of being aquifers. In the Blackbrook and Reservoir catchments, these consist of sandy gravel, alluvium and fissured Precambrian. In the East Dart catchment, they consist of weathered granite residue which give rise to sand, sandy gravel, growan and the fractured rock; while moundy sand and gravel are the probable aquifers in Calder catchment.

In Blackbrook and Reservoir catchments, the sandy gravel occurs in localised patches with a maximum thickness of 20m. It also occurs in the alluvium which consists of clayey material. From the low resistivity values, the sandy gravel is highly contaminated with clay and marl (referred to as dirty). The fissured Precambrian can only be of hydrogeological significance where the joints are open or occupied by sandy gravel; geophysical result did not reveal their form but type sections at the Peldar Tor quarry shows that the joints are sandwiched with clay and marl. The hydrogeological properties of the aquifers including clay and marl are discussed below in section 6.3. Clay and marl are featured because most of the wells in and around the catchments are either dug or drilled into them.

In East Dart catchment, weathered granite in the form of sandy gravel was located using geophysical methods. A maximum thickness of 40m was recorded for the weathered granite although some fresh boulders are found locally in the weathered material. Springs found on some of the tributaries of the East Dart river are as a result of high degree of saturation or change in lithology. Their forms of occurrence are not fully established but the water table is thought to be close to the surface. Because it is moorland, wells are rare and may be restricted to very few houses and these are used only as spring water storage facility. Thus, no pumping test was carried out.

In the Calder catchment, the location of the moundy sand and gravel was made difficult due to lack of well logs and exposures coupled with the fact that the resistivity ranges of morainic sediments masks that of the sand and gravel.

6.3 Pumping Test Analysis

Blackbrook Catchment

Most of the wells extend only into the clay and marl. The wells are located within and outside the catchment (see figure 6.1). Pumping tests were carried out on four wells. The only well drilled into the hard rock is located in Shepshed (Brick Kiln Lane). A pumping test attempt was abandoned because the recording device reacted to the electrical field produced by a submersible pump already in use in the well.

The four wells tested are no longer in use. The water table therefore, fluctuates only seasonally and possibly during heavy storms. Since the pumping test was carried out during a dry period, static water level is believed to be the same as the water table. Under this condition, the data is found to be applicable in the determination of the formation(s) characteristics. Three of the wells are open (not cased) and only the one by the Monastery is cased. During the pumping tests, red muddy water was pumped out of the cased well indicating the dirty nature of the sandy gravel. Some open wells at the Monastery are found to supply the community adequately (pers. comm).

6.3.1 Background: Large Diameter Well Data Analysis

In the absence of boreholes, pumping tests can be carried out on hand dug wells to estimate aquifer characteristics. These ubiquitous wells may serve as ready-made 'experimental stations' for hydrogeological research provided the appropriate theoretical framework is applied.

The classical Theis (1935) procedure is not applicable for the analysis of pumping tests on large diameter wells due principally to the presence of well storage. For large diameter wells dug in unconfined aquifers, decrease in saturated thickness with time results in a further violation of the Theis assumption requiring that the discharge rate be constant. Papadopulous and Cooper (1967) presented a curve matching technique for the analysis of large diameter well tests. To apply this technique, the well must be pumped for a duration $t>250r^2/T$ where . r is the well radius and T is the transmissivity. This duration could be intolerably long in large diameter wells especially when the transmissivity is also low. In other words, Papadopulous and Cooper's solution is not applicable to short duration pumping tests on large diameter wells. Several other authors have also proposed procedures for the analysis of pumping test data from large wells. More recently, Mishra and Chachadi (1985), Patel and Mishra (1983) and Rushton and Singh (1987) presented procedures based on numerical analysis none of which applies to short duration tests - here defined as tests with pumping duration of one hour or less.

6.3.2 Procedure and Associated Theory

The wells were pumped such that the situation illustrated in figure 6.1 results. When a well is quickly dewatered and allowed to refill back, the rate of flow (Q) is a function of the permeability (k) of the subsoil, the initial drawdown (y) and dimensional characteristics of the well. In such a situation, equations derived for flow into auger holes may be applied. The drawdown y is noted. The recovery is then monitored for as long as the data is required. The rate of recovery however, depends on the hydraulic gradient and the radius of the well.

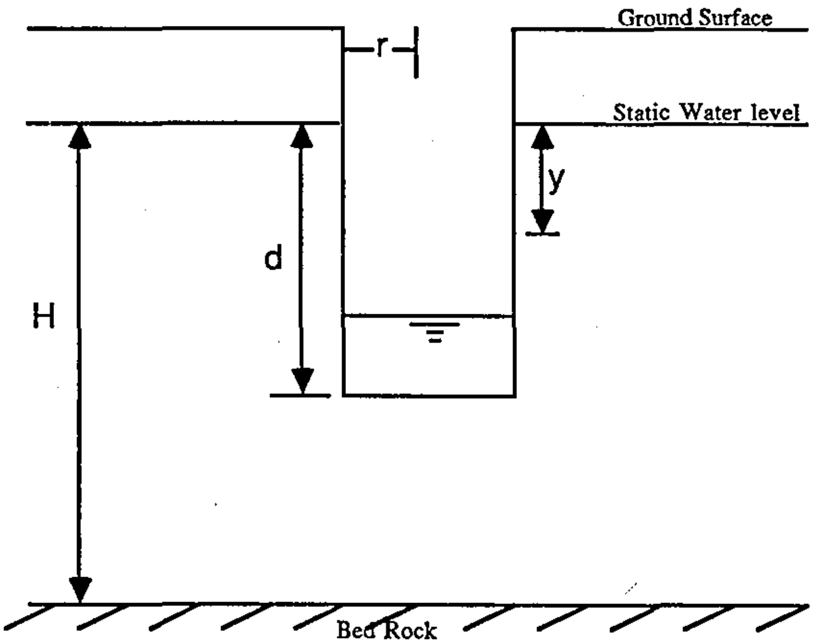


Figure 6.1 Dimensional characteristics for the seepage factor

Boast and Kirkham (1971) gave a relationship between the rate of flow into an auger hole and the hydraulic conductivity of the medium. Their equation originates from Ernst and is given as:

$$K \text{ (m/day)} = (-dy/dt) \text{ [cm/sec] } C \quad \text{......................6.1}$$

where

dy/dt is rate of rise of water during recovery (t = time); for early data (dy/dt = slope of recovery time graph)

C = well shape factor

and

$$C = (4000\, r/y) / [(d/r + 20)(2 - y/d)] \quad \text{.....................6.2}$$

where

y = depth to which water has been lowered below the water table

r = radius of well

d = depth of well below water table.

To harmonise the units, there are 86400 seconds in a day and 100 cm in a metre, equation 6.1 becomes

$$K = (-dy/dt)\, C /864 \quad \text{(m/day) ....6.3}$$

hence K and -dy/dt have same units and C is dimensionless. The shape factor expresses the relationship between the observed rate of flow of water into a well (or rate of rise of water in the well) and the hydraulic conductivity of the surrounding formation.

The equation for the calculation of C applies to a wide range of geometries from d/r = 1 (a very fat well or a circular pit) to d/r = 100 (for a thin auger hole or a root hole). Well number three is out of this range but it has been used so as to provide comparable results.

The variables in equation 6.1 and 6.2 are also illustrated in figure 6.1. Thus the shape factor incorporates the dependence of recovery rate on initial drawdown, y, the depth of the water below the water table, d, and the well radius. Thus a plot of dy versus dt using early recovery data should give a straight line from which slope can be evaluated. Only the initial straight line portion of the plot should be used to determine the slope. To find k, C is first evaluated from equation 6.2 and then multiplied with the experimentally determined rate of recovery (-dy/dt).

Although this equation was derived for auger holes seepage theory and due to the wide range of geometries which it can be applied, hence, it can be used for the analysis of pumping test data of large diameter wells. Therefore, equations 6.2 and 6.3 have been applied to estimate K for the wells pump tested and the results are presented in Table 6.1. Drawdown and recovery graphs are presented in figures 6.2 and 6.3 respectively.

The discharge values (Q) are calculated from the formula of Sen (1986) which are applicable for early drawdown data and this is also given as

$$Q = \pi r_w^2 \frac{ds_w(t)}{dt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6.4)$$

where

$ds_w(t)$ = drawdown

t = time since pumping started

r_w = well radius and

$ds_w(t)/dt$ = the initial slope of the time-drawdown curve.

Owoade et al (1988) have shown that if a large diameter well is suddenly dewatered, i.e. not allowing a cone of depression to develop; then the transmissivity of the well can be estimated from the relationship

$$dh/dt = 2Ti/r \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 6.5$$

where

dh/dt = rate of recovery of water level

T = transmissivity

r = well radius

i = hydraulic gradient in the aquifer

For short duration pumping test, the gradient does not vary during the test. Thus a plot of dh Vs dt result in a linear graph with slope 2Ti/r since r is constant and T also remains constant if there is no decrease in saturated thickness during the test. Thus the value of T can be evaluated. Owoade et al (op. cit.) have tested the validity of this method for the estimation of transmissivity on large diameter wells in South Western Nigeria. However, this method did not work well for Blackbrook catchment since the weathering profile is not similar (uniform)

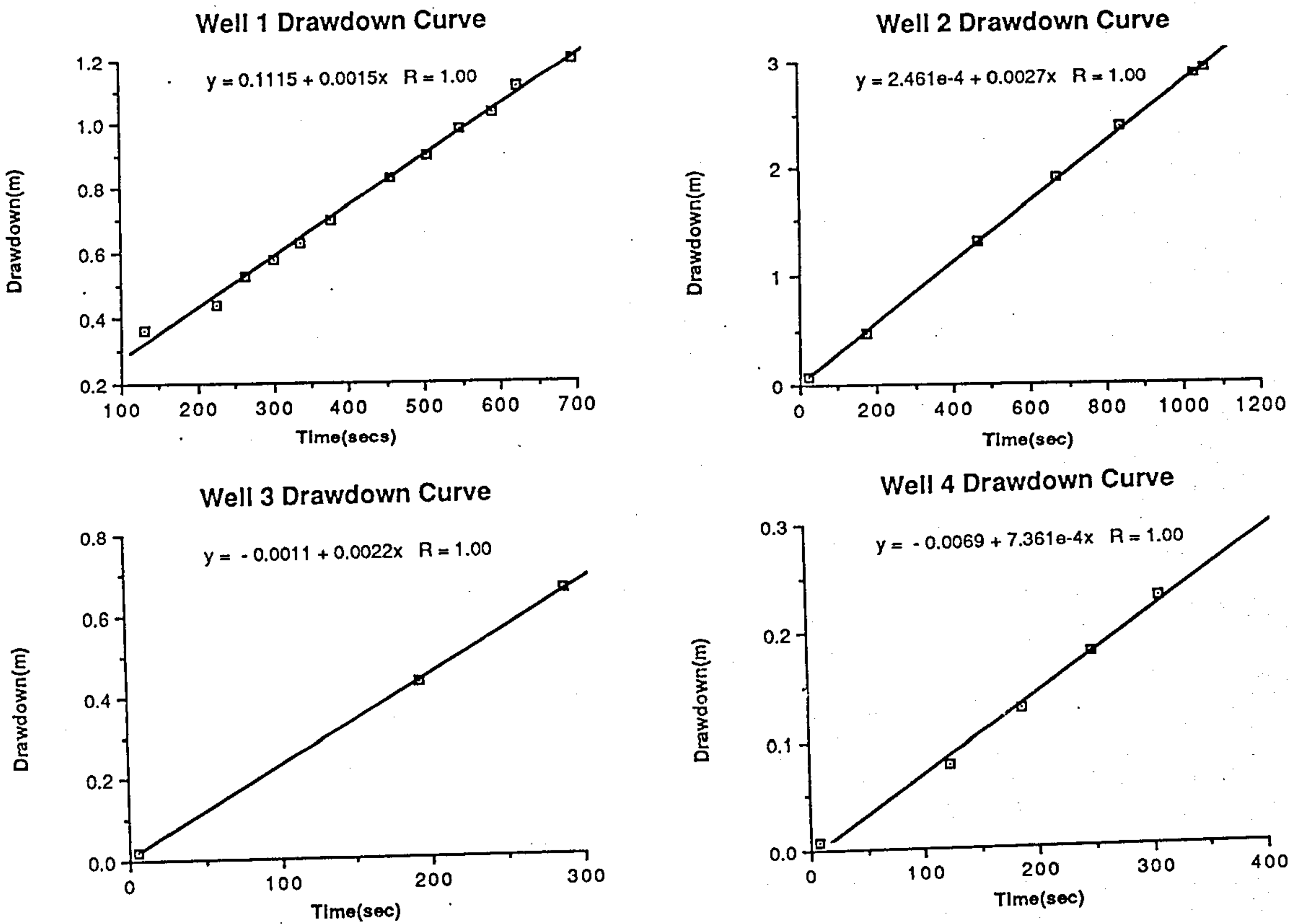


Figure 6.2 Early drawdown curves for wells pump tested in the Blackbrook catchment

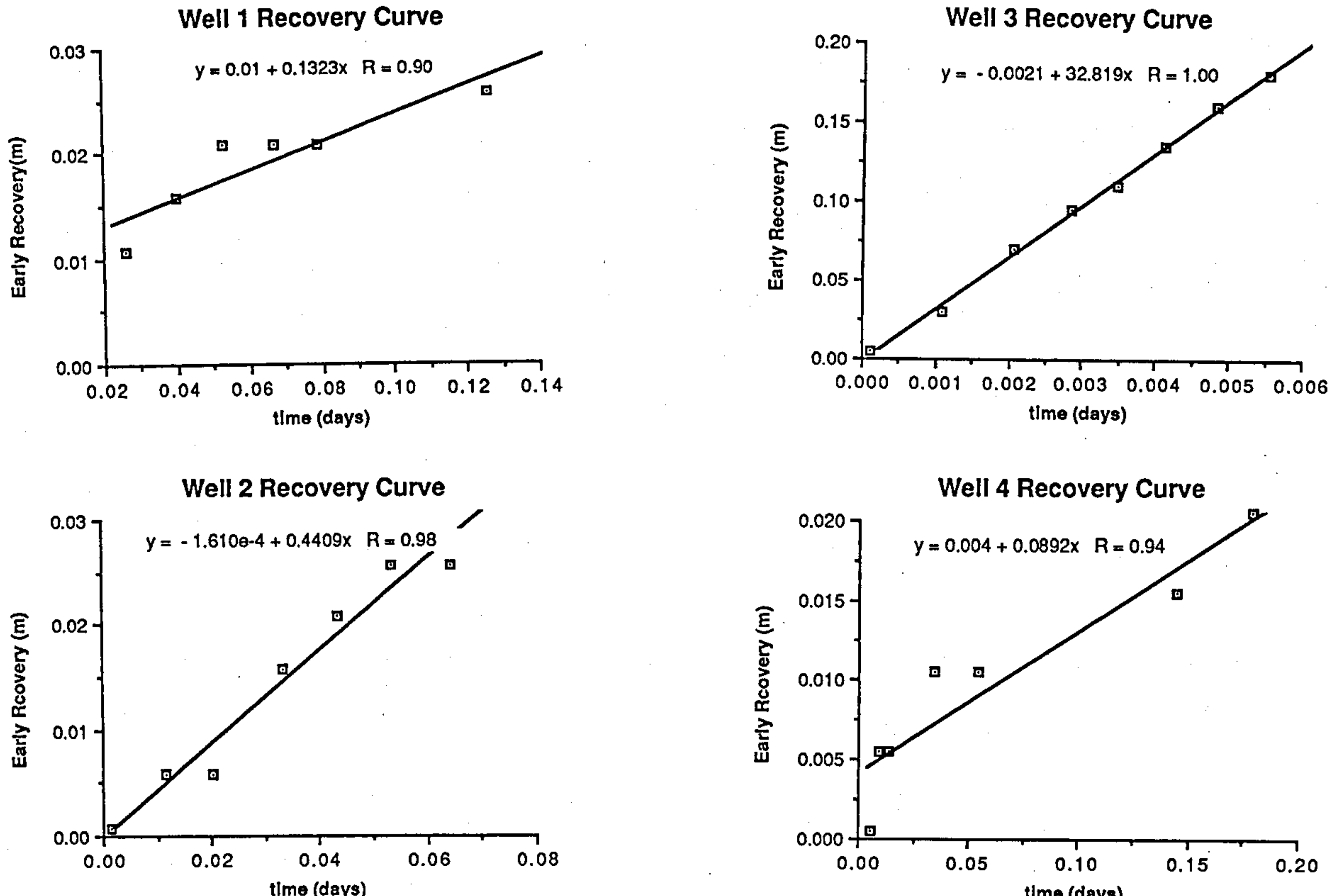


Figure 6.3 Early recovery curves for wells pump tested in Blackbrook Catchment

to where the formula was derived.

A simple estimation of T can be carried out using the familiar equation

$$T = Kb \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(6.6)$$

where

b = the saturated thickness of the formation and in this case, it corresponds to d in figure 6.1 and these are presented in Table 6.1.

d values were obtained from borehole records or sounding of the wells carried out by the author. Equation 6.6 has been used to calculate the T values in Table 6.1. Admittedly, the T values are just a crude method of estimation of the transmissivity since the formations are known to be very poor in their water transmitting ability.

6.3.3 Result Discussion

Table 6.1 Estimated Permeability and Transmissivity values

Well No.	r (m)	d (m)	dy/dt (m/day)	Q (m^3/s) x10^{-3}	C	K (m/day) x10^{-3}	T (m^2/day)
1	0.55	19.54	0.132	1.430	5.080	0.776	0.0150
2	0.50	7.77	0.441	2.120	9.690	4.950	0.0385
3	0.12	28.09	32.820	0.0995	0.360	13.675	0.3840
4	0.70	4.48	0.089	16.200	87.96	9.060	0.0406

The permeability values are generally lower and than the range given for the soils (K = 0.01 to 0.3 m/day) as discussed in chapter 4 except for well number 3. The higher hydraulic conductivity of well 3 was expected since the geology indicates sandy gravel which is more permeable than the boulder clay and marl of the three other wells. Except in areas where subsoils constitute the aquifers; the permeability of the soils and subsoils generally differ by wide margins. This result was expected since the subsoils are more consolidated than the soils. According to Brassington (1988, pp. 57) and Driscoll (1986, pp. 75) the permeability values are representative of unconsolidated materials of silty clay and/or mixtures of sand, silt and clay to fine sand or glacial till.

Transmissivity values for the four wells are far lower than the range given (between 1 and $20m^2$/day; Clark, 1985) for weathered basement in tropical Africa. The low values obtained confirm the subsoils, clay and marl, are very poor aquifers. Well number 3 has confirmed the sandy nature of the formation as reported for the well lithological log in chapter 5. The permeability values have differentiated well number 3 from the other wells sunk into clay and marl. This has further confirmed the resistivity values obtained in chapter 5.

6.4 Water Resources

Considering the geological units in Blackbrook and the solid geology in conjunction with the aquifer characteristics, wells in the catchment will only be adequate for household supply. Communal supply may only be possible in areas of extensive spread and considerable thickness of the dirty sandy gravel or fissured rock of open joints. Hydrogeologically, clay and marl have shown their characteristics: as very poor aquifers. Therefore, open wells in these formations should be of large diameter such as to act as storage facility. This type of well construction has been used by the Monastery and the supply to the community is found to be adequate. For borehole construction in sandy gravel, the depth and lateral extent of the formation needs to be defined.

In East Dart catchment, the high permeability of subsoils may permit the construction of boreholes. Alexander (1983) gave permeability values between 1.106 - 4.61 m day^{-1} for the Narrator Brook catchment in south west Dartmoor and this is comparable to the permeability values for the soils in chapter 4.

The geology of the Calder catchment is dominated by peat and morainic sediments of low permeability. The hydrogeological characteristics of the catchment is similar to Blackbrook except for thick peat cover over most of the catchment. The only aquifers that may be present are the moundy sand and gravel which could be of limited areal extent. Therefore, any groundwater abstraction in this catchment will necessitate the same large diameter wells as in the Blackbrook catchment for small community or household supply.

Springs found within the three catchments could act as sources for rural community supply if they are well developed with storage facilities; this is considering their reliability since they are perennial.

6.5 Summary

Of the three catchments, only East Dart catchment has the characteristics of a tropical basement complex where the rock is found to weather and form regolith above the solid rock. Therefore, borehole site location can be determined by topography, depth and lateral extent of the weathered material.

A pumping test analysis in Blackbrook confirms the poor nature of the subsoils: clay and marl. The subsoils were found to be less permeable than the top soil. The result of the analysis confirmed the fact that the subsoils consists of boulder clay and marl (glacial till) and permeability is not uniform over the catchmnent. The only well sunk into the sandy gravel indicates higher permeability (and transmissivity) than those in clay and marl. For any economical construction of a well in the clay and marl, such a well should be of large diameter (to act as a storage facility) as found at the Monastery. In the case of borehole, depth and lateral extent of the sandy gravel needs to be defined precisely.

From geological and hydrogeological considerations, the terms for groundwater abstraction in Blackbrook applies to the Calder catchment.

The springs are thought to be adequate for rural community water supply especially where storage facilities are constructed; more so when the sparse population in East Dart and Calder catchments are taken into consideration. The water quality from some of the springs and river waters are discussed in chapter 7.

Chapter 7

HYDROGEOCHEMISTRY

7.1 Introduction

The study of interaction between groundwater and aquifer materials has led to the development of many techniques for the presentation and interpretation of water quality data. Six techniques commonly used to portray the chemical analysis of natural waters include:

1. Stiff diagrams
2. Schoeller diagrams
3. Bar graphs
4. Pie diagrams
5. Vector diagrams
6.. Piper or Hill diagrams.

The first five of these techniques are graphical and therefore represent only a means of illustrating up the differences or similarities among waters in a more impressive way than is possible with the numerical data alone. They do not in themselves constitute a closer study which explains any differences in the explanation that is needed. By use of the Piper diagram and related trilinear systems the chemical relationships among waters may be emphasised in more than is possible with any other plotting procedures.

The Piper trilinear diagram has been found to be very effective for genetic studies of groundwater chemistry (Zaporozec, 1971). It is the most widely used nowadays because of its ability to screen a large number of water analyses for critical study with respect to some of the dissolved constituents and the modification in character as water passes through an area. The changes are normally shown by changes in the chemical character of a natural water by progressive increase of some particular mineral or concentration by evaporation. This method has therefore been used to try and determine the flow paths of spring waters in the three catchments that have been investigated. An account of their quality from both surface and groundwater sources is also discussed.

7.2 Interpretation Technique

The principles of interpretation of water chemical data are based on the relationship of ions, or group of ions, forming a chemical type of water. Normally, the ions of the major elements are used for interpretation purposes. The pointwise plotting system pioneered by Piper (1944) has been adopted for the interpretation for reasons earlier mentioned. The concentrations determined in milligram per litre (mg l^{-1}), were converted to milliequivalent per litre (meq l^{-1}) and the percentage of meq l^{-1} (100%) was used for the plotted points on the trilinear diagram.

The trilinear plot utilises two triangles of anions and cations with each vertex representing 100% of the selected ion or group of ions with a central diamond-shaped field on which the projected points from the anion and cation triangles are plotted; to show the essential chemical character of a water according to the relative concentration of its constituents; but not according to absolute concentrations. The plots in the central diamond-shaped field are presented in section 7.3 and the procedure is fully explained in Piper (op. cit.). Over the years, computer programs have been developed to aid the interpretation of water chemistry data. They are most effective in storing, retrieving, and manipulating large volumes of data and can also minimise the mistakes in calculations and the time taken in manual plotting.

The interpretation of the plots may not be as simple as the theory but Piper (op. cit.) and others pointed out that analysis representing two original waters and a mixture will plot on a straight line. For three-component mixtures, the analysis of the mixture plots within a figure bounded by the components. The analysis of waters at different points in a system may plot on a straight line passing through a vertex of the plotting field. The lower plots indicate water from the same source except for added salt either from an inflow of water containing high proportion of salts or from the solution of solid salt from the rock associated with the water. Piper (op. cit.) also found out that orientation towards another vertex could represent, for example, a gain in calcium sulphate, or its loss through precipitation of gypsum. In some environments, the interpretation of added or lost ions through precipitation may not always be the case. Calcium and magnesium may exchange for sodium referred to as base exchange or sulphate for alkalinity referred to as sulphate reduction. Except for these two conditions, the analyses of two waters that are the same will plot on a straight line parallel to one of the bases of the central plotting field.

A system of trilinear plotting called the Palmer system divides the central diamond shaped field into two (upper and lower) halves. Water having secondary salinity formed by salts of strong acids (SO_4, Cl_2 & NO_3) and weak bases (Ca & Mg -permanent hardness) plots in the upper field, and those having the property of primary alkalinity formed by salts of weak acids (CO_3 & HCO_3) and strong bases (Na & K -permanent alkalinity) plot in the lower field.

Piper (op. cit.) gave a quick reference for differentiating water types according to the area within which their point fall in the central diamond-shaped field. This is presented below as given by him in the diagram and the explanations viz:

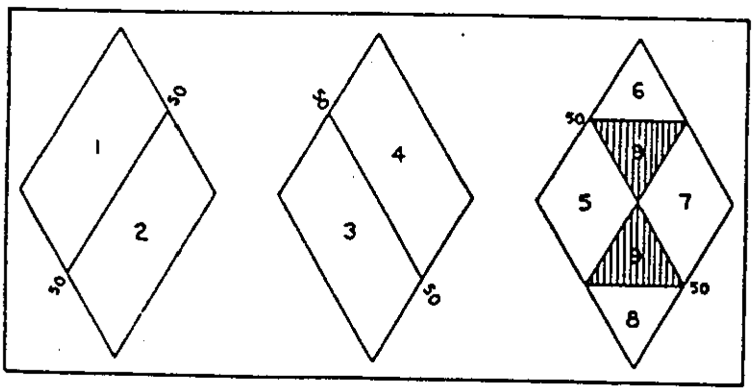


Fig. 7.1 Subdivisions of the diamond-shaped field.

Area:-

1. Alkaline earths exceed alkalies;
2. Alkalies exceed alkaline earths;
3. Weak acids exceed strong acids;
4. Strong acids exceed weak acids;
5. Secondary alkalinity (carbonate hardness) exceeds 50%, i.e. chemical properties of the water are dominated by alkaline earths and weak acids;
6. Secondary salinity (non-carbonate hardness) exceeds 50%;
7. Primary salinity (non-carbonate alkali) exceeds 50%, i.e. chemical properties are dominated by alkalies and strong acids, -ocean water and many brines plot in this area, near its right-hand vertex;
8. Primary alkalinity (carbonate alkali) exceeds 50%, here plot waters which are ordinately soft in proportion to their content of dissolved solids; and
9. No one of the cation - anion pairs of Palmer's classification exceeds 50%.

Individual analysis can be represented by circles of various sizes according to the amount of dissolved solids. The only drawback is its complexity where numerous points are plotted.

7.3 Data Analysis and Result

Rainwater quality data for the Blackbrook catchment were collected from the Human Sciences Department of Loughborough University of Technology.

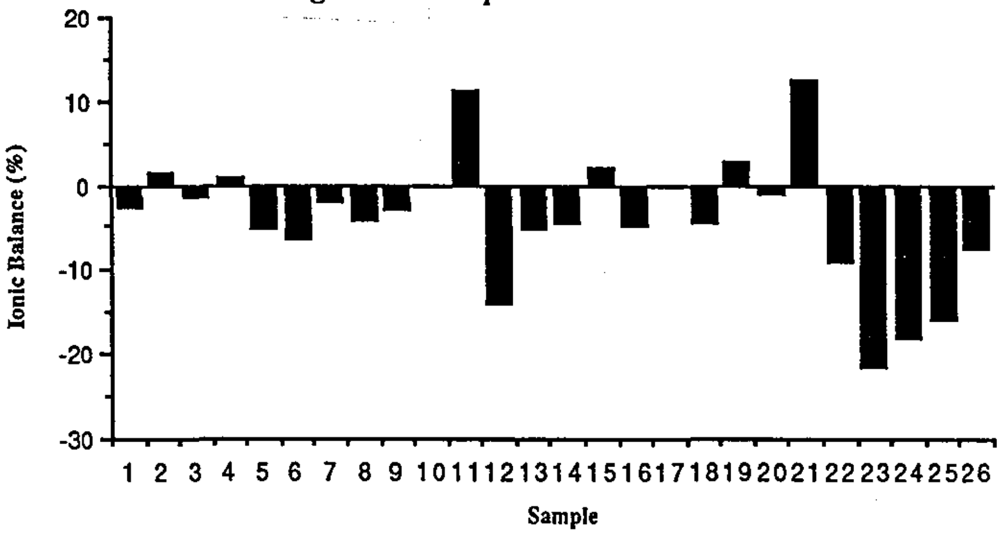
Other water samples were collected from the field by the author in two litre sterilised plastic bottles. Field tests were carried out on the samples during the collection. Duplicate samples were taken at other times of the year.

The water samples were analysed for major ions by titrimetric procedures and flame photometry in the Public Health Laboratory of the Civil Engineering Department. Other tests such as conductivity, TDS and sulphates were carried out using standard laboratory methods (AWWA, 1985). The Human Sciences Department also carried out some of the duplicate water sample analyses. The result of the analyses is presented in appendix 2.

The chemical data was analysed using computer software developed by Lewis (1988) which runs on the IBM PC (or compatibles) for water balance checks and trilinear plots. The data was checked for ionic balance to give an indication of the accuracy of analysis. An ionic balance within $\pm 5\%$ is normally a prerequisite for suitability for further geochemical investigation. To check the validity of the water chemistry data, the result of the ionic balances for each source is plotted as a histogram. This is presented in figure 7.2.

Due to analytical errors and errors arising from the analysis of carbonates and bicarbonates; and also considering the fact that the samples have suffered in transit, $\pm 10\%$ ionic balance has been used to plot the data points in the central diamond-shaped field. Twenty samples have been found to satisfy this condition (out of which 15 satisfies the $\pm 5\%$ criteria). The result of the plot is presented in figure 7.3.

Figure 7.2 Graph of Ionic Balance



The use of few data points for the interpretation of water chemistry of natural waters can be very controversial on the basis that they may not represent prevailing conditions for the areas in question. This is only true for surface water analysis and Hem (1970) states that

"............ a single sample from a groundwater source may represent closely the quality of water from that source for many years."

Hence he suggested resampling in order to correlate with any existing data relating to groundwater quality for acceptance as representative of present conditions. Since the springs are not tampered with, the samples are typical of the aquifers because they are free flowing. In an otherwise stagnant water, the water chemistry would not be a representative of the aquifer conditions. The water samples collected for different periods plot within the same area on the central diamond-shaped field. The total dissolved solids (TDS) of the samples for different times are similar for the same sources, suggesting that the samples are representative of the situation in the aquifers. This supports the point made by Hem (op. cit.) and also shows clearly the differences in the rock types and aquifer characteristics. The consistency in the chemical data plots for each catchment, has made it possible to interpret the data and draw conclusions. The water authorities and the British Geological Survey (BGS) do not monitor groundwater quality in these areas therefore no comparisons could be made with data from other hard rock sources.

From the data in appendix 2, a comparative analysis can be carried out. The data is compared with resistivity data in tables 6.1, 6.2 and 6.3. No salt intrusion or salty connate waters were encountered in any of the catchments. The water quality satisfies the World Health Organization (WHO) standards (Smithurst, 1983; p.133) for potable water supplies except that Holywell spring in the Charnwood Forest has total hardness above the maximum permissible concentrations (300 mg/l). East Dart catchments have lower pHs than the WHO permissible limits of 6.5 - 9.2. Hence, the water requires some treatment for stability to meet the stipulated permissible concentrations. The saturation index, which is an indication of corrosive nature of the water, has been computed for most of the catchments (applicable to waters of pH 6.5 - 9.5). The water in the Blackbrook catchment indicates water of moderate corrosive tendency (between -2 and -0.1, Langlier, 1946 and Ryznar, 1964) and Calder indicates highly corrosive (<-0.2) water; although the pH is on the lower side except for Clovenstone Spring. Therefore, some treatment may be required for stability (positive indices indicate over saturation and the water can precipitate $CaCO_3$ while negative values signify a corrosive water that can dissolve $CaCO_3$). From a table of the relationship between corrosion and soil resistivity (Raghunath,1983), Blackbrook catchment has water between corrosive and non-corrosive (>7Ωm). East Dart and Calder catchments have water of mild to non-corrosive (>50Ωm).

The percentages of the meq l^{-1} concentrations were plotted on Piper trilinear diagrams as shown in figure 7.3. All the points for Blackbrook and East Dart catchments in the central diamond are in the upper half of the field, indicating waters of secondary salinity (strong acids and weak bases) while Calder catchment has its point in both upper and lower halves indicating primary alkalinity as well as secondary salinity (by Palmer's System).

From Piper's method of differentiation of water types, spring and rain waters from Blackbrook & Calder catchments from figure 7.3 indicate alkaline earths exceed alkalies while alkalies exceed alkaline earths in East Dart catchment (Spring & River Waters). Furthermore, spring water from Blackbrook and Calder catchments indicate weak acids exceed strong acids while strong acids exceed weak acids in East Dart and the rainwater from Blackbrook catchment. The spring water from Blackbrook and Calder catchments indicate secondary alkalinity in excess of 50 % (carbonate Hardness) i.e chemical properties are dominated by alkaline earths and weak acids. The spring and river water from East Dart catchment indicate primary salinity (non-carbonate alkali) in excess of 50% i.e. the chemical properties are dominated by alkalies and strong acids. The rainwater from Charnwood Forest indicates no cation-anion pairs in Palmer's classification exceeds 50%.

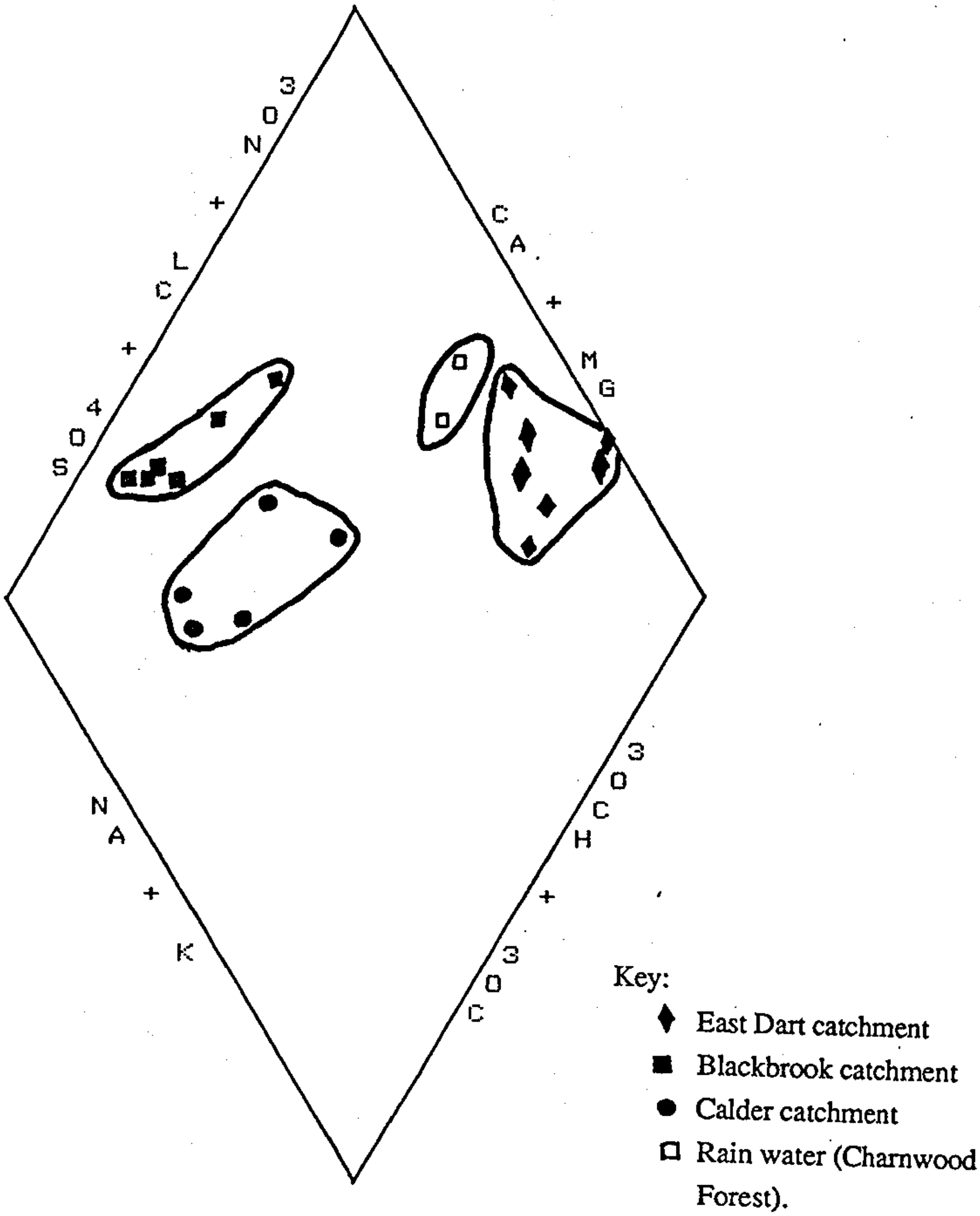


Figure 7.3 Trilinear plots of water chemistry data from East Dart, Blackbrook and Calder catchments.

The plots of rain and spring waters from Blackbrook catchment, indicates that the rainwater has lost some of its alkali ions through base exchange and gained more alkaline earths and sulphate alkalinity (reduction) as it permeates the subsoils and possibly weathered material. Other deductions that can be made from the chemical plots in the Piper trilinear diagram, are:

East Dart catchment has Na^+ and k^+ in excess
Blackbrook and Calder catchments have Ca^{++} and Mg^{++} in excess

Comparing these with the chemical analyses of the rocks in tables 3.1, 3.2 and 3.3 in chapter 3, the alkalies in East Dart catchment are derived from the weathered granite. Na^+ shows a high value in the Blackbrook catchment compared to the alkaline earths. Hence, base exchange has occurred; although the effect of the chemical composition of the clay and marl may not be ruled out. Therefore, it can be deduced that the water is derived from the overburden and possibly the Charnian rocks. In the Calder catchment, only little base exchange may have taken place because the alkaline earths also have high values as the alkalies. The water is therefore derived from the overburden as well as the basaltic rocks and their weathered products. The bedrocks mentioned above may only be the rock fragments found locally in the overburden as discussed in chapter 3.

Generally, the degree of mineralisation is low as can be seen by the values of the TDS for the spring waters and this is characteristic of highland catchments.

7.4 Summary

From the water chemistry data interpretation, a number of conclusions can be reached. Water from East Dart and Calder catchments are slight and non-corrosive while Blackbrook catchment exhibits corrosive and non-corrosive tendencies. Because of the corrosive tendencies of the water, some form of treatment will be required if the water is to be piped. The water chemistry data was compared with WHO standards for potable waters. Generally, most of the spring waters satisfy the WHO standards except that those from the East Dart catchment will require some treatment for pH stability. One of the spring water from Charnwood Forest may also require some treatment for excessive amounts of total hardness.

From the area within which the points fall in the central diamond shaped field, Blackbrook and East Dart catchments have secondary salinity (weak acids and strong bases). Calder catchment has primary alkalinity (formed by salts of weak acids and strong bases) and secondary salinity.

The water from East Dart are alkali dominated while alkaline earths show dominance in Blackbrook and Calder catchments. These were compared to the rock chemistry data found within each of the three catchments and some important conclusions were drawn:

East Dart Catchment
Water is derived from weathered granitic material. This indicates that the water has not permeate deep down to the bed rock. It also supports the argument that the catchment is fully saturated all year round.

Blackbrook Catchment
Base exchange is found to have taken place and the water has therefore permeate the boulder clay, marl and has also come in contact with the Charnian rocks.

Calder Catchment
Only little base exchange has occurred, hence the water is derived from the overburden as well as the basaltic rocks.

The low mineralisation in the water samples indicates short stay in the ground. Thus, partially supporting the deductions that the catchments are almost fully saturated. The low mineralisation is also a characteristic of 'highland' springs.

Chapter 8
BASEFLOW RECESSION ANALYSIS AND ITS APPLICATION

8.1 Introduction

The purpose of this chapter is to derive recession constants for some catchments on hard rock areas in Britain and to relate them to the groundwater flow as geology exerts a great influence on the characteristics of low flows.

The study of baseflow recession provides an estimate of surplus groundwater. Properly evaluated recession curves provide information on short to medium term forecasting, an indication of the threshold of flow and the maintenance of minimum acceptable flow in the water industry. The derivation and quantification of the baseflow recession constant is of importance in low flow studies. Among many other methods for the derivation of the baseflow recession constant, this chapter describes the use of a statistical package on the computer, GENSTAT (Nelder et al, 1975), based on the principle of analysis of covariance. The method outlined in this chapter does not supersede earlier methods suggested by other authors but attempts to ease the laborious and subjective nature of the present manual methods. The recession constants (K) were used in the simple exponential recession equation (Barnes, 1939) to generate a series of baseflows as a test for its use as a predictive model. The fit between the model and historical flow was found to be greater than 99% thus confirming the applicability of the numerical method under field situation.

Catchments of relatively homogeneous hard rock lithology have been selected in Britain. Other data have been selected for comparison. Lithologically heterogeneous catchments have not been considered due to the reduced influence of geology on flow (Ineson, 1963; Browne, 1976).

8.2 Components of River Flow

Streamflow consists of three major components viz:

1. Surface flow
2. Interflow and
3. Baseflow or Groundwater discharge.

Surface flow represents precipitation which flows on the surface of the ground direct into the stream. The interflow is that portion of the precipitation which infiltrates the surface layers of the soil but moves laterally without reaching the saturated layers and consequently is discharged into the stream. At times it is difficult to differentiate the surface flow from the interflow and therefore, both are termed direct flow recession. Baseflow or Groundwater discharge is that portion of the precipitation which infiltrates downward under gravity into the main zone of saturation i.e. below the water table. This portion is discharged in the form of springs or seepages. It is this component that maintains streamflow during long dry periods sometimes referred to as dry weather flow (DWF) and it is this one that is being considered for the baseflow recession analysis.

The fourth component of a stream flow is bank storage. This occurs only when the river stage rises. This takes place during floods, water infiltrates into the permeable deposits adjacent to the stream. It is discharged when the water level falls. Where an extensive spread of alluvium borders a stream, bank storage can be quite considerable and this tends to merge with the baseflow. In any case, bank storage tends to discharge more rapidly than the baseflow.

8.3 Selection of Data

The basic data for the recession analysis is streamflow data. Its availability both in time and space together with its quality is of prime importance for the subsequent analysis.
The basis for the data selection includes:-

1. Natural (non-regulated) discharge of streams as other sources of flow may contribute to the baseflow when regulated. The discharge from a regulated source will introduce a major source of error. The regulation could be as a result of:

    (a) surface abstraction
    (b) surface effluents
    (c) groundwater abstraction
    (d) reservoirs or natural lakes.

2. Geologically homogeneous catchments are selected as it is difficult to accurately identify flows from different formations especially in geologically heterogeneous catchments. Heterogeneous catchments have the tendency to obscure baseflow recession since each formation contributes a different baseflow, even though all the recessions tend to merge into one with time. However, in practice, catchments are rarely completely homogeneous and therefore some combination of two or more formations may be considered. On this basis,

the dominant geology is taken to determine the homogeneity of the catchment area. The superficial deposits constitute only a fraction of the percentage dominant geology in the hard rock areas.

3. Catchments with areas of less than 160Km^2 were selected to allow time for the effects of interflow and bank storage to cease. Large catchment areas require longer dry periods for the interflow and bank storage to cease and therefore, some of the assumptions made in the analysis may not be valid.

Certain parameters such as average gradient, vegetation cover and land use do affect the recession curves but their influence is of secondary importance to geological considerations (Wright, 1968).

Most river gauging stations suffer from a loss of accuracy at their lowest flow due to poor sensitivity and inaccuracy of current meter gauging at low water velocities. Some river recording stations suffer a loss of accuracy at some seasons of the year due to weed growths, sewage fungus, siltation and algal growths that may be present on gauging structures.

Different devices have been used in recording the data collected. The basic recording devices in Britain include continuous recording devices, charts and observer boards. On the recording charts, only one spot is taken and in most cases the minimum reading. Normally, the observer boards are read once or twice daily and the average is taken. The daily means are taken from the continuous recording sites and this tends to average the diurnal effect during the day.

Data from 24 catchments were collected from the Institute of Hydrology (I.O.H), Wallingford, as in Table 8.1.

The periods selected cover the dry summer of 1964, and most of the dry periods of the early 1970s and 1980s.

8.4 Derivation of the Master Recession Curve

8.4.1 Review of Current Methods

The three most commonly used methods for the construction of a master recession curve as suggested by most authors (Toebes & Strang, 1964 and Hall, 1968) are:-

1. Strip Method

This is done by plotting individual recessions on tracing paper and superimposing them on each other to construct the master recession curve. Although it allows for visual inspection of the flows being analysed, a reasonable result may often only be obtained by altering the vertical or horizontal scales of some individual curves.

Table 8.1. Selected Catchments

Name of Stream/Catchment	Area(Km^2)
1. De Lank at De Lank	21.70
2. Warleggan at Trengoffe	25.20
3. East Dart at Bellever	21.50
4. Withey Brook at Bastreet	16.20
5. Blackbrook at One Barrow	8.36
6. Cander Water at Candermill	24.50
7. Little Eachaig at Dalinlongart	30.80
8. Calder at Muirshiel	12.40
9. Senni at Pont-Hen-Hafod	19.94
10. Wye at Cefn Brwyn	10.40
11. Severn at Plynlimon Flume	8.70
12. West Dart at Dunnabridge	49.70
13. West Allen at Hindley Wrae	75.10
14. Gairn at Invergairn	150.00
15. Girnock Burn at Littlemill	30.00
16. Ruchill at Cultybraggan	99.50
17. Ettrick Water at Lindean	37.50
18. Tima at Deep Hope	31.00
19. Coquet at Bygate	59.60
20. Usway Burn at Shillmoor	21.40
21. Kielder Burn at Kielder	58.80
22. Dove at Hollinsclough	8.05
23. Manifold at Hume End	44.03
24. Hamps at Waterhouses	39.63

2. Correlation Method

This method involves plotting discharge at one time against discharge at some time interval later. A curve or straight line is then fitted to the data points. In most cases, some standard curves are prepared to be matched with the one fitted to the data. The value from the standard curve to be used is subjective as it may not fit perfectly with that of the plotted data.

3. Tabulating Method

This method involves tabulating recession periods and after suitable time adjustments the average flows are calculated for the recorded period. It is similar to the strip method.

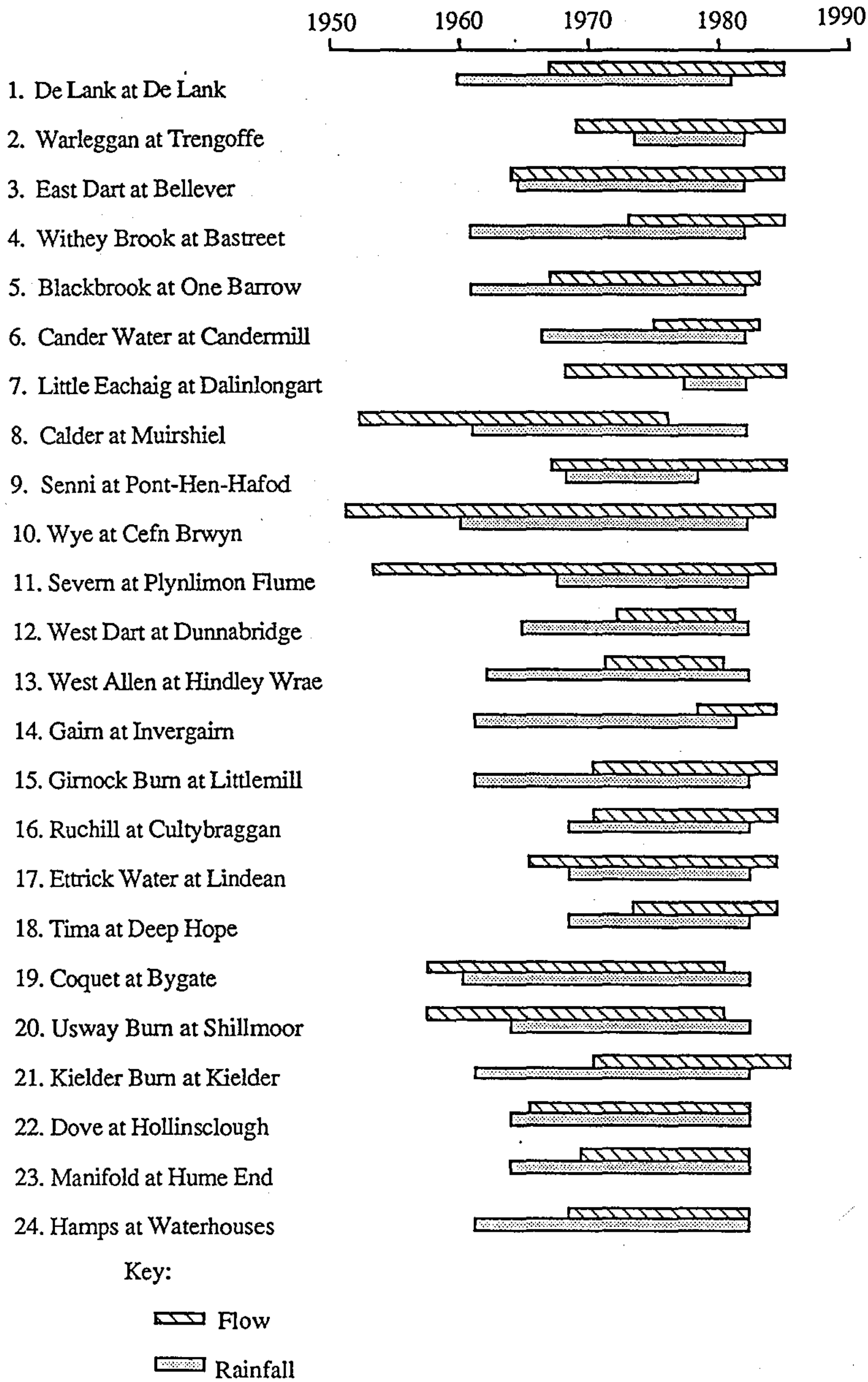


Figure 8.1 Flow and Rainfall Record Length

These methods are subjective, which means that no bounds can be stated for the possible error in the calculated constant. They are also liable to human error. In fact, the strip method becomes much more difficult in cases where many pieces of tracing paper are involved. No matter the intensity of light for the superimposition, it becomes opaque and does not allow for the inspection of the master recession curve.

For natural streamflow in homogeneous catchments, the baseflow recession curve is a short-term event. However, its recession varies from the next one on account of the variations in storage. A master recession curve can be derived from a number of baseflow recession curves of varying length in each DWF.

Baseflows are obtainable only in dry weather conditions over a long period of time. Most authors have tried to define the 'dry weather flow'. Pirt (1983), defines it as the average of the annual series of the minimum (7 consecutive days) flows. This definition corresponds to the SDWF (Seven Day Dry Weather Flow) of Cole (1966) and Hindley (1973). Hindley (1973), presented four definitions of DWF and one has been modified to suit this study, thus

> "long period of at least 7 daily mean flows in a dry weather condition to which none is credited more than 1mm of rainfall".

8.4.2 Curve Matching

The strip method and the simple exponential equation have been adopted for the data analysis. The earlier assumptions of Toebes and Strang (1964) as mentioned in section 8.4.3.1 do not hold true with the advent of computers and advancement in mathematics and statistics.

Ideal conditions for the derivation of a master recession curve is a wet winter followed by a dry summer such as in Britain (Downing, 1964; Ineson and Downing, 1964; Wright, 1968; Price, 1971; Browne, 1976 & 1981). The major problem posed for this sort of work is that there are hardly long enough periods without rain for a complete recession curve to be displayed in any one year in contrast to the tropics, but a synthetic curve can be compiled from the shorter portions during DWF representing dry periods of several years. In countries with only wet and dry seasons, the baseflow recession curve can be obtained more readily.

In order to isolate the DWF portions, the data was processed on the Loughborough

University main frame computer (Honeywell multics). Computer-subroutine programs were written to cope with the data manipulation as discussed in section 8.4.5.

8.4.3 Theoretical Background

8.4.3.1 Recession Equations

Barnes (1939) noted that a plot of river flow components on a semi-logarithmic paper tends to be a straight line which can then be used to describe the characteristics of a catchment. On this basis, many authors have carried out studies on flows using different sorts of equations to try to define the baseflow recession constant (Toebes & Strang, 1964). The most commonly used are:-

$$Q_t = Q_0 K^t \quad \text{.......................(8.1)}$$

$$Q_t = Q_0 K^{t^n} \quad \text{.................(8.2)}$$

$$Q_t = Q_0 e^{-yt} \quad \text{........................(8.3)}$$

Where

Q_0 = the initial discharge ($t = 0$)

Q_t = the discharge at a later time t (usually in days)

K = the recession constant, n and y are constants, while e is the base of the naperian logarithm.

The value of K varies between 0.1 for surface run-off to 0.99 for groundwater or baseflow recessions. Martin (1973), noted that in some 'well behaved' catchments all baseflow tends to have the same value of K; and he suggested that only under this condition can a master baseflow recession curve be derived for the determination of a master K.

Equation (8.2) is a double exponential equation. It has been shown that a semi-logarithmic plot can be a straight line only if a suitable 'n' is chosen (Toebes & Strang, 1964). Equations (8.1) and (8.2) are empirical. Equation (8.3) is similar to the simple exponential when the e^{-y} is replaced by k. This has found more application in the determination of storage coefficients when integrated (Wright, 1968).

Most authors have been critical of the type of equation used and over what length of the data such an equation is applicable (Browne, 1976 &1981). Toebes and Strang (1964) criticized the simple exponential equation and concluded that most authors use it because of its simplicity, lack of data and the use of the correlation methods in establishing a master curve. These assumptions no longer hold true with the advent of computers as will be shown in section 8.4.5. They found that for a simple functional relationship between storage and discharge, or storage and time, the simple exponential or hyperbola is satisfactory since it require only one constant. But for forecasting purposes an accurate fit is advocated especially at the lower end of the curve.

Browne (1976) carried out some studies on low flows around Devon. Because of the curvilinear nature of his graphs, he found it necessary to define two recessions and took only the lower section of the curve to represent the master recession constant.

8.4.4 Analysis of Covariance

The simple exponential equation has been used as a basis for the subsequent analysis. Thus

$$Q_t = Q_0 K^t$$

Taking logarithms the equation becomes

$$\log Q_t = \log Q_0 + t\log K.$$

Let $y_t = \log Q_t$

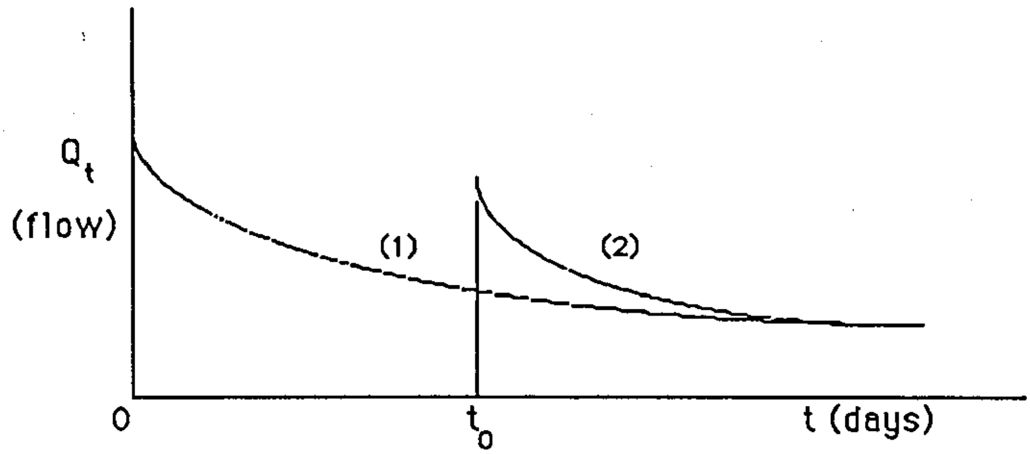
$\alpha = \log Q_0$

$\beta = \log K.$

Then

$$y_t = \alpha + \beta t \quad \text{.....................................(8.4)}$$

Suppose there is another curve with an unknown time origin $t_{0,}$



Then its equation is of the form

$$Q'_t = Q'_0 K^{(t - t_0)}$$

So that

$$\log Q'_t = \log Q'_0 + (t - t_0)\log K$$

$$\log Q'_t = (\log Q'_0 - t_0 \log K) + t\log K.$$

Let $\alpha' = \log Q'_0 - t_0 \log K$

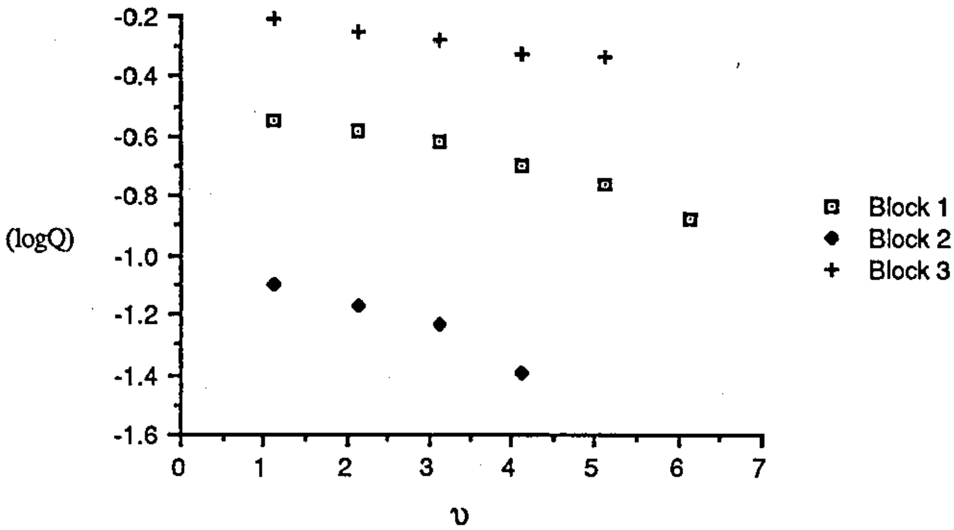
$$\beta' = \log K = \beta$$

Then, if

$y'_t = \log Q'_t$, we have

$$y'_t = \alpha' + \beta t \qquad \text{.................................(8.5)}$$

It can be seen from (8.4) and (8.5) that the recession curves give rise to a series of logflow lines with common slope β but different intercepts. Defining "block i" as the set of observations taken from the i^{th} recession curve, and assigning unit value of time to the initial point of each recession, the curves may be rearranged as shown in the following figure.



The appropriate statistical model for logflow is therefore a one-way analysis of variance with time as an added covariate.

Given $\quad y_{i\upsilon}$ = υth logflow measurement in block i

the model is

$$y_{i\upsilon} = \alpha_i + \beta\upsilon + \xi_{i\upsilon} \quad \text{.......................(8.6)}$$

where $\quad \alpha_i$ = Effect of block i

$\beta\upsilon$ = Effect of time

$\xi_{i\upsilon}$ = Random (error) effect. $\quad E[\xi_{i\upsilon}] = 0 \quad V[\xi_{i\upsilon}] = \sigma^2$.

Referring to Brownlee (1965; p. 378), a formula is given for the estimated average slope of k regression lines fitted to k blocks of observations

$$(X_{i\nu}, y_{i\nu}), \qquad i = 1, \ldots\ldots\ldots, k, \ \upsilon = 1, \ldots\ldots\ldots, n_i$$

where n_i is the number of observations in block i. It is

$$\bar{b} = \frac{\sum_{i=1}^{k} \sum_{\nu=1}^{n_i} (X_{i\nu} - X_{i.})\, y_{i\nu}}{\sum_{i=1}^{k} \sum_{\nu=1}^{n_i} (X_{i\nu} - X_{i.})^2}$$

where $\chi_{i.}$ is the average χ for block i. For our purposes this formula can be greatly simplified since

$$\chi_{i\nu} = \upsilon \qquad\qquad \upsilon = 1, 2, \ldots\ldots\ldots, n_i$$

and hence

$$\chi_{i.} = \frac{1 + 2 + 3 + \ldots\ldots\ldots\ldots + n_i}{n_i}$$

$$= \frac{1}{2}(n_i + 1)$$

It follows that,

$$\sum_{\nu=1}^{n_i} (\chi_{i\nu} - \chi_{i.}) y_{i\nu} = \sum_{\nu=1}^{n_i} (\upsilon - \tfrac{1}{2}(n_i + 1)) y_{i\nu}$$

$$= \sum_{\nu=1}^{n_i} \upsilon y_{i\nu} - \frac{1}{2}(n_i + 1) \sum_{\nu=1}^{n_i} y_{i\nu}$$

$$= \sum_{\nu=1}^{n_i} \upsilon y_{i\nu} - \frac{1}{2} n_i (n_i + 1) y_{i.}$$

where $y_{i.}$ is the average y for block i .

Also,

$$\sum_{\nu=1}^{n_i} (\chi_{i\nu} - \chi_{i.})^2 = \sum_{\nu=1}^{n_i} (\upsilon - \tfrac{1}{2}(n_i + 1))^2$$

$$= \sum_{\nu=1}^{n_i} [\upsilon^2 + \tfrac{1}{4}(n_i + 1)^2 - \upsilon(n_i + 1)]$$

$$= \sum_{\nu=1}^{n_i} \upsilon^2 + \sum_{\nu=1}^{n_i} \tfrac{1}{4}(n_i + 1)^2 - (n_i + 1) \sum_{\nu=1}^{n_i} \upsilon$$

$$= \frac{1}{6} n_i(n_i+1)(2n_i+1) + \frac{1}{4} n_i(n_i+1)^2 - (n_i+1)\frac{1}{2} n_i(n_i+1)$$

(using standard mathematical formulae)

$$= \frac{1}{12} n_i(n_i+1)(n_i-1)$$

$$= \frac{1}{12}(n_i^3 - n_i)$$

Hence

$$\bar{b} = \frac{\sum_{i=1}^{k}\left[\sum_{v=1}^{n_i} v y_{iv} - \frac{1}{2} n_i(n_i+1) y_{i.}\right]}{\sum_{i=1}^{k} \frac{1}{12}(n_i^3 - n_i)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (8.7).$$

The standard error can also be calculated. By analogy with Brownlee (1965; p.351)

$$\mathrm{var}(\bar{b}) = \frac{\sigma^2}{\sum_{i=1}^{k}\left[\sum_{v=1}^{n_i}(\chi_{iv} - \chi_{i.})^2\right]} = \frac{\sigma^2}{\sum_{i=1}^{k}\frac{1}{12}(n_i^3 - n_i)}$$

Further, σ^2 is estimated by

$$(n-k-1)\hat{\sigma}^2 = \sum_{i=1}^{k}\left[\sum_{v=1}^{n_i} y_{iv}^2 - \frac{1}{n_i}\left(\sum_{v=1}^{n_i} y_{iv}\right)^2\right] - \frac{\left[\sum_{i=1}^{k}\left[\sum_{v=1}^{n_i} v y_{iv} - \frac{1}{2}(n_i+1) n_i y_{i.}\right]\right]^2}{\sum_{i=1}^{k}\frac{1}{12}(n_i^3 - n_i)}$$

Denoting the variance of observations in block i by V_i,

$$\hat{\sigma}^2 = \frac{\sum_{i=1}^{k}\left[n_i V_i - \frac{1}{12}\bar{b}^2(n_i^3 - n_i)\right]}{(n-k-1)}$$

so that the estimated standard error is

$$s.e.(\bar{b}) = \left[\frac{12\sum_{i=1}^{k} n_i V_i - \bar{b}^2 \sum_{i=1}^{k} (n_i^3 - n_i)}{(n - k - 1) \sum_{i=1}^{k} (n_i^3 - n_i)} \right]^{\frac{1}{2}} \qquad (8.8)$$

The importance of the standard error lies in constructing confidence limits for β. To apply standard statistical results it is necessary to assume a normal distribution for the errors $\xi_{i\upsilon}$ in (8.6). To assess the validity of this assumption an analysis of residuals was carried out after fitting the model to 215 data points from 30 recessions in the West Dart catchment. A chi-squared goodness of fit test of the residuals to a normal distribution gave a chi-squared statistic of 0.97 on 8 degrees of freedom. It can be concluded that the residuals show a remarkably good fit to a normal distribution. Given that an assumption of normally distributed errors appears reasonable, P% confidence limits for the common slope b can be calculated in the usual way

$$\text{estimate} \pm t \times \text{standard error}$$

Here t is taken from tables of the student's t distribution with n - k - 1 degrees of freedom.

8.4.5 Computer Analysis

8.4.5.1 Method of Data Preparation for Analysis

With rainfall and flow data running for many years, a computer subroutine program was used to match corresponding days of rainfall and flow. The data was further divided into winter and summer water years to see if there were any significant differences between the two seasons. Winter is the season of recharge, therefore such differences are expected in the recession constants. Winter is considered from and October-March while summer is considered from April-September. Thereafter, flows on dry days were selected; specifying the consecutive number of days required. To account for the effects of interflow and bank storage which tends to distort the master recession curve, flow values for the first few days were discarded. The choice of values to discard is made by inspection using graphs and this is illustrated in section 8.5. Since the simple exponential equation represents a decay function, only decay flow values were considered in each block. The consecutive flows on dry days are numbered from 1, 2, 3,.....,n, in a block while blocks are numbered according to the order in the data set.

The blocks are then arranged in such a way that the data can be recognised by GENSTAT. The model (8.6) can be fitted within GENSTAT using the multiple regression subroutines (see Table 8.3). In fact internally the GENSTAT package separates the block effect into two parts

$$\alpha_i = \gamma + (\alpha_i - \gamma)$$

where γ is the overall constant effect and $(\alpha_i - \gamma)$ is the effect of block i adjusted for constant effect.

The model is fitted using the method of least squares. Least squares parameter estimates are produced, together with their standard errors. Note that the estimate for block 1 is set to zero, i.e. the effect of block 1 equals the constant, "time" is the estimate of β and "blocks i" are the estimates of $(\alpha_i - \gamma)$ the effect of the ith recession.

An analysis of variance table is also produced, enabling the model fit to be assessed by an F-test in the usual manner. The test statistic

$$F = \frac{\text{MS Regression}}{\text{MS Residual}}$$

is compared with the 5% (or stronger, 1%) value in tables of the F-distribution with degrees of freedom υ_1= DF Regression, υ_2 = DF Residual.

This process was carried out for 10 catchments chosen at random in Britain. The result is found to be an excellent fit by the F-test and also the percentage variance accounted for, $\%R^2$. (See Table 8.2).

Table 8.2. Computer Results from 10 Catchments in Britain (Summer)

Catchment	%R^2	F	υ_1	υ_2	$K=e^{\beta}$
West Dart at Dunnabridge	99.2	894.2	30	184	0.9726
East Dart at Bellever	98.4	472.7	55	354	0.9808
Severn at Plynlimon Flume	95.3	158.8	46	308	0.9574
Wye at Cefn Brwyn	97.1	225.6	49	278	0.9370
Blackbrook at One Barrow	96.0	174.8	64	401	0.9627
Ruchill at Cultybraggan	97.8	316.9	47	285	0.9385
Ettrick Water at Lindean	97.7	264.8	47	251	0.9372
Manifold at Hume End	97.1	252.1	52	336	0.9419
Withey Brook at Bastreet	99.3	841.3	23	120	0.9562
De Lank at De Lank	99.1	804.9	53	332	0.9623

8.4.6 Numerical Example

Data

For the purpose of illustration, three blocks of fictional data are presented.

time	block	flow(m^3)	logflow			
1	1	0.56	-0.5798	$n = 15$, $n_1 = 6$	$k = 3$, $V_1 = 0.01327$	$y_{1\cdot} = -0.7165$
2	1	0.54	-0.6162		$n_1^3 - n_1 = 210$	
3	1	0.52	-0.6539		$\Sigma\upsilon y_{1\upsilon} = -16.2002$	
4	1	0.48	-0.7340			
5	1	0.45	-0.7985	$SUM_1 = -16.2002 - 21(-0.7165) = -1.1537$		
6	1	0.40	-0.9163			
1	2	0.32	-1.1394	$n_2 = 4$	$V_2 = 0.01144$	$y_{2\cdot} = -1.2609$
2	2	0.30	-1.2040		$n_2^3 - n_2 = 60$	
3	2	0.28	-1.2730		$\Sigma\upsilon y_{2\upsilon} = -13.0748$	
4	2	0.24	-1.4271	$SUM_2 = -13.0748 - 10(-1.2609) = -0.4658$		
1	3	0.78	-0.2485	$n_3 = 5$	$V_3 = 0.00201$	$y_{3\cdot} = -0.3167$
2	3	0.75	-0.2877			
3	3	0.73	-0.3147	$n_3^3 - n_3 = 120$		
4	3	0.70	-0.3564	$\Sigma\upsilon y_{3\upsilon} = -5.0491$		
5	3	0.69	-0.3711	$SUM_3 = -5.0491 - 15(-0.3167) = -0.2986$		

$$\left(SUM_i = \sum_{\upsilon=1}^{n_i} \upsilon y_{i\upsilon} - \tfrac{1}{2}(n_i+1)n_i y_{i\cdot} \right)$$

Therefore, to calculate for the ESTIMATE form (7),

$$\bar{b} = \frac{12(-1.1537 - 0.4658 - 0.2986)}{210 + 60 + 120}$$

```
GENSTAT V     MARK 4.03
(C)1980 LAWES AGRICULTURAL TRUST (ROTHAMSTED EXPERIMENTAL STATION)

'refe'match
'unit' $ 15
'caption' ''EXAMPLE''
'vari' flow,time
'fact' blocks $ 3
'read/prin=em'time,blocks,flow
'calc' logflow=log(flow)
'terms' time,blocks,logflow
'y' logflow
'fit/prin=acu'time,blocks
'run'

EXAMPLE
    time      MNMINMAX        3.0667        1.0000        6.0000    15  VALUES
\c  0 MISSING
    flow      MNMINMAX        0.5160        0.2400        0.7800    15  VALUES
\c  0 MISSING

   ......................................................................


***** REGRESSION ANALYSIS *****


*** REGRESSION COEFFICIENTS ***

Y-VARIATE: logflow
                  ESTIMATE        S.E.          T

CONSTANT         -0.508076     0.031619      -16.07
time             -0.059535     0.007523       -7.91
blocks 2         -0.603958     0.028686      -21.05
blocks 3          0.370964     0.026239       14.14

*** ANALYSIS OF VARIANCE ***

               DF          SS           MS

REGRESSN        3      2.10169     0.700562
RESIDUAL       11      0.02023     0.001839
   TOTAL       14      2.12192     0.151566

  CHANGE       -3     -2.10169     0.700562

PERCENTAGE VARIANCE ACCOUNTED FOR 98.8

*** OBSERVED AND FITTED VALUES ***
                  OBSERVED       FITTED      RESIDUAL

             1     -0.580       -0.568       -0.012
             2     -0.616       -0.627        0.011
             3     -0.654       -0.687        0.033
             4     -0.734       -0.746        0.012
             5     -0.799       -0.806        0.007
             6     -0.916       -0.865       -0.051
             7     -1.139       -1.172        0.032
             8     -1.204       -1.231        0.027
             9     -1.273       -1.291        0.018
            10     -1.427       -1.350       -0.077
            11     -0.248       -0.197       -0.052
            12     -0.288       -0.256       -0.031
            13     -0.315       -0.316        0.001
            14     -0.357       -0.375        0.019
            15     -0.371       -0.435        0.064
```

Table 8.3 Computer Printout.

$$\bar{b} = -0.0590184$$

The GENSTAT printout in Table 8.3 is a confirmation. It should be noted that the slight difference in the two ESTIMATES is due to differences in working decimal places.

$$\sum_{i=1}^{k}(n_i^3 - n_i) = 390$$

$$\bar{b} = -0.059535$$

$$s.e(\bar{b}) = \left[\frac{12(0.1354102) - (0.059)^2 \times 390}{11 \times 390}\right]^{\frac{1}{2}}$$

$$= 0.007894$$

With 11 degrees of freedom, from tables of the Student's t distribution the 95% value is t = 2.20. Hence 95% confidence limits are

$$-0.0590 \pm 0.0174$$

8.5 Result and Discussion

The result of the baseflow recession analysis is presented in Table 8.4.

It can be noted that there is a lack of sensitivity at higher values of K, as there is a clear bunching of K as it approaches unity. At times, three or four decimal places have to be taken into account after the 0.9 for any differences to be noticed between catchments. This has generated a lot of confusion. Martin (1973), took advantage of the simple exponential decay in nuclear physics ($N = N_0e^{-bt}$) by substituting e^{-b} term with K. The physicist makes use of 'half life' which is the time for a radioactive substance to half or as the hydrologist may put it, the time for the streamflow to half.

If $t_{0.5}$ is the time required for the baseflow of a stream to half, accordingly substituting in equation (8.1)

$$Q_{t0.5} = Q_0K^{t0.5} \quad \text{.................................}(8.9)$$

where

$Q_{t0.5}$ is the discharge at time $t_{0.5}$

by definition

$t_{0.5} = (\log 1/2)/\log K$ ....(8.10)

The values of $t_{0.5}$ have been found (Martin, 1973; Browne, 1976) to range between zero and infinity but in practice, they are found to rarely exceed 200. This increased sensitivity permits a more reliable comparison between recessions to be made and it has a much greater physical meaning than 'K'. Singh and Stall (1971), suggested a time for the recession to fall by one log cycle (0.1).

Table 8.4 Baseflow Recession Constants (K) and $t_{0.5}$

Name of Stream	Winter(K)	$t_{0.5}$	Summer (K)	$t_{0.5}$
1. De Lank at De Lank	0.9571	16	0.9623	18
2. Warleggan at Trengoffe	0.9573	16	0.9646	19
3. East Dart at Bellever	0.9460	12	0.9808	36
4. Withey Brook at Bastreet	0.9474	13	0.9562	15
5. Blackbrook at One Barrow	0.9595	17	0.9627	18
6. Cander Water at Candermill	0.9239	10	0.9239	9
7 Little Eachaig at Dalinlongart	0.9025	6	0.9025	7
8. Calder at Muirshiel	0.8403	4	0.9246	9
9. Senni at Pont-Hen-Hafod	0.9285	9	0.9584	16
10. Wye at Cefn Brwyn	0.9146	8	0.9370	11
11. Severn at Plynlimon Flume	0.9101	7	0.9574	16
12. West Dart at Dunnabridge	0.9497	13	0.9726	25
13. West Allen at Hindley Wrae	0.9328	10	0.9502	14
14. Gairn at Invergairn	-	-	0.9626	18
15. Carron at Sgodachail	0.9125	8	0.9369	11
16. Girnock Burn at Littlemill	0.9321	10	0.8921	6
17. Ruchill at Cultybraggan	0.9084	7	0.9385	11
18. Ettrick Water at Lindean	0.9303	10	0.9372	11
19. Tima at Deep Hope	0.8790	5	0.9237	9
20. Coquet at Bygate	0.9590	17	0.9705	23
21. Usway Burn at Shillmoor	0.9587	16	0.9708	23
22. Kielder Burn at Kielder	0.9554	15	0.9641	19
23. Dove at Hollinsclough	0.9342	10	0.9566	16
24. Manifold at Hume End	0.9360	10	0.9419	12
25. Hamps at Waterhouses	0.9178	8	0.9348	10

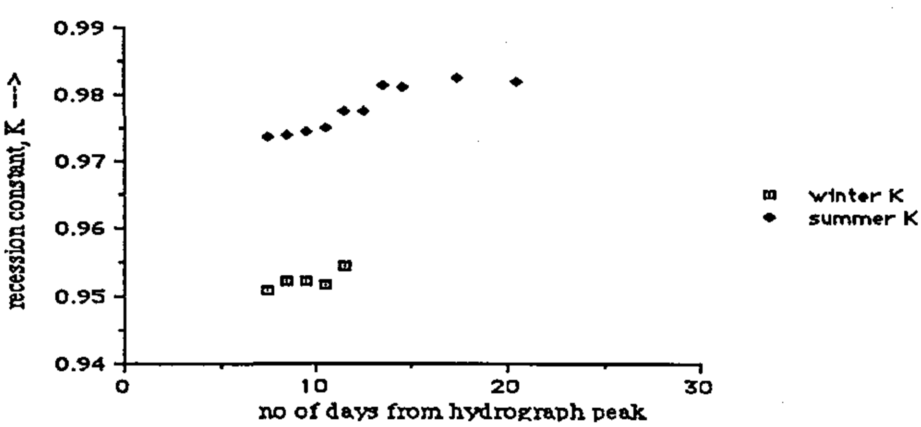
Some of the winter and summer results were tested by varying the number of consecutive DWF to check for any differences in the recessions. The result of such a test for West Dart is presented in the Table 8.5.

Table 8.5 The Effect of Length of Recession Block(s) on K

	Winter			Summer		
No. of Days	Blocks	K	$t_{0.5}$	Blocks	K	$t_{0.5}$
7	13	0.9497	13	30	0.9726	25
8	8	0.9510	14	27	0.9729	25
9	4	0.9511	14	24	0.9733	26
10	3	0.9505	14	19	0.9739	26
11	1	0.9532	14	14	0.9763	29
12	-	-	-	11	0.9765	29
13	-	-	-	7	0.9803	34
14	-	-	-	6	0.9800	34
17	-	-	-	2	0.9813	37
20	-	-	-	1	0.9808	36

Because winter is wetter than summer there were fewer blocks of consecutive DWF. The $t_{0.5}$ for summer shows that it takes more days for the flow to halve than in winter. This indicates that the most sustaining source, baseflow, is the most contributing flow in the riverflow during summer season. In general, this also confirms the low K values for winter recessions as in Table 8.5. A typical plot of the k values in Table 8.5 is presented in figure 8.2.

Figure 8.3 Sensitivity of K to number of days in recession block



From the figure, it can be inferred that summer recessions consist of the most sustaining flow, baseflow. The winter values indicate steeper recession, showing that they are affected by other components of the river flow. This is however, not surprising since the ground is fully saturated in winter in temperate regions and also considering the melt waters from frozen ground or bodies of water. Therefore, summer values have been used to characterise the catchments. The result is presented in Table 8.6.

However, some authors have made conclusions that in summer, recessions are steeper than in winter (Browne, 1976). They attributed this to evapotranspiration and less viscosity of water in summer and hence the increase in velocity and consequently the rate of depletion. The viscosity of water is found to decrease by 20% from 4^0C to 10^0C (Weast, 1984). Some authors however, attributed this to the presence of more storage in winter than in summer (Ineson & Downing, 1964; Browne, 1981).

The result of this study has shown that there are steeper recessions in winter than summer because of other residual contributing components of the riverflow other than the baseflow. The difference in winter and summer recessions are significant compared to the findings of Wright (1968) and Browne (1976).

On the basis of the above findings, the summer values have been used to represent the recession constants of the selected catchments as in Table 8.6.

Generally, the $t_{0.5}$ values indicate that Scottish catchments exhibit short and steeper recessions reflecting both the limited groundwater potential and low permeability than the rest of the study areas. Devon and Cornwall sites have higher groundwater potentials than both Wales and Scotland. It immediately looks apparent that if Devon and Cornwall represents the southern part of Britain, Charnwood and Wales the Midlands while Scotland the north, the result as regards the groundwater potentials reflects the glacial activities during the Pleistocene; during which most of the soil cover in Scotland was eroded, in the Midlands there was erosion as well as deposition while little or no erosion took place in the south. However, this is not the case since weathering of considerable depth has been recorded in Scotland and the Midlands (Moore & Gribble, 1980; Glending, 1981 & Alexander, 1983).

Table 8.6 is comparable to Table 4.1 of the soils summary. The water bearing potentials of the catchments based on the groupings is related closely to the soils and the superficials. The soils of Dartmoor and Cornwall are most permeable while the Scottish catchments are the least permeable; and those representing the Midlands are intermediate. This obviously indicates that the soils play an important role in the process of groundwater recharge through infiltration.

Table 8.6. Geology, Baseflow Recession Constants (K) and $t_{0.5}$ Values for Different Sites

Area	Name of Stream/Catchment	Dominant Geology	Summer (K)	t0.5
Devon and Cornwall	De Lank at De Lank	Granite	0.9623	18
	Warleggan at Trengoffe	Granite	0.9646	19
	East Dart at Bellever	Granite	0.9808	36
	West Dart at Dunnabridge	Granite	0.9726	25
	Withey Brook at Bastreet	Granite	0.9562	15
Wales	Senni at Pont-Hen-Hafod	Old Red Sandstone	0.9584	16
	Severn at Plynlimon Flume	Mudstones & Shales	0.9574	16
	Wye at Cefn Brwyn	Mudstones & Shales	0.9370	11
Charn-wood Forest	Blackbrook at One Barrow	Precambrian	0.9627	18
Scotland	Cander Water at Candermill	Coal Measures	0.9239	9
	Little Eachaig at Dalinlongart	Mica Schist	0.9025	7
	Calder at Muirshiel	Basaltic	0.9246	9
	Girnock Burn at Littlemill	Granite & Schist	0.8921	6
	Ruchill at Cultybraggan	Quartz-Mica-Schist	0.9385	11
Other Areas	Coquet at Bygate	Andesitic Lavas	0.9705	23
	Usway Burn at Shillmoor	Andesitic Lavas	0.9708	23
	West Allen at Hindley Wrae	Limestone	0.9502	14
	Gairn at Invergairn	Gneiss & Granite	0.9626	18
	Ettrick Water at Lindean	Grits/Graywacke/Shale	0.9372	11
	Tima at Deep Hope	Grits/Graywacke/Shale	0.9237	9
	Kielder Burn at Kielder	Limestone/sst/dyke	0.9641	19
	Dove at Hollinsclough	Limestone/Shale/sst	0.9566	16
	Manifold at Hume End	Mudstone/sst/Shale	0.9419	12
	Hamps at Waterhouses	Limestone	0.9348	10

In as much as this is a well established fact, the superficials also play a useful role in the water bearing and transmitting ability of a catchment. The superficials in Dartmoor and Cornwall, referred to as subsoils consist mostly of river alluvium and weathered granite with some highland peat. Blackbrook superficials consists of boulder clay, alluvium, localised sand and gravel with Keuper marl (Mercian mudstones) as clastics. The Scottish catchments consist mainly of morainic sediments, boulder clay, highland peat and some localised sand and gravel. From the aforementioned, it is apparent that the Dartmoor and Cornwall catchments are more permeable than the Scottish and Blackrook catchments considering the fact that rainfall is not lacking.

From the result in Table 8.6, it can be seen that the time taken for the baseflow to halve ($t_{0.5}$) has a greater application in this study. In Devon and Cornwall sites, it takes East Dart 36 days for the baseflow to halve, indicating a higher groundwater potential than the rest of the catchments. By analogy, Severn and Senni have more groundwater potentials than the rest of the Welsh catchments. It follows that in Scotland, Calder and Ruchill at Cultybraggen have more groundwater potential than the rest of the catchments.

Therefore, East Dart, Blackbrook and Calder catchments were chosen for detailed study. Calder was chosen in Scotland instead of Ruchill because permission to access Ruchill was turned down by the estate agents.

In comparison to permeable catchments (Browne, 1976 & 1981), it takes fewer number of days for the baseflow on hard rock areas to halve. This result is expected since hard rock areas have lesser storage capacity than permeable catchments due to the nature of their geology.

However, some baseflow studies have given ranges of the baseflow index (I.O.H, Wallingford, (1980)), and the recession constants (Wright, 1968) for certain lithologies and catchments respectively which tend to overlap. The overlapped values make it difficult to ascertain the contribution from different lithologies.

There is little or no difference between the values of the hard rock and other selected formations as the initial catchment selection was based on 'soil 5' (100% hard rock catchments) of the Institute of Hydrology, Wallingford (1980), signifying little or no permeabilities.

8.6 Field Application of the Method

To test the applicability of the model under field conditions, nine of the catchments were selected at random for this purpose. The flow data (recession blocks) was divided into two data sets for the purpose of calibration and validation respectively. The numerical equation (8.7) was applied to the data set I to derive K (Table 8.7). The value derived was then inserted in the simple exponential equation using flow values in data set II to predict their mean flows. The GENSTAT statistical package was used for the analysis. The percentage variance accounted for (R^2) was greater than 99% for all the catchments. The statistics of the observed and predicted flows are compared in Table 8.7. The observed and predicted flows indicate that the two samples are identical and could have been drawn from the same population.

Table 8.7 Statistical Characteristics of the Observed and Predicted Flows (cumecs)

Catchment	K(day^{-1}) Set I	Observed Flows Mean I	Predicted Flows mean II	Residuals mean
East Dart at Bellever	0.9692	0.2362	0.2352	0.0010
Withey Brook	0.9621	0.2096	0.2117	-0.0021
Blackbrook	0.9616	0.0243	0.0243	0.0000
Calder	0.8972	0.1057	0.1037	0.0020
Wye	0.9307	0.0920	0.0922	-0.0002
Severn	0.9453	0.0822	0.0821	0.0001
Ruchill	0.9363	0.5212	0.5224	-0.0012
Ettrick	0.9439	0.2613	0.2648	-0.0035
De Lank	0.9724	0.1478	0.1514	-0.0036

8.7 Application in the Water Industry

The master recession constant K, which represents the slope of the baseflow is versatile and can be used for a number of purposes. In its application, the climatic factors such as evaporation and evapotranspiration are considered secondary to geological factors in the derivation are assumed to average out in a water year.

Apart from the fact that high K values indicate high permeability and possibly storage potential and also the time for flow to halve, other applications include forecasting, derivation of formation constants, formation yield and infiltration rates.

Making use of the simple exponential equation and taking Q_o as the flow at the start of a forecasting period, the flow Q_t at time t later can be forecast. This method enables the prescription of low flow values for a river or the catchment concerned. The prescribed low flow values are important in the water industry especially for water abstraction in dry season or drought situations.

To determine the yield or volume of water released from storage from a catchment, equation

(8.1) is integrated with t as the time units; and also remembering that the volume of water discharged during time dt is qdt and is equal to the decrease in storage S_t remaining in the basin at any time t, viz:

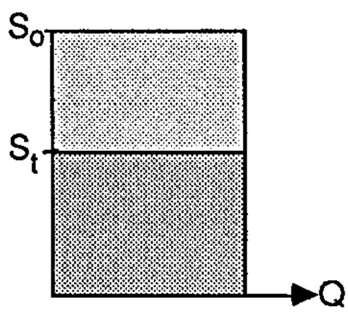
$$S_t = -\frac{Q_t}{\ln K} \quad \text{.........................} (8.12)$$

as given by Lindsley et al (1982)

By analogy, it follows that volume in active storage at time t = 0 (at Q_o) is

$$S_o = -\frac{Q_o}{\ln K} \quad \text{.........................} (8.13)$$

Therefore, the volume of water released from storage, ΔG, (baseflow) over a period of time as illustrated below



is

$$\Delta G = S_0 - S_t$$

and combining equations (8.12) and (8.13)

$$\Delta G = -\frac{Q_o}{\ln K} - \left[-\frac{Q_o K^t}{\ln K}\right]$$

$$\Delta G = \frac{Q_o\left[K^t - 1\right]}{\ln K} \quad \text{.........................} (8.14)$$

Equation (8.14) can be used to estimate the yield or volume of water released from storage.

The flow values (Q_0) for the three selected catchments are as follows:-

East dart:	8.303×10^4 m^3/day	K = 0.9808
Blackbrook:	1.720×10^4 m^3/day	K = 0.9627
Calder:	7.989×10^4 m^3/day	K = 0.9246

Substituting the above values in equation (8.14), the volume of water that would be released from storage in each catchment per water year is

East Dart:	$\Delta G = 1.032 \times 10^6$ m^3
Blackbrook:	$\Delta G = 0.003 \times 10^6$ m^3
Calder:	$\Delta G = 0.086 \times 10^6$ m^3

The volume released is a function of the storage and the area of the catchment. The more area available for recharge the greater the quantity of water in active storage assuming all parts of the catchment is permeable.

To assess the effective infiltration rates, the impervious areal coverage for each catchment was mapped out. In the Blackbrook catchment, Martin (1967) carried out an investigation into the parameters affecting runoff. His calculation of the land utilization provides information on land available for recharge. The impervious areas consist of roads, rock outcrops, paved and roof areas. Martin's values and those for the other two catchments are presented in Table 8.8.

Table 8.8 Rock outcrops and paved and roof areas

Catchment	Rocky Outcrops (Km^2)	Roads, Paved & Roof areas (Km^2)	Total Impervious Area (Km^2)	Area Available for Recharge (Km^2)
East Dart	1.075	0.237	1.30	20.20
Blackbrook	0.120	0.167	0.287	8.07
Calder	0.17	-	0.17	12.23

Dividing the volume of water released from storage per year by the area of the catchment gives an indication of the average annual infiltration rate. The average annual infiltration rates are 0.05m/yr, 0.4×10^{-3}m/yr and 0.7×10^{-2}m/yr for East Dart, Blackbrook and Calder catchments respectively.

East Dart has the highest infiltration rate and this confirms the permeable nature of the subsoils as they consist of weathered granite material, gravel and sands with small proportion of clay. Both Blackbrook and Calder catchments have very low infiltration rates, this can be attributed to the impermeable nature of the subsoils which are mainly boulder clay, marl and morainic sediments. These approximate values of infiltration rates should not be confused with soil permeabilities because the soils and subsoils are not saturated at field capacity all year round. The result generally supports the fact that East Dart catchment is more permeable than Blackbrook and Calder catchments as earlier deduced from the findings of chapter 4. More investigations on permeability for the subsoils in Blackbrook catchment (the only catchment with wells) is carried out in chapter 6.

To deduce the specific yield or storage coefficients of the catchments, there is a need to know the groundwater levels. Wright (1974) has used baseflow data in conjunction with groundwater levels to derive the storage coefficient of a limestone catchment. This is not possible in this investigation because there are either few wells or none in the catchments and the British Geological Survey does not monitor ground water levels in hard rock areas (pers. comm. January, 1988).

8.8 Summary

Baseflow recession constants have been shown to be a useful tool in characterising the behaviour of low flows. From a combination of theoretical, empirical and practical consideration, it has been possible to use the simple exponential decay function aided by a computer statistical package to derive baseflow recession constants for some British hard rock catchments. The computer statistical package has been found to be very effective and allows for rapid and accurate result, and is more flexible than manual methods. The baseflow recession constant which reflects the permeability of a catchment can be used as a preliminary tool in a regional survey because of its suitability as an index of geology. The method can be used as an explanatory as well as a predictive model. The procedure of the derivation of the recession constants has also been shown to be consistent and this is necessary if inter-catchment comparison or interpolation of K values is to be meaningful.

Its applicability in the water industry has been shown to be invaluable for flow prediction and the determination of mean infiltration rates.

Chapter 9

CONCLUSION, RECOMMENDATIONS AND FURTHER RESEARCH

9.1 Conclusion

An investigation of groundwater potential in three hard rock catchments for domestic and/or industrial supply has been carried out. Water balance computations for the three catchments supports the evidence of surplus water and shows that potential evapotranspiration is not crucial in any of the catchments investigated. It is concluded that in none of the three catchments was there sufficient groundwater to satisfy industrial demand. However, in two of the catchments the groundwater could prove sufficient for domestic supply provided that:

(a) large diameter wells are constructed to act as reservoirs and
(b) wells are positioned to make most effective use of the sandy gravel aquifers.

Because geology has a great influence on the characteristics of low flows, baseflow recession analysis was carried out on relatively small catchments as a prelude to selecting catchments for detailed investigation. A number of conclusions from this initial baseflow recession analysis can be made:

1. That baseflow recession analysis is a useful tool in a preliminary work in field investigation in a hydrogeological study.
2. From a combination of theoretical, empirical and practical considerations, aided by a computer based statistical package, a simple decay function has been adopted to develop a model for the derivation of baseflow recession constants.
3. The methodology developed is very effective and allows for rapid and accurate results and gives more flexibility than manual plotting of a master recession curve.
4. Winter values have been found to be influenced by other components of river flow such as melted ice, interflow and bank flow. Hence, summer recessions better represent recession constants.
5. It has been shown also that the time taken for flow values to halve can be used as a predictive model for gauged catchments.

The results can be used for both explanatory and predictive purposes. The procedure for the derivation of baseflow recession constant (K) was shown to be consistent; this is necessary if inter - catchment comparison or interpolation of K values is to be meaningful. By characterising the catchments using recession constants, East dart, Blackbrook and Calder catchments were selected; each representing the South, Midlands and the North respectively.

An intensive study of the geology in chapter 3 reveals that the three catchments are not similar geologically; but hydrogeologically, Blackbrook is similar to the Calder catchment. The hydrogeological units of importance are the weathered material (regolith), structures, glacial sands and gravels and superficial deposits. In order to determine their existence, thickness and lateral extents, geophysical survey (resistivity and electromagnetic methods) were carried out. A maximum thickness of 20m was recorded for sandy gravel in Blackbrook catchment and 40m of weathered granitic material in East Dart catchment.

This study has shown that resistivity alone cannot be used to delineate formations hence borehole and auger hole logs are necessary for correlation purposes.

Because soil plays an important role in aquifer recharge, a study of the soils supported by their particle size distribution analysis indicated that East Dart catchment is the most permeable of the three catchments. Subsequent conclusions from baseflow analysis and aquifer characteristics have supported this claim.

Pumping tests were carried out in the Blackbrook catchment. Transmissivity and permeability values were found to be generally very low for wells sunk in boulder clay and marl confirming they are aquicludes. The permeability values are however comparable to the ranges given for the soils ($K = 0.01$ to $0.3 m\ day^{-1}$). One borehole sunk in the sandy gravel had a higher permeability ($K = 2.41 m\ day^{-1}$) than those in the boulder clay and marl. The East Dart catchment was found to be comparable to the basement complex areas of Nigeria (Fadama) and the Dambos of Zambia; with a characteristic weathered granite head. It was concluded that borehole construction in East Dart catchment can be economical if topography, depth of weathered material and lateral extents of the aquifers are taken into consideration in borehole siting. Borehole construction is only feasible in the sandy gravel in the Blackbrook catchment. Large diameter open wells are feasible in areas of clay and marl for small community or household supply. The conditions for groundwater abstraction in Blackbrook catchment are applicable to Calder catchment since they are hydrogeologically similar.

Low mineralisation has shown that the spring waters have passed through the subsoils but only for short period. Their flow paths through the subsoils is further substantiated by ionic exchange as the water permeates the subsoils and the weathered bedrock material. In East Dart catchment, the water permeates only the weathered rock material. In Blackbrook and Calder catchments, the water permeates the subsoils and also come in contact with the bedrock. A comparison of the water chemistry data with WHO standards for potable waters shows generally that the spring waters are of good quality and can be used as sources of water supply, except that spring waters from East Dart catchment require some treatment for pH stability.

9.2 Recommendations and Further Research

Joint and fissure systems are known to be important groundwater conduits in hard rock catchments. Further research is required to determine the extent, nature of joint and fissure systems. It would therefore be useful to further investigate them with the electromagnetometer: the equipment was found to be effective for this purpose in order to locate the trend of main joints and the fissure system especially in the Blackbrook catchment.

The nature and form of occurrence of the springs are not well established in the Blackbrook catchment although they are known to be reliable. A further investigation is necessary to support their mode of occurrence as claimed in Chapter 6: that they issue out from the boundary between permeable and impermeable layers.

In order to delineate the groundwater flow regimes, water table data is vital. Since it requires a lot of effort and time to acquire the necessary licence from the government and permission from farmers who are mostly tenants, further research on this subject is recommended for the Blackbrook catchment because of easy accessibility and its proximity to Loughborough coupled with the availability of few wells. Although the catchment is not enough to supply Loughborough, it may act as a potential source in times of natural disaster (such as radioactive contamination of surface supply) and war.

Although the study was based on British catchments, the method of investigation can be applied to regions of similar geological characteristics.

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Appendix 1A EM34-3 Traverse graphs and VES 1, 2, 11 and 12 for the Blackbrook at One Barrow Catchment

Figure a **EM34-3 TRAVERSE 2**

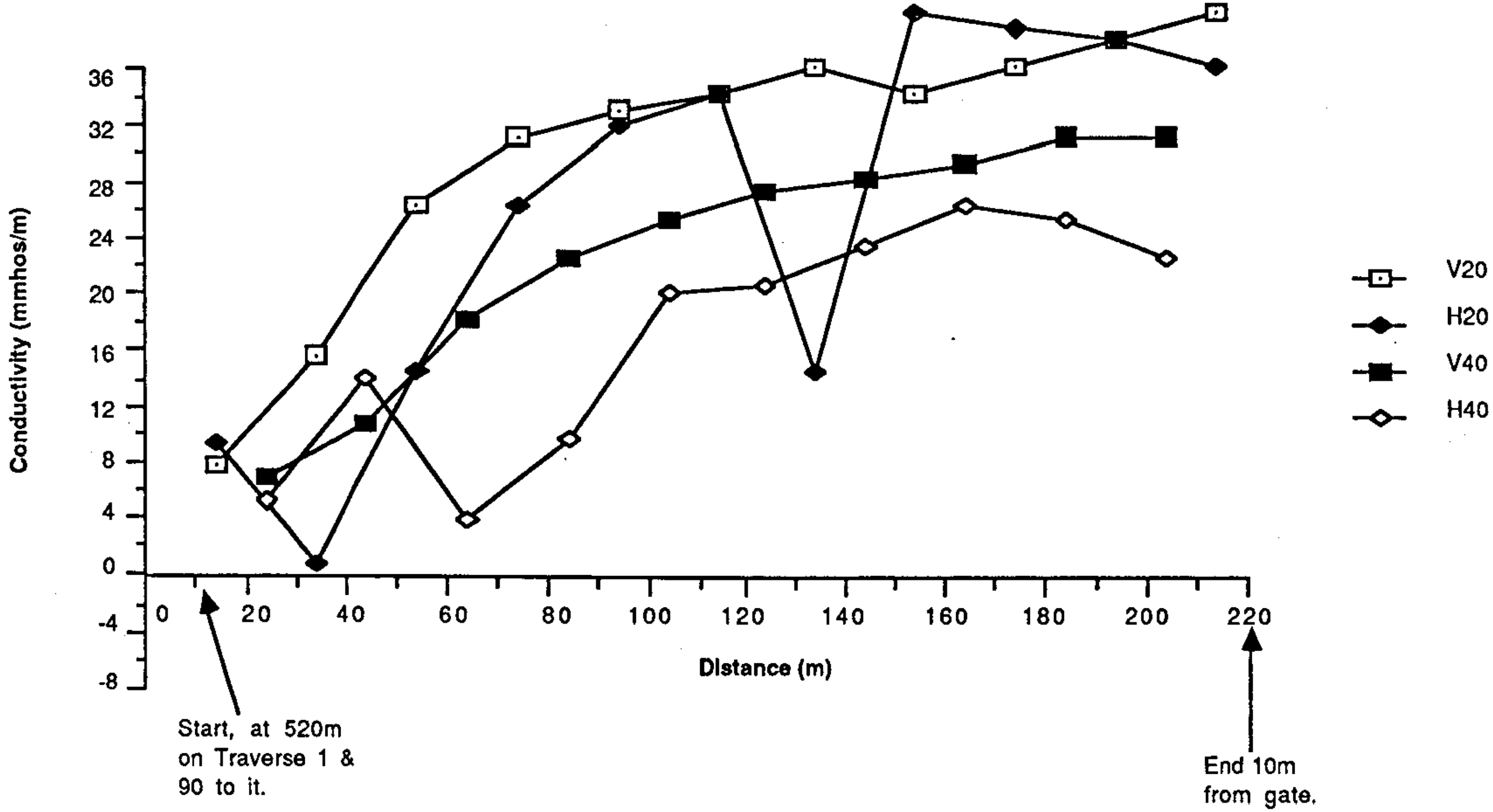
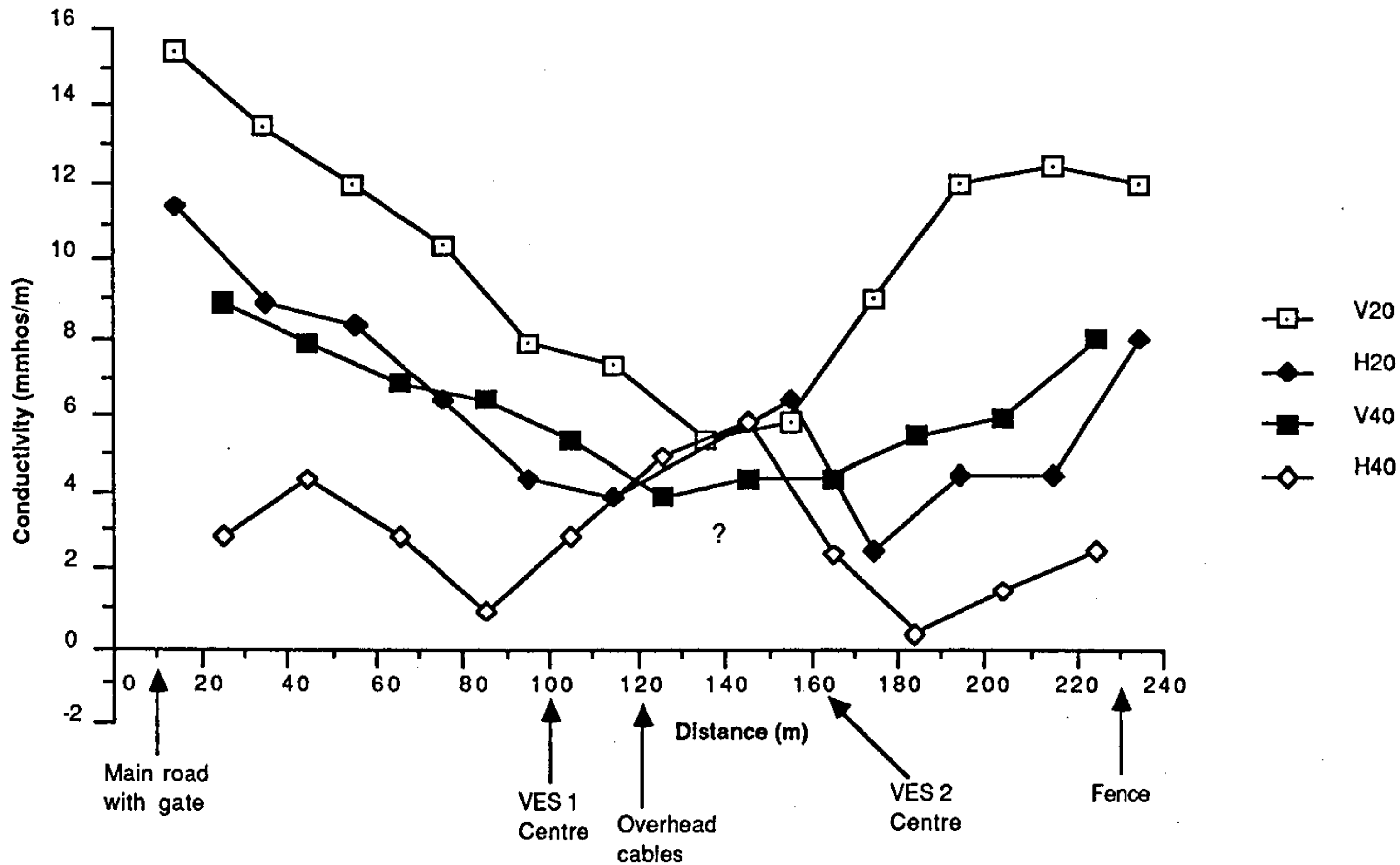
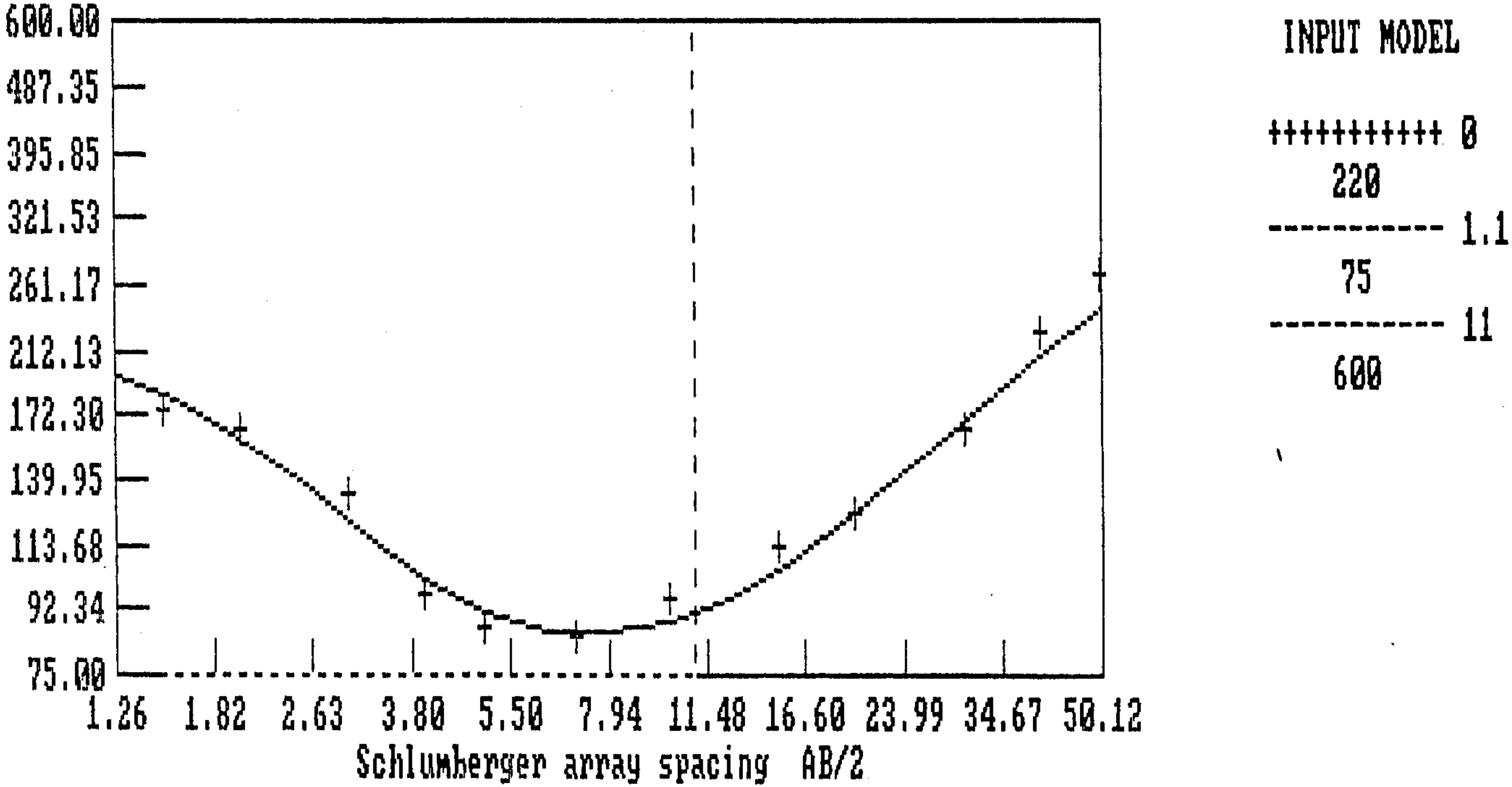


Figure b **EM34-3 TRAVERSE 3**



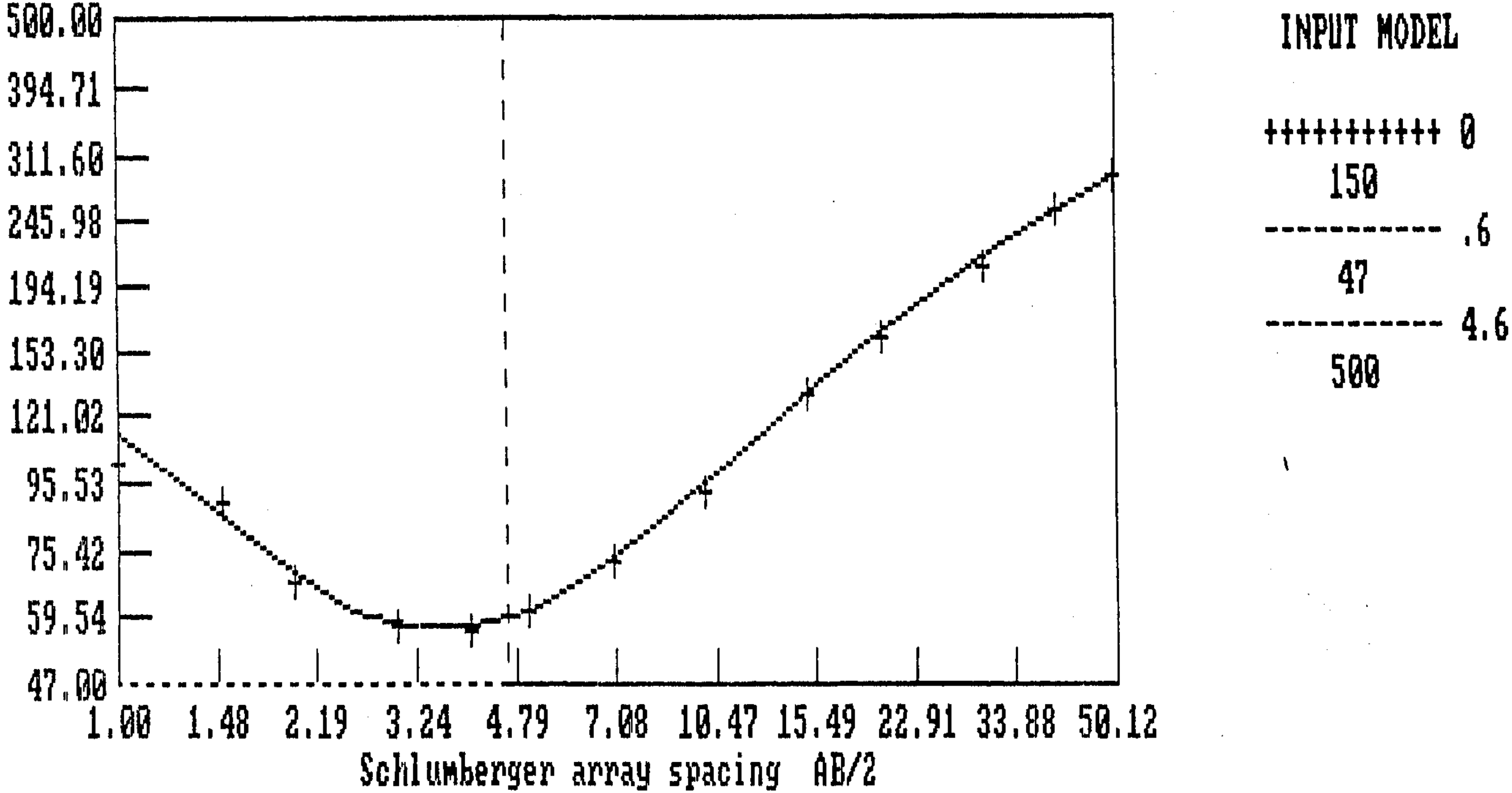
BBROOK1 **Figure c** VES1

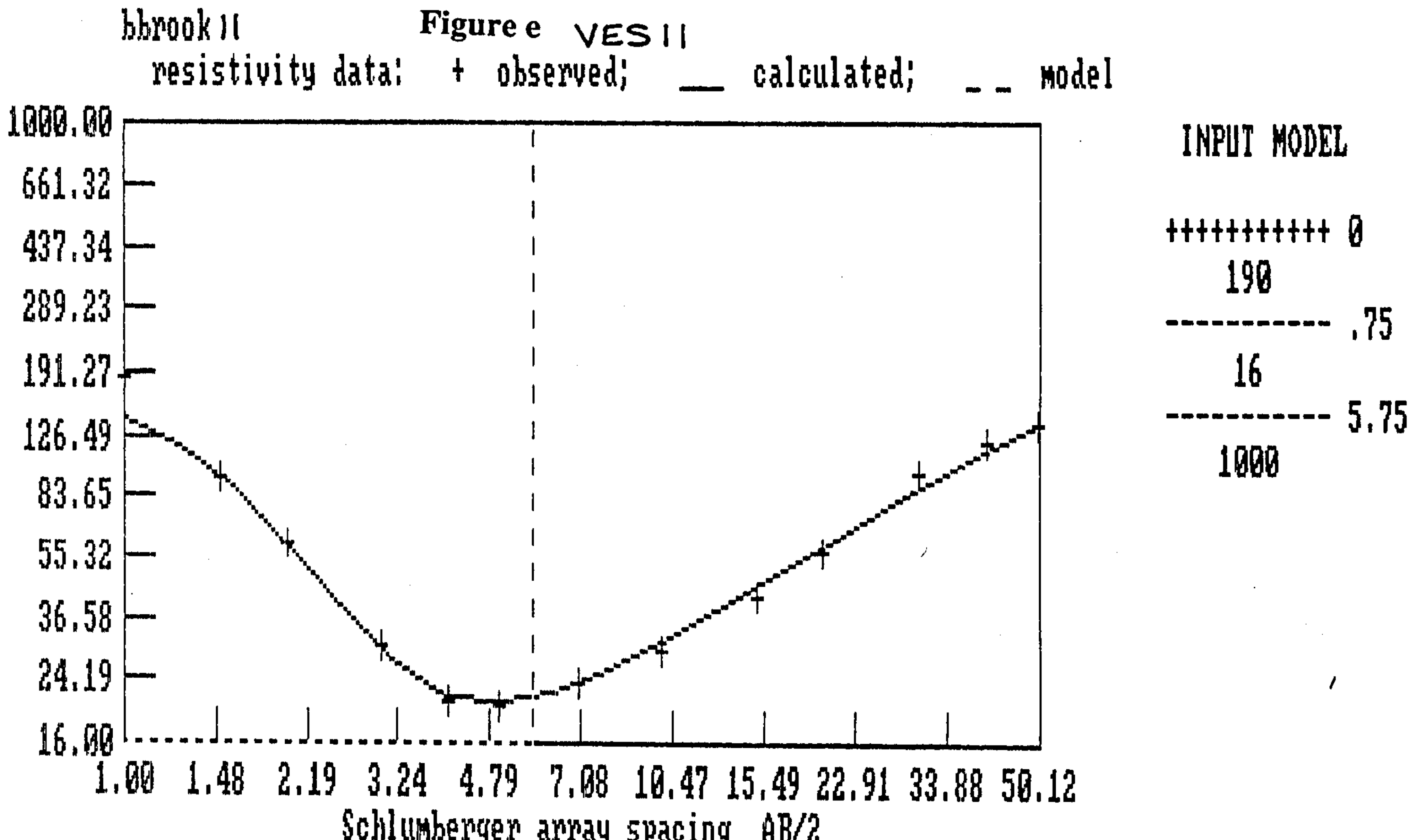
resistivity data: + observed; ___ calculated; _ _ model



BBROOK2 **Figure d** VES2

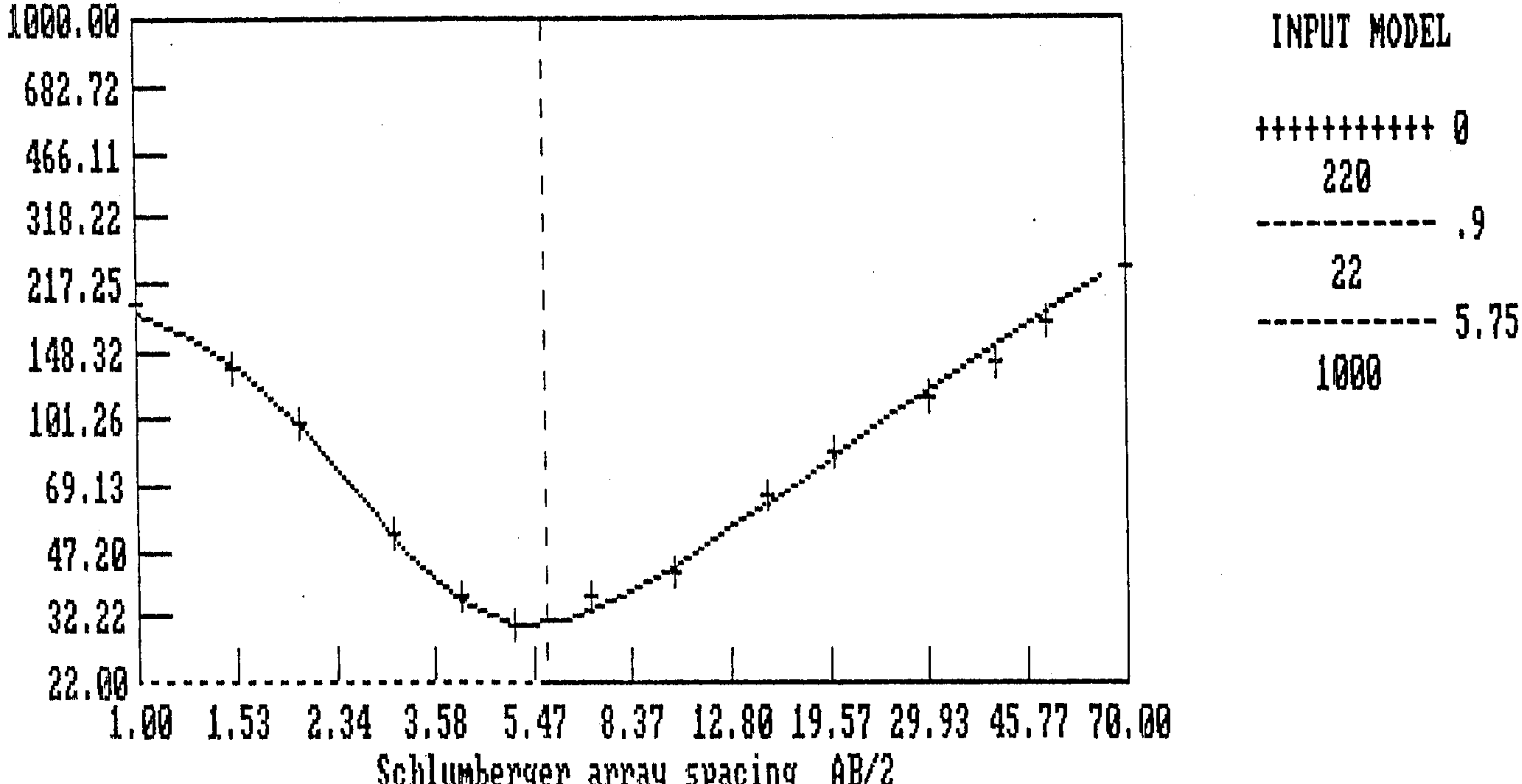
resistivity data; + observed; ___ calculated; _ _ model



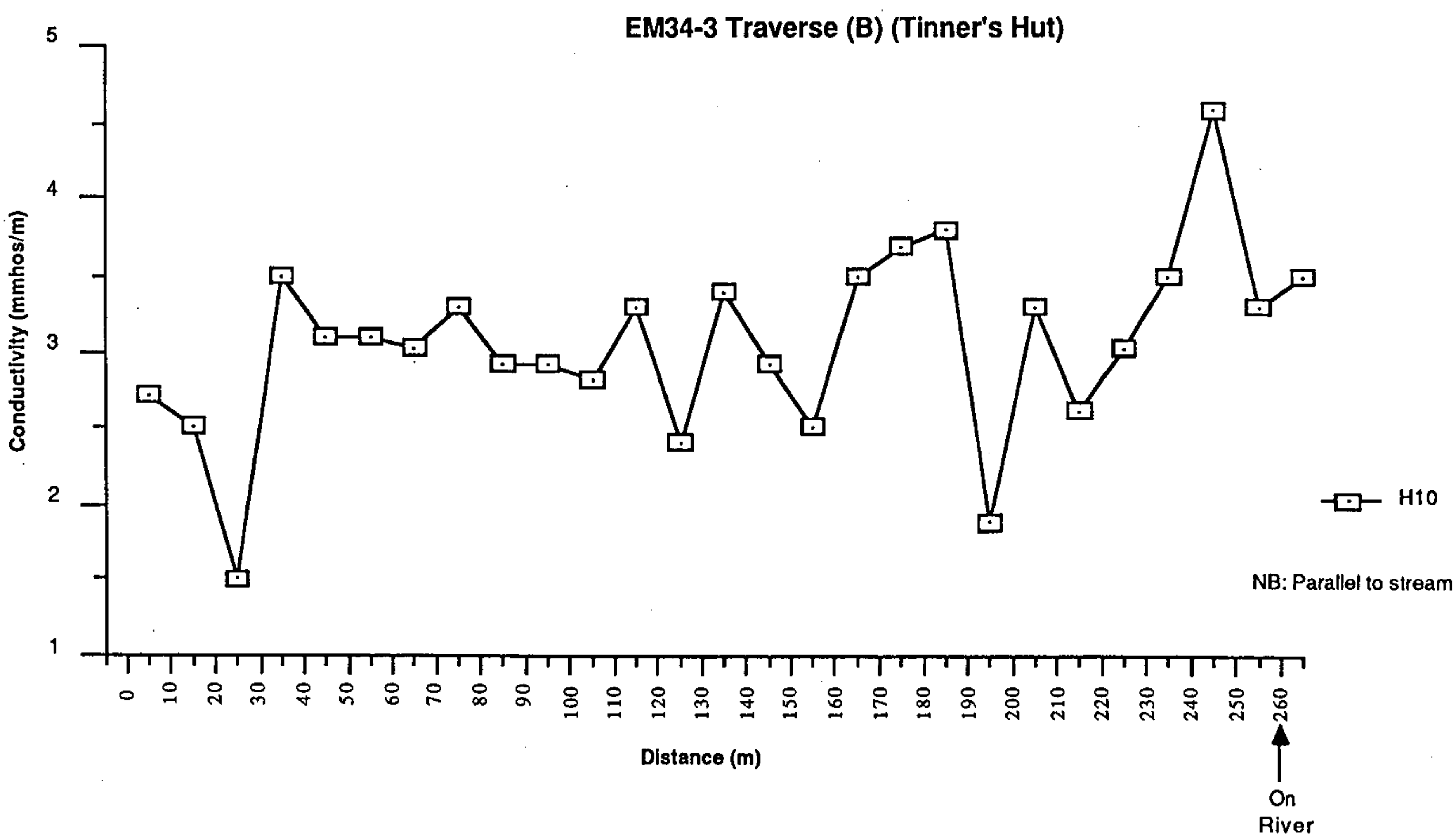

bbrook 11
Figure e VES 11
resistivity data: + observed; ___ calculated; _ _ model
1000.00
661.32
437.34
289.23
191.27
126.49
83.65
55.32
36.58
24.19
16.00
1.00 1.48 2.19 3.24 4.79 7.08 10.47 15.49 22.91 33.88 50.12
Schlumberger array spacing AB/2
INPUT MODEL
+++++++++++ 0
190
----------- .75
16
----------- 5.75
1000

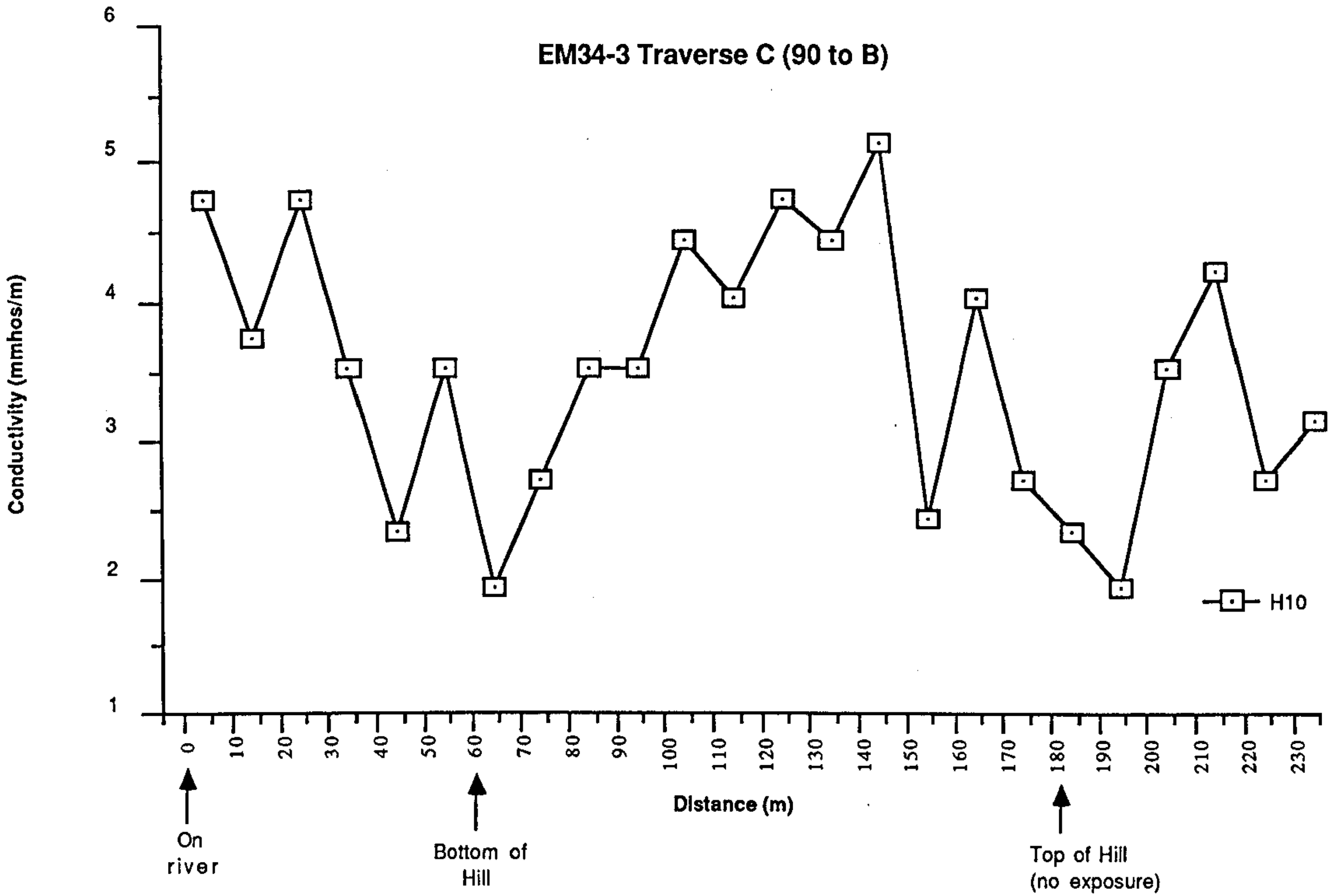
bbrook12 **Figure f** VES12

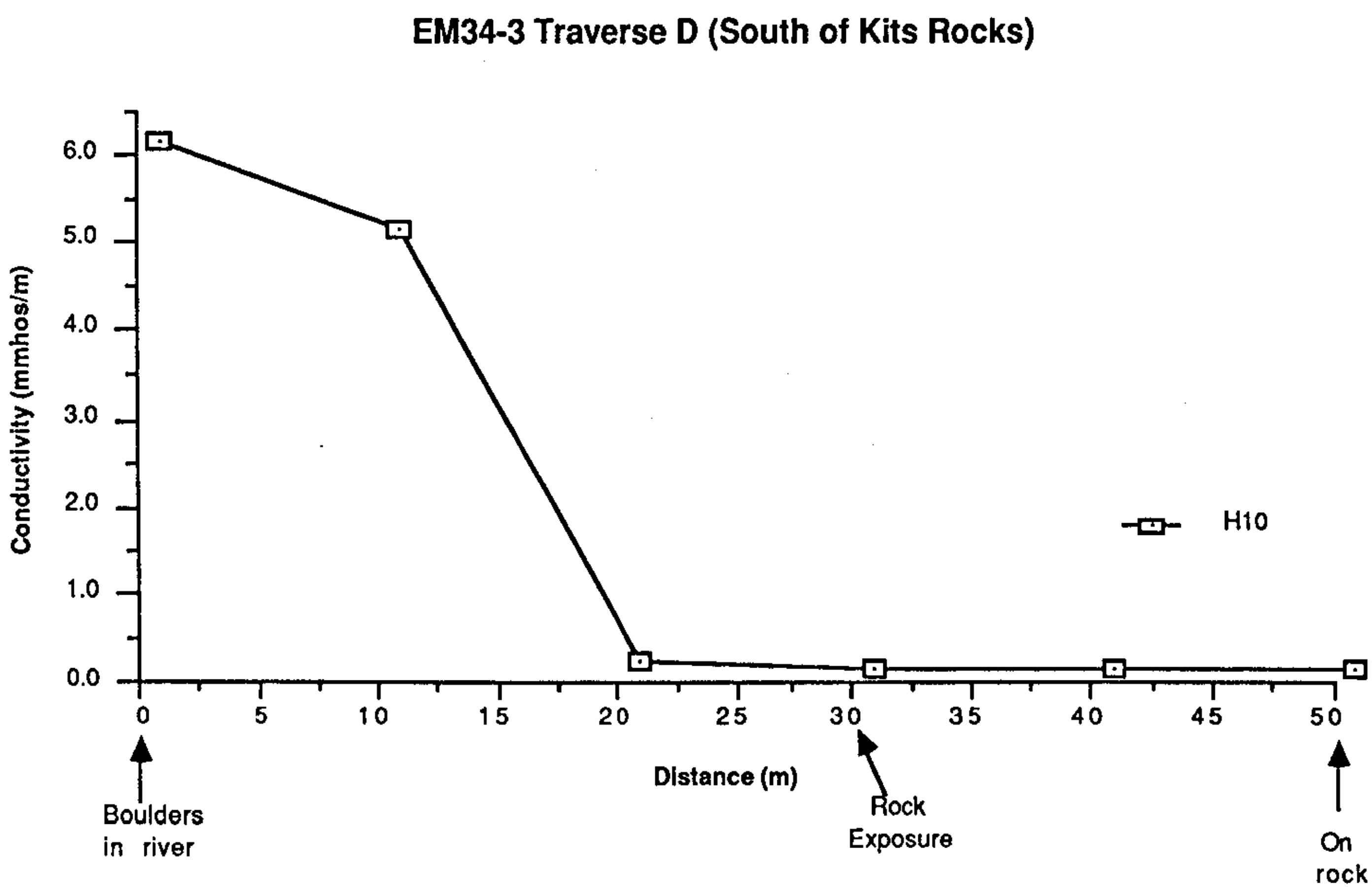
resistivity data; + observed; ___ calculated; _ _ model

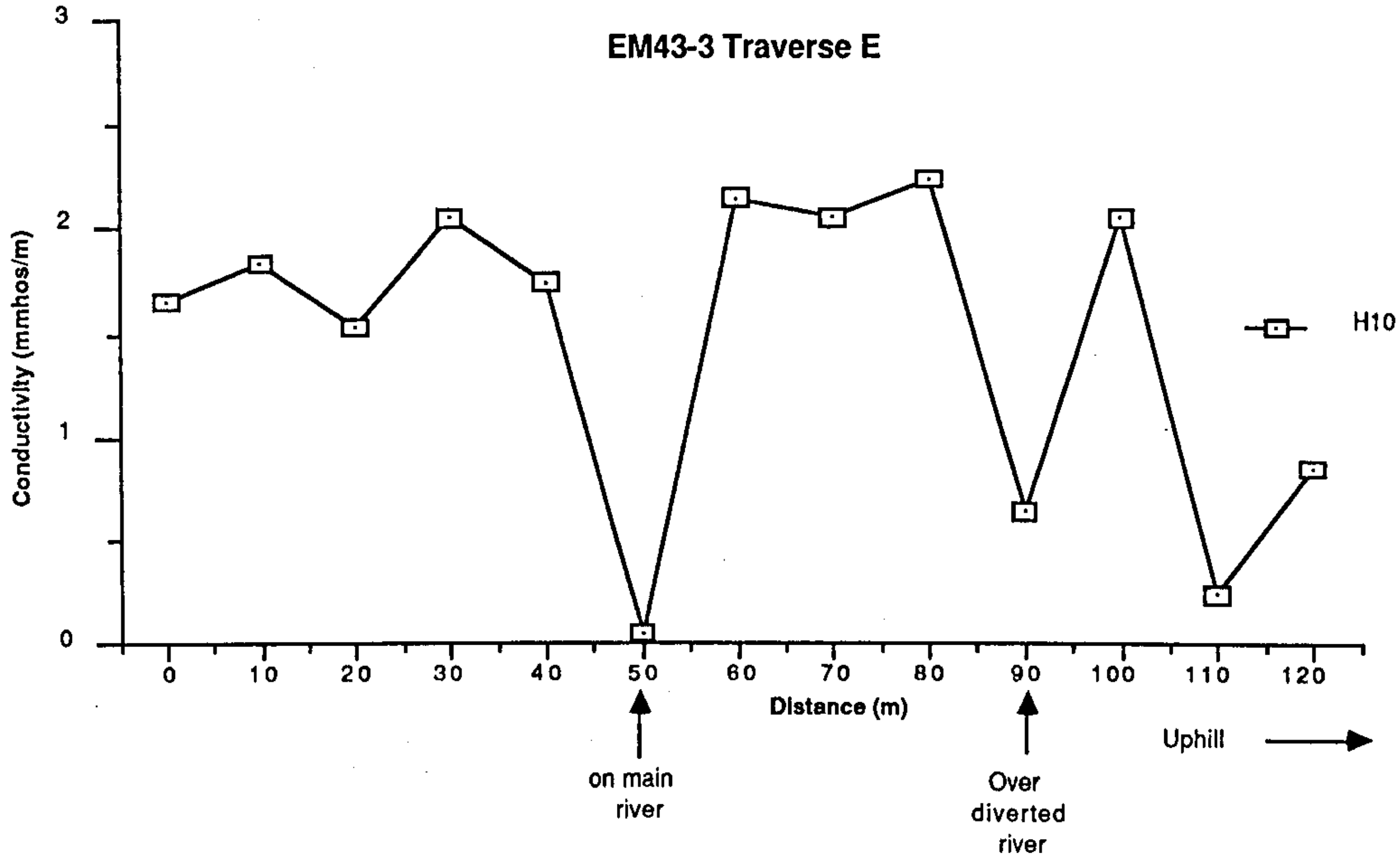


Appendix 1B EM34-3 Traverse graphs for the East Dart at Bellever Catchment


EM34-3 Traverse (B) (Tinner's Hut)
Conductivity (mmhos/m)
1
2
3
4
5
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
Distance (m)
H10
NB: Parallel to stream
On River

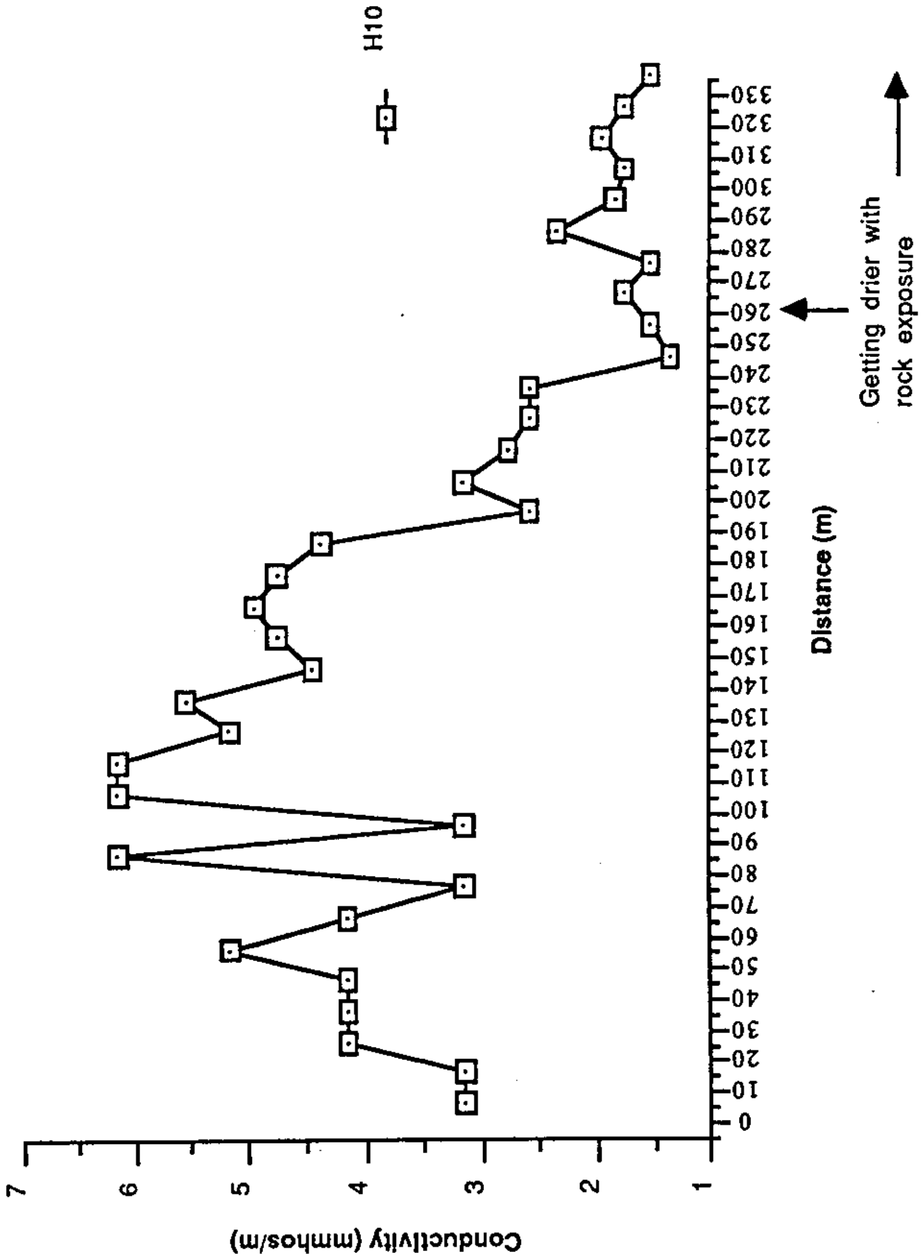

EM34-3 Traverse C (90 to B)
Conductivity (mmhos/m)
1
2
3
4
5
6
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
Distance (m)
H10
On river
Bottom of Hill
Top of Hill (no exposure)

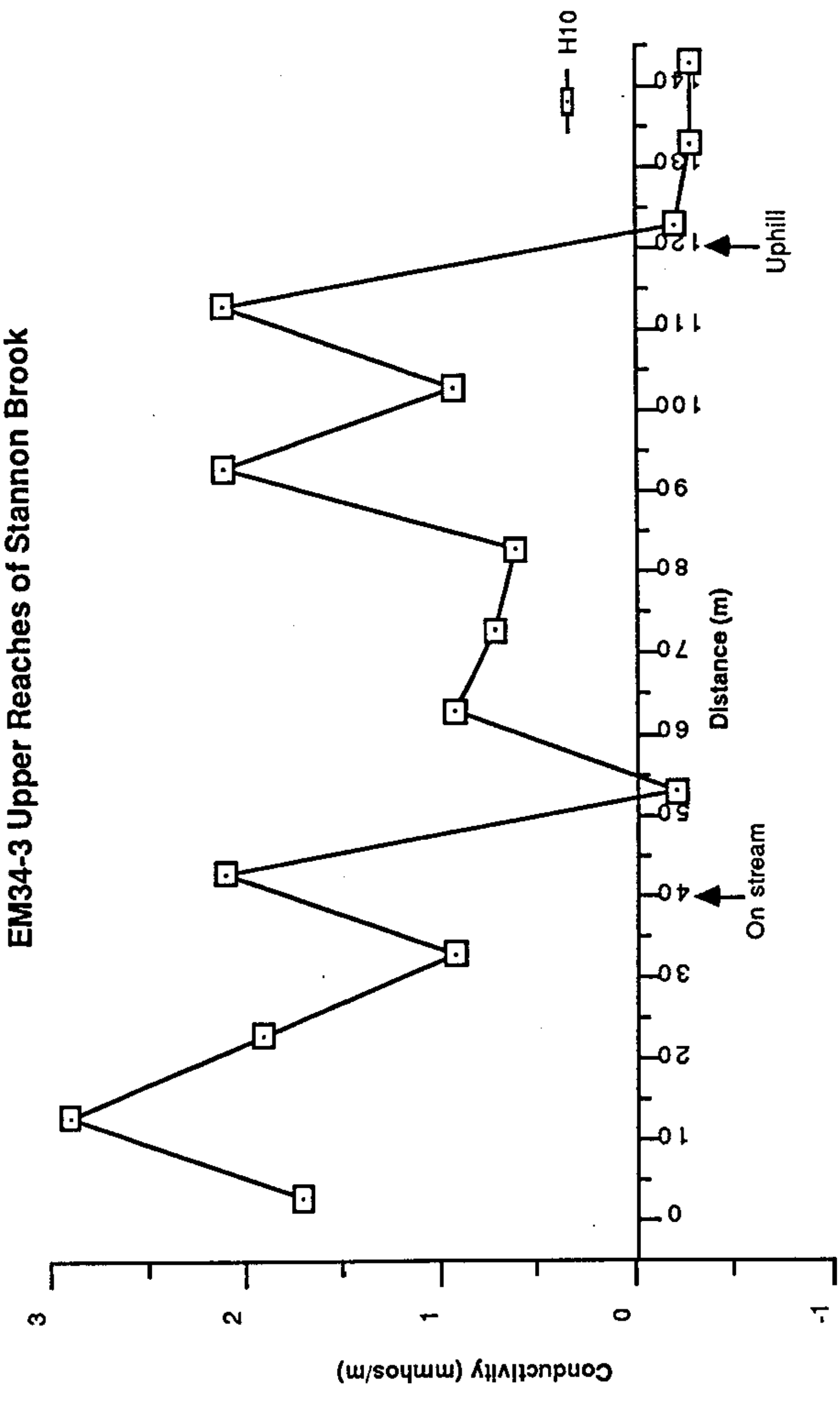

EM34-3 Traverse D (South of Kits Rocks)
Conductivity (mmhos/m)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
5
10
15
20
25
30
35
40
45
50
Distance (m)
H10
Boulders in river
Rock Exposure
On rock



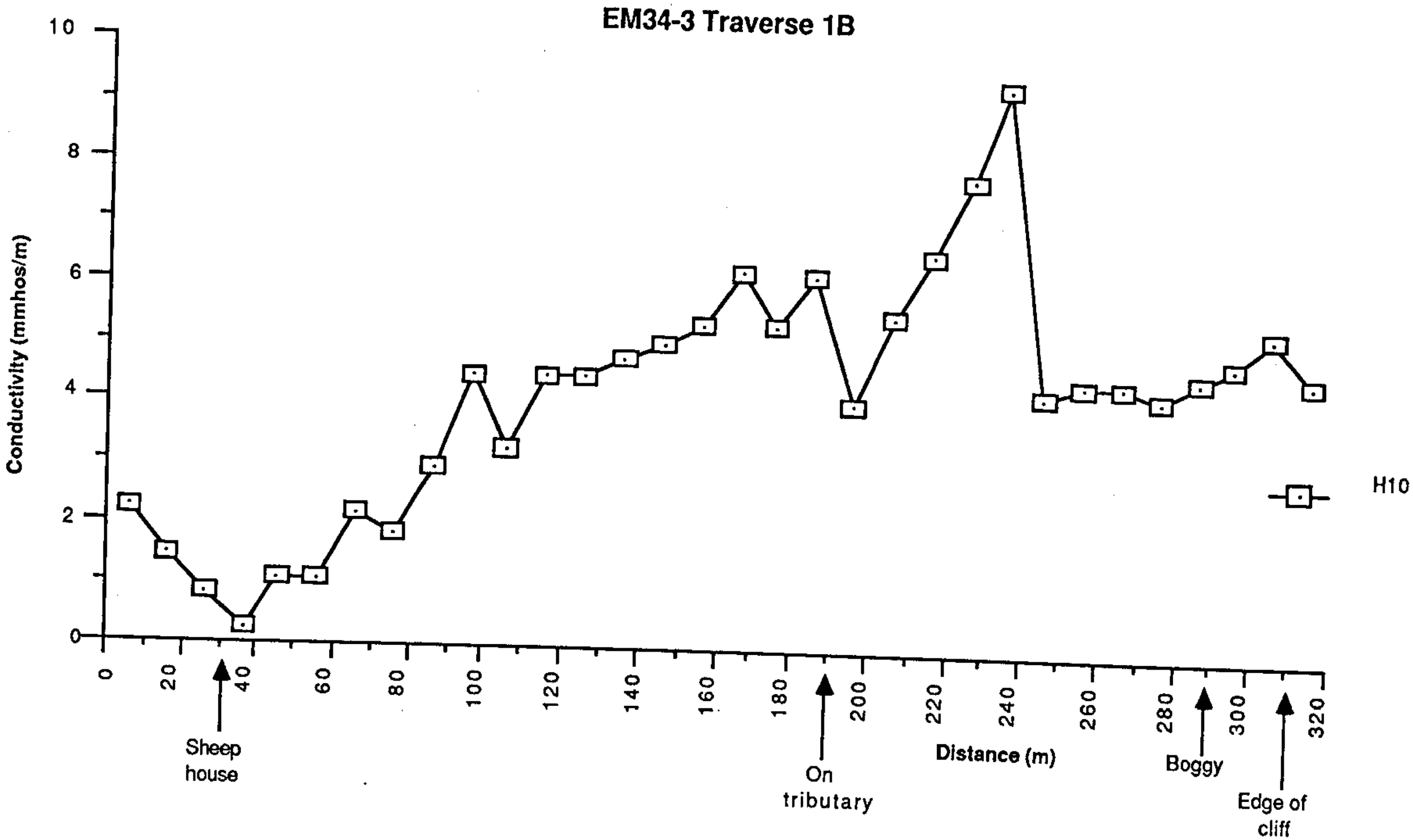
EM43-3 Traverse E
Conductivity (mmhos/m)
0
1
2
3
0
10
20
30
40
50
60
70
80
90
100
110
120
Distance (m)
H10
on main river
Over diverted river
Uphill

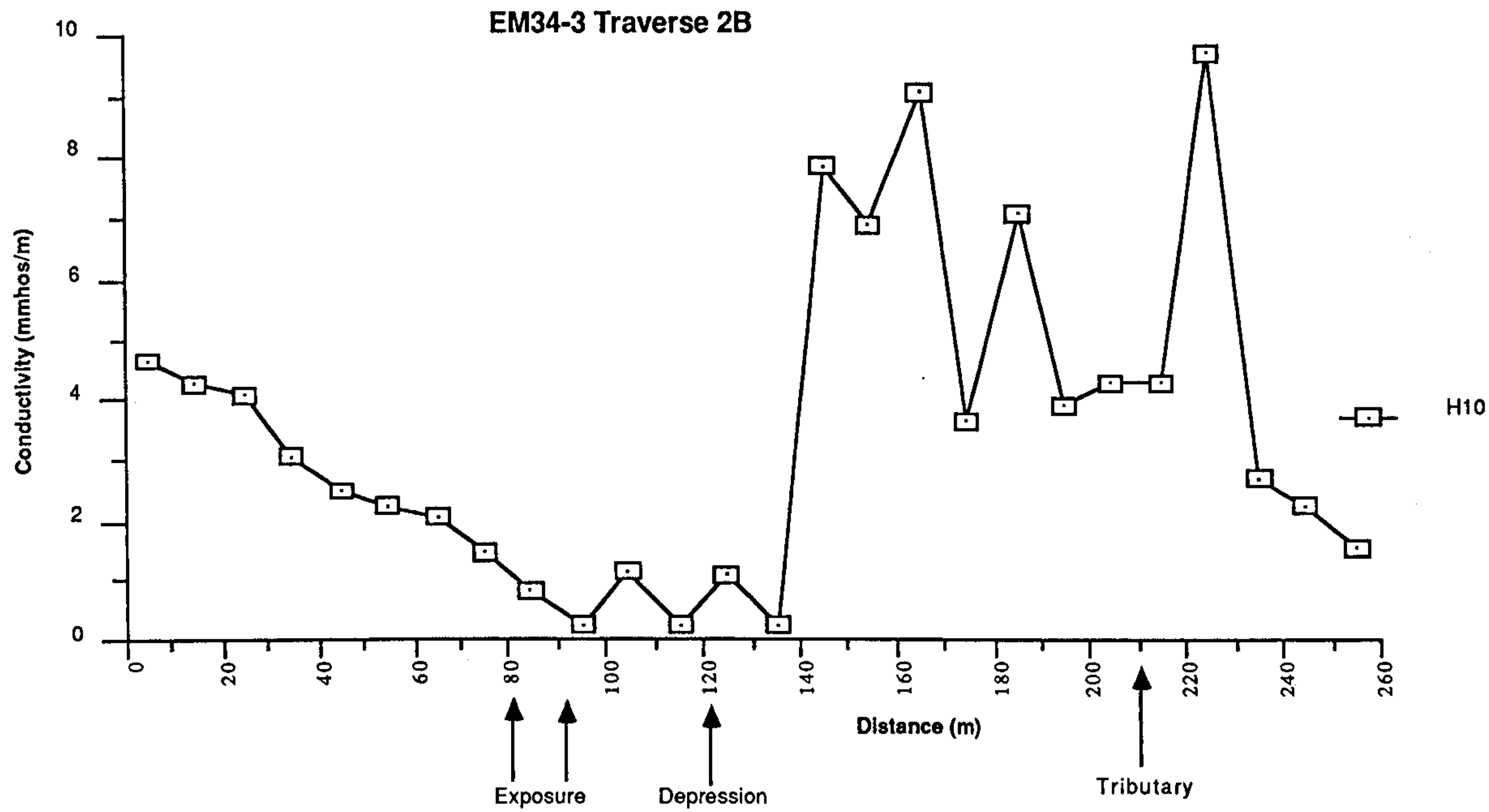
EM34-3 Upper Reaches of Gawler Brook



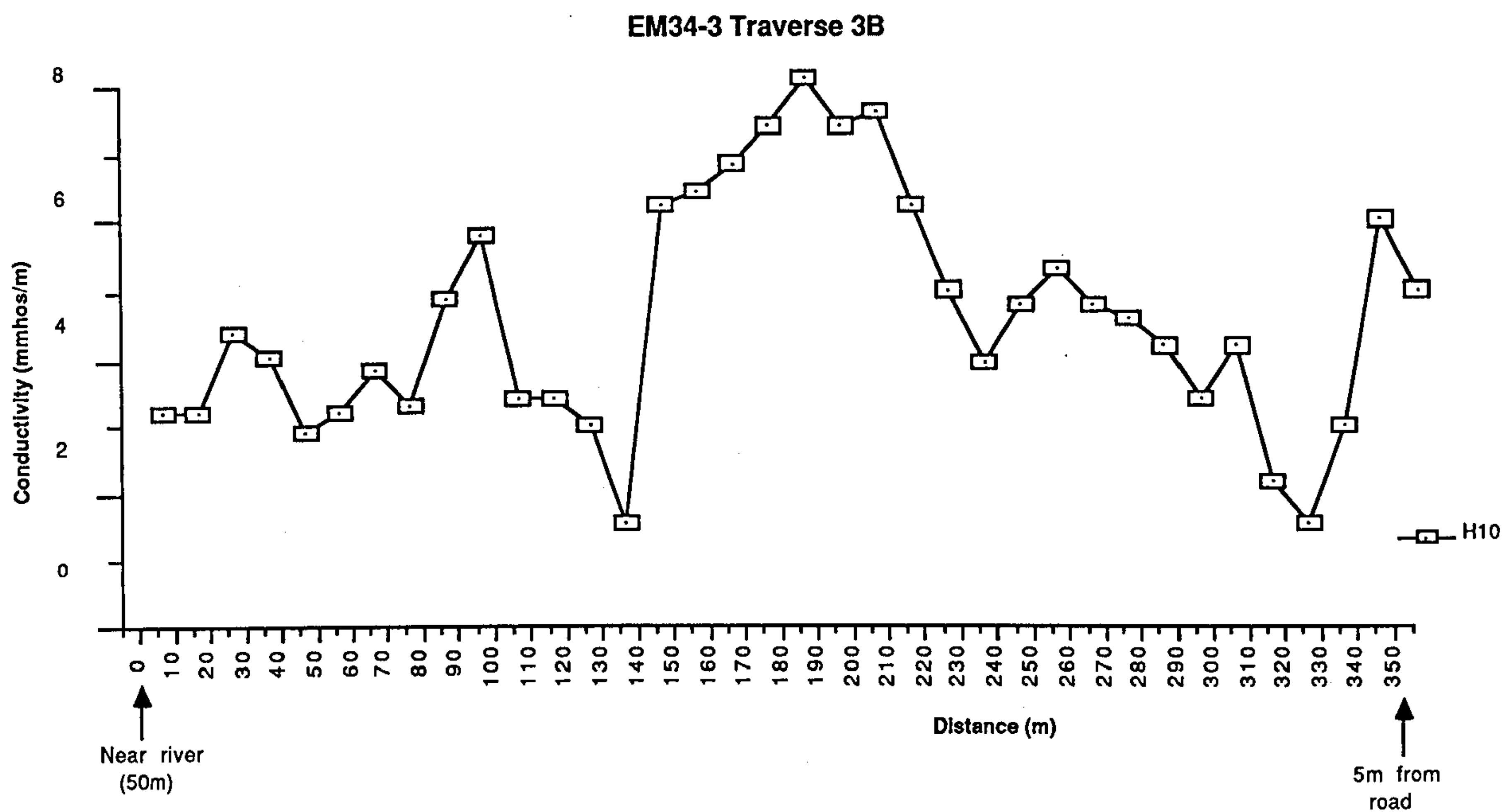

EM34-3 Upper Reaches of Stannon Brook
Conductivity (mmhos/m)
3
2
1
0
-1
Distance (m)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
On stream
Uphill
H10

Appendix 1C EM34-3 Traverse graphs for the Calder at Muirshiel Catchment

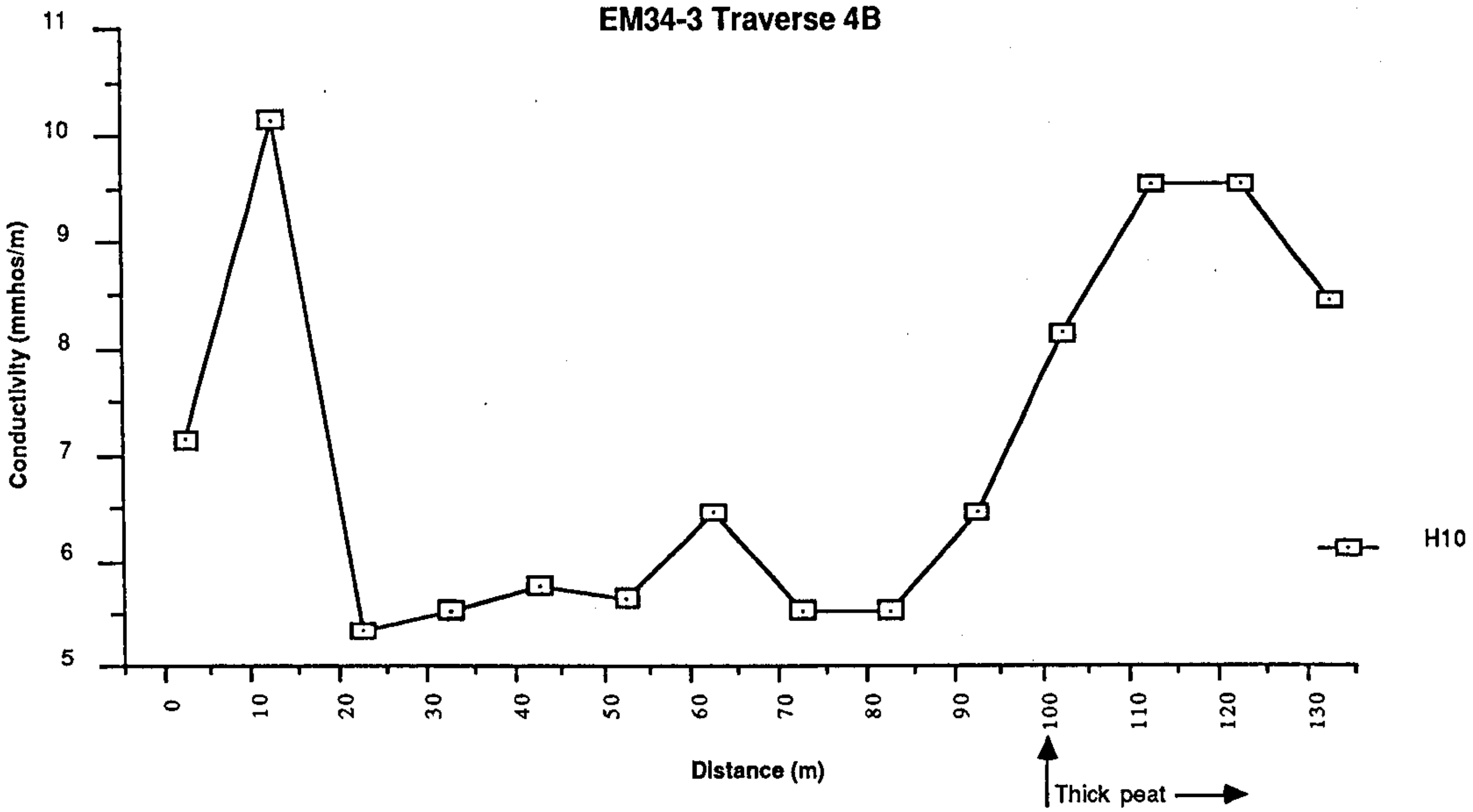

EM34-3 Traverse 1B
Conductivity (mmhos/m)
Distance (m)
H10
Sheep house
On tributary
Boggy
Edge of cliff
0
2
4
6
8
10
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320

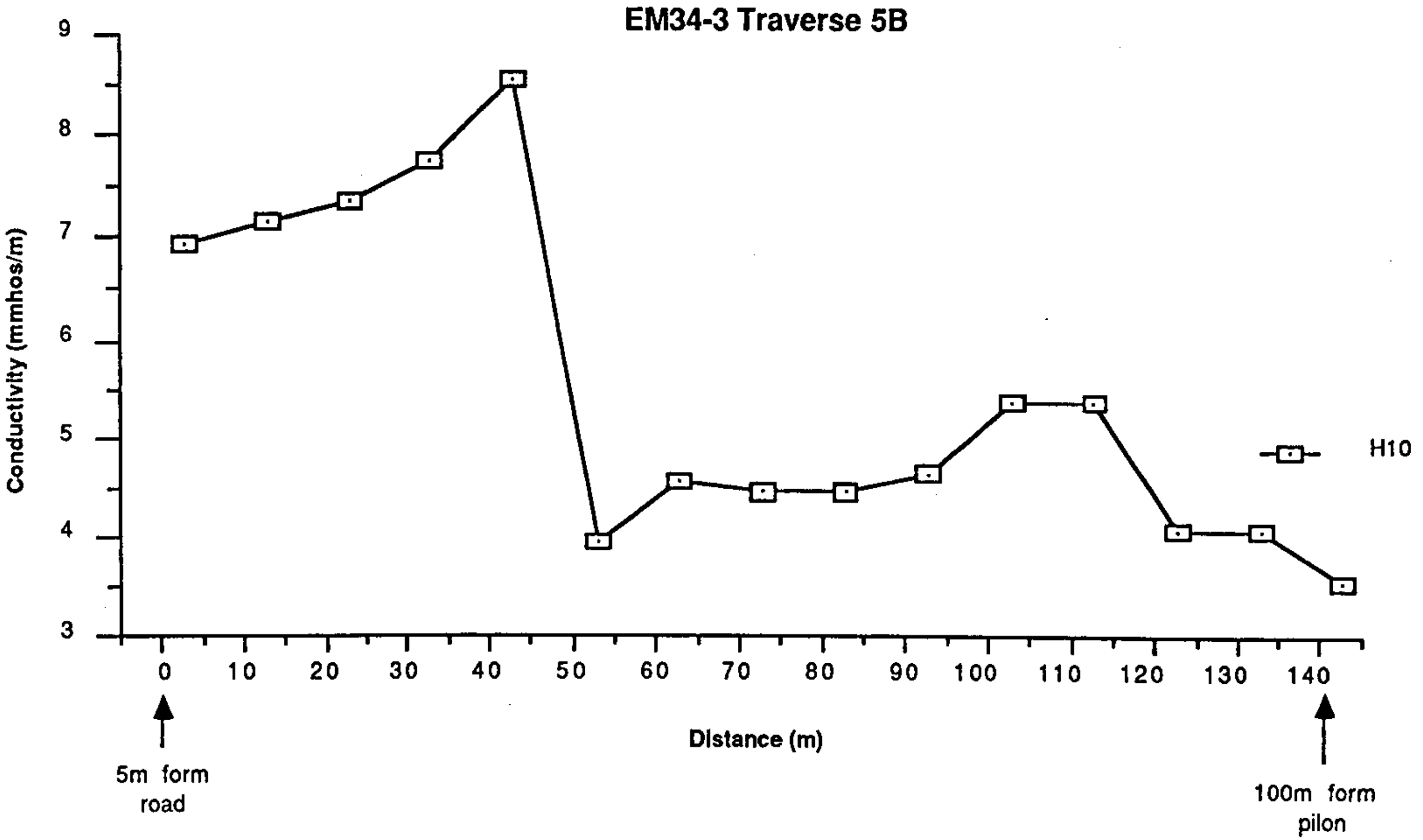


EM34-3 Traverse 2B
Conductivity (mmhos/m)
0
2
4
6
8
10
0
20
40
60
80
100
120
140
160
180
200
220
240
260
Distance (m)
H10
Exposure
Depression
Tributary



EM34-3 Traverse 3B
Conductivity (mmhos/m)
0
2
4
6
8
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300
310
320
330
340
350
Distance (m)
Near river
(50m)
5m from
road
H10


EM34-3 Traverse 4B
Conductivity (mmhos/m)
11
10
9
8
7
6
5
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Distance (m)
Thick peat
H10


EM34-3 Traverse 5B
Conductivity (mmhos/m)
9
8
7
6
5
4
3
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Distance (m)
H10
5m form
road
100m form
pilon

Appendix 2 Water Chemistry Data

Lab No. Date Sampled 8/88 Grid Ref
Source ID. Blackbrook Catchment
Sample Point Holywell Spring

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	7.60
Bicarbonate	294.63	4.828	Lab pH	0.00
Chloride	32.06	0.904	EC	450.00
Sulphate	50.71	1.056	Computed EC	740.24
Nitrate	13.17	0.212	TDS	330.00
Fluoride	0.06	0.003	Computed TDS	370.30
			Ionic Balance %	-2.44
		7.004		
Sodium	14.52	0.632	Silica	0.00
Potassium	4.41	0.113	Susp. Solids	0.00
Calcium	76.67	3.826	NTU	1.50
Magnesium	33.83	2.784		
Iron	0.00	0.000	Hardness (CaCO3)	330.69
Manganese	0.00	0.000	Alkalinity (CaCO3)	241.60
			Saturation Index	0.35
		7.355		

Lab No. Date Sampled 1987 Grid Ref
Source ID. Blackbrook Catchment
Sample Point Charnwood Lodge Spring

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	7.20
Bicarbonate	78.86	1.292	Lab pH	0.00
Chloride	15.96	0.450	EC	200.00
Sulphate	57.72	1.202	Computed EC	323.80
Nitrate	2.70	0.044	TDS	323.79
Fluoride	0.14	0.007	Computed TDS	163.02
			Ionic Balance %	1.69
		2.995		
Sodium	12.23	0.532	Silica	0.00
Potassium	2.21	0.057	Susp. Solids	0.00
Calcium	13.33	0.665	NTU	1.69
Magnesium	19.95	1.642		
Iron	0.00	0.000	Hardness (CaCO3)	115.40
Manganese	0.00	0.000	Alkalinity (CaCO3)	64.67
			Saturation Index	-1.31
		2.896		

Lab No.		Date Sampled 8/88	Grid Ref
Source ID.	Blackbrook Catchment		
Sample Point	Charley Mill Farm Spring		

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	8.00
Bicarbonate	171.65	2.813	Lab pH	0.00
Chloride	14.71	0.415	EC	300.00
Sulphate	39.06	0.813	Computed EC	434.18
Nitrate	7.44	0.120	TDS	210.00
Fluoride	0.15	0.008	Computed TDS	217.91
			Ionic Balance %	-1.28
		4.169		
Sodium	11.66	0.507	Silica	0.00
Potassium	3.53	0.090	Susp. Solids	0.00
Calcium	31.11	1.552	NTU	2.00
Magnesium	25.85	2.128		
Iron	0.00	0.000	Hardness (CaCO3)	184.08
Manganese	0.00	0.000	Alkalinity (CaCO3)	140.75
			Saturation Index	0.17
		4.277		

Lab No.		Date Sampled 7/88	Grid Ref
Source ID.	East Dart Catchment		
Sample Point	River East Dart at Postbridge		

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	5.90
Bicarbonate	3.84	0.063	Lab pH	0.00
Chloride	7.26	0.205	EC	0.00
Sulphate	1.81	0.038	Computed EC	36.57
Nitrate	0.18	0.003	TDS	20.00
Fluoride	0.00	0.000	Computed TDS	17.88
			Ionic Balance %	0.92
		0.308		
Sodium	4.49	0.195	Silica	0.00
Potassium	0.86	0.022	Susp. Solids	0.00
Calcium	0.81	0.040	NTU	3.00
Magnesium	0.52	0.043		
Iron	0.06	0.002	Hardness (CaCO3)	4.27
Manganese	0.00	0.000	Alkalinity (CaCO3)	3.15
			Saturation Index	-5.03
		0.303		

Lab No.		Date Sampled 7/88	Grid Ref
Source ID.	East Dart Catchment		
Sample Point	Lydgate Spring		

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	4.30
Bicarbonate	3.84	0.063	Lab pH	0.00
Chloride	9.74	0.275	EC	0.00
Sulphate	4.44	0.092	Computed EC	71.85
Nitrate	8.43	0.136	TDS	30.00
Fluoride	0.00	0.000	Computed TDS	37.98
			Ionic Balance %	-5.05
		0.566		
Sodium	7.91	0.344	Silica	0.00
Potassium	1.53	0.039	Susp. Solids	0.00
Calcium	2.76	0.138	NTU	1.00
Magnesium	1.28	0.105		
Iron	0.00	0.000	Hardness (CaCO3)	12.16
Manganese	0.00	0.000	Alkalinity (CaCO3)	3.15
			Saturation Index	-6.12
		0.626		

Lab No.		Date Sampled 7/88	Grid Ref
Source ID.	East Dart Catchment		
Sample Point	Wala Brook Spring		

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	5.20
Bicarbonate	3.07	0.050	Lab pH	0.00
Chloride	7.88	0.222	EC	0.00
Sulphate	3.22	0.067	Computed EC	48.88
Nitrate	2.54	0.041	TDS	20.00
Fluoride	0.00	0.000	Computed TDS	24.49
			Ionic Balance %	-6.31
		0.381		
Sodium	5.49	0.239	Silica	0.00
Potassium	1.34	0.034	Susp. Solids	0.00
Calcium	1.46	0.073	NTU	2.00
Magnesium	1.04	0.086		
Iron	0.01	0.000	Hardness (CaCO3)	7.94
Manganese	0.00	0.000	Alkalinity (CaCO3)	2.52
			Saturation Index	-5.58
		0.432		

Lab No.		Date Sampled 7/88	Grid Ref
Source ID.	East Dart Catchment		
Sample Point	Dury Farm Spring		

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	5.30
Bicarbonate	3.07	0.050	Lab pH	0.00
Chloride	8.21	0.232	EC	0.00
Sulphate	5.06	0.105	Computed EC	62.53
Nitrate	7.27	0.117	TDS	30.00
Fluoride	0.00	0.000	Computed TDS	33.13
			Ionic Balance %	-1.82
		0.505		
Sodium	5.62	0.244	Silica	0.00
Potassium	1.34	0.034	Susp. Solids	0.00
Calcium	2.92	0.146	NTU	1.00
Magnesium	1.20	0.099		
Iron	0.00	0.000	Hardness (CaCO3)	12.23
Manganese	0.00	0.000	Alkalinity (CaCO3)	2.52
			Saturation Index	-5.19
		0.523		

Lab No.		Date Sampled 7/88	Grid Ref
Source ID.	East Dart Catchment		
Sample Point	Head of Stannon Brook Spring		

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	5.30
Bicarbonate	3.07	0.050	Lab pH	0.00
Chloride	7.43	0.210	EC	0.00
Sulphate	3.56	0.074	Computed EC	43.32
Nitrate	0.73	0.012	TDS	20.00
Fluoride	0.00	0.000	Computed TDS	21.48
			Ionic Balance %	-3.97
		0.346		
Sodium	5.55	0.241	Silica	0.00
Potassium	0.83	0.021	Susp. Solids	0.00
Calcium	1.30	0.065	NTU	2.00
Magnesium	0.57	0.047		
Iron	0.00	0.000	Hardness (CaCO3)	5.59
Manganese	0.00	0.000	Alkalinity (CaCO3)	2.52
			Saturation Index	-5.53
		0.374		

Lab No.		Date Sampled	9/88	Grid Ref	
Source ID.	Calder Catchment				
Sample Point	Tandlemuir Spring				

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	7.60
Bicarbonate	56.36	0.924	Lab pH	0.00
Chloride	6.02	0.170	EC	85.00
Sulphate	5.68	0.118	Computed EC	127.33
Nitrate	0.06	0.000	TDS	60.00
Fluoride	0.00	0.000	Computed TDS	65.53
			Ionic Balance %	-2.68
		1.213		
Sodium	7.96	0.346	Silica	0.00
Potassium	1.16	0.030	Susp. Solids	0.00
Calcium	15.14	0.755	NTU	1.50
Magnesium	1.80	0.148		
Iron	0.00	0.000	Hardness (CaCO3)	45.21
Manganese	0.00	0.000	Alkalinity (CaCO3)	46.22
			Saturation Index	-0.94
		1.280		

Lab No.		Date Sampled	9/88	Grid Ref	
Source ID.	Calder Catchment				
Sample Point	Clovenstone Spring				

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	7.40
Bicarbonate	40.99	0.672	Lab pH	0.00
Chloride	5.49	0.155	EC	100.00
Sulphate	6.95	0.145	Computed EC	101.96
Nitrate	0.32	0.005	TDS	50.00
Fluoride	0.00	0.000	Computed TDS	53.06
			Ionic Balance %	0.07
		0.976		
Sodium	7.32	0.318	Silica	0.00
Potassium	1.65	0.042	Susp. Solids	0.00
Calcium	9.43	0.471	NTU	1.50
Magnesium	1.75	0.144		
Iron	0.00	0.000	Hardness (CaCO3)	30.75
Manganese	0.00	0.000	Alkalinity (CaCO3)	33.61
			Saturation Index	-1.48
		0.975		

Lab No.		Date Sampled 9/88	Grid Ref
Source ID.	Calder Catchment		
Sample Point	Orblis Hill Spring		

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	7.10
Bicarbonate	38.43	0.630	Lab pH	0.00
Chloride	8.32	0.235	EC	300.00
Sulphate	6.95	0.145	Computed EC	103.99
Nitrate	3.48	0.056	TDS	50.00
Fluoride	0.00	0.000	Computed TDS	56.18
			Ionic Balance %	11.19
		1.065		
Sodium	7.93	0.345	Silica	0.00
Potassium	2.65	0.068	Susp. Solids	0.00
Calcium	6.67	0.333	NTU	1.50
Magnesium	1.28	0.105		
Iron	0.00	0.000	Hardness (CaCO3)	21.92
Manganese	0.00	0.000	Alkalinity (CaCO3)	31.51
			Saturation Index	-1.95
		0.851		

Lab No.		Date Sampled 9/88	Grid Ref
Source ID.	Calder Catchment		
Sample Point	River Calder(at Bridge)		

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	6.60
Bicarbonate	5.12	0.084	Lab pH	0.00
Chloride	2.90	0.082	EC	25.00
Sulphate	1.86	0.039	Computed EC	25.94
Nitrate	0.00	0.000	TDS	10.00
Fluoride	0.00	0.000	Computed TDS	13.15
			Ionic Balance %	-13.97
		0.204		
Sodium	3.54	0.154	Silica	0.00
Potassium	0.24	0.006	Susp. Solids	0.00
Calcium	1.29	0.064	NTU	2.30
Magnesium	0.38	0.031		
Iron	0.42	0.015	Hardness (CaCO3)	5.54
Manganese	0.00	0.000	Alkalinity (CaCO3)	4.20
			Saturation Index	-4.00
		0.271		

Lab No.		Date Sampled 1987	Grid Ref
Source ID.	Blackbrook Catchment		
Sample Point	Holywell Spring		

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	7.50
Bicarbonate	287.00	4.703	Lab pH	0.00
Chloride	36.00	1.016	EC	600.00
Sulphate	30.00	0.625	Computed EC	679.74
Nitrate	2.00	0.032	TDS	399.00
Fluoride	0.00	0.000	Computed TDS	329.72
			Ionic Balance %	-4.91
		6.376		
Sodium	13.20	0.574	Silica	0.00
Potassium	1.40	0.036	Susp. Solids	0.00
Calcium	71.00	3.543	NTU	2.00
Magnesium	35.00	2.881		
Iron	0.00	0.000	Hardness (CaCO3)	321.35
Manganese	0.00	0.000	Alkalinity (CaCO3)	235.34
			Saturation Index	0.22
		7.034		

Lab No.		Date Sampled 1987	Grid Ref
Source ID.	Blackbrook Catchment		
Sample Point	Charnwood Lodge Spring		

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	6.70
Bicarbonate	98.00	1.606	Lab pH	0.00
Chloride	21.00	0.592	EC	300.00
Sulphate	34.00	0.708	Computed EC	322.94
Nitrate	0.90	0.015	TDS	220.00
Fluoride	0.00	0.000	Computed TDS	156.09
			Ionic Balance %	-4.27
		2.921		
Sodium	12.40	0.539	Silica	0.00
Potassium	0.60	0.015	Susp. Solids	0.00
Calcium	18.00	0.898	NTU	1.00
Magnesium	21.00	1.728		
Iron	0.00	0.000	Hardness (CaCO3)	131.38
Manganese	0.00	0.000	Alkalinity (CaCO3)	80.36
			Saturation Index	-1.58
		3.181		

Lab No. Date Sampled 1987 Grid Ref
Source ID. Blackbrook Catchment
Sample Point Charley Mill Farm Spring

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	7.00
Bicarbonate	140.00	2.294	Lab pH	0.00
Chloride	17.00	0.480	EC	290.00
Sulphate	20.00	0.416	Computed EC	322.93
Nitrate	0.90	0.015	TDS	231.00
Fluoride	0.00	0.000	Computed TDS	163.24
			Ionic Balance %	2.34
		3.205		
Sodium	6.80	0.296	Silica	0.00
Potassium	1.70	0.043	Susp. Solids	0.00
Calcium	38.00	1.896	NTU	3.80
Magnesium	10.00	0.823		
Iron	0.00	0.000	Hardness (CaCO3)	136.05
Manganese	0.00	0.000	Alkalinity (CaCO3)	114.80
			Saturation Index	-0.80
		3.059		

Lab No. Date Sampled 01/09/86 Grid Ref
Source ID. Blackbrook Catchment
Sample Point Beacon Hill Rain Water

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	0.00
Bicarbonate	2.00	0.033	Lab pH	0.00
Chloride	2.60	0.073	EC	0.00
Sulphate	2.10	0.044	Computed EC	20.04
Nitrate	0.70	0.011	TDS	0.00
Fluoride	0.00	0.000	Computed TDS	10.08
			Ionic Balance %	-4.69
		0.161		
Sodium	1.70	0.074	Silica	0.00
Potassium	0.40	0.010	Susp. Solids	0.00
Calcium	1.20	0.060	NTU	0.00
Magnesium	0.40	0.033		
Iron	0.00	0.000	Hardness (CaCO3)	4.64
Manganese	0.00	0.000	Alkalinity (CaCO3)	1.64
			Saturation Index	
		0.177		

Lab No.		Date Sampled	01/01/87	Grid Ref
Source ID.	Blackbrook Catchment			
Sample Point	Beacon Hill Rain Water			

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	0.00
Bicarbonate	2.00	0.033	Lab pH	0.00
Chloride	4.30	0.121	EC	0.00
Sulphate	3.00	0.062	Computed EC	26.15
Nitrate	0.90	0.015	TDS	0.00
Fluoride	0.00	0.000	Computed TDS	14.48
			Ionic Balance %	-0.09
		0.231		
Sodium	2.40	0.104	Silica	0.00
Potassium	0.10	0.003	Susp. Solids	0.00
Calcium	0.40	0.020	NTU	0.00
Magnesium	0.40	0.033		
Iron	2.00	0.072	Hardness (CaCO3)	6.23
Manganese	0.00	0.000	Alkalinity (CaCO3)	1.64
			Saturation Index	
		0.231		

Lab No.		Date Sampled	1987	Grid Ref
Source ID.	East Dart Catchment			
Sample Point	Wala Brook Spring			

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	0.00
Bicarbonate	0.00	0.000	Lab pH	0.00
Chloride	7.30	0.206	EC	60.00
Sulphate	4.50	0.094	Computed EC	44.47
Nitrate	2.70	0.044	TDS	58.00
Fluoride	0.00	0.000	Computed TDS	22.50
			Ionic Balance %	-4.30
		0.343		
Sodium	5.20	0.226	Silica	0.00
Potassium	1.00	0.026	Susp. Solids	0.00
Calcium	0.80	0.040	NTU	3.00
Magnesium	1.00	0.082		
Iron	0.00	0.000	Hardness (CaCO3)	6.11
Manganese	0.00	0.000	Alkalinity (CaCO3)	0.00
			Saturation Index	
		0.374		

Lab No.		Date Sampled	1987	Grid Ref	
Source ID.	Calder Catchment				
Sample Point	Tandlemuir Spring				

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	6.00
Bicarbonate	61.00	1.000	Lab pH	0.00
Chloride	5.10	0.144	EC	125.00
Sulphate	6.50	0.135	Computed EC	131.08
Nitrate	2.40	0.039	TDS	88.00
Fluoride	0.00	0.000	Computed TDS	69.29
			Ionic Balance %	2.94
		1.318		
Sodium	6.30	0.274	Silica	0.00
Potassium	1.30	0.033	Susp. Solids	0.00
Calcium	16.10	0.803	NTU	5.00
Magnesium	1.60	0.132		
Iron	0.00	0.000	Hardness (CaCO3)	46.79
Manganese	0.00	0.000	Alkalinity (CaCO3)	50.02
			Saturation Index	-2.48
		1.242		

Lab No.		Date Sampled	1987	Grid Ref	
Source ID.	Calder Catchment				
Sample Point	Orblis Hill Spring				

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	5.30
Bicarbonate	24.00	0.393	Lab pH	0.00
Chloride	7.80	0.220	EC	100.00
Sulphate	6.40	0.133	Computed EC	94.44
Nitrate	5.80	0.094	TDS	45.00
Fluoride	0.00	0.000	Computed TDS	50.10
			Ionic Balance %	-0.87
		0.840		
Sodium	7.20	0.313	Silica	0.00
Potassium	2.10	0.054	Susp. Solids	0.00
Calcium	7.80	0.389	NTU	0.00
Magnesium	1.20	0.099		
Iron	0.00	0.000	Hardness (CaCO3)	24.42
Manganese	0.00	0.000	Alkalinity (CaCO3)	19.68
			Saturation Index	-3.88
		0.855		

Lab No.		Date Sampled	1987	Grid Ref	
Source ID.	Blackbrook Catchment				
Sample Point	Beacon Hill Rain Water				

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	0.00
Bicarbonate	1.90	0.031	Lab pH	0.00
Chloride	5.70	0.161	EC	0.00
Sulphate	3.10	0.065	Computed EC	31.02
Nitrate	1.30	0.021	TDS	0.00
Fluoride	0.00	0.000	Computed TDS	15.93
			Ionic Balance %	12.48
		0.277		
Sodium	2.70	0.117	Silica	0.00
Potassium	1.00	0.026	Susp. Solids	0.00
Calcium	0.80	0.040	NTU	0.00
Magnesium	0.40	0.033		
Iron	0.00	0.000	Hardness (CaCO3)	3.64
Manganese	0.00	0.000	Alkalinity (CaCO3)	1.56
			Saturation Index	
		0.216		

Lab No.		Date Sampled	1987	Grid Ref	
Source ID.	East Dart Catchment				
Sample Point	River East Dart at Postbridge				

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	0.00
Bicarbonate	0.00	0.000	Lab pH	0.00
Chloride	8.30	0.234	EC	60.00
Sulphate	1.80	0.037	Computed EC	38.51
Nitrate	0.70	0.011	TDS	85.00
Fluoride	0.00	0.000	Computed TDS	18.40
			Ionic Balance %	-8.80
		0.283		
Sodium	5.00	0.217	Silica	0.00
Potassium	0.80	0.020	Susp. Solids	0.00
Calcium	1.50	0.075	NTU	3.00
Magnesium	0.30	0.025		
Iron	0.00	0.000	Hardness (CaCO3)	4.98
Manganese	0.00	0.000	Alkalinity (CaCO3)	0.00
			Saturation Index	
		0.337		

Lab No.		Date Sampled	1987	Grid Ref	
Source ID.	East Dart Catchment				
Sample Point	Head of Stannon Brook Spring				

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	0.00
Bicarbonate	0.00	0.000	Lab pH	0.00
Chloride	7.50	0.212	EC	50.00
Sulphate	0.90	0.019	Computed EC	37.54
Nitrate	0.80	0.013	TDS	32.00
Fluoride	0.00	0.000	Computed TDS	17.60
			Ionic Balance %	-21.23
		0.243		
Sodium	5.10	0.222	Silica	0.00
Potassium	1.30	0.033	Susp. Solids	0.00
Calcium	1.40	0.070	NTU	0.00
Magnesium	0.60	0.049		
Iron	0.00	0.000	Hardness (CaCO3)	5.97
Manganese	0.00	0.000	Alkalinity (CaCO3)	0.00
			Saturation Index	
		0.374		

Lab No.		Date Sampled	1987	Grid Ref	
Source ID.	East Dart Catchment				
Sample Point	Warren Inn Spring				

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	0.00
Bicarbonate	0.00	0.000	Lab pH	0.00
Chloride	8.50	0.240	EC	50.00
Sulphate	4.30	0.090	Computed EC	51.35
Nitrate	0.90	0.015	TDS	23.00
Fluoride	0.00	0.000	Computed TDS	24.80
			Ionic Balance %	-18.07
		0.344		
Sodium	6.20	0.270	Silica	0.00
Potassium	1.70	0.043	Susp. Solids	0.00
Calcium	2.50	0.125	NTU	2.00
Magnesium	0.70	0.058		
Iron	0.00	0.000	Hardness (CaCO3)	9.11
Manganese	0.00	0.000	Alkalinity (CaCO3)	0.00
			Saturation Index	
		0.496		

Lab No. Date Sampled 1987 Grid Ref
Source ID. Calder Catchment
Sample Point River Calder (at Bridge)

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	5.80
Bicarbonate	0.00	0.000	Lab pH	0.00
Chloride	6.85	0.193	EC	50.00
Sulphate	2.52	0.052	Computed EC	38.53
Nitrate	1.35	0.022	TDS	48.00
Fluoride	0.00	0.000	Computed TDS	18.19
			Ionic Balance %	-15.57
		0.267		
Sodium	3.31	0.144	Silica	0.00
Potassium	0.12	0.003	Susp. Solids	0.00
Calcium	3.50	0.175	NTU	7.00
Magnesium	0.54	0.044		
Iron	0.00	0.000	Hardness (CaCO3)	10.96
Manganese	0.00	0.000	Alkalinity (CaCO3)	0.00
			Saturation Index	

Lab No. Date Sampled 1987 Grid Ref
Source ID. Calder Catchment
Sample Point Clovenstone Spring

	mg/l	me/l		
Carbonate	0.00	0.000	Field pH	9.10
Bicarbonate	24.40	0.400	Lab pH	0.00
Chloride	6.50	0.183	EC	100.00
Sulphate	5.30	0.110	Computed EC	85.73
Nitrate	2.30	0.037	TDS	103.00
Fluoride	0.00	0.000	Computed TDS	43.50
			Ionic Balance %	-7.27
		0.731		
Sodium	4.60	0.200	Silica	0.00
Potassium	1.60	0.041	Susp. Solids	0.00
Calcium	9.80	0.489	NTU	3.00
Magnesium	1.40	0.115		
Iron	0.00	0.000	Hardness (CaCO3)	30.23
Manganese	0.00	0.000	Alkalinity (CaCO3)	20.01
			Saturation Index	0.02
		0.845		