"There are More Questions than Answers

And the More I Find Out, the Less I Know."

A STUDY OF THE GROUND WATER OF THE CLARENDON PLAINS

BY

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ABSTRACT

Hydrogeology was formerly considered by many to be an art. However, it has increasingly been shown that scientific methods can be successfully applied. Were it not that many of the facts about a given situation remain concealed and not a few of the processes involved are little understood, the full apparatus of science could be brought to bear. As it is, much judgement, tempered by experience, is needed to offer practical advice in developing groundwater resources.

The thesis gives an account of a practical hydrogeological investigation of an aquifer system in the island of Jamaica. The background of the study is given in the early chapters, followed by a discussion of the possible generation conditions for the aquifer. The Hydrology and Hydrogeology are discussed, followed by sections on the application of numerical techniques. The thesis ends with concluding remarks on the utility of the methods used and an appraisal of the groundwater water resource situation.

Three main groups of techniques have been applied, these are: statistical methods, numerical simulation (groundwater modelling) and computer plotting and mapping. Statistical techniques for processing groundwater data are coming into wider use. These are used to examine relationships between variables and to identify common patterns among groups of data. Not much needs to be said here about groundwater models since their utility and application has long been recognized. Methods for computer plotting of data exist and remain to be developed. They offer the potential advantages of being able to handle large quantities of data and to be able to extract much from small amounts of data. Many of the techniques used are, as far as many hydroegologists are concerned, simply 'solutions in

search of problems'. Practicing hydrogeologists need to experiment with these techniques and use them in order that they can find out which ones are relevant to their subject. It is hoped that this thesis will help this search for relevance.

PREFACE

The groundwater data utilized in this research project was primarily collected by the writer during the time that he was employed by the Water Resources Division of the Jamaican Geological Survey Department.

For much of that time the writer was seconded to the UNDP-FAO Special Fund Project, assigned to investigate the water resources of selected areas of Jamaica, and some of the general descriptions and background information are based on unpublished reports and memos prepared by the writer at that time.

In this thesis the above two organizations are respectively referred to as the Water Resources Division and the Project.

ACKNOWLEDGEMENTS

I wish to thank my supervisors, Dr. T.R.E. Chidley and Dr. R.J. Johnson for their advice and guidance during the course of this study, the Department of Civil Engineering for the awarding of a Research Studentship which made the work possible and the Head of the Water Resources Division, Jamaica, for kindly allowing me to utilize the basic data collected whilst I was employed by that organization.

I also wish to thank the firm of James F. MacLaren Limited of Ontario, Canada, for their support in the final stages of this project and, not least, my wife Barbara for encouraging me throughout.

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1 GENERAL

1.1 Introduction

Jamaica is one of the most westerly islands of the Antillean Island Arc and lies some ninety miles south of Cuba and one hundred miles west of Haiti (Fig. 1.1). The nearest point on the American continent is Cape Gracias a Dios, in Honduras, which lies three hundred and ten miles to the south west.

Jamaica is one peak of a submarine chain which also contains Cuba, Hispaniola, Puerto Rico and several smaller islands. This structure owes its origin to periods of earth movement commencing in late Cretaceous times which also produced the volcanic activity of Central America and Mexico. Two branches extended to make up the bifurcating Greater Antillean mountain chain, the northern one passing through the Cayman islands, Cuba and northern Hispaniola, and the southern one passing through Jamaica and southern Hispaniola. These two high areas are separated by the Cayman or Bartlett Trough which extends some one thousand miles from Honduras in the west and, in places, exceeds 20,000 ft. in depth.

1.2 Geography

The island of Jamaica covers an area of 4,450 square miles with a length of 148 miles and a width which varies from 22 to 52 miles (Fig. 1.2). There are three main physiographic features in the island with contrasting topography, the most striking being the interior mountain ranges. These consist of Cretaceous and lower Eocene pyroclastics, with acid and basic intrusions, and form the core of the island with elevations ranging from 3,000 ft. in western and central areas to over 7,400 ft. in the eastern part. The trend of these older rocks runs NW - SE in the region of the main Blue Mountain Ridge but tends to sweep round to an E - W direction towards the centre of the island. The topography of the mountain areas consists of much eroded hillsides cut by gullies and deep valleys.

The flanks of the older rocks and, in the east the axis itself are covered with karstified limestone plateaux and hills which rarely rise above 3,000 ft. In the higher regions an extreme form of karstification known as "Cockpit" occurs and this contrasts with the gentler hills of the lower limestone areas.

The third type of physiographic region includes the coastal plains and the less important interior valleys. The coastal plains are best developed along the south coast and they extend inland for several miles before abutting against the limestone hills. They are composed of chiefly alluvial sands, gravels and clays and are ideal for large scale cultivation. These plains, however, have a total area of only 650 square miles.

The Clarendon Plains, which constitute the main part of the study area, are over one hundred square miles in area and are situated about half-way along the south coast of the island (Fig. 1.3). They are covered with alluvium and surrounded on three sides by the Tertiary White Limestone Formation which crops out as the Brazilletto Hills on the east, the Mocho Mountains on the north and the Manchester Highlands on the west. It also crops out at several localities within the Plains themselves where small limestone hills penetrate the alluvium. In the south and southeast the plains end in mangrove swamps which cover fairly small areas adjacent to the coast and limestone is seen again at Portland Ridge (Fig. 1.4).

The Plains and the surrounding catchment area, including a large part of the central inlier, are drained by two rivers (Fig. 1.5). The Milk River enters the plains at the north-western corner and flows southward along the western edge of the plain, whereas the Rio Minho enters the plains at the north-eastern corner and meanders southwards adjacent to the Brazilletto Hills at the eastern edge of the plains. The rivers will be described in more detail later but, in general, it can be said that the tributaries of the Milk River drain most of the plains and that the Rio Minho drains the upper parts of the study area, including the central inlier, and a small proportion of the plains.

1.3 Climate

The climate in Jamaica is hot and humid with the mean temperature varying from the upper seventies in January to the lower eighties in July. The annual mean is 78.7°F at sea level and 56.5°F at the highest point, and the diurnal variations are of the order 10°F to 15°F in the lowlands and 20°F to 25°F in the upland areas. The variation of temperature with altitude is approximately 1°F per 300 ft.

In Kingston the average high temperature in July is 90.7°F and the average low is 75.1°F, compared with January where the corresponding figures are 86.7°F and 69.1°F.

The mean annual temperature in the Clarendon Plains calculated from ten years of records at Monymusk is 79°F. January is the coolest month with a mean of 76.2°F and, in contrast to the national average, September has the highest mean temperature of 81.3°F.

The climate of Jamaica is greatly influenced by the Trade Winds which are moisture laden, but not normally rain-bearing. Because of the high humidity of these winds (70 - 80%), however, only a small disturbance is required for them to produce precipitation. The North-East Trade Winds are forced upwards by the north-eastern flanks of the

Blue Mountains and this frequently leads to rainfall in the area inland from Port Antonio with the mean annual rainfall here exceeding 200 inches. Because of this direction of the prevailing winds Kingston and the Clarendon Plains are in a rainfall shadow area, as can be seen in Fig. 1.6.

In Jamaica, convection caused by warm air rising over the land, frequently leads to precipitation when the air cools. This also helps to produce sea breezes which start in the morning and reach speeds of up to twenty knots by early afternoon. At night the process is reversed and off-shore breezes occur, reaching speeds of about five knots.

During the summer months the point of convergence of the North-East Trade Winds tends to move northwards and affects Jamaica in the form of squall lines which move from east to west, sometimes with associated hurricanes. A fourth and much less important source of rain is the southward movement of cold fronts during the northern winter, though an analysis of the seasonal distribution of rainfall shows that this is not very significant and that the bulk of the precipitation is convective and orographic. The greatest effect of the rain from these cold fronts is felt on the northern side of the island and not in the Clarendon Plains.

The months of lowest rainfall throughout the island are December to March (see Fig. 1.7), with the latter being the driest. Significantly these coincide with the cold fronts which, in addition to carrying little rain, also serve to lower the temperature and reduce the convective processes. These processes are also affected by the lower angle of the sun during the Winter and the only rain during this time is orographic.

The wet season runs from May to June and from

August to November when convective processes have increased and, during the latter period, when the easterly squalls and tropical depressions are passing. Direct hits by hurricanes are not common in Jamaica, averaging less than once every fifteen years, but a miss of up to 200 miles can result in heavy rainfall. Within the Rio Minho - Milk River basin the average rainfall varies from less than 40 inches at the coast to 55 inches at the back of the plains and as high as 75 inches in the upland areas. However, periods of several years in succession have been recorded where the rainfall has been less than 30 inches over the plains.

1.4 Land Use

Within the Clarendon Plains the principal land usage is agricultural and the most important crop is sugar cane. There are several large company-owned estates and many small farmers cultivate sugar cane and sell it to one of the three factories operating in the area. Citrus is grown in the lowlands and to a greater extent in the valley of the upper Rio Minho. Bauxite is mined extensively in the high limestone areas and there are two alumina plants, one at Mandeville, and the other at Halse Hall (Fig. 1.8).

The land capability of the area, as evaluated by the Ministry of Agriculture, and their assessment of the actual land usage, are shown in Figs. 1.9 & 1.10. Recent years have seen an increase in the land used for cattle and a reduction in the acreage of tobacco, though some is still grown, chiefly in the area south of May Pen. Much of the area in which the limestone crops out is only marginally useful for agricultural purposes, owing to its thin soil covering and lack of water. One crop that has been successfully produced under these conditions on the Brazilletto Hills is sisal, which is used for the manufacture of rope. In the main, however, cultivation in the highlands is restricted to subsistence level farming, often in the karstified depressions, where banana, yam, sweet potato, Irish potato, corn, peas, and cassava are produced for domestic consumption.

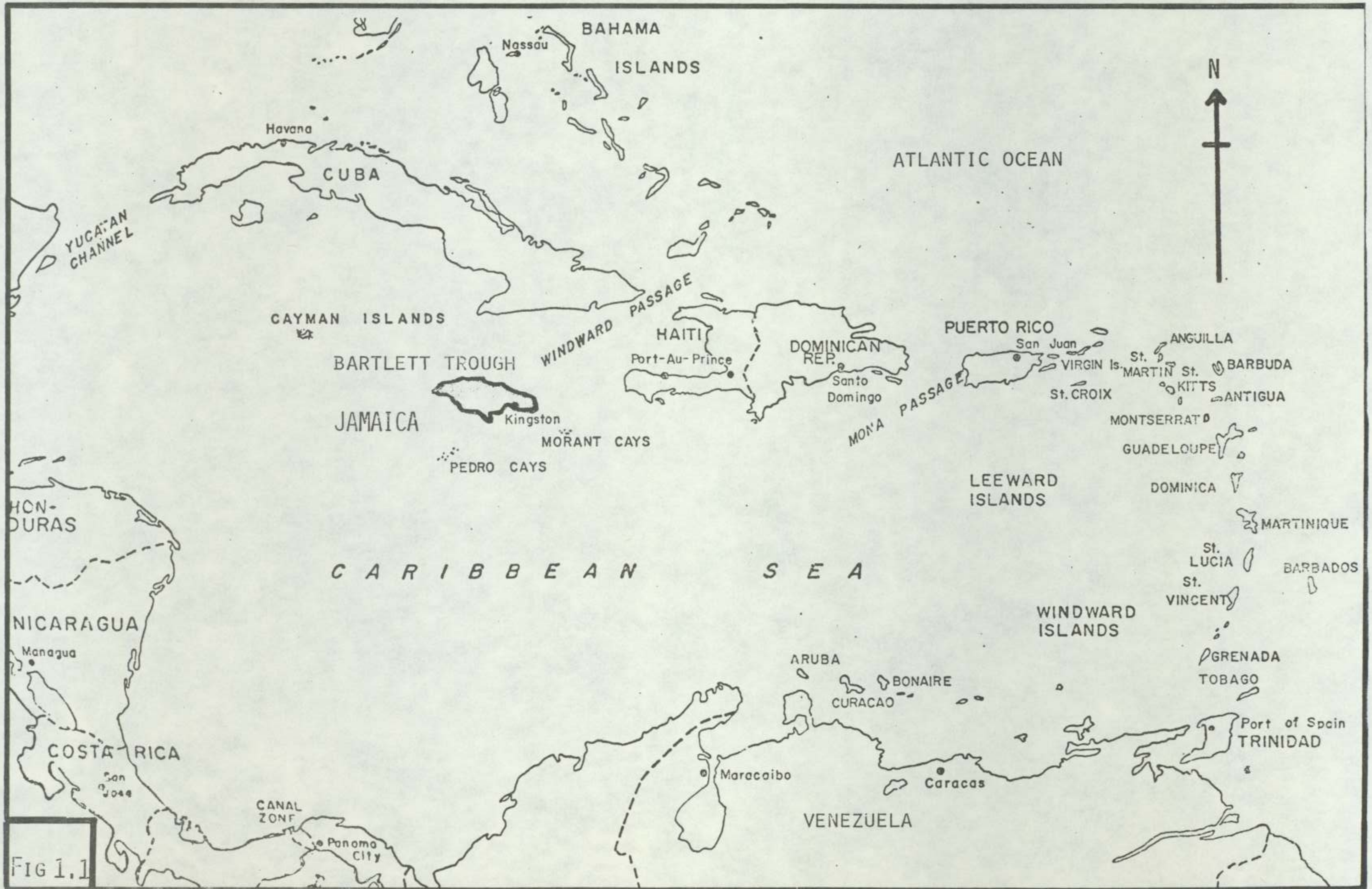

BAHAMA ISLANDS
Nassau
N
Havana
CUBA
ATLANTIC OCEAN
YUCATAN CHANNEL
WINDWARD PASSAGE
CAYMAN ISLANDS
BARTLETT TROUGH
HAITI
Port-Au-Prince
DOMINICAN REP.
Santo Domingo
PUERTO RICO
San Juan
VIRGIN Is.
St. CROIX
MONA PASSAGE
ANGUILLA
St. MARTIN
St. KITTS
BARBUDA
ANTIGUA
MONTSERRAT
GUADELOUPE
DOMINICA
MARTINIQUE
St. LUCIA
BARBADOS
St. VINCENT
GRENADA
TOBAGO
Port of Spain
TRINIDAD
JAMAICA
Kingston
MORANT CAYS
PEDRO CAYS
LEEWARD ISLANDS
WINDWARD ISLANDS
HON-DURAS
C A R I B B E A N S E A
NICARAGUA
Managua
COSTA RICA
San Jose
CANAL ZONE
Panama City
ARUBA
CURACAO
BONAIRE
Maracaibo
Caracas
VENEZUELA

FIG 1.1

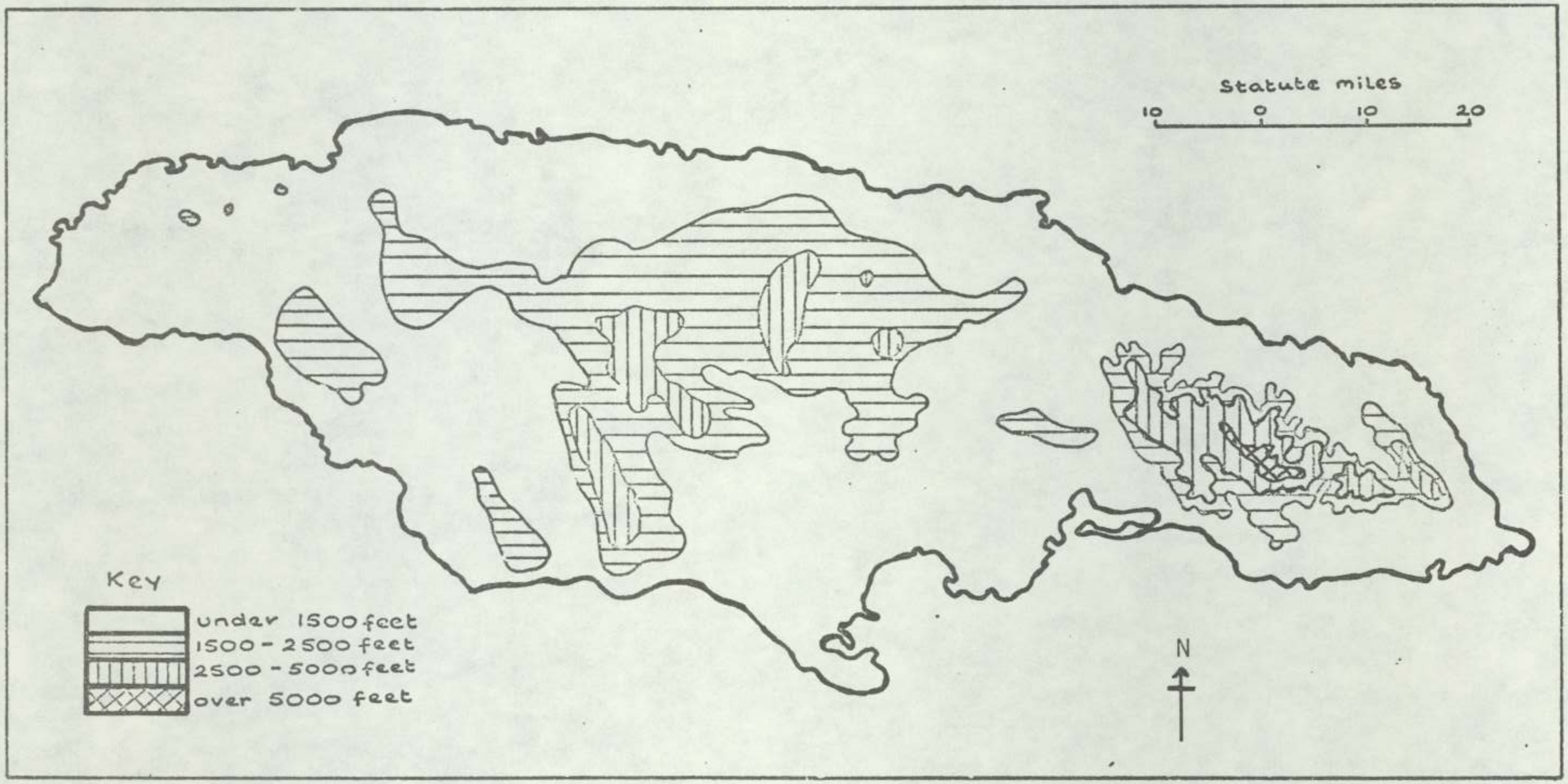


FIG. 1.2 MAP SHOWING GENERALISED TOPOGRAPHY OF JAMAICA

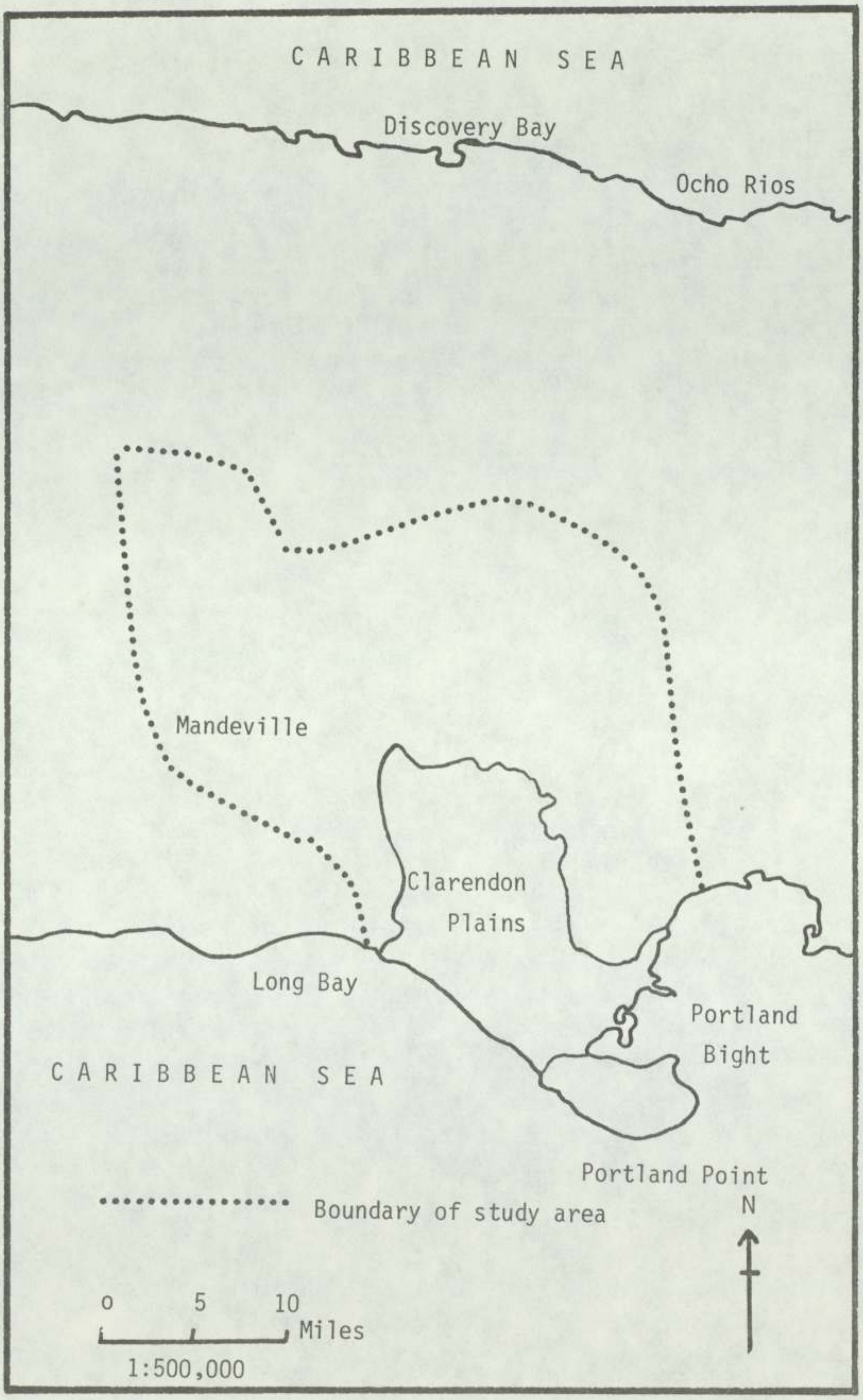


FIG. 1.3 LOCATION OF STUDY AREA

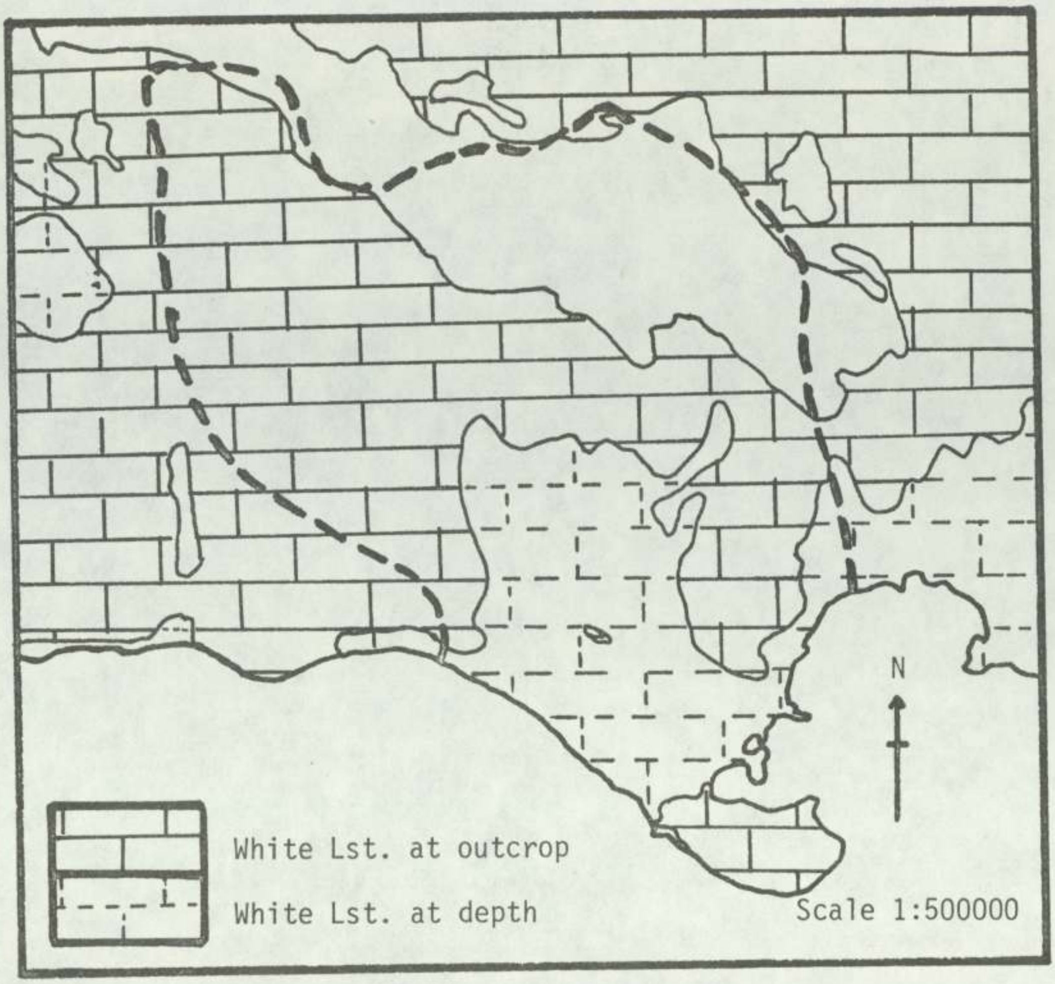


Fig 1.4 Distribution of White Limestone at Outcrop and Depth in Study Area.

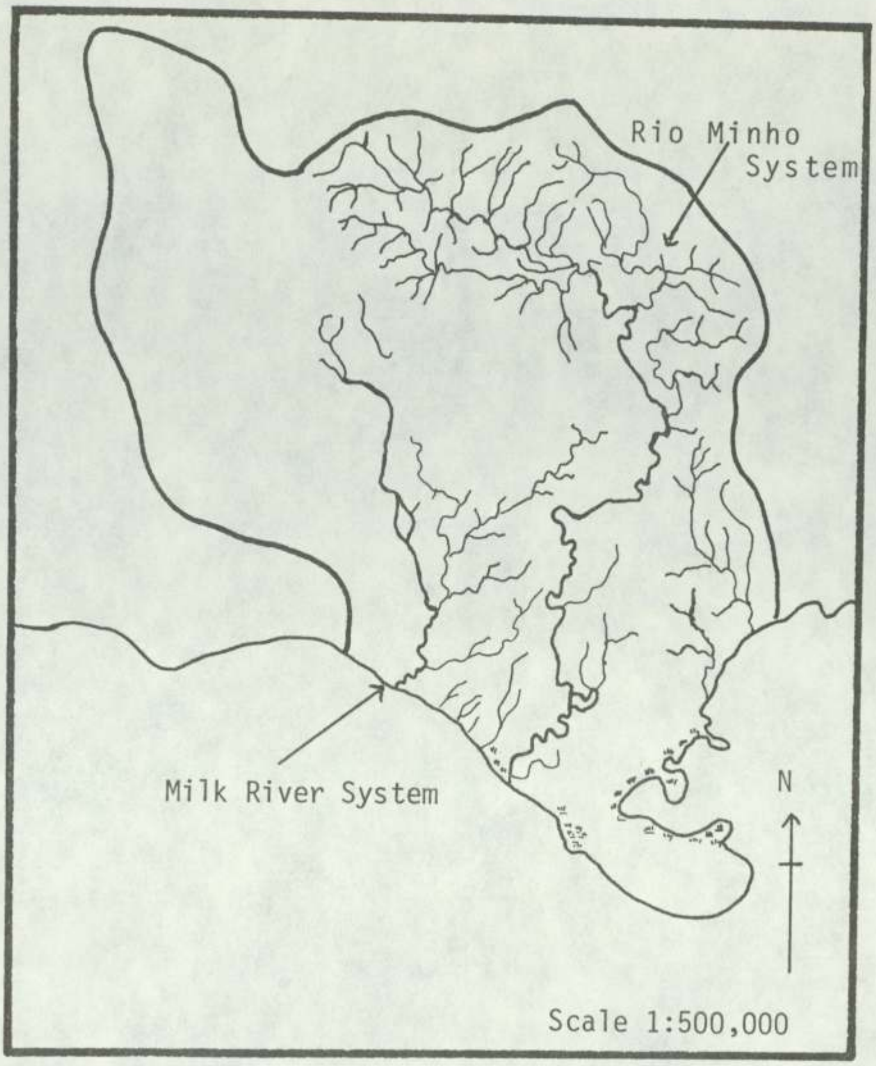


FIG 1.5 SURFACE DRAINAGE.

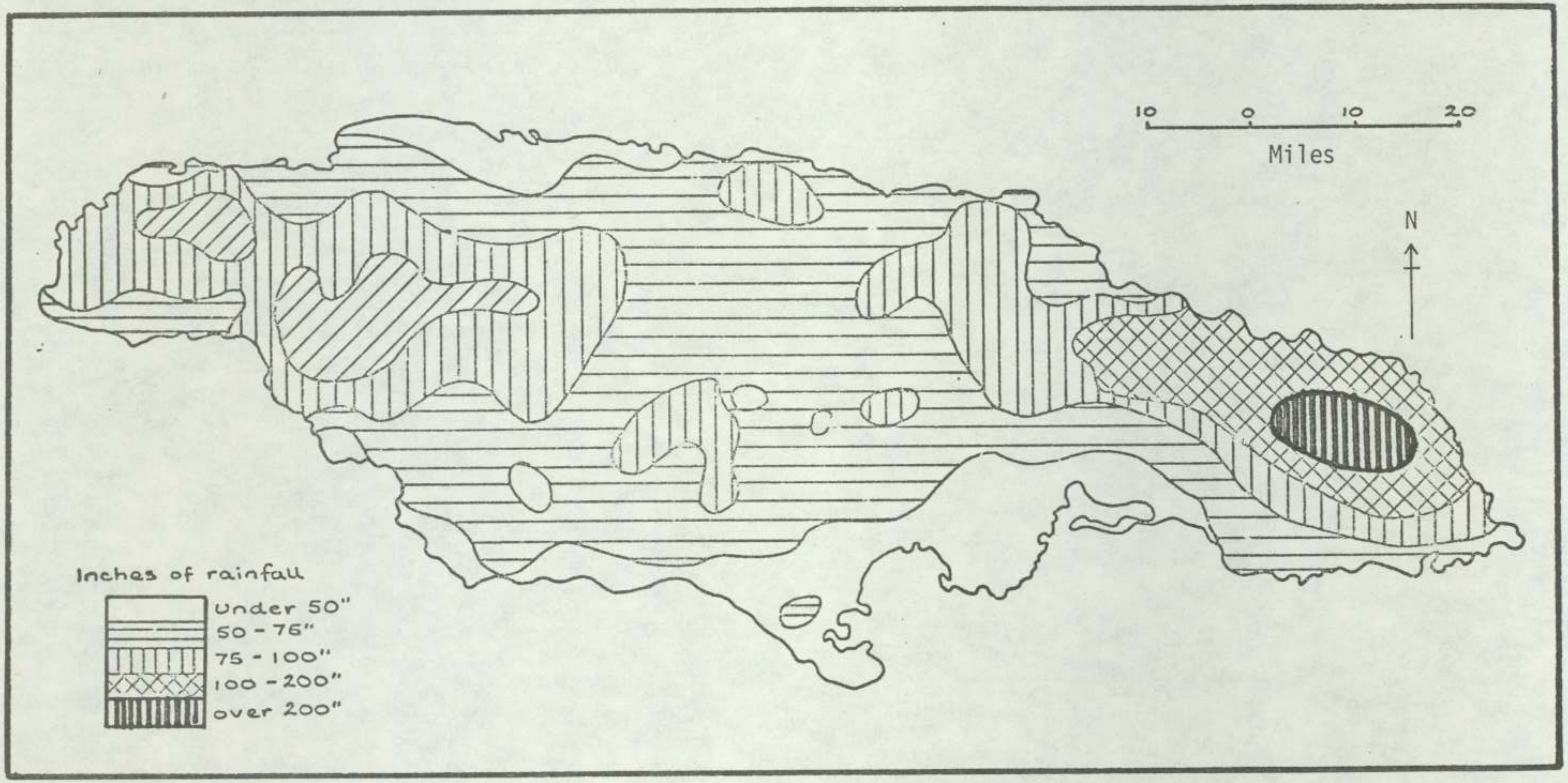


Fig 1.6 Map Showing Average Annual Rainfall in Inches.

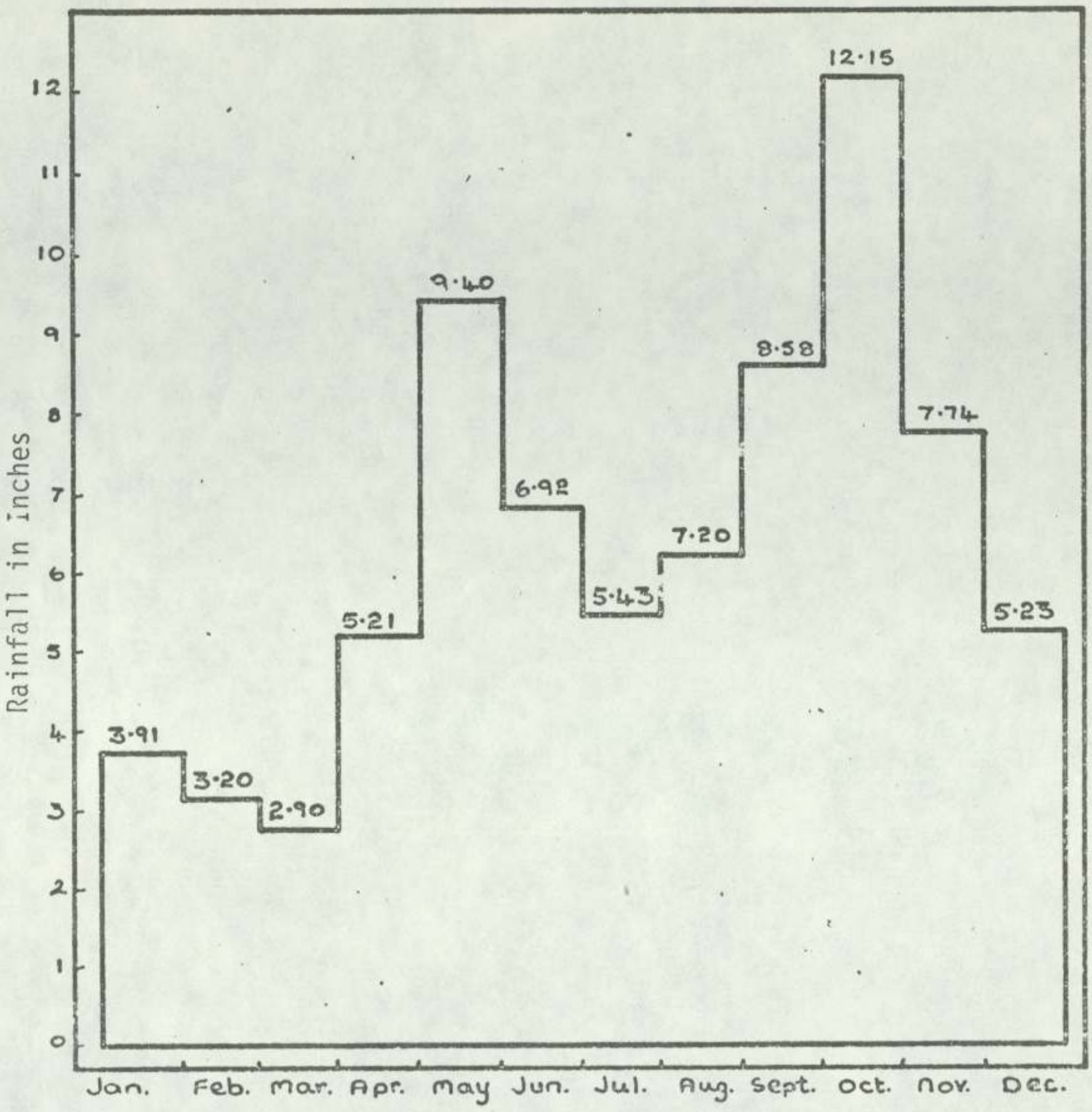


FIG 1.7 HISTOGRAM OF MEAN MONTHLY RAINFALL TOTALS (1870-1960).

As published by the Scientific Research Council

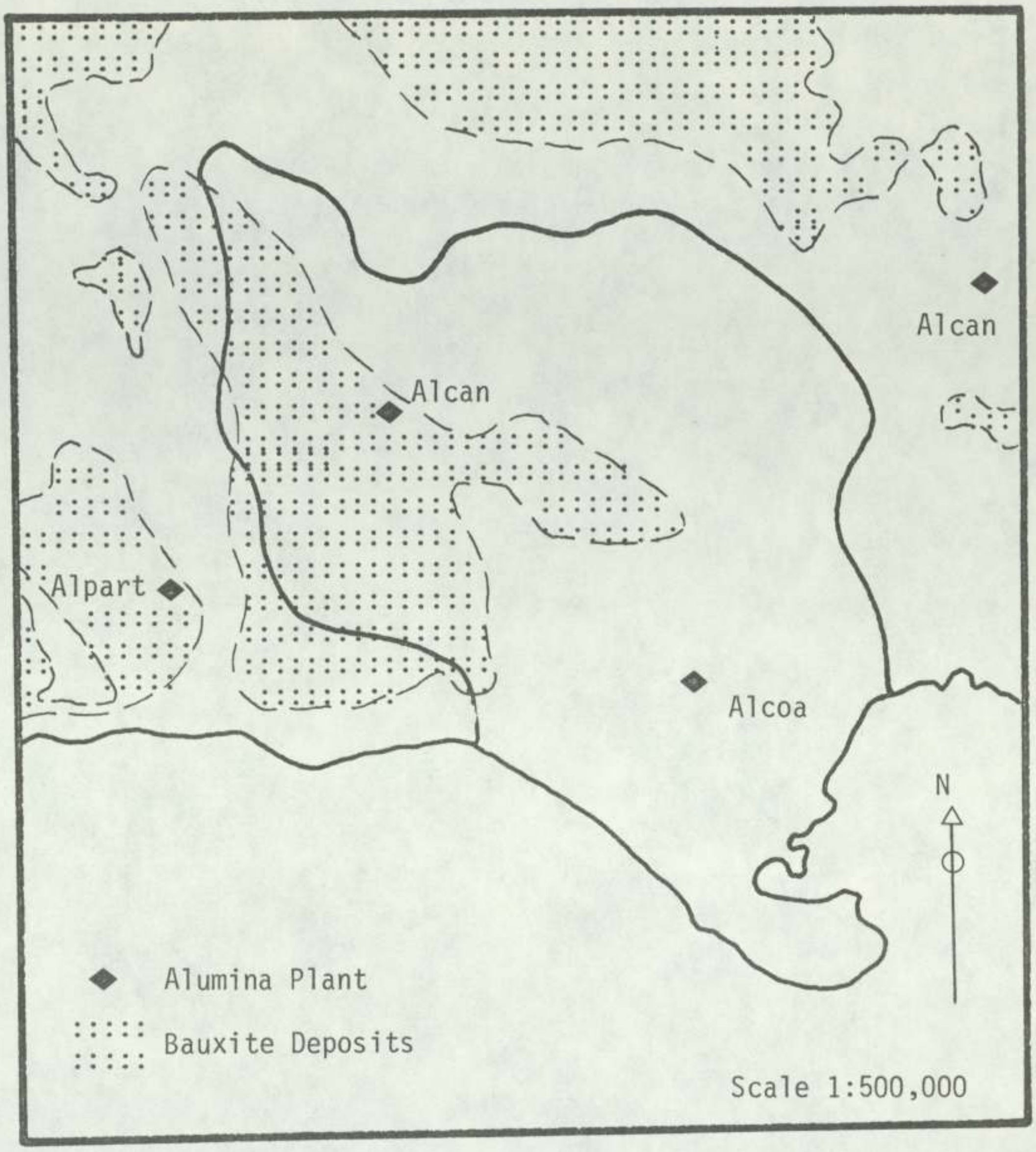
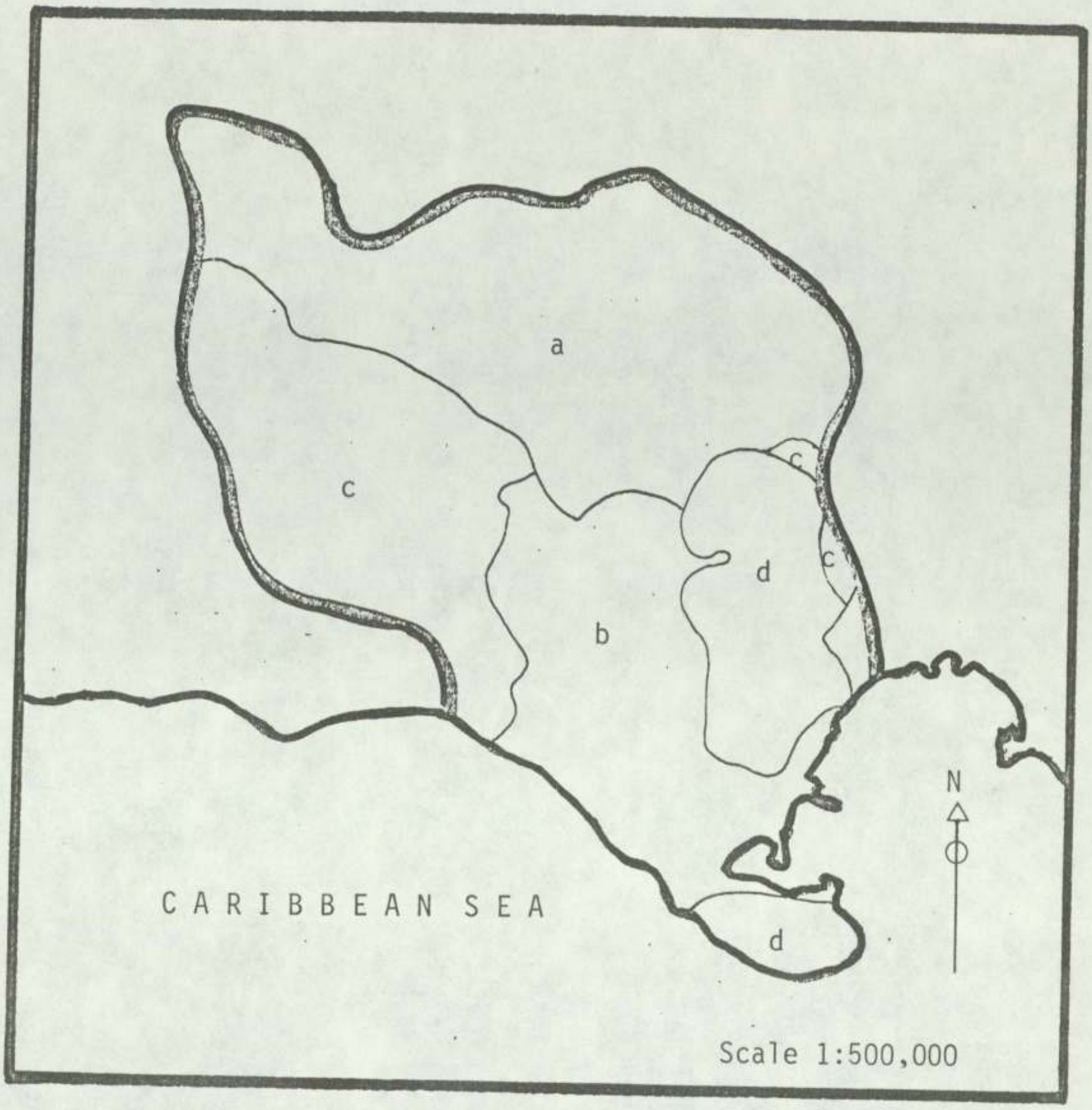


FIG. 1.8 DISTRIBUTION OF BAUXITE DEPOSITS.



a Suitable for cultivation but strongly susceptible to erosion.
b Suitable for cultivation but irrigation required.
c Marginally suitable for cultivation but susceptible to erosion.
d Not suitable for cultivation.

FIG. 1.9 LAND CAPABILITY

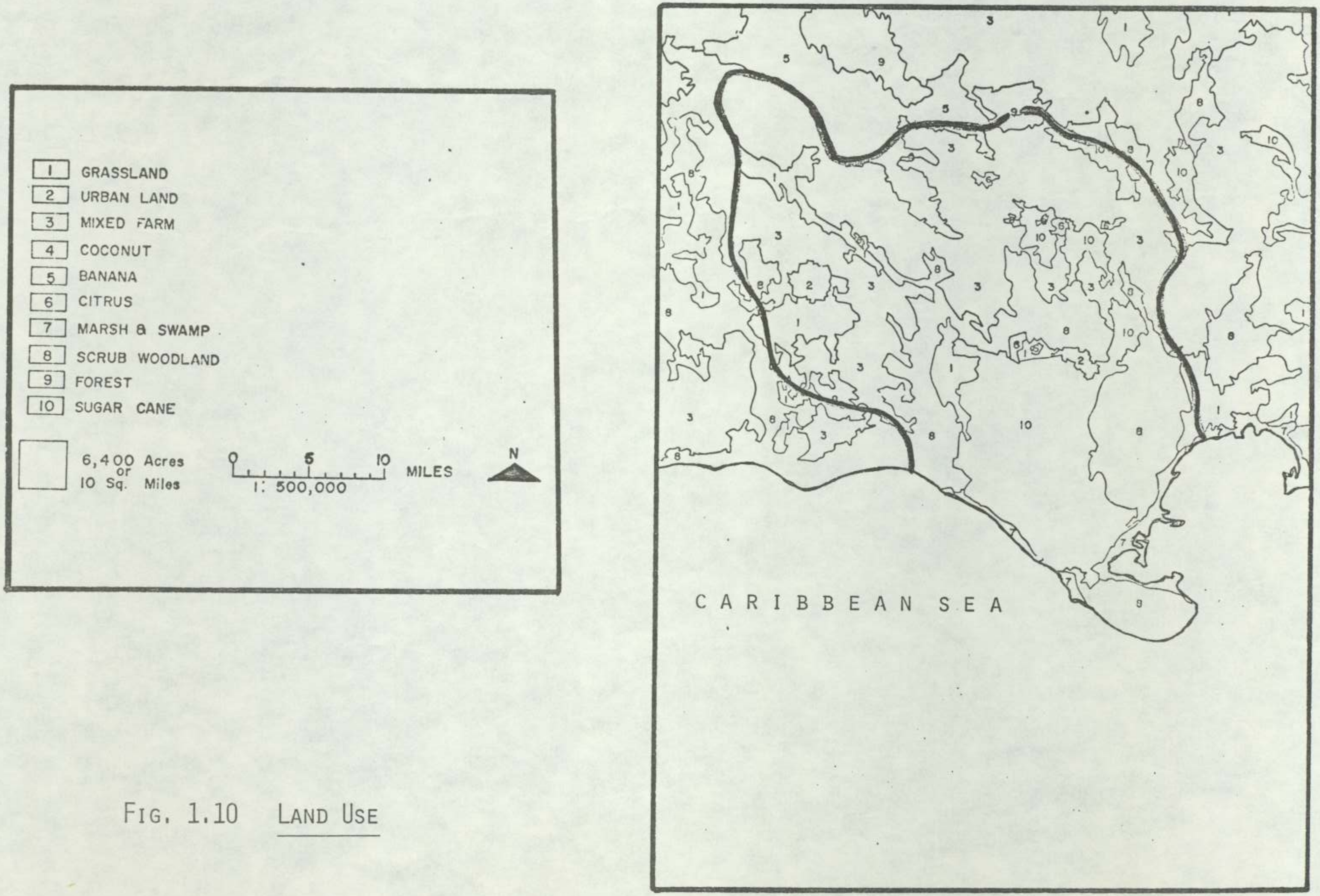


FIG. 1.10 LAND USE

2 GEOLOGY

2.1 Geomorphology

The three types of topography described in the first chapter all occur in the Rio Minho - Milk River drainage basin, with Cretaceous pyroclastics exposed in the area which will be referred to as the Upper Rio Minho Basin. This basin covers part of the Central Inlier and the Rio Minho is fed by streams which drain southward off the NW - SE trending main ridge and northward off the northern side of the Mocho Mountains. The valley follows the E - W axis of the anticlinal structure of the rocks of the central inlier and Wirtz (1970) suggested that the course of the river in this area has been inherited from the original subsurface drainage pattern which existed in the limestone that formerly overlaid the Cretaceous rocks.

The second physiographic unit described includes all the areas in which limestone crops out. A closer examination, however, reveals that in fact this unit covers three basic types of land form which are related to the type and degree of karstification. Versey (1972) believes that any such sub-division should be based on the extent to which groundwater circulation has influenced the physiographic development, depending on whether it was so deep that it produced little effect or whether the water table actually intersected the ground surface.

The extreme form of karst is that known as Kegel Karst which produces a land surface consisting of rounded hills with steep or vertical sides up to several hundred feet high, separated by irregular depressions. Kegel Karst occurs in the north west of the study area and the northern part of the Mocho Mountains, and extends eastward across the Rio Minho above Moores. It is best developed in the lower members of the White Limestone Group.

The second type of limestone topography is found in the May Day Mountains and the lower parts of the Mocho Mountains where slopes between Valley floor and hilltop are usually less than thirty degrees and where large thicknesses of bauxite are developed. Finally, the Harris Savanna - Brazilletto Hills differ greatly from the above categories in that it consists of a peneplain which is probably undergoing rekarstification.

The various theories about the development of the different types and degrees of karstification in tropical limestones in general and the Clarendon Basin in particular, will be examined in Chapter 3.

The third broad physiographic unit described in Chapter 1 was the coastal plains which stretch inland to the foot of the limestone hills. These are floored with alluvium which consists of interstratified sands, gravels and clays and attains a thickness in excess of 750 ft. in the south central part of the plains. Borehole logs indicate that a bed of estuarine clays separates the actual alluvium from the underlying limestone and the hydrological significance of this will be discussed later.

2.2. Stratigraphy

The Cretaceous rocks are the oldest and occur in the northern part of the study area where they form the Central Inlier (see Sheet 1). They consist of tuffs, conglomerates and some sandstones, cut by igneous intrusions of andesitic and dioritic character. The rocks are folded into an E-W trending anticline. In general they can be considered to be impermeable and their relevance to the groundwater study is as a lower limit to groundwater circulation.

The oldest rocks of Tertiary age are the Yellow Limestone Group which represent the first Tertiary marine transgression over the older Cretaceous rocks. They are of Lower Eocene age and vary from sandy estuarine deposits at the base to impure limestone higher in the sequence. The total thickness normally varies from 200 to 300 ft. but locally may be as much as 500 ft. These rocks were not thought to be hydrologically significant in the study area and only crop out around the Central Inlier and as small inliers in the lowest member of the overlying White Limestone Group. It will be seen, however, that a convincing hypothesis can be advanced linking these rocks with the occurrence of saline groundwater.

Rocks of the White Limestone Group are the most common rocks in the study area. They underlie the whole of the Clarendon Plains and crop out in the surrounding hills.

Versey (1956) mapped four separate units of the White Limestone but MacFarlane (1972) found that no clear boundary could be mapped between the top of the Somerset and the bottom of Walderstone and thus the succession is as shown in Fig. 2.1.

The Troy formation is conformable upon the upper beds of the Yellow Limestone Formation and is distinguishable from the other members of the White Limestone Group by the fact that it is totally recrystallised and partially dolomitized in the lower and middle portions. MacFarlane describes the dolomitised part as having a pseudobrecciated appearance and says that the uppermost horizon of the Troy Formation is a "Vuggy" white or pink micro-crystalline limestone with no fossils, which reaches a thickness of about 20 ft. The total thickness of the Troy Limestone is probably in the region of 700 ft. and the outcrop is in the form of a belt running NNE - SSW right across the study area parallel to the southern edge of the inlier.

The Somerset - Waldeston limestones are foraminifera and miliolid-rich sparites which show little recrystallisation other than right at the base where they rest conformably on the Troy. MacFarlane found that the most obvious change when passing up from Somerset to Walderston was a gradual disappearance of the foraminifera Fabularia Verseyi. The lower and middle parts of what would be the Waldeston Limestone have a mottled brown and pink appearance and Versey (1962) described them as an intra-formational conglomerate. The total thickness of the Somerset - Walderston Limestones is probably in the region of 800 ft. Their outcrop follows a similar pattern to that of the Troy.

Whilst it is likely that the whole White Limestone Group acts, broadly, as a single hydrological unit, the Newport Limestone is by far the most predominant and, therefore, the most important. A description of its outcrop is much the same as that given for the group as a whole, and it is this formation that is encountered in the numerous boreholes which have passed through the alluvium in the plains.

There is no obvious unconformity at the base of the Newport but it is considered likely that there was a break in deposition at the end of Oligocene times. The Newport Limestone has been described as a micrite and in its lower horizons it is characterised by corals, algae and Pectens. It exhibits a wide diversity of character and varies lithographically from a soft chalky or marly limestone to a harder more dense fine-grained rock with some patchy dolomitisation. The so-called May Pen Beds, which are exposed in the railway cuttings around May Pen, represent the middle horizons of the Newport limestone and are sandy and clayey with some siliceous pebbles and yellow marly limestones. MacFarlane (1972) includes in the May Pen Beds the yellow rubbly limestones which occur north of Four Paths and says that "The May Pen Beds thus appear to outcrop in a band stretching across the northern limit of Harris Savanna, through Sandy Bay and May Pen, and as isolated hills along the foot hills of the Mocho Mountains". The total thickness is in excess of 4000 ft. Overlying the Newport Limestone unconformably are the impure limestones and grits which belong to the August Town Formation of the Coastal Limestone Group. They do not crop out over any great area in the Clarendon Plains but can be seen around the flanks of the Brazilletto Hills at Cockpit and Hayes, at Kemps Hill and at Round Hill. The rocks are shallow water deposits probably laid down when the Clarendon Plains were a bay in post mid-Miocene times. Fossiliferous calcareous sandstones and conglomerates 180 ft. thick were found to occur above the Newport Limestone in a borehole (Exploratory II) at Content Village (E 4511 N 3790) and on the basis of palaeontological evidence, MacFarlane assigned them to the Coastal Group.

The term alluvium is generally used in this area to describe the superficial deposits which overlie the Newport and Coastal Limestones and stretch seaward from the foot of the Mocho Mountains. Their lateral extent is roughly defined by the 200 ft. contour and the deposits consist of interstratified sands, gravels and clays. Sand and clay predominate with coarser material concentrated in buried valleys. Variation in thickness of the alluvium is considerable, ranging from greater than 750 ft. at Banana Walk (E 4477 N 3464) to almost absent in a few small areas within the plains.

A contour map of the base of the alluvium was first produced by Versey (1956) but, in the light of more recent evidence, this was found to be inaccurate in a number of places. Consequently the map shown in Fig. 2.2 was prepared by the present author. From this map it can be seen that the most striking feature in the limestone surface is the large depression running southward from west of May Pen to west of Kenps Hill. It is not a simple erosional feature as first thought and the term "Buried Valley", as used by Versey, is probably a misnomer. It is wide at its upper end and becomes narrower towards its lower end with a restricted entrance. It is almost certainly a structural feature bounded on its eastern side by a fault, the hydrological effect of which plays a big part in the present study. At its southern end this feature is intersected by the E - W trending South Coast Fault system which downthrows the limestone to the south, where the true thickness of the alluvium, though known to be in excess of 750 ft., has never been ascertained. In the Needham area (E 460 N 340), however, there is a tongue of limestone pointing southward across the supposed fault zone. This may represent some form of land slip, particularly as it can be linked with the minor depression in the limestone surface which runs north-south along the present coarse of the Rio Minho. In the area stretching from the eastern boundary of the major depression to the western edge of the Brazilletto Hills, the base of the alluvium is an almost horizontal plane. There are many minor variations but no major features other than the shallow depression which follows the course of the Rio Minho.

From the centre of the main depression, in the Vernamfield area, the base of the alluvium slopes upwards towards the north-west at a gradient of about 200 ft. per mile for about 3 miles before levelling off into a gentle sloping plain which continues to the Clarendon Park area.

The character of the alluvium varies both vertically and horizontally, but in very general terms there is a layer of estuarine clays and sands at the base which separates the true alluvium from the underlying limestone. Cross-sections, based on the lithological logs of various wells, show no simple correlations (Figs. 2.3). However, the examination of drillers' logs for wells which fully penetrate the superficial deposits do indicate the presence of a basal clay horizon. The existence of such an aquiclude, separating the groundwater in the two aquifers, is obviously hydrologically important. It is also likely that the clay plays a role in confining the groundwater in the limestone aquifer, though there is some evidence to indicate that this is at least partly due to marly horizons within the limestone itself.

2.3 Geological History

The first phase of the Laramide orogeny affected the island towards the end of Cretaceous times and the rocks of that age were folded and uplifted, except in the Wagwater Belt along the western edge of the Blue Mountains where deposition may have been continuous. This is outside the present study area. The second phase of the Laramide orogeny during lower Eocene times led to the re-submergence of the island and the deposition of the impure Yellow Limestones in a shallow water estuarine environment. This estuarine environment became entirely marine around mid-Eocene times, but with the Clarendon Block essentially a shallow water zone surrounded by deeper water and remaining so until the end of the Oligocene.

The contact between the Walderston and Newport Limestone is not obviously unconformable, but it is generally accepted that there was an island wide uplift followed by re-submergence at the end of the Oligocene.

Deposition of the Newport Limestone continued into upper Miocene times on the south coast, though it had ceased in the north coast area. It is probable that the uplifting of these northern areas led to the appearance of the May Pen Beds on the south coast. Further uplift and resubmergence in the upper Miocene led to the deposition of the rocks of the Coastal Group in Upper Miocene - Lower Pliocene times.

The estuarine clays which underlie the alluvium were probably a result of high sea level at the end of the Pliocene and conversely the first glacial period, with associated lowering of the sea in Pleistocene times, may well have been the origin of the alluvial deposit.

2.4 Structure

The main or Clarendon block, of which the study area forms a large part, is bounded by two sets of faults which are almost perpendicular to each other. The E - W Duanvale Fault system which runs for some 45 miles along the north coast marking the northern limit, and the South Coast Fault, marking the southern limit, make up one set. The Wagwater Fault in the east and the Santa Cruz Fault in the west, trending generally NNW - SSE delineate the east and west boundaries respectively and constitute the other set. Versey (1972) believes that they are not rejuvenations of a Laramide or pre-Laramide system but are simply a product of the warping of the Cretaceous basement.

The Manchester Highlands, or more precisely the Don Figuerero Mountains, constitute an easterly dipping block bounded on the west by the Spur Tree Fault and separated from the Clarendon block by an apparent synclinal structure running north-westwards along the Porus-Williamsfield Trough to Mile Gully. Matley (1924) believed this to be a syncline but it is more probably a zone of intense faulting and should be described as a graben. The northeast side of this zone is bounded by the Whitney Fault and the south-west by the Queens Town Hill Fault which, at its southern end, forms the eastern edge of the Manchester Highlands.

The dip of the limestone in the Mocho Mountains is in a more southerly direction than the Manchester Highland block and the faulting takes the form of NW - SE steps with the downthrow on the western side. As was said earlier, it is thought by the present author that there is a fault along the eastern edge of the sub-alluvial depression, running NNE -SSW, with downthrow on the western side. In the groundwater section it will be seen how this affects subsurface flow.

The South Coast Fault system runs right across the plains from the Brazilletto Hills in the east to Round Hill in the west and beyond the study area to St. Elizabeth. It passes south of Kemps Hill, which is on the upthrown side, and the limestone to the south of the fault is downthrown. The picture is complicated by the reappearance of upthrown limestone at Portland Ridge and Round Hill on the supposed downthrown side of the fault, suggesting that in fact there must be a second fault to the south of the known fault. Unfortunately no boreholes in this southern area have been continued to a depth great enough to determine just what is happening beneath the thick alluvial cover. All the other faults which intersect it are apparently truncated thus suggesting a large lateral displacement.

A number of NE - SW faults of small displacement are found in the southern part of the Manchester Highlands.

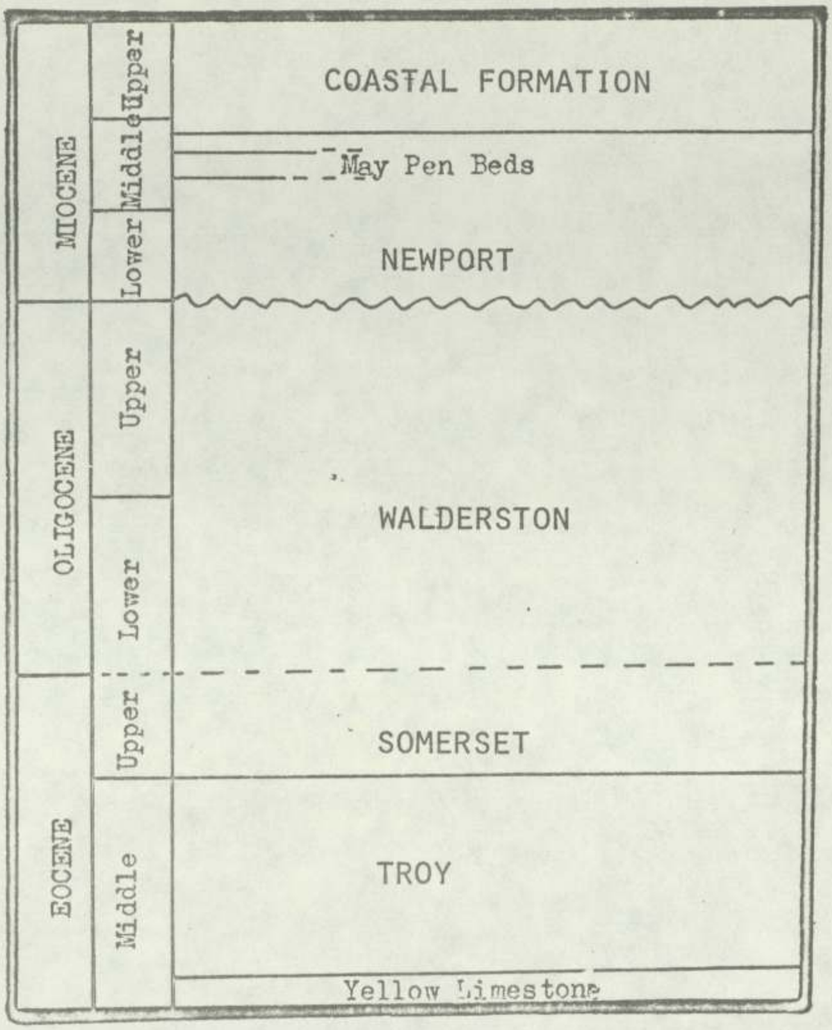


FIG. 2.1 TERTIARY SUCCESSION, CLARENDON

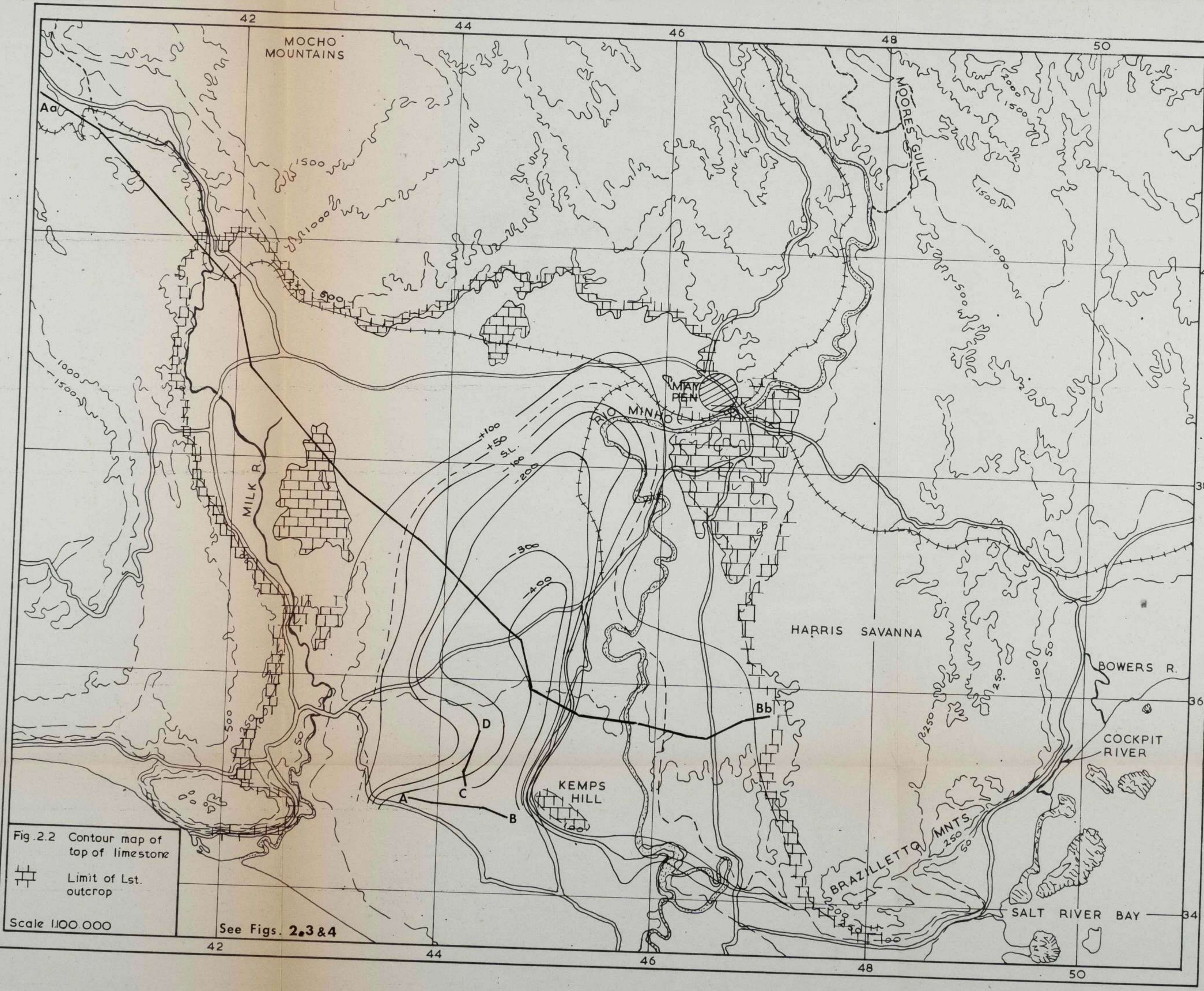


Fig. 2.2 Contour map of top of limestone

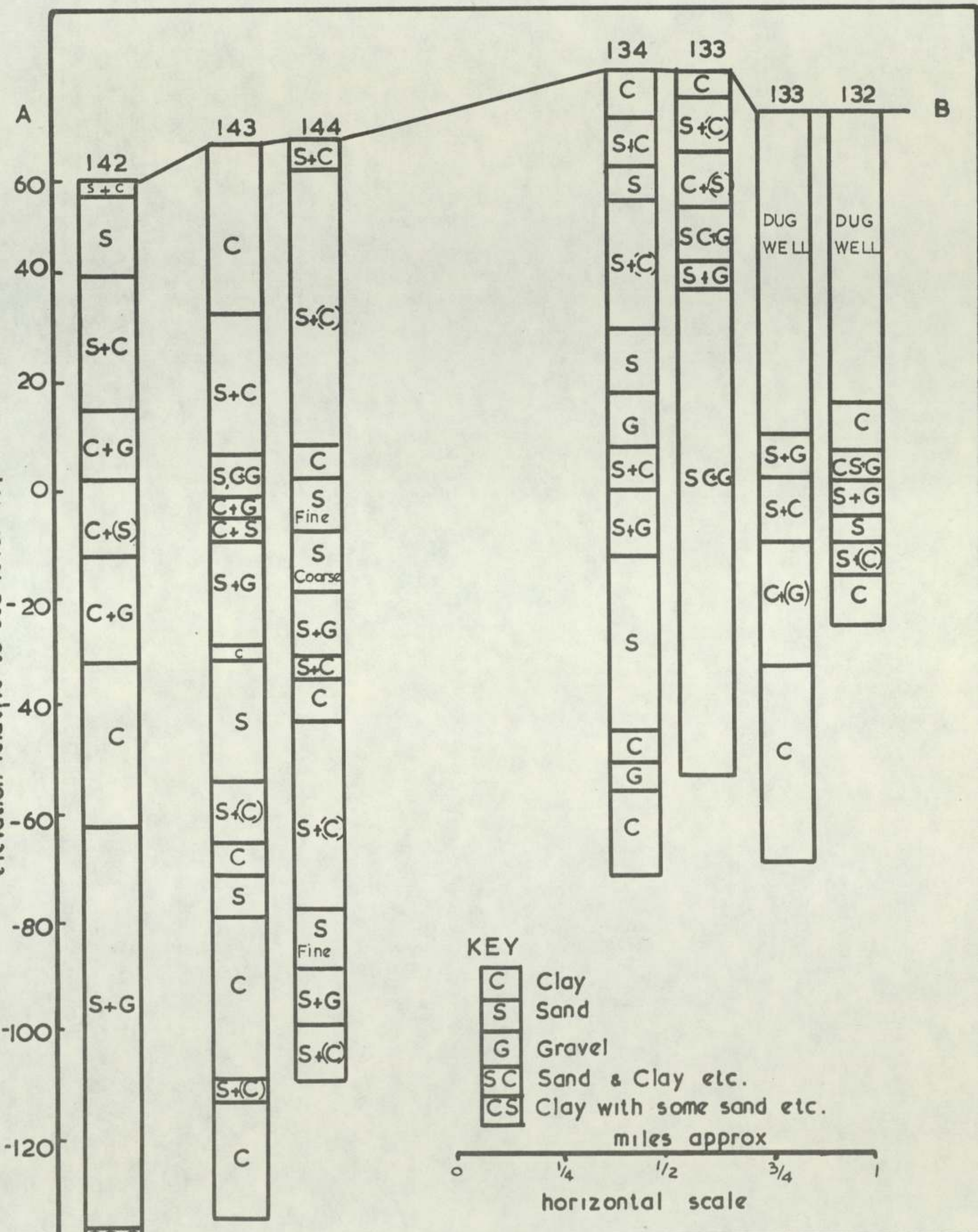


Fig. 2.3.1 Cross section A - B showing lithology of alluvium

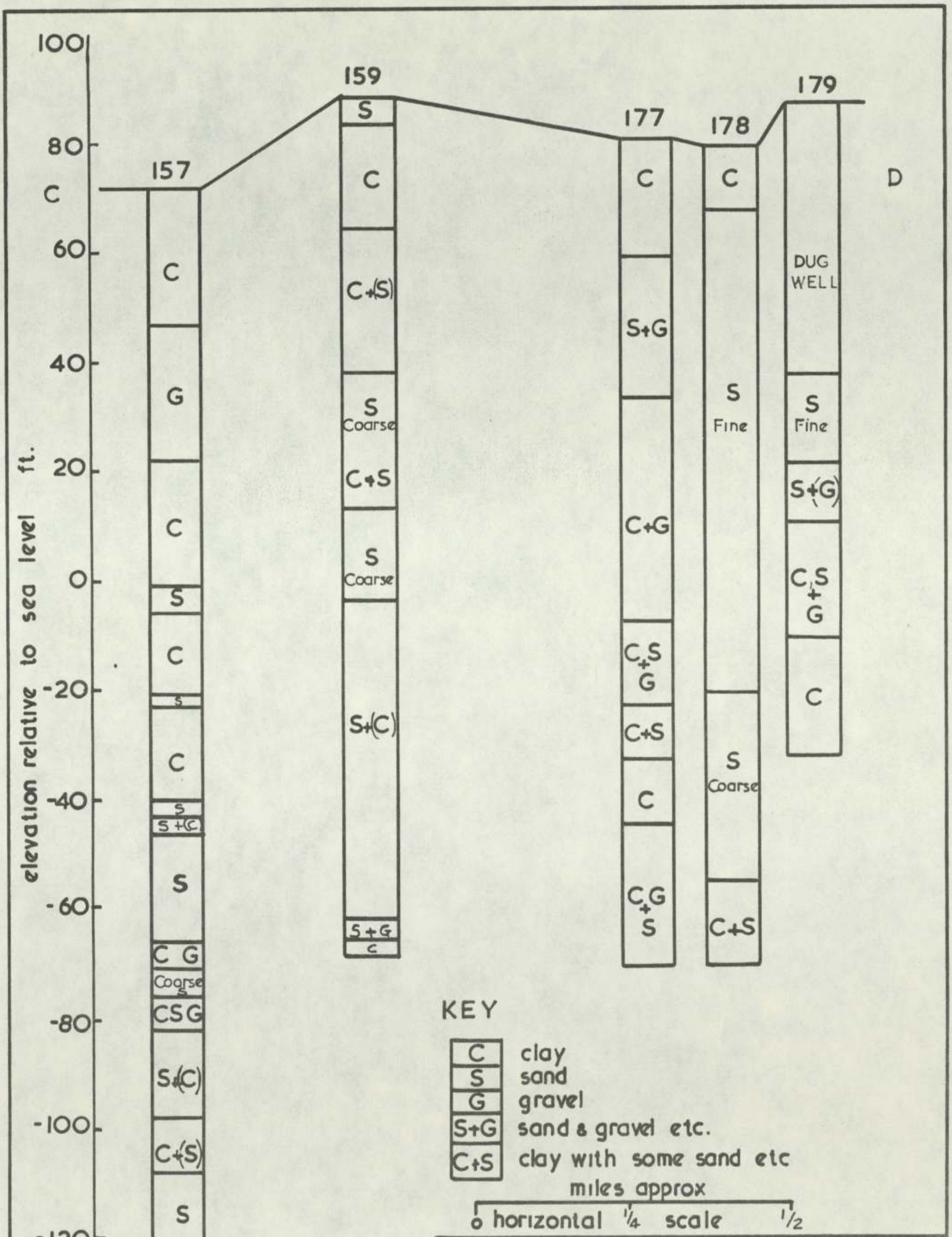


Fig 2.3.2 cross section C-D showing lithology of alluvium

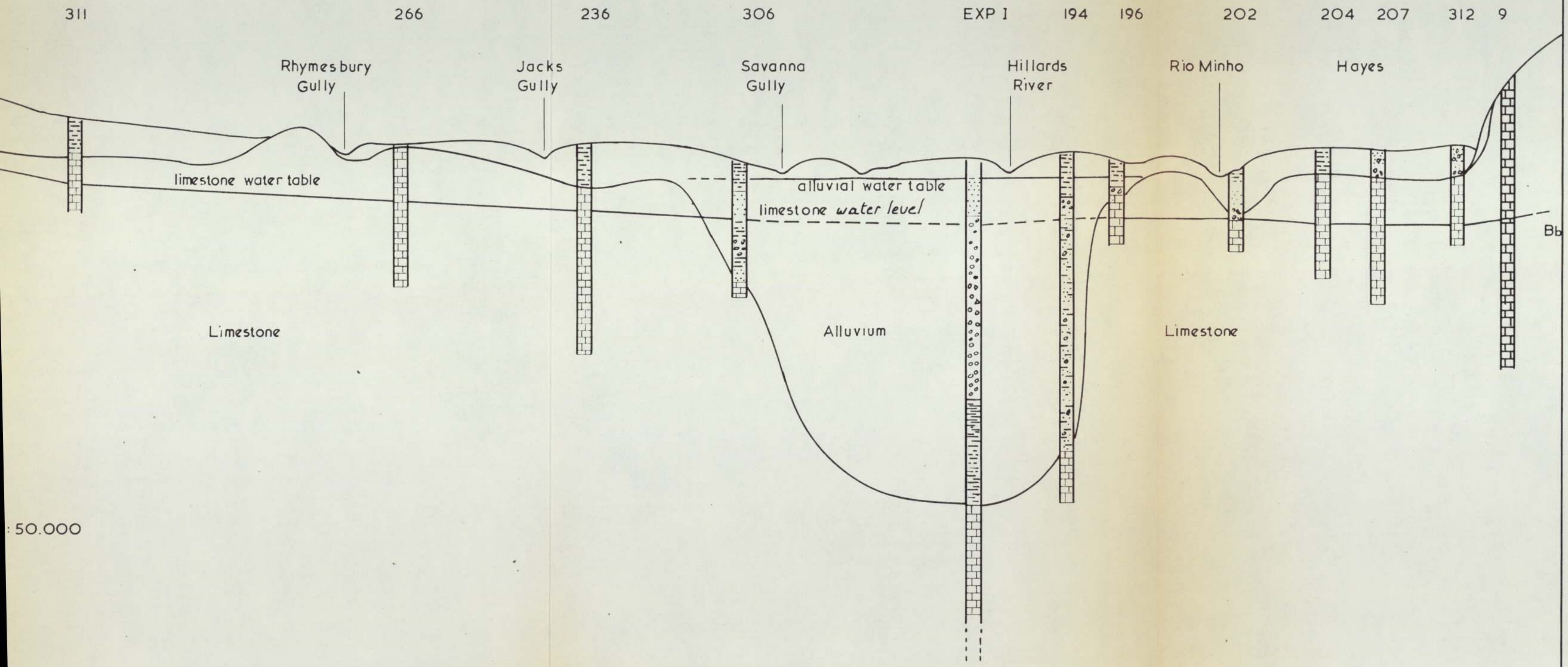


FIG. 2.4

For location see Fig 2.2

3 KARST PROCESSES

3.1 Introduction

In the previous chapter, an outline of the geological history of the area was given and reference was made to some of the theories for the development of the three types of karstic land-form that can be seen in the study area. In this chapter these theories will be examined in more detail and, after a brief look at the chemical and physical background to the karstification of limestones, an attempt will be made to reconstruct the history of these processes as they took place in the White Limestone of the study area.

3.2 Chemistry of Limestone Solution

Although there are numerous theories about the way in which karst develops, it is generally agreed that the main process is one of solution of the rock by meteoric water and that most of the limestone that has been removed from an area has suffered chemical rather than mechanical erosion.

The relatively high solubility of limestone in the field has been explained in three general ways. It has been attributed to organic acids in the infiltrating rain water, which owe their origins to animal and plant life at the surface, Miller (1952). It has been attributed to carbon dioxide in the rainwater which is derived either from the atmosphere or from the soil, and finally, some writers have suggested that the calcium carbonate may, in fact, be in colloidal form in the water, Bamber (1951).

Smith and Mead (1962) discussed these various theories and, based on a series of analyses of limestone waters in the Mendips (U.K.) they concluded that the high solubility of limestone, at least in that area, is due to the presence of carbon dioxide in the water.

Hem (1959) says that distilled water at 25°C will dissolve 13.4 m.g. of calcium carbonate per litre of water, which is equivalent to 5.4 ppm of calcium, but that rainwater which has only been in contact with the atmosphere will dissolve sufficient calcium carbonate to give a concentration of calcium of 20 to 30 ppm.

The significant difference between distilled water and rainwater is the presence of carbon dioxide which has been taken into solution from the atmosphere to form carbonic acid.

$$H_20 + C0_2 = H_2CO_3$$

This then dissociates as far as the first step in the following equation,

$$H_2CO_3 = H^+ + HCO_3 = 2H^+ + CO_3$$

but will not continue to dissociate if sufficient carbon dioxide is available. In the presence of H^+ ions calcium carbonate is soluble as follows:

$$CaCO_3 + H^+ = Ca^{++} + HCO_3$$

Thus it can be seen that bicarbonate ions are, in fact, derived from both the carbon dioxide and from the calcium carbonate. Mead and Smith (1962) report that the presence of the common product actually inhibits the solution process and that another acid of similar strength, which did not produce bicarbonate ions, would increase the solubility of the limestone.

Thus calcium carbonate passes into solution as calcium ions and bicarbonate ions, and will remain in solution provided that the pressure of dissolved carbon dioxide is equal to the pressure of the free gaseous carbon dioxide. If the pressure of the dissolved carbon dioxide falls below that of the gaseous phase, then calcium carbonate will be precipitated.

In the case of underground water there is often sufficient pressure on the system to enable a greater quantity of calcium carbonate to be taken into solution than would exist at atmospheric pressure. One predictable result of this is that at springs or wells, where the pressure is reduced, deposition of calcium carbonate takes place, though this may also be partly due to concentration by evaporation.

The dissolved content of carbon dioxide in rainwater which has only been in contact with the atmosphere is not sufficient, however, to account for the concentrations of calcium which have been recorded from water in limestone aquifers (e.g. values in the range of 70 - 100 ppm from wells in the Clarendon Plains). The additional quantity of dissolved carbon dioxide necessary to dissolve this much calcium carbonate is picked up as the water passes through the soil zone, where the partial pressure of CO_2 is higher due to gas being given off both from living and decaying vegetation.

Sweeting (1972) quotes the French worker Birot as saying that the pressure of carbon dioxide in cracks in the bedrock may be as much as 100 times that in the atmosphere, thus enabling up to 110 ppm of calcium to be taken into solution. In cases where the rocks are dolomitised then the solubility of magnesium carbonate obviously becomes important but, for the purposes of this study, it will suffice to say that the chemistry is somewhat similar to that of calcium, with small quantities of magnesium actually increasing the solubility of calcium.

The presence of sodium and potassium have a similar effect and Askew (1923) showed that 600 ppm of sodium chloride actually doubled the solubility of calcium carbonate. This factor has significance in areas like the Clarendon Plains where there is a salinity problem.

3.3 Karst Development

In the past there has tended to be two main schools of thought about the development of karst and these have disagreed on whether groundwater occurs as a saturated zone, whose upper surface constitutes a water table, or whether water moved entirely in discrete channels and solution cavities. Sweeting (1972) traces the development of these theories and concludes that most American workers seem to favour the existance of a water table, as do many British workers, whereas Europeans have tended to think of the water as travelling in independent networks. It will be seen that these two conditions are end members of a continuous series and that in the Clarendon area, in the opinion of the present author, both situations occur.

The foundations for the two opposing schools of thought were laid by the works of Grund and Katzner in the early part of this century. The former postulated a mobile integrated body of water circulating above a relatively stagnant zone, the contact between the two being defined by sea level, whereas Katzner believed that water circulates through what are essentially caves and passages and that flow can take place throughout the whole thickness of aquifer regardless of sea level. This factor of sea level control as it relates to the Clarendon Plains will be discussed later.

Grund's other major contribution to the theory of Karst was his paper of 1914 which set out the concept of a karst cycle, though he had been greatly influenced by the earlier work of W.M. Davis. Grund's cycle was summarized by

LeGrand and Stringfield (1973) as consisting of a youthful stage in which water percolates down to the water table and then moves laterally, followed by a mature stage when sinks that developed in the youthful stage are enlarged to form dry valleys and when caverns, and the aquifer in general, are fully developed. The final stage of old age is represented by less extreme relief, with an association of collapsed caverns. By this time the land surface itself has been lowered relative to the water table. Whilst this concept of a karst cycle has attractions, it attempts to impose a rule on natural events which may vary both with time and space.

Sweeting (1972), writing a year before LeGrand and Stringfield, suggested that the cyclic idea had outlived its usefulness, and that specific features in karstic development occur primarily due to conditions which favoured their development rather than as the result of a progressive sequence. It follows therefore that every area must be treated separately and looked at with references to its own individual development, and with this in mind the Clarendon area has been examined.

It is likely that the karstification of the White Limestone began in the Clarendon area at the end of mid-Miocene and start of Upper Miocene times when the first major uplift of the Lower Miocene deposits occurred. These deposits, however, were soon resubmerged and thus the really extensive solution and erosion would not have taken place until the time of the block faulting which occurred at the end of the Pliocene. At this time the sea level is estimated to have been 600 feet above the present sea level (F.A.O. UNDP 1971).

At the time of the Upper Miocene uplift it is assumed that the limestone had a relatively low primary permeability with some downward movement of rainwater, this being aggressive due to its passage through the atmosphere and any soil cover which had developed. It could also be expected that some degree of secondary permeability may well have been present owing to joints and fissures which would have developed during the epeirogenetic upheaval. Thus to postulate a homogeneous isotropic block as the starting point for karstification, as was done by Wirtz (1970) is, in the opinion of the present writer, an unrealistic premise from which to develop a conceptual model.

Though the infiltration rate was obviously lower than at present, owing to both pores and fissures being smaller, solution would still take place accompanied by a gradual widening of these features from the surface downwards. Initially this effect would not extend to any great depth as the water would rapidly become saturated with calcium carbonate, though as the features increased in width the water would be able to reach greater depths before coming into prolonged contact with the limestone.

In considering the fate of the saturated water as it made its way through and, ultimately, out of the system, something akin to the 'chicken and egg' conundrum arises with regard to the presence or absence of sea water in the aquifer. If sufficient primary or secondary permeability existed below sea level in the limestone before karstification commenced, then sea water would have saturated these voids and cavities and the infiltrating fresh water would gradually form a lens floating on the denser saline water.

Alternatively it was suggested by Wirtz (1970) that the limestone was virtually impermeable at this depth and would not therefore have been invaded by sea water. Whilst accepting that permeability decreases with depth, the present author believes that it would not have been entirely absent below sea level. Thus it is postulated that a zone of saline water existed from the outset. An idealized representation of the situation is given in Figure 3.1. It can also be seen that, moving away from the coast, the underlying impermeable rocks rise above sea level and thus would control the movement of the sea water inland through the limestone.

Initially the downward percolating fresh water would float on the denser saline water and, as the freshwater head built up, the interface between the two would be depressed according to the Ghyben-Hertzberg relationship (further discussion of this classic phenomenon is given later. Ultimately the situation depicted in Figure 3.2 would exist, though circulation would be still relatively slow owing to the solution effect not having yet progressed to any great depth. However, horizontal movement in the zone of saturation would take place due to the difference in head and groundwater would be discharged along the coast.

At this point the views of the writer diverge from those of several others who have discussed karstification of the White Limestone in Jamaica, and who have postulated that sea level at any given time would be a base control for solution. Wozab et al (1972) working in the nearby Pedro Plains, found that water movement was confined to the top 20 or 30 feet of the saturated zone and they developed a theory similar in principle to that of Grund, concluding that sea level had been a base control for solution. This idea was accepted by other workers in the area. Wirtz (1970) and MacFarlane (1972) both state that where sea level is higher than the contact with underlying impermeable strata then the lower limit of solution is a horiztonal plane which corresponds to sea level. Whilst these theories did not preclude the development of a drainage pattern below the lowest known sea level in the case of a confined aquifer, which could account for its occurrence beneath the Clarendon Plains, it will be shown that solution below sea level in a water table aquifer, though likely to be considerably less than in the upper zones, can take place.

Returning to the theoretical model depicted in Figure 3.2 it is obvious that the hydraulic gradient would be at its steepest at that time as the total permeability was at its lowest. If we look at this situation in terms of hydrostatics, then the horizontal component at point A must be equal to the same component at point B. However, we have accepted that the enlargement of solution cavities extends from the surface downwards and thus the permeability in the upper zone must increase first and consequently flow in the zone will also increase first. Nevertheless, the important fact is that flow, however slow, does take place below sea level and that ultimately some enlargement of solution passages will take place in this zone. In fact, if flow were not taking place the salt water would gradually invade the limestone below sea level by the process of diffusion.

Returning to the upper zones it is obvious that as limestone is removed from below the surface, this will be reflected to varying degrees in the topography by the appearance of sink holes, dry valleys and other karstic phenomena, the net effect of which is a lowering of the land surface. Beneath the ground the widening of the solution cavities will lead to a progressive lowering of the water table, due to the increase in effective storage and the lowering of the hydraulic gradient as a result of increased secondary permeability. Thus the steady and continual progress is a downward movement of the upper limit of the groundwater flow system towards sea level. At this point it can be seen that sea level would act as a control because, as the water level approached it, the rate of groundwater movement would decrease until, ultimately, all flow in the system would cease.

Thus, sea level controls solution insofar as when the water table approaches it then solution decreases, but it does not itself act as a base for solution. In the Clarendon basin however, there is a definite base for solution in the area away from the present coast line where the underlying impermeable strata rise above present and past sea levels. For here the base of the White Limestone itself would be the maximum depth to which karst processes could take place and, incidentally, would also control the hydraulic gradient, imposing a minimum which would almost certainly be in excess of that which developed nearer to the coast.

It is at the coast itself that the most rapid downcutting would take place and the upper level of the saturated zone would quickly approach sea level, assuming that aggressive rainwater was available. Once this had taken place the overall effect would be one of back-cutting away from the coast until the stratigraphic control of the underlying rocks came into play. From reference to Figure 3.2 it can be seen that a smaller area of cross-section of aquifer carries fresh water at the coastal boundary due to the shape of the lens, which has least vertical extent at this point. Thus, in order for the outflowing water to be transmitted through this zone the permeability must be increased. In practical terms, this means an increase in pore and cavity sizes. A similar argument applies to the lower hydraulic gradient in this section compared with the area subject to stratigraphic control where, due to the dip of the strata, a minimum gradient of 20 to 30 degrees must exist.

Whilst it has been postulated that both the so-called primary and secondary permeabilities are likely to be increased by solution, it seems reasonable to assume that the maximum effect will occur in the largest faults and fissures where the water can circulate more freely, and thus the fastest down cutting will also occur here. In the case of those which run parallel to the direction of flow and, consequently, are normal to the coast line, the process is likely to be very rapid and greatly in excess of the rest of the aquifer. These paricular features will thus tend to act as drains and influence the flow pattern in the surrounding formation. They effectively become discharge points from which minor solution cavities will cut back. This suggests that there could be two sets of hydraulic systems in operation which have two different storage capabilities and, more important, which transmit water through the system at two different rates.

Shuster (1971), describing a limestone valley in Central Pennsylvania (U.S.A.), found that some springs vary greatly from season to season, in both chemical quality and discharge, whereas others vary only slightly. From a knowledge of the hydrogeology of the area he was able to determine, with a fair degree of accuracy, that some of the springs are fed from a conduit system, whereas others receive water by a flow system which approximates to Darcy's law.

In addition to these two extremes, he recognized a whole range of intermediate stages where springs are the result of mixing between varying proportions of water from both systems. He defined this range of conditions digrammatically by means of two end-members as shown in Figure 3.3. He found that temperature and hardness were the two most useful parameters for classifying springs and that those fed by a conduit system showed pronounced lowering of hardness values in times of high flow.

The calcium-magnesium ratio shows little seasonal variation for a given spring thus indicating that the solubility of magnesium varies in a similar way to that of calcium.

Further discussion of the groundwater chemistry will be left until Chapter 6, but the work of Shuster seems to underline the feelings of the present writer that, in this type of limestone aquifer, two groundwater flow systems can be operating simultaneously.

Returning briefly to the initiation of solution in limestone it is worth considering the work of Davis (1966) in which he argued that many joints are too small to permit the flow of water under the natural hydraulic gradient. He then postulated a theory whereby water movement could be accentuated in just such features.

Using a permeability figure of 10^{-12} cm^2 (Archer 1952) and porosity of less than 10%, Davis calculated that flow velocities in crystalline limestone would have a maximum value of 3 inches per year in slightly porus rocks, with an average of less than 3 m.m./year in the denser varieties.

Using the higher flow rate he showed that it would still take almost 100,000 years to increase the porosity of the rock by 1%, and thus effectively excluded the possibility that large solution channels were caused by the passage of water through the solid matrix of limestone.

Turning to the alternative theory of solution along faults and joints he accepted that the former created a situation where large quantities of water could travel rapidly through the rock, dissolving large quantities of limestone, but questioned whether many of the latter features were large enough to enable this to take place.

Based on his observations of joints at the surface, and at depth, he concluded that many were initially less than 10 to 20 microns in width. He then derived an approximate relationship between velocity of flow and width of joint for different hydraulic gradients (see Figure 3.4) using the following equation -

$$v = \frac{b^2}{12} \times \frac{gp}{u} \times \frac{\partial h}{\partial x}$$ de Weist (1965)

where v = average velocity in a fixed direction
b = spacing between smooth surfaces
g = gravity
p = density of fluid
u = viscosity of fluid

For water at 20°C the equation reduces to

$$v = 8.16 \times 10^3 \ (b^2) \ \frac{dh}{dx}$$

From this it can be seen that joints of 10 micron width or less would not significantly increase the bulk permeability of dense limestone.

Thus Davis postulates that water may be forced through the joints by pressures other than those attributable to the normal hydraulic gradient, a process which he calls 'Groundwater pumping'. His tentative calculations indicate that with a joint 10 microns wide, extending 10 metres from a rock-water interface, an earthtide induced movement of 0.5 microns perpendicular to the joint would increase the velocity of water movement to as much as 200 cm/day at the rock-water boundary.

Considering that water level fluctuations of up to 1 metre have been recorded by Parker and Stringfield (1950) in association with distant earthquakes, and that frequent but smaller fluctuations have been correlated with earth tides in New Mexico by Robinson (1939), the theory of groundwater pumping may have significance.

In addition to considering lateral variations in homogenity of the aquifer some thought should also be given to the effect of variations in lithology and how they might affect the development of subsurface drainage. Some horizons are more susceptible to solution than others and the enlargement of cavities takes place preferentially along these beds. If the general inclination of the strata had been in a significantly different direction to the hydraulic gradient this might have led to more complex drainage patterns. In the study area, however, this is not so.

Finally, before trying to link the hypothetical model to an actual geological time scale, consideration must be given to the effects of fluctuations in sea level on the development of karst drainage. If the drainage pattern had recently matured and the sea level fell, then it can be seen that this would lead to a partial re-juvenation with the down and back cutting processes re-commencing. If the drainage had only partly developed however, then the time taken to reach a reasonably stable state would be that much longer.

In the case of rising sea levels most horizontal groundwater movement would return to the upper levels where it had originally taken place. The deeper solution channels would then be invaded by salt water, the extent of which would be controlled by the head of fresh water retained in the system.

Looking at all the above processes in terms of known events in the geological time scale, it can be concluded a relatively brief period of uplift in Upper Miocene times may have inititated karstification, but that solution is unlikely to have developed extensively before resubmergence and the deposition of the Coastal Formation took place in Lower Pliocene times.

By the end of the Pliocene the final major block faulting is thought to have been completed and the sea to have been some 600 feet above the present level (F.A.O. UNDP 1971).

Thus it follows that the processes of karstification, which were described above, would be taking place in what is now regarded as the recharge area, and that most of the present Clarendon Plains would be both below sea level and beyond the coast and therefore outside the zone of circulation of groundwater. At the same time marine and estuarine sediments were deposited on the submerged limestone, though some of these younger deposits were subsequently eroded. During the subsequent Pleistocene period, the sea level would fall and rise several times due to the various glaciations and inter-glacial periods. It is generally accepted that the lowest levels were in the Illinoin and Wurm-Wisconsin glaciations when the sea level was at -520 feet and -450 feet respectively and that the maximum inter-glacial highs were +100 and +290 feet (see Figure 3.5). The situation during these glacial times would be one of karst drainage development in the limestone which now underlies the plains and probably removal by mechanical erosion of some of the marine and estuarine deposits from the northern edge of the plains. The Rio Minho was also, no doubt, cutting channels in these deposits which would later be filled with material derived from the Central Inlier.

3.4 Karst Landforms

As already outlined in Chapter 2, three types of karst land form occur in the study area and there are differing theories to account for their origin. In fact, viewed on an island wide basis, disagreement starts with the terminology used to describe the more extreme forms, though the locally derived expression 'Cockpit' seems to find general acceptance.

One of the main types of karst landforms consists of features known as dolines, to which extensive references are made by most workers in this field. In essence dolines are small to moderately large closed hollows which, when occuring in large numbers, give limestone terrain its characteristic appearance. Despite much having been written on the subject there is still no rigorous definition of dolines and, in Jamacia, the term has been used in at least two different contexts. The writer prefers to restrict its use to structures formed principally by solution which are greater in diameter than in depth. An exception can be made in the case of collapsed dolines which have nearly vertical sides and are deeper than they are wide. The most striking difference between classical dolines and cockpits is that, in the former, the depressions are circular whereas in the latter they are star-shaped with the residual hills or intervening high areas being conical.

The type area for this feature, the so called 'Cockpit Country' is situated in the northwest of the study area where its eastern boundary encircles the western end of the Central Inlier (Figure 3.6). It is an inhospitable area, virtually uninhabited and with little sign of surface water. The topography consists of rounded hills, several hundred feet high with sides sloping in excess of 30 degrees and separated by irregularly shaped sink holes. The difference between these typically tropical structures and temperate dolines was excellently illustrated by Williams (1969) as can be seen in Figure 3.7.

Lehmann (1927) was one of the first workers to classify tropical karst, distinguishing two main types which he called Kegelkarst and Pinnacle Karst, and in a later work (1954) he described the occurence of these in several islands in the Greater Antilles, including Jamaica. The name Turmkarst (or Tower Karst) has tended to replace Pinnacle Karst in general usage.

Subsequent workers, and in particular Sweeting

(1972), have described the Cockpit country as Keglkarst and, though she declines to describe the depressions as dolines because of their sinuous shape, she does believe that they owe their origin to a similar process. Surface erosion by torrential flows along joints and fissures may well have inititated the pattern, which tends to be quite regular, but Sweeting says that downward rather than horizontal movement has been the principal agent, and that solution was the process. Versey (1972) disagrees fundamentally with the above classification which, he says, does not take into account the processes by which the Cockpits were formed, these being different from those giving rise to true kegelkarst. Whereas a doline is formed by the downward percolation of rainwater, Versey believes that the Cockpit Karst comes about because of massive rises in water level both during, and after, heavy tropical rain, thus bringing the zone of circulation of groundwater within reach of the bottoms of the karst depressions. The resultant erosion leads to a collapse and removal of soil cover which will continue as long as up-lift proceeds at a rate not so great that deep circulation develops. The process is thus mechanical erosion by turbulent underground waters with suspended sediments.

C.F. Aub carried out an examination of over 160 cockpit depressions and, in an unpublished study, found no evidence for collapse of the floors. He did however locate swallow holes with signs of temporary surface drainage channels from which he concluded that development of the cockpits had been by solution. He also failed to find evidence of groundwater circulation reaching as high as the base of the depressions, at least within the area which he studied.

It has been suggested by various people that the pattern of vegetation and, in particular, the ringing of the depressions by trees might lead to a funnelling of rainfall into the centre of the sink holes and thus accelerate solution at this point. Here again Aub did useful work by taking rainfall measurements at a number of localities over a period of more than a year. He was able to show that the average precipitation in the centres of the depressions was 13 - 15% higher than on the hills, a factor which could be of significance in the development of the depressions.

Turmkarst (or tower karst) is used to describe isolated, steepsided (70-90°) limestone outcrops with flat alluvial-covered depressions between. It is not as extensive in Jamaica as Kegelkarst, though the two may occur in association. It is most commonly found where streams flow off inliers of older impermeable rocks. Turmkarst appears to be a product of lateral surface erosion and Sweeting describes it as a more extreme form of karstification than the cockpits.

A third type of heavy karst which Sweeting described was somewhat more subdued than her Kegelkarst, but still had depressions with sides sloping at 20-30°. This she believes to be simply cockpit karst which is no longer suffering extreme chemical erosion. It contains considerable thicknesses of bauxite and she describes the karst as having been degraded. It is interesting to note though that in her description of such a landform in the Dry Harbour Mountains, which is to the north of the Central Inlier (Reference 1958), she attributes the degradation of the karst to the fact that it is now "situated well above the inundation level". This statement is similar to the approach of Versey which, elsewhere, she finds hard to accept.

Versey, in earlier work (1959) did not accept Sweeting's "Degraded" cockpit karst, saying that the landform was pure doline karst, but at a later date (1972) he seems to have changed his opinion, postulating that it was in fact derived from cockpit structures in which the zone of groundwater circulation had dropped to a great depth. He restricts the expression kegelkarst to yet a third category, in which the slopes are gentle and there has been no overdeepening. Here he accepts that the only process has been solution and gives as examples of this the Mocho and Don Figuerero Mountains. It would seem that this coincides with the category which Sweeting describes as doline karst. Versey attributes the features to rapid uplift and deep circulation whereas Sweeting believes that lower rainfall and the marly character of the Newport Limestone are key factors.

Thus, to sum up, Versey and Sweeting disagree about the application of the word kegelkarst, with Versey restricting it to the gentler form which Sweeting called doline karst. More fundamentally, however, they disagree about the processes which lead to the formation of the different land forms, only agreeing that the so called degraded cockpit karst was derived from the true cockpit karst after the processes of karstification had become less effective.

Having looked at the conflict of ideas concerning the origin of the more spectacular forms of karst within the island as a whole it is necessary to see how this relates to the study area.

In the northwest of the Manchester highlands, and along the northern edge of the Mocho Mountains, there occurs a rugged form of karst which conforms with the outcrop of the lower members of the White Limestone Formation and continues eastward across the course of the Rio Minho. In the lower parts of the Mocho Mountains, and in the upland area known as the May Day Mountains, a much gentler form of karst is found and this tends to be associated with considerable thicknesses of bauxite. The valley sides slope at angles which are usually less than 30 degrees.

The third type of karst to occur in the study area is that found in the Harris Savanna-Brazilleto Hills region and this bears little resemblence to either of the other areas, appearing to be at a relatively early stage of re-development on a peneplained surface.

None of the actual Cockpit Country extends into the study area but some of the rugged karst of the Rio Minho - Milk River basin certainly deserves to be classified as kegelkarst, at least by the less rigorous method of Sweeting if not by Versey's genetic system, and may well be degraded cockpit karst. In seeking to explain why this rugged karst should be confined to one particular part of the study area it becomes obvious that several factors distinguish it from the rest. Firstly it is at a higher elevation and this means that it was subject to the highest rainfall and, possibly, a longer period of karstification. More important, however, is that this extreme landform within the study area is mainly confined to the Troy Formation and, to a lesser extent, the base of the Somerset Formations. This means that not only is the rock hard and well jointed, due to dolomitisation and recrystallization, but also the underlying impermeable strata is not far below the surface, thus giving a relatively shallow zone of circulation of underground water.

In the opinion of the present writer this combination of circumstances is sufficient to produce a distinctive landform which would not be seen in the softer chalks and marls of the Newport Formation. The replacement of calcite by dolomite leads to a reduction in volume which must have played a significant part in the initial development of joints. These would then become subject to solution as described earlier.

It also seems likely that a process something akin to that favoured by Versey, i.e. upwelling of sub-surface flow after heavy rain, must have played a part but not necessarily in the exact way that he visualized. It was part of Versey's theory that uplift must have continued at such a rate that a base level of solution could not be established, but observations show that such a level has almost certainly been reached with erosion of the White Limestone continuing down to the Yellow Limestone in one or two places. This results in surface runoff over relatively short distances before the water disappears back into the White Limestone, where it can be seen to move in discrete channels or caves.

This leads to speculation as to the ultimate fate of the water in these lower formations of the White Limestone Group. As the Troy Limestone passes beneath the younger rocks in the direction of the plains, it is likely that the fractures and joints will become much tighter due to the pressure of the overlying formations and thus less able to transmit the water. As the system is a dynamic one the water must have an outlet and it is likely that it will pass into the overlying beds, ultimately reaching the Newport Formation, probably along fault zones. It is not inconceivable that the numerous springs at the lower end of the Williamsfield - Porus Trough are associated with this phenomenon. The significant factor however is that the highly karstified lower members of the White Limestone Group are likely to rapidly transmit a proportion of the water from the recharge area.

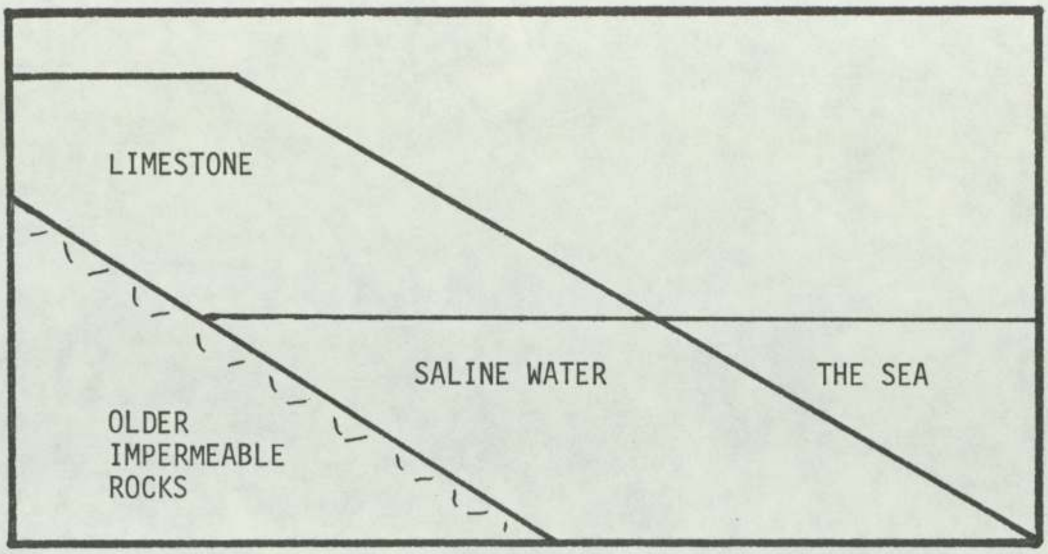


FIG. 3.1 An idealised cross-section showing sea water in the Limestone after uplift and before infiltration.

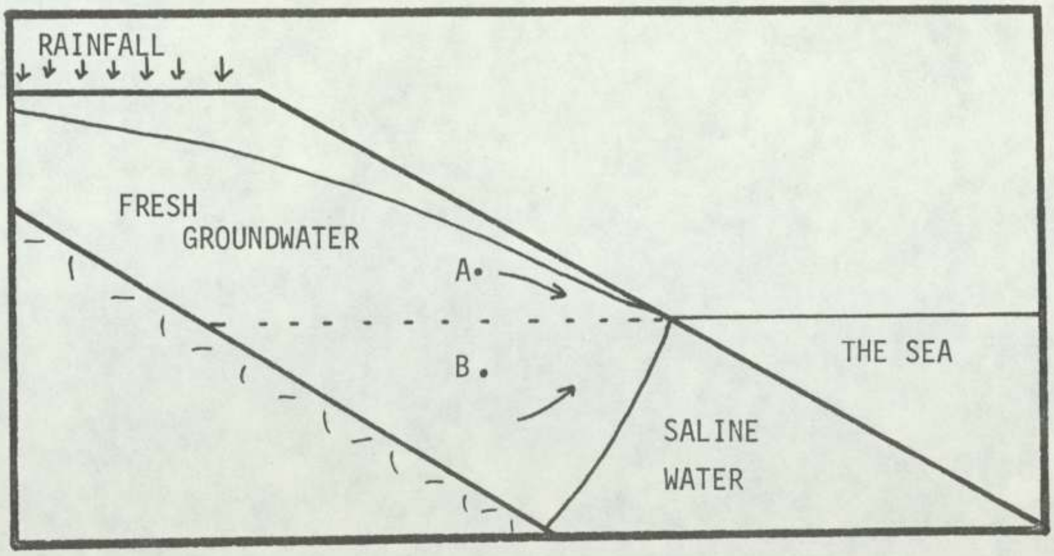


FIG. 3.2 An idealised cross-section after infiltration of rainfall has created a fresh groundwater body.

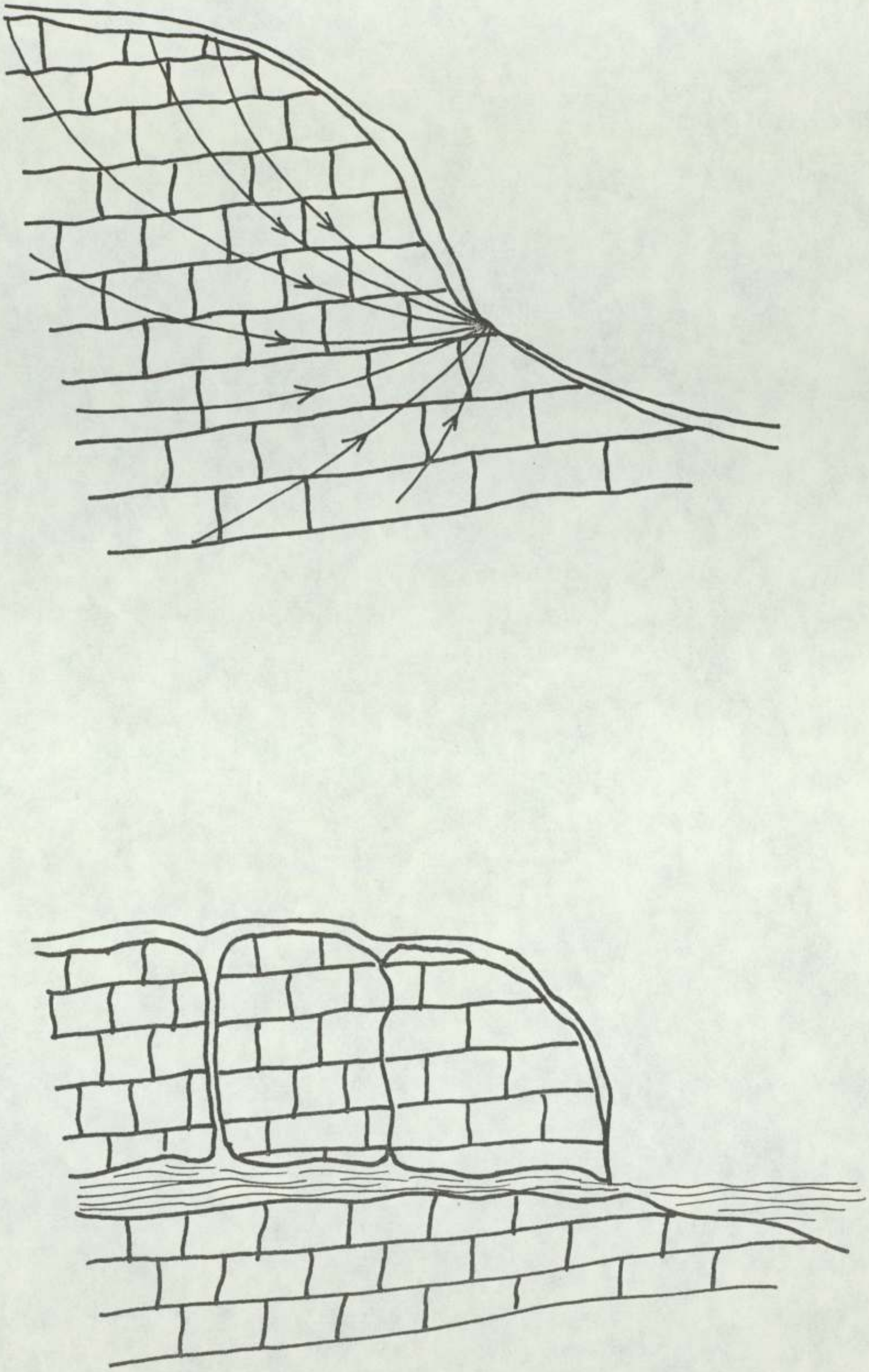


Fig. 3.3 End-members of Carbonate Aquifer Flow Systems (after Schuster 1971)

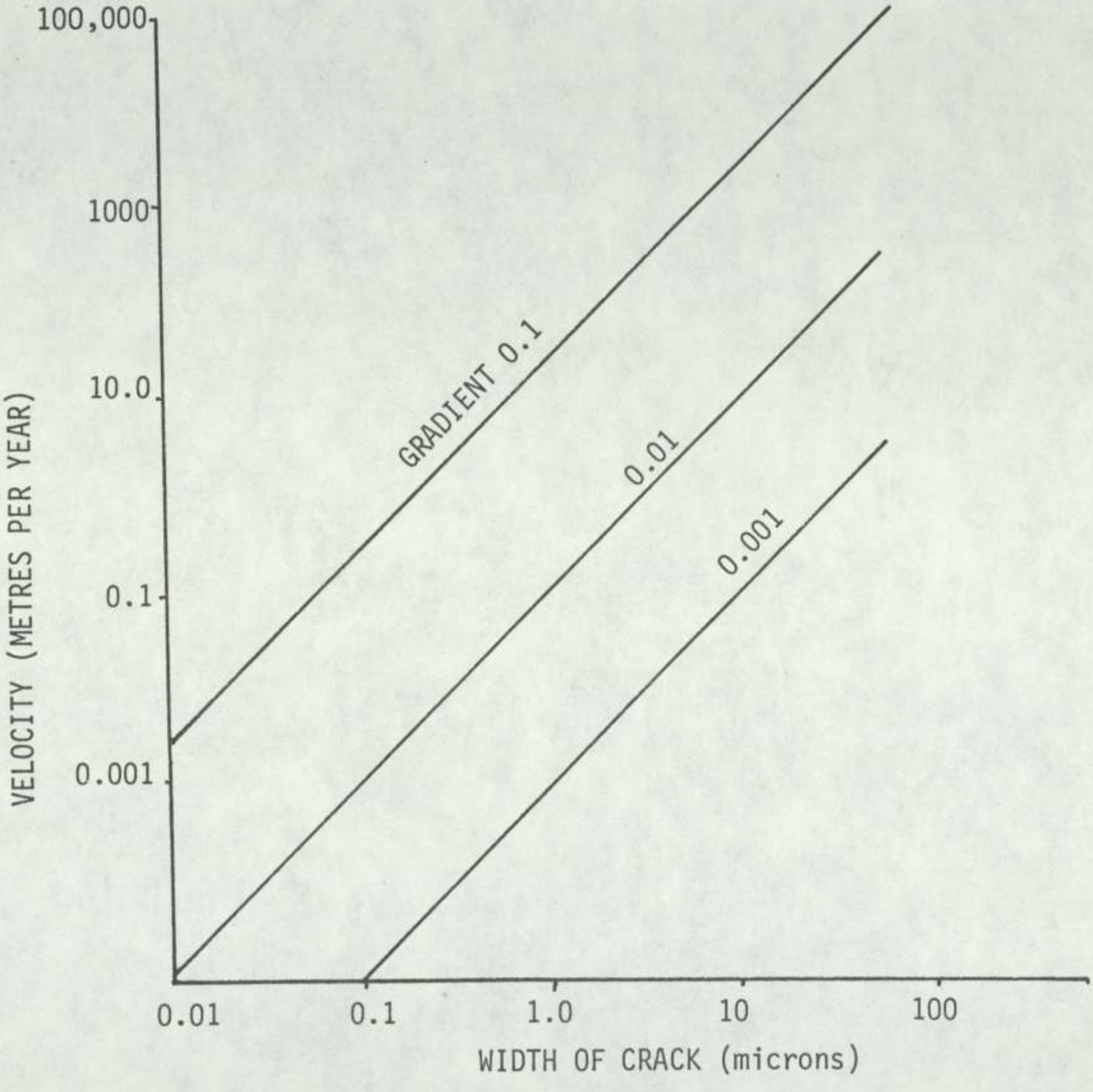


FIG 3.4 RELATIONSHIP BETWEEN WATER VELOCITY, HYDRAULIC GRADIENT AND WIDTH OF CRACK FOR FLOW BETWEEN PARALLEL SMOOTH PLATES.

(after Davis 1966)

FIG. 3.5

SUMMARY OF GEOLOGIC HISTORY - LATE TO RECENT

PLIOCENE AND QUATERNARY TIME

EPOCH	GLACIAL STAGES (age in years)	APPROXIMATE DURATION (years)	LOWEST LEVEL OF SEA WITH RESPECT TO PRESENT LEVEL (ft)
Late Pliocene			+ 600
	1,500,000		
	Nebraskan Glacial	120,000	- 30
	1,300,000		
	Aftonian		
	Interglacial	180,000	+ 290
	1,200,000		
	Kansan Glacial	140,000	- 120
	1,060,000		
	Yarmouth		
	Interglacial	640,000	+ 100
Pleistocene	420,000		
	Illinoian		- 450
	Glacial	80,000	- 520
	340,000		
	Sangamon		
	Interglacial	220,000	+ 10
	120,000		
	Wurm-Wisconsin		- 350
	Glacial	100,000	- 450
	20,000		
	Recovery phase from		- 170
	Wisconsin Glacial	14,000	- 110
	6,000		- 75

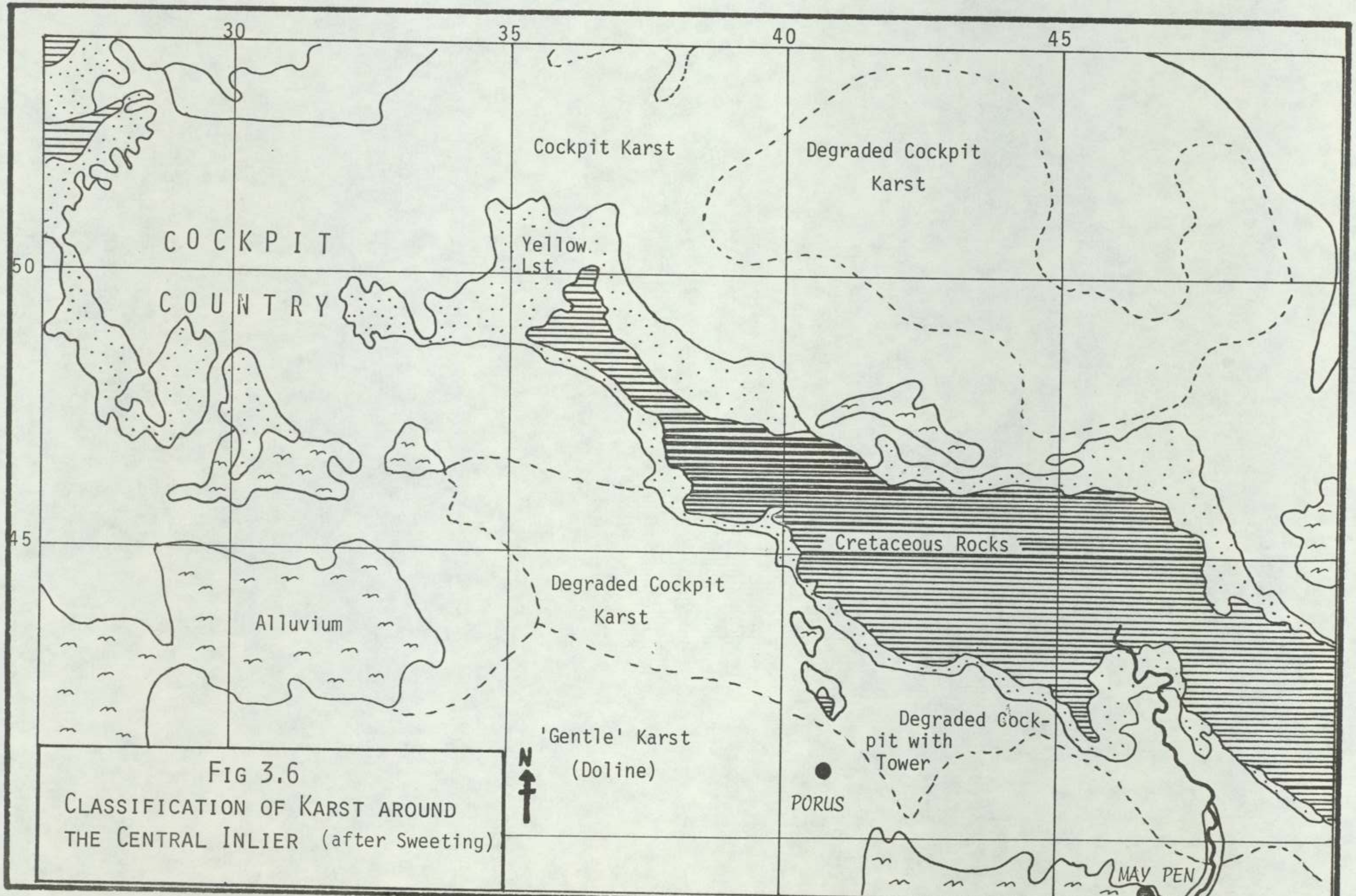
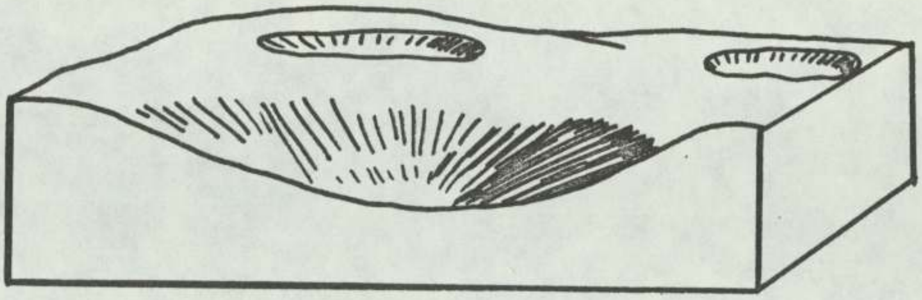
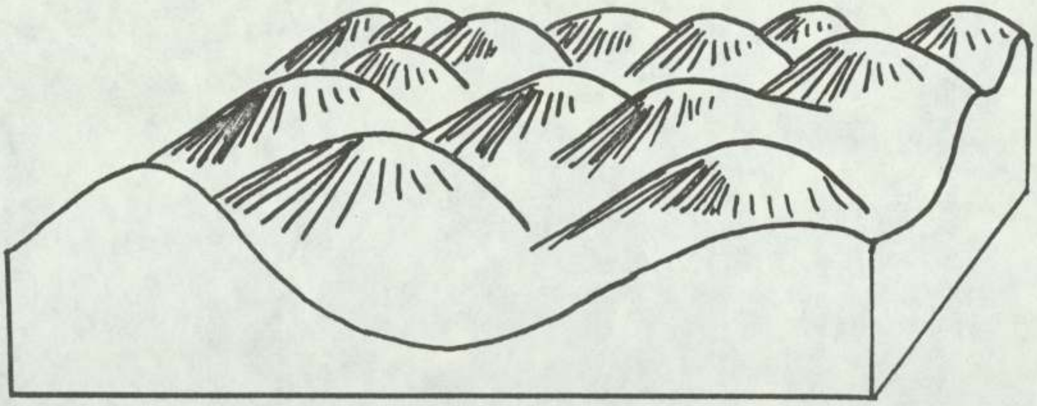


FIG 3.6
CLASSIFICATION OF KARST AROUND THE CENTRAL INLIER (after Sweeting)



TEMPERATE DOLINES



TROPICAL KARST

FIG.3.7 (after Williams, 1969)

4 SURFACE WATER HYDROLOGY

4.1 General Description

As described in Chapter 1 the area is drained by two principal rivers, the Milk River and the Rio Minho. In addition to these, however, there are three minor rivers which occur on the eastern margin of the study area and flow for short distances before discharging into the sea. These are the Bowers, Cockpit and Salt rivers and they are all located at the foot of the coastal flanks of the Brazilletto Hills - Harris Savanna uplands.

The Rio Minho rises at the district of White Shop (E 3970 N 4550) some 1-1/4 miles east of Spaldings, in northern Clarendon, and flows in an east-south-easterly direction across the Central Inlier for about 12 miles to the gauging station at Danks. Here it turns and flows southward for about 2-1/2 miles before doubling back northward and entering into a broad sweep which turns southward again and passes through a gap in the limestone hills some 7 or 8 miles north of May Pen. Continuing in a generally southerly direction, it flows through a limestone gorge and, turning westwards, passes south of the town of May Pen before entering the Clarendon Plains in the northeast corner. From here, it sweeps broadly round to the south and meanders in this direction across the alluvial-covered plains for about 12 miles before entering the sea 2-1/2 miles south east of the Alley.

In its upper catchment the Rio Minho is fed by numerous small streams and tributaries which drain off the northern side of the Mocho Mountains, both sides of the main ridge, and the southern flanks of the Bull Head Mountains. The total drainage area above May Pen gauging station is 160 sq. miles and the main tributaries are the Thomas and Pindar rivers. In addition to the two gauging stations mentioned, the Project also maintained one at the Alley, near to the mouth of the river, and one each on Pindars River and Moores Gully.

As described above, the Rio Minho enters a limestone gorge south of Chapelton and during some dry periods, though there is appreciable flow at this point, the river is dry at May Pen. At the time that the writer first visited the area this situation existed and the course of the river was followed from Moores down to May Pen in an attempt to determine where the losses were occurring. The river was flowing from Moores to Sevens without any apparent loss and at Sevens the flow increased slightly due to the discharge of dunder from the Sevens Sugar Factory. The flow could then be seen to decrease as the river approached May Pen and, about a mile above the bridge, the last movement of water could be seen in the form of trickles between otherwise still-looking ponds in the river gravels. There were several similar waterfilled depressions downstream from this point and the obvious conclusion was that subsurface flow through the gravels were taking place. An attempt was made to verify this by drilling 15 ft deep auger holes in the river bed at May Pen but no water was struck. Thus, it would appear that the water was finding its way down into the limestone beneath. At this point, where the final flow was seen, old reports refer to the "Barrel Hole Sink" which can no longer be located, presumably having been covered by alluvium. It is interesting to note that this spot lines up with the physiographic feature known as Webber's Gully which is thought to have been the original course of the Rio Minho. Further reference will be made to this in a subsequent section of this thesis.

At a time when the river was flowing at May Pen the flow was measured with current meters at several points between there and Chapelton and it was found that the recorded differences were often less than the errors inherent in the method used for the measurements, though an analysis of available records showed that over a long period the losses varied considerably. It is likely that these variations depend on the degree of sorting of the river deposits which overlie the limestone. A high flow will remove the finer sediments that have been deposited by earlier lower flows and thus allow the downward seepage of water into the limestone.

During the times that the river is dry at May Pen there is found to be no flow for several miles until water is seen again at Parnassus, and from this point southward the flow increases as the river picks up excess irrigation water which drains from the surrounding cane fields.

Though for much of the year the flow in the Rio Minho is relatively low, it takes only a short period of heavy rainfall in the upper catchment to turn the river into a raging torrent, a feature which has been accentuated over the years by the deforestation of the hillsides in the Central Inlier.

The drainage area of the Rio Minho, south of May Pen, is relatively small and it is the tributaries of the Milk River that drain most of the plains. The Milk River normally rises as a small seepage just to the south of Porus at the lower end of the Williamsfield - Porus trough or graben, though in times of heavy and continuous rainfall some flow may occur to the northwest of this point along the course shown on the map (see sheet 2). From here it flows to the south-east, through Scotts Pass, and then turns south and flows along the foot of the Manchester Highlands to reach the coast near Round Hill. Between Porus and St. Jago there are numerous springs rising from the limestone which all contribute to the Milk River, and which can be divided into three groups.

The first group, including the actual source of the river (E 4110 N 4090), stretches from Porus down to Scotts Pass and the most striking of these is Spanish Well where, except during droughts, water flows out of a hole in the river bed. Taylor (1954) reports that in 1931, following 10 years of low rainfall, the water level in Spanish Well fell to 53 ft. below ground level and, in 1968, it was observed by the writer to be about 20 ft. below ground level, though it soon recovered during the rains of the following summer.

The second group of springs occur about four miles to the south east of Spanish Well. These are known as the St. Toolies Springs. The third group are two miles to the south of these,at St. Jago, both being at the foot of the May Day Mountains. All three groups of springs go dry during droughts with the Spanish Well set being the first to start flowing again. Accurate assessments of the discharge of these groups of springs are difficult due to the fact that the Mid-Clarendon Irrigation Authority, at certain times, diverts water from the river for irrigation and, at other times, pumps from wells into the river as part of their distribution system, but without having much idea of the quantities involved. The Project installed a gauging station at Scotts Pass which became operational in 1970 and this indicated that the flow from the first group of springs was in the region of 8,000 acre-feet in 1971.

In the lower reaches of the Milk River there is always flow and this is thought to come from two sources. The so-called Baldwin and Hilliards rivers, both of which drain extensive areas of the Plains but are nevertheless better classed as gullies, are tributaries of the Milk River and they maintain steady but small flows of what is believed to be excess irrigation water. The writer believes that another component of flow in the lower reaches of the Milk River is base-flow from the limestone, a theory which tends to be supported by the old name for this area of Milk Spring.

In addition to the Scotts Pass gauging station mentioned above, the Project also maintained a gauging station at Rest, two miles from the mouth of the river.

The Bowers river, with a catchment area of about 20 sq. miles at the eastern edge of the study area, is a small river formed where two usually dry gullies, the Clarendon and the Palmetto, merge about a mile south of Freetown (E 5000 N 3640). Though the gullies only flow after heavy rain, several small springs maintain flow in the 1-1/2 miles long river, where the flow is further augmented by excess irrigation water from surrounding cattle pasture.

The Cockpit River is formed from a number of small springs which issue from the limestone just below the road along a 1-1/2 mile stretch of coast on the eastern side of the Brazilletto Hills. Under natural conditions these merged together to form the river which then flowed through a strip of coastal swamp to the sea. The discharge from these springs does not seem to vary much and has been estimated at 110,000 acre-feet, the water being derived from rainfall on the Brazilletto Hills and, probably to some extent, the water lost by the Rio Minho above May Pen. Since 1917 some 30,000 acre-feet have been diverted from the Cockpit system for the irrigation of the southern parts of the Clarendon Plain.

Salt River is situated about 2-1/2 miles to the south of the Cockpit River and rises as a highly mineralised spring at the southern end of the Brazilletto Hills. The stream flows eastward through coastal swamps and opens out into Salt River Bay. Hydrologically the river is of little importance but the significance of the mineralised water will be discussed later.

4.2 Quantitative Data

Rainfall, evapotranspiration and runoff data were collected by the Surface Water Branch of the Water Resources Division and used to derive estimates of recharge to the aquifers. These results were then used by the present writer, with some modifications, as one of the input parameters for the digital groundwater model and it is thus appropriate to describe here the background to the collection and collation of the surface water data.

4.2.1 Rainfall

The Jamaica Weather Report was first published in 1870 and, at the time of data collection for the present study, had last been published in 1964. It is through this medium that rainfall data is made available to the public. Monthly totals are available on magnetic tape from 1901 to 1968 and may be supplied in the form of punched cards from the Government Computer Centre. From 1969 onwards, however, the meteorological Office is storing daily rainfall values on magnetic tape and thus it is possible to get more useful data for the later years.

The total number of rain-gauges in the parishes of Manchester and Clarendon is 124, of which 112 were suitable for use in the Rio Minho - Milk River Basin study. These all supply data to the Meteorological Office but are, in the main, operated by three different organizations. Those owned by the Meteorological Office are operated by the Public Works Department. A sizeable proportion of the gauges in the plains area are owned and operated by the sugar estates who supply the results to the Sugar Manufacturers Association for forwarding on to the Meteorological Office. Finally, the Water Resources Division operates thirteen rain gauges which were installed by consultants in 1967.

The distribution of the gauges was considered by the Surface Water Branch to be good in the low lying plains, on the high ground of the Manchester Highlands and the Upper

Rio Minho Basin, but rather sparse in what might be called areas of intermediate elevation such as Harris Savannah and the slopes of the Mocho Mountains. The actual distribution is 1 gauge to every 4 sq. miles which is well within the W.M.O. recommended density of 1 to 10 sq. miles for this type of basin.

Apart from the obvious problem of recruiting reliable observers in a rural area, there are other factors which tend to affect the reliability of the data. A United Nations Survey in 1966 showed that there was a wide variation in height between the gauges, with 22% being less than 40" from the ground and 27% being over 5 ft. The problem is further magnified by natural causes, in that much of the rainfall is localized and very intense, with the result that neighbouring gauges can give widely differing daily readings.

4.2.2 Climatological Stations

There were seven climatological stations within, or close to the study area, which provided data suitable for use in the water balance calculations. These were operated by a variety of organizations but all submitted their results to the Meteorological Office.

All seven recorded rainfall and temperature and five were equipped with wet bulb thermometers thus enabling relative humidity to be calculated. Pan evaporation was measured at three of the stations and sunshine at four. Wind speed was only recorded at Worthy Park which is outside the study area. A description of the climate of Jamaica was given in Chapter 1 but it is appropriate here to give the range of values of some of the parameters recorded during the 18 month study period. The average monthly run of wind varied from 55 miles a day in October 1970 to 158 miles in June 1971. Humidity was found to vary diurnally with its highest value occurring around 9.00 a.m. and the lowest at

3.00 p.m. The extremes were 72% in April and June 1971 and 84% in September 1971. Sunshine, expressed as the ratio of actual to maximum possible, varied from a low of 0.45 in July to 0.69 in January 1971.

Of the three stations which recorded pan evaporation those at Bodles and Clarendon College were equipped with U.S. Weather Bureau Class A pans and that at Worthy Park was a 6'x6' sunken pan. There was a fair degree of correlation between the three pans and November 1970 showed the lowest value of 4.37 inches as opposed to July 1971 with a high of 7.48 inches. Longer records have previously been kept by W.I.S.Co. at Monymusk and they calculated the 1-year annual mean evaporation as 67.6 inches. For the water balance calculations both the Penman and Blaney-Criddle methods were used to derive monthly evaporation figures and it was found that the former gave the best agreement with the pan figures.

4.2.3 Runoff

Engineering Consultants Inc. of Denver Colorado started a gauging programme for the upper Rio Minho and its tributaries in 1965 and established nine gauges between then and 1967. In the following two years the Project established or improved a further eight gauging stations of which two were on the Rio Minho, five on the Milk River and its tributaries, and one on Bowers River. Finally in 1970 five more stations were established and one improved, two being on the Rio Minho system and four on the Milk River system. The longest record in the basin is the Rio Minho at Suttons which dates back to 1955, but for which nearly 40% of the data is missing.

In addition to these relatively recent gaugings there are records for the Rio Minho covering the period August 1922 to August 1929, when measurements were taken by means of a concrete control at Trout Hall. S.A.G. Taylor

(1954) gives details of flows in the Milk River between 1909 and 1923 and reports that records were also kept from 1949 to 1953.

Of the 22 stations which were established in recent years, eleven are staff gauges that are read twice a day by observers and eight have float-operated Leupold and Stevens A-35 recorders. The remaining three are bubble gauges.

During the study period the Surface Water Branch carried out current meter readings at all the stations once a month in dry periods and twice a month in the wet season. They also attempted to catch flood flows over a six week period in October and November 1970 but were unlucky in that only one occurred during that time, and this was missed as it resulted from rainfall higher up the catchment and passed with no warning to the team.

It was stated by the Surface Water Branch that the Clarendon stream gauging stations were the most difficult in the island to operate, particularly in the case of the Rio Minho, as they were badly affected by shifting controls, siltation, and excavation of gravel for construction work. The high velocity of flood flow, due to the steep river gradient, also posed major problems for the stream-gaugers.

It is likely that large errors arise in compiling rating curves for the higher flows as it proved impossible to obtain discharge measurements for more than the lowest 20% of the total range of gauge heights recorded, and Herbertson (1972) reports that attempts to estimate flows for a 30 ft. gauge height at Danks, using two different but accepted methods of extrapolation, gave values of 10^5 and 10^6 cusecs.

Thus it can be seen that serious problems arise in the measurement of the surface water parameters of the water balance equation and that the tendency to first question the apparently more subjective data supplied by the hydrogeologist may, in tropical climes at least, be somewhat unfair.

The actual monthly runoff data for key stations on both the Rio Minho and the Milk River are given in table 4.1 for the period 1967 - 1971. Herbertson (1972) made a comparison of mean daily flows at different points on the Rio Minho for 28 days on which the actual flow was measured during the period January 1968 to October 1971, (see table 4.2), and from this he concludes that the average annual loss above May Pen is 20,000 acre-feet.

4.2.4 Recharge

The study area was divided into ten subcatchments based on groundwater units, surface drainage and the gauging station network. The three groundwater units are described in Chapter V and the sub-catchments are shown in Fig. 4.1.

In the case of the limestone aquifer only catchments 2, 3, 5, 6 and 10 contribute to groundwater recharge and these were further subdivided, on the basis of five soil groups and the runoff coefficient, according to their moisture retaining characteristics. Land use maps were available and, combined with the soil types, enabled runoff coefficients, root depths and evapo-transpiration to be calculated, Penman's method being used for the latter.

For rainfall, monthly values were calculated for the study period using the isohyetal method for 112 stations. Daily values were then calculated by reference to the P.W.D. gauge at May Pen, as this gave the best all round correlation with the other gauges.

A 17-year set of data was also derived from 1956 onwards but less gauges were available and thus the Theissen

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual Total
Rio Minho at Danks						5627	2479	1714	19256	9120	12722	2910	
Rio Minho at Suttons	1970	1880	5370	9720	2260	(6000)	2580	1340	21150	10360	11870	4090	78590
Pindars River at Arthurs Seat						530	640	210	800	(1100)	1570	540	
Pindars River near Rock River							494	357	1242	2310	1202	646	
Rio Minho at May Pen													
Rio Minho at Alley													
Milk River at Scotts Pass													
Milk River at Toll Gate													
Milk River at Cherry Hill													
Milk River at Rest													
Rhymesbury Gully at Gravel Hill													

TABLE 4.1.1

MONTHLY RUNOFF DATA FOR RIO MINHO

MILK RIVER BASIN (acre-feet)

1967

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual Total
Rio Minho at Danks	2850	1561	1442	1114	998	3362	1311	5096	8295	18438	8959	3957	57383
Rio Minho at Suttons	2944	1886	(1500)	(1100)	(1000)	5469	1535	5228	9808	25946	10322	(4000)	70738
Pindars River at Arthurs Seat	460	370	140	120	300	355	190	380	710	1206	1182	380	5793
Pindars River near Rock River	643	423	439	169	171	177	147	550	1260	3340	2780	575	10674
Rio Minho at May Pen	2200	470	212	0	0	160	(100)	4000	10180	20300	10000	(2800)	50422
Rio Minho at Alley	(3180)	1110	835	1045	683	3280	202	3120	12900	23600	11250	1960	63165
Milk River at Scotts Pass													
Milk River at Toll Gate													
Milk River at Cherry Hill													
Milk River at Rest	1212	823	1390	1319	569	1025	547	369	833	1364	1331	1158	11940
Rhymesbury Gully at Gravel Hill													

TABLE 4.1.2

MONTHLY RUNOFF DATA FOR RIO MINHO

MILK RIVER BASIN (acre-feet)

1968

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual Total
Rio Minho at Danks	4693	1426	791	3181	58187	75725	5367	5518	11903	19587	8267	7349	201994
Rio Minho at Suttons			1112	3772	69220	(80000)	5506	7020	11879	23663	(9000)	(8000)	
Pindars River at Arthurs Seat	290	130	160	370	5750	5890	(1290)	(1500)	(1800)	(4000)	(1700)	(1500)	24380
Pindars River near Rock River	485	290	232	565	16700	(22000)	3446	2940	3744	(7500)	(3200)	(2800)	63902
Rio Minho at May Pen													
Rio Minho at Alley	5350	(1500)	(800)	1650	63000	(90000)	(7300)	(7500)	24800	28200	13100	12250	255450
Milk River at Scotts Pass													
Milk River at Toll Gate										2997	3287	3312	
Milk River at Cherry Hill										3056	2978	2729	
Milk River at Rest	1896	446	420	490	8200	14098	1196	1845	2017	8410	6807	4382	50207
Rhymesbury Gully at Gravel Hill													

TABLE 4.1.3

MONTHLY RUNOFF DATA FOR RIO MINHO

MILK RIVER BASIN (acre-feet)

1969

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual Total
Rio Minho at Danks	12021	2638	2217	1564	18589	9435	10232	10038	18057	22468	21082	5585	133926
Rio Minho at Suttons													
Pindars River at Arthurs Seat	1270	550	570	320	2000	1240	980	1040	1570	(4100)	(2200)	(870)	16710
Pindars River near Rock River	2630	1090	885	541	4035	2000	1965	2442	3200	8370	(6350)	(1450)	32258
Rio Minho at May Pen	9398	2630	1700	(1400)	20000	(7750)	(10000)	(11000)	18000	22000	28000	6350	
Rio Minho at Alley	10500	2763	1250	1250	10580	11764	8350	11716	22590	33358	29460	9500	153081
Milk River at Scotts Pass	NO RECORD			696	3580	2076	2134	2370	2926	4703	4508	1960	
Milk River at Toll Gate	4217	3047	(2700)	(1200)	(4000)	(2500)	(2567)	3330	(3200)	(4600)	(5000)	(2700)	39061
Milk River at Cherry Hill	3260	2320	1940	1400	4614	2780	3240	3770	3570	4595	5110	2374	38973
Milk River at Rest	6600	3550	2650	1658	10826	4816	6401	6538	5700	7315	7650	4407	68111
Rhymesbury Gully at Gravel Hill	920	950	740	780	4310	1500	1970	2160	1360	1540	1970	3840	22040

TABLE 4.1.4

MONTHLY RUNOFF DATA FOR RIO MINHO

MILK RIVER BASIN (acre-feet)

1970

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual Total
Rio Minho at Danks	4625	2084	1802	4332	6857	3217	1732	6115	8920	17145	11583	3703	72,115
Rio Minho at Suttons													
Pindars River at Arthurs Seat	773	520	390	690	2240	722	360	1130	1710	1960	2140	750	13,385
Pindars River near Rock River	1305	806	(700)	619	(3500)	1079	520	(2000)	(3000)	(4000)	(4000)	(1300)	22,829
Rio Minho at May Pen	6550	3970	2970	5000	9920	4100	685	6400	15800	29100	15200	3220	102,915
Rio Minho at Alley	5260	1910	1160	5810	14150	5240	1210	6900	11970	21310	20780	2770	98,470
Milk River at Scotts Pass	1234	730	658	672	521	520	230	704	666	754	1117	497	8,303
Milk River at Toll Gate	3209	1626	1305	1335	986	1363	1188	1496	1305	1485	2578	(950)	18,826
Milk River at Cherry Hill	2572	1549	958	680	424	1210	347	535	941	1790	2235	415	13,656
Milk River at Rest	4046	1866	1880	2122	2430	2794	1674	2686	2085	4110	2904	1319	29,916
Rhymesbury Gully at Gravel Hill	1670	924	1110	874	1110	1310	1020	2120	1320	2900	956	670	15,984
Baldwin River at Gravel Hill	522	601	408	401	436	637	361	(600)	(500)	(700)	(450)	309	5,925

TABLE 4.1.5

MONTHLY RUNOFF DATA FOR RIO MINHO

MILK RIVER BASIN (acre-feet)

	1	2	3	4	5		
DATE	DANKS	ROCK RIVER	MOORES GULLY	MAY PEN	ALLEY	4 - (1+2+3)	5 - 4
1968							
4-1	28	9	0	12	-	-25	12
17-1	58	13	0	82	-	11	82
8-5	14	2	0	0	12	-16	12
27-6	17	4	0	0	25	-21	25
28-8	37	7	0	30	38	-14	8
26-9	68	24	0	34	144	-58	10
10-10	90	22	2	109	62	- 5	-47
17-10	194	43	15	261	314	9	53
1969							
20-2	18	5	0	7	13	-16	6
4-3	16	5	0	3	12	-18	- 9
9-9	86	39	7	112	128	-20	16
13-10	50	51	10	124	214	13	90
29-10	158	82	41	285	785	4	500
12-11	104	44	21	133	139	103	6
2-12	77	43	34	272	634	118	362
1970							
13-1	237	127	30	606	1150	392	544
5-2	52	21	1	45	63	-29	18
23-2	45	19	0	28	35	-36	7
9-3	38	14	0	25	29	-27	4
24-6	79	28	3	60	133	-50	73
15-7	41	17	0	27	20	-31	- 7
28-7	79	20	2	36	146	-65	110
8-12	92	38	5	104	125	-31	21
1971							
5-1	83	25	3	122	104	11	-18
19-1	49	18	1	81	47	13	-34
8-6	53	23	1	49	77	-28	28
25-8	97	15	0	84	80	-28	- 4
6-10	95	21	4	145	102	25	-43

TABLE 4.2

Comparison of daily mean flow (cfs) on the Rio Minho for days on which discharge measurements have been made (after Herbertson, 1972) method was used, with daily values being calculated by reference to a gauge at New Yarmouth.

As pumping records were available, allowance was made for the application of irrigation water, though this was only of minor importance in the case of the limestone aquifer as most water is applied to areas of thick alluvial cover. It was assumed that the water was applied evenly throughout the month and for the 17-year period the average of the available data, 1969-1971, was taken; a not unreasonable approximation as the majority of boreholes were drilled prior to 1956.

The above data was then used in a computer water-balance model developed by the Surface Water Branch, a description of which is outside the scope of this thesis. In general, however, it can be said that the model simulates the behaviour of the root zone and computes values for direct surface runoff. These values are then compared with actual measured values and adjusted by means of varying the maximum soil moisture retention and the direct runoff coefficient until a good correlation is obtained.

Calibration was based on the results for subcatchments 2 and 6 and, for the former, the computed values could be compared with direct runoff for Scotts Pass, this being based on a base-flow separation of the Cherry Hill hydrograph. For the 18-month study period, with a direct runoff coefficient of 0.03, the computed direct runoff was 2.57 inches compared with a measured value of 3.13 inches. On first sight this might not seem to be a very good correlation but, when it is compared with the total rainfall of 99.6 inches, it can be seen that further refinement of the model, by adjusting the runoff coefficient, would produce only a small change in the quantity of infiltrating water, as this made up 46% of the total rainfall.

For catchment 6 it was not possible to carry out a baseflow separation of the hydrograph and thus a comparison of computed direct runoff and measured total runoff was made and a reasonable degree of correlation obtained for high flows. Errors in the case of low flow can be attributed to the greater significance of base and spring flow.

The eighteen month data was used to adjust the soil moisture characteristics of the model so that a reasonable balance was obtained and then the model was used to calculate the 16 years of recharge data for the five subcatchments which contribute to the limestone aquifer. The data was received by the author in the form shown in table 4.3 and adjustments had to be made to fit this to the groundwater model, including an extrapolation over to the Cockpit - Freetown area which was not included in the watershed model.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1956	0	0	10.7	5.2	30.2	11.4	17.8	6.3	1.1	31.0	11.4	2.3	127.4
1957	0	16.9	11.7	15.1	18.0	2.8	9.7	0	30.9	29.0	3.2	0	137.3
1958	15.9	0	0	0	36.0	60.9	11.6	19.6	19.2	83.0	0	1.5	247.7
1959	0	0	0	5.9	21.3	0	0	0.8	8.1	27.7	23.9	6.1	93.8
1960	0	0	5.4	16.5	6.1	31.2	1.0	3.1	17.6	29.7	13.7	1.1	125.4
1961	0	0.7	10.1	4.6	21.4	0	3.4	7.8	28.0	31.1	5.1	4.0	116.2
1962	0.5	0	4.6	14.4	14.6	23.8	1.2	7.7	14.0	25.0	5.6	5.2	126.6
1963	0	0	4.9	4.6	37.1	30.0	1.6	9.0	21.8	82.2	22.5	12.9	226.6
1964	11.4	0	0	7.1	7.1	14.3	1.2	3.8	8.9	38.2	0	0	92.0
1965	1.7	0	0	4.0	37.2	1.1	3.7	8.0	22.3	12.4	15.7	7.1	113.2
1966	0	0	8.5	5.0	19.6	73.4	9.7	0	7.3	29.0	13.6	0	66.1
1967	0	0	17.6	13.4	0	21.8	0	0	27.3	18.0	11.0	0	109.1
1968	3.9	0	0	0	0.5	15.4	5.3	1.3	9.8	45.0	7.2	0	88.4
1969	5.6	0	0	22.7	80.2	61.5	21.7	15.1	20.7	27.3	4.7	19.2	278.7
1970	14.8	0	0	2.0	55.1	15.2	5.5	16.1	1.1	28.5	11.2	1.0	150.9
1971	7.8	0	2.4	8.5	23.0	0	0	17.1	7.8	14.2	12.2	0	93.0

TABLE 4.3

MONTHLY AND ANNUAL RECHARGE - LIMESTONE CATCHMENT 2

(in acre-feet x 10^3)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1956	0	0	3.3	0.1	16.6	2.3	2.4	2.3	3.7	21.6	3.3	0	55.6
1957	0	1.2	3.9	1.7	3.8	0	0	0	9.6	16.8	0.9	0	37.9
1958	0.1	0	0	0	18.4	28.1	0.7	0.3	8.8	51.7	0.4	0	108.5
1959	0	0	0	0.5	6.7	0	0	0	0.1	10.7	7.5	1.6	27.1
1960	0	0	0	0	0	28.4	0	0	8.8	14.1	6.9	1.6	59.8
1961	0	0	0	0.1	0	0	0	1.7	18.3	26.4	0.4	8.6	55.5
1962	0.9	0	0	0	0.3	6.2	0	0.1	0.7	12.8	2.8	1.6	25.4
1963	0	0	0	0	7.4	10.7	0	0	5.4	32.6	11.8	1.4	69.3
1964	1.3	0	0	0.3	0.9	4.8	1.5	0.9	7.1	26.1	0	0	42.9
1965	0	0	0	0	4.8	0	0	0.2	12.7	13.2	1.3	3.3	35.5
1966	0	0	0	0	3.8	20.4	0	0	0	9.9	12.7	0	46.8
1967	0	0	5.8	0	0	0.1	0	0	1.9	3.5	5.6	0	16.9
1968	0	0	0	0	0	0	0	0.1	0.3	12.2	0	0	12.6
1969	0	0	0	0	38.8	32.6	0	8.9	19.4	17.9	6.1	8.3	132.0
1970	0.9	0	0	0	20.4	6.4	14.1	7.1	12.0	12.1	4.0	0	77.0
1971	3.3	0	0	0	0.1	0	0	2.1	2.7	30.3	10.4	0	48.9

TABLE 4.3 (cont'd)

MONTHLY AND ANNUAL RECHARGE - CATCHMENT 4

(in acre-feet x 10^3)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1956	0	0	1.2	0	3.3	3.9	3.4	0	0	6.9	0.5	0	19.2
1957	0	3.5	1.9	0.7	6.5	0	0	0	6.1	9.6	0.3	0	28.6
1958	3.6	0	0	0	9.9	16.5	0	4.8	6.7	26.1	1.4	0.5	73.0
1959	0	0	0	0.1	4.5	0	0	0	0.1	3.7	3.9	2.7	15.0
1960	0	0	0	0	0	5.7	0	0	4.3	13.1	1.8	1.0	25.9
1961	0	0	0	0	0	0	0	0.1	9.7	8.7	0	1.0	9.7
1962	0.1	0	0	0	4.3	2.3	0	0	1.0	6.9	2.6	0.9	18.1
1963	0	0	0	0	3.4	8.3	0	0	2.8	13.0	4.5	2.2	34.2
1964	2.9	0	0	0	1.4	1.8	0.5	2.5	2.0	11.7	0	0	22.8
1965	0.1	0	0	0	1.8	0	0	0.3	2.6	9.6	4.7	1.4	20.5
1966	0	0	0	0	3.3	16.2	0	0	0	3.0	6.5	0	29.0
1967	0	0	2.9	2.3	0	2.5	0	0	1.8	0	3.0	0	12.5
1968	0	0	0	0	0	0.9	0	0	0.0	8.6	1.0	0	10.5
1969	1.3	0	0	0	15.4	13.7	0	1.0	2.7	7.6	4.6	5.2	51.2
1970	0.8	0	0	0	11.0	1.3	5.1	5.1	5.4	5.4	0.8	0	34.9
1971	0.7	0	0	0	0.2	0	0	0.9	1.4	1.7	6.8	0	11.7

TABLE 4.3 (cont'd)

MONTHLY AND ANNUAL RECHARGE FOR CATCHMENT 5

(in acre-feet x 10^3)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1956	0	0	0	0	1.1	0.2	0.4	0	0	6.4	0	0	8.1
1957	0	0.3	0.7	0	1.9	0	0	0	1.0	5.0	0.1	0	9.0
1958	1.6	0	0	0	7.8	11.0	0	0.1	1.8	19.6	0.4	0	42.3
1959	0	0	0	0	2.0	0	0	0	0	0.9	0.8	2.1	5.8
1960	0	0	0	0	0	17.6	0	0	2.1	9.0	0.9	0	29.6
1961	0	0	0	0	0	0	0	0.3	9.4	8.3	0	0	17.9
1962	0	0	0	0	1.4	2.2	0	0.2	0	1.9	1.7	0	7.4
1963	0	0	0	0	0	0	0.4	0.5	1.8	7.7	0	0	10.4
1964	0	0	0	0	0.5	0.6	0	0	1.6	5.3	1.0	0	9.0
1965	0	0	0	0	1.7	2.8	0	0.3	0.3	8.7	2.2	2.1	18.1
1966	0	0	0	0	1.8	6.2	0	0	0	0.0	5.7	0	13.7
1967	0	0	2.3	0.5	0	0.6	0	0	2.2	0.2	1.9	0	7.7
1968	0.1	0	0	0	0	0.1	0	0	0	4.4	0	0	4.6
1969	0	0	0	0	8.0	6.3	0	0.2	0.5	2.6	3.1	1.3	22.0
1970	0	0	0	0	5.5	0.2	2.6	0.9	1.8	1.2	0	0	12.2
1971	0.4	0	0	0	0.1	0	0	0.7	0.1	1.9	1.6	0	4.8

TABLE 4.3 (cont'd)

MONTHLY AND ANNUAL RECHARGE FOR CATCHMENT 6

(in acre-feet x 10^3)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1956	0	0	0.6	0	1.0	0.4	0.2	0.3	1.6	2.7	0	0	6.8
1957	0	0	0	0	0.8	0	0	0	0.5	1.5	0	0	2.8
1958	0.2	0	0	0	4.3	4.7	0	1.5	0.1	8.7	0	0.1	19.4
1959	0	0	0	0	0.8	0	0	0	0	0.8	0	0	1.6
1960	0	0	0	0	0	10.2	0	0	1.9	3.5	0.6	0	16.2
1961	0	0	0	0	0	0	0	0.0	3.3	4.5	0	0	7.8
1962	0	0	0	0	0	1.1	0	0.1	0	0	0.8	0	2.0
1963	0	0	0	0	2.3	2.7	0	0	0	5.7	1.0	0.2	11.9
1964	0.1	0	0	0	1.1	0.9	0	0	2.1	2.8	0.6	0	7.6
1965	0	0	0	0	0.8	0	0	0.4	1.3	1.4	0.5	0.2	4.6
1966	0	0	0	0	0.5	3.0	0	0	0	1.1	2.4	0	7.0
1967	0	0	0.6	0	0	0.7	0	0	1.1	0.8	2.8	0	6.0
1968	0	0	0	0	0	0	0	0	0.1	2.3	0	0	2.4
1969	0	0	0	0	3.1	3.1	0	0.2	0.4	2.6	1.7	1.7	12.8
1970	0	0	0	0	2.3	0.6	1.4	0.1	1.7	1.0	0.4	0	7.5
1971	0.1	0	0	0	0	0	0	0.5	0.5	0.5	0.9	0	2.4

TABLE 4.3 (cont'd)

MONTHLY AND ANNUAL RECHARGE FOR CATCHMENT 10

(in acre-feet 10^3)

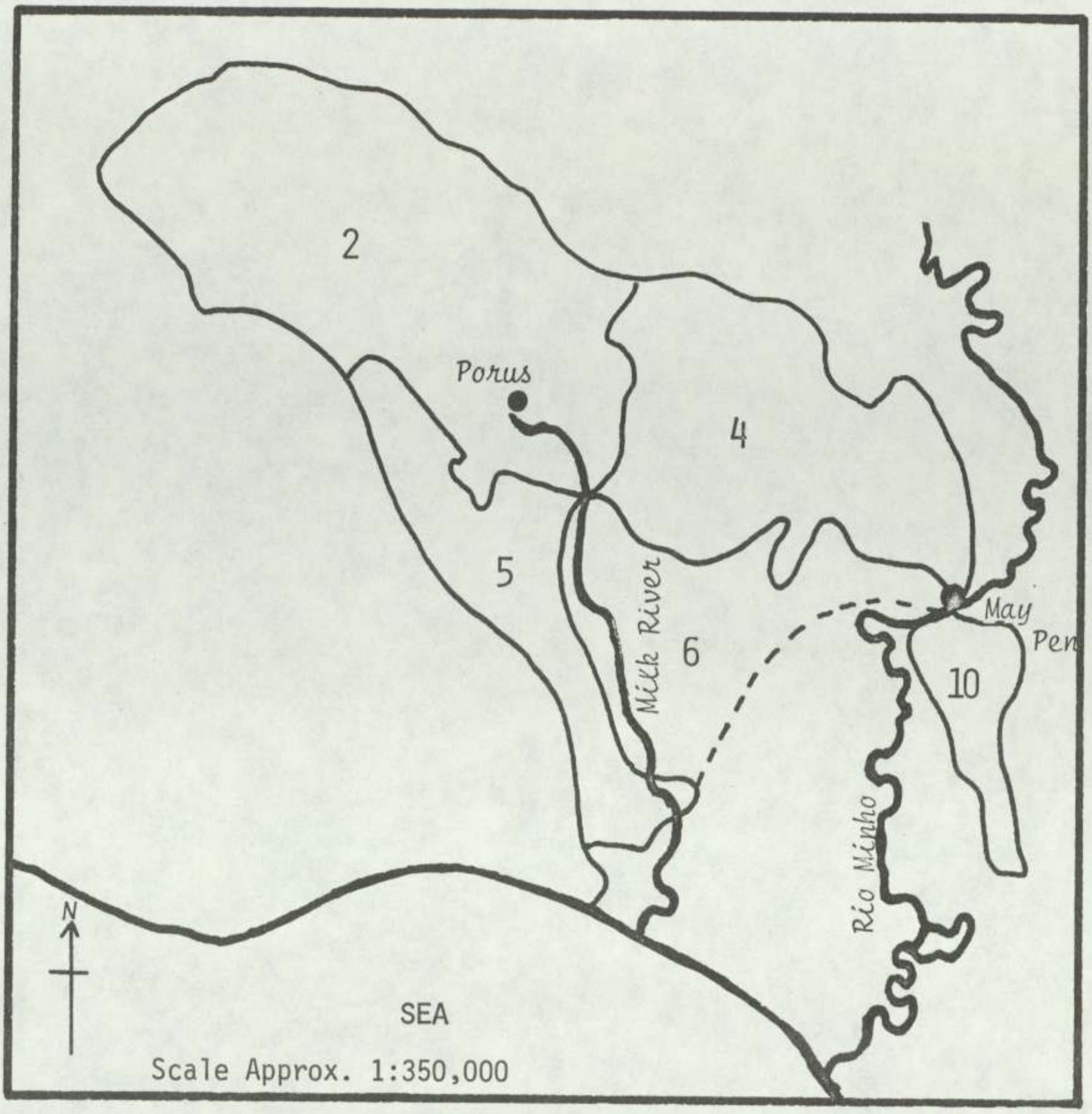


FIG. 4.1 SKETCH MAP OF SUB-CATCHMENTS USED TO CALCULATE RECHARGE TO LIMESTONE.

5 GROUNDWATER HYDROLOGY

5.1 General

The people in the Clarendon plains had relied on shallow hand-dug wells for their domestic water supply since the 1700s but Taylor (1949) reports that the first well to be constructed for irrigation was at Perrins Estates in Vere. This was said to give a good yield from the alluvium, but has long since been abandoned and filled in. In 1909, a well was constructed on the Morelands Estate (E 4726 N 3368) and after striking water at 20 feet the main water-bearing horizon was encountered at 40 feet. It gave a yield from the alluvium of 2000 U.S. GPM and, after being reconstructed, is still giving similar yields; it is now known as McLeod's Well (E 4726 N 3368). Since then, many alluvium wells have been constructed in Clarendon over the years and have met with varying degrees of success. The McLeod Well, besides being one of the first, seems also to be one of the best.

In 1912 a well which was being constructed on the Caswell Hill property passed through the alluvium and encountered limestone at a depth of 35 feet. As no water had been struck the well was considered to be a failure but the owner decided to continue the excavation into the limestone and, after passing through 30 feet of the rock, a seepage of water was observed to be issuing from a small fissure. After the subsequent enlargement of this fissure, water poured into the shaft and rose six feet bringing it to a height of sixteen feet above sea level. A pump was installed and a yield of 2000 U.S. GPM obtained with a drawdown of 18 inches. This was the first well in the area to obtain a large quantity of water from the limestone and marked a turning point in the agricultural development of the Clarendon Plains.

In 1929 the United Fruit Company, who then owned property in the area, initiated a programme of well drilling in hope of obtaining a large supply of water from the limestone aquifer. The site chosen was 1,500 feet from the original Caswell Hill well and, though water was encountered at the same depth, the yield was very small. Drilling was continued and at a depth of 174 feet a large quantity of water was obtained from a hard fissured horizon in the limestone; subsequent tests gave a yield of 5,000 U.S. GPM for a drawdown of only three feet. This well is now known as Caswell Hill No. 2 (E 4564 N 3500).

With the success of Caswell Hill No. 2 it was realized that the water in the limestone could be tapped with reasonable consistency and, over the years, many more wells were constructed of which only a few were failures. Most of the early development took place in the central area, south of Hayes, but in 1947 the government started the Mid-Clarendon Irrigation Scheme which was designed to improve the agricultural development of about 25,000 acres of land in the north-western part of the plains. In the first three years three limestone wells were constructed giving a total yield of 18,000 GPM. The number has since been increased to eighteen wells from which, in total, about 40,000 GPM are abstracted.

In 1956, according to Versey and Prescott (1956), over 150 wells in Clarendon were being used to irrigate some 40,000 acres of land; since then there has been a further increase until at present there are about 180 wells, pumping for industry, irrigation and public supply (Fig. 5.1). During this time, however, there has been an increase in the salinity of the groundwater in certain areas and the basin was declared a critical area under the terms of the Underground Water Control Law. Due to this same deterioration in quality, a number of wells, principally alluvial wells near the coast and limestone wells in the Kemps Hill and Cotton Tree Gully areas, have had to be abandoned.

5.2 Alluvium

In the Clarendon Plain the alluvium is less important as an aquifer than the limestone, both in terms of areal extent and quantity of water extracted from it. As mentioned previously, there are considerable variations in the character of the "alluvium", both vertically and laterally, but there is sufficient clay content to separate the water in the alluvium from that in the limestone. This is borne out by the large differences in elevation between the water table in the alluvium and the piezometric level in the limestone. At four of the locations where drilling was carried out under the direction of the writer, (Vernamfield, Content Village, Gimme-me-bit and Rhymesbury) observation holes penetrating the two aquifers were sited side by side to determine the actual difference in hydraulic head (Fig. 5.2) and it proved to be considerable over much of the area, varying from 28 feet at Gimme-me-bit to 108 feet at Content.

Although the alluvial deposits cover most of the plains they cannot be considered as an aquifer with exploitable groundwater over the whole area. On the evidence of borehole records it is possible to delineate the water bearing or "wet" alluvium from the dry alluvium (Fig. 5.3) and it can be seen that the actual productive aquifer covers about half of the plains and corresponds roughly to the area where the alluvium is thickest. There is also a narrow strip of alluvium adjacent to the river, running from Parnassus to Caswell Hill, which is frequently saturated, presumably indicating hydraulic continuity with the Rio Minho.

To talk about 'the alluvial aquifer' is probably misleading in that the wide variations in lithology, both vertically and laterally suggest not one, but several aquifers, some interconnected and some, at least locally, isolated and of quite small extent. Charts from automatic water level recorders indicate that groundwater occurs in both the confined and unconfined states. The important factor as far as recharge is concerned, however, is that the surface elevation does not vary to any great extent, and thus the rainfall is low and fairly evenly distributed over most of the area.

The rainfall is one of three possible sources of recharge to the alluvium but, unlike the limestone, it is not likely to be the most significant. Of more importance is the fact that virtually all the area underlain by productive alluvium is used for the growing of sugar cane and thus irrigation is carried out virtually year round, with large quantities of water being applied to the fields, some of which must infiltrate to the water table. The third possible source of recharge to the alluvium is by loss of water from the Rio Minho to the aquifer.

It is likely that most of the recharge which occurs as a result of rainfall will be limited to the four wettest months and that any recharge which occurs during the rest of the year will be as a result of excess irrigation, with the exception of a small amount from the Rio Minho.

The general flow pattern in the alluvial aquifer is very simple but the details are almost certainly complicated due to the complex nature of the aquifer itself. From the groundwater map it can be seen that the overall direction of flow is from the north to the south and follows the slope of the plains (Fig. 5.4). In the area north of Springfield however, the 30-foot groundwater contour doubles back on itself and there would appear to be an almost northward flow of water over a small area. The writer believes that this represents water flowing from the upper alluvial aquifer into the underlying limestone and this will be described in the next section.

Along the length of the aquifer running from

Parnassus to Caswell Hill there is no data available to determine the configuration of the water table. It is significant, however, that the known elevations at the northern and southern ends of this strip tie in very closely with those in the major portion of the aquifer to the west, suggesting that the gradients in these areas are comparable.

The flow pattern of the groundwater adjacent to the lower reaches of the Rio Minho is complicated in that, over a relatively short distance, it does an about turn. From Ashley Hall to Broken Bank water is flowing from the river to the aquifer but from Water Lane to the sea it is flowing from the aquifer into the river. In fact, what is gained by the aquifer in the former section is almost certainly returned to the river in the lower reaches. The significance of this is that the river can be considered as a hydrological boundary of one sort or another. The most important factor contributing to this loss from the aquifer to the river is probably the extensive irrigation carried out in the lower portion of the plains, thus artificially raising the water table over the years, particularly in the large area to the east of the lower reaches of the Rio Minho. No doubt in the past the flow pattern was generally similar but the gradient has been steepened and the flow towards the river induced.

It will have become fairly obvious that there are several possible ways in which water is being discharged from the alluvial aquifer. In addition to the losses to the river and to the limestone there is obviously some outflow to the swamps along the coast and to the sea itself. Apart from the natural methods of outflow there is also the artificial abstraction of water by means of the numerous pumping wells.

The alluvial aquifer is believed to be like a basin or dish which cannot be overfilled without water spilling out. This is schematically represented in Fig. 5.5 and it can be seen that if water is put in at a rate greater than it is able to discharge either by pumping or flow to the sea, then it will overflow into the limestone. This situation would also contribute to the stability of the alluvial water levels, which do not seem to vary much throughout the year.

The anomaly in the groundwater contour map to the north of Springfield represents a situation where, figuratively speaking, the edge of this hypothetical dish or basin is slightly lower and thus a fairly constant spilling takes place from the alluvium into the limestone, the water table map for which shows a high area in this locality,presumably due to the recharge effect (Fig. 5.9). As there is no direct hydrological continuity between the two aquifers, however, it is virtually impossible to separate this component of natural discharge, quantitatively, from the others.

The extent of the losses to the river are equally difficult to estimate but it is certain that a reasonable proportion of this is balanced by the flow from the river to the aquifer.

Along the coast there is an extensive swamp development which must be fed, at least in part, by water from the alluvium. The water which is not lost to the limestone or river, and which has not been extracted by wells, will either appear at the surface in these swamps or be discharged to the sea. The water in the swamps will then be lost by evaporation to the atmosphere. The abstraction of groundwater by means of wells, whilst not being comparable in quantity to that abstracted from the limestone, is still extensive for such a small aquifer.

5.3 Limestone

5.3.1 General

Cretaceous rocks, overlain unconformably by Tertiary sands and clays, outcrop in the north of the study area, and these sands and clays are in turn overlain by a limestone sequence ranging from mid-Eocene to early Pliocene, which is exposed over much of the study area. Most of this limestone sequence is made up of the White Limestone Group with only isolated outcrops of Coastal Formation occurring.

As described in Chapter 2, the White Limestone Group in this area consists of three mappable units, these being:-

1. Troy Formation
2. Somerset and Walderston Formation
3. Newport Formation

Though it is likely that the White Limestone Group acts mainly as a single hydrological unit, the Newport is by far the most predominant, outcropping in the highlands of the Brazilletto, Mocho and May Day Mountains, and underlying the alluvial deposits of the plains, where it is the principal source of ground water. It also forms the Portland Ridge in the south and is exposed at several localities in the plains.

The extent of the limestone outcrop within the basin boundaries is shown in Fig. 5.6. In general, the areas of exposed limestone are the areas of recharge, where rainfall percolates downwards to the water table before draining from the highlands to the low-lying plains. Throughout all the limestone areas ground water in some form can be expected, though in parts of the higher region it may be at considerable depth.

5.3.2 Aquifer Thickness

In the southern part of the Clarendon Plains the thickness of the limestone is thought to be in excess of

4,000 feet and it varies lithologically from a soft marly or chalky limestone to a hard, dense fine-grained rock with some local dolomitization. The softer less indurated rock exhibits some primary permeability but in the harder limestone the groundwater occurs mainly in the joints, fractures and solution cavities. It is often confined due to the presence of almost impermeable clay layers in the overlying alluvium, and in places it is confined by relatively impermeable horizons in the limestone itself. In fact an examination of drilling records showed that by far the majority of boreholes had a rest water level higher than the elevation at which water was struck (see Fig. 5.7), though this could be a side effect of cable tool drilling in a marly formation.

Differing views have been expressed on the position and vertical extent of the water-bearing horizons in the limestone, with Versey (1959) saying that the limestone appeared to be compact but with a broken up rockhead which constituted the aquifer. Taylor (1954) however, describes horizons within the limestone which appear to be the principal waterbearers and this was confined by the writer's own observations. The first limestone boreholes in Clarendon, which were drilled in the area to the west of Kemps Hill, mainly received their supplies from between 75 and 85 feet below sea level, with the exception of two wells which tapped a horizon 10 feet above sea level. Other wells which were drilled later, appear to strike the main supply between 40 and 50 feet below sea level and those in the Clarendon Park - St. Toolies area from between 95 and 110 feet below sea level.

One of the purposes in drilling the exploratory well at Vernamfield (E 4476 N 3591) was to determine the maximum depth at which circulation was taking place in the limestone, in order that an estimate could be made of the aquifer thickness. The borehole entered the limestone at 500 feet and drilling was continued to a depth of 947 feet, cores being taken at regular intervals and examined for signs of solution. The evidence indicated that there was high secondary permeability down to this depth, and that the saturated thickness of the aquifer must therefore be at least 500 feet. As this is the deepest well in the plains, and as none of the production wells extract water from such a depth, it will be assumed, for the purpose of this study, that the saturated thickness of the limestone aquifer in the plains is 500 feet, though it must be recognized that the actual figure is almost certainly in excess of this. As far as the lateral extent is concerned, successful limestone wells have been constructed throughout the plains, north of the South Coast Fault, and up to the base of the Mocho Mountains. Wells have been successfully sited up the valley of the Rio Minho north of May Pen, and northwest of Porus in the Williamsfield - Porus Trough where the alluvium is absent. Alcoa have also constructed a well at an elevation in excess of 500 feet in the Pleasant Valley area of the Mocho Mountains and this proved to be moderately successful with a yield of 257 GPM with only a 20" drawdown.

A well at Kendal in Manchester (E 38 N 42) was not successful as the water table was always at a depth in excess of 600 feet below the ground level and, during dry periods, it fell to below 1,100 feet, (Fig. 5.8).

Thus, it can be seen that groundwater occurs in the White Limestone throughout the basin but that its availability tends to be restricted to the lower lying area where it can be tapped at an economic depth and where the seasonal fluctuation in the water table is less extreme.

5.3.3 Catchment Boundaries

During the early stages of the study the basin boundaries were drawn on a topographic basis, being sketched initially from the 1:50,000 maps and then being accurately defined in the field. This gave the project area shown in Fig. 5.6, which is divided into two basic units separated by the ridge of the Mocho Mountains. It was realized at the time, however, that this boundary did not necessarily coincide with the groundwater divide. Thus, in the area of the May Day Mountain, a study was made of the aerial photographs in order to determine the faults and major structural features occurring in the limestone. On the basis of these data the western catchment boundaries were drawn.

The most easterly of these western boundaries is considered to be the principal groundwater divide and defines the western limit of the area which consistently recharges the limestone aquifer of the Clarendon Plains. The other line, which is further to the west, defines an area which might under certain circumstances contribute to the ground water of the plains. The area is hatched in Fig. 5.6 to distinguish it from the known recharge area which is shaded.

The conditions under which this area may contribute to the groundwater of the plains would probably be at times of exceptionally high rainfall when its normal means of outflow, generally southward towards Round Hill, cannot cope with the increased discharge. The groundwater would, in effect, back up and spill over into the Rio Minho - Milk River Basin. It is likely that this occurs at times of high recharge, when the abstraction from the limestone aquifer in the area is considerably less than the total recharge, and thus when it will not critically affect the calculations of safe yield. Consequently, for the purposes of water balance calculations, this area has been ignored because it is difficult to assess accurately when the area might contribute to the basin, and in what quantity. It is worth noting that, during normal times, the total recharge to this part of the May Day Mountains is lost to the island by discharge to the sea and that, until recently, was not exploited in any way, though it is understood that the National Water

Authority has been drilling in the southern part of this area since the present study was undertaken.

The northern boundary of the recharge area has been taken to be the topographic divide which runs from the Christiana - Spaulding area in the northwest to intersect the Rio Minho between Moores and Chapelton. This line does not coincide with the northern limit of the limestone but rather parallels it about two miles to the south and, though it may not exactly represent the groundwater divide, it is thought to approximate to it over most of its length.

Rain falling on limestone to the north side of the topographic divide will percolate downward into the limestone and then move northward. It reappears as the numerous springs which occur along the outcrop of the Yellow Limestone and supply the tributaries of the Upper Rio Minho.

The eastern boundary has, like the western, been divided into two, one defining the area of recharge to the limestone of the plains and the other being the boundary of the study area. The groundwater divide down this eastern side of the plain is the only one which has actually been drawn on the basis of borehole data and groundwater contour maps.

From the point where the Rio Minho is intersected by the northern boundary, to a point northeast of May Pen, the groundwater divide appears to follow the course of the river. This is due to the fact that, though the river is not in direct hydrologic continuity with the groundwater in the limestone, as indicated by the evidence from the coreholes at Moores (E 4780 N 4085) and Sevens (E 4791 N 3975), some recharge of groundwater is taking place from the river. At certain times the river, while flowing at Moores, is dry by the time it reaches May Pen, the water having presumably infiltrated into the limestone. Thus, it would appear that there is a recharge mound beneath this length of the river which acts as a groundwater divide.

Moving south from this point, the groundwater divide runs along the western edge of the Brazilletto Hills until it intersects the east-west South Coast Fault which, for practical purposes, is the southern boundary of the limestone aquifer. As described above, this line defines the recharge area of the plains and precipitation falling on the Harris Savannah and Brazilletto Hills, to the east of this line, will flow eastward to the Cockpit Springs, or in the case of the more northernly parts, to the Free Town area. The line at the eastern extremity of the map is the limit of the study area and it follows the topographic divide which runs from Port Esquivel in the south to Cocoa Ridge and Juan de Bolas in the North.

5.3.4 Recharge

Over most of the plains the limestone is covered by alluvium which has an appreciable clay content and thus recharge over most of this area is unlikely to take place to any great extent, though there may be a limited amount of vertical seepage from the alluvium down into the limestone. There are, though, several areas of exposed limestone in the plains, such as Kemps Hill, which will receive some recharge from rainfall. In the previous section it was seen that approaching the southern end of the Western edge of the alluvial aquifer (or "wet" alluvium) there was an anomaly in the alluvial groundwater contours which could be best explained by the idea that the water was "spilling" out of the aquifer into the underlying limestone.

The loss of water from the Rio Minho above May Pen was discussed in Chapter 4 where the figure of 20,000 acre-feet was given as an estimate of the annual contribution of the river to the groundwater system. Of this a proportion probably remains as subsurface flow in the alluvial deposits and recharges the main body of the upper aquifer in the northeast corner of the plain though, as was described earlier, attempts to locate this by means of auger holes in the river bed were not successful. Thus, it seems likely that by far the largest proportion finds its way down into the limestone where it has been observed to produce a recharge mound. The possible directions of flow of this water are shown in Fig. 5.10.

Thus far we have discussed the minor sources of recharge to the limestone aquifer whereas the majority of available groundwater is derived initially from rainfall on the higher areas of outcropping limestone. The actual quantities were given in Table 4.3, where it could be seen that the area described as sub-catchment 2 (see fig. 4.1) supplied by far the largest amount of recharge, averaging almost 60% of the total for the 16-year period from 1956 to 1971. Although it has a larger area than any of the others this alone would not account for the higher recharge. It has an area of 78 sq. miles compared with 54 sq. miles for catchment 4 but on average receives nearly three times as much recharge, the significant factor, however, is the higher elevation and the resulting higher rainfall.

The present study led to the identification of three units of the limestone aquifer within the plains area which, though not entirely separate, are at least distinct. The units are shown in Fig. 5.11 and have been labelled A, B and C. Unit A is by far the largest and is separated from B by the postulated fault which run NNE from Kemps Hill to west of May Pen, and across which there is thought to be restricted groundwater flow. Unit B is in turn separated from unit C by a groundwater divide which runs southward along the western edge of the Harris Savanna and the Braziletto Hills. Any discussion of recharge will obviously have to take into account the contributions made to each of these units, this however is left until Chapter 9 where an attempt will be made to assess the water resources of the area.

5.3.5 Groundwater Flow

Only a proportion of the rain which falls in the recharge area actually infiltrates to the groundwater body. The mechanics of water movement through the zone of aeration (i.e. the unsaturated zone) is important in a groundwater study but, unfortunately, very little is known about this subject. It is known, however, that precipitation is discontinuous. It might, in fact, be visualized as occurring at irregular intervals in the form of "slugs" of water. The actual paths followed by these slugs of water through the zone of aeration are many and diverse.

In the highland recharge areas of the limestone aquifer several different conditions can be recognized. In the northern part of the Mocho Mountains, near to the groundwater divide, the situation is hydrologically complex. There is very little surface water, other than the several small streams which flow for short distances before disappearing back into the limestone, and probably no available groundwater. Of the surface streams the Whitney River and Peace River are probably the most striking. In addition, there are a number of caves in the area and experiments were carried out using dyes in order to establish the connection, if any, between these.

Peace River rises from a swamp about 150 feet inside a cave and flows out of the cave, across a glade for about 1/4 of a mile, before sinking into the White Limestone. It is probably not seen again, above ground, within the area. Victoria Cave has its entrance located in the side of a glade some 2,000 feet north, north-west of Peace River Cave. A large, normally dry, passage which functions in wet weather as both a rising and a sink, leads into a river passage trending southeastward towards Peace River Cave 800 feet away. Discharges at the two caves seem comparable and dye tracing experiments were tried between Peace River and Whitney River, though the results were inconclusive.

There are two possible hypotheses to explain the behaviour of the water in this area. It may be that the water flows from the northern boundary in a series of discrete conduits at a shallow depth, occasionally reappearing at the surface, before dropping down to much greater depth somewhere on the southern flank of the Mocho Mountains. Alternatively, the water may collect in individual small catchments and drop to some depth below the surface within a very short horizontal distance, not to appear in this area again. The fact that the tracing experiments failed to detect any connection between the springs, and that differing hardness values were obtained, tend to support the second theory. Thus it may be that the upper areas of the Mocho Mountains act as a series of semi-independent catchments, hydraulically controlled by the White Limestone - Yellow Limestone contact or, as will be seen later, by the Yellow Limestone-Cretaceous Contact. Moving to the south, the Yellow Limestone dips steeply downwards and allows the water in the White Limestone to move to a greater depth where it is more likely to act as unified water body, though even here it will be seen that the picture is not at all simple.

Groundwater moves in accordance with the hydraulic gradient, from points of high head to points of low head. The contour lines of water table and piezometric surface maps connect points of equal head and the movement of groundwater is perpendicular to these lines.

In the northern part of the study area it has been shown that at least a little is known about the occurrence of groundwater, due to the appearance at the surface of several small rivers and streams which flow for short distances before returning underground. In the northwestern and western parts of the catchment area, however, and indeed throughout the whole of the Manchester Highlands, there is a dearth of hydrogeological data, broken only by knowledge of the springs along the coast of Long Bay.

Over much of this area it is reasonable to assume that the portion of rainfall which infiltrates through the soil zone will make its way more or less vertically downwards until it reaches the water table, or zone of saturation. North of Mandeville, however, it is known that the contact between the permeable White Limestone and the less permeable underlying Yellow Limestone is at a considerable elevation and that for much of the time there may be no zone of saturation. The situation here is comparable to that described in the Mocho Mountains, but differs in that there is sufficient thickness of White Limestone for the infiltrated waters not to reappear at the surface.

In the geological section of this thesis, it was seen that the regional dip in the Manchester Highlands is towards the southeast and thus it is assumed that groundwater flow is in that direction.

The occurrence of faults in the limestone is widespread and the nature and extent of the effect they have on groundwater flow is a point for debate. It is possible for faults to act as both channels for, and barriers against, groundwater movement. The former occurs if the fault raises underlying impermeable rocks into the line of flow or if, due to crushing, the aquifer rock itself is greatly reduced in permeability in the fault zone.

It is likely that faults act as both barriers and channels of groundwater flow in the Manchester Highlands, where the major fault system trends NNW - SSE. A number of small faults can be detected running at right angle to these but probably do not extend to any great depth. The most striking structural feature is the Williamsfield - Porus Trough which runs south-eastward from Balaclava in the northwest and disappears at the northwest corner of the Clarendon Plains. It is certain that this faulted structure, probably best described as a graben, serves as a major flow path for much of the groundwater which ultimately supplies a large part of the Clarendon Plains limestone aquifer, and it could be argued that it is the graben which acts as the channel of flow and not the faults themselves. In fact resistence to flow across the Queens Town Hill Fault, which forms the south-western edge of the graben, may very well be responsible for the phenomenon known as Harmons Lake. The locality of Harmons (E 4050 N 3900) is located in a closed valley marked on the 1:50,000 map as a depression surrounded by the 750 foot contour. It is reported that, on occasions, this valley has been known to flood to a considerable depth and local residents say that the last time this happened was in 1933. The valley gradually began to flood, with water building backwards from a sinkhole until it covered houses and tall palms and it persisted for several months. It would seem that after times of particularly heavy rainfall the natural drainage system is unable to cope with the increased recharge and the waters back up due to restricted flow across the Queens Town Hill Fault. A similar explanation would account for the temporary lake known as Green Pan (E 4150 N 4100) which appears from time to time at the lower end of the Porus Trough and is situated several hundred feet higher than the Milk River.

A fault which almost certainly acts as a barrier to groundwater flow is the one which runs along the Sixteen Mile Gully. Versey (1971) describes the probable development of the drainage in some detail. He believes that sometime in the island's development the coast lay along the eastern end of the Sixteen Mile Gully and that the groundwater from the Manchester Highlands was discharged as springs along this faulted coastline. Thus a drainage pattern was established to the north of the fault but not on the southern side. Subsequent uplift saw a deepening of the system but no development on its southern side and, at present times, the groundwater is diverted eastwards towards the valley of the Alligator Hole River, where it then flows southward to the coast, partly appearing as spring flow at Alligator Hole. As described earlier, the writer believes that after periods of heavy rainfall, when high recharge has taken place, the build-up of groundwater beneath this part of the Manchester Highlands (the hatched area in Fig. 5.6) may exceed the quantity which can flow out down the Alligator Hole river valley. Under these circumstances it is likely that some flows eastward to the Clarendon Plains, though the quantities involved are unknown, and the area has not been included in the water balance calculations.

In Chapter 3, where karst processes were discussed, the idea was put forward that two different flow systems might have developed in the limestone, one being based on small fissures and fractures and the other resulting from the development of large flow paths along the major discontinuities within the limestone. It was suggested that the large joints had suffered such rapid solution that the level of saturation had quickly reached its lower limit and that these features had then acted, in effect, like coast-lines themselves with other solution cavities cutting back perpendicular to them. This concept may be difficult to accept for those who wish to see the groundwater of the White Limestone as occurring under normal water table conditions, and indeed the evidence from boreholes suggests that a water table does exist. However, it will be seen in Chapter 7 that when the groundwater model was being calibrated it was necessary to have extremely high values of transmissibility in order to get the recharging water down into the plains area but that with these high values it tended to drain out the water too quickly from the recharge area. Thus the idea of two separate flow systems once again became attractive.

An alternative way in which this double drainage system could exist was touched on briefly in an earlier chapter in which it was said that the lower members of the White Limestone Series act independently from the Newport, at least in the recharge area. It was shown that the most extreme form of karstification occurred in the Troy Limestone and this was partly attributed to its hard brittle texture and the possible development of joints and fissures due to shrinkage during dolomitization. It is indeed easy to conceive of this underlying formation with a high secondary permeability transmitting water rapidly from the higher regions, whilst the rainfall that infiltrated into the younger, marlier rocks is still making its way down to the saturated zone and contributing to the increase in storage. Having travelled through what was essentially a conduit system the water would reach a point where it would tend to merge with that which existed in the overlying limestone because the resistance to flow in the downdip direction would have increased until it was comparable with that existing in a vertical direction.

Evidence of a similar situation taking place in the Chalk of Hampshire, England, was highlighted by a report of a groundwater tracing experiment carried out by Atkinson and Smith (1974). Rhodamine dye was introduced into a sink hole and springs some 6 km. away were monitored for its appearance. The experiment was carried out at the end of the summer and hence groundwater levels were low and still falling. The hydraulic gradient between the two points was 1.6 m/km and it was calculated, using average permeability values for the chalk, that the rate of flow would be 26 m/day. In fact the dye first appeared after 53 hours and reached its peak concentration after 62-1/2 hours indicating that the rate of flow was over 2.2 km/day or 85 times that which was calculated. They concluded that the flow must have been turbulant and along fissures systems, though it is known that a groundwater body as such exists in the area. Thus it seems to the present writer that the two flow systems are co-existing in what is supposedly one aquifer.

In the discussion of groundwater flow we have been concerned, so far, with the areas characterized by lack of data. It was seen, however, that in the very high areas there is practically no groundwater body as such, but that the groundwater movement is primarily controlled by the White Limestone - Yellow Limestone contact, and in general is towards the Clarendon Plains, i.e. southward from the Mocho Mountains and southeastward from the Williamsfield-Porus Trough. As the Yellow Limestone falls away, the water in the White Limestone starts behaving more as a groundwater body and moves into the area where wells have been drilled to exploit this resource. As a result of this development more data is available and thus it is possible to construct a groundwater contour map from which the directions of groundwater movement can be determined with a reasonable degree of accuracy (see Fig. 5.9).

From the map it can be seen that there is a tight bunching of the groundwater contours in the St. Toolies area, probably due to a large reduction in transmissibility, and that there is a convergence of groundwater on the District of Lime Savannah, in the north and northwestern part of the Plain, indicating that this area is the most suitable area for any new wells or increased abstraction. From here the direction of flow turns southward and the groundwater moves into the deeper part of the aquifer where the limestone is several hundred feet below sea level. As described earlier, the writer believes that this depression is bounded on the eastern side by a NNW - SSE fault across which there is restricted groundwater movement. Thus the water which has flowed through the limestone from the north-west must, if not abstracted by wells, flow southward to the sea.

The alluvial filled depression known as Webbers Gully, running from Halse Hall to intercept the Rio Minho above May Pen, appears to be fault-bounded and it was thought likely that a considerable proportion of the so-called "Lost waters of the Rio Minho" found their way along this depression, either in the alluvium or in the underlying limestone. In an attempt to prove this an exploratory well was drilled at Palmers Cross with negative results. The alluvium was found to be dry and the borehole entered the limestone at 78 feet (or about 128 feet above sea level). The water level is surprisingly low, remaining fairly constant at about 6 feet above sea level and, when test-pumped, the borehole failed to yield enough water to fill the pump column. All this evidence appears to negate the theory of appreciable groundwater flow down Webbers Gully, but it may be that the borehole struck some anomalous pocket in the aquifer. It was found impossible to include in the groundwater contour map the elevation of the water table in this well, other than by drawing a "bull's eye" depression around it, and the other data clearly suggest that there is in fact a high ridge in the water table along the course of Webbers Gully. Thus the possibility of groundwater flow from the Rio Minho finding its way into the limestone aquifer of the plains, via this feature, should not be ruled out.

The regional flow pattern can best be seen from Fig. 5.12 which shows the general directions of flow based on the ground water contour map. It can be seen that some of the water lost from the Rio Minho may in fact go to supply the Cockpit Springs, along with water derived from rainfall on the Brazilletto Hills and Harris Savannah. The water table depression in the Hayes area was probably caused by the continued pumping of the public supply well at the locality shown on Fig. 5.9, whereas the shutting down of irrigation wells to the south allowed the water levels there to recover.

In this section on groundwater flow some reference should be made to salt water encroachment in the limestone aquifer, though this topic is covered in more detail in the section on groundwater quality. Due to the fact that the groundwater unit B is overdeveloped, in so far as abstraction considerably exceeds recharge, it is not surprising that salt water has moved into the southern part of the area. This salt water may be sea water but, whatever the cause, it seems that its movement is associated with the South Coast Fault. If it is sea water then it is probably moving in from the east along the fault, whereas connate, juvenile or meteoric water is more likely to migrate vertically up the fault from its point of origin.

5.3.6 Discharge

There are three possible ways in which groundwater may be discharged from the limestone aquifer in the Clarendon Plains. It may be by natural outflow, either as springs or submarine discharges, or by the artificial means of abstraction from pumping wells.

Springs occur at several localities along the northern side of the Mochc Mountains where they form small tributaries of the upper Rio Minho but, as described earlier, these are outside the catchment area of the aquifer. There are also some on the southern side of the Mocho Mountains, two examples being the Whitney River and Peace River. As both these disappear back into the limestone, however, they do not represent a net discharge from the aquifer.

The major springs which occur in the limestone are those at the source of the Milk River, in the northwestern corner of the plain, and the Cockpit Springs situated along the coast on the eastern side of the Brazilletto Hills. These have been described in some detail in an earlier section of this thesis.

The second method of discharge from the aquifer, as mentioned earlier, is by outflow to the sea. The position here is complicated by the lack of knowledge of what happens to the limestone south of the South Coast Fault, but from the groundwater contour map (see Fig. 5.9) it is evident that some outflow takes place along an extension of the buried valley and also in the vicinity of the mouth of the Milk River. The actual points of discharge into the sea, however, may be some distance off-shore,where the White Limestone is exposed in the sea bed. In the water balance calculations this figure is the unknown which, when determined, gives some idea of the availability of water in the aquifer.

The final method of discharge from the aquifer is by abstraction from pumping wells. As described in section 5.1 the first well to obtain large quantities of water from the limestone was constructed on the Caswell Hill property in 1912, and over the years many more have been drilled until, at the present time, there are over 100 wells in the study area which abstract water from the limestone.

The distribution has not been uniform throughout the basin as there has been a tendency to exploit an area of good yield to its fullest. Thus if a land owner has one successful well on his property he is likely to drill any new wells which he requires in close proximity to the first. This process, whilst being perfectly understandable, is a dangerous policy in the lower regions of a coastal aquifer where a large cone of depression around a group of wells could initiate sea water intrusion.

The situation at the present time is that wells and boreholes are abstracting 116,000 acre feet per year of water from the limestone aquifer within the Clarendon Plains and the surrounding recharge area. The Hayes Common-Raymonds area has the greatest abstractions, along with the Free Town area in the east. It is significant that the former area of high abstraction is also suffering from salt water contamination.

5.3.7 Aquifer Characteristics

The five most important characteristics of an aquifer are porosity, permeability, transmissibility, specific yield and storage coefficient. Porosity is the ratio of pore space to total volume and is a measure of the water bearing properties of the aquifers, though not necessarily of its ability to transmit water. In the case of limestone the porosity can vary from three or four percent for a compact crystalline type to over thirty percent in the case of chalk (Davis and DeWeist 1966).

The permeability of an aquifer is its capacity for transmitting water and is quantitatively defined as the rate of discharge of water through a unit cross-sectional area, at right angles to the direction of flow, under a unit hydraulic gradient (Meinzer, 1923). The permeability which results from voids and interstices in the original rock structure is known as primary permeability whereas that resulting from joints, fractures and solution cavities is called secondary permeability.

In the case of the White Limestone, the success as an aquifer is mainly due to its possessing a relatively high secondary permeability, though this in itself depends partly on the original character of the rock. A soft marly limestone is less likely to be fractured than a hard crystalline variety such as the Troy which will tend to be more brittle.

In order to relate permeability to an aquifer as a whole, the coefficient of transmissibility is used. This is the product of aquifer thickness and permeability, and is defined as the rate of flow of water in gallons per day through a vertical strip of aquifer one foot wide and extending the full saturated thickness, under a hydraulic gradient of one foot per foot at prevailing water temperature.

Important characteristics of an aquifer are those related to the amount of water which can be released from storage. These characteristics are given by the specific yield and the storage coefficient. The specific yield is the amount of water which can be drained by gravity from an unconfined aquifer and is expressed as the ratio between the drained amount of water to the unit volume of the saturated aquifer. The storage coefficient is defined as the volume of water that an aquifer releases from, or takes into, storage per unit surface area per unit change in the component of head normal to that surface. For an unconfined aquifer this corresponds to the specific yield (Todd, 1966).

In general, the methods of determining aquifer characteristics fall into two groups;, laboratory methods and field methods. Laboratory determination involves the passing of water through a sample of the material under a constant or falling pressure head, whereas in the field observations are made on the effect of pumping a well at a known rate. Of the two methods the field tests are considered to give a more reliable indication of the aquifer characteristics because a larger, and therefore more representative, volume of the aquifer is involved. With a non-homogenous aquifer like the White Limestone the chances of obtaining a representative sample for laboratory tests are quite small.

Thus, during the time that the writer was collecting the data that has ultimately been used in this study, it was necessary to assess the ways in which pumping test data could be obtained. The most obvious source was the results of earlier workers in the area and, of these, only Versey (1959) had carried out pumping tests which had yielded information about the aquifer characteristics. He worked with existing irrigation wells and the majority of the tests were based on the recovery method in which residual drawdowns, at various times after the pump had been shut off, were recorded and used to solve the equation:-

$$T = \frac{264.Q}{s_1 - s_2} \quad \text{Log } \frac{t^1}{t_2}$$

Where T is transmissibility
Q the pumping rate
s the drawdown
at time t.

He gives the results of 9 tests (Table 5.1) and arrives at an average value of 800,000 g.p.d. per foot.

TABLE 5.1

(after Versey, 1959)

Well	Transmissibility (g.p.d. per foot)
Raymonds 6	540,000
Yarmouth 4	1,180,000
Cotton Tree 2	850,000
Springfield	450,000
Damlands 4	1,150,000
Raymonds 4	634,000
St. Jago 2	740,000
Caswell Hill 3	1,380,000
Windsor Lodge 3	430,000

It was hoped to carry out tests on existing wells as part of the present study but to use a small drilling rig to put down observation holes. In this way values for the coefficient of storage might reasonably be calculated, in addition to transmissibility. In fact it proved very difficult, despite the large number of boreholes that exist in the area, to find ones which were suitable. Ideally, it should be possible to measure the water level in the well and, most important, it must be possible to measure accurately the discharge of the well. In addition to these points, the well must be sufficiently far from other pumping wells to avoid interference and the owners must be prepared to allow the well to be shut down long enough for the water levels to recover, prior to the test. Eventually a short list was compiled of suitable wells including ones that only penetrated the alluvium, both aquifers being under investigation at that time.

It was decided, at management level, to give first priority to the alluvial holes as this posed least problems for the drilling rig and several tests were carried out with varying degrees of success. Time, however, did not permit this exercise to be undertaken for the limestone wells, though tests on the alluvium revealed serious problems in the accurate measurement of pumping rates.

The next, and most promising, source of pump test data was the availability of a Davey Rotary drilling rig operated by the Project, with the capability of drilling large diameter boreholes of up to 1000 ft. depth (limited by the amount of drill pipe available). This was moved to the Clarendon Plains at the end of 1970 and remained in the area for approximately 12 months during which time it completed 6000 ft. of drilling at five localities.

The writer considered that the first priority should have been the drilling of four large diameter exploratory holes along a section through the main area of recharge into the Plain. The holes would have had an average depth of 300 ft. with the exception of one which would have continued down to 1000 ft. in order to try and determine the total thickness of the White Limestone at this locality. Test pumping of these wells would have yielded values for transmissibility and, combined with the hydraulic gradient, this would have enabled a reasonable estimate to be made of the quantities of water flowing into the limestone aquifer beneath the plains. In addition the holes would have been so located that they could ultimately have been used either as sources of increased abstraction or as replacements for salinity-affected wells in the south. Only on completion of this first phase would the rig have moved south, into the plains area proper, where it would then have been used to investigate the salinity problem probably first drilling a deep hole south of the eastwest Kemps Hill - Round Hill Fault.

Unfortunately, a decision was taken to commit the rig to drilling at different localities within the Plains area where, with one or two exceptions, it failed to produce sufficient information to justify the cost of the program. The sites recommended by the writer and those finally selected are shown on Fig. 5.13 and a description of the drilling and pump testing of the limestone aquifer is given below.

Exploratory I and Ia were drilled at Vernamfield with the former, and its associated observation hole, penetrating the limestone and the latter, also with an observation hole, stopping in the alluvium. This site is situated along the axis of the structural depression which runs northeastwards from east of Kemps Hill and almost 500 ft. of alluvial deposits and marine clays were passed through before the limestone was encountered. The initial purpose of this hole was to supply information in an area where little was available for the limestone aquifer, due to its considerable depth. Thus it was envisaged that, in addition to giving details about the depth to which solution had occurred in the limestone, it would enable the contour maps of both the limestone surface and the peizometric surface for that aquifer to be refined. As a significant cost in drilling is the lost time when the rig is moving between sites, it was considered economical to drill Exploratory Ia just into the alluvium and carry out a pumping test on that aquifer as well. In fact it was to be this hole which was most successful as far as test pumping goes and a value of 150,000 GPD/Ft was calculated for the transmissibility of the alluvium..

The limestone well and its observation hole were 46 ft. apart and the water in them stood at similar levels indicating that, although the observation hole did not penetrate to the same depth as the pumped well, they were in hydraulic continuity. On test pumping the well however, it was found that although the pump was discharging at 935 GPM, there was no drawdown in the observation hole. As it had not proved possible to get a tape into the pumped well there were no drawdown measurements on that hole either and thus, from the point of view of determining the aquifer characteristics, the test was a failure. It had, however, raised interesting points regarding the hydraulics of the limestone in this locality and thus an artificial recharge experiment was set up to investigate the relationship between the two limestone holes.

As pumping tests were scheduled for the alluvial hole (Exp. 1A) it was decided to combine the two tests by discharging the water into a tank and then allowing it to flow by gravity into the limestone well. This arrangement allowed the pumping rate to be measured in the usual way, by means of a manometer and orifice plate. The test was carried at a constant discharge of 768 GPM for five days and an automatic water level recorder was maintained on the limestone observation hole in order to monitor any effect. Prior to the start of the test there appeared to be a slight rise in regional water levels as can be seen from the chart (Fig. 5.14) but the artificial recharge did not increase this in any way and, in fact, before the completion of the test, the level in the well started to fall. After the alluvial well had reached equilibrium, and before completion of the test, an additional experiment was carried in that the pump was shut off and then restarted at a rate of 1000 GPM for 30 minutes in the hope that some response would be generated in the limestone observation hole. This again proved negative and thus it would seem that there is little direct hydraulic connection between the two limestone holes at Vernamfield though, interestingly, they have similar water levels and appear to follow the same trend over longer periods of observation.

It had not proved possible to monitor water levels in the recharge well during pumping, due to the falling water, but after the pump had been switched off the following measurements were obtained, indicating that a high cone of recharge had built up.

Time in Minutes since Pump Stopped	Depth to Water in Feet
5	59'
10	68'
20	95'
30	96.22'
Original Static Water Level	96.46

In order to remove doubt about the possibility of the observation hole not being in proper contact with the aquifer a slug injection test was carried out. 800 imperial gallons of water were injected into the well under gravity causing a 9 ft. head to build up and this took 10 minutes to dissipate. Thus, it would seem that, once again, we must return to the theory of at least two systems within the aquifer itself, though the situation at Vernamfield could be attributed to upper and lower horizons acting independently, rather than lateral variations in the limestone.

Exploratory II and IIA were drilled at Content Village, some miles to the southeast of May Pen and the main purpose in selecting this site was to collect information about the alluvium and its possible relationship with the Rio Minho. A configuration of wells similar to that at Vernamfield was completed and test pumping of the limestone was carried out successfully with constant discharge, a step drawdown and recovery tests being completed. This data was analyzed for both the pumping and observation wells.

Exploratory III was situated at Gravel Hill, about midway down the western flank of the plain and the principal purpose in drilling at this locality was to determine the depth of solution in the limestone. Unfortunately, the Drilling Branch of the Project, who were operating the rig, did not receive a replacement core-barrel in time to use it on this hole and consequently, due to lost circulation, little information about the formation was obtained. Two observation holes were completed, however, and this enabled a successful test pumping of the limestone aquifer to be carried out.

The drilling rig moved next to the district known as Palmers Cross to the west of May Pen and here Exploratory IV was drilled to a depth of 300 ft., penetrating 230 ft. of limestone. This site was considered by the writer to be of both scientific and economic value, in that it was hoped to shed some light on the 'Lost waters of the Rio Minho' and was also in an area where the National Water Authority could, if the borehole was successful, subsequently use it for the water supply of the fast growing town of May Pen.

The selected site was in the structural depression known as Webbers Gully and, as was reported in an earlier section of this chapter, the results were very disappointing, with insufficient water being available.

The final site at which exploratory drilling was carried out by the Project in Clarendon was at Savanna

Gully, to the north of Exploratory I, and here an alluvial well was completed and a limestone hole started. The operations at this site were dogged by misfortune, however, and the deeper hole was not completed before the rig was transferred to the adjoining Rio Cobre study area. Thus, at the end of 12 months' exploratory drilling the aquifer characteristics of the limestone had only been determined at 2 localities.

It is not the aim of the writer to examine the economics of groundwater investigations in this thesis but the experiences of the Project in the Clarendon study must cast doubts on the cost effectiveness of organizations such as the F.A.O. operating their own large drilling rigs. If the work is put out on contract to an independent drilling company, then financial pressure can be brought to bear if the results are not satisfactory.

It will be shown in later chapters that the paucity of transmissibility or permeability data is not in itself a serious deficiency. The fact that some values were obtained enabled an estimate to be made of regional averages which could then be used as a basis for the adjustment of the groundwater model. Further discussion of aquifer characteristics is given in Chapter 7 where the input parameters of the model are discussed.

5.3.8 Water Level Fluctuations

During the period 1956 - 59, when the groundwater branch of the Geological Survey Department was active in the Clarendon Plains, water level measurements were taken on a number of wells which penetrated the limestone and from these Versey and Prescott produced a groundwater contour map, see Fig. 5.15. On only two of these wells, Belle Plain (E 4394 N 3906) and Denbigh Crawle (E 4494 N 3919) however, were measurements maintained after this time, though fortunately these are situated at the back of the plains and are therefore in a good position to reflect overall water level trends in the basin.

In 1967 the Project established a monthly measuring programme covering some 65 wells, of which nearly half penetrated the limestone, though many of these were pumping wells which could not be relied on to give an accurate indication of changes in static water level. Thus, when the writer became involved in the study, additional wells were added to the programme, either through the drilling of small diameter coreholes or the commissioning of abandoned pumping wells, until the position was reached where 26 pumping wells could be dropped from the network and still leave 74 index wells of which 36 reflected water levels in the limestone.

Prior to 1956 few water levels were taken, other than at the time of drilling, and these are of doubtful accuracy. Unfortunately, by 1956 the basin was already extensively developed as a source of groundwater and, consequently, the map produced by Versey and Prescott does not reflect natural conditions of the area or assist in evaluating the impact of abstraction of groundwater on the limestone. One factor which does give some indication of long term trends up to this time, however, is the depths of the old hand-dug wells which occur in the area. These were, by necessity, dug to just below the water table and, in times of drought, deepened until water was struck again. Thus the fact that many of these had gone dry and had been deepened by drilling during the period from the late 1930's through to the fifties, suggests that the increase in groundwater abstraction had been accompanied by a decline in water levels in the limestone aquifer. The evidence is so vague, however, that it does not allow a comparison to be made between recharge, abstraction and water levels.

The earliest record that shows the relationship between rainfall and water table fluctuations is a graph which was found in the files of the Geological Survey Department. This refers to a borehole which was drilled by a bauxite company at Kendal, in the Manchester Highlands (E 380 N 430) and in which water level measurements were taken from September 1945 to December 1948. Weekly rainfall totals for the same period from a nearby station are plotted (Fig. 5.8) and it can be seen that high rainfall is usually followed by a rise in the water table within 1 to 2 weeks. The total variation in elevation of water level is approximately 350 ft.

It would appear from a comparison of the 1956 map and that produced by the writer that, at least in certain areas, water levels were lower at the earlier date. This particularly applies to the area to the east of the Rio Minho where the 20 ft. contour does not even appear. Unfortunately, the circumstances under which this data was collected are not known, and the number of wells which were pumping at the time could be considerably different from the conditions in November 1970. Significantly, however, the recharge as derived from the catchment model was slightly below average for 1956 and above for 1970.

Although water levels over a long time period are restricted to wells in fairly close proximity, they do provide important information about fluctuations in water table and changes in storage in the limestone. In Fig. 5.16 the hydrographs for the two wells have been plotted for the period 1959 to 1971 and it can be seen that there was an overall fall in water levels up to 1968 when the wells went dry.

In order to estimate how quickly the aquifer in this area responds to the effect of rainfall, the monthly totals for a rainfall station near to the Belle Plain and Denbigh Crawle wells were plotted on the same graph (Fig. 5.16) and it can be seen that above average rainfall occurring during a period when groundwater levels were falling would produce, in monthly terms, an immediate response by the water table. The decline in water levels stops and, by the time that the next month's well measurements are taken, the water table is seen to have risen and to continue with its upward trend for up to 3 months, depending on the intensity of rainfall during that period.

It is obvious that effective rainfall in any given month is dependent on the preceding months and thus a comparison of water levels in the wells and the recharge for subcatchment 4, as derived from the water balance model, was attempted. From Fig. 5.17 it can be seen that a very good correlation exists between these two parameters and that in periods such as the first half of 1961, when some rainfall occurred in every month, the water table fell steadily because virtually none of this precipitation reached the groundwater body. On the same figure, the annual recharge to catchment 4 has been plotted and the direct, and albeit expected, relationship is apparent. In years when recharge fell below the mean, then the water levels started or continued to fall, but in years with above average rainfall, such as 1960, 1963, 1969, and 1970 the water table, and hence the volume of water in storage, rose.

The long records at Belle Plain and Denbigh Crawle enabled synthetic recession curves to be build up for these two wells, Fig. 5.18. These were compiled by plotting falling water levels for periods when little or no recharge occurred and then superimposing the graphs with a common horizontal time axis. The data points were seen to lie on a straight line over most of the range without the expected curving at the lower end as the rate of fall declined. As the head in the aquifer falls, according to Darcy's law the rate of flow in the aquifer will decrease and, logically, this will be reflected in the hydrograph which will show a change in gradient. At first sight, it is remarkable that the synthetic recession curves for these wells should be so straight over most of their range, but this can be explained by the fact that the wells are not deep enough to cover the lower limits of water table fluctuation in the area and did in fact go dry in 1967 and 1968.

Although long term records are not available for other wells in the area, thus precluding the construction of similar curves, it was possible to compare natural recession curves at Arcadia (E 4061 N 4130) and at Kendal, the latter being the borehole referred to earlier, for which some historic data is available for the period 1945 to 1948. At Arcadia, the water level fell consistently throughout 1971 although some recharge did occur in subcatchment 2 during this time. From the hydrograph shown in Fig. 5.19, it was calculated that the rate of decline of the water level was 0.14 ft/day in 1971 compared to 0.7 ft/day at Kendal during 1946. The rate at Belle plain, based on the synthetic recession curve, was 0.005 ft/day. These three values were then plotted on logarithmic graph paper against the distance of the wells from the coast and it can be seen from Fig. 5.20 that they fell on a straight line.

Looking at the area as a whole, it can be seen that the above average wet year of 1969 caused widespread recovery of water levels throughout the basin, which had suffered a drought in the previous few years, but that the relatively dry months at the start of 1970 saw a renewed decline which was only halted by the heavy rains in May of that year. In 1971, it is easy to see the difference in responses between wells which are situated in or close to areas of heavy abstraction and those which are not. Virtually all the wells show a fall in water levels from the start of the year but, in the case of those adjacent to pumping well fields, there was a recovery in June apparently due to the fact that most irrigation wells were shut down following the

May rains. In other wells, particularly those in or close to the recharge areas (i.e. Tollgate, Arcadia, Comfort, Belle Plain, Denbigh Crawle) the decline in water levels continued for several more months, with only slight rises in water levels occurring towards the end of the year. Meanwhile, in the former group of wells, significant recoveries had started in August and continued at least until the end of November. Moores and Sevens coreholes form a third category in that they also respond in the more pronounced way to the wetter months although they are unlikely to be affected by pumping wells. In their case it is the effect of increased flows in the Rio Minho which lead to a rise in recharge from that source. Curatoe Hill appears to be linked to the same system as it showed similar recovery patterns.

Thus it can be seen that in the southern parts of the plains the effect of pumping wells on limestone water levels is of major importance whereas it appears to have little influence on storage in the recharge area. It is interesting to note that the regional effect of pumping within the plains itself is also limited, in that, wells such as Ebony Park which are not in close proximity to zones of major abstraction, are not significantly affected.

5.4 Hydraulics of the Two Aquifer Systems

The Clarendon Basin is particularly complicated in that it involves two separate river drainage systems and two distinct aquifers and the purpose of this section is to summarize the hydrogical relationship between the latter. It has been shown that the two aquifers are not in direct hydraulic continuity but that the tight impermeable clays in the alluvium prohibit or severely restrict flow between the two, with the water level in the alluvium always being higher than that in the limestone. Consequently, any flow that is taking place between the two aquifers, despite the presence of the relatively impermeable layers, must be from the alluvium into the limestone.

Fig. 5.21 is a schematic representation of the two aquifer systems pictorially depicting their hydraulic relationship. It may be regarded as a flow diagram of the water movement.

That proportion of the rain falling on the highlands which is not lost by evapotranspiration is likely to percolate downwards to the water table, although a small proportion may be lost by direct runoff, particularly after heavy rains (3% according to the catchment model). On reaching the water table it will cause a rise in water level as it is taken into storage. Due to the relatively low coefficients of storage in these higher areas, the water level changes are likely to be sharp and drastic. This storage, however, is of a temporary nature and the water levels will soon start to fall as the water moves towards the plain. It should be noted that no attempt has been made in Fig. 5.21 to depict the two possible flow systems within the limestone because, although the water may move from the recharge area at two different rates, it ultimately reaches the same area of abstraction.

Some of this water will appear as springs along the foothills, but the remainder will flow into the main reservoir area and be taken into storage. From here it will flow seawards, either to be discharged by coastal springs or to be lost to sea at some point offshore.

Most of the water that is abstracted by wells is used for irrigation and is thus applied to the surface of the alluvium where it joins the rain that falls directly on that area. Both the irrigation water and the precipitation on the plains are subjected to evapotranspiration losses and direct runoff. Ideally, the irrigation would be so managed that the latter is kept to a minimum but, in practice, the runoff may be significant. The remaining water will once again infiltrate into the ground where it joins the groundwater body in the alluvial aquifer. From here it may then take one of several paths, either being pumped out by wells, flowing laterally into the river, spilling over into the limestone aquifer or finally discharging at or beyond the coastal zone and thus being lost to the system.

The proportion which is abstracted by wells will be mainly used for irrigation and will find itself back at the point in the cycle where it was first either deposited by rainfall, or discharged at the surface by pumping from limestone wells. Thus, it can be seen that a given proportion of the water may follow very diverse paths before passing out of the system, with the simplest possible route being by subsurface flow through the limestone aquifer to be discharged to the sea. However, from Fig.5.21 it can be seen that a far more complex path might be taken before the water finally passes out through this system.

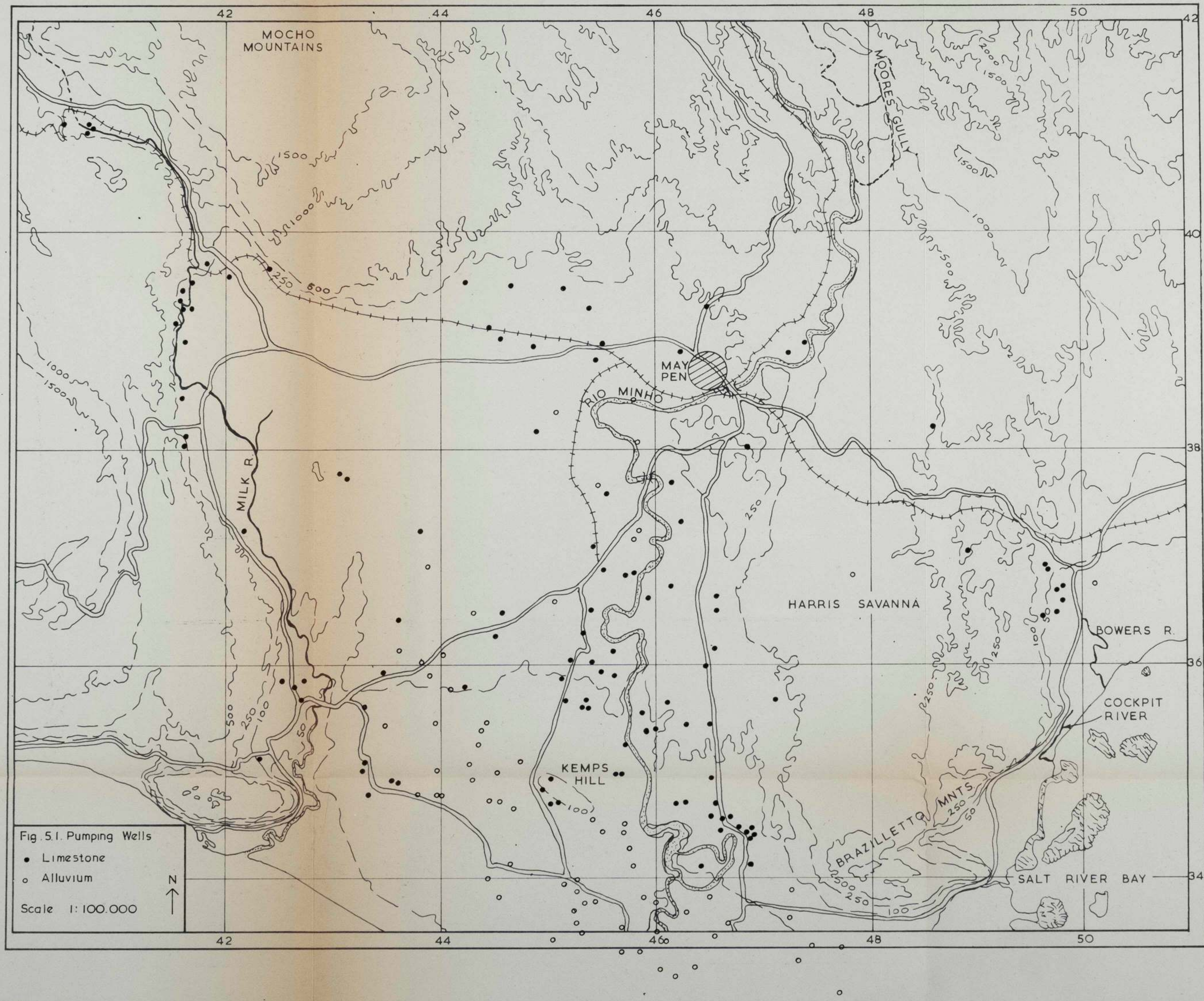


Fig. 5.1. Pumping Wells

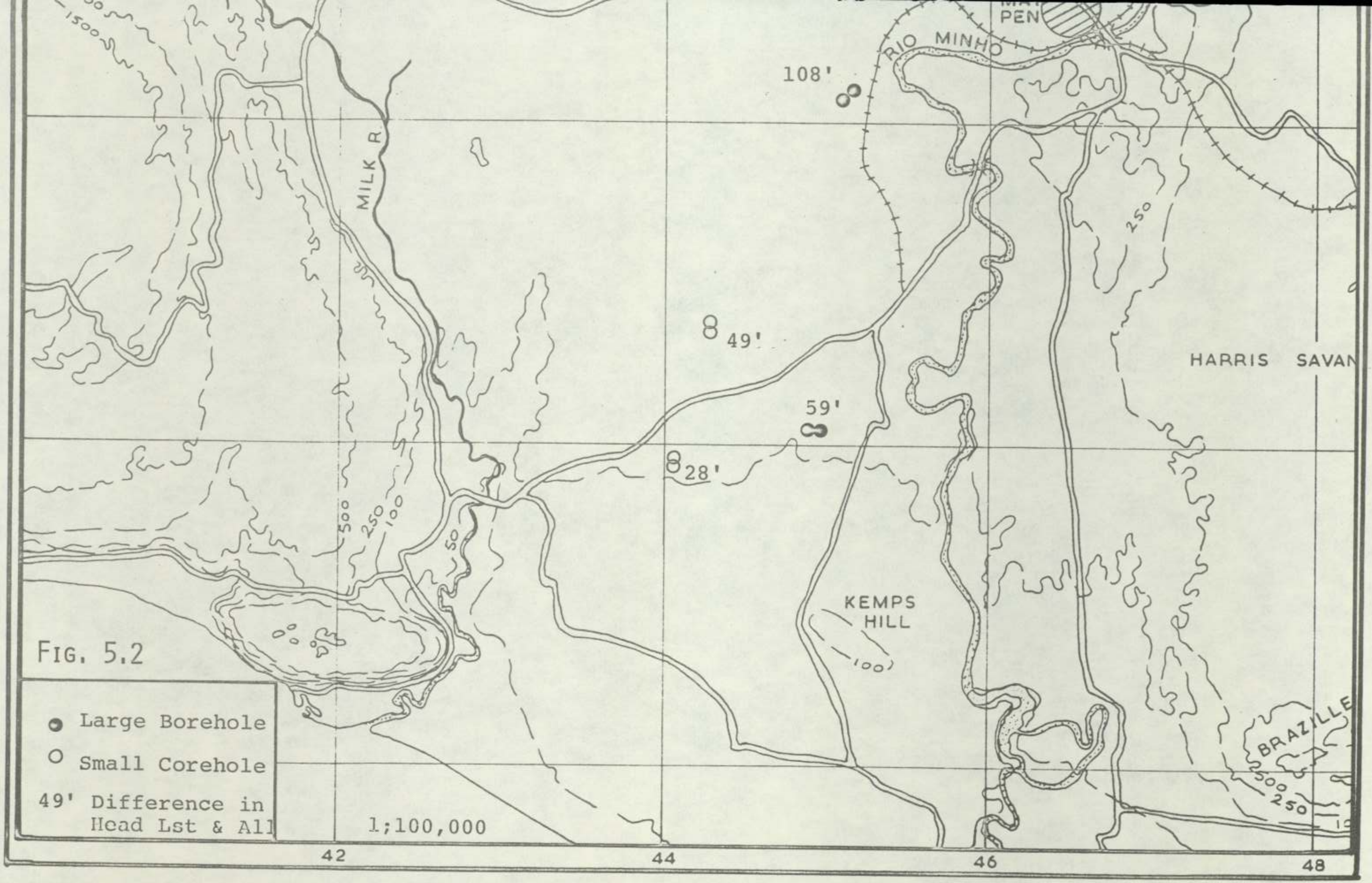


FIG. 5.2

● Large Borehole
○ Small Corehole
49' Difference in Head Lst & All
1;100,000
42
44
46
48
MILK R
RIO MINHO
PEN
HARRIS SAVAN
KEMPS HILL
BRAZILLE
108'
49'
59'
28'
1500
500
250
100
50

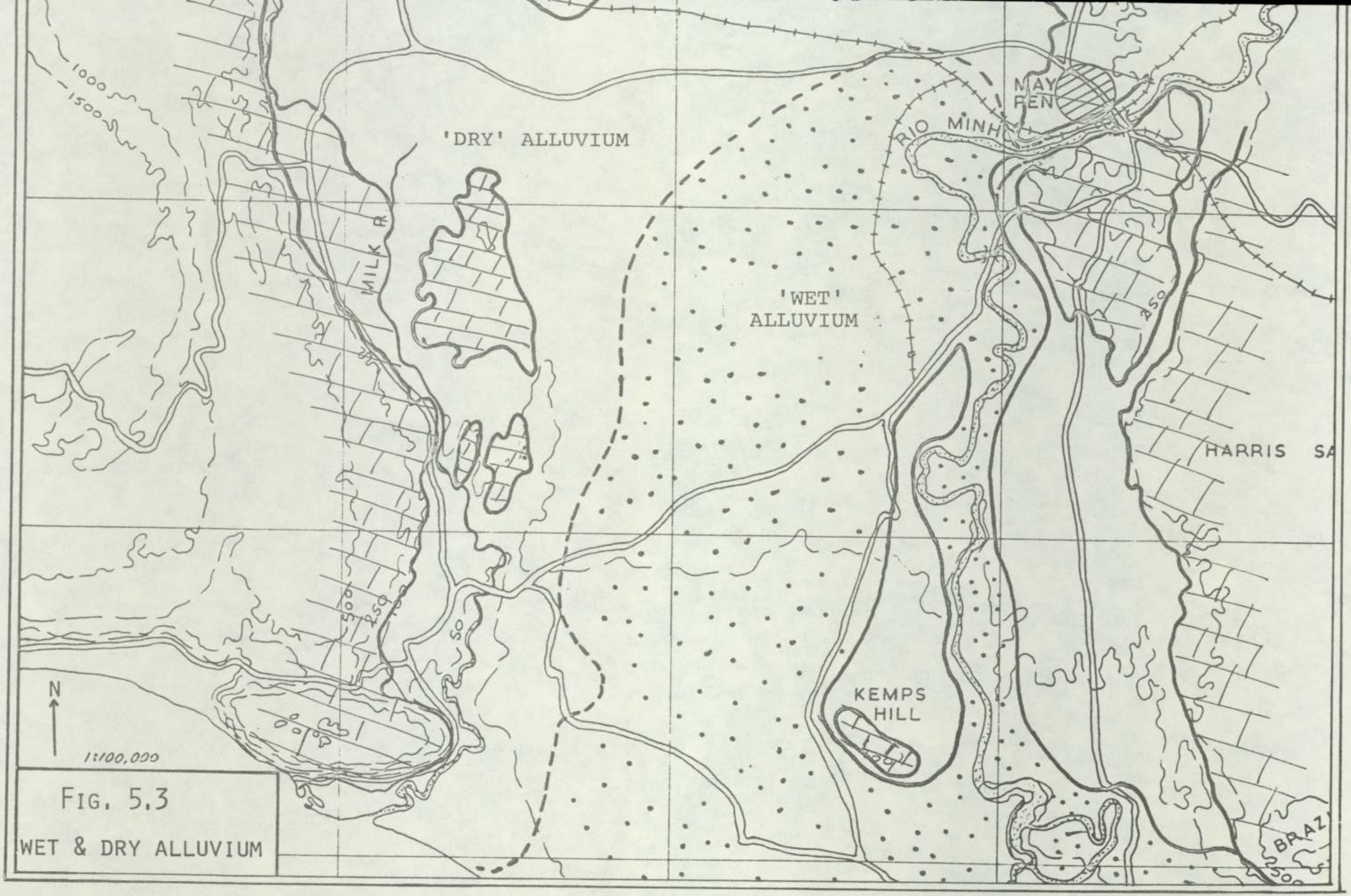
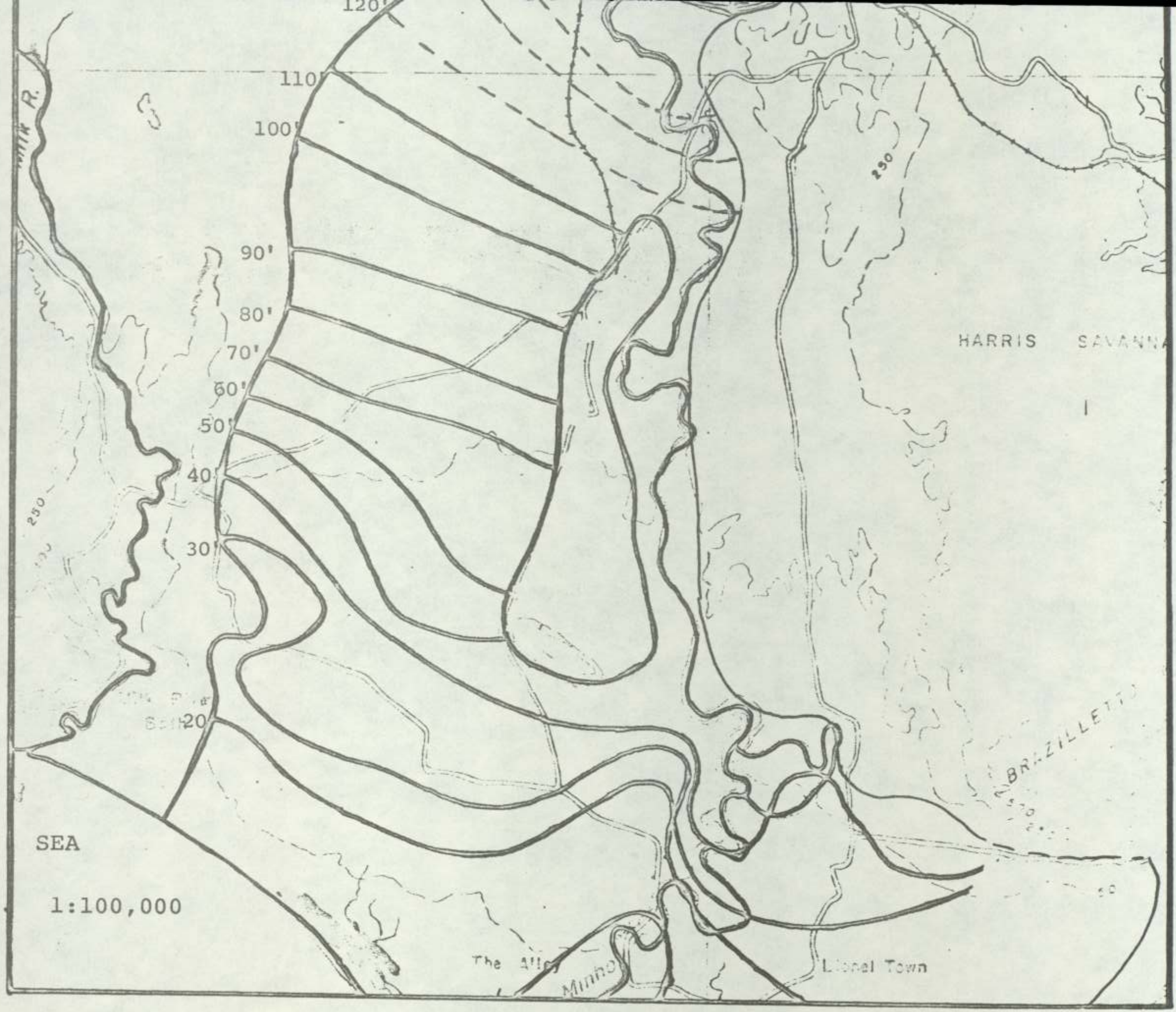


FIG. 5.3

WET & DRY ALLUVIUM



GROUNDWATER CONTOUR MAP -

ALLUVIAL AQUIFER

Elevation of Water Table
Feet A.S.L.

NOVEMBER 1970

FIG. 5.4

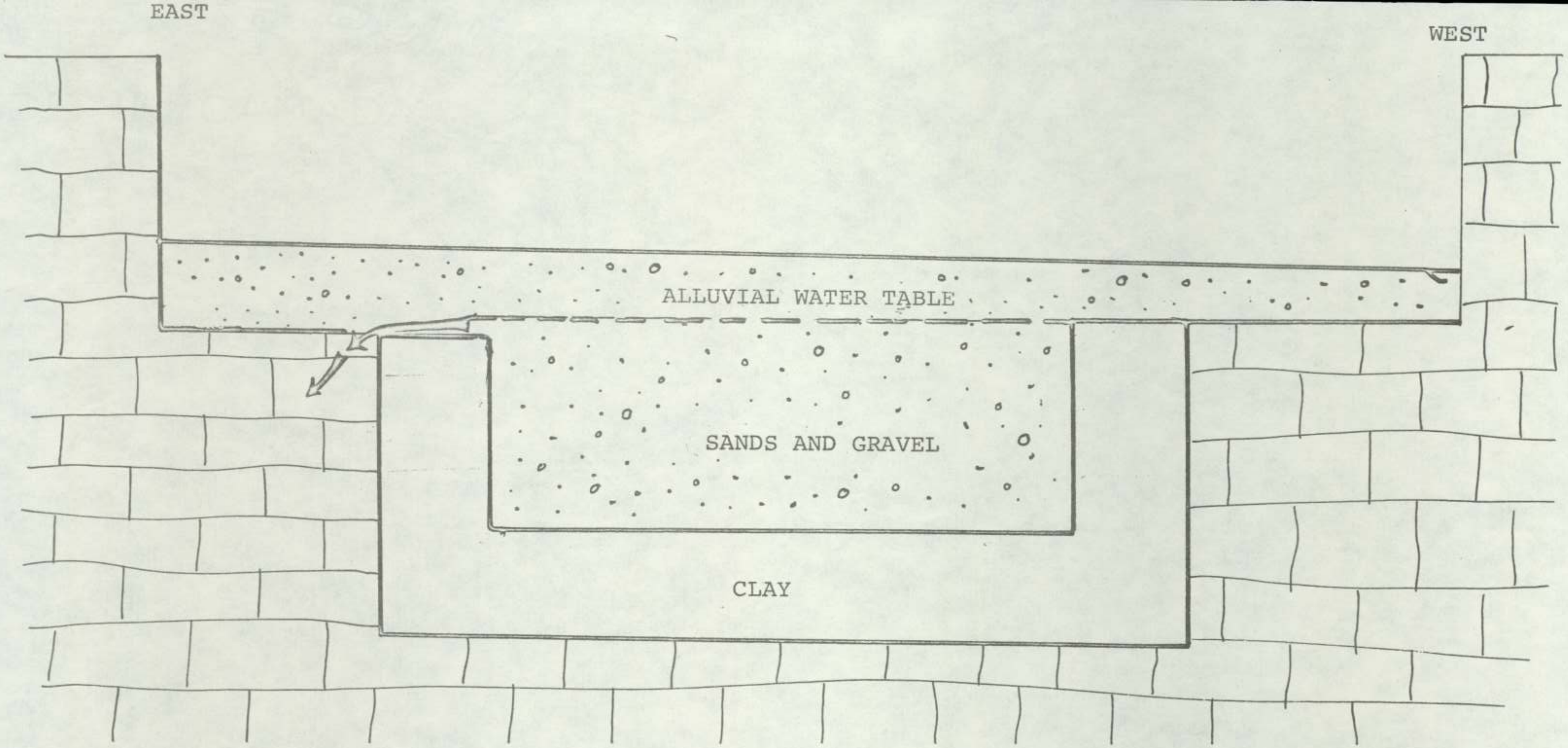


Fig. 5.5 Schematic Representation of Recharge to Limestone from Alluvium.

🟩 OUTCROP OF WHITE Lst. WITHIN BASIN BOUNDARIES

▨ AREA OF Lst. WHICH CONTRIBUTES GROUNDWATER TO TO THE BASIN ONLY IN TIMES OF HIGH RECHARGE.

— GROUNDWATER BASIN BOUNDARY

- - - - SURFACE WATER CATCHMENT BOUNDARY

SCALE 1:100,000

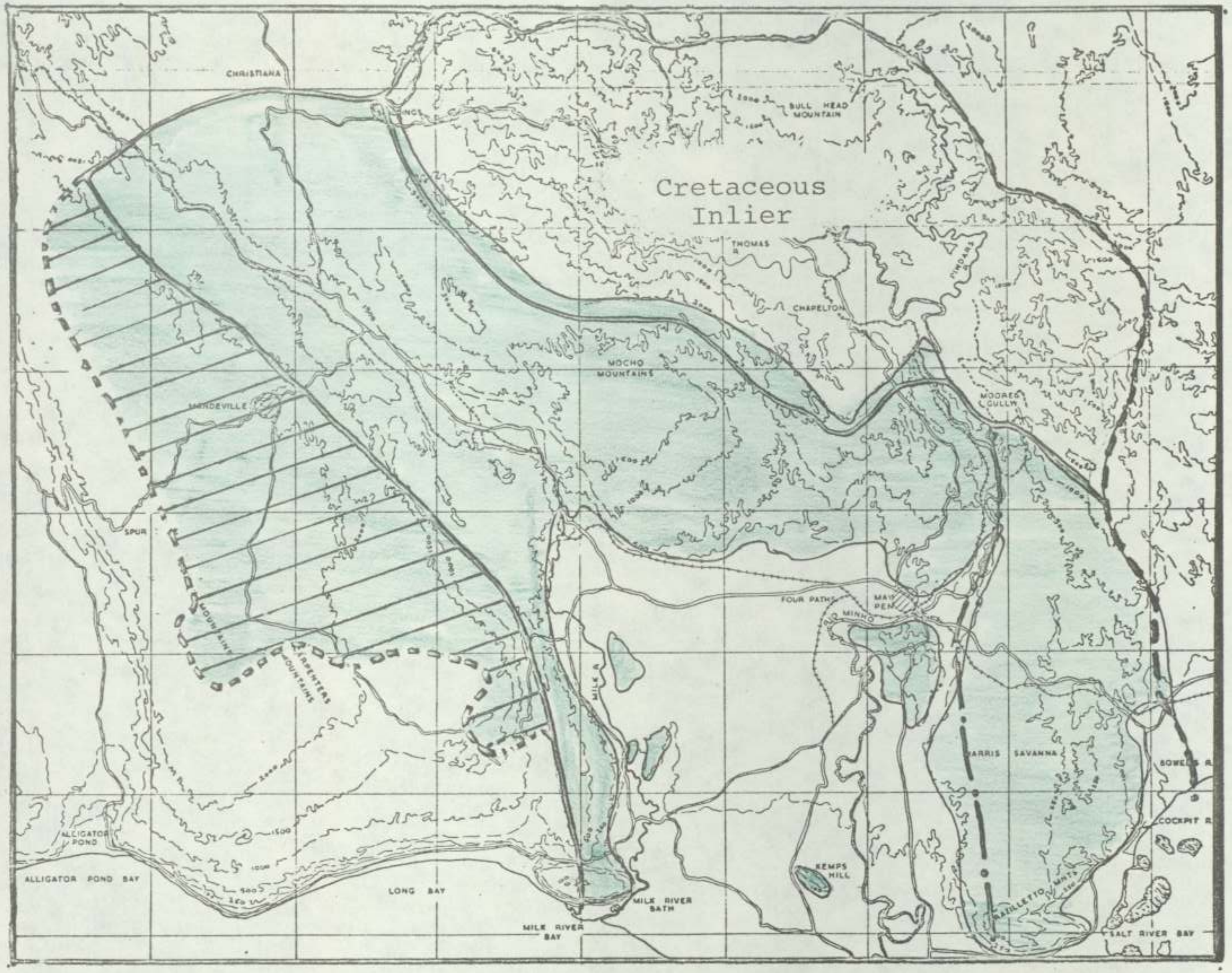


FIG. 5.6

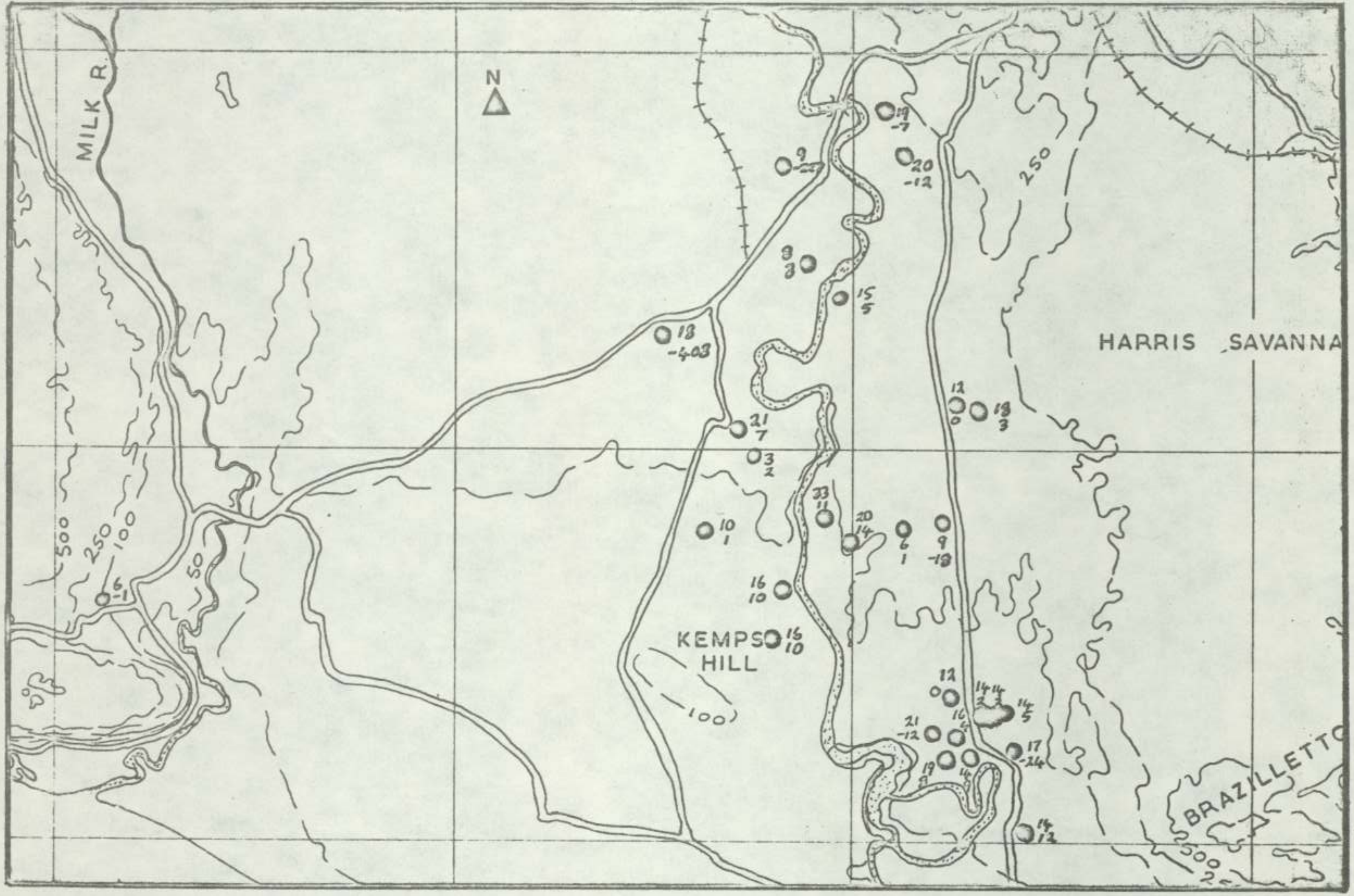


FIG. 5.7 RELATIONSHIP BETWEEN REST WATER LEVEL AND ELEVATION AT WHICH WATER WAS STRUCK (Area to North on next page.)

$\circ^{23}_{-6}$ Static Water Level (Ft. above Sea Level)
Depth at Which Water was Struck (Ft. above sea level)

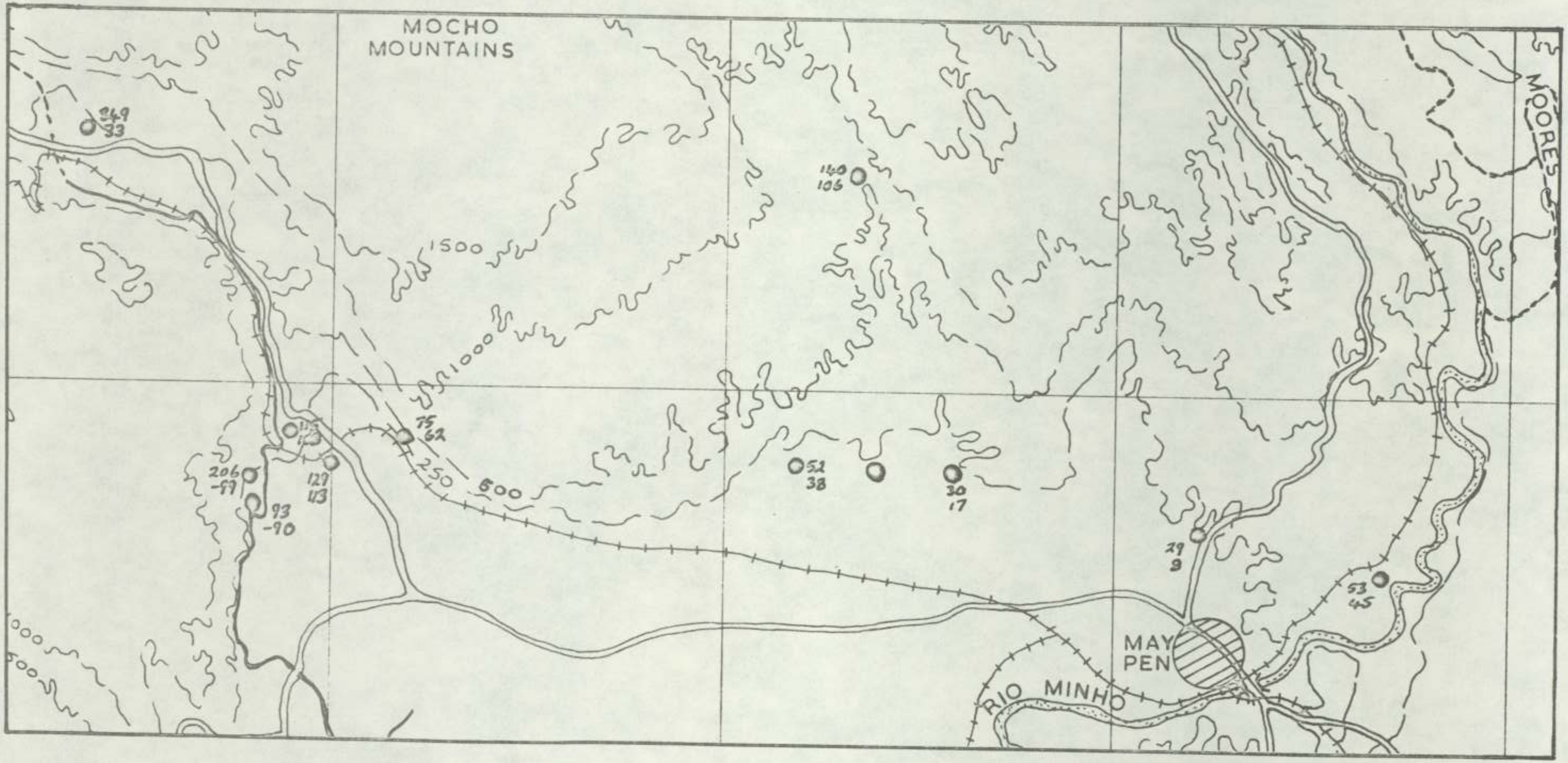


FIG. 5.7 (CONTINUED) AREA TO SOUTH IS SHOWN ON PREVIOUS PAGE)

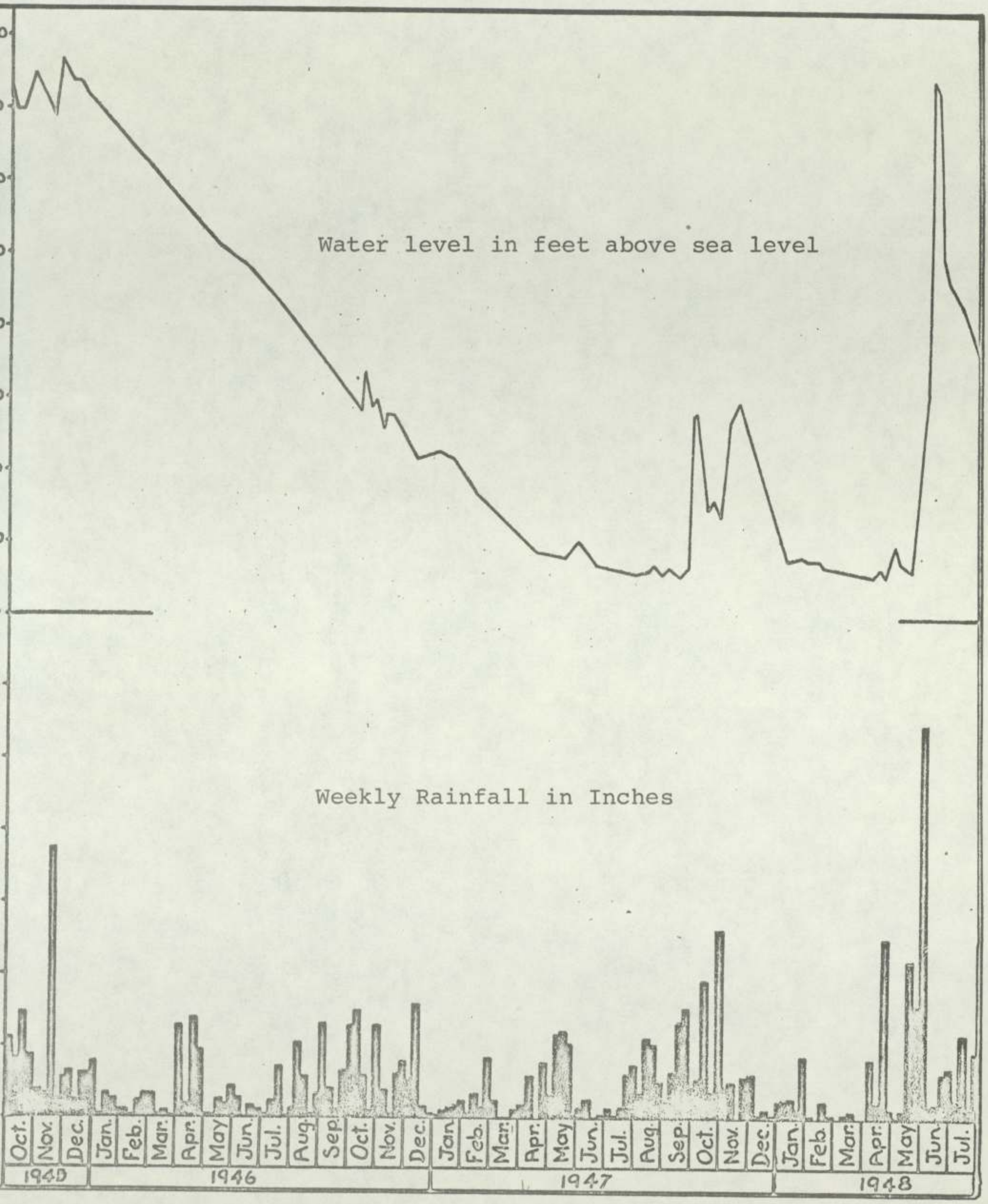


FIG. 5.8 HYDROGRAPH - KENDAL BOREHOLE

(after Geol. Survey)

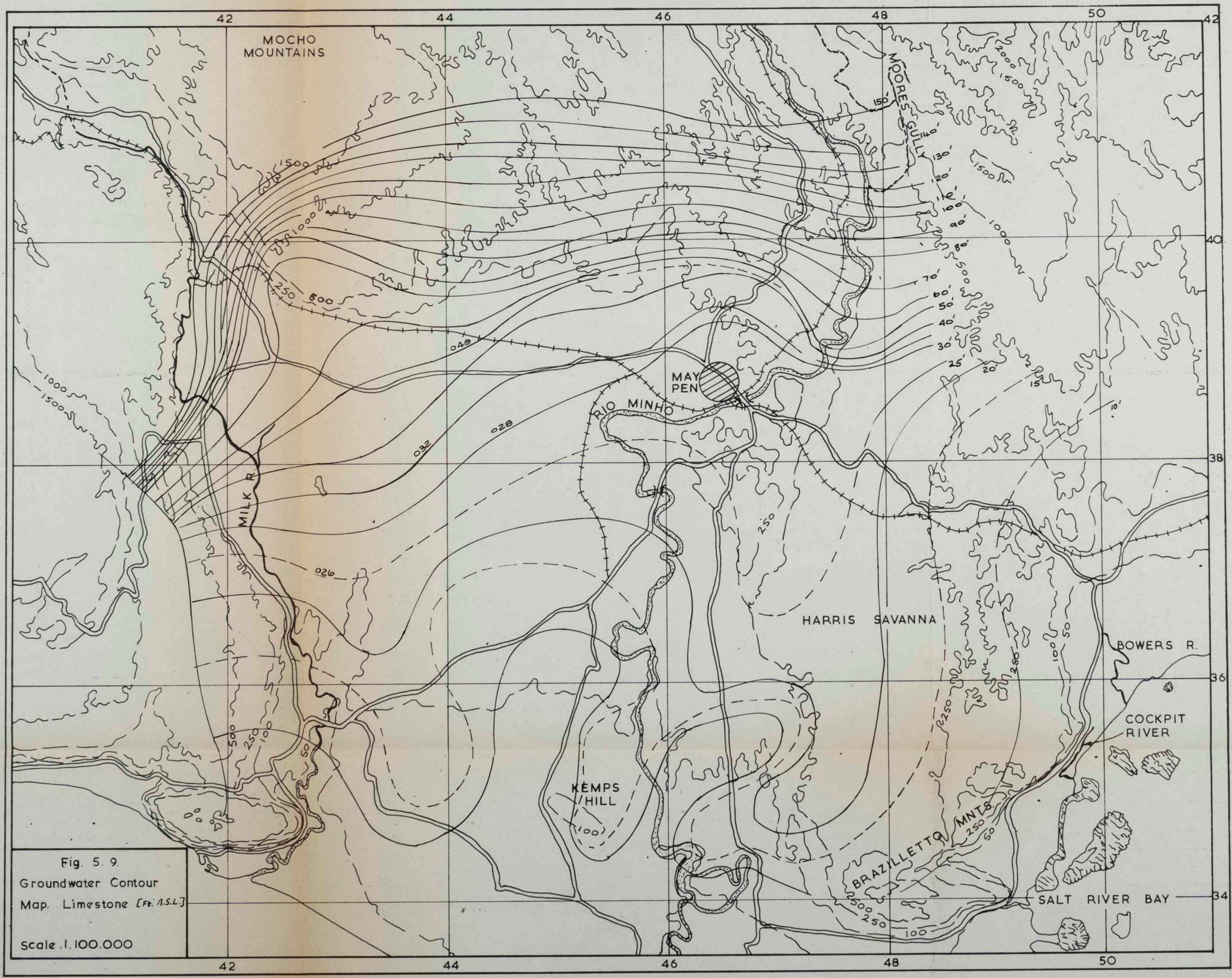


Fig. 5. 9.
Groundwater Contour
Map. Limestone [Ft. A.S.L.]

Scale .1.100.000

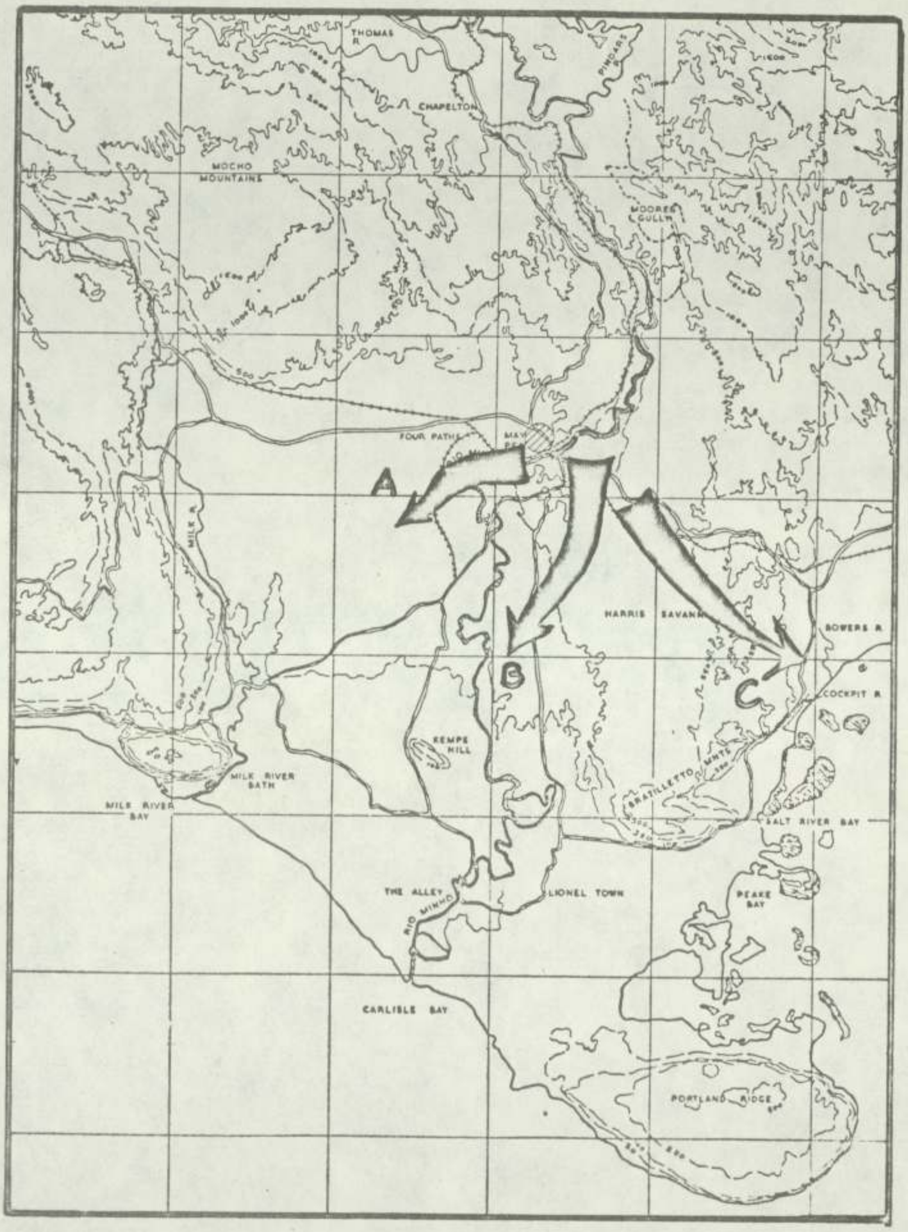


FIG. 5.10 POSSIBLE DIRECTIONS OF FLOW OF THE 'LOST WATERS OF THE RIO MINHO'.

A is in the Alluvium
B and C are in the Limestone.

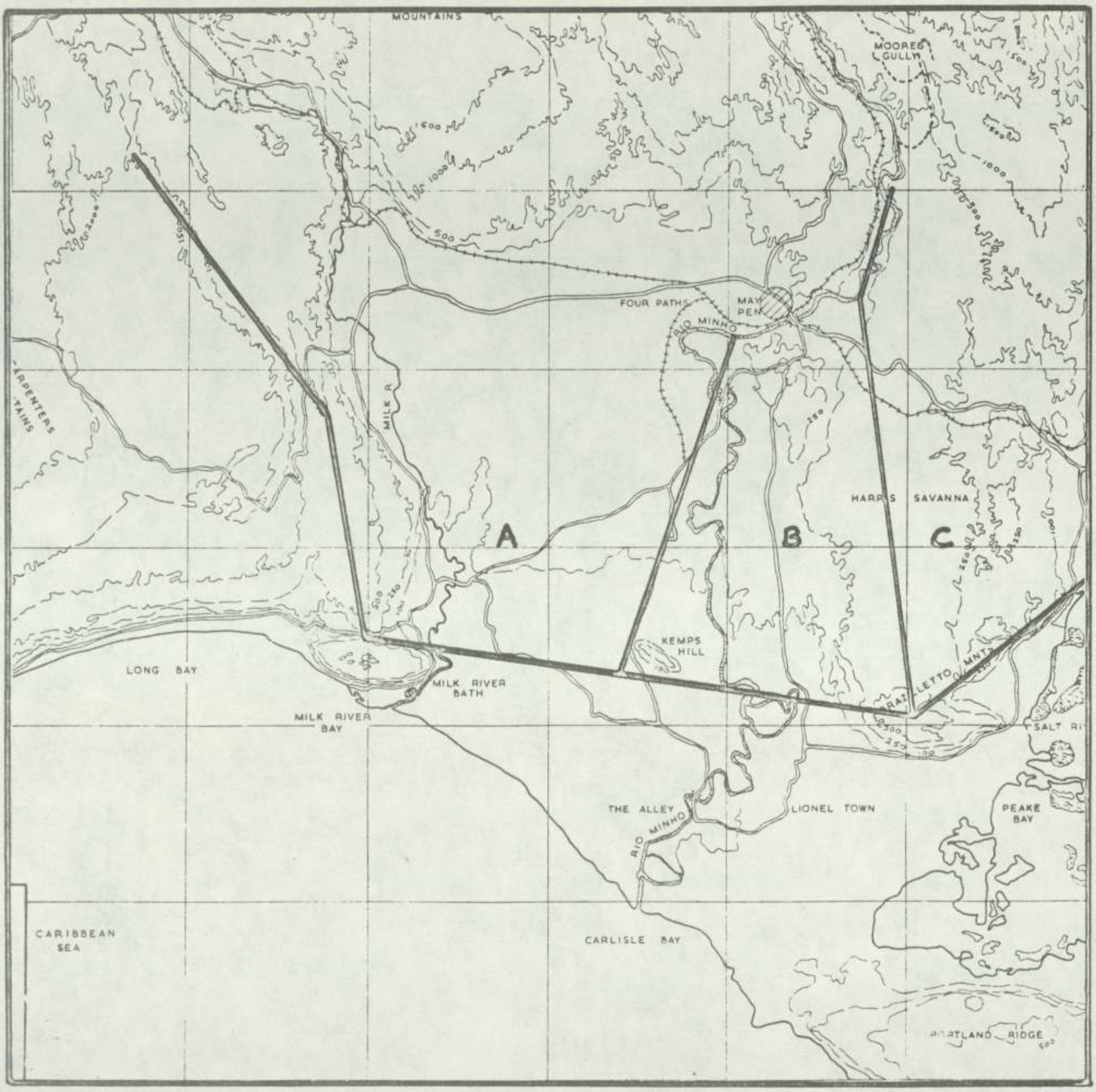


FIG. 5.11 GROUNDWATER UNITS OF THE LIMESTONE AQUIFER

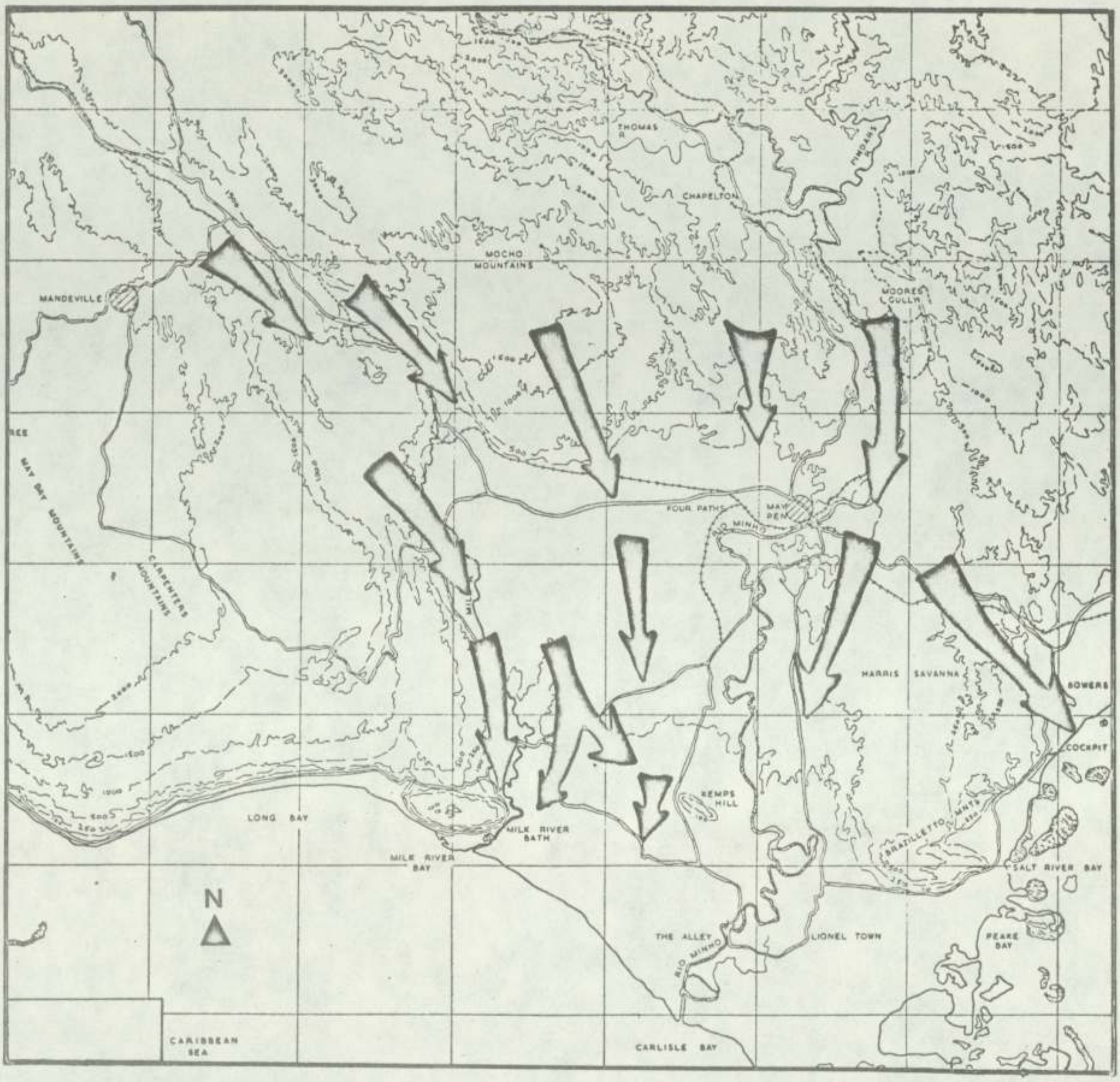


FIG. 5.12 GENERAL DIRECTIONS OF GROUNDWATER FLOW IN THE LIMESTONE AQUIFER.

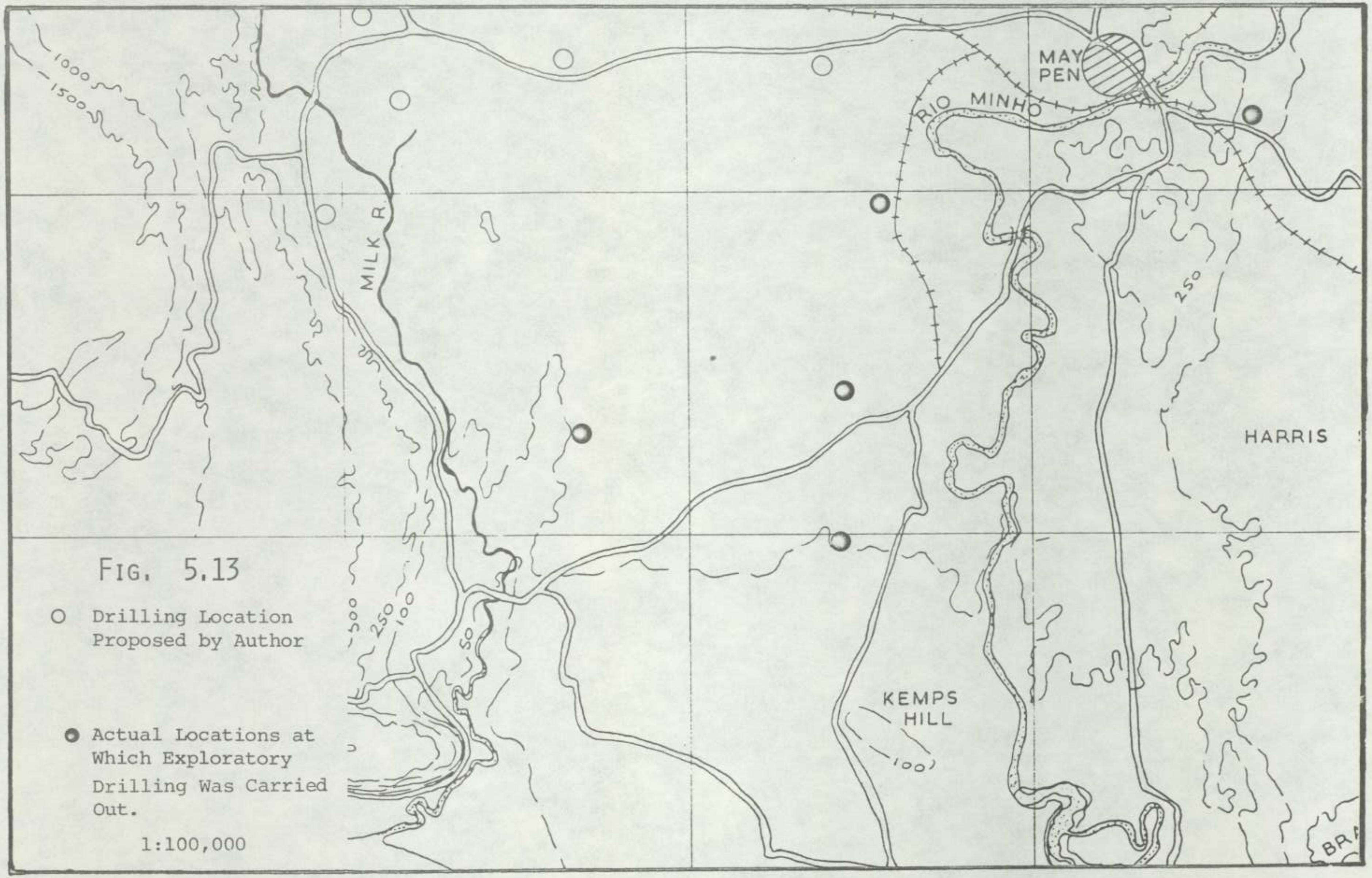
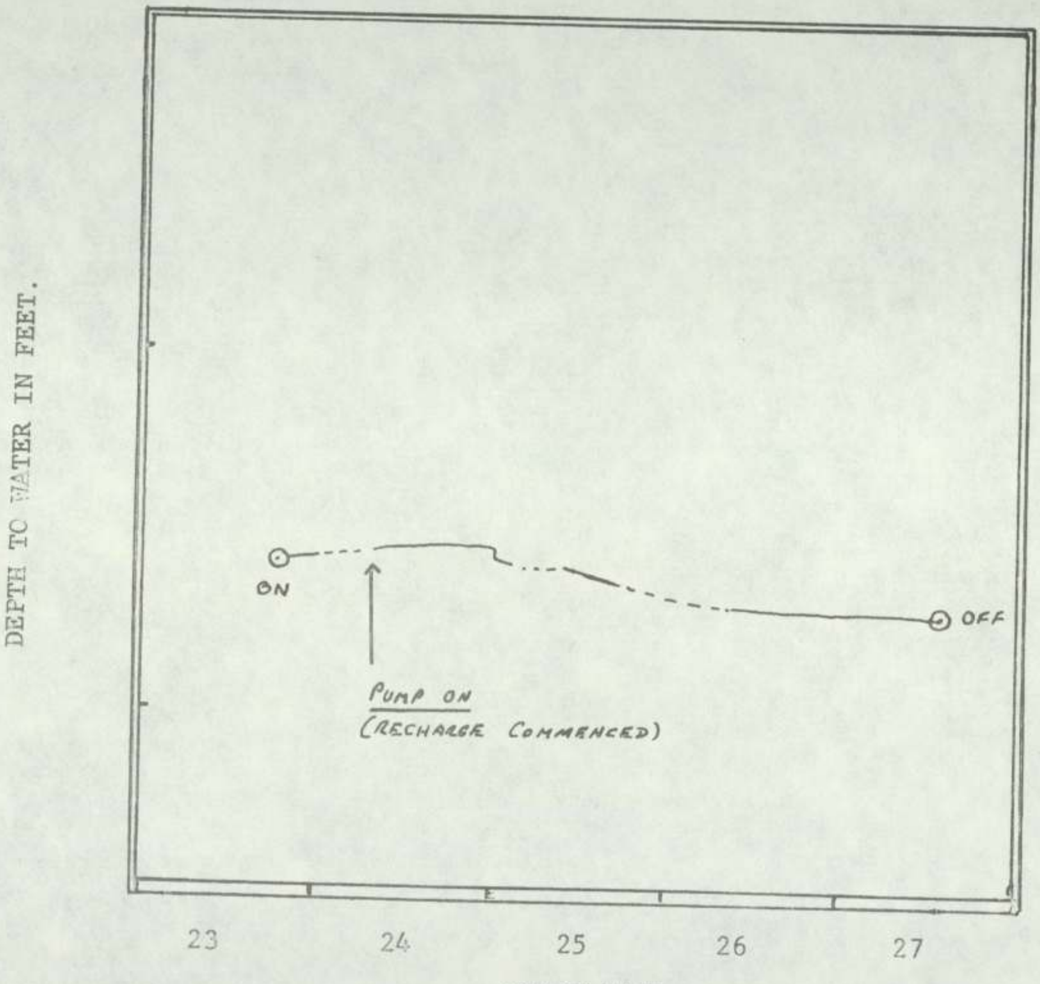


FIG. 5.13

○ Drilling Location Proposed by Author
● Actual Locations at Which Exploratory Drilling Was Carried Out.
1:100,000
MAY PEN
RIO MINHO
MILK R.
HARRIS
KEMPS HILL
BRA
1000
1500
500
250
100
50
250
100

OBSERVATION HOLE No. 1, VERNAMFIELD.



Pump switched on 08.00 on March 24th. at 768 GPM.

FIG. 5.14 HYDROGRAPH DURING RECHARGE EXPT.

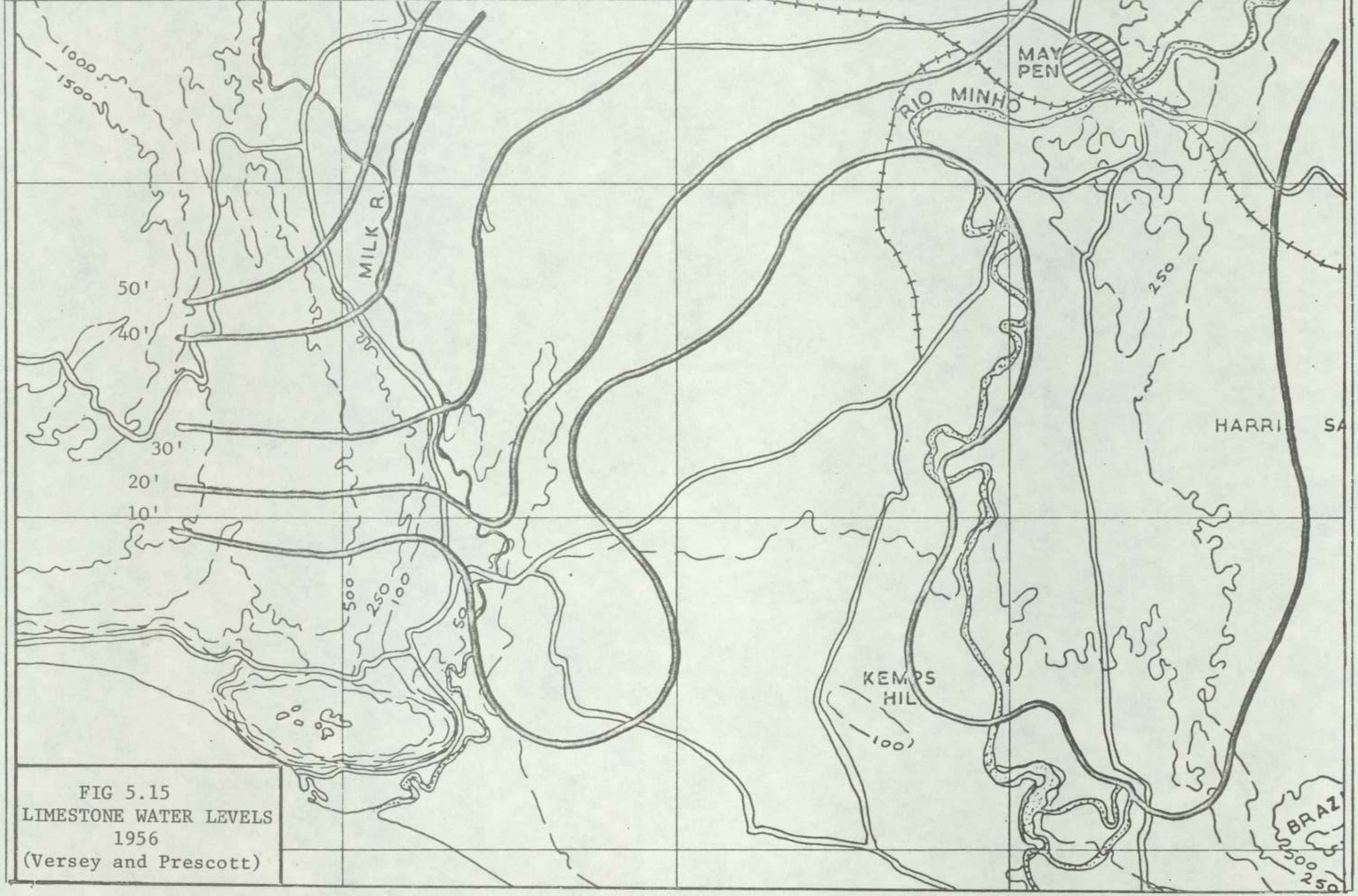
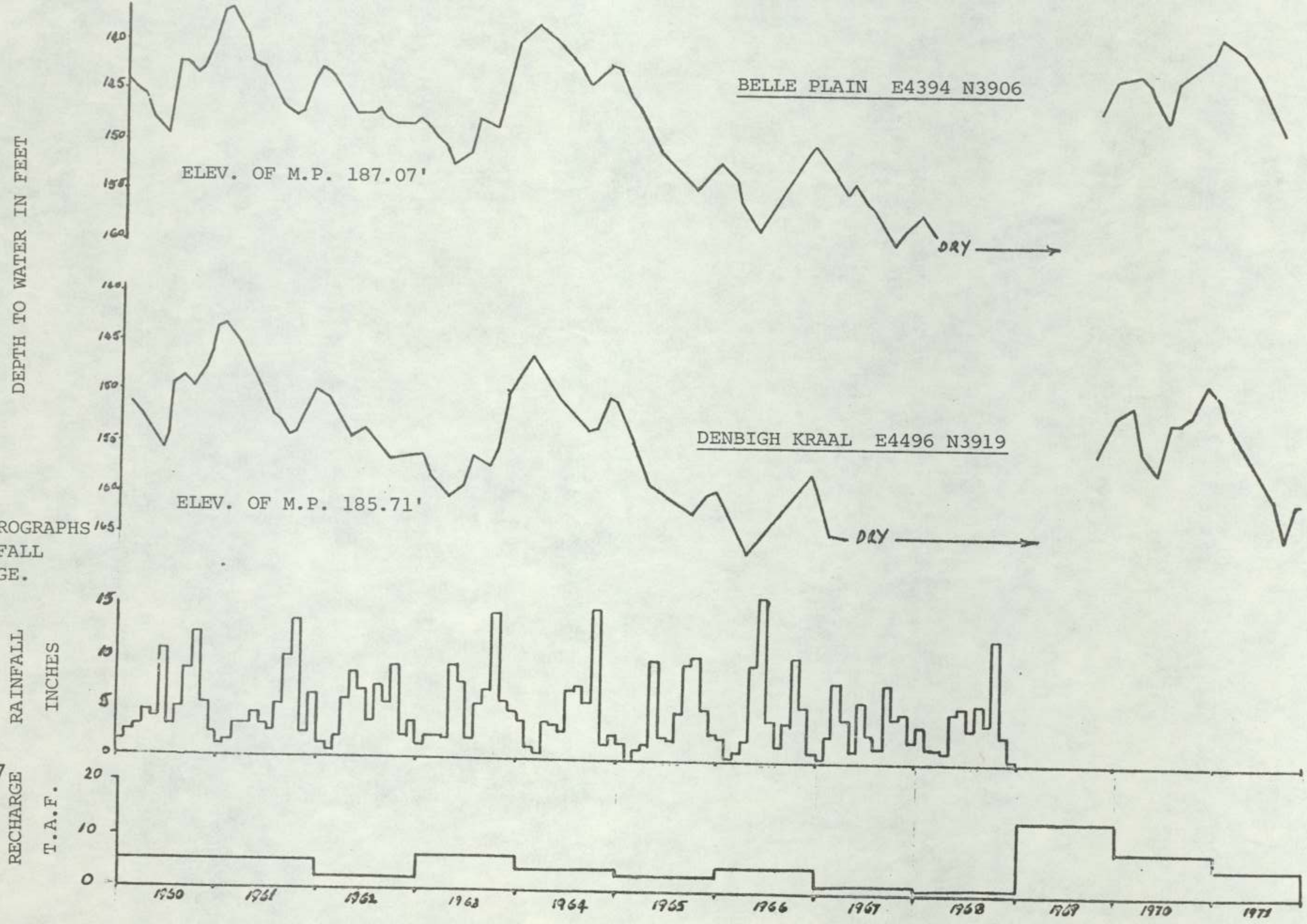


FIG 5.15
LIMESTONE WATER LEVELS
1956
(Versey and Prescott)



COMPARISON OF HYDROGRAPHS WITH MONTHLY RAINFALL AND ANNUAL RECHARGE.

FIGS. 5.16 & 17

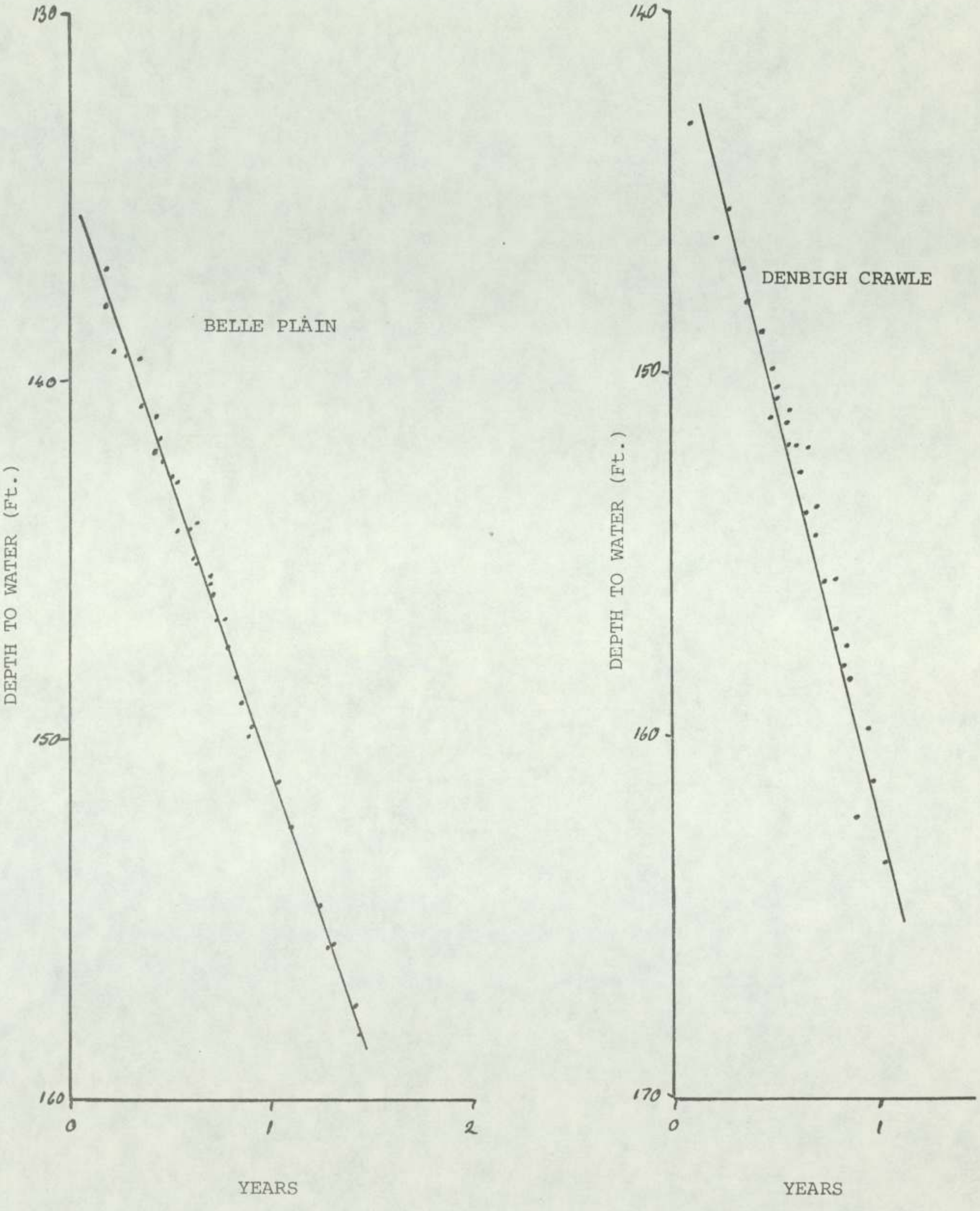


FIG. 5.18 SYNTHETIC RECESSION HYDROGRAPHS.

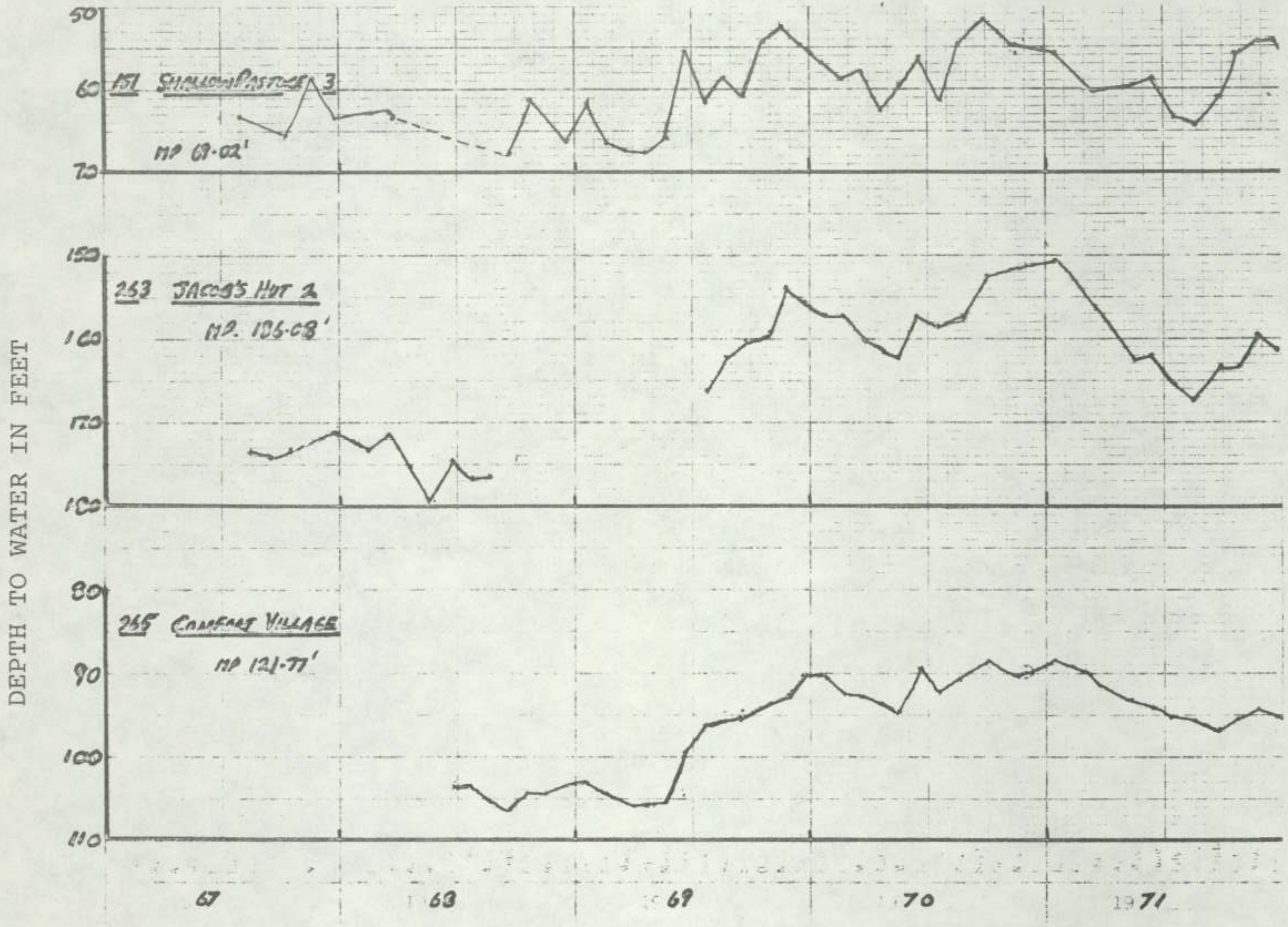


Fig. 5.19 Well Hydrographs (Elevation of Measuring Point Ft. ASL)

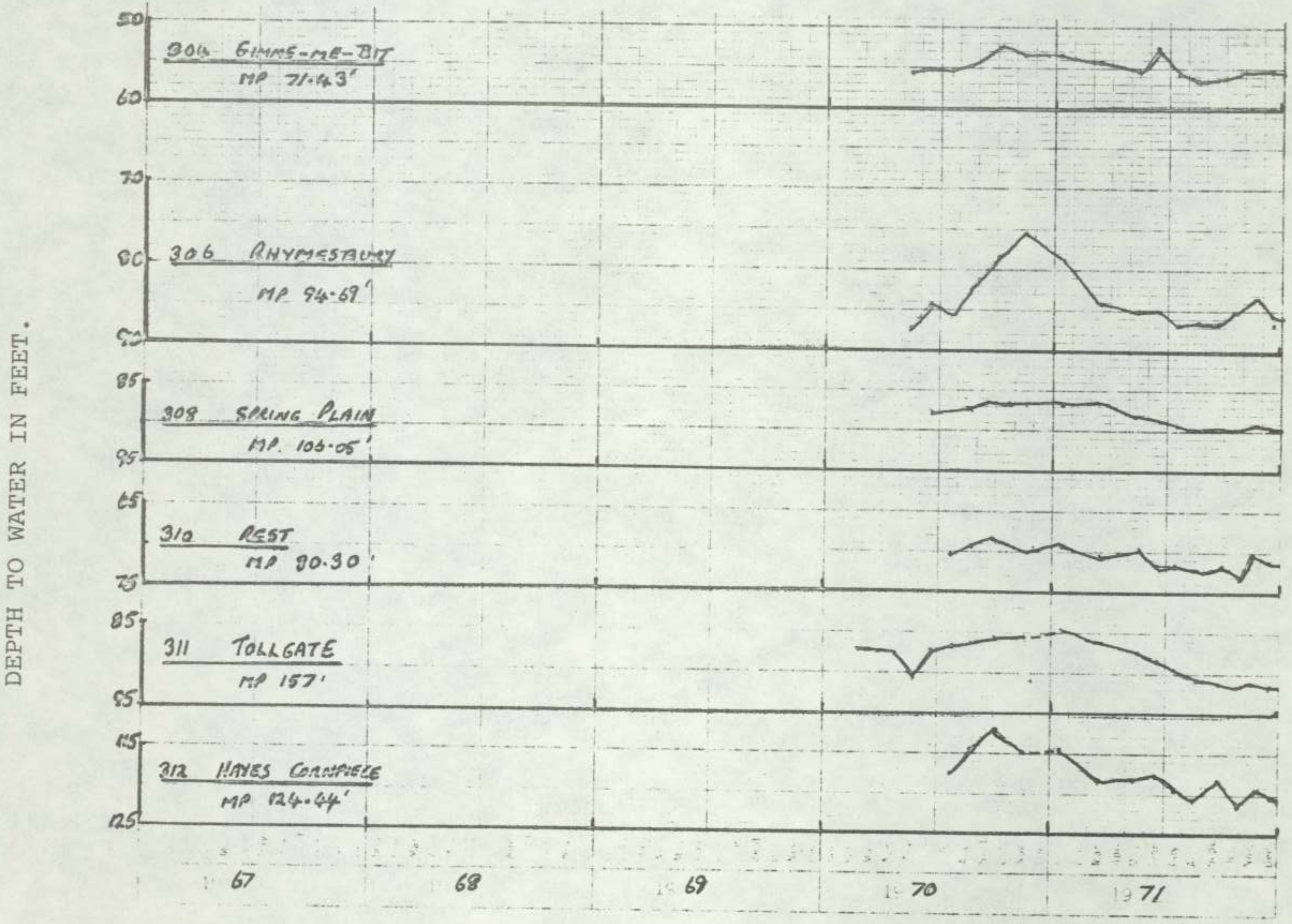

DEPTH TO WATER IN FEET.
50
60
70
80
90
85
95
65
75
85
95
115
125
304 GIMME-ME-BIT
MP 71·43'
306 RHYMESBURY
MP 94·69'
308 SPRING PLAIN
MP. 105·05'
310 REST
MP 80·30'
311 TOLLGATE
MP 157'
312 HAYES CORNFIELD
MP 124·44'
67
68
1969
1970
1971

FIG 5.19 (CONT.)

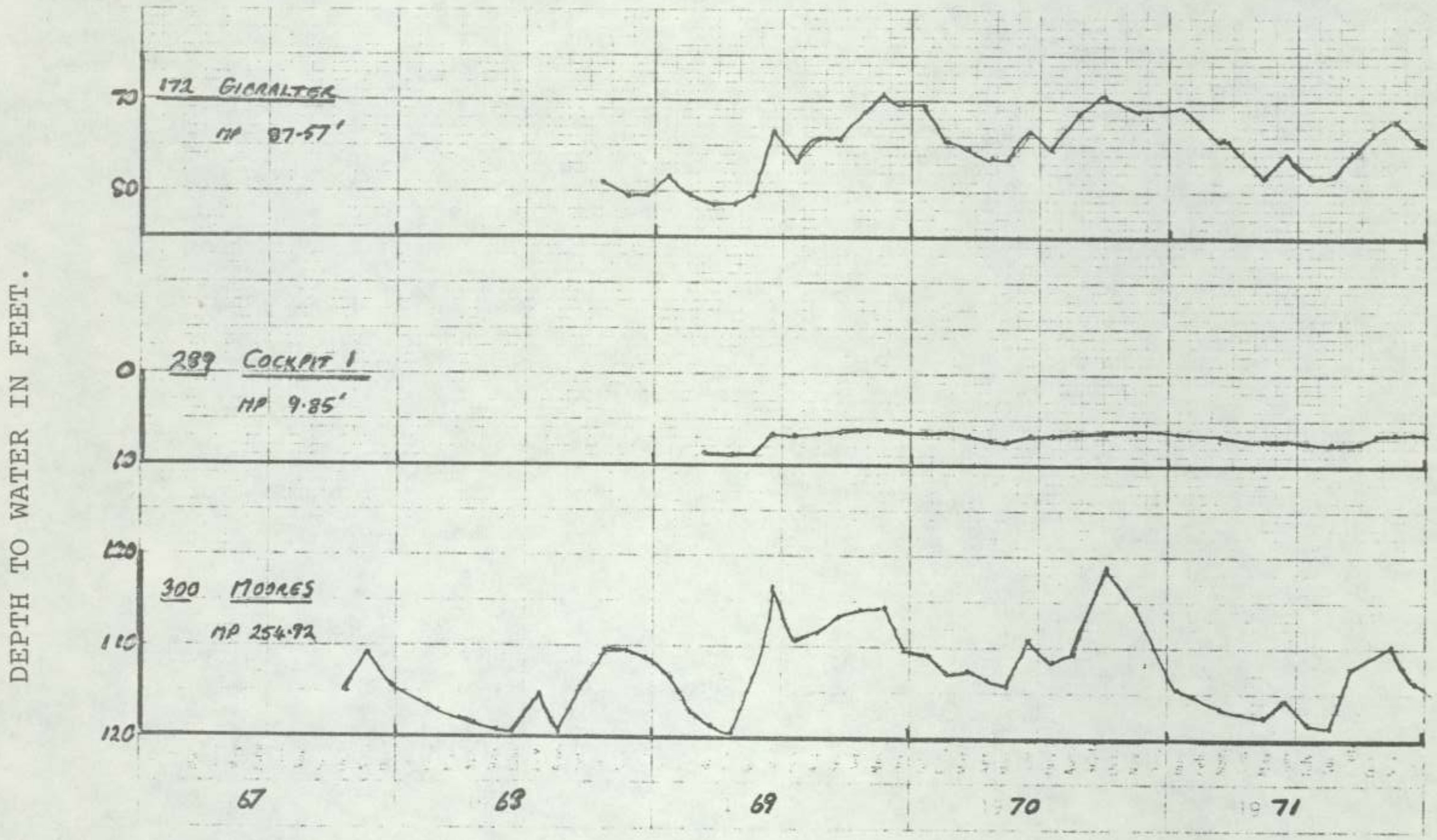
DEPTH TO WATER IN FEET.
172 GIBRALTER
MP 87.57'
70
80
289 COCKPIT I
MP 9.85'
0
10
300 MOORES
MP 254.92
100
110
120
67
68
69
70
71

FIG. 5.19 (CONT.)

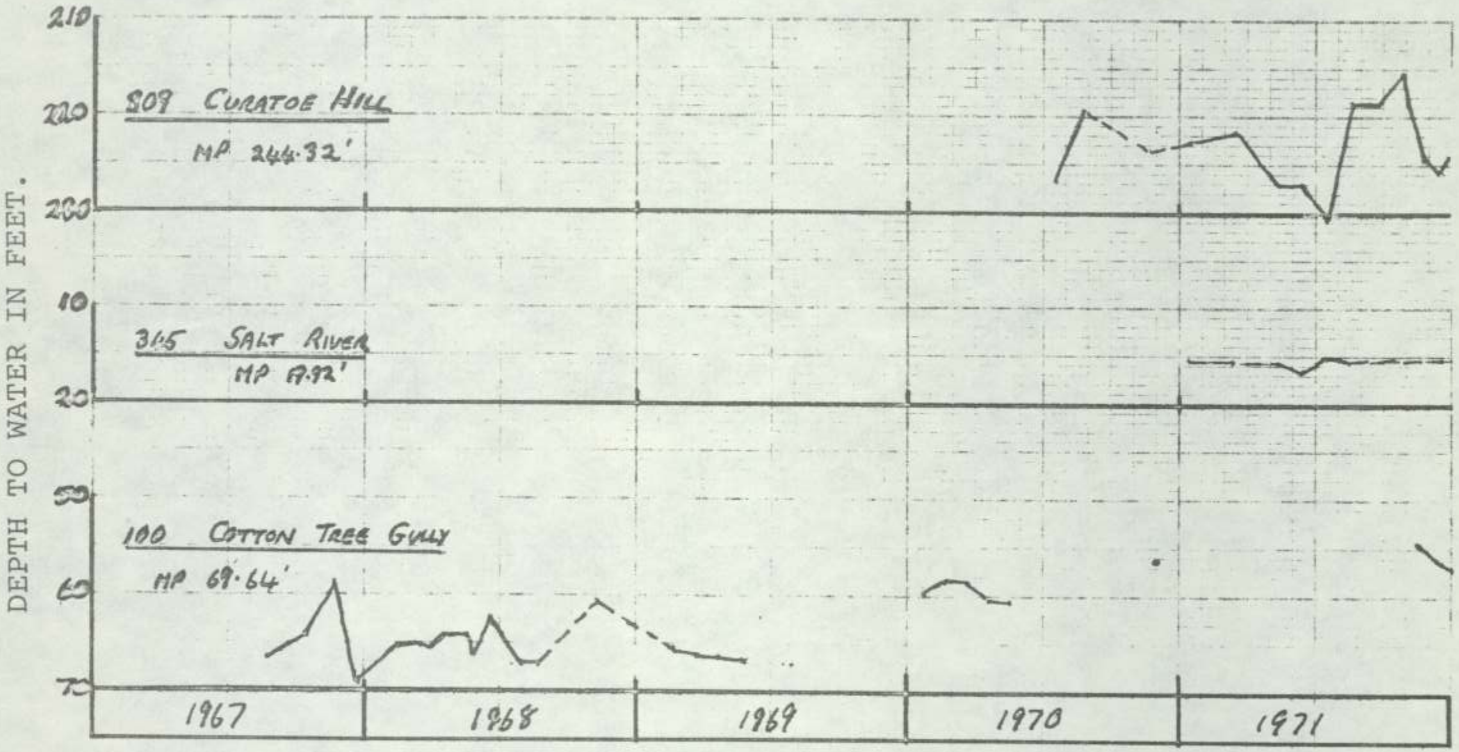

DEPTH TO WATER IN FEET.
210
220
200
10
20
50
60
70
809 CURATOE HILL
MP 244·32'
315 SALT RIVER
MP 17·92'
100 COTTON TREE GULLY
MP 69·64'
1967
1968
1969
1970
1971

FIG. 5.19 (CONT.)

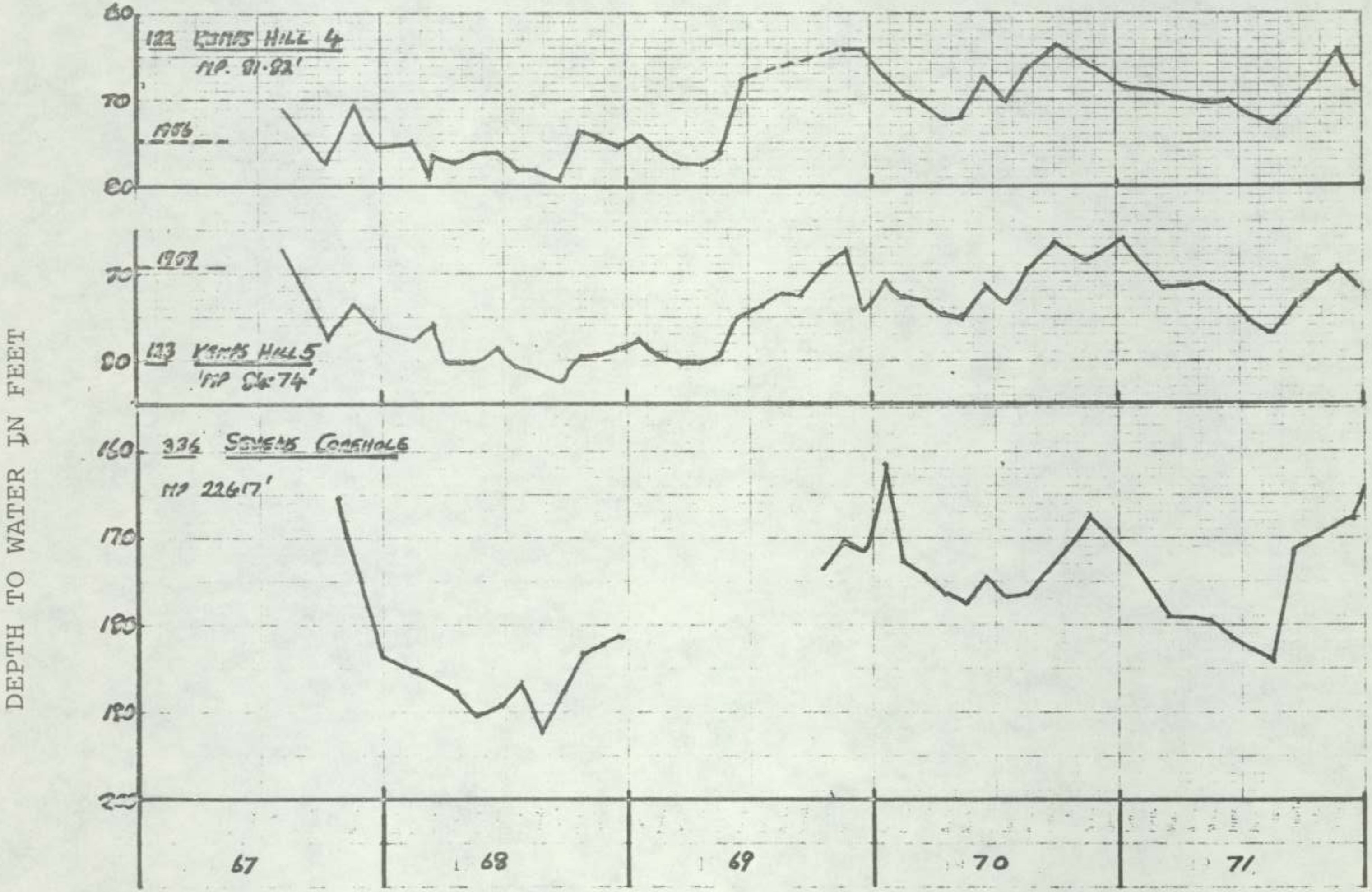

DEPTH TO WATER IN FEET
60
70
80
122 KEMPS HILL 4
MP. 81·82'
1956
70
80
1959
123 KEMPS HILL 5
MP 86·74'
160
170
180
190
200
336 STEVENS BOREHOLE
MP 226·17'
67
68
69
70
71

FIG. 5.19 (CONT)

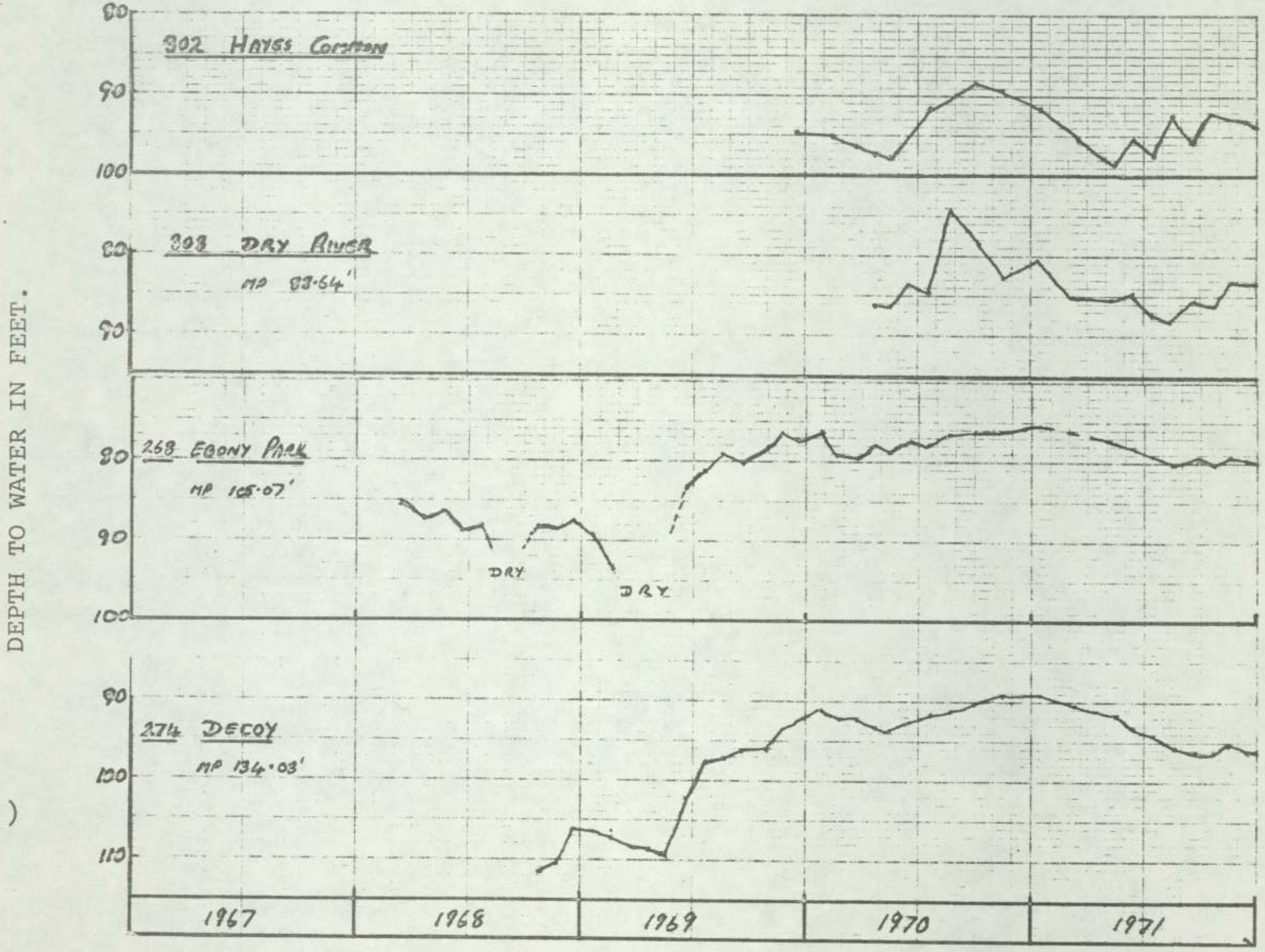

DEPTH TO WATER IN FEET.
302 HAYES COMMON
80
90
100
303 DRY RIVER
MP 83·64'
80
90
268 EBONY PARK
MP 105·07'
80
90
100
DRY
DRY
274 DECOY
MP 134·03'
90
100
110
1967
1968
1969
1970
1971

FIG. 5.19 (CONT.)

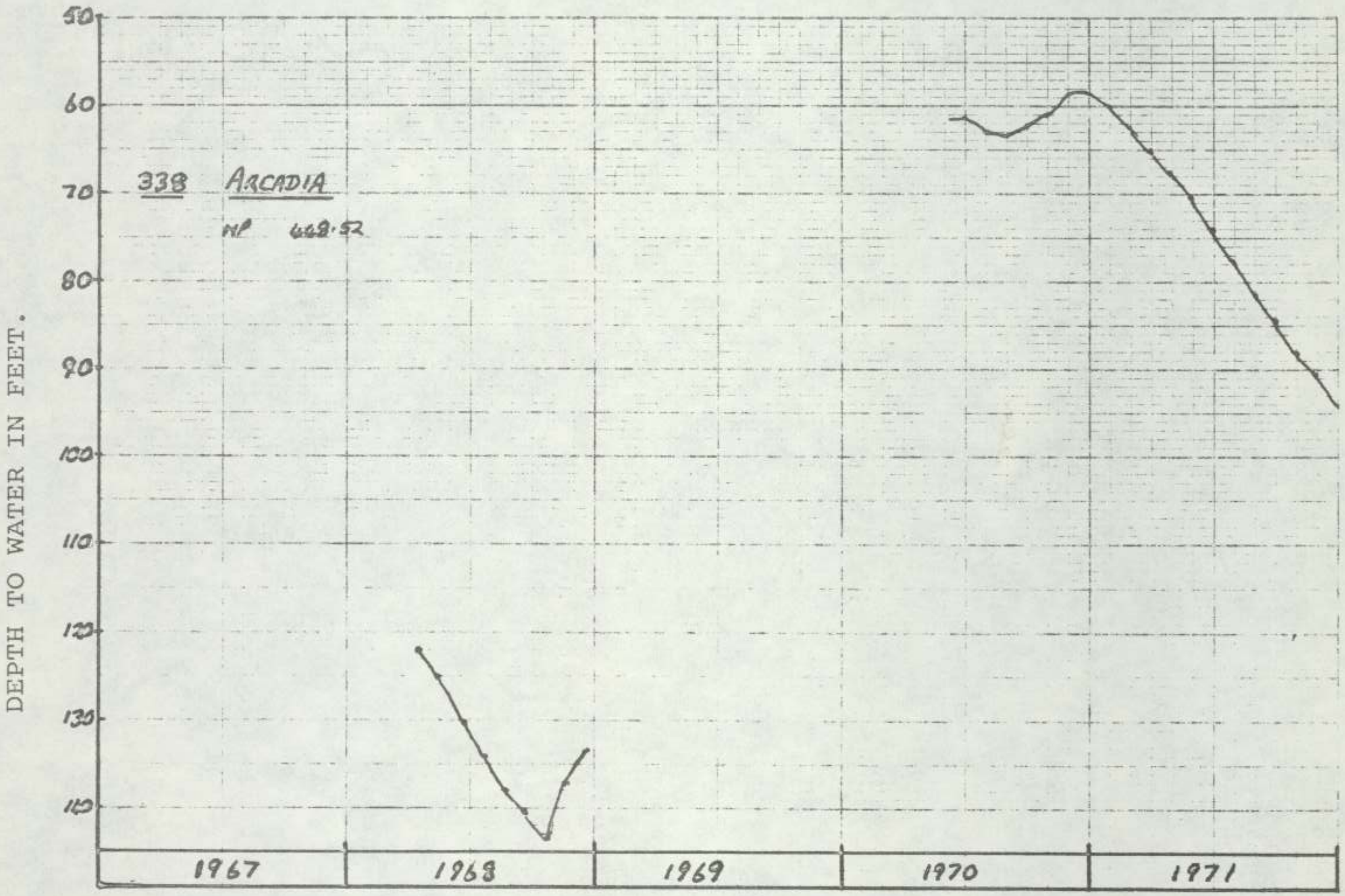

DEPTH TO WATER IN FEET.
50
60
70
80
90
100
110
120
130
140
338
ARCADIA
MP 448·52
1967
1968
1969
1970
1971

FIG. 5.19 (CONT)

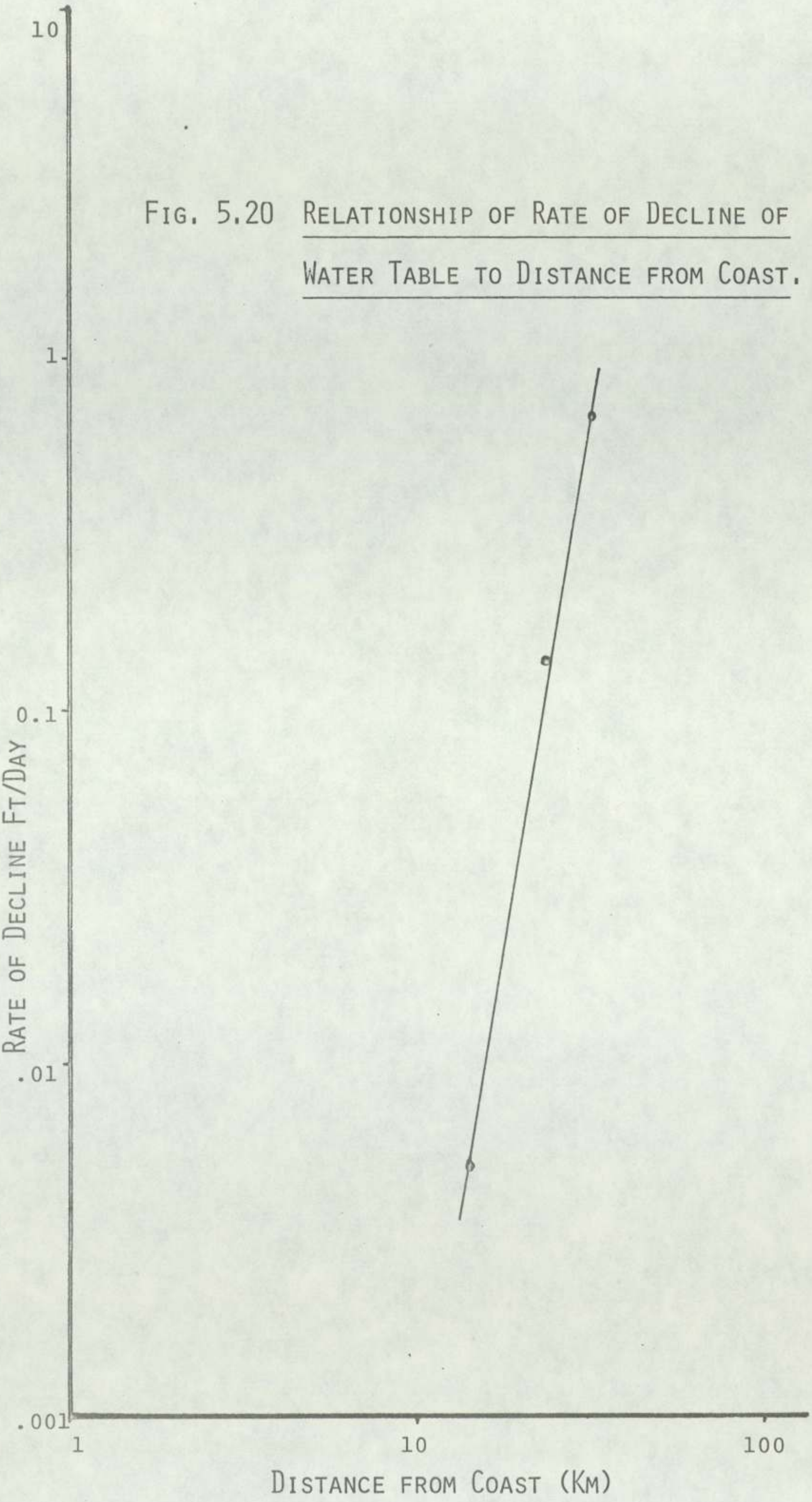


Fig. 5.20 Relationship of Rate of Decline of Water Table to Distance from Coast.

HYDROLOGY OF THE TWO AQUIFER SYSTEM CLARENDON, JAMAICA

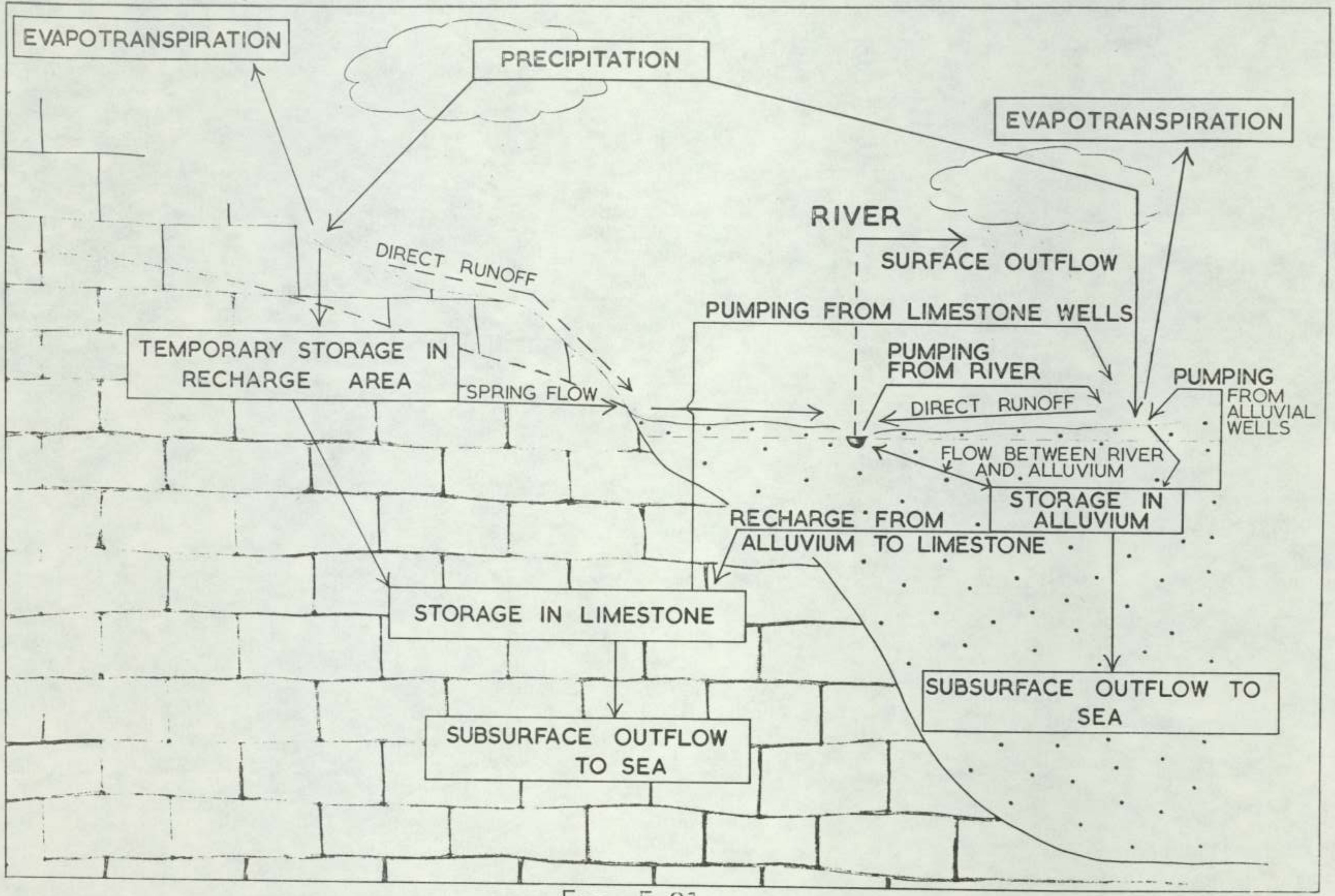


FIG. 5.21

6 WATER QUALITY

6.1 Availability of Data

The West Indies Sugar Company collected samples of water from all their wells and relift pumps approximately every month, from as early as 1949, and were still doing so in 1972 when the writer last visited the area. These samples were then analyzed for chloride content in the company's own laboratory and the results expressed as parts per million of sodium chloride. These records were made available for this research project and, after those referring to alluvial wells and surface water pumps had been removed, there remained 35 sets of analyses for limestone wells, of which most covered more than 12 years and 14 went back to before 1952. Similar data was available for 13 wells owned by other estates in southern Clarendon, mainly covering the period 1959 - 1971. These analyses were carried out for the Sugar Research Association at the same laboratory and the S.R.A. kindly made them available for this study.

In addition to these time series data for chloride content, a number of analyses of common anions and cations were available covering, somewhat irregularly, the period 1956 - 1971, and a further sampling was carried out in 1972 specifically for this study. The total number of analyses, not including the chloride data mentioned above, is 157, representing samples collected from 91 limestone wells over 16 years. These figures require some qualification, however, as there have been occasions, such as a pump testing, when a number of samples have been taken from one well within a relatively short period of time and are thus of little use in looking at long-term changes in quality. If each of these closely spaced sets of results are counted as only one analysis then the total is 140 from the same 91 wells with 46 being carried out in 1972 and 27 in 1969.

6.2 Reliability of Data

In a study of this nature, where historical data are important, the researcher frequently has to accept the results of earlier workers without having much idea of their reliability. In addition, similar problems arise with recent data such as chemical analyses, as these involve the assistance and co-operation of fellow workers in other disciplines. This last point particularly applies where the data collection is done as part of professional rather than academic study, and hence where there is little opportunity for the hydrogeologist to devote time to mastering the skills of the analytical chemist.

In the case of the present study the problem was further complicated by the fact that the Project and the Water Resources Division did not have their own facilities for laboratory analyses and that, consequently, they were dependent on other government departments and in particular the National Water Authority, for the chemical analysis of water samples.

It can be seen from the above description that it was necessary to try and evaluate the quality of the analyses carried out by the N.W.A. and also, if possible, the chloride measurements carried out over the years by W.I.S.Co.

The analysis for chloride content is carried out by a simple silver nitrate titration using methyl orange indicator and, as the process is relatively straightforward, there is no reason to suppose that serious errors will have occurred. Some kind of cross-check has been possible, however, for the months when samples were collected from the same or nearby wells for analysis by the N.W.A. As they were not collected on the same day, an accurate comparison is not possible but it would be expected that similar chloride values would be recorded in those wells which did not normally show wide fluctuations from month to month. The results of this comparison can be seen in Table 6.1.

During the collecting of samples for anion and cation analysis, the writer attempted to test the reliability of the laboratory in two ways. Firstly, a field test for chloride content was carried out using a 'Hach' portable test kit and, for the most part, these results agreed with those reported by the laboratory, within the limits of accuracy of the field testing kit. The second method was to occasionally submit two samples of the same water under different identification numbers in order that the two analyses might be compared for discrepancy. This again indicated that the results were generally acceptable or, possibly, that any errors were consistent.

The above evaluations, however, were only superficial and of no value in assessing the results of analyses for anions and cations which had been carried out prior to the initiation of the study. Thus, the various checks which can be done on such data were gathered together and written into a simple computer program so that large quantities of data could be processed quickly. The tests are described below.

The most obvious check on analyses of this nature is to calculate the total concentrations of both the anions and cations in milligram equivalents per litre (m.eq/l.) and compare them to see if the totals are approximately equal. This may then indicate either an error in one or more of the ions or may indicate that one of the less common ions is present in significant quantities but was not analyzed for. In fact, in many of the Clarendon analyses, this test was not possible because sodium and potassium had not been included, due to the unavailability of suitable equipment, and had themselves to be calculated by difference. Consequently the programme was written to go one step further and, in the case where sodium and potassium had been given, it also calculated them by difference and compared the results, thus giving an indication of the errors inherent in calculating these common ions by difference.

Having calculated the total ionic concentrations in equivalent parts it was possible to do a further test by multiplying them by 100. This should result in a figure which is approximately equal to the electrical conductivity expressed in micromhos/cm. Thus, if the totals had not balanced in the first test then this would indicate whether the error was in the values for the anions or the cations.

Davis and De Weist (1966) describe the following empirical relationship for accurately relating conductivity to the concentration of anions or cations in equivalent parts per million.

B = Total EPM and C = Conductivity

When B is less than 1.0, $C = 100B$
When B is between 1.0 and 3.0, $C = 12.27 + 86.38B + 0.835B^2$

When B is between 3.0 and 10.0, $C = B[95.5 - 5.54(\log B)]$
When B exceeds 10.0 and HCO_3 is the dominant anion,
$C = 90.0B$

When B exceeds 10.0 and Cl^- is the dominant anion,
$C = 123B^{0.939}$

When B exceeds 10.0 and $SO_4^{=}$ is the dominant anion,
$C = 101B^{0.949}$

This relationship, derived by Logan (1961), is no doubt useful under some circumstances but was considered unnecessarily detailed for the purposes of the present study. In more general terms, the ratio of the total dissolved solids to the electrical conductivity should fall in the range of 0.55 to 0.75 and this holds up to concentrations of several thousand milligrams/litre. Generally, calcium sulphate and calcium bicarbonate waters will have a lower conductivity than a sodium chloride water with the same concentration of total dissolved solids.

It can be seen that these two relationships can be combined to exclude electrical conductivity from the calculation, thus providing a further test of the reliability of the data which would be valid if the conductivity value happened to be wrong.

Total Anions (meq/litre) x 100 = Conductivity
Total Cations (meq/litre) x 100 = Conductivity

and $$\frac{\text{TDS}}{\text{EC}} = 0.55 \text{ to } 0.75$$

Therefore $$\frac{\text{TDS}}{\text{Anions}} = 55 \text{ to } 75$$

and $$\frac{\text{TDS}}{\text{Cations}} = 55 \text{ to } 75$$

In addition to the above tests, it is also worthwhile checking those parameters which are calculated from one of the other given values, as this will throw some light on the overall reliability of the analyses.

Hardness is usually reported in terms of an equivalent amount of calcium carbonate but is actually computed from the concentration of calcium and magnesium ions. These are converted to milligram equivalents/litre, summed and multiplied by 50 to give hardness in parts per million $CaCO_3$.

A test which, though extremely simple, proved important in the case of the present study involved the bicarbonate concentration. An initial examination of the data showed an anomaly in that the bicarbonate concentration was often equal to the alkalinity, although the latter was expressed in terms of calcium carbonate. Occasionally, the bicarbonate itself was expressed in the same way, though for no obvious reason. Thus, the bicarbonate was recalculated from the alkalinity by dividing by 0.8202 and checked against the given value.

All the above tests, although quick and simple, are also time consuming and thus, it was an obvious and easy step to use the computer to carry out the calculations.

Having carried out the above tests on all the available analyses there were various ways in which the results could be used. Initially, it was intended that each analysis would be examined in the light of the test results and then either retained or rejected on the strength of these. It was soon realized, however, that the relationships used in the tests were only approximate and that failure to match up to the expected results did not necessarily mean that the whole analysis as reported, was incorrect. For example, the error might only be in one parameter, either an individual cation or anion, or possibly in the value reported for the conductivity or total dissolved solids. Alternatively, all the ions which were tested for may have been correctly recorded, but a less common ion, not included in the analysis, may have been present in the water.

Thus, it became obvious that the best way of using the reliability tests would be as a check on analyses which appeared as anomalies in the various techniques used to evaluate the overall water quality data. It will be seen that, in this way, the tests proved extremely useful, not only in detecting errors in the actual analyses but also in picking up the far commoner typographical and punching errors.

6.3 Presentation and Interpretation of Data

This section of the thesis briefly describes the various graphical and analytical techniques which were used in processing and presenting the available chemical data. With regard to graphical methods the primary purpose is in presenting the data so that a reader can quickly understand the characteristics and variations of the chemistry of the water or waters under discussion. The essential criteria on which a method is judged is the ease with which the reader can accurately accomplish this task.

Numerous graphical methods have been described in the past and many of these have found acceptance at one time or another. Whilst an evaluation of all these methods is beyond the scope of this study, it is fair to say that most have some merit for particular problems and that none is ideal for every purpose. In addition to simply presenting data, however, it is frequently necessary to demonstrate chemical or physical processes such as ion exchange or the mixing of two dissimilar waters. In this case, a different type of graphical method would be selected.

6.3.1 Time Series

As described earlier, monthly analyses for chloride content were carried out by W.I.S.Co. both for their own wells and for selected wells from other estates in the area.

As this data covered a number of years, it obviously lent itself to presentation as a set of time series graphs with the chloride content, in parts per million, plotted as the ordinate against time as the abscissa. A simple visual appraisal of these graphs was then carried out in order to determine the long term fluctuations in salinity and, in particular, to determine the relationship between recharge, extraction and quality of groundwater in the limestone aquifer.

The graphs of chloride content against time are shown in Fig. 6.1 and the significance of the trends is discussed in the final section of this chapter.

6.3.2 Scatter Diagrams

Probably, the simplest and most widely used method of comparing a number of chemical analyses is by means of the scatter diagram. In a scatter diagram the various values of one parameter are plotted against the corresponding values of another, on either arithmetic or logarithmic scales. Frequently, specific conductivity or total dissolves solids are used as the independent variable and the concentrations of one of the various ions as the dependent variable.

It is by no means uncommon, however, to plot the relationship of one anion to another, or of a particular anion to a cation, though Hem (1959) excellently discusses the dangers inherent in interpreting the apparent correlations between the various chemical parameters.

It is a fact that the chemical analyses of a number of water samples which are loosely related will have, built into them, certain constraints which may produce correlations that are not hydrogeologically significant. Hem points out that the total concentration of anions must equal the total concentration of cations and that, consequently, if all the waters in the group being studied have the same dominant anion and cation then these ions will have a high degree of correlation. Similarly, there may be a correlation between the lesser ions due to their part in the overall ionic balance. This is not to say that the relationships between the ions are of no significance but rather that caution should be exercised in drawing conclusions based on such apparent correlations.

In the present study scatter diagrams were drawn for a number of pairs of parameters but only those for SO_4/Ca, Ca/Mg, HCO_3/TDS have been included (Figs. 6.2 - 6.4).

6.3.3 Distance-Concentration Graphs

The name distance-concentration is used in the thesis to describe those figures in which the concentrations of common ions have been plotted for selected wells against the distance down stream (i.e. with respect to groundwater flow) of the well. This was actually done for two lines, one representing water as it moved from the foot of the Williamsfield - Porus trough down towards the coast (Fig. 6.5) and the other for a line in the eastern half of the plain, running from west of May Pen towards Kemps Hill (Fig. 6.6). Similar studies of carbonate aquifers by other workers had shown that certain distinct changes took place for various physicochemical reasons, including cation exchange and that distinct chemical zones can be recognized.

It will be seen in the last section of this chapter that these zones were not so apparent in this study but that a very general approximation into zones was possible in one case.

6.3.4 Schoeler Diagrams

The diagram proposed by Schoeler for comparing a number of chemical analyses was used to a limited extent in the present study. The various cations and anions are represented by a number of points along the arithmetic scale of semi-log paper. The logarithmic scale is then used to depict the concentrations of the ions in milli-equivalents/litre and, due to the nature of a logarithmic scale, large ranges in concentration can be accommodated and hence compared (Fig. 6.7).

The relative slopes of the lines joining two parameters in two different samples are a measure of the relationships between these ions in the two waters. For example, if the line joining the Na^+ and Cl^- in sample A is parallel to the line joining the same ions in sample B, then the ratios of the two ions are the same in the two samples.

The Schoeler diagram can also be used for more detailed data analysis, such as the determination of whether a particular water would dissolve or deposit limestone (Brown et al. 1972). This requires an accurate knowledge of the pH of the water in the aquifer which, in the case of the present data, was not known. The pH values were measured in the laboratory some time after the samples were collected and hence are not representative of the values occurring in the aquifer.

6.3.5 Contouring

Under the general heading of contouring there are a number of variations which might be used in order to visually present certain aspects of the water quality data. In the present study chloride values in parts per million were plotted on appropriate base maps. Lines passing through points of equal chloride concentration were then constructed.

These are known as isochlors. Contouring was carried out to show both variations with respect to space and, in the case of the alluvial aquifer, with respect to time.

Chloride was selected due to the large number of analyses available and also because it appeared to be diagnostic of the changes in groundwater quality occurring in the limestone and alluvial aquifers.

A map on the scale of 1:100,000 was produced for the limestone aquifer for 1969, as that was the year in which the widest coverage was available (Fig. 6.8). A more detailed map on the scale of 1:50,000 was produced for the critical Kemps Hill - Hayes - Windsor Lodge area for 1972 as a water sampling programme had been carried out specifically for this purpose (Fig. 6.9).

In order to compare the water quality problems of the two aquifers, an isochlor map of the alluvium for 1969 was produced (Fig. 6.10) and also a map which showed the relative positions of the 250 ppm contour in the years 1950, 1960 and 1967. (Fig. 6.11).

6.3.6 Trilinear Plotting

The major constituents of most naturally occurring groundwaters can be considered as falling into three groups of cations and three groups of anions. These are calcium, magnesium and the alkali metals and sulphate, chloride and the sum of bicarbonate and carbonate. It thus follows that the composition of water can be represented by two trilinear or triangular diagrams. This method of representing analyses has been in use since the early part of this century and, over the years, various techniques have been suggested for combining the two triangles or projecting the two points into a common field.

Piper (1944) suggested projecting from the two triangular fields, the apices of which represent 100% of the cation or anion groupings outlined above, into a diamond shaped field (Fig. 6.12). This method, which was adopted by the United States Geological Survey and has since been used extensively in that country, has much to recommend it. In common with other trilinear plots, however, it has more value as an interpretive tool than as a method of visual presentation. One of the major shortcomings as a method of presentation is that it is based on percentage composition rather than actual concentrations. One method of getting around this is to plot the projection in the diamond shaped field as a circle, the diameter of which is a function of the concentration of total dissolved solids. This has been done in Fig. 6.12 and it can be seen that, in the case of small differences, these are not so obvious and, with high concentrations, the diagram can quickly become confusing.

One problem with the Piper diagram is that it characterizes a water on the basis of relationships between Na+K, Ca+Mg, CO_3+HCO_3 and Cl+SO_4. In many cases this is acceptable but, for some studies, the hypothetical salt combinations are of interest, in which case the Durov diagram in one of its forms is preferable. The basic Durov diagram consists of two triangles, similar to the cation and anion fields of the Piper diagram, but with their bases at right angles (Fig.6.13). The general plotting field is rectangular. Durov (1948) published his original work in Russian and Challenger (1956) gave a summary in English in which five classes of water are described. These classes are primary water, secondary water, sulphate water, chloride water and alkaline bicarbonate water, and each can easily be identified on the Durov diagram.

In an attempt to standardize in the presentation of water quality data, Burdon and Mazlouns (1958) and, subsequently, Lloyd (1965) introduced the concept of the

Extended Durov diagram. In this method of plotting, the anion and cation triangles are each exploded into a pattern similar to the Piper diagram and the common point is plotted on the rectangular field of the basic Durov diagram (Fig. 6.14). The ionic concentrations are expressed as a percentage of the total composition rather than just of the cations or anions.

The extended Durov diagram appears to achieve a more obvious separation of different types of water and, for this reason, it has been used in this thesis in preference to the Piper diagram. In some circumstances, however, this method must be used with caution. For example to take an extreme case, the four waters given below are closely similar as far as chemical composition is concerned but the ratios shift sufficiently to push the waters over the 25% mark into different plotting fields. Because of this, the four analyses are relatively far apart on the resulting diagram. This example is not meant to detract from the value of the method but only to illustrate that the separation on the basis of dominant ions can plot in such a way as to suggest a break in a natural series which does not, in fact, exist (Fig. 6.14).

PERCENTAGE COMPOSITIONS

	A	B	C	D
Ca	25.5	24.5	25.5	24.5
Mg	10.0	10.0	10.0	10.0
Na+K	14.5	15.5	14.5	15.5
HCO_3	25.5	25.5	24.5	24.5
SO_4	10.0	10.0	10.0	10.0
Cl	14.5	14.5	15.5	14.5

6.3.7 Multivariate Analysis

6.3.7.1 General Methods

The standard techniques used by hydrogeologists for looking at multivariate data were described in the previous section. In addition to these methods, however, there are numerous techniques of numerical taxonomy which merit further examination as possible tools in the evaluation of groundwater quality data. These methods present great prospects for both geology and hydrogeology but their implementation is hampered by the sometimes complex theory on which they are based. In the following pages, an attempt will be made to discuss the general fundamentals and this will be followed by descriptions of some specific techniques.

Group Formation - In this process, individual sampled points are formed into groups, the members of which appear to be similar to each other. A sampled point in this case would be a water sample upon which various chemical and/or physical tests had been carried out. Each property measured is a variable property or attribute. The technique is an aid to the formation of hypotheses about how to commence classification of the data and indicates what degree of classification may be possible.

Discrimination and Identification - In this process, methods to discriminate between known classifications are sought and subsequently an attempt is made to identify and classify samples of uncertain origin.

Finding Typical and Atypical Members of a Group - For each group it may be desirable to find samples which are most typical or least typical of that group.

Showing Geographical Trends and Variations - The groups, as formed, may show spatial variations which are not obvious from the mass of data in its original form. This can give clues as to the causes and effects of various situations.

Not all of the possible methods have been discussed in this introduction and, of those discussed, not all have been used in this study. This section is included, however, in order to place the work done in the overall picture of work in this field.

6.3.7.2 Cluster Analysis

Cluster Analysis has recently become widely used by taxonomists in various fields such as geology, biology, geography and medicine (Hall, 1969, Cole 1969 and Parks 1972). It should, in theory, be a method well suited to handling water quality data, which is measured on a continuous scale and can be conveniently transformed by a wide variety of methods which have physical meaning e.g. molecular weight. The techniques of cluster analysis, of which there are many, look at a set of multivariate data and try to place each data point in a group, all members of which are in some way similar to each other.

The process starts off by forming a matrix of similarity coefficients showing how similar each point is to each other point in the whole set. The exact method of computing similarity varies. One widely used statistic is the Euclidean distance between each point. Other methods are the angular distance, the 'City block' distance and the correlation coefficient between each data point. These are illustrated in Fig. 6.15 for the case of two points and two variables. The two points are represented in the two dimensional space by A and B. The Euclidean distance is the distance AB, the 'City block' distance is AC+CB and the angular distance is the angle . It can be seen that the angular distance does not discriminate with actual distance and is sensitive to the choice of origin. The correlation coefficient between each pair of points is obtained by pairing each row in the original data matrix (each row representing a point, each column representing the value of the variable measured for that point) with each other row and computing the correlation in the usual way.

It is usual with cluster analysis to use statistically standardized data before commencing any analysis. This places the origin of all variables at zero, with zero being the centroid of the whole data set. This does not of course preclude the modification of data by the worker prior to the statistical standardization. The particular form of statistical standardization used is usually the reduction of each variable to zero mean and unit standard deviation.

Having selected a measure of similarity from the many available, a similarity matrix is formed. As each point is compared with every other point the matrix is symmetrical, square and may be very large. The matrix is then analyzed to find ways of grouping the data in such a way that the members of the groups are in some sense similar to each other within the groups. Groups of data are formed which appear to cluster together, hence the name cluster analysis.

In cluster analysis the usual procedure is to first assume that each point is a cluster on its own and then to define a measure of closeness between each cluster which will be used to merge clusters to form larger clusters. The similarity between each point is compared and, if two points are closer together than some specified tolerance, then they are lumped together. After the first application, there may still be a few isolated points which will not form pairs. Each cluster is then analyzed to form another similarity matrix (which may not actually be formed but remains a concept) where the measure of similarity may be the weighted mean similarity between members of the cluster or the distance between centroids of the clusters or, indeed, many other possibilities. This new matrix is analyzed in the same manner as before and clusters are formed which will contain four or less members. The procedure is repeated until all points are driven into one cluster. The process can be illustrated graphically by means of the dendrogram, which depicts the fusion of the clusters against the statistic used to measure similarity, see Fig. 6.16.

Other methods of cluster analysis exist which avoid the formation of the similarity matrix as such. In these methods each point is processed one at a time and, if found to belong to a cluster already in existence, it joins it. Clusters already in existence may fuse.

6.3.7.3 Principle Component Analysis

This is a technique which can be applied at two levels. It can be applied to the original data or it can be applied to the similarity matrix. When applied to the original data, it is more akin to factor analysis. However, in factor analysis it is necessary to make some hypothesis about the factors which it is believed are significant. In component analysis the factors weights are selected automatically. When studying means of classification and discrimination it probably makes more sense to use principle component analysis. The reason for this is that the technique attempts to account for as much variance as possible in the original data by as few statistics as possible. Fig. 6.17 illustrates the principle. The technique seeks a set of linear transformations of the original data which will have the property of accounting for as much of the original variance as possible by the first transform and, once that has been removed, as much as possible of the residual will be accounted for by the next transform and so on, until all variance is accounted for. Obviously, if the original data is perfectly correlated then all variance will be accounted for by the so-called first principle component. If data is poorly correlated, then many components may be necessary.

In Fig. 6.18 the point C in the original co-ordinate system is represented by $x_1' \, x_2'$. In the principle component axes the point C is represented by $Y_1' \, Y_2'$. The two axes are chosen so that they are at right angles. In statistically standardized data, the origin of the standardized data will be at the origin of the transformed data, which will be at zero.

In grouping data, whether using original data or a similarity matrix, one, two or three of the principle components are used to form a group by a graphical procedure. Fig. 6.19 illustrates the kind of results that might be obtained by plotting the first two components. It can be seen here that the aim is to enable clusters to be identified more easily by concentrating the variance into a few variables.

6.3.7.4 Discriminant Analysis

After carrying out a cluster analysis of some kind, or because a set of samples is available from known sources, a discriminant analysis can be carried out. This is done by finding the linear combination of the variables that produces the maximum separation between two previously defined groups. The resultant statistic can be visualized in Fig. 6.20 for two groups. If the two groups are considered as clusters of points in space then the discriminant function would be the line along which the projection of the points had the greatest separation, combined with the actual groups themselves having the least spread. The curves are frequency or probability curves and the area of overlap, if any, is the probability of misclassification.

When a function has been determined a new sample of uncertain origin can be classified by finding the value of the discriminant function for that point and determining to which group it most likely belongs.

6.3.7.5 Discussion

There is a bewildering array of techniques available for analyzing multivariate data with the purpose of classifying it. Often the question can be asked, Why bother? An experienced analyst in the area of study could probably separate the data quite adequately by visual appreciation. There is still something to be gained, however, from automatic methods. Firstly, they provide a backstop against the overlooking of something significant and, secondly, they might provide an extra insight which would be missed by conventional analysis and interpretation.

Even with automatic methods there is room for interpretation. It is not necessary to use all the available variables in a particular analysis. Indeed, it may be that cluster analysis will not provide useful results if all the data is used. Consider the situation in Fig. 6.21 where it could be argued that different clusters appear at different values of the variable x_3 which would not necessarily be detected by cluster analysis where distance was being used as a measure of similarity.

All points denoted by an x lying in plane 1 could be said to form a cluster. This would be so if only x_3 were used in the analysis but not necessarily so if x_1, x_2 and x_3 were used.

Having evaluated the potential benefits and possible shortcomings of the various techniques of multivariate analysis, it was decided to attempt a cluster analysis of at least part of the available data from the Clarendon Plains. As the data was also being analyzed by the more conventional means, it presented an excellent opportunity to compare results and assess the suitability of cluster analyses for groundwater chemistry data.

The details of the programmes used are described in the next chapter of this thesis and the results are utilized and evaluated in the final section of this chapter.

6.4 Long Term Trends

From the outset, it was found that wells and boreholes penetrating the limestone aquifer in certain localities around the southern end of the Brazilletto Hills (on the properties known as Tarentum, Hillside and Gibbons) yielded highly saline water. Apart from these, however, the quality of groundwater in the limestone throughout the plains was generally good at the time that the boreholes were constructed.

Versey (1959) reports that the first significant increase in salinity occurred in 1948. He does not give specific details about the extent of the increase or the number of boreholes affected, but does say that heavy rains in 1950 and 1951 caused a rise in water levels and a corresponding drop in salinity. In view of this, the problem was forgotten until 1958 when, after three years of below average rainfall combined with a significant increase in groundwater abstraction, there was an unprecedented decline in the quality of water from some wells. This time the consequences were more serious, however, as the Kemps Hill complex of limestone wells, which supplied 15,000 gpm or 14% of all the water obtained from that aquifer, was affected. An examination of the graphs of chloride content for those wells (Fig. 6.1) will show that, in the case of Kemps Hill 3 (No. 121), warning signs were present from as early as 1954 and, in the cases of Kemps Hill 1, 2 & 4 (Nos. 119, 120 & 122) from late 1956.

At the end of 1958 it can be seen that there was a fall in salinity in most of the Kemps Hill wells, which can be related to a rise in water levels in the limestone aquifer. Nevertheless, it should be noted that none of the wells returned to their original condition and that the chloride content generally remained in excess of 300 ppm. This condition persisted through the first half of the next decade with the salinity in most wells being stable, though Nos. 122 & 125 showed significant fluctuations.

In 1965 & 1966, the first signs of further increase in salinity were recorded in most of the wells in the Kemps Hill area and this proved to be the start of a major invasion of saline water from which the wells could not recover. By mid 1967, all the Kemps Hill wells owned by W.I.S.Co. (Nos. 119, 120, 121, 122 & 123) were showing chloride concentrations of over 1000 ppm and the values continued to climb until Nos. 119 and 121 had to be abandoned when the chloride content exceeded 2000 ppm in 1968. Pumping from the remaining W.I.S.Co wells in the Kemps Hill area was also virtually discontinued and, within the next year or two, all the pumps were removed.

After W.I.S.Co. ceased pumping from their Kemps Hill wells, there was, in the long term, a noticeable improvement in the quality of water from the remaining wells in this critical area, as can be seen from an examination of the graph for Nos. 117, 124 and 125. This may have been due, at least in part, to the above average recharge in 1969 & 1970, as discussions with the well owners revealed that when all the wells were still in operation, the switching off of the W.I.S.Co. pumps would usually lead to a sudden increase in salinity of the water from wells No. 124 & 125. It is worth noting at this point that the chloride content in well No. 128, situated on the north side of Kemps Hill, rarely exceeded 200 ppm throughout the critical period and that it continues to give water of acceptable quality.

In a discussion of the decline in quality of groundwater in a coastal aquifer, the relationship between sea level and the pumping water levels in the wells and boreholes is of obvious significance. For W.I.S.Co. wells, there are some data available for the period 1961 to 1967 but many of the recorded values for both static and pumping water levels appear to be of doubtful value, probably due to the fact that they were recorded by means of pressure gauges which were poorly maintained. In general, however, based on both of these values and the original well records, it would appear that Nos. 119 and 120 usually pumped from 20 to 30 feet below sea level and that No. 121, 122 & 123 had pumping water levels at, or just above sea level.

The other area in which the limestone aquifer has been seriously affected by increase in salinity is the Hayes Common - Raymonds - Cotton Tree gully area, which lies some 3 to 4 miles east of Kemps Hill. Here, the pattern of increase in salinity has been broadly similar to that of Kemps Hill but with some significant differences. From the outset, an interesting situation occurred in the Raymonds property. From the time of drilling the chloride content in well No. 87 was of the order of 500 ppm whereas wells No. 86 and 88, only 500 feet away, were only 100 ppm and 75 ppm respectively. Over the years, the salinity of No. 87 has increased steadily, but not by a great amount, whereas the rest of the Raymonds wells (Nos. 85, 86, 88, 89 & 90) have more than doubled their chloride content. Raymonds 2 and 4 (Nos. 86 & 88) had chloride contents of around 100 ppm up to 1955 at which time there was an increase which continued through to 1969, when chloride values of over 400 ppm were recorded.

The Cotton Tree Gully wells (Nos. 100, 101 and

102) also started out with chloride contents of a little over 100 ppm. In the case of Nos. 100 & 102, however, the gentle increase in salinity began in the early 1950s with the rate increasing in 1957. By 1966, a value of 1400 ppm had been recorded in Cotton Tree Gully 1 (No. 100) and the well was abandoned. Cotton Tree Gully 3 (No. 102) recorded its highest values, which were in excess of 800 ppm, in 1968 & 1969. Subsequently, the quality improved slightly. A similar trend was exhibited by Cotton Tree Gully 2 (No. 101).

The Hayes Common well field, situated to the east of the Cotton Tree Gully wells and northwest of the Raymonds wells, exhibits some interesting characteristics with respect to quality. Wells Nos. 95, 96 and 97 are situated in a straight line and only a few yards apart. Initially, the three wells had chloride contents of approximately 100 ppm. Once the general decline in quality commenced, however, then this was most pronounced in No. 95 and least in No. 97. All these boreholes are drilled to the same depths, they have similar yields and drawdowns and yet, as an example, in 1969 the following chloride values were recorded simultaneously; No. 95 - 738 ppm, No. 96 - 354 ppm and No. 97 - 163 ppm. In these three wells the first significant decline in quality commenced in 1965 and the highest chloride content was recorded in 1969. Hayes Common 5 (No. 99) a short distance to the north exhibited a similar trend.

With regard to the pumping levels of the Hayes Common, Raymonds, and Cotton Tree Gully wells, once again, relatively reliable data is scant. It is clear, however, that many of these wells are pumping from below sea level.

The Dry River well field, a mile or so to the north of the Cotton Tree - Hayes Common area, had good quality water throughout most of the early and mid sixties. The chloride content was usually around 100 ppm and exhibited only minor fluctuations. By 1969, however, small significant increases had occurred and in 1970 and 1971 Dry River 5 (No. 205) had several measurements in excess of 200 ppm and one in excess of 300 ppm.

The southernmost limestone wells at the western edge of the plain have not exhibited increases in salinity to the same degree as those described above. However, an examination for the graphs for the Springfield and Milk Spring wells (Nos. 145, 152, 153 & 154) will show that some increases did occur from 1965 onwards, with significantly high levels being recorded in 1968 and 1969.

Thus, it can be seen that the problem of saline contamination was beginning to extend throughout a considerable part of the eastern half of the plains by the end of the 1960's, and was affecting a high proportion of the high yielding limestone wells. Small increases were detected at the southern edge of the western half of the plain but these appear to have been far less significant. In a later section of this chapter an attempt will be made to explain why the salinity problem should have manifested itself in this way and a theory will be developed to explain the origin of this saline water.

Whilst discussing the long term trends of the limestone aquifer, it is worth taking a look at the increases in salinity that occured concurrently in the alluvium. Fig. 6.11 shows the position of the 250 ppm isochlor for the years 1950, 1960 and 1967 and it can be seen that, in the area to the south of Kemps Hill, this contour moved northwards whereas in the vicinity of the Rio Minho little change occurred. According to information received from W.I.S.Co. the general pattern of salinity increase in the alluvial aquifer in later years was the same for all wells, regardless of whether the chloride concentrations were low (300 ppm), medium (700 ppm) or high. There was a fairly constant but gradual increase through the dry years of 1966, 1967 & 1968 but this fell off slightly in the high rainfall years of 1969 and 1970.

In the first half of 1971, however, which was a dry period, there was a rapid increase followed by a return to the normal salinity values after the heavy rains which occurred in August through October of that year. It is possible that the increase in salinity in the alluvium was a combination of inefficient irrigation and the use of saline waters from the Kemps Hill limestone wells to irrigate the sugar cane. Both of these factors, occurring at a time of below average rainfall, would quickly lead to a decline in quality of water in the alluvium.

It is unlikely that the salinity in the superficial deposits is due to seawater intrusion, as the phenomenum is observed in wells whose pumping water level is above sea level. It is appreciated that this may not necessarily preclude seawater intrusion if the saline wedge extends beneath the pumped well. According to the Ghyben-Herzberg relationship, a relatively small drawdown in a well could be accompanied by an upconing of seawater, (Fig. 6.22). However, measurement of salinity at varying depths in several alluvial boreholes failed to show any vertical variation in concentration. Similarly, there has been no measured decline in alluvial water levels since 1956 and no new wells drilled since 1959. Thus, it would appear that the recycling of irrigation water, which had a significant salt content from the contaminated limestone wells in the first place, has been the principal cause of the deterioration in groundwater quality in the alluvium. This theory is borne out by the relatively high salinity of drainage waters in the ditches alongside the cane fields.

Huie & Ramdial (1971) reported that 83 inches/year of water are applied to the W.I.S.Co. fields and that in early 1971 the average salinity of this water was approximately 960 ppm (expressed as sodium chloride). Calculations show that this would deposit 8.75 tons of sodium chloride/acre/year.

6.5 Regional Patterns

In order to obtain a further appreciation of the overall pattern of saline contamination, as it is occurring in the limestone aquifer, two isochlor maps were produced. The first of these was for 1969 (Fig. 6.8) when analyses covering most of the plains are available, and the second was for 1972 (Fig. 6.9) when a detailed sampling programme was carried out in the eastern half of the study area. The latter programme covered the critical Kemps Hill - Hayes Common well field. In both these cases, the available data was supplemented, where necessary, by analyses from other years. In the case of the 1969 map, values for 1968 and 1970 were used to give guidance in the construction of the isochlors. In the case of the 1972 map it was found that, in wells which had been sampled in both 1969 and 1972, a reasonable relationship generally existed between the two values. Thus, it was possible to derive an approximate 1972 value from those which had only been sampled in 1969. It should be stressed that the derived values were used only for guidelines in constructing the map and did not have the same influence as the actual measured values.

With regard to the regional map (1969) it can be seen that the general trend is, not surprisingly, one of increasing chlorides towards the coast, with two notable exceptions. In the north-western part of the plain three boreholes had chloride contents slightly in excess of 20 parts per million, whereas the general trend indicates that the 20 ppm isochlor would be situated further to the south. The differences are small and may not be significant, but the fact that it appears on the map suggests that it requires some discussion. There are some outcrops of limestone in that general area and it may be that excess irrigation water, with a higher chloride content, is recharging the aquifer. This theory is reinforced by the apparent shape of the 25 ppm isochlor which extends in the general direction of groundwater flow.

The other anomolous area is in the vicinity of the Windsor Lodge property,some miles to the north of Kemps Hill. Here the general trend of a decline in salinity from 1969 to 1972 was reversed and, in fact, the 3 boreholes which were analyzed in both these years showed an increase in chloride content of over 200 ppm. The striking feature about this area of high chloride content is the steep concentration gradient in all directions, but particularly towards the west. Further discussion of this phenomenon and the possible causes will be given in a later section of this chapter.

The pattern of isochlors in the Raymonds area (the south-east corner of the 1972 map) is noteworthy for the apparent tongue of less saline water which pushes southward, though this may be the result of alluvial water, which is relatively fresh in this area, finding its way into the boreholes.

In general, the encroachment of saline water seems to be extremely directional, as is exhibited by the Hayes Common boreholes 1, 2 and 3 (Nos. 95, 96 & 97) which exhibit a steep salinity gradient. It appears that Cotton Tree No. 1 is in the direct line of saline movement, or intercepts the major conduit along which this movement is taking place, and that this consequently leads to a significantly higher chloride content than nearby wells. It should also be borne in mind that, at the time that the samples were taken, this well had been abandoned for some time and was thus not creating a cone of depression which could have led to upconing of salt water.

The greatest salinity gradient of all is seen at Kemps Hill where, in 1969, chloride values in excess of 2,000 ppm were recorded in wells on the south side of the hill and yet at Pond Pasture (No. 128) on the north of the hill, the chloride content was only 74 ppm.

6.6 Mineral Springs

There are two mineral springs within the study area; Milk River Bath at the southwest of the plains and Salt River Spring at the southeast end of the Brazilletto Hills. The waters of these two springs are of a similar type and differ only in concentrations. Both have highly mineralized waters which are radioactive and slightly hyperthermal.

At Milk River Bath the temperature is 33.5°C and total dissolved solids of up to 35,000 ppm have been recorded. The ionic ratios are similar to seawater but the spring rises at 4 ft. above sea level. The distinctive characteristic of the water is its radioactivity which reaches 16,000 micro microcuries/litre but the analyses for uranium oxide (U_3O_8) have indicated relatively low values (.002 - .003) mg/l). S.A. Vincenz (1959) has demonstrated the main source of the radioactivity to be the gas radon and spectrographic analyses revealed no anomolous trace element values. The discharge of the spring is normally between 300 and 800 U.S. GPM but, with high groundwater levels, the flow increases and the radioactivity and mineral content decrease. At a time when the discharge rose to over 2,000 U.S. GPM, the dissolved solids dropped to 14,500 ppm. over a short period.

A magnetometer survey led the Geological Survey Department to conclude that an anomoly existed at a depth of some 300 ft. below Round Hill and, consequently, a small diameter corehole was drilled just above the spring. It was expected that Mesozoic rocks would be encountered but the hole was continued to more than 1,000 ft. and was still in the White Limestone on completion.

At Salt River Spring, the water is very similar to that of Milk River Bath and its temperature is only a little lower (31.2°C). Analyses showed a U_3O_8 content of .006 mg/l or about twice that of Milk River Bath. Radioactivity is, however, much less than that of Milk River spring suggesting that the two waters have a common origin but that the radon daughter product is given off before the water reaches this discharge point.

An analysis of the oxygen 18 content of Salt River Spring showed that it was enriched, a fact which can be indicative of contamination from seawater. Similarly, the work of the U.S.G.S. in Florida has indicated that coastal springs discharging above sea level can contain seawater. The presence of the uranium salts and radon, however, indicate that seawater is not a major constituent of these springs.

Versey (1959) plotted the concentrations of the various ions against the discharge of the Milk River Spring and, assuming that the mineral content of the natural limestone water was negligible by comparison, he prepared a set of logarithmic master curves relating concentrations of the mixture as a percentage of that of the undiluted water to the degree of dilution by unmineralized water. By matching these with the curves of individual ionic concentrations against discharge, he was able to estimate both the concentration of the original mineralized water and the discharge rate below which there was no dilution. The rate was approximately 290 GPM., the concentrations are given in Table 6.1 and compared with corresponding values for seawater. On the basis of this, he concluded that the waters did not owe their origins to seawater but suggested that they were probably connate.

In the light of the above discussion, it would appear that there are three, not necessarily mutually exclusive possibilities for the origin of the springs. These are connate water, juvenile water and mineralized meteoric water. the most recent known volcanism in Jamaica dates back to Eocene times and thus mineralization by juvenile waters or gasses is not considered likely. Similarly, the idea of connate water is not acceptable to the present writer, simply on the basis of the nature of the continuous discharge of mineralized waters at the springs. Connate water has, by definition, no source of recharge and is thus a finite entity.

Having favoured the exclusion of juvenile and connate water, the writer is left with the alternative theory that the mineral springs are essentially derived from mineralized meteoric water. If this is so, then the water obviously must be coming into contact with rocks capable of yielding distinctive chemical composition. Given the mineral content of the White Limestone, and the fact that much of the flow is in conduits and fissures with a relatively low contact time between water and rock, then this formation does not appear as a likely source of mineralization.

The Yellow Limestone Formation, which underlies the White Limestone, is frequently granular in nature and can be seen to be water-bearing by the occurrence of small springs in the upper Rio Minho basin. Now this, in itself, would not be indicative of any potential for mineralization, but recent work by the Geological Survey Department has identified evaporite deposits of Yellow Limestone age at two locations in the island. Although these have not been recorded in the study area, the limited outcrop of Yellow Limestone rocks does not necessarily preclude their existence. Further, elsewhere in the world, some evaporite deposits are known to contain uranium and radium salts and thus, logically, it is not unreasonable to postulate that the two mineral springs in the Clarendon area derive their mineralization from passage through the Yellow Limestone Formation. The mechanism by which this might have taken place is relatively easy to describe.

Rain on the high ground of the Mocho Mountains might find its way down through the relatively thin covering of White Limestone into the underlying Yellow Limestone formation. From here, it would then move downdip towards the ocean, picking up mineralization as it encounters the evaporites, until its path is intercepted by the South Coast Fault system. This fault perpendicularly intersects the direction of flow and if, for a variety of reasons, it acts as a barrier for continued southerly flow, then the water will move either laterally along the fault zone or vertically upwards. As the recharge area is at the highest part of the basin, the hydrostatic head will be high relative to that of the shallower groundwater in the overlying limestone but, probably, only by a small amount. Under natural conditions the upward flow would be very small but, if the head in the White Limestone were reduced through either low recharge or pumping, then the vertical flow from the Yellow Limestone might increase significantly.

Radon has a relatively short half-life of a little over 4 days and thus it would appear that the water at Milk River Bath reaches the surface relatively quickly, a fact commensurate with passage of water through a fault zone. A consideration of the temperature of the water also indicates relatively quick movement from a considerable depth. With a geothermal gradient of 1°C per 100 ft. and a temperature some 10°C in excess of the ambient groundwater temperature it would appear that the water has come from at least 1000 ft. below ground level. This calculation ignores the heat generated from radioactive decay but, allowing for cooling during ascent and mixing with shallow groundwater, it is apparent that the water has, in fact, come from a significantly greater depth than this. Indications are that the White Limestone is in excess of 2,000 ft. at this point and thus the depth from which the water has risen is comparable with the estimated depth to the Yellow Limestone Formation.

It might be asked as to why the water should be confined in the Yellow Limestone and not pass freely into the overlying White Limestone which is, in general, considered to be an aquifer. In an earlier section of this thesis, however, it was shown that there are definite confining horizons within the White Limestone itself and also that karstification did not extend to the base of the formation. Thus, the only permeability will be the relatively low primary permeability.

In summary, it would appear likely that the mineral springs are fed by meteoric waters which have been recharged in the highlands, probably through a thin cover of White Limestone and then moved southward through granular deposits of Eocene age. On encountering evaporite deposits the waters have taken on a mineralized character and, with the flow to the seas impeded by the south coast fault, they have moved vertically upwards to appear at the surface.

6.7 Chemical Classification of the Limestone Waters

6.7.1 Introduction

Much has been written on the chemical classification of groundwater but, in general, it has proved difficult to establish rules which are universally applicable. The material of the aquifer is obviously of prime importance in bringing about changes in groundwater chemistry but, for example, water from granite in humid regions will be significantly different from granite waters in arid regions. Thus it can be seen that a rigorous genetic classification cannot be set up, though Schoeller established the following rules which go some way towards this.

1. Water from rocks of the same petrographic nature exhibit the same characteristics regardless of age of the rocks.

2. Water from rocks of the same petrographic nature will not necessarily have the same chemical composition.

3. Water from formations of the same petrographic nature and of the same age and climatic region usually have common characteristics, though those of a given age have more in common.

4. Water from two separate parts of the same aquifer may differ in chemical composition, and the greater the distance between the parts, the greater the difference is likely to be.

5. Water from the same groundwater unit in the same aquifer have relatively constant chemical characteristics compared with water from separate systems.

Whittaker and Thresh (1916) drew attention to the fact that as water moved down dip and beneath overlying formations in the Chalk of Essex, England, changes in chemistry took place. Ineson and Downing (1963) reported that similar changes occurred in a number of British aquifers as they pass from outcrop to beneath overlying argillaceous strata. They defined criteria on which the aquifer could be divided into zones and suggested processes by which these changes could have come about. Further work on this topic was done by Downing and Williams (1969) in their study of the Lincolnshire limestone and, like the earlier workers, they spoke predominantly of ion exchange as the main process. Foster (1967), working in coastal regions of the U.S.A., found that ionic concentrations in saline groundwater did not correspond to the theoretical values for a mixture of fresh groundwater and seawater. She concluded that base exchange had played a significant role in modifying the chemistry.

Cederstrom (1946), studying the coastal plains sands of Virginia, described mixing as the major mechanism bringing about changes in groundwater chemistry and, amongst recent workers, Lawrence, Lloyd and Marsh (1976) postulated that this was the main process occurring in a particular area of the Lincolnshire Limestone of England.

6.7.2 Discussion

All the available analyses for the limestone wells and spring were plotted on extended Durov diagrams (Fig. 6.2.3) and, allowing for the separation which occurs with this type of plotting, it can be seen that the analyses represent a continuous series passing from a calcium bicarbonate type of water to a sodium chloride water. In Fig. 6.23,which represents all the available analyses, the well numbers have been omitted for the sake of clarity. In Figs. 6.24, 6.25 and 6.26, however, the analyses have been split into different years and the well numbers included. From this, it can be seen that the position on the diagram, with some exceptions, is related to the geographical location of the boreholes. Those which are situated close to the recharge area tend to plot in the top lefthand corner (i.e. they are calcium bicarbonate waters) whereas the ones approaching the coast plot in the bottom right hand corner (i.e. they are sodium chloride waters).

Figs. 6.27 to 6.33 have been used to illustrate the cases where several analyses are available for a particular borehole or sampling point. From these it can be seen that three conditions can be identified. These are typical limestone water, typical saline water and those which fluctuate in composition due to their being in the transition zone. Typical examples of the transition type of borehole are Nos. 126 and 128 (Kemps Hill NWA and Pond Pasture). These wells are situated close to the badly contaminated wellfield but have continued to give water which, though slightly saline, is acceptable to the users. It can be seen that in both cases the analyses vary depending on the year in which the samples were collected.

Further, in the case of Pond Pasture, there is a clear relationship between the type of water and the total salt content.

The analyses of St. Jago (No. 270) which is situated in the northwest corner of the plain, plot firmly in the calcium bicarbonate field (Fig. 6.28) whereas the analyses for Kemps Hill 2 (No. 120) are situated in the sodium chloride field (Fig. 6.30). On the same figure it can be seen that Hayes Common NWA (No. 207) plots at the top of the diagram but, with its higher total dissolved solids, it does not sit so firmly in the calcium bicarbonate field.

Fig. 6.33 shows that, not surprisingly, the highly mineralized waters, i.e. Salt River Spring, Milk River Bath, Salt River corehole and seawater, plot at the extreme corner of the sodium chloride field.

For comparison, some alluvial waters have been plotted on Durov diagrams and, here again, a continuous spread of composition is found, (Fig. 6.34).

In order to obtain a further appreciation of the changes which occur as the water moves downdip, the various ionic concentrations have been plotted against distance from an arbitrary datum. Two lines of flow were selected for this exercise, one representing water moving from the foot of the Williamsfield - Porus trough towards the coast (Fig.

6.5) and the other representing flow in the eastern half of the plain, from May Pen towards the Kemps Hill area (Fig. 6.6).

The pattern downdip in the western half of the plain is one of a general increase in most ionic concentrations, including total dissolved solids. In the 8-10 mile zone, however, there are some reversals in this trend which deserve further examination. It can be seen that the total dissolved solids, the bicarbonate, the chloride and the sodium and potassium concentrations fall significantly before increasing again. Similarly in the 12-13 mile zone, the bicarbonate falls off again. These graphs are based on single analyses and it is dangerous to attach too much importance to them. However, it is interesting to note that these trends could be construed as conforming loosely to the zones of Ineson and Downing (Fig. 6.35). The initial fall in concentrations described above would correspond to their zone 3 and the subsequent increase in bicarbonate marks the onset of zone 4. The final steep rise in the major ions, coupled with the decrease in bicarbonate, could be interpreted as zone 5 which, in their classification, marks the mixing of fresh groundwater and saline connate waters.

The patterns exhibited along the flowpath in the eastern half of the plains is one of greater fluctuation but, in very general terms, the trends are similar with a final fall in bicarbonate concentrations as the saline zone is reached.

6.8 Causes of Salinity in the Limestone Aquifer

The discussion so far has centred around the occurrence and nature of the saline waters, either as springs or from boreholes, and it should have been apparent that in most cases, this occurred in proximity to the east-west trending South Coast Fault system.

6.8.1 Kemps Hill -Raymonds - Hayes Common Wellfields

The origin of the mineral springs has been discussed and, with regard to the boreholes, there would seem to be three possible sources. The salinity could have the same origin as the springs, it could be caused by seawater intrusion or it might be associated with salinity in the alluvium.

Taking the above ideas in reverse order, it seems unlikely that the major salinity in the limestone is derived from the alluvium. It has been shown that, over most of the area in which the two systems occur, they are not in hydraulic continuity and that hence a large scale passage of water from the surficial deposits into the limestone aquifer will not take place. Further, the salinity in the alluvium is principally south of Kemps Hill and thus 'downstream' of the areas of affected limestone. In fact, in the Raymonds area, the salinity of the alluvial groundwater is significantly less than that of the underlying aquifer.

The only place in which contamination from the alluvium is conceivably occurring is the Springfield area where the groundwater from the upper formation is thought, by the writer, to be spilling over into the limestone aquifer. This is further reinforced by the long term trends in quality exhibited by wells in that area. Here the onset of increases in chloride content took place later than in most areas and was, to some extent, synchronous with the northward movement of the salinity contour in the alluvium (Fig. 6.11).

In the case of the Kemps Hill wells, the salinity values are far higher than those recorded in the alluvium and this suggests that any transfer of salinity is likely to be from the limestone to the alluvium and not vice versa.

If the salinity in the limestone wells is caused by sea water intrusion then this could occur either by lateral movement along the fault or, alternatively, by direct inland movement through the downfaulted limestone to the south of the fault.

In the case of lateral movement this means that the sea water travels some 7 or 8 miles from either the east or west, in order to reach the Kemps Hill area, and that there must be a continous zone of high permeability along this length. Alhough this is not impossible, it does seem easier to envisage selected zones of high vertical permeability rather than one continuous zone stretching both vertically and laterally.

If seawater were reaching the boreholes by moving northward through the down-faulted block, then the distance to the Kemps Hill area would only be some 4 miles. For this to occur it would mean that, prior to the artificial abstraction of groundwater, the natural outflow of groundwater from the limestone aquifer would have been primarily through this block. The water, on encountering the fault, would be partially dammed up by the surficial deposits on the downthrow side of the fault, which must abutt into the southern face of the limestone on the upthrow side. The water would then move vertically down in the fault zone until it encountered the downthrown block of limestone, through which it would be able to continue its seaward journey. It is likely that appropriate solution passages exist in this downthrown block, as karstification would have commenced in the Newport Limestone long before the late Pliocene faulting took place.

The existence of the Portland Ridge suggests that there is another major fault parallel to, and south of, the main E-W fault and hence, the groundwater would probably discharge into the sea along that feature. Once significant quatities of water were abstracted from wells and boreholes in the limestone then the natural equilibrium would be disturbed and a reverse flow through the downfaulted block would occur. This would come about due to the fresh water head being less, at the point of discharge, than the hydrostatic pressure of the seawater.

Initially it is possible that intermittent flow reversals in both directions would have occurred, depending on the influence of recharge and abstraction on the hydraulic head of the fresh water reservoir at one end, and on tidal fluctuations at the other end of the system. This would result in a thorough mixing of the fresh water and sea water with little stratification. Under conditions of sustained pumping from the fault zone, mixing would have occurred there as well, gradually giving rise to a brackish water zone.

This theory is perfectly plausible but does not account for the highly saline limestone boreholes which were drilled, and abandoned, on the Tarentum and Gibbons properties at an early stage of the development of groundwater in the area.

The remaining theory for the occurrence of the saline waters in the limestone aquifer is that they owe their origin to the same source as the mineral springs. If this is the case then the principal direction of movement is likely to have been vertically upwards by much the same mechanism as that postulated for the spring water. The significant difference, however, is that the springs flow naturally whereas the movement into boreholes has apparently been induced by pumping.

This difference in flow mechanism was cited by Wirtz (1970) as a major argument against the idea that the two groups of saline waters could have a common origin. An examination of the groundwater map (Fig. 5.9) however, will show that the regional groundwater elevations in the vicinities of the two mineral springs are some 8 to 10 feet lower than in the vicinity of the contaminated boreholes. Thus, it is easy to envisage a situation where, under natural conditions, the head in the limestone aquifer would be adequate to maintain a vertical hydraulic gradient that decreased with depth. On pumping from these boreholes, however, the induced lowering of the piezometric level would enable the mineralised waters to move upwards in the fault zone. With this theory, it is easier to explain the existence of saline water in those boreholes in which it was encountered at the time of construction, and before major groundwater abstraction had taken place.

6.8.2 Windsor Lodge Wells

A discussion of the salinity in the limestone wells would not be complete without looking at the problem encountered in the Windsor Lodge boreholes, which was described in an earlier section. These boreholes are some four to five miles north of Kemps Hill and exhibit chloride contents in excess of the regional trends for that area (see Fig. 6.9). Here again there are several possible causes of this salinity and each will be described and evaluated.

River Water - On first consideration, this would appear to be a likely cause. The Sevens Estate Sugar Factory, situated on the Rio Minho north of May Pen, discharges large quantities of processing waste into the river at certain times of the year. No analyses of the chemical content of this effluent were made available to the writer but simple field observations have shown that it has a marked visual impact on the quality of the river water. Thus it would appear to be a potential source of poor quality water that might find its way into the limestone aquifer south of May Pen, and hence into the Windsor Lodge boreholes. An examination of the available analyses for the Rio Minho water at various localities however, suggests that this is not the case. Samples from the river, south of the area under discussion, show extreme variations with the chloride content increasing from 14 ppm in April 1971 to 450 ppm in June 1971. It is likely however, that this effect does not reflect the water quality at the upper end of the plain but is a combined effect of seawater and returned irrigation water. What is more important is that a sample collected at May Pen in April 1971, when the river was said to be 'badly polluted' by the sugar factory, had a chloride content of only 16 ppm. Thus it would appear that, even if a mechanism could be developed to explain the recharging of the limestone aquifer by the river, the chloride content of the river would not be high enough to explain the salinity in the Windsor Lodge boreholes.

Alluvial Aquifer Water - The hydraulic head in the alluvial aquifer is greater than the head in the limestone aquifer. Thus, in areas where some flow is possible between these two formations, it is likely to be from the upper aquifer down into the limestone. In addition to this, it is possible that water from the alluvium might flow into boreholes which had not been adequately cased during construction. As the alluvium is likely to be recharged by excess irrigation water, it is conceivable that the leaching of salts has caused the decline in quality of the water in this surficial aquifer. Leonard (1970) showed that in an area in Kansas the chloride content of the groundwater increased as irrigation continued. Law et al (1970) succeeded in quantifying this phenomenon and showed that percolating irrigation water carried down about ten tons of salt per acre-foot.

Once again, however, an examination of the available water analyses shows that, though a theoretical mechanism might be developed to explain the movement of water from that particular source, the actual salt content in the alluvial water at this location is insufficient to account for the chloride content in the limestone boreholes. Samples from alluvial boreholes numbers 216 and 292, collected in 1969, show chloride contents of only 26 and 24 ppm respectively, thus negating the theory that saline alluvial water is responsible for the poor quality of the Windsor Lodge boreholes.

Saline Limestone Water - Having excluded the possibility that the salinity is derived from a source above the limestone aquifer in the immediate vicinity (i.e. from the alluvium or from the river), the remaining alternative is that it is associated with the main salinity problem that occurs in the limestone. The high chloride values in the Windsor Lodge area represent an apparent anomaly in that, as you move southward towards the coast, and towards the exceptionally high values at Kemps Hill, then the salinity decreases before it starts to increase again. In constructing the isochlors, it is necessary to have a number of closed loops which form a bullseye around borehole number 222. This implies that, apart from the remote possibility that there is a virtual point source of salts, then the salinity must be reaching the boreholes by moving vertically. As it has been effectively shown not to come from the surface then it must be moving upwards within the limestone aquifer.

An examination of the salinity gradient around borehole no. 222 reveals an interesting effect. Moving in a generally easterly direction the chloride content only falls to 240 ppm at borehole number 215, which is at a distance of of approximately 1/2 mile and to 74 ppm at borehole no. 212 which is 1 mile away. In contrast to this, however, borehole 221 which is approximately 1/2 mile to the north-northwest and borehole 230, which is 1 mile to the southwest, both had 1972 chloride values of only 27 ppm. This is significant in that the lower values are on the opposite side of the fault which runs NNE from Kemps Hill towards May Pen. Thus there is further evidence that the flow of groundwater within the Clarendon Plains is controlled to a great extent by this north-south fault. In fact it would seem likely that the saline water is present at depth within this fault zone and, due to the hydraulic characteristics of the limestone unit to the east, it manifests itself predominantly in that area.

The fact that lower salinity values actually occur within the fault zone to the south seems to preclude the lateral movement of seawater and indicates that the principal mechanism here is one of vertical movement, probably from beneath the White Limestone.

6.8.3 Summary

The saline water in the limestone may be either from the same source as the mineral springs or it may be a result of seawater intrusion. If the former is the case then movement is likely to have been vertical and associated with faults. If the latter is the case, then movement may have been either laterally along faults or directly inland through solution cavities in the down-faulted limestone.

It appears likely that both the mineral springs and the Windsor Lodge boreholes receive their saline water from mineralised meteoric water rising from Eocene deposits, rather than from seawater. In the case of the Kemps Hill - Hayes Common wells the origin is not so clearcut. However, in view of their proximity to the East-West fault zone, and the fact that boreholes at Tarentum and Gibbon were highly saline from the outset, the writer is inclined to accept this as circumstantial evidence of a common origin with the mineral springs.

In the section on water resources it is shown that the area to the east of the North-South fault is suffering from the over abstraction of groundwater and, thus, it is easy to see why the saline waters would be given an opportunity to move into the wellfields.

The Kemps Hill wells are situated at the junction of the East-West and North-South fault zones and thus they would be doubly susceptible to this problem.

The fact that the uprising of mineralised meteoric waters is favoured as the source of salinity does not necessarily exclude seawater intrusion as a contributing factor in the southern areas. Similarly, it was shown that contamination of the limestone by downward percolating alluvial water might have been a factor in the South-Western part of the plain.

6.9 Results of Cluster Analysis

The programs used for cluster analysis are described in Chapter 8. There it is explained that the initial work was carried out using a library program on an I.C.L. 1905E computer, but that the research was completed on a smaller machine using a somewhat simpler program.

The initial run on the larger machine was carried out using the chemical data from the 1972 sampling programme. Some 51 analyses were available, predominantly from limestone wells, and the concentrations of the various parameters in parts per million were input, along with the conductivity. The program standardised this data and then clustered the various samples on the basis of the degrees of correlation.

The resulting dendrogram (Fig. 6.36) does not, on first appraisal, appear to be particularly conclusive as most of the analyses cluster together with about the same degree of correlation. A closer study, however, reveals that this pattern is reasonably representative of the actual waters.

Sample 45 is from well no. 345 (Salt River Corehole) in which the water is considerably more saline than in the other wells. Samples 46 and 51 are from the only alluvial wells which were included in this batch analyses, and samples 1 and 2 (wells 85 and 86) were significantly different when plotted on the extended Durov diagram Fig. 6.26).

Samples 4, 5 and 15, at theleft-hand end of the dendrogram (wells 89, 95 and 125) and samples 3 and 39 at the right-hand end (wells 87 and 222) appear to be different to the main group of analyses and, indeed, when reference is made to the Durov diagram (Fig. 6.26) it can be seen that these analyses all plot in the lower central field. Well No. 222 is the Windsor Lodge borehole with the abnormally high salinity values, which was shown earlier to be something of an anomaly in that area. An examination of the overall distribution of these analyses on the extended Durov diagram reveals that, in fact, most of the remaining analyses are similar, with bicarbonate being the dominant anion and calcium the dominant cation. Thus the similarity shown on the dendrogram is actually representative of the chemical characteristics of the waters.

Encouraged by the qualified success of the above attemps at cluster analysis of chemical data, it was decided to continue the work in the hope of arriving at some more conclusive results. As the 1972 limestone data was not totally representative of the full range of chemical characteristics, the 1970 and 1971 limestone data, which had been plotted on the extended Durov diagram shown in Fig. 6.26, was used. As the writer no longer had access to the University computer the work was continued on the in-house computer of James F. MacLaren Ltd., of Ontario, Canada. The size of this machine was such that a less sophisticated program, as described in chapter 8, was used for the cluster analysis. For the first few runs the basic data (i.e. concentrations in ppm) were input and the results were far from satisfactory. It then became apparent that the main problem was the lack of a standardization routine in the program. Thus the clusters were being formed on the basis of total concentrations (particular total dissolved solids) rather than on the types of water (Fig. 6.37).

In order to overcome this problem the data was input in the form of reacting values of the common ions rather than the straight concentrations. In this way, there was a significant improvement in the clustering and the resulting dendrogram bore a close resemblance to the groupings shown on the extended Durov diagram. The options of grouping by correlation and distance were used and it was found that the latter gave a marginally better correlation with the Durov diagram. The two dendrograms are shown in Figs. 6.38 and 6.39 and the appropriate Durov diagram has been redrawn in Fig. 6.40 in order to facilitate comparison with the cluster analysis.

In summary it would seem that cluster analysis is feasible as a means of classifying waters on the basis of their chemical characteristics. The results from the more sophisticated programme, although not developed fully in this present work, appear to offer the most potential as a means of achieving a greater degree of sophistication in the analysis of groundwater chemistry. With the simpler program the data has to be standardized before input and, unless further statistical manipulations are to be carried out, this is best achieved by reducing the concentrations to percentage reacting values. Thus, although this program achieves similar results to the graphical methods, and allows a cross-check to be made, it does not go much further. The more sophisticated clustering program, on the other hand, offers an improved form of classification, in that it combines the relative concentrations of the various ions with the overall concentration of dissolved ions or, indeed any parameter that is deemed significant. Thus it might be that, for example, pH would be included in the basic data if this was thought to be significant.

Where cluster analysis would seem to be of the greatest value is either in the handling of large numbers of analyses or, alternatively, as a cross-check on graphical methods where it may highlight differences which would not otherwise be obvious.

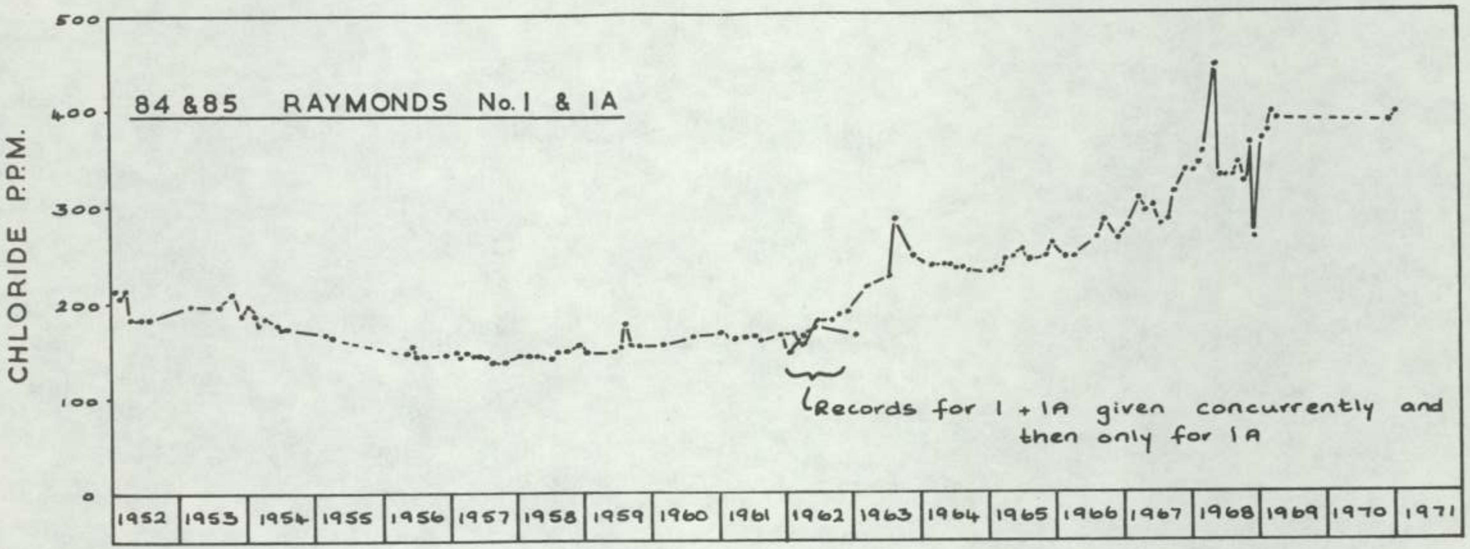
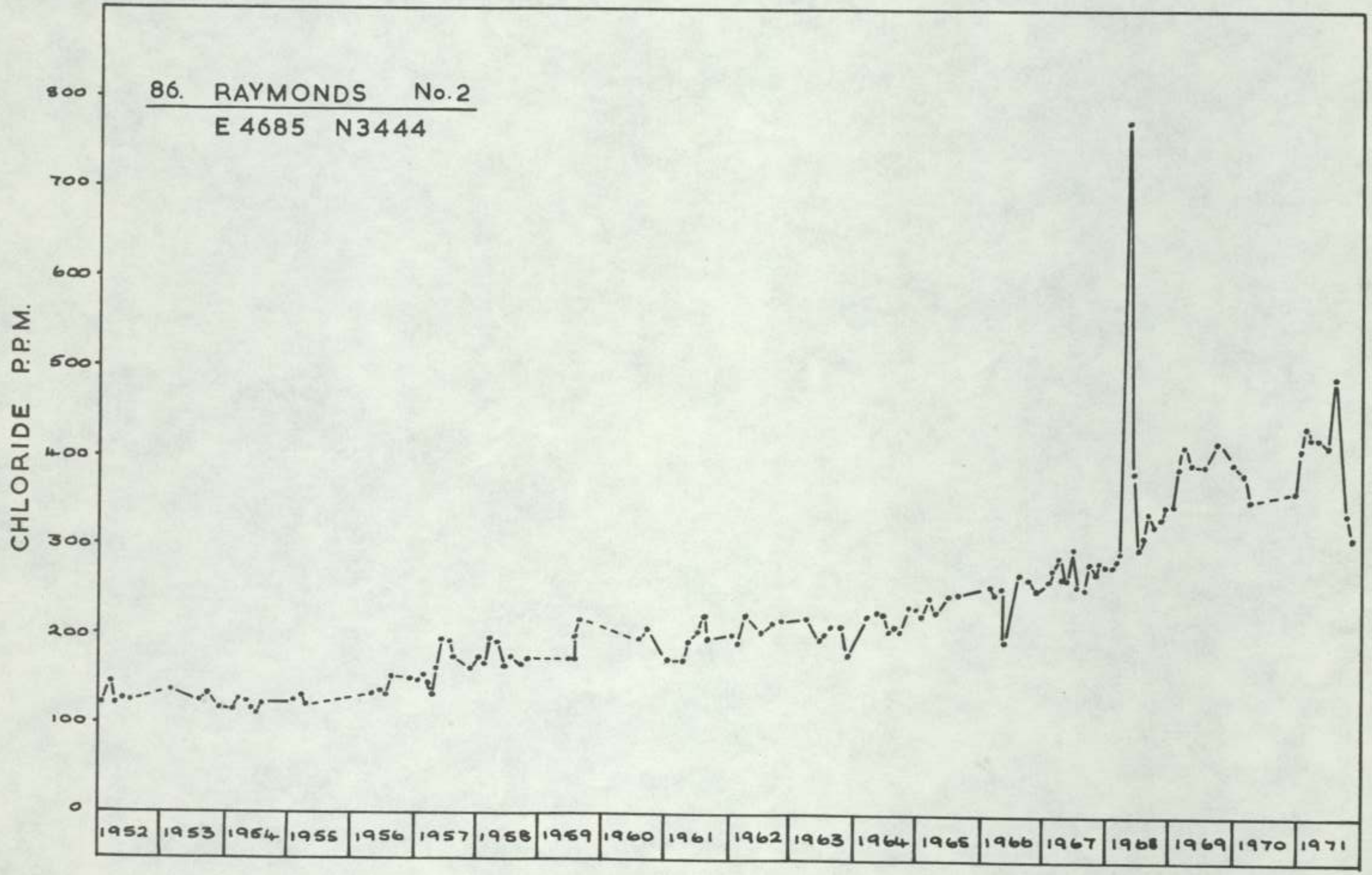


FIG. 6.1 VARIATION OF CHLORIDE CONTENT (PPM)

(CONT./)


86. RAYMONDS No.2
E 4685 N3444
CHLORIDE P.P.M.
800
700
600
500
400
300
200
100
0
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
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1965
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1967
1968
1969
1970
1971

FIG 6.1 (CONT)

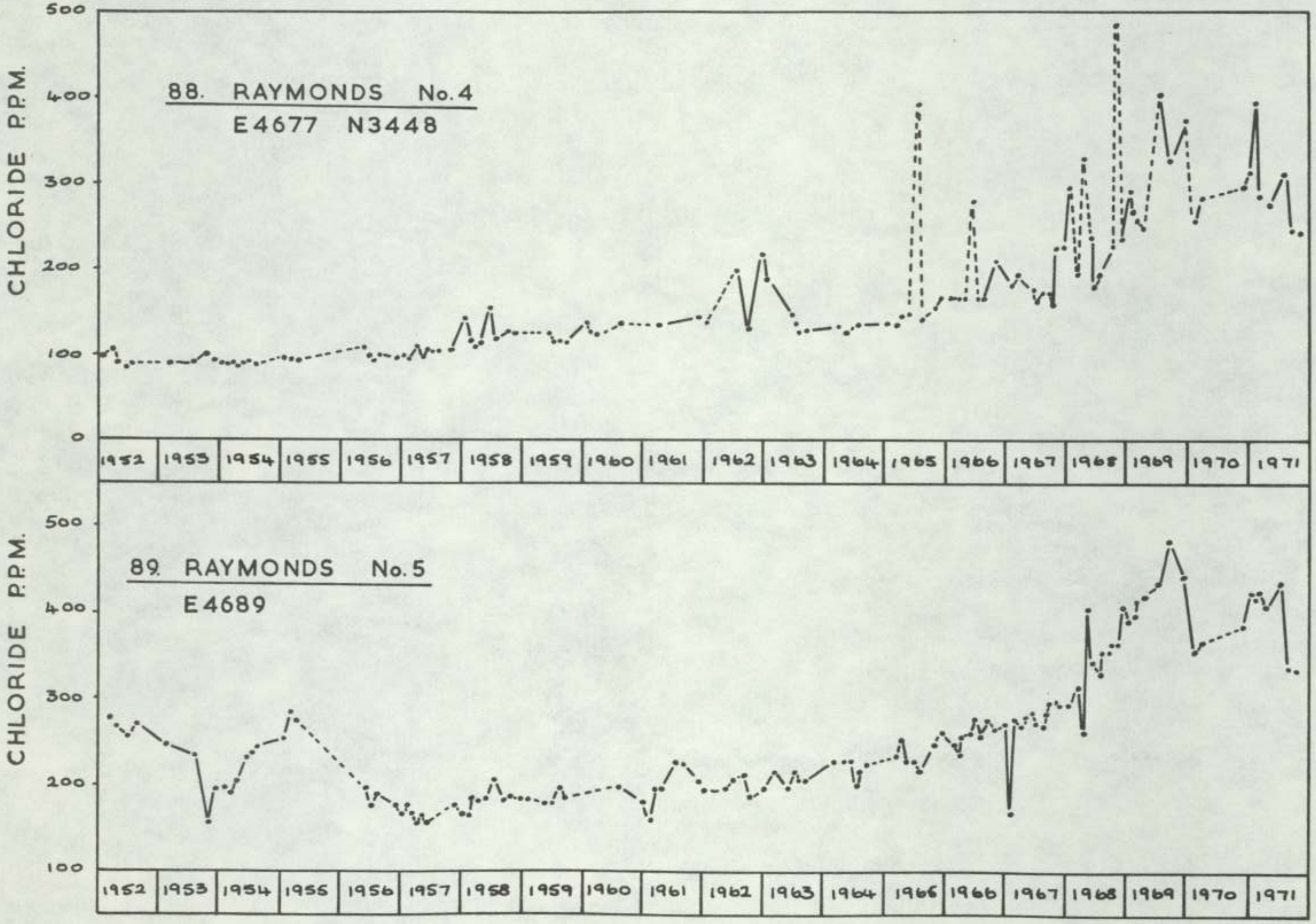

88. RAYMONDS No. 4
E4677 N3448
CHLORIDE P.P.M.
500
400
300
200
100
0
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
89. RAYMONDS No. 5
E4689
CHLORIDE P.P.M.
500
400
300
200
100
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1966
1966
1967
1968
1969
1970
1971

FIG. 6.1 (CONT)

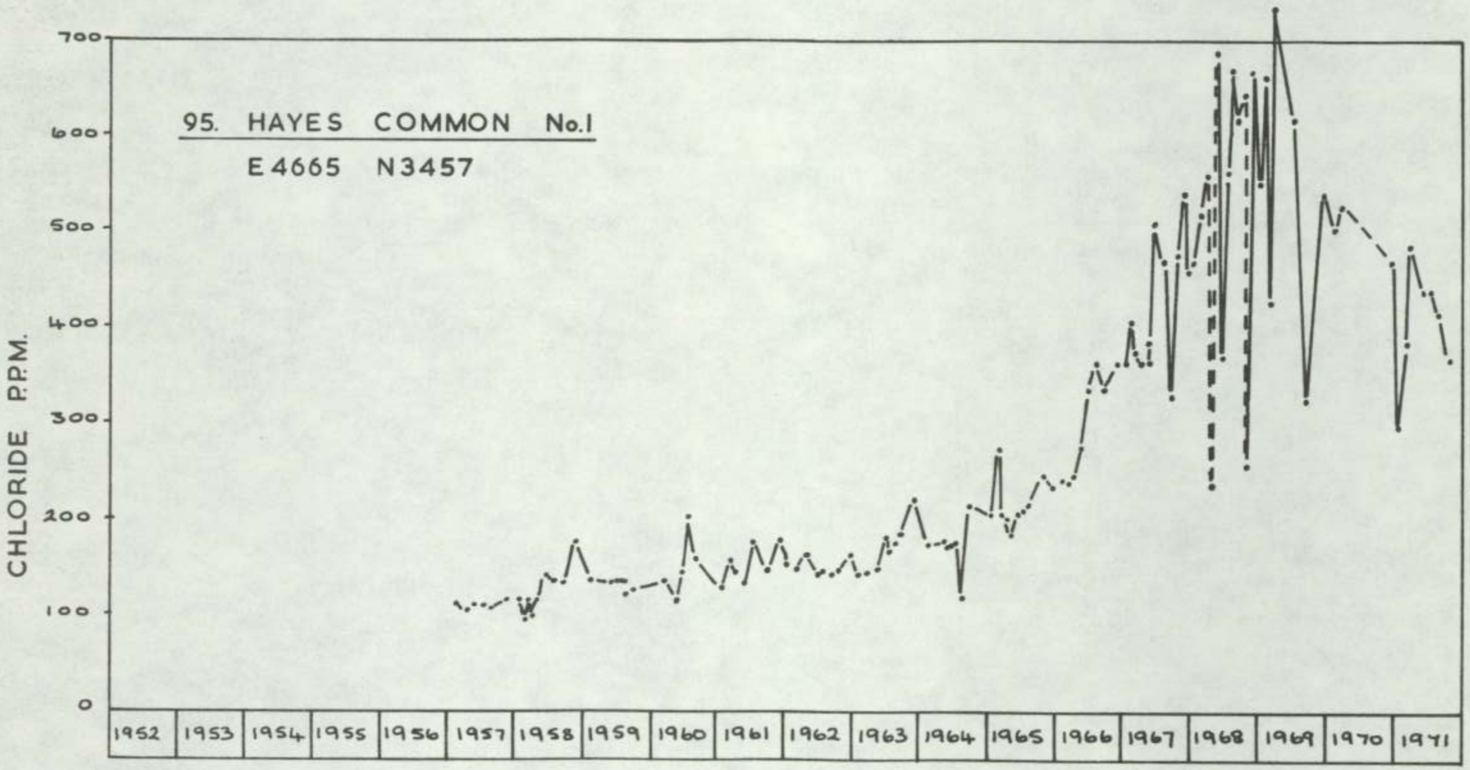
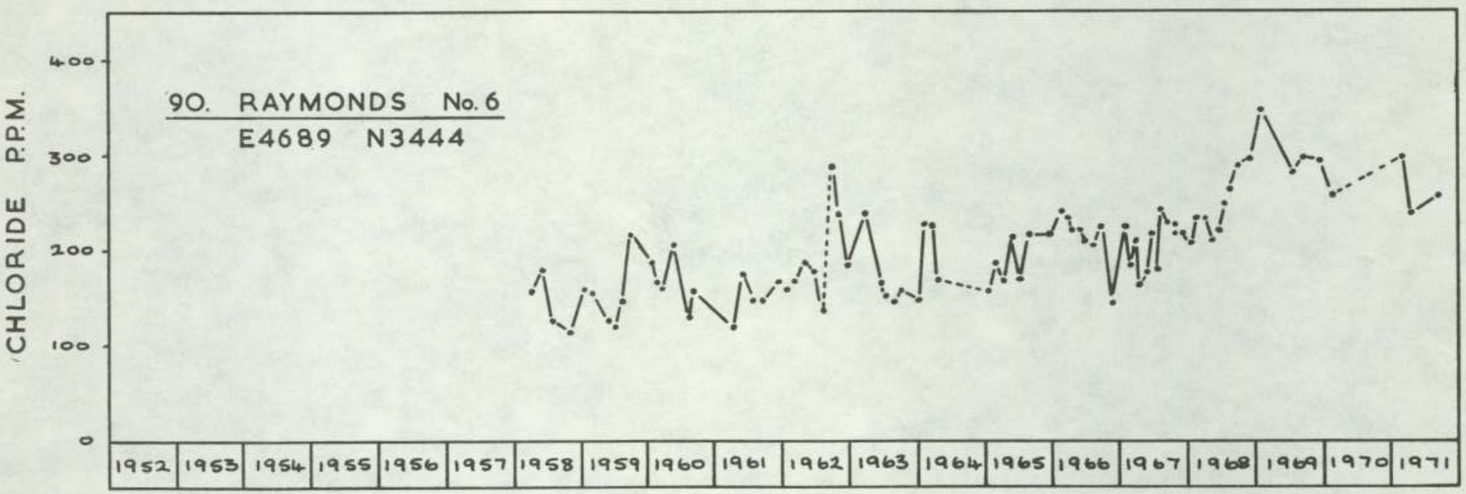

95. HAYES COMMON No.1
E 4665 N3457
CHLORIDE P.P.M.
700
600
500
400
300
200
100
0
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971

FIG. 6.1 (CONT)


90. RAYMONDS No. 6
E4689 N3444
CHLORIDE P.P.M.
400
300
200
100
0
1952
1953
1954
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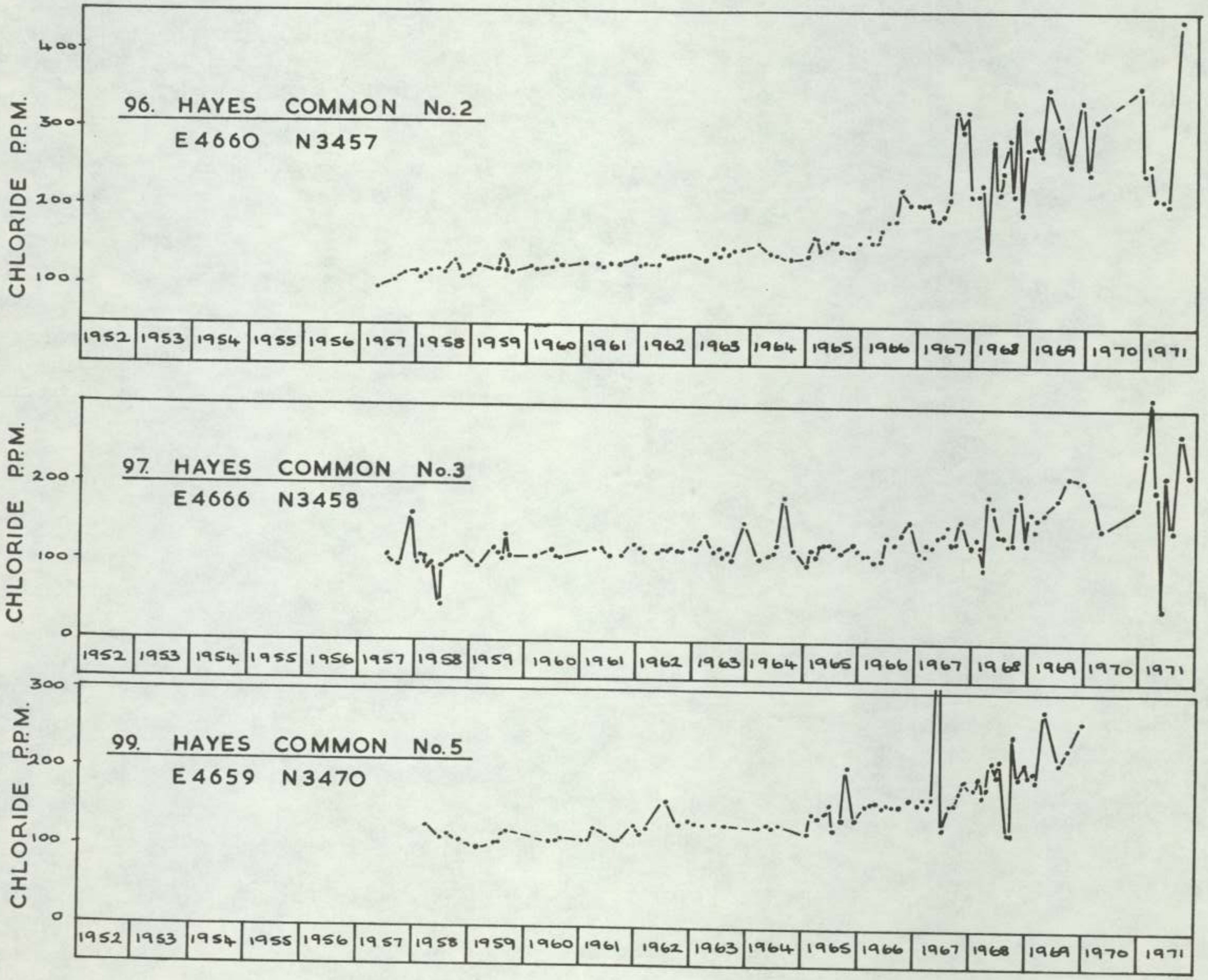
1963
1964
1965
1966
1967
1968
1969
1970
1971

FIG. 6.1 (CONT)


96. HAYES COMMON No.2
E 4660 N3457
CHLORIDE P.P.M.
400
300
200
100
97. HAYES COMMON No.3
E4666 N3458
CHLORIDE P.P.M.
200
100
0
99. HAYES COMMON No.5
E4659 N3470
CHLORIDE P.P.M.
300
200
100
0
1952
1953
1954
1955
1956
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1959
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1965
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1967
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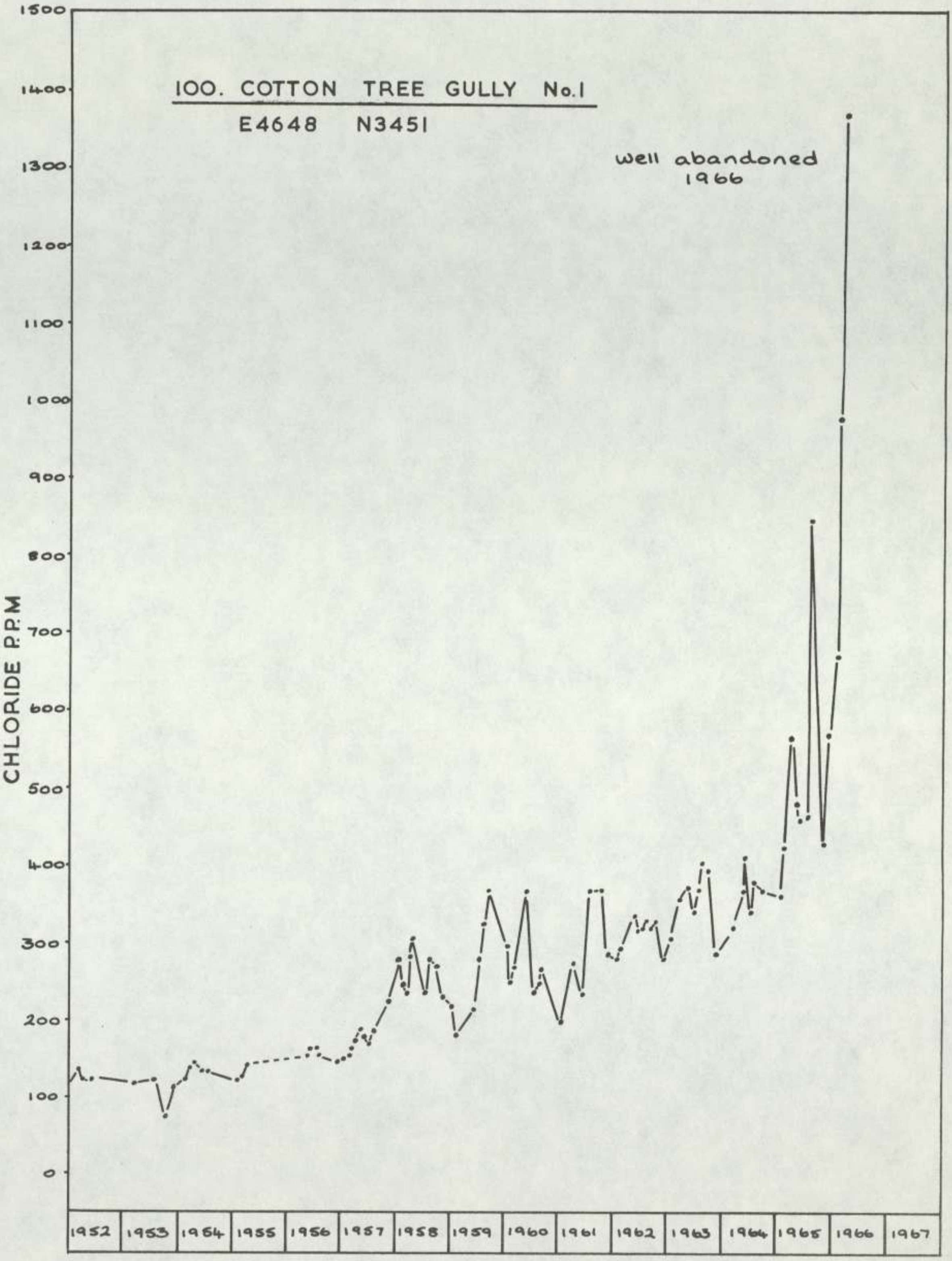
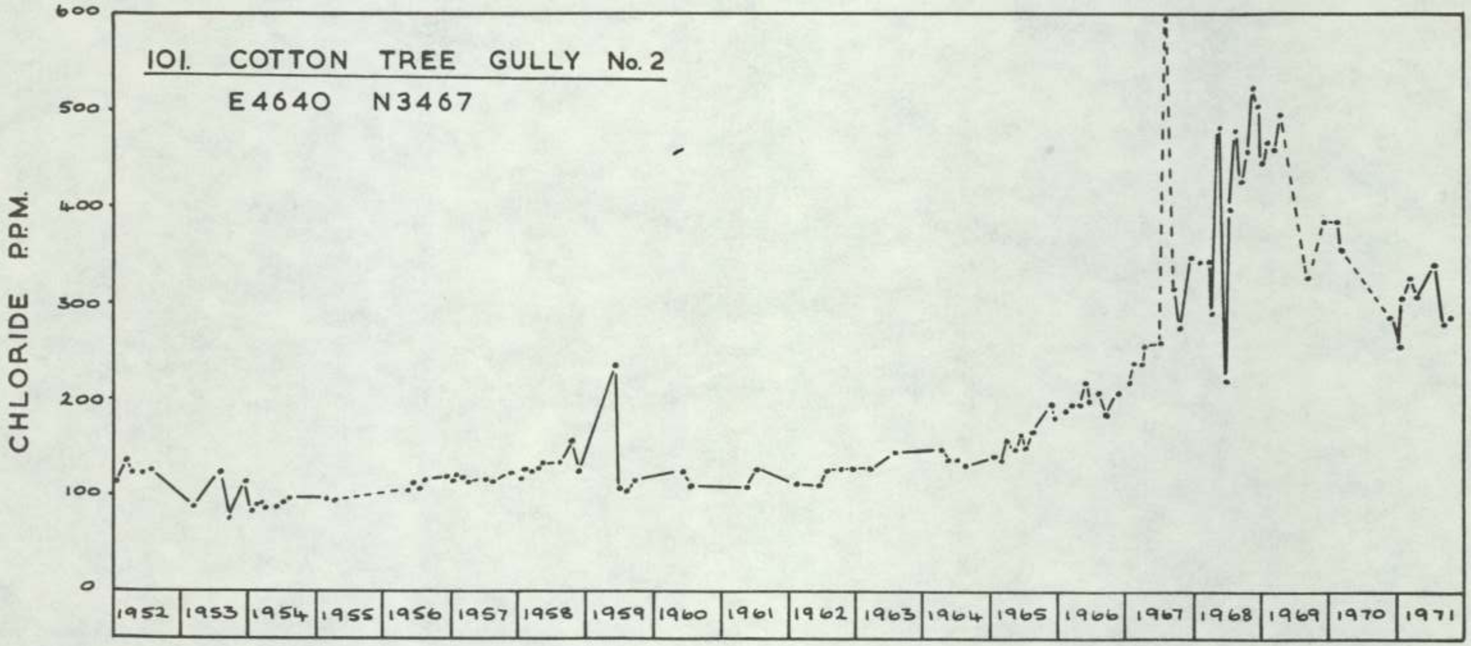
1971

FIG 6.1 (CONT)



100. COTTON TREE GULLY No.1
E4648 N3451
Well abandoned 1966
CHLORIDE P.P.M
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967

FIG. 6.1 (CONT)


101. COTTON TREE GULLY No. 2
E4640 N3467
CHLORIDE P.P.M.
600
500
400
300
200
100
0
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
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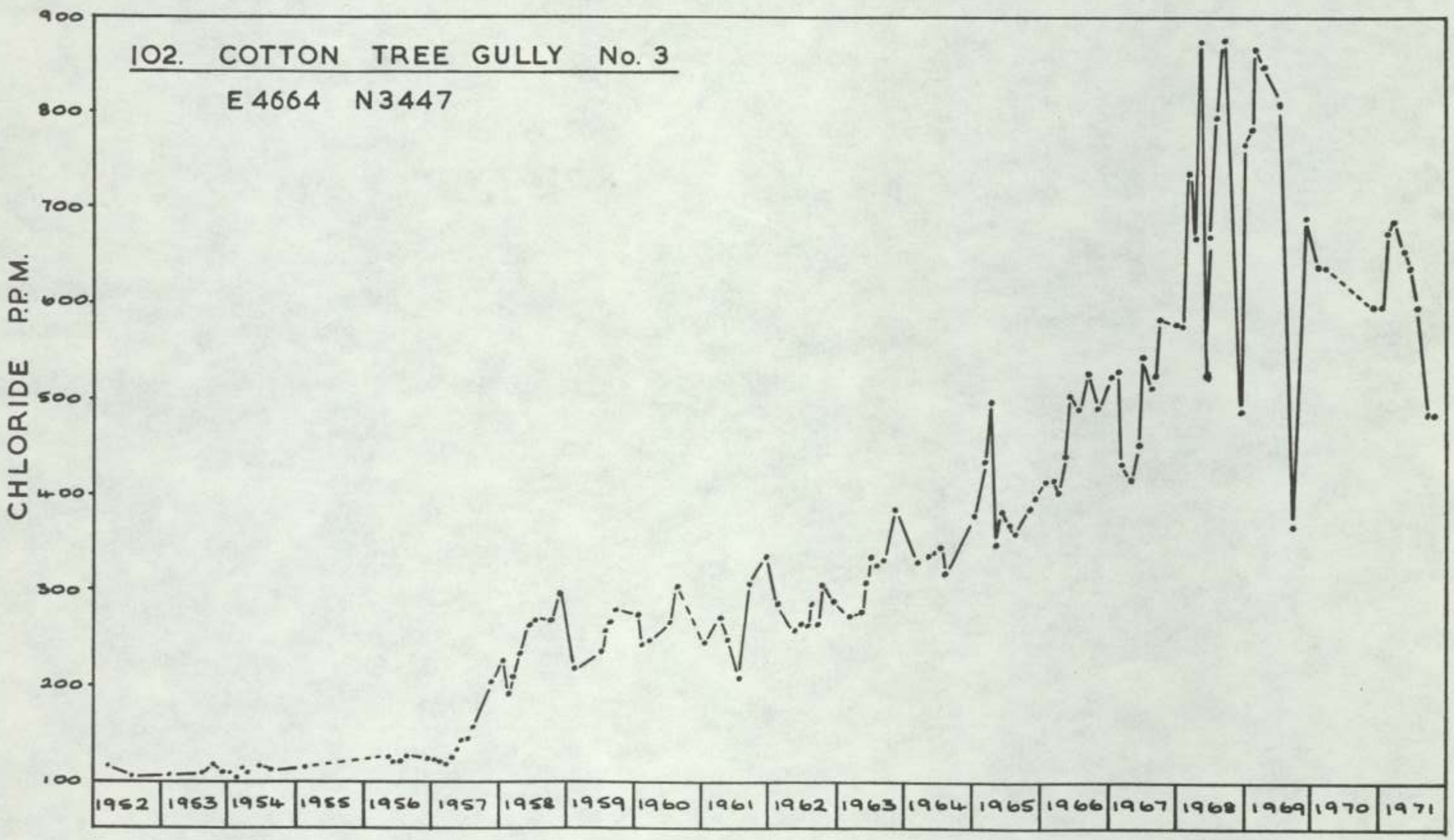
1965
1966
1967
1968
1969
1970
1971

FIG. 6.1 (CONT)


102. COTTON TREE GULLY No. 3
E 4664 N3447
CHLORIDE P.P.M.
900
800
700
600
500
400
300
200
100
1952
1953
1954
1955
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1959
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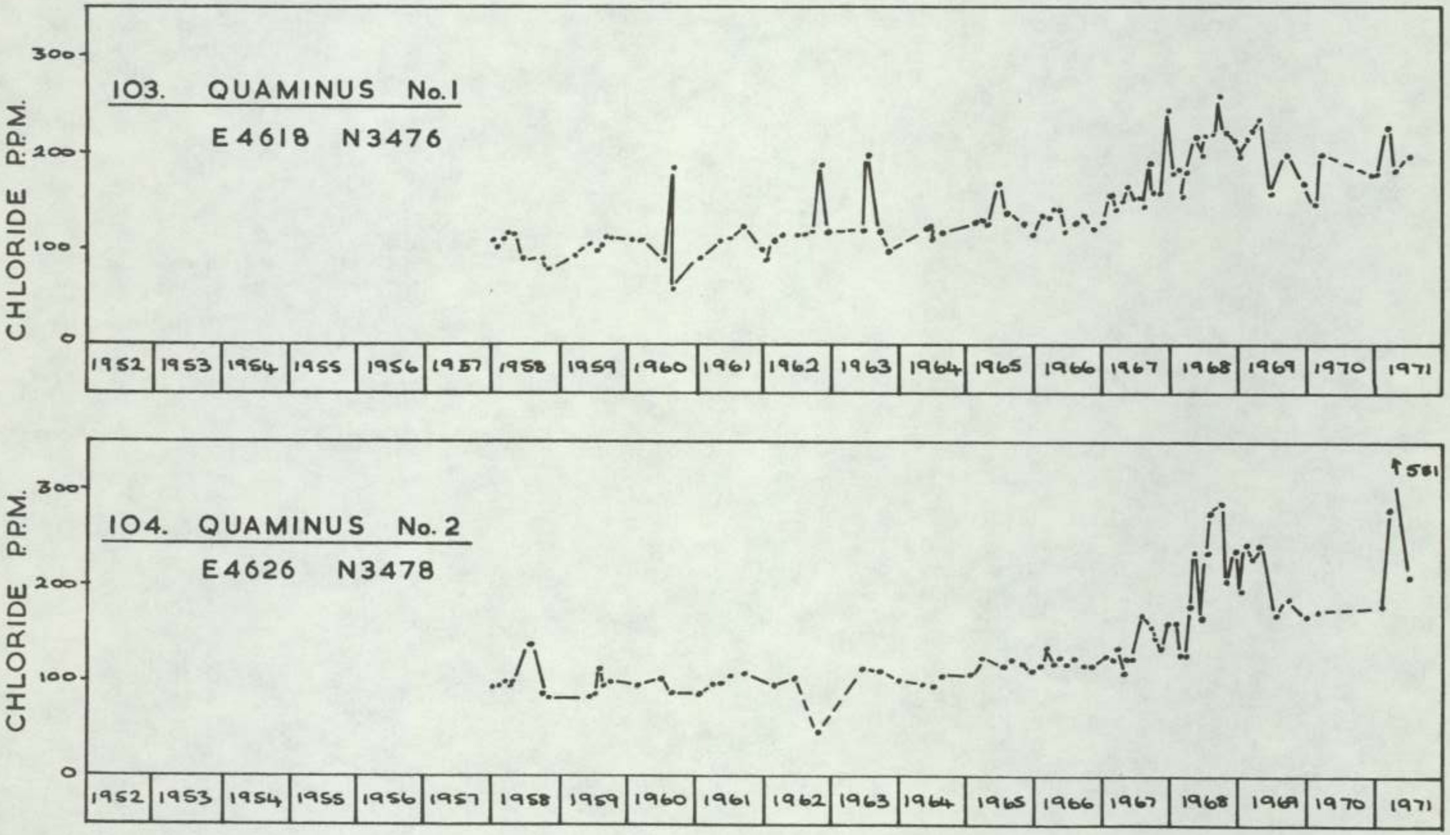
1970
1971

FIG. 6.1 (CONT)


103. QUAMINUS No. 1
E4618 N3476
CHLORIDE P.P.M.
300
200
100
0
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
104. QUAMINUS No. 2
E4626 N3478
CHLORIDE P.P.M.
300
200
100
0
↑581
1952
1953
1954
1955
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1967
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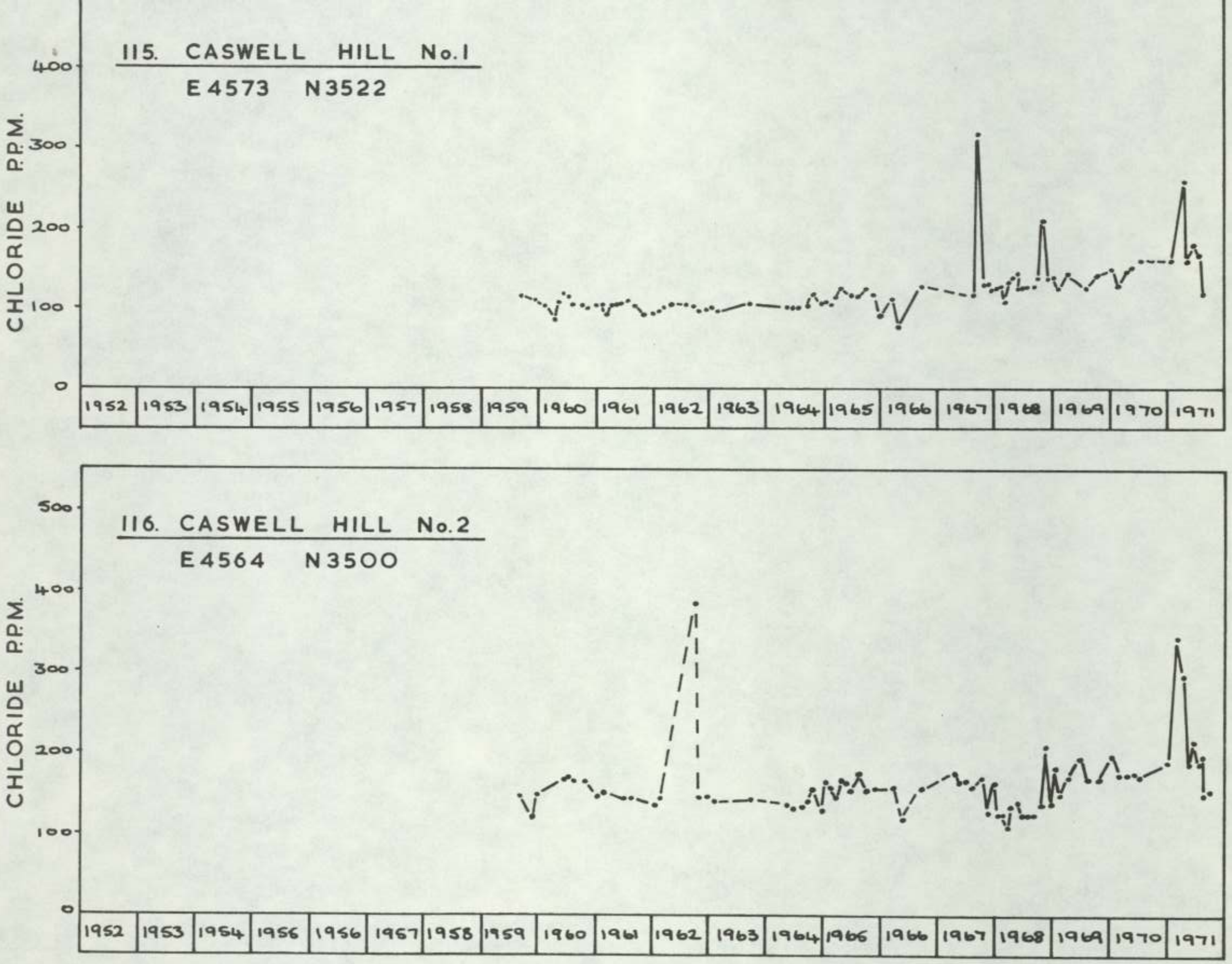
1970
1971

FIG. 6.1 (CONT)


115. CASWELL HILL No.1
E4573 N3522
CHLORIDE P.P.M.
400
300
200
100
0
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
116. CASWELL HILL No.2
E4564 N3500
CHLORIDE P.P.M.
500
400
300
200
100
0
1952
1953
1954
1956
1956
1967
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1959
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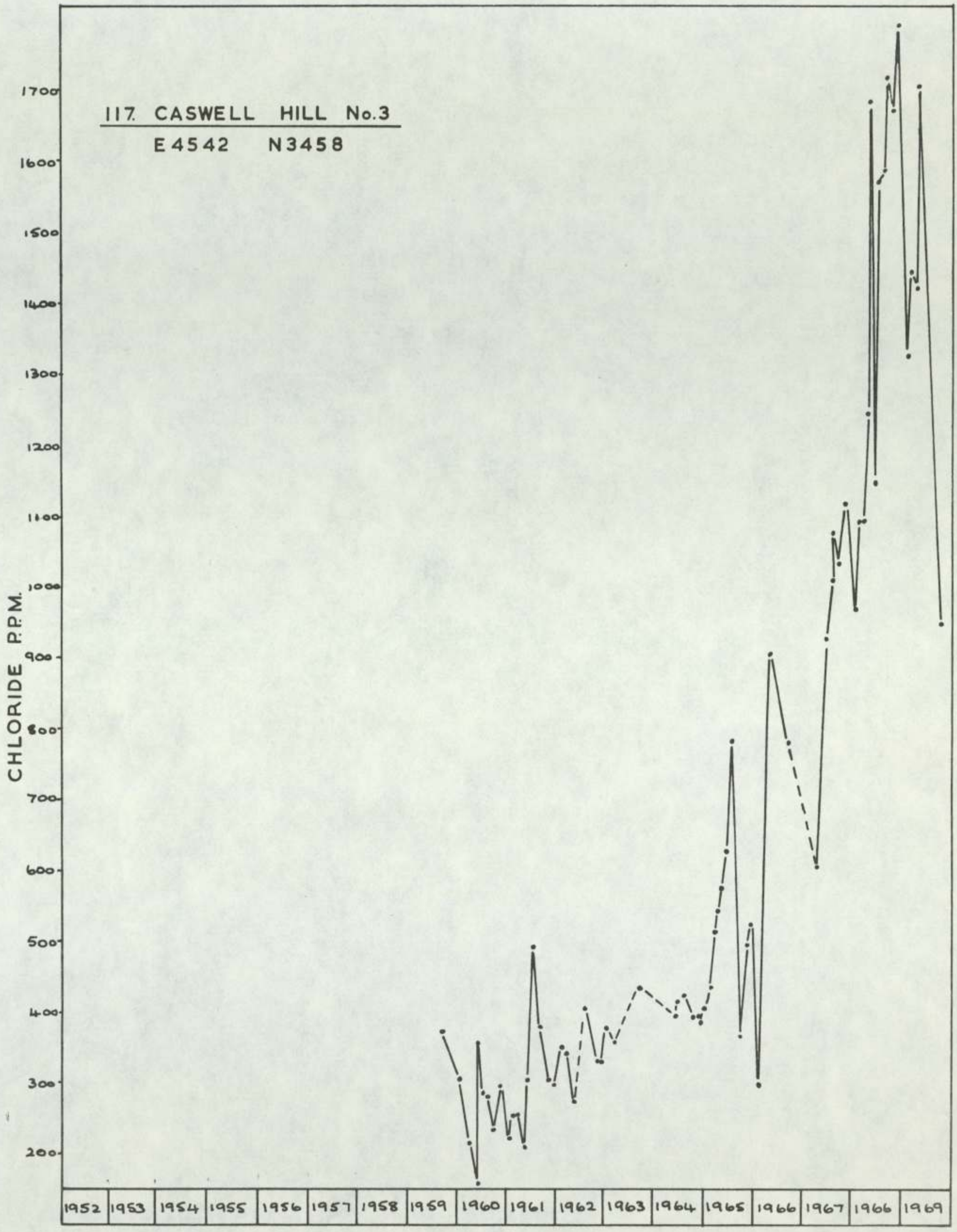
1971

FIG 6.1 (CONT)



117. CASWELL HILL No.3
E4542 N3458
CHLORIDE P.P.M.
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
1952
1953
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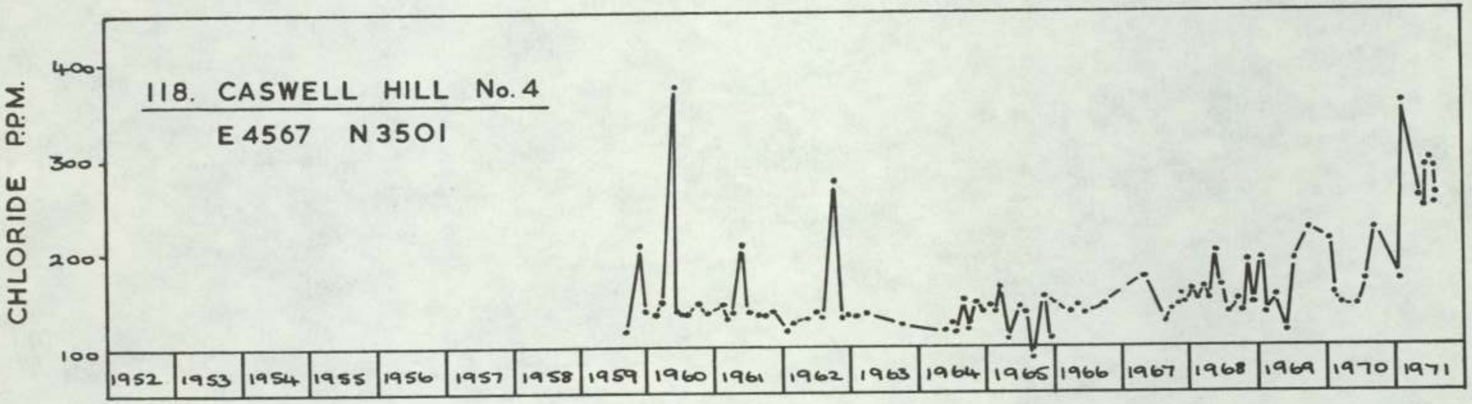
1969

FIG 6.1 (CONT)


118. CASWELL HILL No. 4
E 4567 N 3501
CHLORIDE P.P.M.
400
300
200
100
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
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1965
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1967
1968
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1970
1971

FIG 6.1 (CONT)

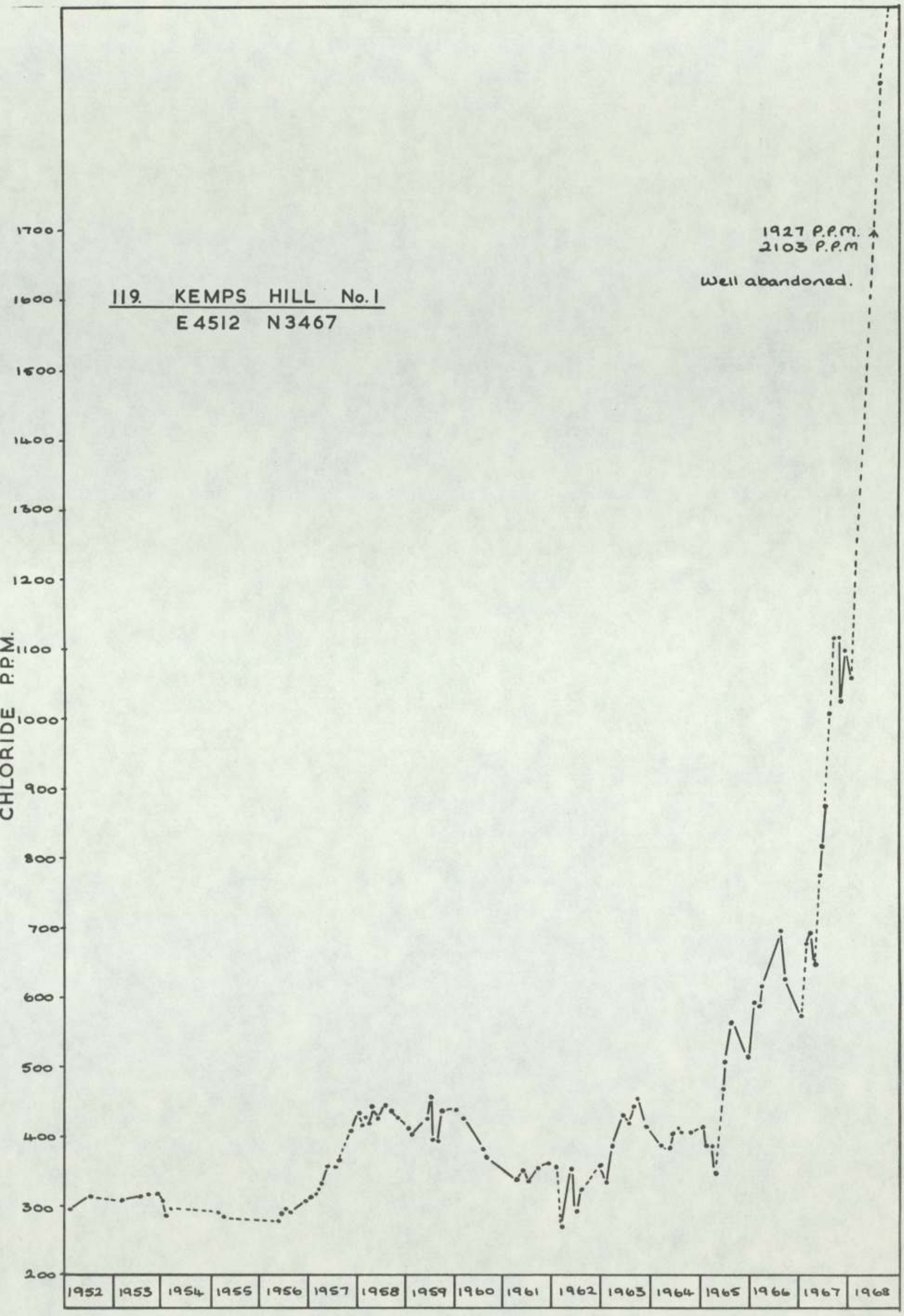
119. KEMPS HILL No. 1
E 4512 N 3467
1927 P.P.M.
2103 P.P.M
Well abandoned.
CHLORIDE P.P.M.
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
1952
1953
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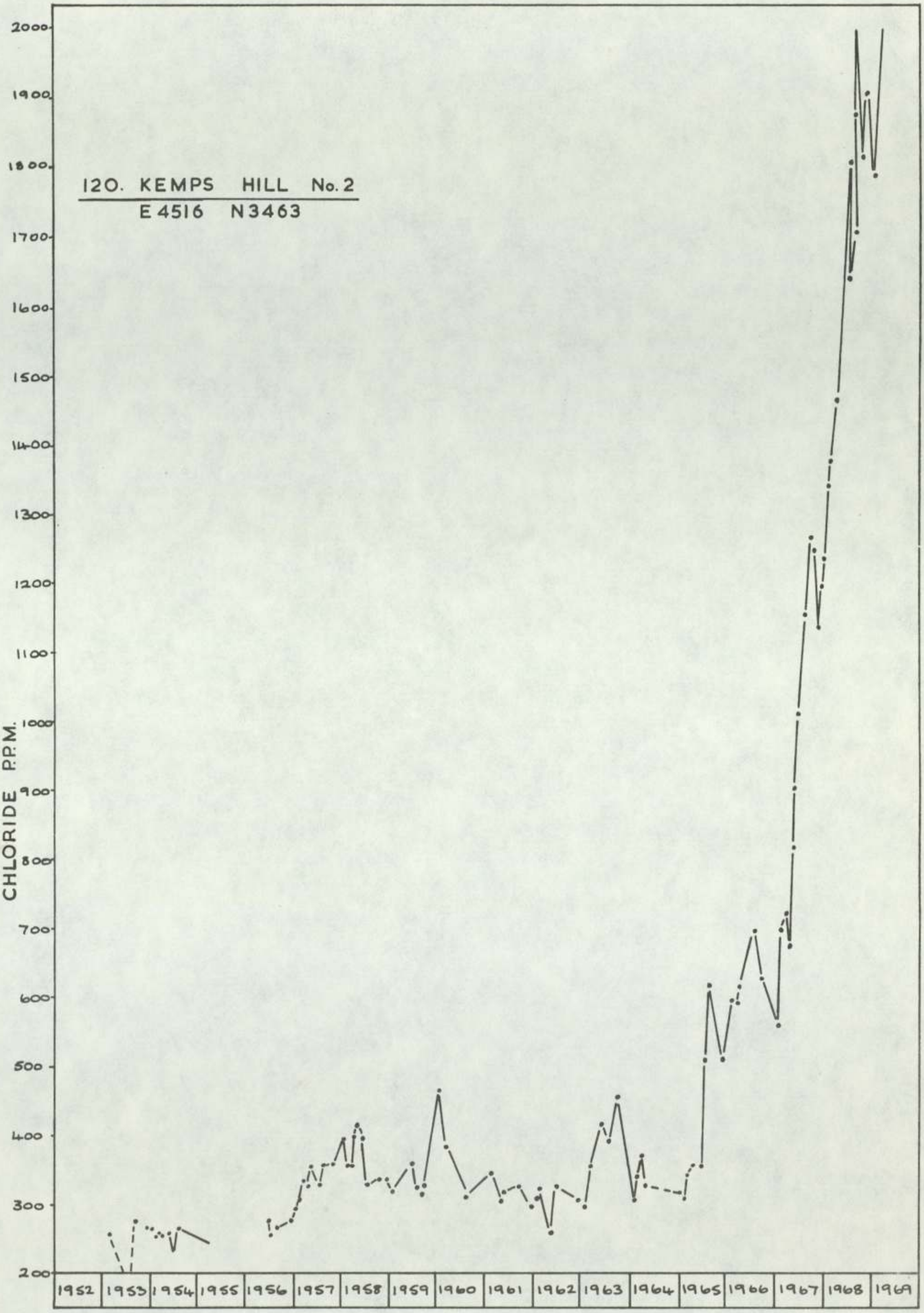
FIG. 6.1 (CONT)

120. KEMPS HILL No. 2
E 4516 N 3463
CHLORIDE P.P.M.
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
1952
1953
1954
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1965
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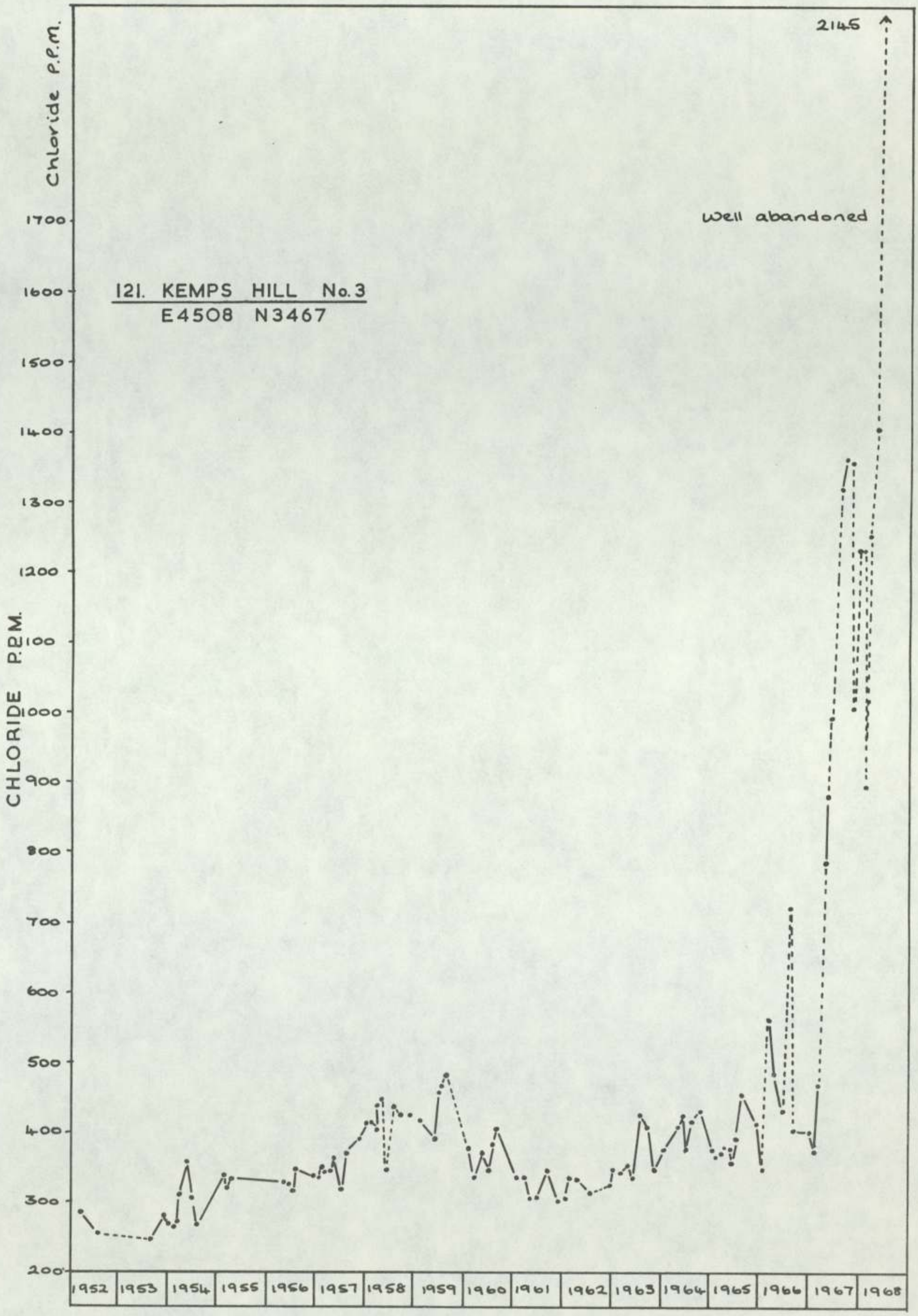
1967
1968
1969

FIG 6.1 (CONT)



Chloride P.P.M.
121. KEMPS HILL No. 3
E4508 N3467
Well abandoned
2145
CHLORIDE P.P.M.
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968

FIG. 6.1 (CONT)

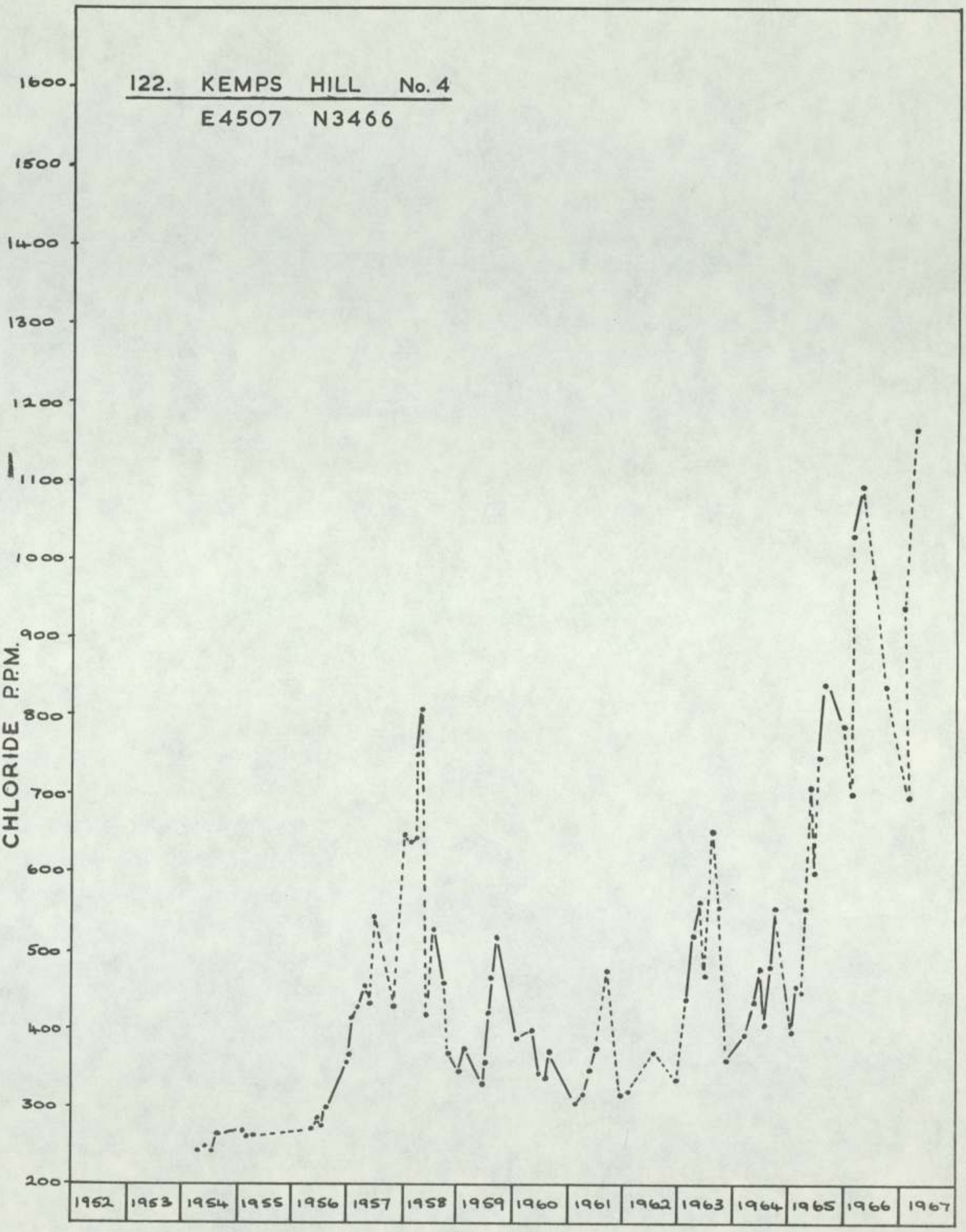

122. KEMPS HILL No. 4
E4507 N3466
CHLORIDE P.P.M.
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967

FIG. 6.1 (CONT)

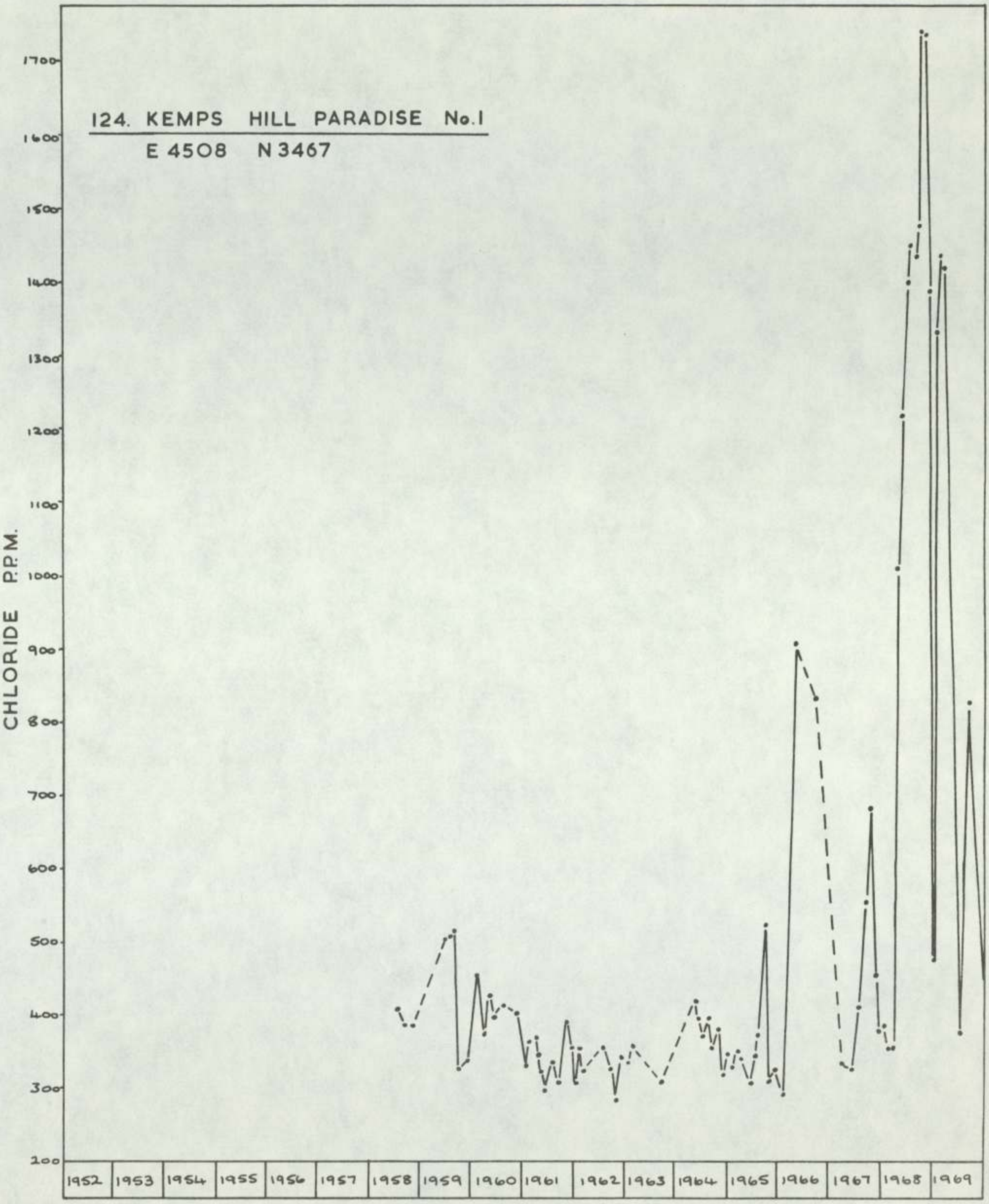

124. KEMPS HILL PARADISE No.1
E 4508 N 3467
CHLORIDE P.P.M.
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969

FIG. 6.1 (CONT)

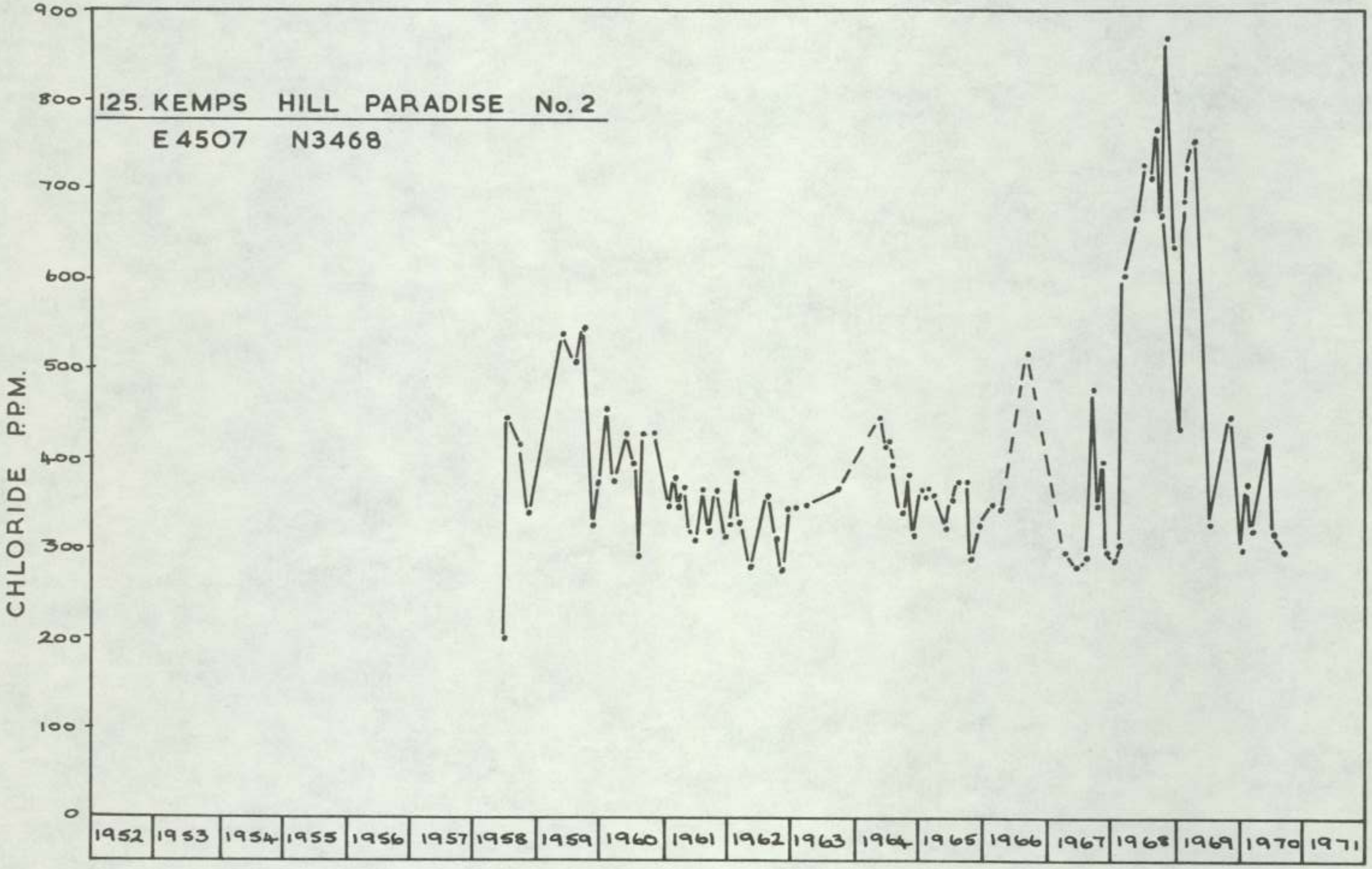

125. KEMPS HILL PARADISE No. 2
E 4507 N3468
CHLORIDE P.P.M.
900
800
700
600
500
400
300
200
100
0
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971

FIG 6.1 (CONT)

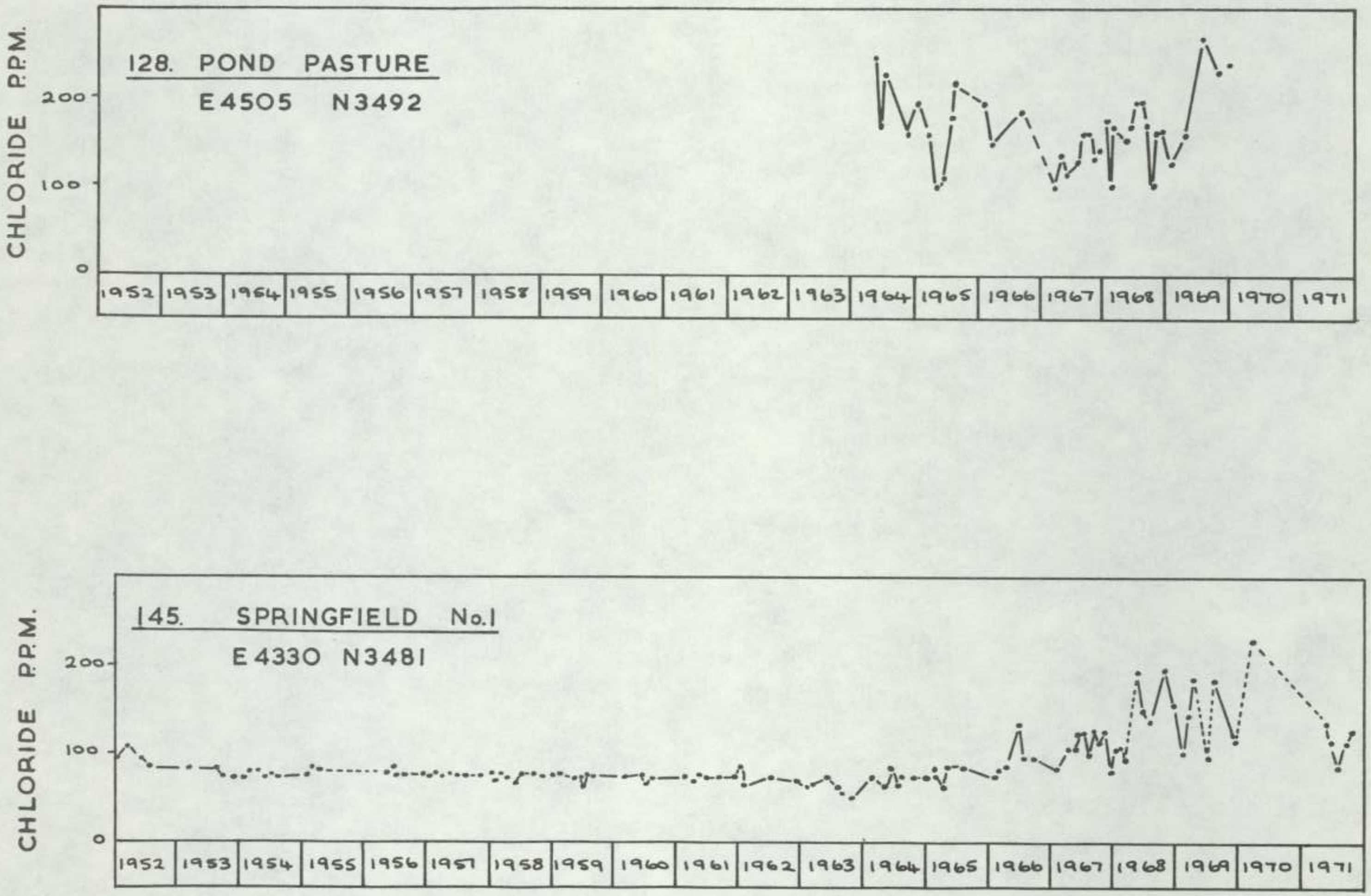

128. POND PASTURE
E4505 N3492
CHLORIDE P.P.M.
200
100
0
1952
1953
1964
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
145. SPRINGFIELD No.1
E 4330 N3481
CHLORIDE P.P.M.
200
100
0
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971

FIG. 6.1 (CONT)

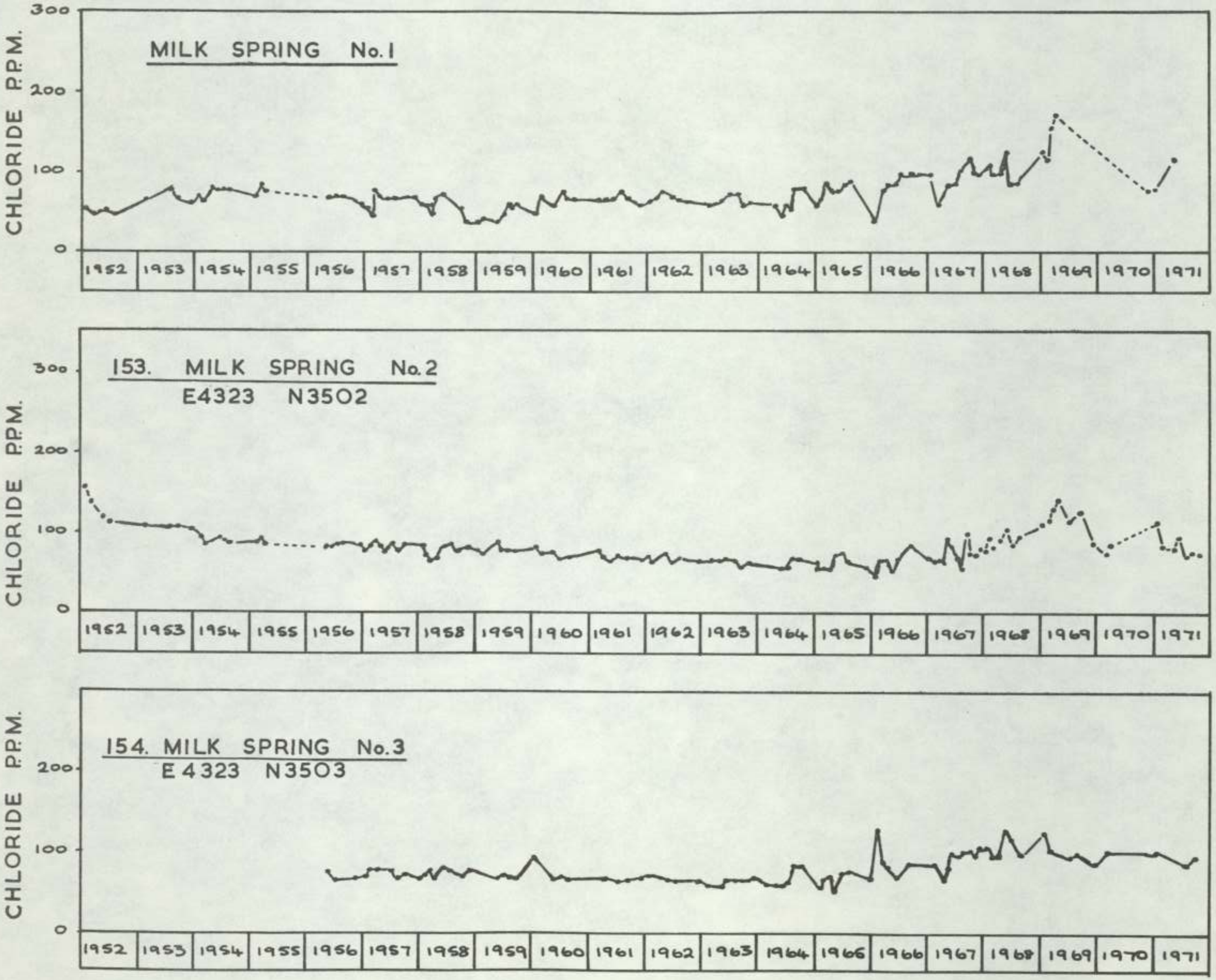

MILK SPRING No. 1
CHLORIDE P.P.M.
300
200
100
0
1952 1953 1954 1955 1956 1957 1958 1959 1960 1961 1962 1963 1964 1965 1966 1967 1968 1969 1970 1971
153. MILK SPRING No. 2
E4323 N3502
CHLORIDE P.P.M.
300
200
100
0
1952 1953 1954 1955 1956 1957 1958 1959 1960 1961 1962 1963 1964 1965 1966 1967 1968 1969 1970 1971
154. MILK SPRING No. 3
E 4323 N3503
CHLORIDE P.P.M.
200
100
0
1952 1953 1954 1955 1956 1957 1958 1959 1960 1961 1962 1963 1964 1966 1966 1967 1968 1969 1970 1971

FIG. 6.1 (CONT)

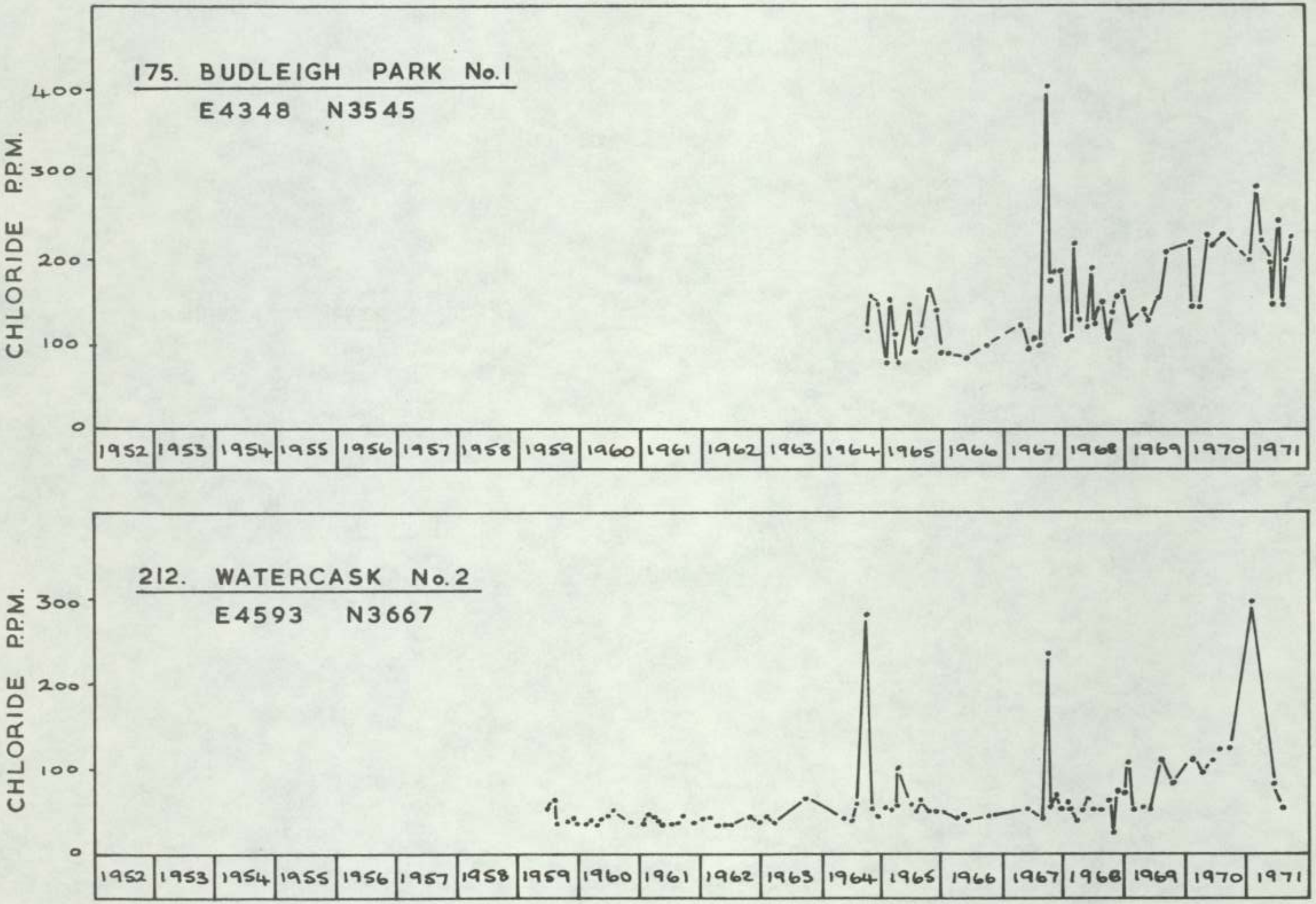

175. BUDLEIGH PARK No.1
E4348 N3545
CHLORIDE P.P.M.
400
300
200
100
0
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
212. WATERCASK No.2
E4593 N3667
CHLORIDE P.P.M.
300
200
100
0
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971

FIG. 6.1 (CONT)

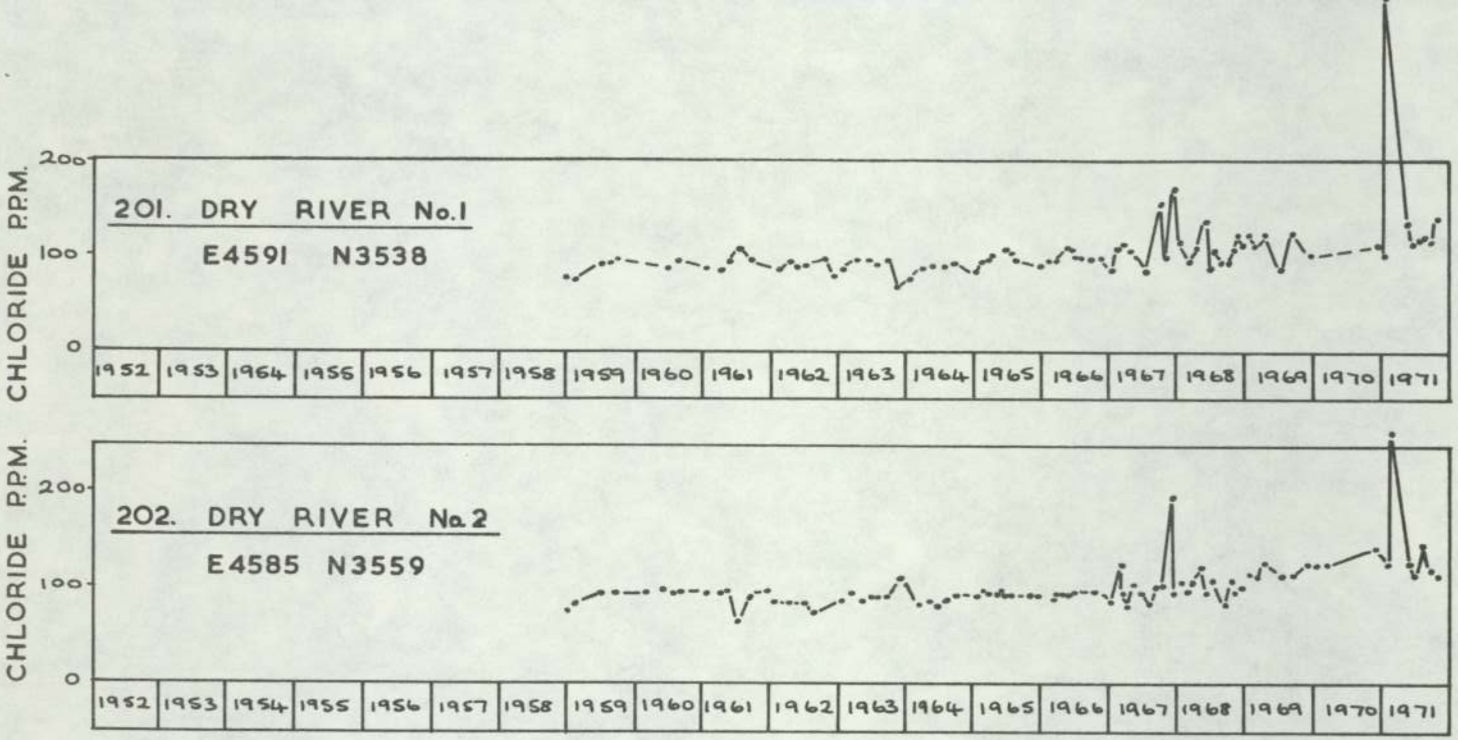

CHLORIDE P.P.M.
200
100
0
201. DRY RIVER No.1
E4591 N3538
1952 1953 1964 1956 1956 1957 1958 1959 1960 1961 1962 1963 1964 1965 1966 1967 1968 1969 1970 1971
CHLORIDE P.P.M.
200
100
0
202. DRY RIVER No.2
E4585 N3559
1952 1953 1954 1955 1956 1957 1958 1959 1960 1961 1962 1963 1964 1965 1966 1967 1968 1969 1970 1971

FIG 6.1 (CONT)

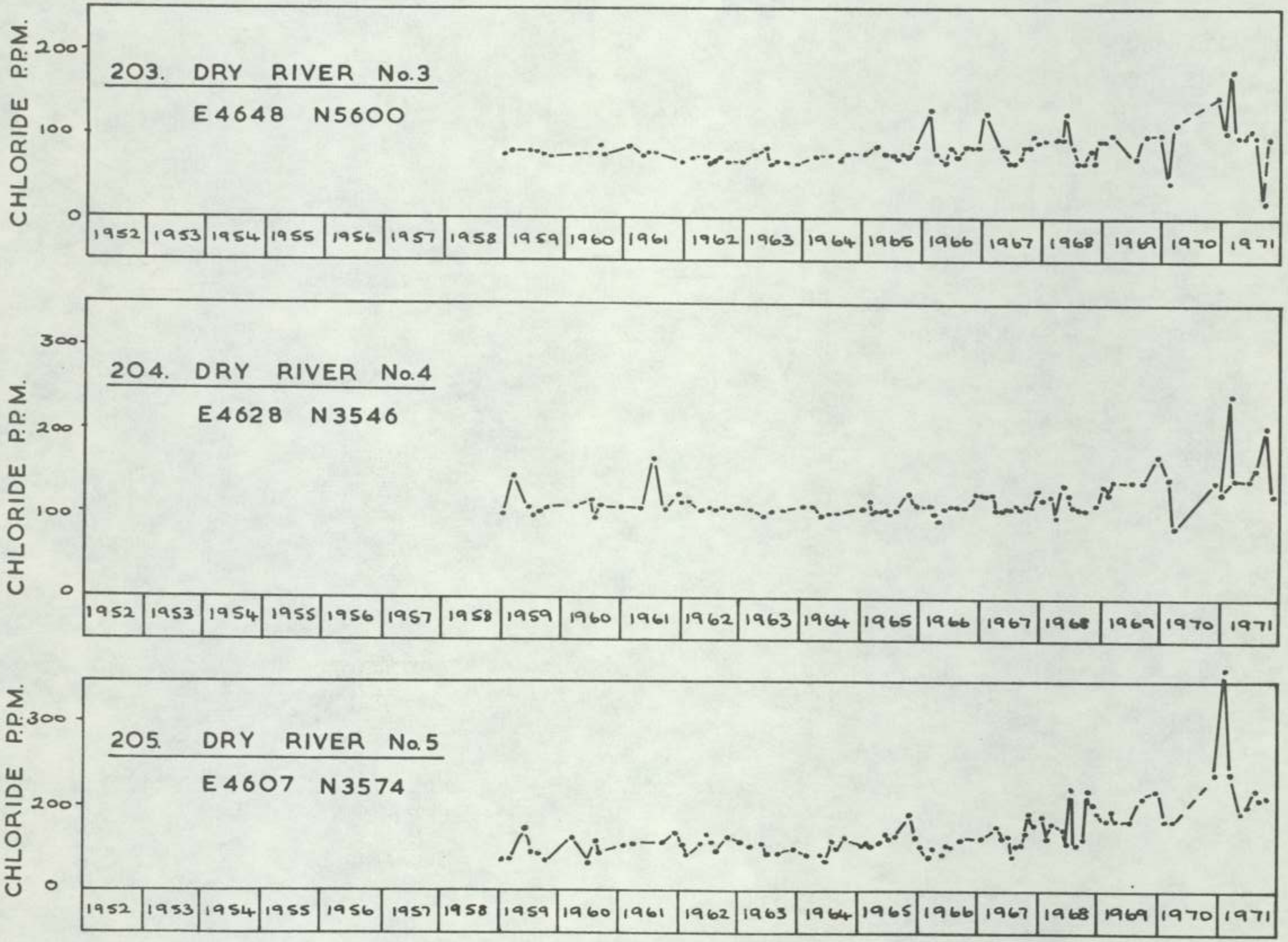

203. DRY RIVER No.3
E4648 N5600
204. DRY RIVER No.4
E4628 N3546
205. DRY RIVER No.5
E4607 N3574
CHLORIDE P.P.M.
0
100
200
300
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971

FIG. 6.1 (CONT)

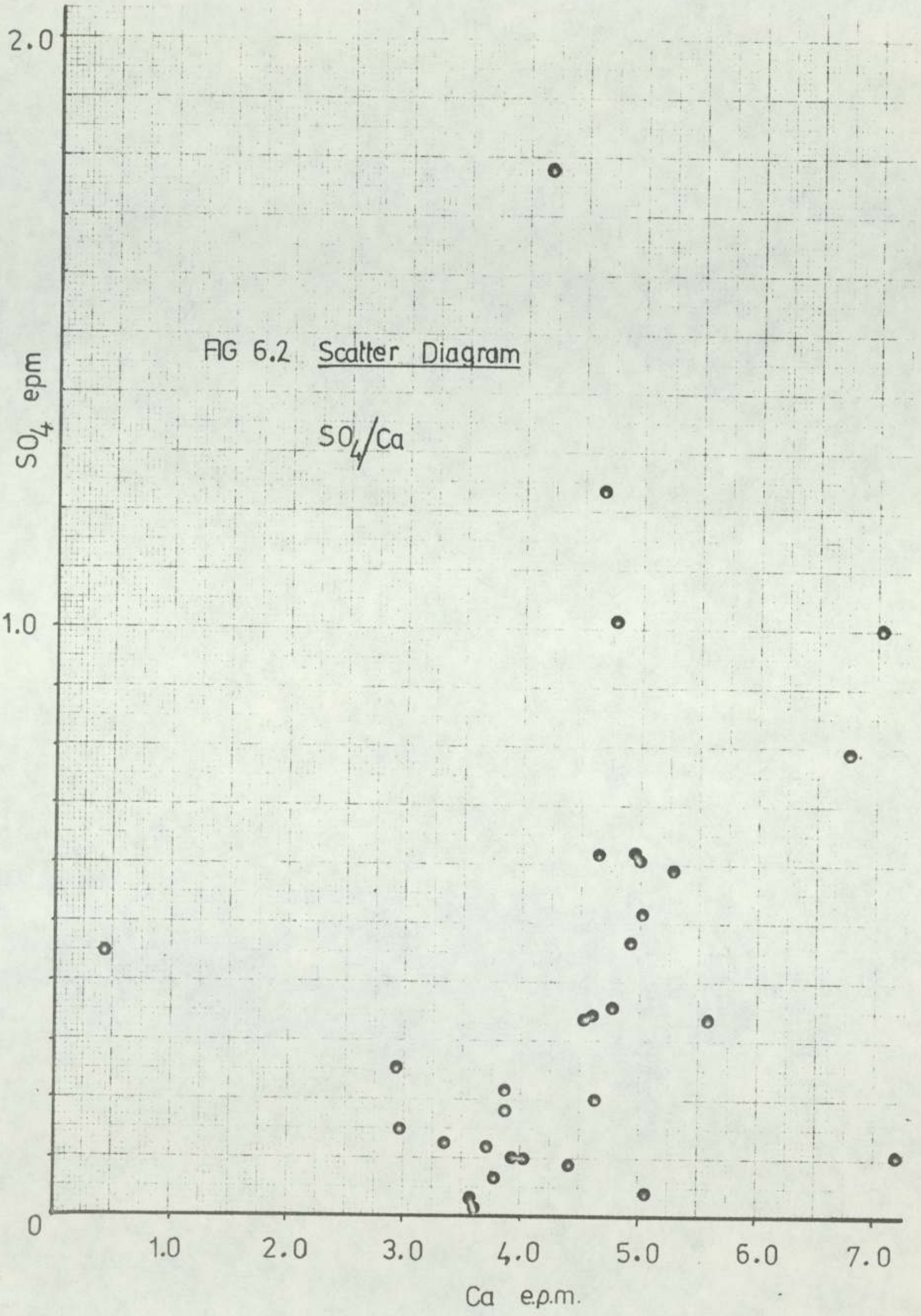
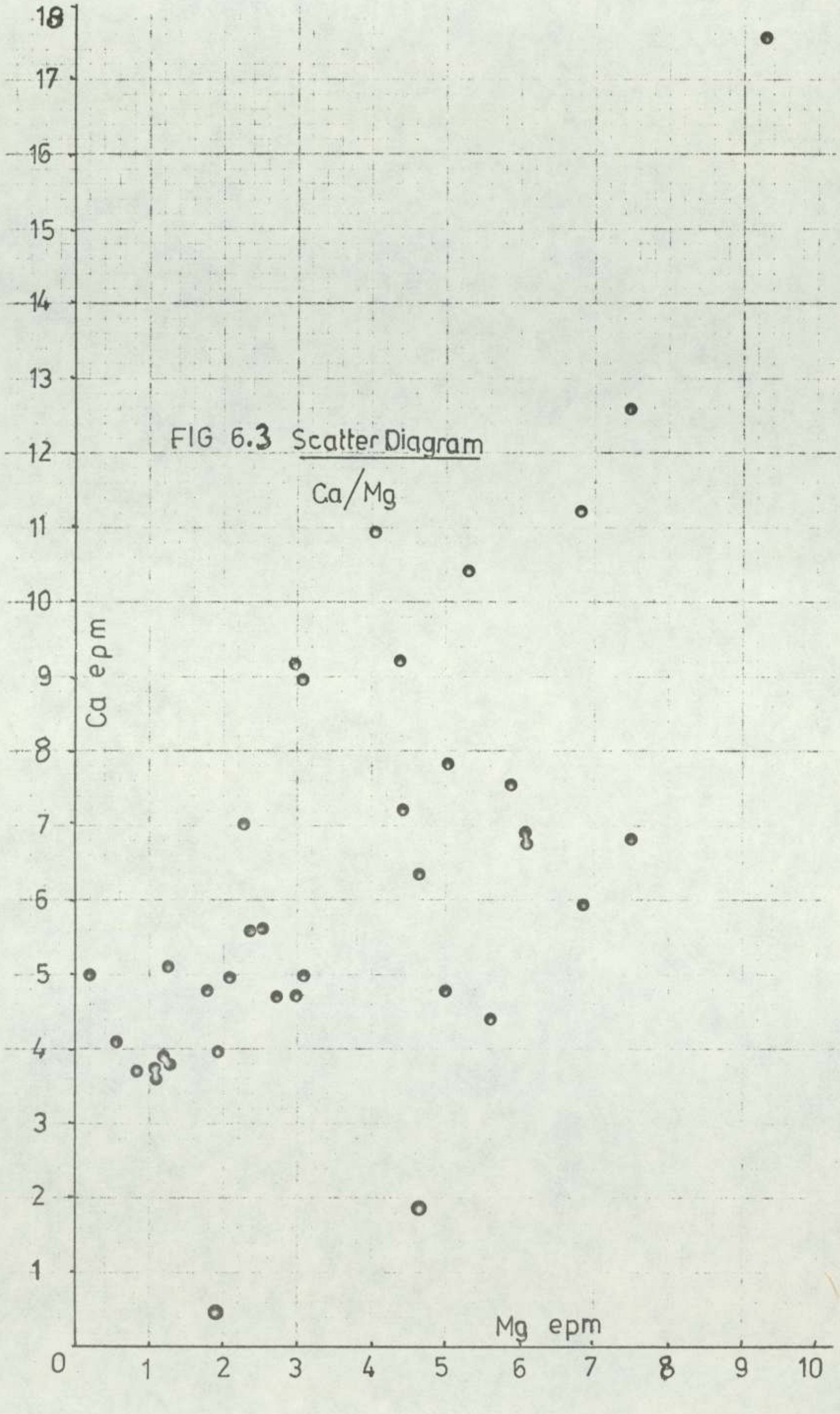


FIG 6.2 Scatter Diagram

SO_4/Ca

FIG 6.3 Scatter Diagram

Ca/Mg



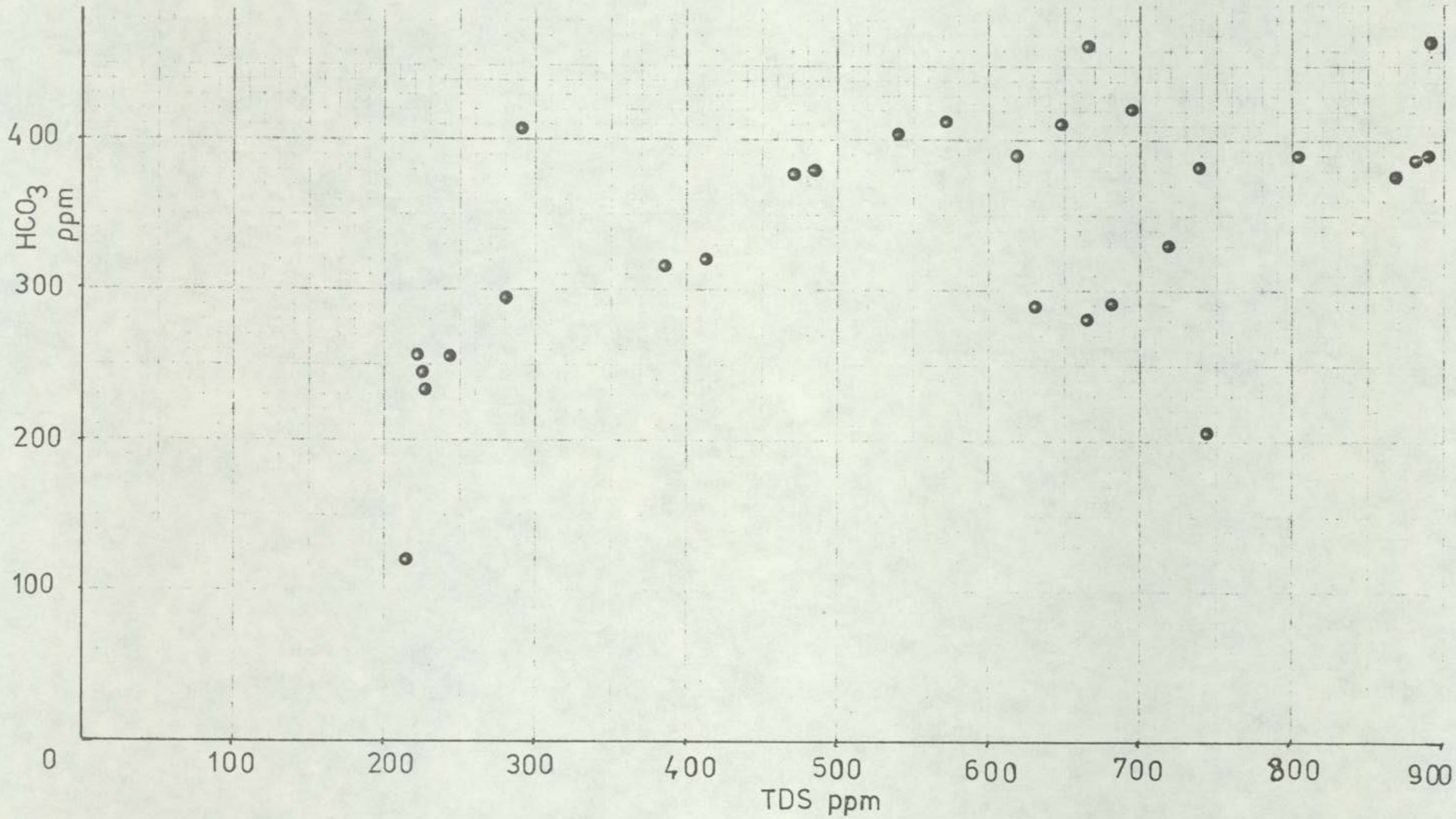


Fig. 6.4 Ratio of Bicarbonate to Total Dissolved Solids - Selected Wells.

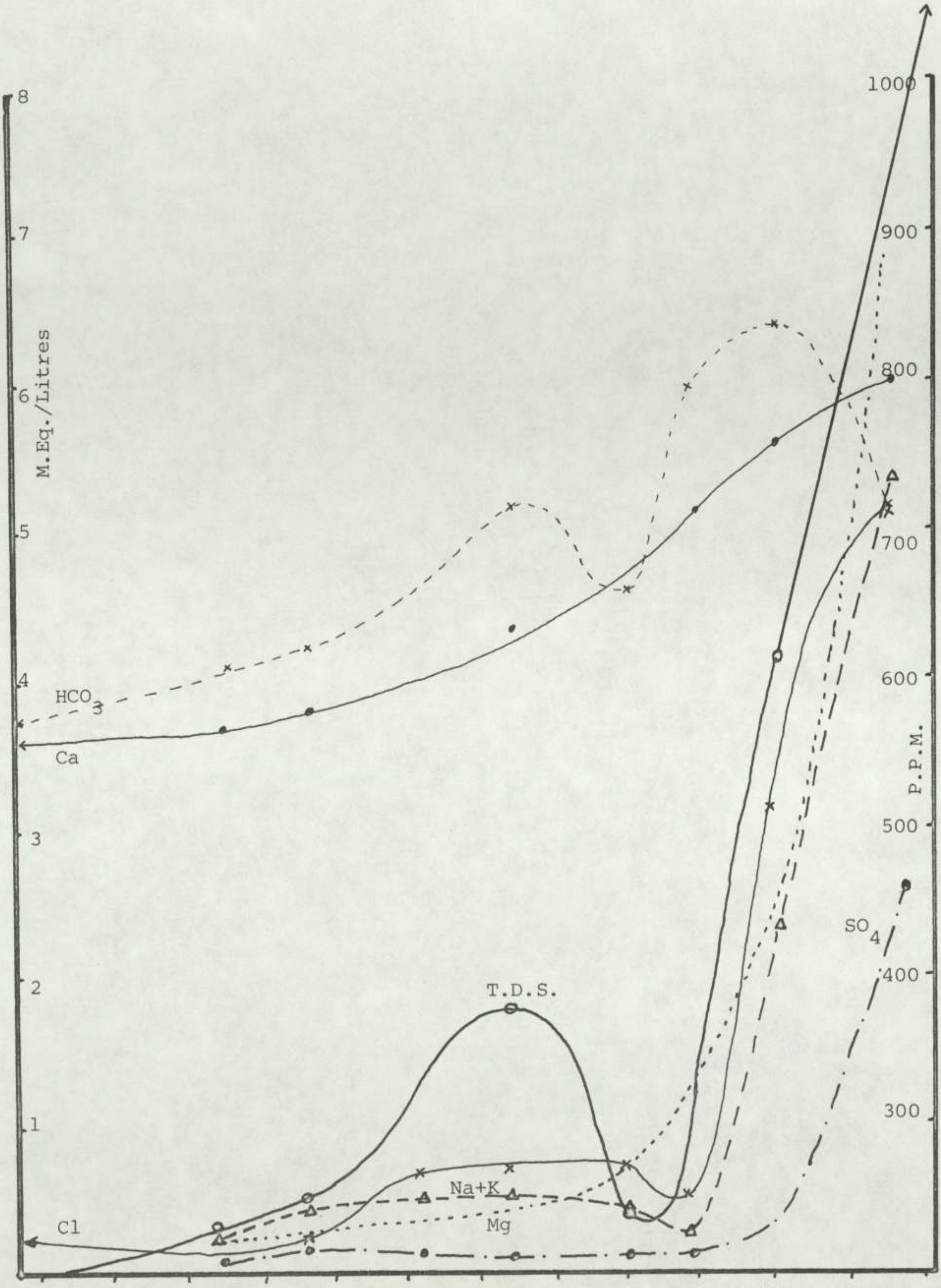


FIG. 6.5 VARIATIONS OF CHEMICAL COMPOSITION PORUS TO THE SOUTH COAST FAULT. (ONLY TDS in PPM)

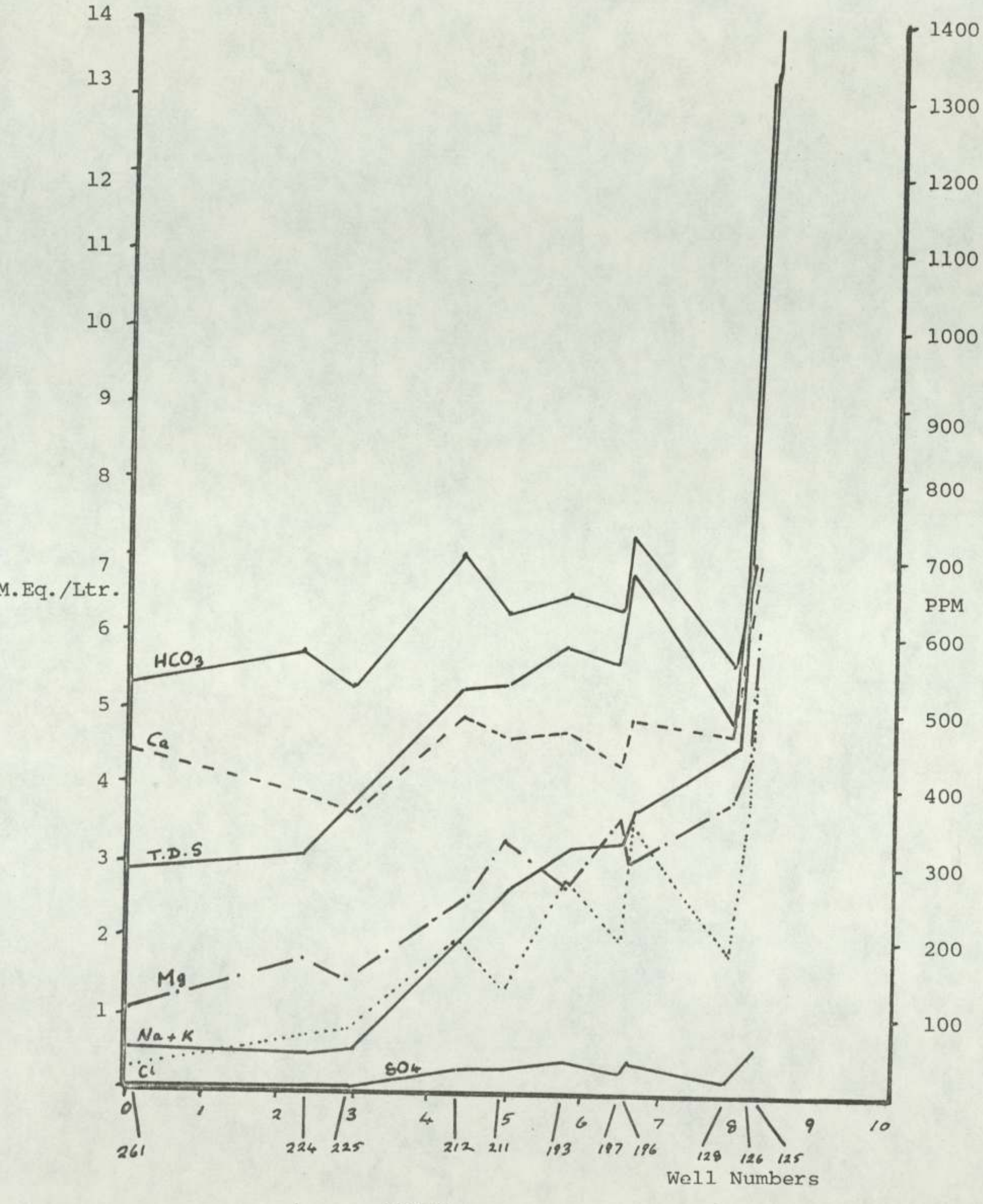


FIG. 6.6 VARIATIONS IN CHEMICAL COMPOSITION

MAY PEN TO THE SOUTH COAST FAULT

(only TDS in PPM)

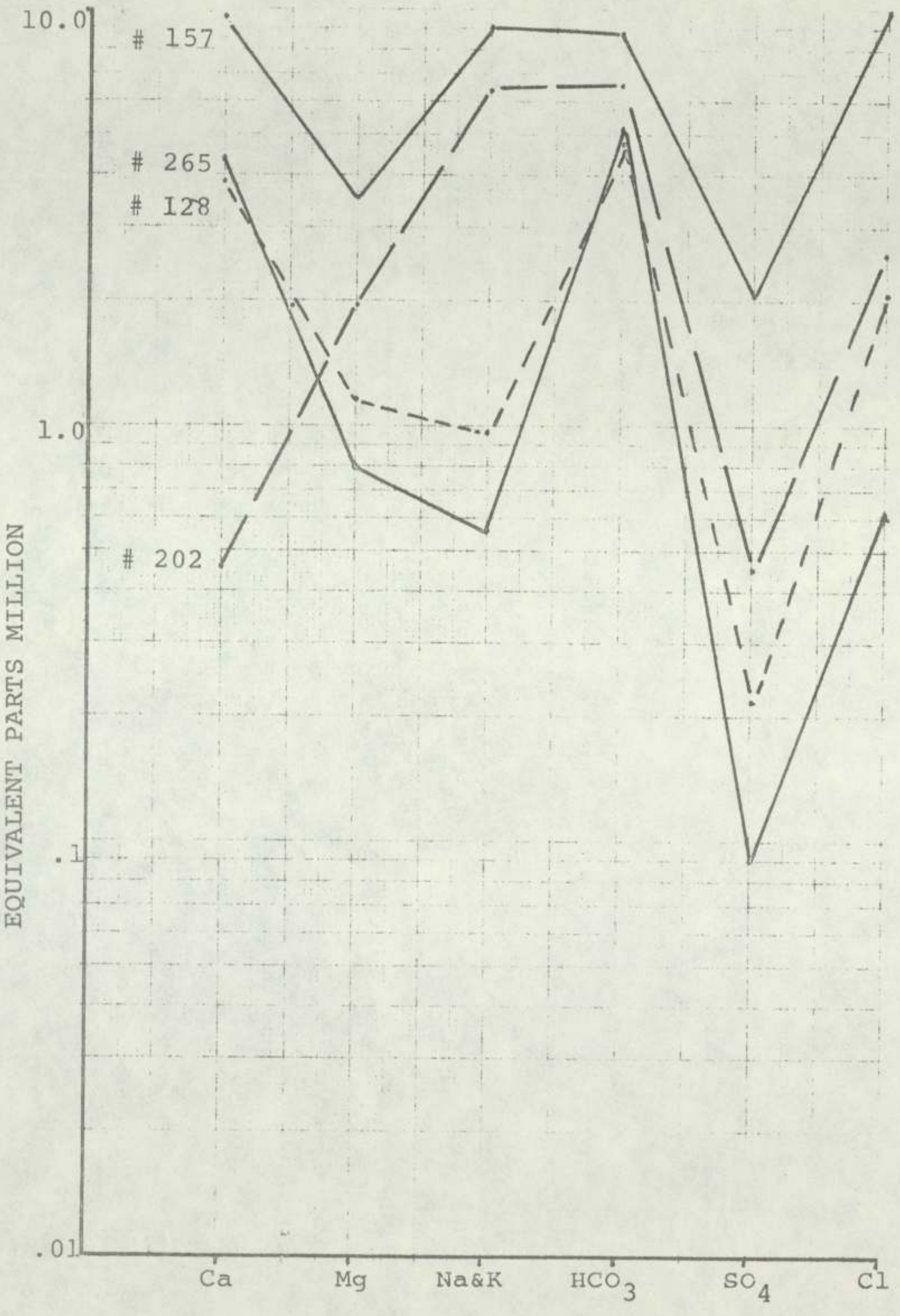


Fig. 6.7 <u>Schoeller Diagram for Selected Wells.</u>

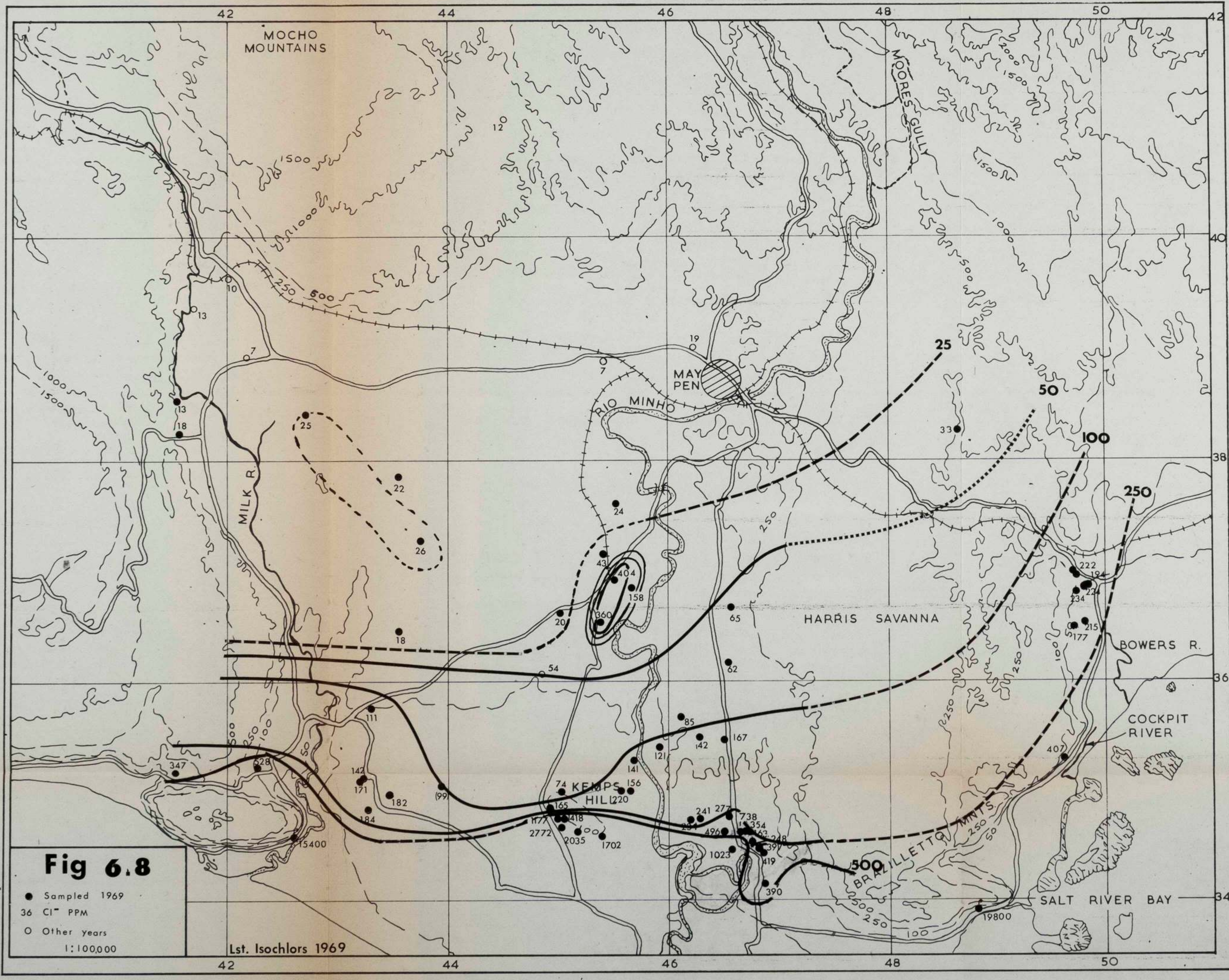

MOCHO MOUNTAINS
MOORES GULLY
MAY PEN
RIO MINHO
MILK R.
HARRIS SAVANNA
BOWERS R.
COCKPIT RIVER
KEMPS HILL
BRAILLETTO MNTS
SALT RIVER BAY
25
50
100
250
500
42
44
46
48
50
34
36
38
40
42
● Sampled 1969
36 Cl⁻ PPM
○ Other years
1:100,000
Lst. Isochlors 1969

Fig 6.8

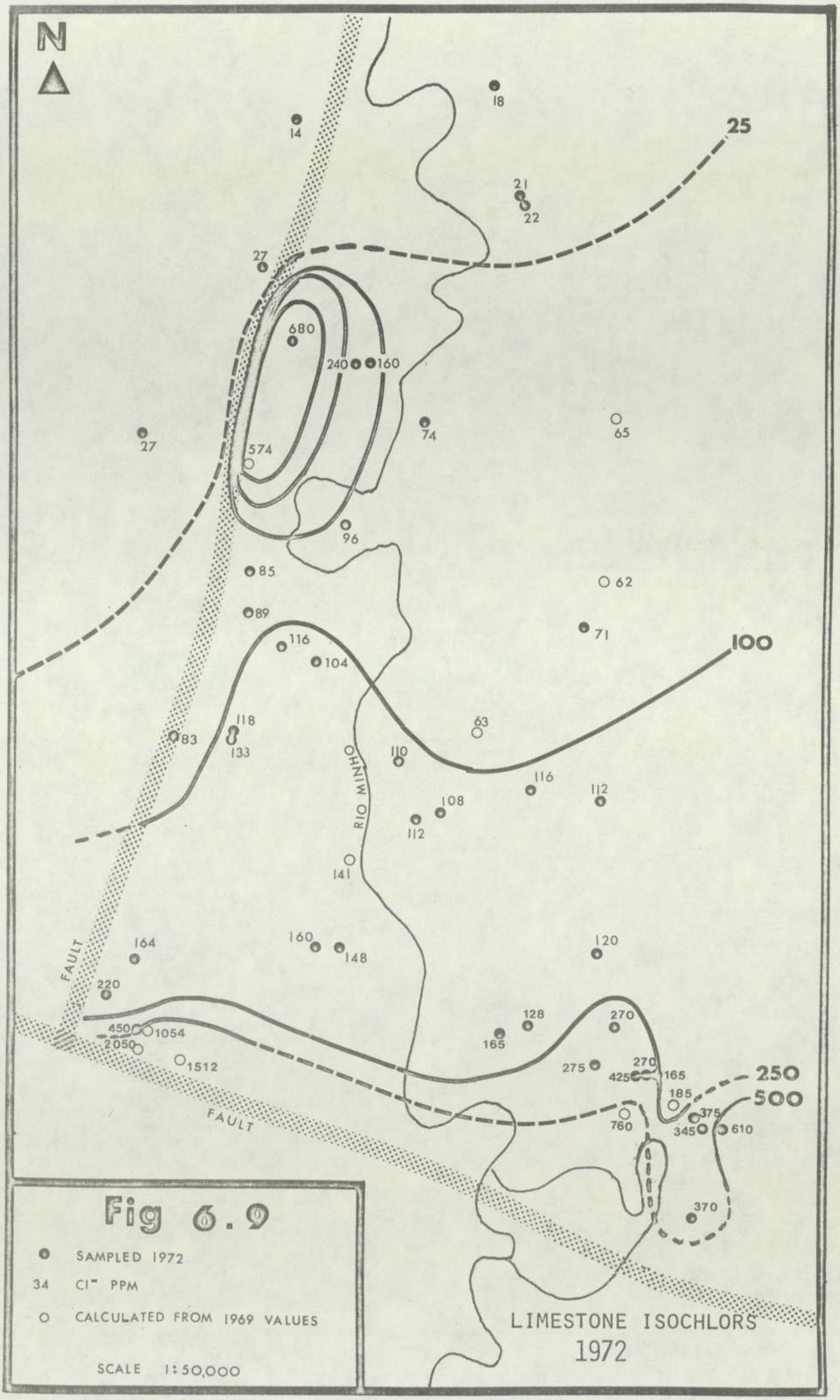


Fig 6.9

LIMESTONE ISOCHLORS 1972

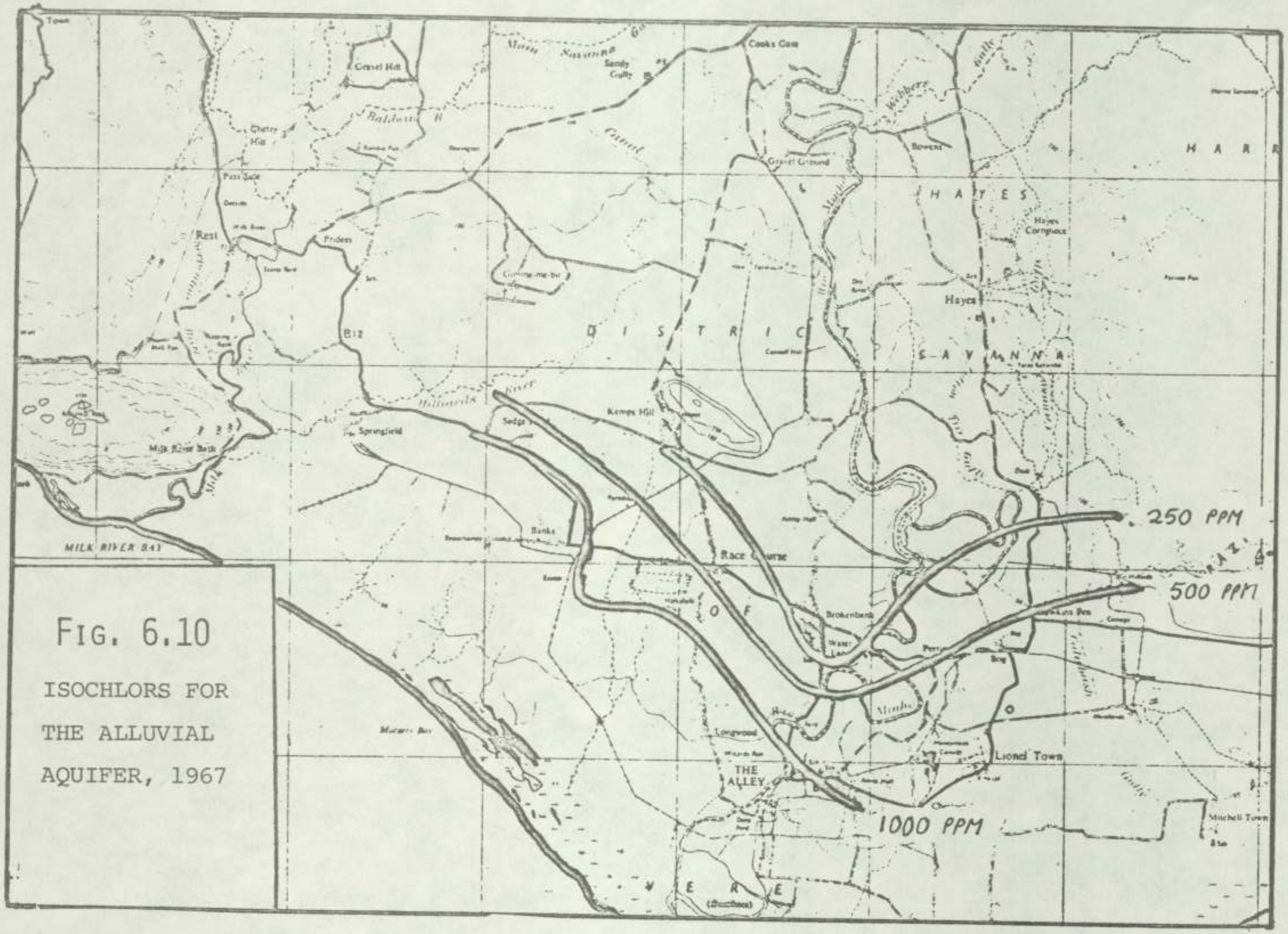


FIG. 6.10

ISOCHLORS FOR THE ALLUVIAL AQUIFER, 1967

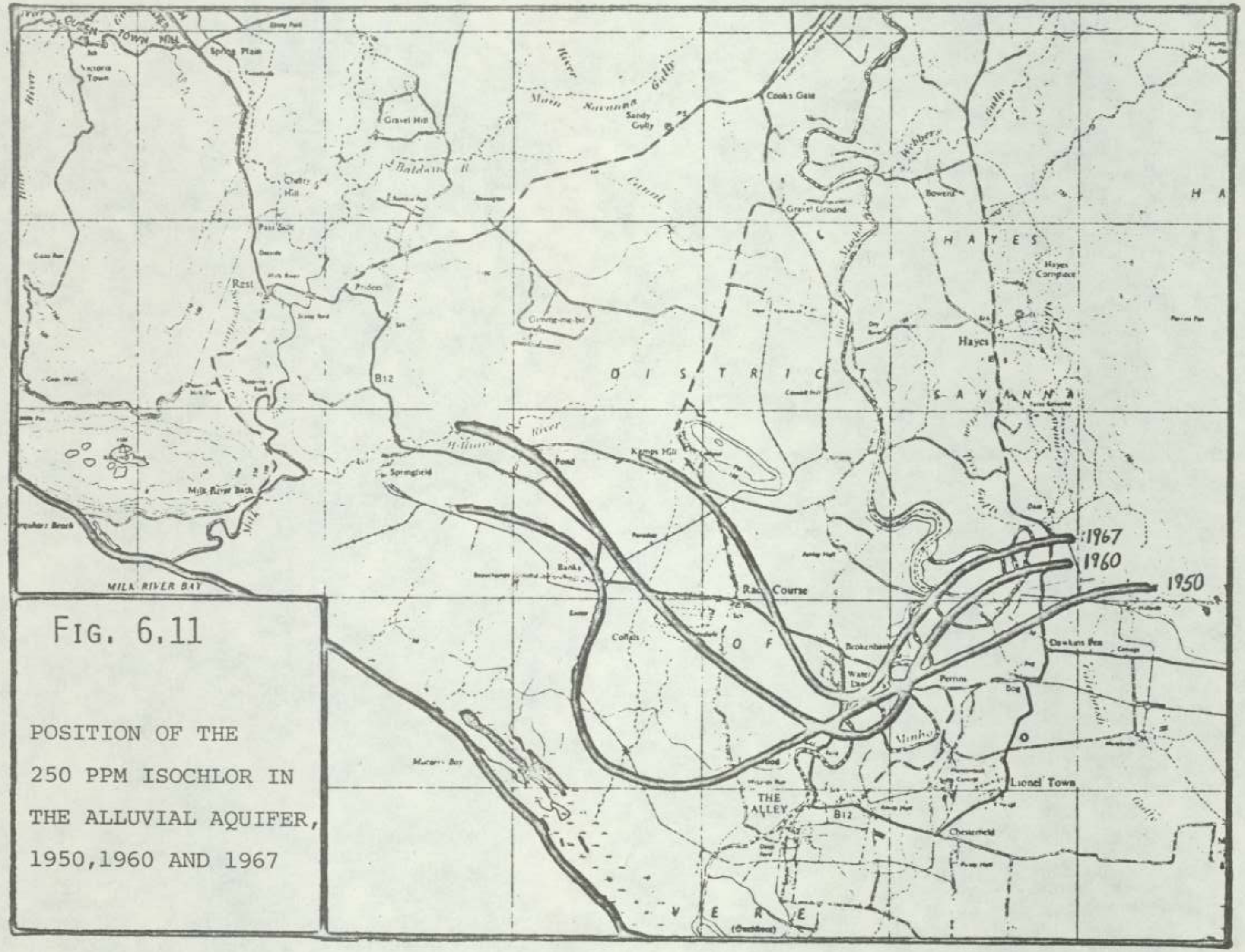


FIG. 6.11

POSITION OF THE
250 PPM ISOCHLOR IN
THE ALLUVIAL AQUIFER,
1950,1960 AND 1967

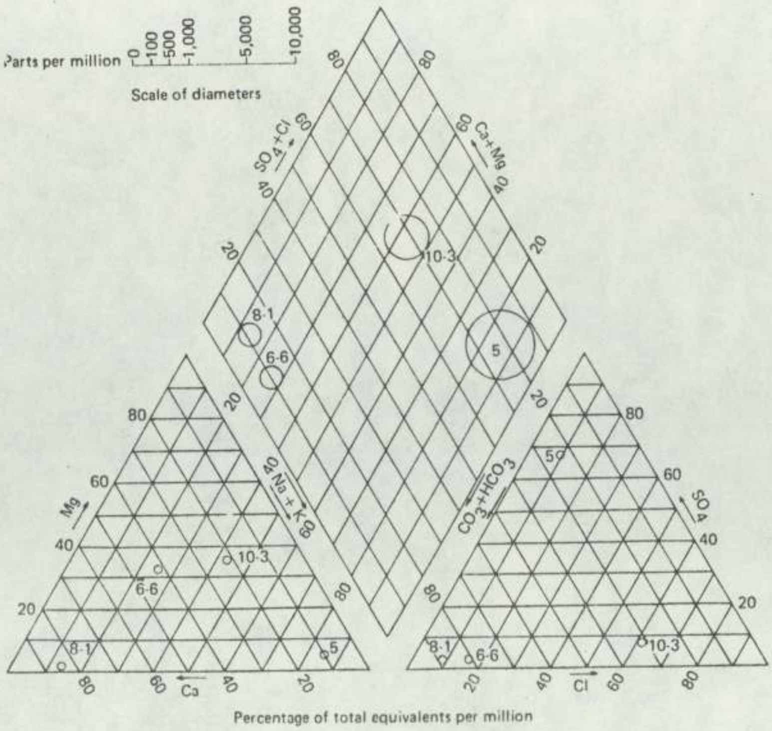


FIG. 6.12 PIPER DIAGRAM (AFTER PIPER, 1944)

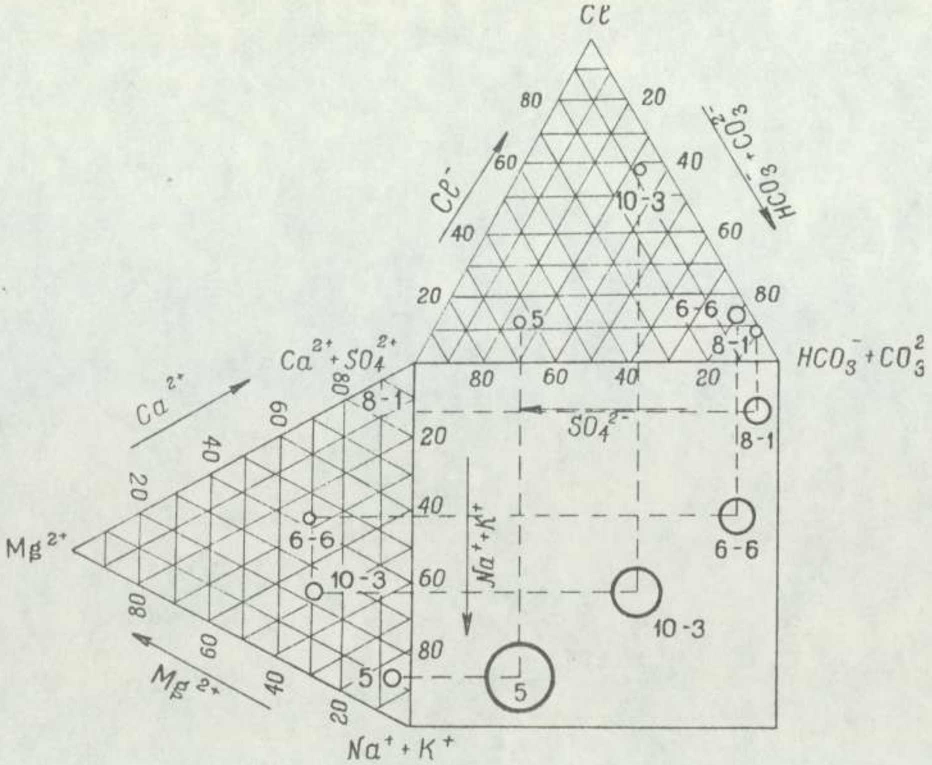


FIG. 6.13 BASIC DUROV DIAGRAM (AFTER DUROV, 1948)

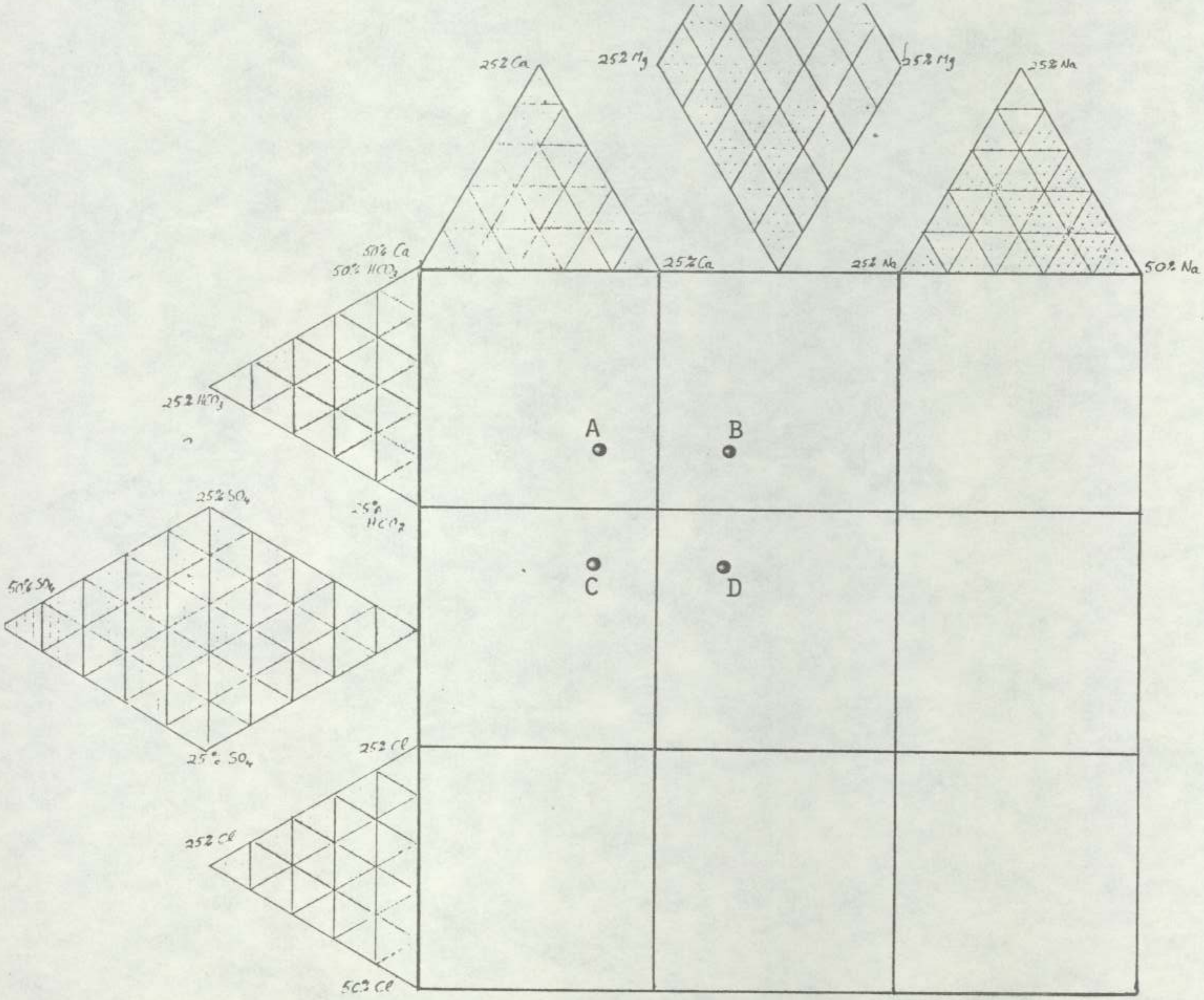
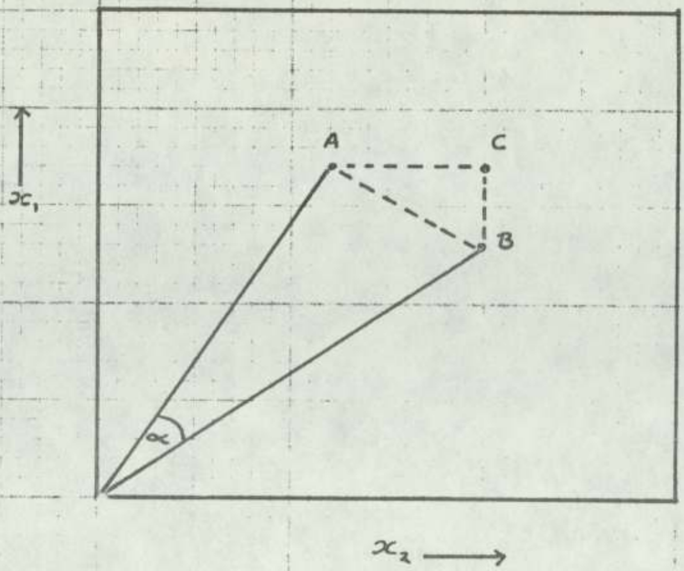


FIG. 6.14 COMPARISON OF PLOTS OF FOUR WATERS.



6.15 MEASURES OF SIMILARITY

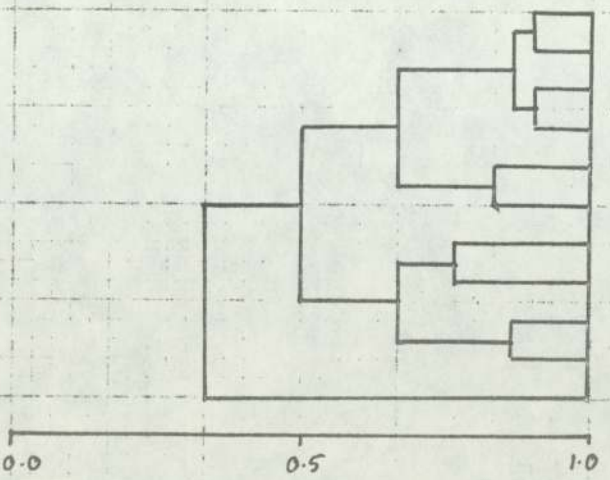


FIG. 6.16 DENDROGRAM

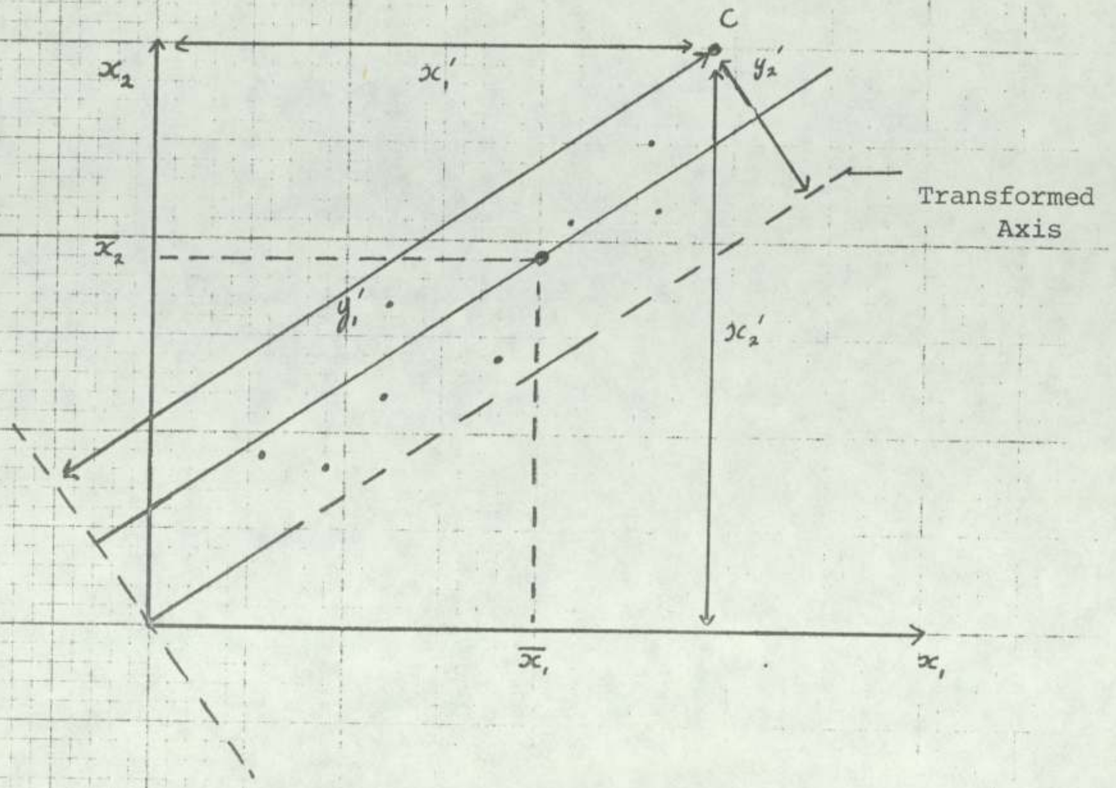


FIG. 6.17 PRINCIPLE COMPONENTS.

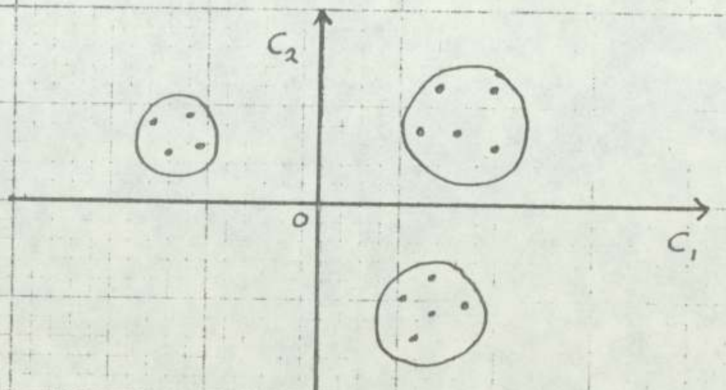


FIG. 6.19 CLUSTERS FROM PRINCIPLE COMPONENTS.

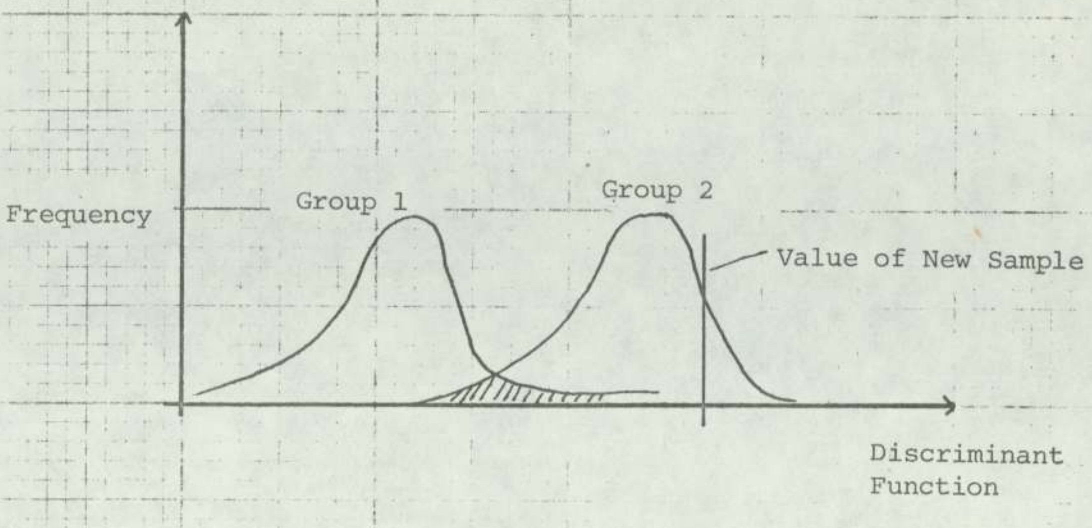


FIG. 6.20 DISCRIMINANT ANALYSIS

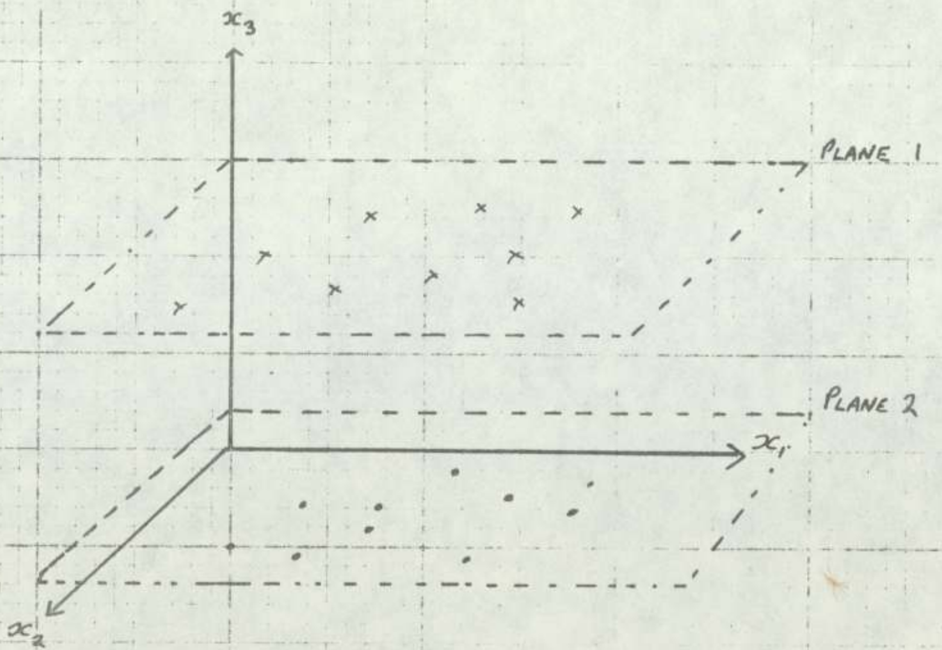


FIG. 6.21 3-DIMENSIONAL CASE

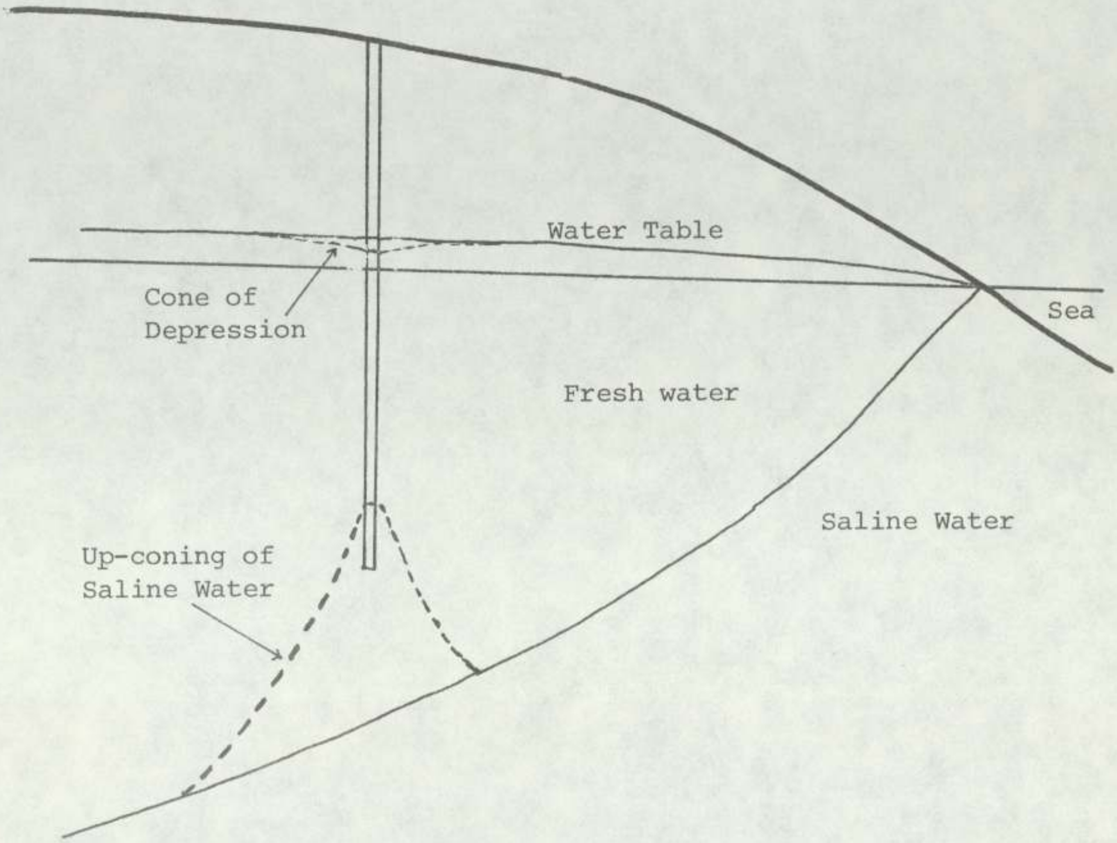
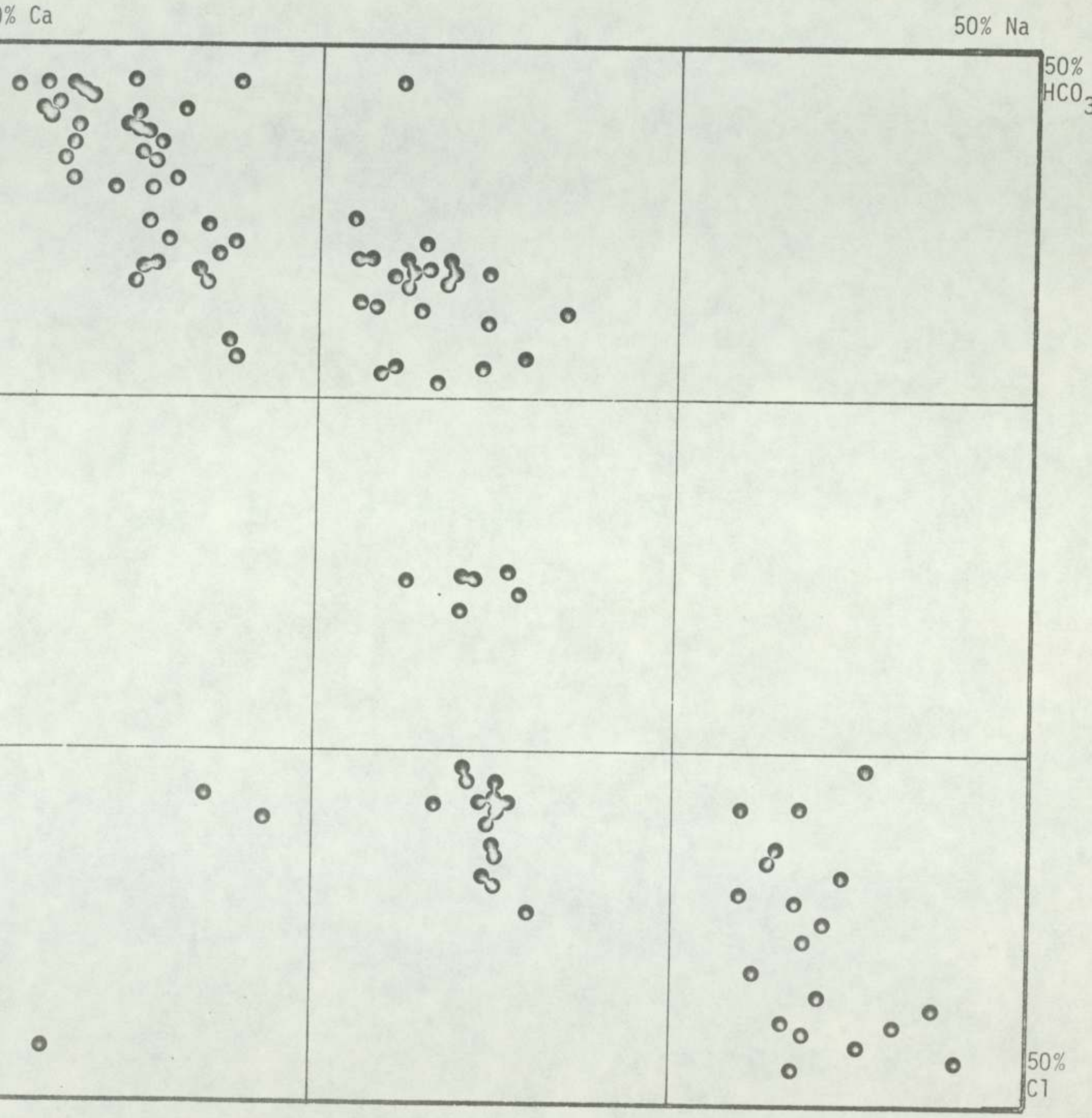


FIG. 6.22 UP-CONING OF SALT WATER ACCORDING TO THE GHYBEN-HERZBERG RELATIONSHIP.



Extended Durov Diagram

FIG. 6.23 PLOT OF ALL AVAILABLE ANALYSES FOR LIMESTONE WELLS

(well numbers ommitted for sake of clarity)

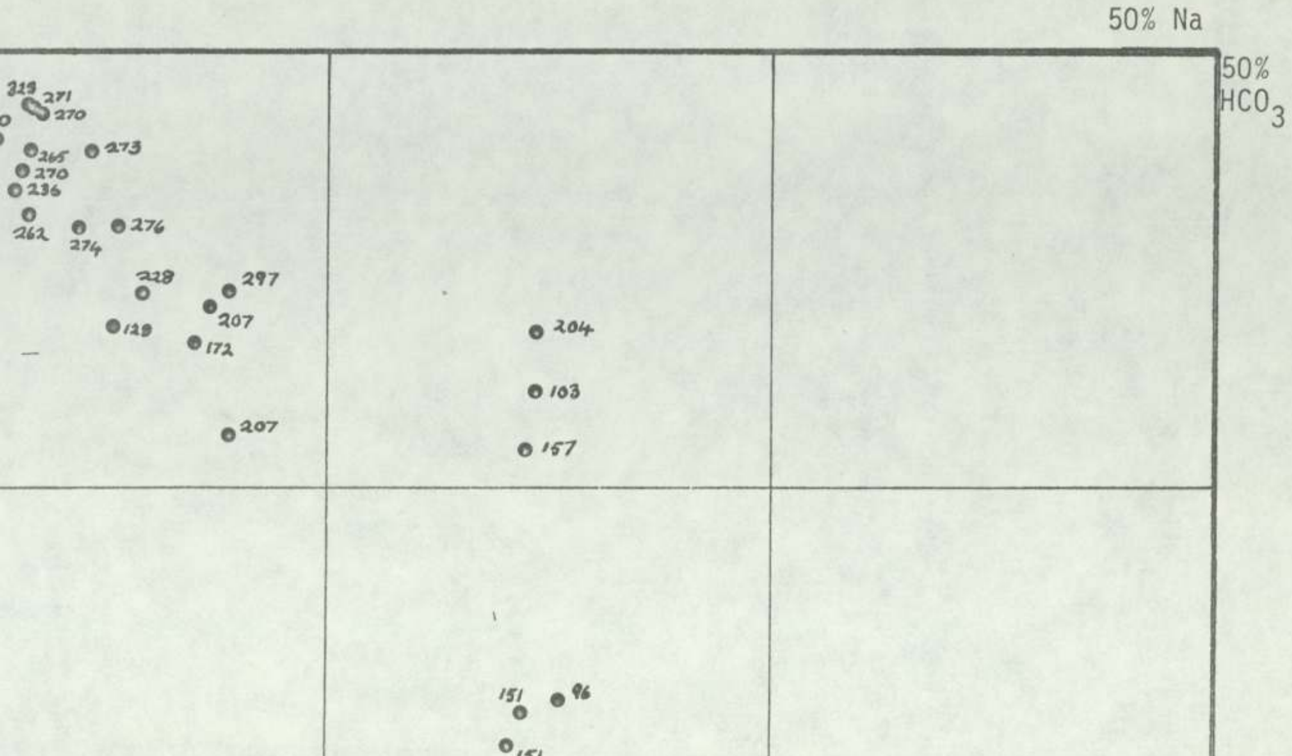
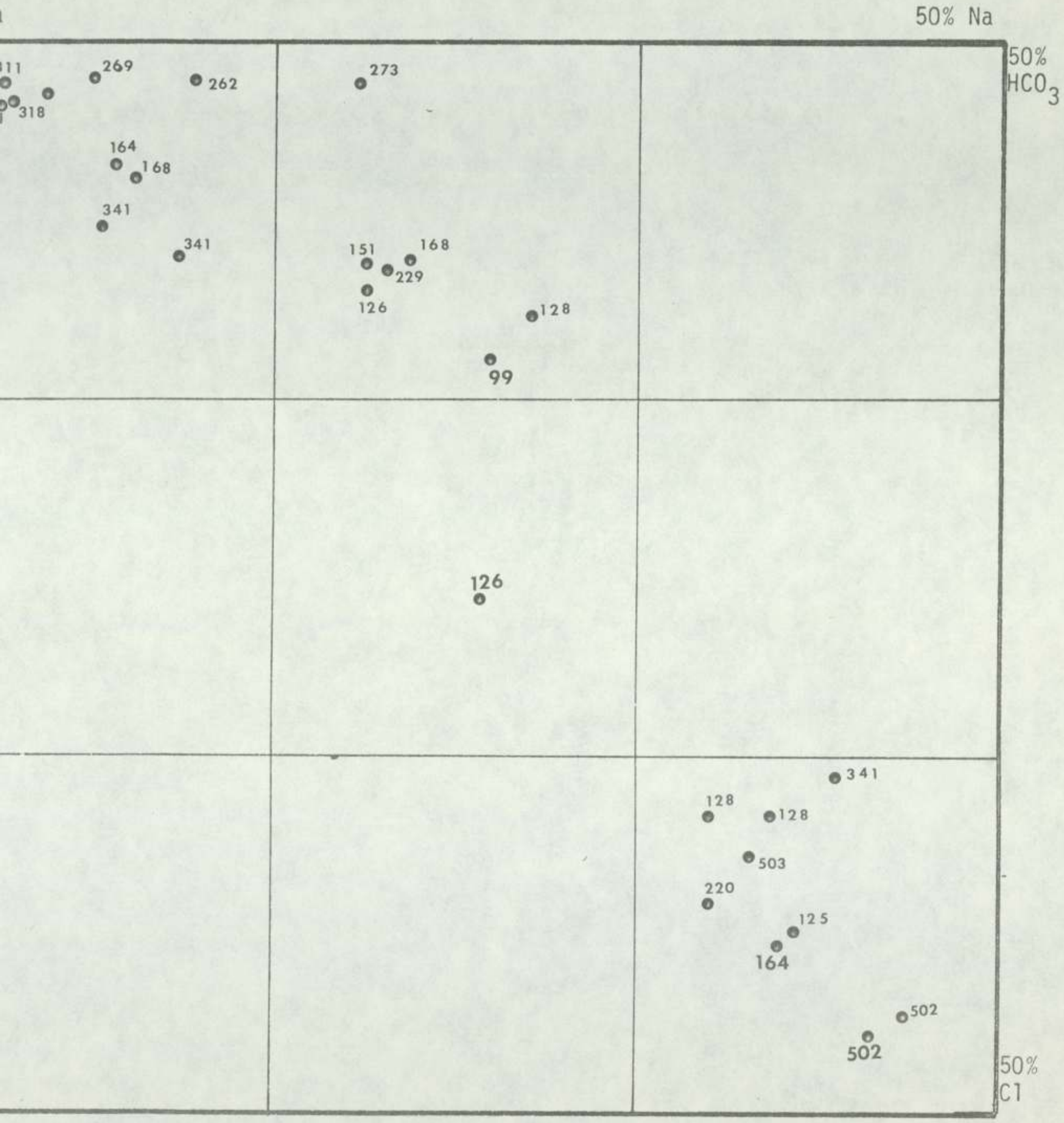


FIG. 6.24 <u>LIMESTONE WELLS 1968-69</u>

● 265 WELL No.



Extended Durov Diagram

FIG. 6.25 <u>LIMESTONE WELLS 1970-71</u>

55

Well No.

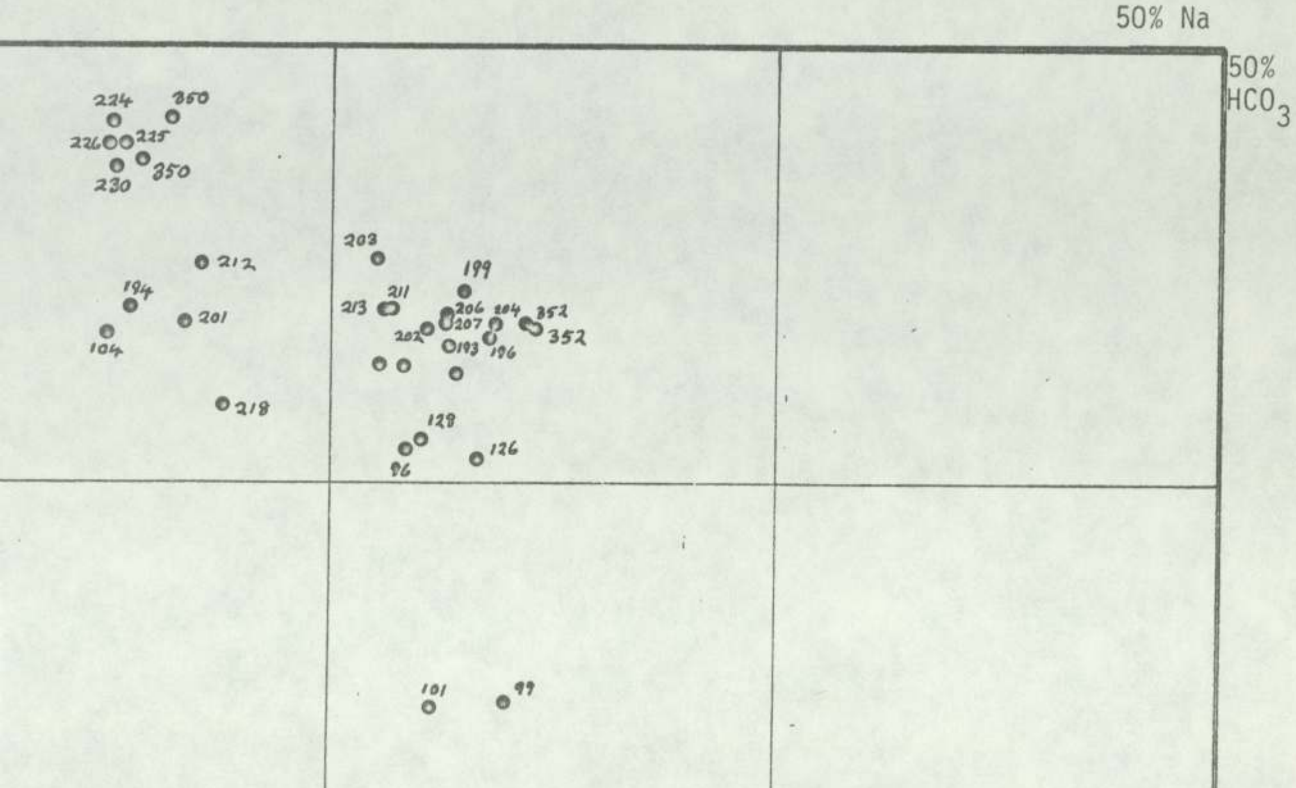
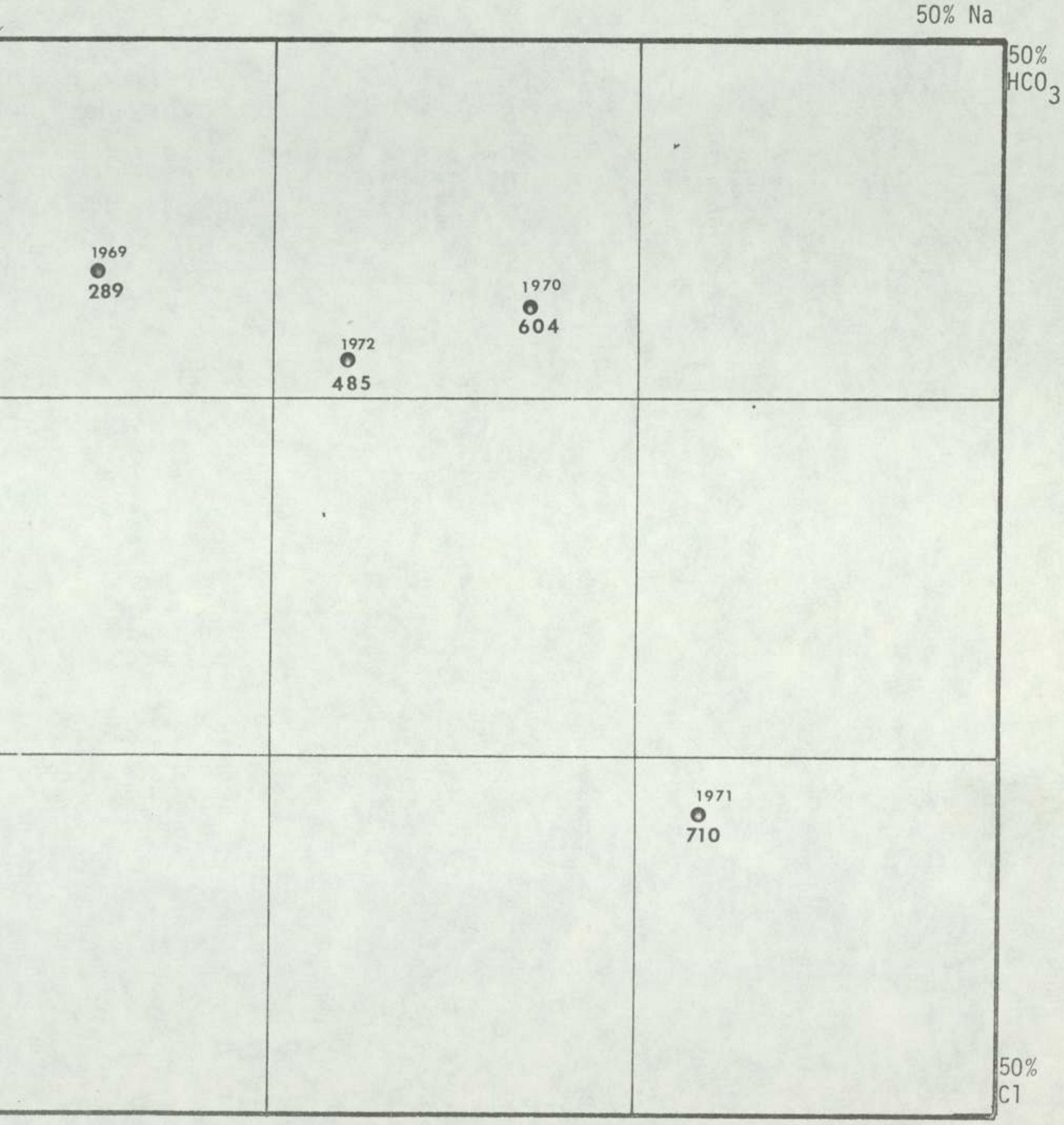


FIG. 6.26 <u>LIMESTONE WELLS 1972</u>

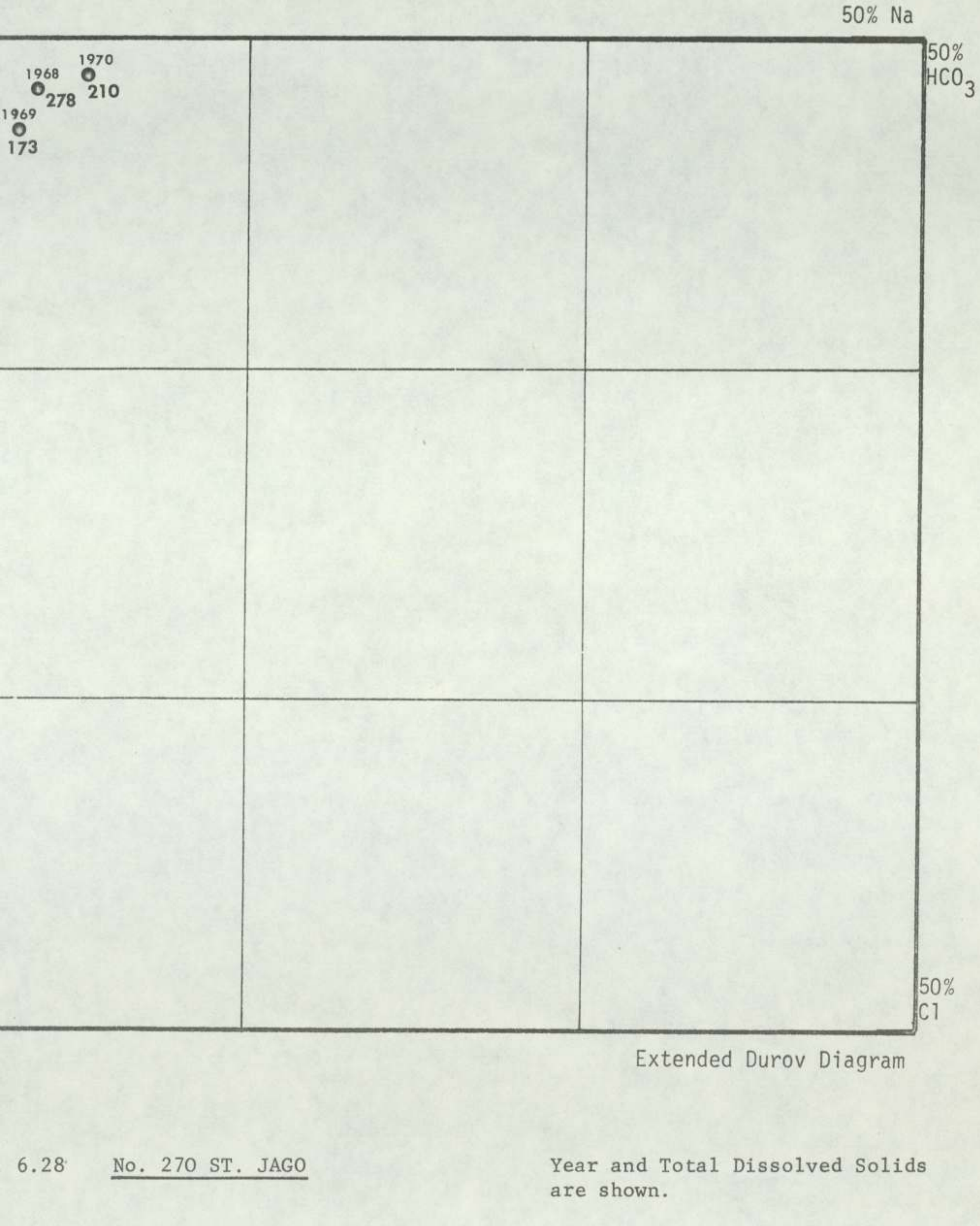
WELL No.



nd Total Dissolved Solids are shown.

Extended Durov Diagram

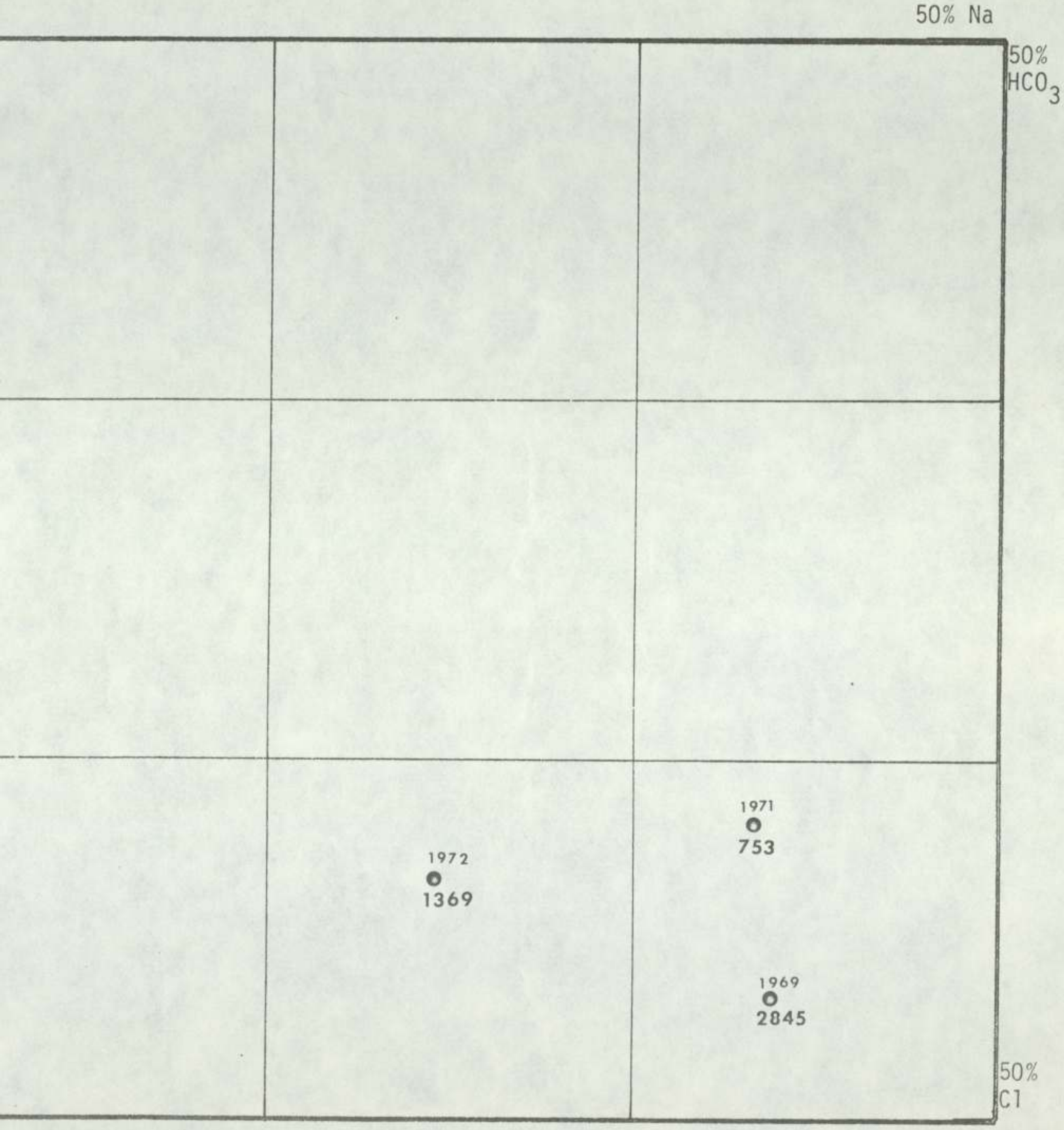
Fig. 6.27 No. 128, POND PASTURE



Extended Durov Diagram

6.28 No. 270 ST. JAGO

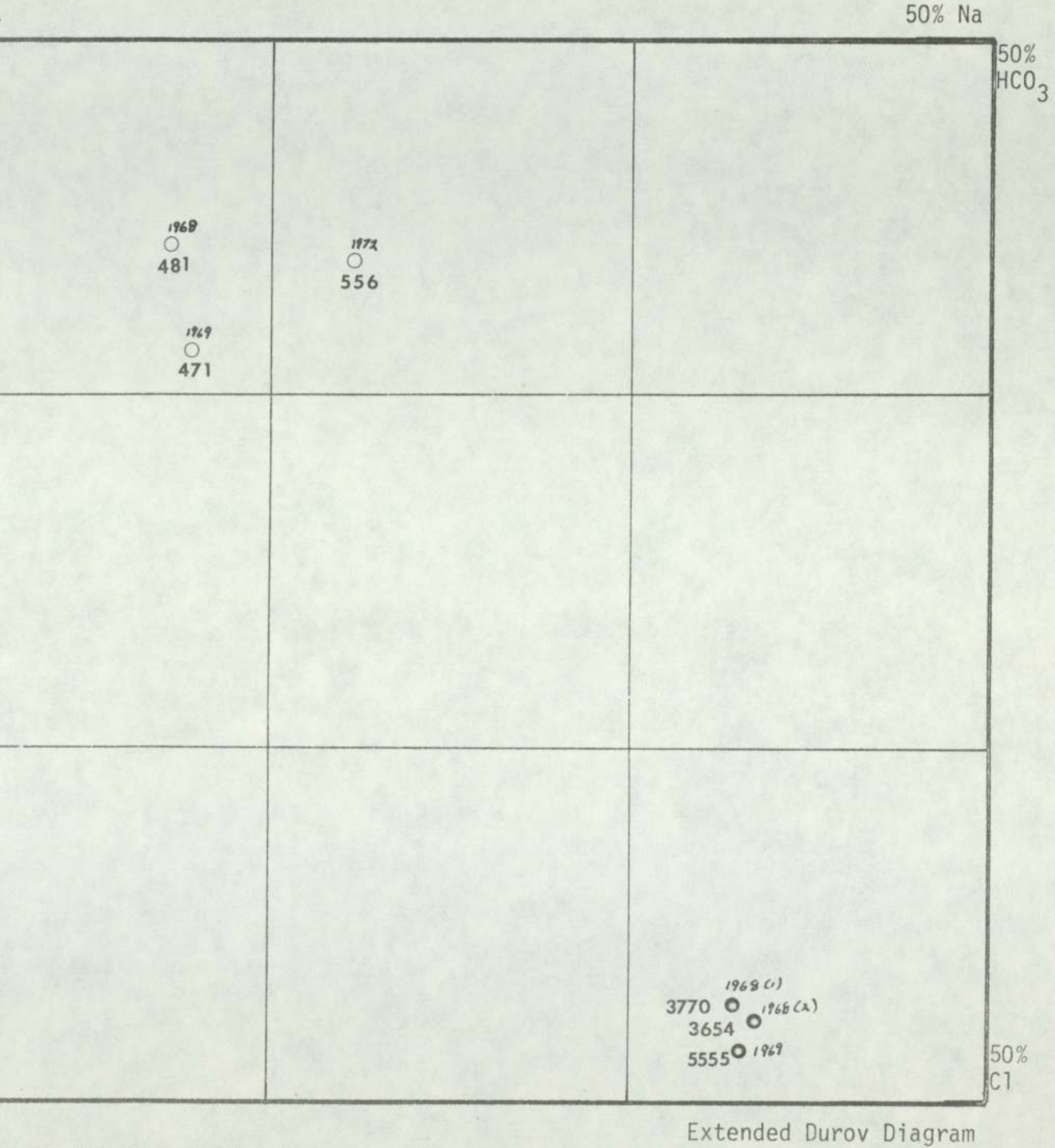
Year and Total Dissolved Solids are shown.



Extended Durov Diagram

Year and Total Dissolved Solids are shown.

FIG. 6.29 No. 125 PARADISE 2.

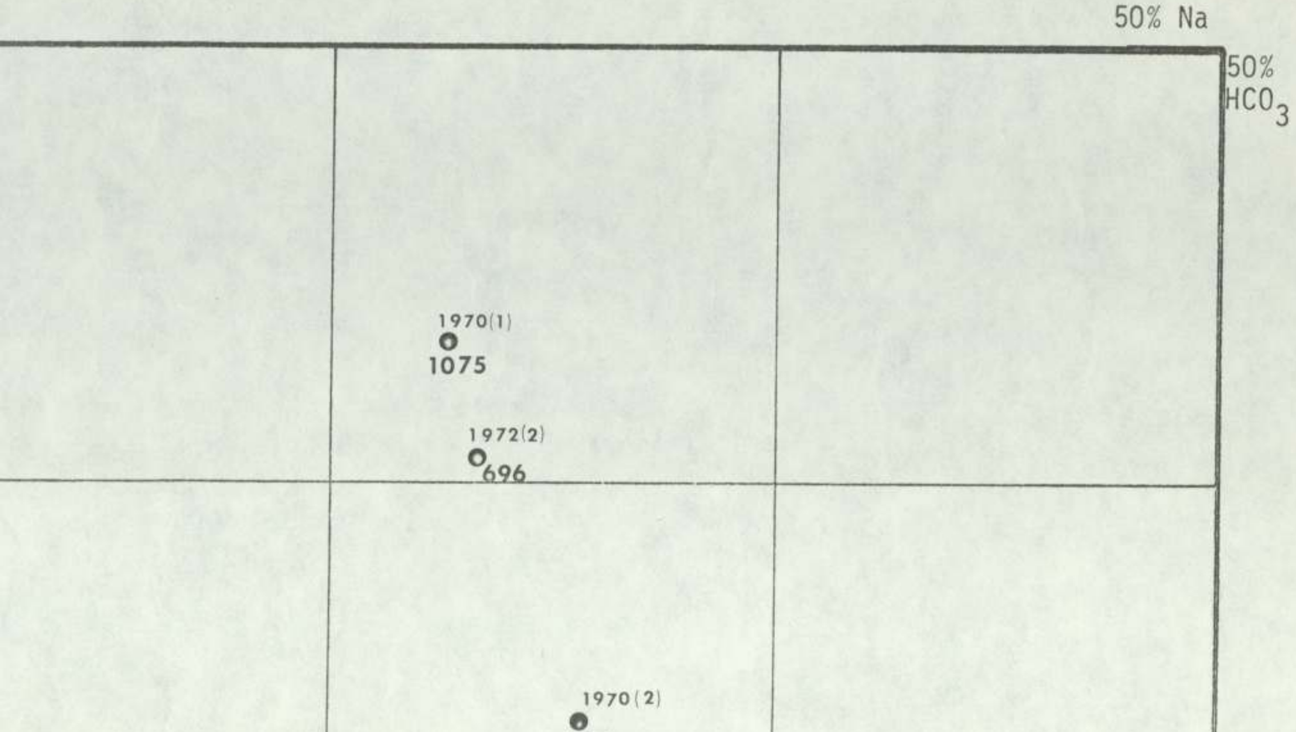


nd Total Dissolved Solids are shown.

FIG. 6.30 No. 127 Kemps Hill 2 and No. 207 Hayes NWA

○ Hayes NWA

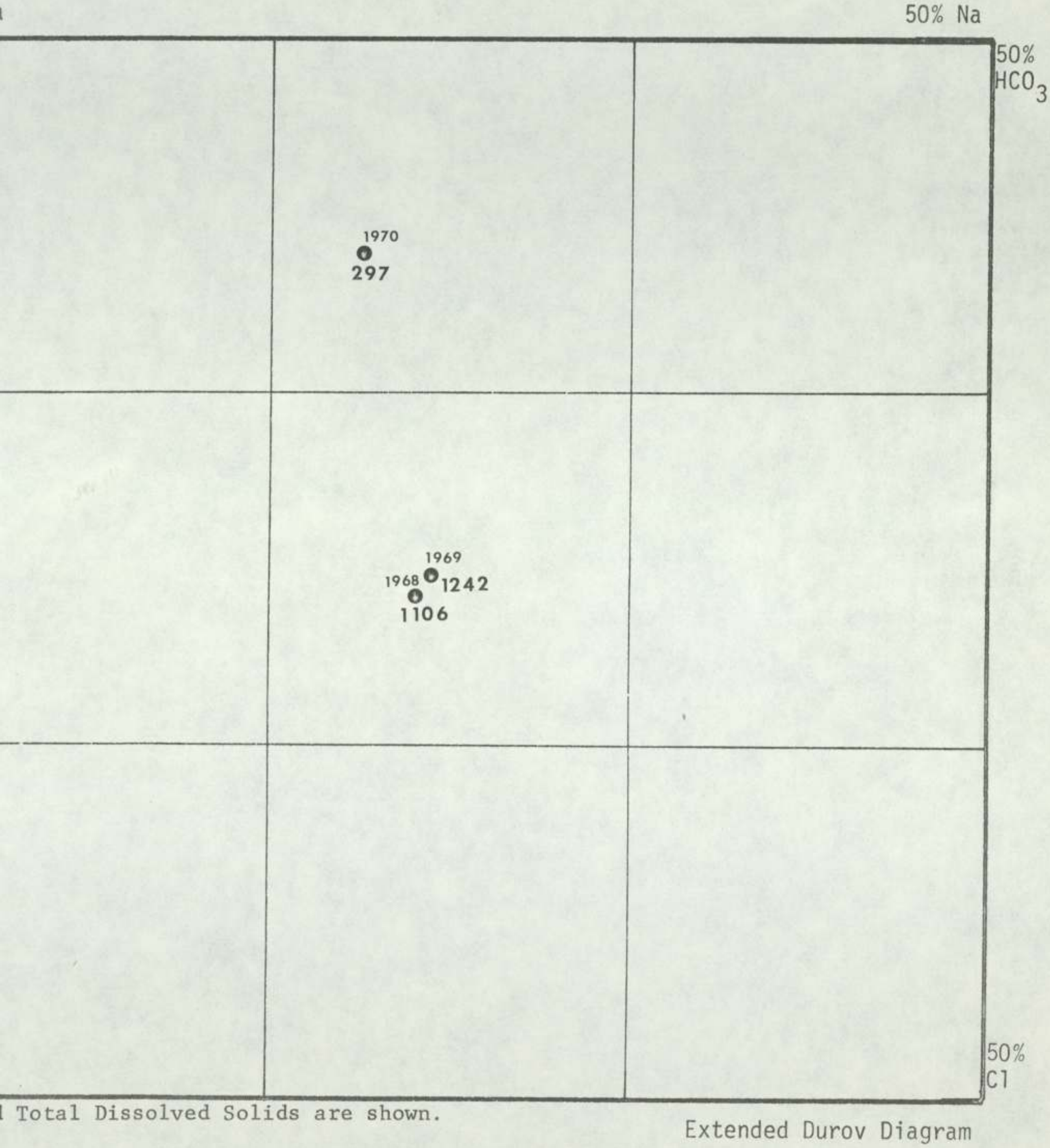
● Kemps Hill 2



Extended Durov Diagram

d Total Dissolved Solids are shown

FIG. 6.31 <u>No. 126 , KEMPS HILL N.W.A.</u>



Total Dissolved Solids are shown.

FIG. 6.32 No. 151 SHALLOW PASTURE 3

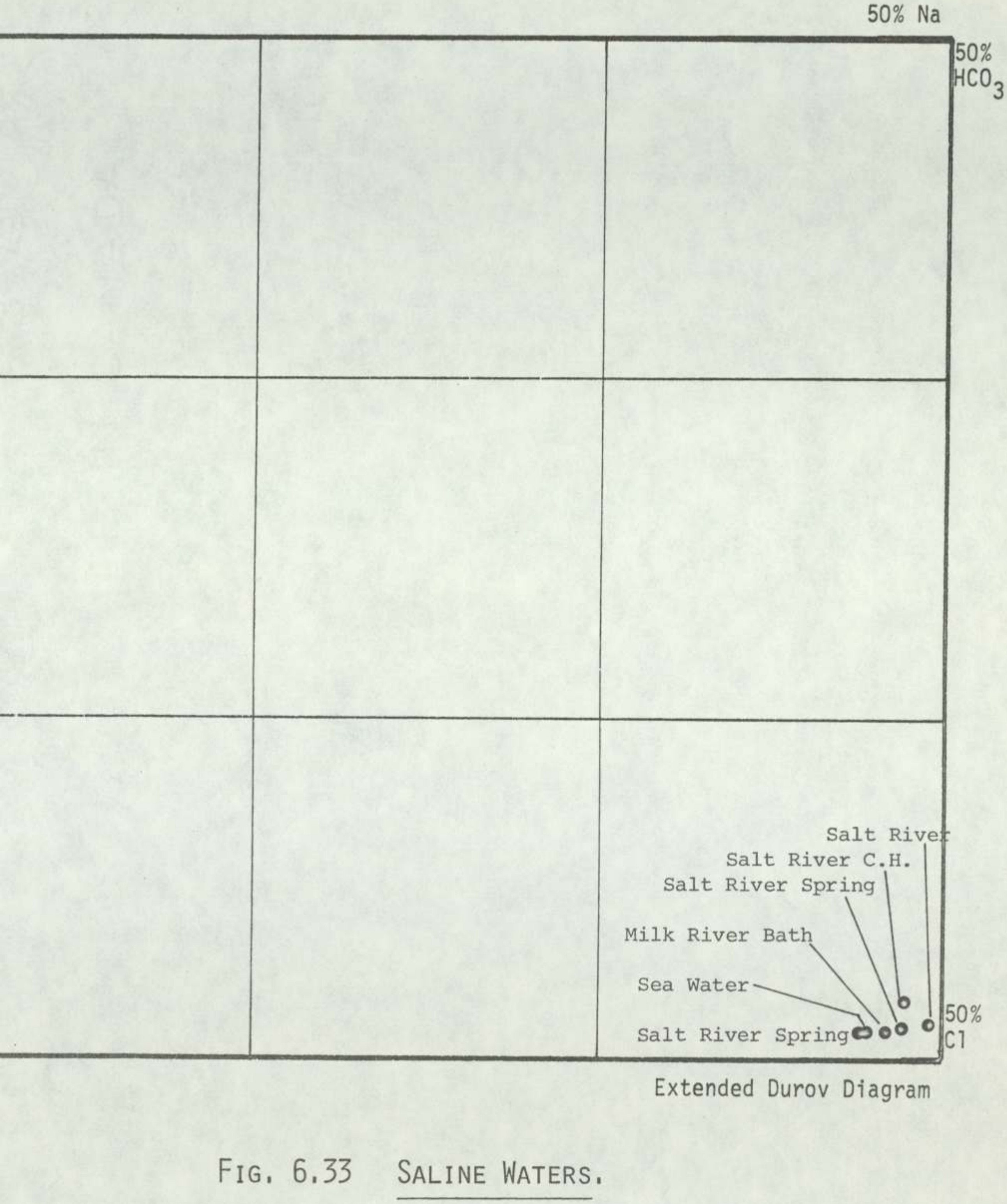


FIG. 6.33 SALINE WATERS.

Extended Durov Diagram

FIG.6.34 ALLUVIAL WELLS

ZONE	1	2	3	4	5
Calcium	Dominant	Increase	Decrease		Increase
Magnesium	Relatively small in comparison with calcium ions	Slight increase or remains constant	Initially may increase but subsequently decrease	Decrease	
Sodium		Begins to rise	Increase		
Bicarbonate	Dominant	Increase	Decrease to minimum value	Increase	Increase or decrease
Sulphate	Relatively small in comparison with bicarbonate ions	Remains constant or slight increase	Slight decrease	Decrease	Increase
Chloride		Remains constant or slight increase			
T.D.S	Absolute values will vary according to individual hydrogeological conditions	Increase	Remains constant or slight decrease	Slight increase	Increase
Carbonate Hardness			Decrease to minimum value		
Total Alkalinity			Decrease	Increase	
Non-carb. Hardness		Remains constant or slight increase followed in some cases by decrease, occasionally to zero	Decrease most frequently to zero or remains zero	Zero	

FIG 6.35 CLASSIFICATION OF GROUNDWATER INTO CHEMICAL ZONES.

(after Ineson and Downing)

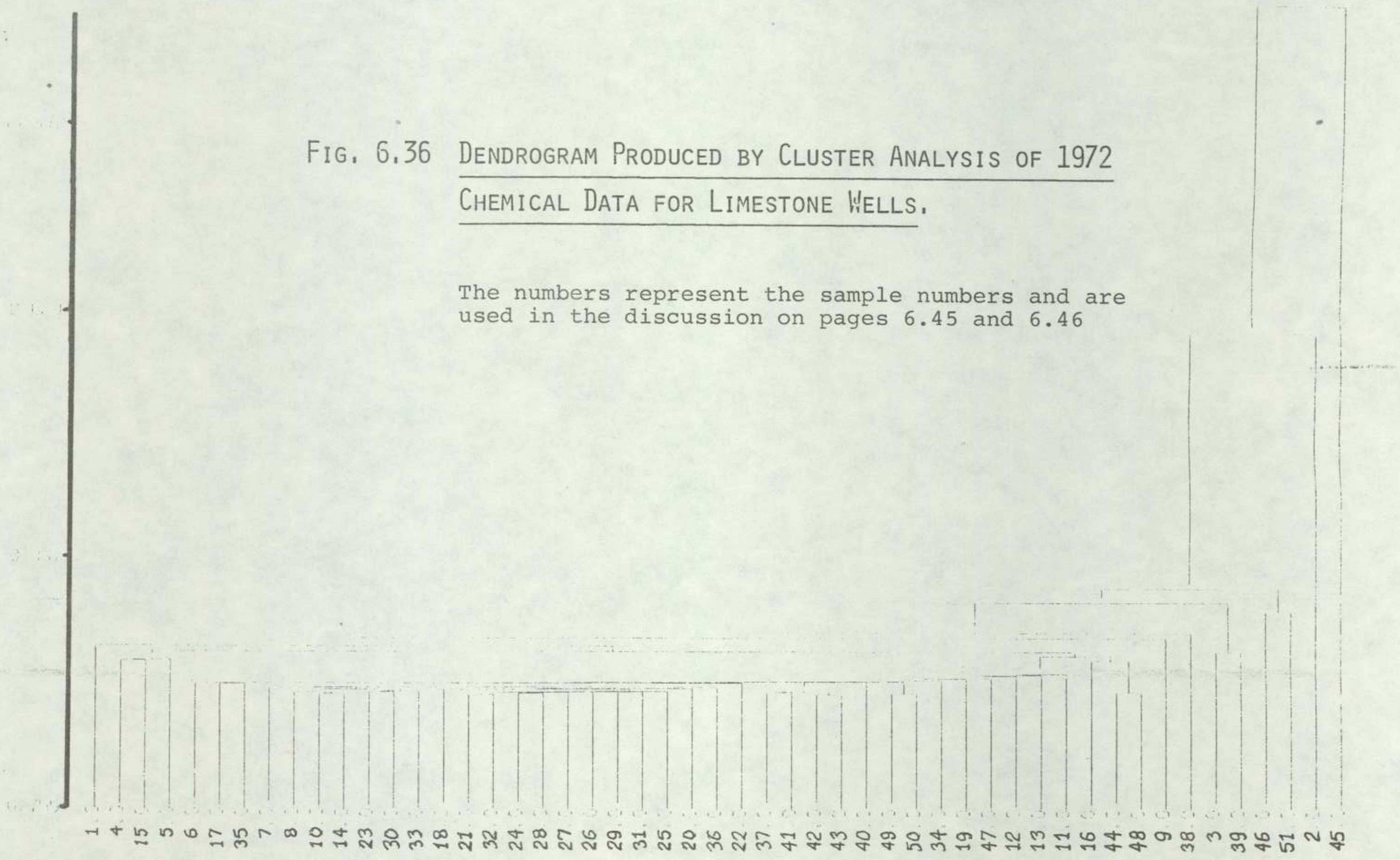


Fig. 6.36 Dendrogram Produced by Cluster Analysis of 1972 Chemical Data for Limestone Wells.

The numbers represent the sample numbers and are used in the discussion on pages 6.45 and 6.46

FIG. 6.37 CLUSTER ANALYSIS USING BASIC DATA.

```
                                                                    T.D.S.
                                                      .----    1 | 1075
                                                      I
                                                      I.---   13 | 932
                                                      II
                                                      I.---   16 | 1298
                                                      II
                                                      .----   25 | 779
                                                      I
                                                      I.---    2 | 604
                                                      II
                                                      I.---   10 | 647
                                                      II
                                                      I.---   15 | 448
                                                      II
                                                      .----   11 | 632
                                                      I
                                                    .------   12 | 555
                                                    I
                                            .--------------   24 | 2101
                                            I
                                            I   .----------    3 | 297
                                            I   I
                                            I   I      .---    4 | 404
                                            I   I      I
                                            I   I      .---   17 | 419
                                            I   I      I
                                            I   I      .---   21 | 325
                                            I   I      I
                                            I   I     .----   14 | 432
                                            I   I     I
                                            I   I     I.---    5 | 421
                                            I   I     II
                                            I   I     I.---    6 | 210
                                            I   I     II
                                            I   I     .----   20 | 318
                                            I   I     I
                                            I   I     I.---    7 | 251
                                            I   I     II
                                            I   I     I.---    8 | 344
                                            I   I     II
                                            I   I     I.---   19 | 217
                                            I   I     II
                                            I   I   .------   22 | 174
                                            I   I   I
                          .--------------------------------   18 | 366
                          I
-----------------------------------------------------------   23 |

-----------------------------------------------------------    9 | 246
   --+----+----+----+----+----+----+----+----+----+----+
60    0.3432    0.4804    0.6177    0.7549    0.8921    1.0293
  0.2746    0.4118    0.5490    0.6863    0.8235    0.9607

ROGRAM -  VALUES ALONG X-AXIS ARE SIMILARITIES
```

input data for the above clustering was in its original form and not
dardised in any way. The concentration of total dissolved solids in
s per million is given in the right-hand column. From this it can be
that the TDS, although not included in the input data, did exert an
ceptable influence on the clustering process.

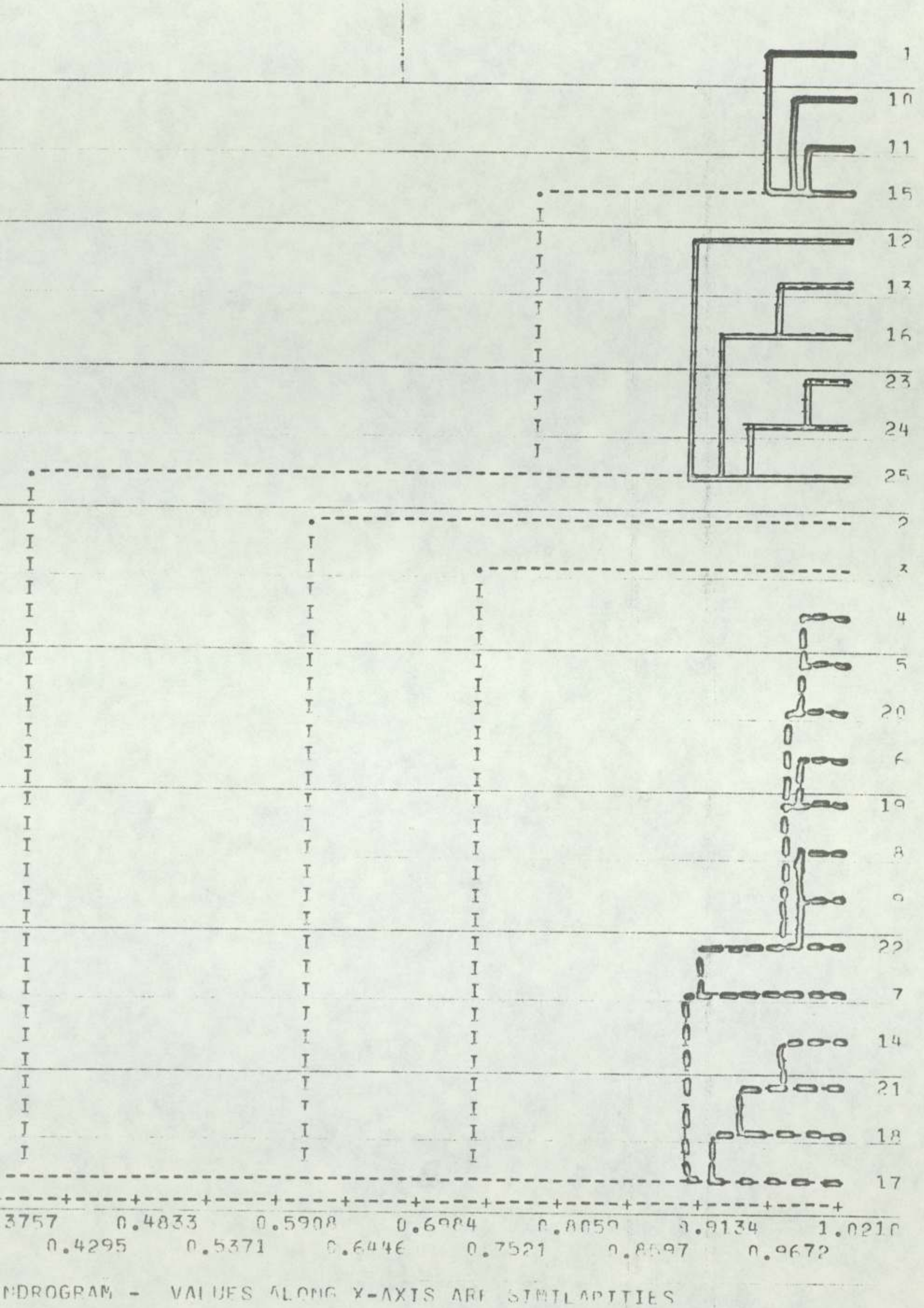
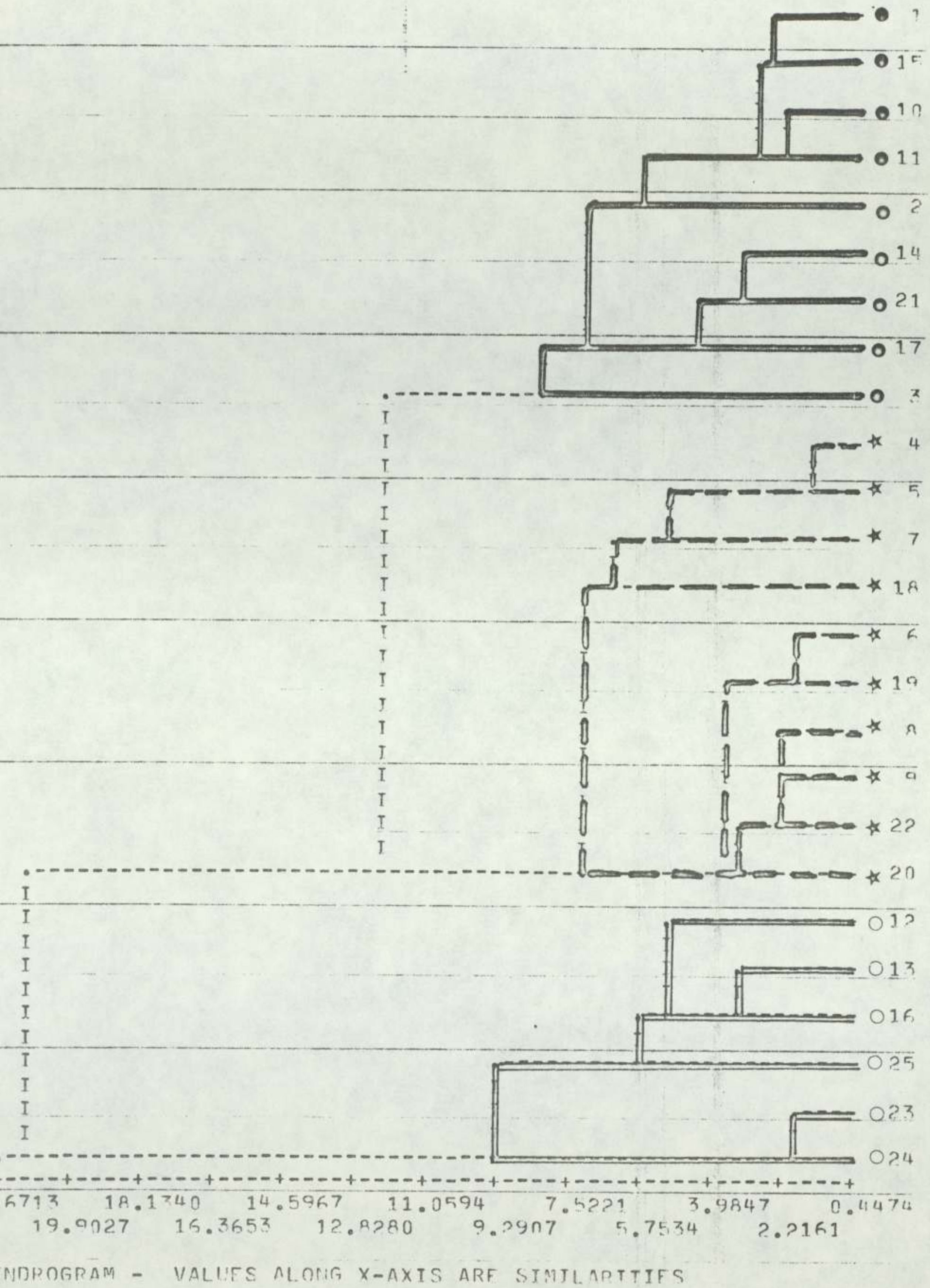


FIG. 6.38 DENDROGRAM DERIVED FROM CLUSTER ANALYSIS USING CORRELATION COEFFICIENTS.



mbol adjacent to sample number correlates with Durov plot in Fig. 6.40

FIG. 6.39 DENDROGRAM DERIVED FROM CLUSTER ANALYSIS USING DISTANCE COEFFICIENTS.

e symbols used above serve to correlate
e points on the Durov Diagram with the
usters in Fig. 6.39.

Fig. 6.40 Plot of Chemical Data which was Analysed by Clustering.

7 THE GROUNDWATER MODEL

7.1 Introduction

A water resources appraisal will usually include recommendations as to future development of the basin and consequently the hydrogeologist will be required to define additional sources of groundwater and possibly recommend which, if any, of the existing wells should be shut down or relocated. Unlike the surface water hydrologist who, with his engineering background, is used to supplying positive solutions qualified by confidence limits, the hydrogeologist often concludes that the best solution is a programme of 'phased development with continuous monitoring of water levels and quality'. Whilst this cautious approach may seem commendable on first site, the fact that often several man-years of expert opinion have arrived at a conclusion that the developer should 'Suck it and see', does suggest that the data collected during the study is not being efficiently utilized. Many hydrogeologists, believing that these facts make their position less secure, resort to the geological maxim that their subject is "more an art than science". In this way they perpetuate the myth that the hydrologist produces facts whereas the hydrogeologist can supply only theory.

It is obvious that any tool or technique which will enable the groundwater hydrologist to predict how an aquifer or basin will behave under different conditions, without actually going to the expense of carrying out lengthy experiments on the basin itself, would be invaluable. Hence groundwater models or analogues were developed and these enable several years of natural events to be simulated in a matter of minutes or, at the most, hours. Davis and DeWiest (1966) define these as physical systems or mathematical models obeying partial differential equations with boundary conditions similar to those in the prototype.

There are a variety of techniques for modelling an aquifer and a description of all these is outside the scope of this thesis. In general, however, it can be said that only electrical resistance-capacitor networks and mathematical digital computor models are used to any great extent. In the former, the flow of electricity through a mesh of resistors is assumed to be analogous to the flow of groundwater through a porous medium and the storage of water is simulated by means of capacitors. The equations are actually solved by finite difference methods which, it will be seen, are the common technique used in mathematical models. The R-C method has the advantage that the analogy is easily seen and hence the solution more readily understood, but the disadvantage that it requires a considerable investment in time and money to construct the model in the first place. Many such models are also somewhat inflexible and not readily adaptable to different areas, though this is not always the case.

In the last few years, with the rapid spread of digital computers, the use of mathematical models has increased considerably and they are now a powerful tool in the hands of the hydrogeologist. It is interesting to note, however, that considerable work is being done on so called hybrid models, which rely on the interaction of R-C networks and digital models. The fundamental difference between the two types of models is that R-C analogues are discrete only in space, whereas digital models are discrete in both space and time.

7.2 Theory

7.2.1 Groundwater Flow

Following experimental work on pipe flow by Hagen in 1839 and Poiseuille in 1841, both Darcy and Dupuit recognized the similarities to groundwater flow (Davis and

De Wiest 1966). It was not until 1856, however, that Darcy followed his inclination towards experimental work by proving that the rate of laminar flow through uniform sands was proportional to the hydraulic gradient and thus established the rule which became known as Darcy's Law.

$$Q = KA \frac{(h_1-h_2)}{L} \qquad \ldots\ldots\ldots\ldots\ldots\ldots 7.1$$

Where Q = Flow Rate
A = Area of Cross-Section
h_1-h_2 = Difference in Head
L = Length of Flow Rate

In 1857, Dupuit used the equation of flow in an open channel to derive an expression for flow through sand by assuming that the pore spaces acted as an infinite number of parallel pipes. He pointed out that the expression involving the square of the velocity could be neglected, due to the low rate of flow, thus giving the equation

$$V = K.S \qquad \ldots\ldots\ldots\ldots\ldots\ldots 7.2$$

Where $V = Q/A$ and is a Hypothetical Concept Known as the Specific Discharge
S = Hydraulic Gradient

Thus he derived theoretically the same equation which Darcy had developed experimentally in the previous year.

The constant K in equations 7.1 and 7.2, whilst obviously being dependant on the porous medium, will also vary with the fluid and it has been shown, by reference to flow in small pipes, that the following relationship holds.

$$K = C.d^2.\frac{\rho}{v} \qquad \ldots\ldots\ldots\ldots\ldots\ldots7.3$$

Where d = Mean Diameter of Grains

ρ = Density of Fluid

v = Viscosity

and C is a constant which takes into account the various characteristics of the medium including grain size, packing, porosity and stratification. Hubbert (1940 and 1956) verified equation 7.3 experimentally. As the viscosity and density of the fluid will vary with temperature it is apparent that the constant K, usually known as the coefficient of permeability or hydraulic conductivity, will also vary but, for practical purposes, the changes in groundwater temperature are such that this can be ignored. The term intrinsic permeability is used to define the characteristics of the medium alone and is given by $k=Cd^2$.

Darcy's Law may be written in differential form as follows:

$$v=-K.\frac{dh}{dl} \qquad \ldots\ldots\ldots\ldots\ldots\ldots7.4$$

where the minus sign signifies that the fluid moves in the direction of decreasing head

and the components of velocity along the directions of rectangular co-ordinates x, y and z are:

$$V_x=-K\frac{dh}{dx} \quad V_y=-K\frac{dh}{dy} \quad \text{and } V_z=-K\frac{dh}{dz} \quad \ldots.7.5$$

In order to derive a general equation of groundwater flow, which would then be applicable on a regional scale, it is necessary to base it on the principle of conservation of mass (also known as the continuity equation). If a given volume of aquifer is considered then the net inflow of water into that unit must be equal to the net accumulation of water in the unit, or

INFLOW - OUTFLOW = CHANGE IN STORAGE 7.6

Assuming that pressure distribution throughout the depth is hydrostatic, then the pressure head at any point is equal to the distance from that point to either the water table or the piezometric surface. Thus if the properties of the aquifer do not change with depth then the flow, assuming that it is laminar, through any unit cube will depend only on the pressure head gradient and the aquifer properties.

If flow is assumed to be horizontal then there will be no component in the z-direction and, substituting back in equation 7.5 for v_x and v_y gives:

$$\frac{Q_x}{A_x} = -K_x \frac{dh}{dx} \quad \text{and} \quad \frac{Q_y}{A_y} = -K_y \frac{dh}{dy} \quad \text{........7.7}$$

thus flow through the element in the x and y directions is:

$$Q_x = -K_x \frac{dh}{dx}.A_x \quad \text{and } Q_y = -K_y \frac{dy}{dx}.A_y \text{ ....7.8}$$

and flow through the full saturated thickness in each direction is:

$$Q_x = -K_x.t.\frac{dh}{dx} \quad \text{and } Q_y = -K_y.t.\frac{dh}{dy} \quad \text{.....7.9}$$

where $K_x.t$ and $K_y.t$ are the transmissibilities of the aquifer in the each direction and can be expressed by T_x and T_y giving:

$$Q_x = T_x.\frac{dh}{dx} \quad \text{and} \quad Q_y = T_y.\frac{dh}{dy} \quad \text{..........7.10}$$

If there is no change in storage then, according to the equation of continuity,

$$\frac{dQ_x}{d_x} = -\frac{dQ_y}{d_y} \quad \text{or} \quad \frac{d(T_x\frac{dh}{dy})}{d_x} + \frac{d(T_y\frac{dh}{dy})}{d_y} = 0 \qquad ...7.11$$

It is likely, however that the volume of water in the unit of aquifer under consideration will change with time, thus introducing another expression into the continuity equation. If recharge also enters through the surface of the aquifer at a rate per unit area of R, then the equation becomes:

$$\frac{\partial\ (T_x\frac{\partial h}{\partial x})}{\partial_x} + \frac{\partial\ (T_y\frac{\partial h}{\partial y})}{\partial_y} - R = S\frac{\partial h}{\partial t} \qquad ....7.12$$

where S is the coefficient of storage.

Using the standard notation the continuity equation for groundwater flow can be expressed as

$$\nabla T.\nabla h - S\frac{\partial h}{\partial t} - R = 0 \qquad ....7.13$$

An equation for which there is no general solution.

7.2.2 Mathematical Solution of Groundwater Flow

As there is no general solution to equation 7.13 the usual method adopted is one of finite difference approximation. The aquifer is divided into a number of discrete units and a set of simultaneous equations derived to describe the flow between each. These can then be solved to give the water level at the centre of each unit or node point at selected time intervals.

The method used in the present study is based on the work of Tyson and Weber (1963) and either rectangular or polygonal elements can be selected.

If a polygonal unit of unconfined aquifer is considered, as shown in Figure 7.1, then equation 7.13 can be replaced by the following difference - differential equation:

$$\sum_{i=1}^{6} \left[\frac{(h_i - h_B)}{L_{iB}} . T_{iB} . W_{iB}\right] = A_B . S_B \frac{dh}{dt}\beta . A_B . R_B \quad ....7.14$$

Where A_B = Area Associated with Node B

$T_{i.B}$ = Transmissibility between Nodes i and B

S_B = Storage Coefficient of Node B

R_B = Recharge Through Surface of Node B

T_{iB} = Transmissibility Between Nodes i and B

W_{iB} = Width of Boundary Between Nodes i and B

h_i = Water Table Elevation at Node i

h_B = Water Table Elevation at Node B

t = Time

Equation 7.14 is a finite difference approximation to the groundwater flow equation and can be solved for h_i by an iterative process.

7.2.3 Solution By Digital Computer

The program used in the current study solves the finite difference equation by an implicit method. There are several of these available, some of which combine the use of heads at both time t and at time t-dt. The Backward Difference Implicit Method, however, relies entirely on heads at time t. By way of contrast, the explicit methods of solution place greatest emphasis on heads at the previous time increment.

The general topic of finite difference approximations and their related problems was discussed at some length by Rushton (1973 and 1976).

The method used to solve the simultaneous equations is that known as Gauss-Seidel and this is best illustrated by means of the following example. Assume there are three simultaneous equations with three unknowns x_1, x_2 and x_3:

$$ax_1 + bx_2 + cx_3 = d$$

$$ex_1 + fx_2 + gx_3 = h$$

$$ix_1 + jx_2 + kx_3 = l$$

In order to solve these equations by Gauss-Seidel relaxation, values for x_2 and x_3 are assumed and substituted in the first equation. It does not matter whether these values are close to the real values or not. This then gives a first approximation for x_1, which can be written with a prime, hence:

$$x_1' = \frac{d-bx_2-cx_3}{a}$$

This value for x_1 is then substituted in the second equation, along with the original assumed value for x_3, thus giving a first approximation for x_2:

$$x_2' = \frac{h-ex_1-gx_3}{f}$$

Similarly for the third equation:

$$x_3' = \frac{l-ix_1-jx_2}{k}$$

This process of computing an approximate value for all the variables is known as an iteration, and it is then repeated using the newly computed values to obtain a further set of approximations. On each successive iteration the computed values should approach or 'converge' on the true values and the differences between the computed values of successive iterations should decrease. Some criteria is then established to measure when the convergence has produced acceptable approximations to the values of the variables (i.e. when the differences between values from one iteration to the next have become less than a specified amount.

The above discussion is somewhat simplified and does not outline certain necessary criteria which must be met before convergence can take place. It does serve, however, to illustrate the fundamentals of the iterative process in solving simultaneous equations by means of the Gauss-Seidel technique.

In the case of the groundwater model it is the heads that are the unknown variables and the convergence is evaluated by means of calculating the residual in the water balance. For the Node B, from equation 7.14, at time t

$$\mathrm{RES(B)} = \sum_{i=1}^{6} \left[\frac{T_{iB} \cdot W_{iB}}{L_{iB}}(h_i^t - h_B^t)\right] - A_B S_B (H_B^t - H_B^{t-dt}) + A_B R_B \quad \ldots 7.15$$

Where RES(B) is the residual in the water balance for Node B.

In order to establish a method of adjusting H_B^t so that RES(B) approaches zero, it is necessary to differentiate equation 7.15 with respect to H_B

$$\frac{d\ \mathrm{RES(B)}}{dH_B} = -\sum_{i=1}^{N} \frac{T_{iB} \cdot W_{iB}}{L_{iB}} - A_B S_B \quad \ldots\ldots\ldots\ldots 7.16$$

Where N = Number of Sides of Node

However, $d\,RES(B) = RES(B)^{t} - RES(B)^{t-dt}$
and $dH_B = H_B^{t} - H_B^{t-dt}$

Therefore, substituting in 7.16 gives:

$$\frac{RES(B)^{t} - RES(B)^{t-dt}}{H_B^{t} - H_B^{t-dt}} = -\sum_{i=1}^{N} \frac{T_{iB}.W_{iB}}{L_{iB}} - A_B.S_B \quad ...7.17$$

$$\text{or} \quad H_B^{t} = H_B^{t-dt} + \frac{RES(B)^{t} - RES(B)^{t-dt}}{\sum_{i=1}^{N} \frac{T_{iB}.W_{iB}}{L_{iB}} - A_B.S_B} \quad ....7.18$$

However, the purpose of this exercise is to reduce the new residual to zero and hence equation 7.18 becomes:

$$H_B^{t} = H_B^{t-dt} + \frac{RES(B)^{t-dt}}{\sum_{i=1}^{N} \frac{T_{iB}.W_{iB}}{L_{iB}} - A_B.S_B} \quad ....7.19$$

In the program all the nodal errors in the water balance are summed and convergence continues until this is reduced to less than a value specified at the outset of the run. The specified value will depend on the study area, and is conveniently estimated on this basis of the annual recharge.

7.3 Data Preparation

In the early discussion it was seen that the finite difference model was discrete in both space and time. Thus some consideration has to be given to this discretisation process, in order to ensure that the spacial or temporal steps are not of such a size that the finite difference approximations are invalid.

The discrete spatial steps are, in fact, the polygons or nodes and thus the initial construction of the grid or network must be carried out with some care.

The preparation of data can be split into a number of parts. The first is to delineate the boundaries of the model, the second is to construct a nodal network, the third is to assign values to the hydrogeological parameters of the nodes and interconnects, the fourth is to prepare water level data and recharge estimates.

The delineation of the boundaries is relatively simple in the case of the sea or a river, or if there is an impermeable barrier to groundwater flow. It is not easy, however, in the case of head controlled boundaries when the external head is unknown. In this case the head has to be either measured in the field or supplied by educated guesswork. If no information is available then it is essential that various values should be tried in the model and the sensitivity of the system to this unknown data be assessed. If it is not very sensitive then any reasonable values can be used.

Before the nodal network can be drawn up the following information is required:

1. Water elevation contour maps for the duration of the calibration period; these should show all existing wells.
2. Surface topography contours.
3. A transmissibility contour map.
4. A storage coefficient contour map or data.
5. A bedrock contour map.
6. A contour map of the top of the aquifer.

If these maps are all to the same scale then a transparent overlay of the polygonal network can be superimposed on them. With these maps,and bearing in mind the basic ideas of finite difference theory, it is then a fairly straightforward job to see where the nodes need to be small and where they need to be large. This of course does not apply in the case of a square grid.

Once the nodal network has been drawn up every node is numbered; first the internal nodes starting at 1 and then the external ones following consecutively from the last internal one.

The next task is to assign the hydrogeological data to the model for each node and its interconnect with its neighbour. The following values have to be assigned:

1. Initial water levels at each node.
2. Monthly water levels at each node for the calibration period.
3. Storage coefficients for each node. Two values are assigned depending upon the water level elevation or piezometric head.
4. Ground surface elevation for each node to enable surface outflow to be calculated, if any.
5. Bedrock elevation for each node.
6. Elevation of top of aquifer at each node.
7. Transmissibility or permeability value for each interconnect.
8. Elevation of head in each node.

The dimensions of the nodes must be fed into the computer, as must the monthly recharge values, the initial water levels for each node and the historic water levels covering the calibration period. The latter values are not used in the calculation but provide a standard against which the computer values can be compared.

At the start of this section it was pointed out that the finite difference approximation was discrete in both space and time. The spatial aspects have been discussed above and are relatively easy to assess. With respect to time, however, the parameters are more difficult and the choice of values tends to be a combination of intuition and trial and error.

In the program used, a full description of which is included in Chapter 8, the parameters controlling the iterative process are PCNT, ERROR and RCOEF.

PCNT is the maximum timestep, in years, to be used. Its choice, based upon experience, is initially arbitrary, although if it is too big then the approximation of the finite difference differentials with respect to time will cease to be valid and, assuming the equations will converge to a solution, the results will be in error. The program sets a maximum value of one month (1/12 year).

If it is desired to ensure that the program runs at optimum speed then the values of PCNT can be progressively increased until a significant change in the results occurs. The maximum value before the change occurred is then assumed to be optimum time step for that aquifer.

ERROR is the test for convergence which was mentioned at the end of Section 7.2.3. The choice of value for ERROR is important as it determines the accuracy of the final results and also the amount of time necessary to complete the relaxation process. Goodwill (1971)reports the difference in machine time is difficult to ascertain due to the fact that when a process is converging it often does so at an exponentially increasing rate. He estimates that if the numerical value of ERROR is halved the number of iterations would probably only increase by 1 or 2 which, on average, would increase run time by about 10 - 15%.

The relaxation coefficient RCOEF has a value between 0.8 and 1.2. Tyson and Weber (1963) suggested that such a coefficient increases the speed of convergence without affecting the end results. An optimum value can be obtained in the same manner as for PCNT and ERROR, by comparing runtimes.

7.4 Clarendon Limestone Models

7.4.1 Introduction

The theory described in the preceding sections of this chapter is based on the assumptions that the aquifer is homogeneous, isotropic and that the flow velocities are relatively low. It is also assumed that the groundwater equation is linear. In the case of a karstified limestone aquifer it is certain that the first two criteria are not satisfied and it is also likely that some high flow velocities occur in fissures and fractures. In an unconfined aquifer the saturated thickness, and hence the transmissibility, is likely to vary with time and thus introduce non-linearity.

In the case of the White Limestone it was obvious that the criteria were frequently not satisfied on a localized basis. However, as a distinct water table/piezometric surface existed, it was felt that the criteria were reasonably satisfied on a regional basis.

With regard to non-linearity, this would only occur in the recharge areas where the groundwater was unconfined, or in confined areas where the pressure surface fluctuated about the base of the confining horizon. In the latter case the problem was overcome by an in-built facility which allowed the storage coefficient to change appropriately.

7.4.2 Coarse Models

The first attempt at modelling the limestone aquifer was a 16 node model, which covered only the plains and did not extend into the recharge area. This was done with limited input data and without a full appreciation of the regional hydrogeology. It served, however, to familiarize the writer with the procedures for the preparation of data and the method of computation.

One of the main constraints on the success of this model was the lack of knowledge about flow conditions at the boundaries. In view of this, it was decided to extend the model to include the recharge area and this led to the 33 node model shown in Figure 7.2.

The 33 node model extended to the basin limits, as defined in Chapter 5, with the exception of the eastern boundary. Here an attempt was made to restrict the model to those areas which contributed to groundwater flow in the plains, thus excluding the Bowers River and Cockpit Spring areas. In the southern part it was probably realistic to consider this as a boundary across which there was no flow. In the northern part of this eastern boundary, however, there was no obvious groundwater divide and hence a head controlled boundary had to be used. This permitted outflow from nodes 8 and 9 to the external nodes.

The polygonal nodes were constructed with the larger ones in the recharge area and the smaller ones in the plains, where the hydrogeology was known in more detail. The confined area in the centre of the plains was covered with nodes 17, 23 and 30 and these were drawn so that their eastern boundaries coincided with the NNE-SSW fault. In this way the theoretical barrier effects of this fault could be simulated.

No flows were permitted across the northern and western boundaries, as these corresponded to the limits of the groundwater basin. However, the southern boundary, which corresponded to the south coast fault, was modelled as a head controlled boundary. In this way outflow of fresh groundwater and inflow of saline water could be simulated.

The option of reading the recharge as four components was used and these were input as recharge, pumping and springflow. The recharge values derived from the surface water catchment model, as described in Chapter 4, were distributed among the appropriate nodes.

Initial estimates of transmissibility were made, based on the available data (See Chapter 5), and a storage coefficient of 0.1 was used for the unconfined limestone within the plains. This value was reduced somewhat in the recharge area, where the storage was known to be less, and values of 0.001 were used in the confined nodes. The physical dimensions of the aquifer at each node were taken from the geological and topographical maps and water levels obtained from the well monitoring programme.

Once the calibration runs were undertaken it became apparent that a major problem was to move the recharge from the upland areas, through the model, and out to the sea. There was always a tendency for the water to stack up at some point in the system. If very high values for transmissibility were used then this water could be shifted out of the recharge area, but only to produce unreasonably high water levels in the plains.

After numerous tries, however, a reasonable simulation was achieved for most of the plains area with a system of transmissibility values that, in general, increased from north to the south. In the area to the east of the NNE-SSW fault, values as high as 4.0×10^6 gpd/ft were required, strongly suggesting flow through large solution cavities.

The storage and transmissibility values used in this final run of the 33 node model are depicted on Figure 7.2 and the resulting hydrographs in Figure 7.3.

An examination of the cross-flows along the southern boundaries (Tables 7.1 and 7.2) shows that saline intrusion would have occurred in the eastern half of the plain in 5.0% of the simulated months and not at all in the western half. A trend which conforms to the geographic pattern of observed saline contamination.

7.4.3 Fine Grid Model

7.4.3.1 Reasons For A Fine Mesh Model

The coarse model described above was an invaluable aid in understanding the groundwater regime, and in highlighting the problems associated with modelling that regime. It did not, however, enable a detailed study to be made of the movement of saline water as the mesh was too coarse. Thus it was decided to construct a more detailed model and, this time, to extend the eastern boundary to include the Brazilletto Hills, Cockpit Springs and Bowers River. In this way, the model would include the entire basin.

7.4.3.2 The Rectangular Grid

Having decided to produce a more detailed model the option remained as to whether the nodes should be polygonal, as in the coarse model, or whether a rectangular grid should be used. The polygonal model is more flexible, in that the sizes of the nodes can be varied to suit the hydrogeological conditions but, with a large number of such nodes, the computational time increases significantly.

YEAR	MONTH	NODES 29 → 37		NODES 30 → 36	
		INFLOW	OUTFLOW	INFLOW	OUTFLOW
1970	A		1.971		0.209
	M		2.0171		1.181
	J		2.255		1.279
	J		2.378		1.123
	A		2.561		1.834
	S		2.760		2.477
	O		2.913		2.395
	N		2.292		1.818
	D		2.820		1.368
1971	J		2.721		1.294
	F		2.620		1.139
	M		2.483		0.735
	A		2.345		0.723
	M		2.209		0.333
	J		2.115		0.698
	J		2.022		0.145
	A		1.949		0.446
	S		1.956		0.767

Million Cubic Metres

TABLE 7.1 CROSS-FLOWS OUT OF 33 NODE MODEL

YEAR	MONTH	NODES 31→35		NODES 32→34	
		INFLOW	OUTFLOW	INFLOW	OUTFLOW
1970	A	0·229		0·153	
	M	0·636		0·183	
	J	0·517		0·118	
	J	0·365			0·063
	A	0·236			0·189
	S		0·044		0·366
	O		0·306		0·386
	N		0·425		0·401
	D		0·442		0·331
1971	J		0·330		0·219
	F		0·259		0·232
	M		0·086		0·091
	A		0·030		0·098
	M		0·018		0·034
	J	0·109			0·026
	J	0·257		0·033	
	A	0·365		0·077	
	S	0·357		0·043	

Million Cubic Metres

Table 7.2 Cross-Flows out of 33 Node Model

As one characteristic of the program is that it can be run on relatively small machines, particularly for use in developing countries, it would seem to defeat some of the purpose if the array sizes were increased to the point where this was no longer possible. One way of keeping the array sizes manageable, with an increased number of nodes, would be to use a rectangular or square grid. The performance of this model under these conditions, however, had not been tested.

After evaluating the above factors the decision was made to simulate the Clarendon Limestone aquifer using a square grid in which the sides of the nodes were 1 kilometer in length. The resulting network of 127 internal nodes is shown in Figure 7.4.

7.4.3.3 Basic Data

7.4.3.3.1 Starting Conditions

The work with the coarser model had demonstrated the importance of the initial water levels or starting conditions. In that model the values used had no greater accuracy than the monthly historic water levels and, in fact, due to the completion of some observation holes in mid 1970, were actually less detailed than the later historic levels. In view of this it was decided to calibrate the 127 node model over a 12 month period commencing at the end of November 1971. A comprehensive water level measurement programme had been carried out in that month, at a time when the vast majority of the pumping wells were shut down, and hence the best possible groundwater contour map was available.

Another factor in selecting this 12 month calibration period was that it represented the time when the best coverage of monthly water levels was available. This was due to the number of additional monitoring holes which had been completed in the preceding 12 month period, thus expanding the observation network.

The matter of starting conditions is actually more complex than just accurately extrapolating from the recorded field measurements. Rushton and Wedderburn (1973) considered the question in relation to electrical analogue models and suggested recycling a specified period of discharge until the model reached a state of dynamic equilibrium. In the present study this method was used, at one stage in the calibration, in order to obtain approximate water levels in those areas for which field measurements were not available.

7.4.3.3.2 Historic Water Levels

As described above, the initial starting values were primarily derived from the hand produced groundwater contour map for November 1970. The historic water levels were based on the values observed as part of a monthly measuring programme. Hydrographs for each observation hole were plotted and the elevations of the water level at the end of each month were read directly off these graphs. The values were then fed into a computer contouring program, as described in Chapter 8, and the appropriate water level for selected nodes generated. It was obviously unreasonable to extend the water levels much beyond the area covered by the monitoring network (i.e. into the recharge area) and hence this was not attempted.

7.4.3.3.3 Recharge

The four component option for recharge was used, with borehole abstraction and some spring flow being simulated as negative recharge. The natural monthly recharge, as derived from the watershed model (Chapter 4), was distributed amongst the relevant nodes and some extrapolation was required for the Brazilletto area. This was done by taking the recharge in inches for sub-catchments 4 and 10 and applying it to the nodes in the new area. The actual way in which the distribution was carried out is shown in Table 7.3

Monthly pumping figures were available for most of the limestone wells and, in the case of the few exceptions, estimates were made by comparison with suitable nearby wells.

Spring flows were handled in two different ways in the model. The flow of springs situated in the northwest of the plains, which are the source of the Milk River, were estimated on a monthly basis and simulated as negative recharge in the appropriate nodes. It was assumed that all the runoff at Scotts Pass was spring flow and this was shared between nodes 42, 43 and 54. For the St. Jago springs the difference between river flow at Scotts Pass and Toll Gate was taken and augmented by some 1,000 acre-feet/month to allow for known irrigation diversions. These monthly discharges were then shared between nodes 65 and 77.

Similarly an estimate of the monthly discharge from Milk River Bath was included in node 120.

In the case of the Cockpit Springs and Bowers River, these were also initially modelled as negative recharge. After the first few runs, however, it was decided to simulate these as outflow across the external boundary of the model. In this way the discharge could be allowed to fluctuate naturally with the seasons. Thus head-controlled boundaries were introduced at nodes 109 and 119.

CATCHMENT 2		
	VOLUME to NODES	1 – 23, 27-31, 41-43 53-54
CATCHMENT 4		
	VOLUME to NODES	24-26, 32-38, 44-50 55-61, 72
	DEPTH (inches) to	35, 51, 62, 63, 74 75.
CATCHMENT 5		
	VOLUME to	40, 52, 64, 65, 76, 77, 99 100, 110.
CATCHMENT 6		
	VOLUME to	66 – 71, 78 - 81 88, 89.
CATCHMENT 10		
	DEPTH (inches) to	83-87, 93-98 105-109, 116-119 126, 127.

TABLE 7.3 DISTRIBUTION OF RECHARGE, 127-NODE MODEL.

7.4.3.3.4 Aquifer Characteristics

The preliminary coarse model was particularly useful as an aid in assigning the transmissibility and storage values in the 127 node mode. The adjustment which had been made to these parameters in the early model, in order to achieve a reasonable calibration, provided a starting point for the larger model. In this way, considerable computer time was saved.

7.4.3.3.5 Aquifer Dimensions

Initially an attempt was made to reproduce the actual dimensions of the aquifer in each node as closely as possible. Hence, along the northern limits of the basin, where the White Limestone is known to be thin, the bottom of the aquifer was placed at a relatively shallow depth below ground level. It was hoped that, in this way, the problem of an unrealistically large reservoir of groundwater, which occurred in the earlier model, would be avoided. It was assumed that, as the water levels in these nodes approached the bottoms, then the model would simply invoke the in-built mechanism and cut off outflow from the nodes. It will be seen that complications occurred with these high base levels and that, in fact, the model failed to converge.

7.4.3.4 Calibration

Calibration of the 127 node model was undertaken with the above mentioned basic data and initially it failed to converge for the reason mentioned in the previous section. It was apparent that the attempts to model the steep gradient of the base of the White Limestone in the northern nodes created the situation shown in Fig. 7.5. It can be seen that the mean water levels between adjoining nodes was less than the elevation of the base of the aquifer in the higher node. If this only occurred in one or two nodes, then the model was able to cope. In this case, however, it occurred in a number of nodes and the model failed to converge, thus necessitating that the bottom levels be dropped to sea level.

This lowering of the base levels did not render the model any less effective but only added to the complications of calibration. If the original configuration had been successful then the model would automatically have prevented excess water being drawn from storage, whereas with the new configuration, this had to be checked manually.

When the first runs were carried out, this problem of excess water from storage immediately manifested itself and it can be seen from Fig. 7.6 that the nodes along the northern edge of plains (i.e. south of the recharge area) suffered rising water levels. In fact spring flow took place in several areas where, in nature, it could not possibly occur.

In view of this, various strategies were developed to try and cope with the problem. The first was to introduce two storage coefficients for the nodes in question. The normal one, down to the supposed bottom of the aquifer, and then a much reduced one below that point. In this way, the water levels would fall normally until reaching the critical horizon after which they would drop very rapidly until the hydraulic gradient was reversed. The total quantity of water would be relatively small and out-flows would be quickly cut off. For reasons which were not apparent, however, the model would not converge.

An alternative strategy, which proved partially successful, was to stop all outflow from these northerly nodes during the early calibration runs and then gradually re-introduce it in a controlled manner once the other parameters had been reasonably defined. The most effective approach, however, and the one which led to the successful calibration of the model, was to significantly reduce the initial water levels in the recharge areas and thereby reduce both the amount of water in storage and the hydraulic gradient. In this way the natural behaviour of the aquifer within the plains area could be successfully simulated by means of a compromise solution in the recharge area.

The idea of lowering the water levels was obtained from recycling this original model for 5 years. The resulting hydrographs did not correlate well with the historic water levels in the early stage, and an extensive build up of water occurred in the foothills. Nevertheless it appeared that once the excess water had been removed from the higher regions then the model appeared to be responding to the natural events in an improved manner. Thus, for the recharge nodes in which historic water levels were not available new estimates were made, based on the results of recycling the 12 months of data for 5 years.

The calibration process of the 127 node model proved much more difficult than that of the 33 node model and more than 50 computer runs were required before this process was completed. It should be said, however, that several of these were not strictly part of the calibration process but were attempts to see how the model responded to extreme conditions.

For example, if it appeared that transmissibility values should be increased in a certain area then, before this was done on a node by node basis, it was found to be useful to increase all values by changing the conversion factor. This could be done very quickly and the effects evaluated. In this way some idea of the magnitude of required changes could be obtained.

The actual initial water levels used in the successful calibration are shown in Fig. 7.7 and, for comparison, the computed water levels at the end of the 12 month run are shown in Fig. 7.8. From these it can be seen that there has been no excessive drawing of water from storage or, conversely, no mason build-up of water in any of the nodes.

The coefficients of storage are shown in Fig. 7.9 and it can be seen that these vary from 0.001 in the confined area to 0.1 in some of the unconfined nodes. The only apparent anomalies are in nodes 103, 114, 121 and 122 where, although the aquifer is believed to be confined, it was necessary to increase the storage to 0.01 in order to achieve an accratable calibration. It is significant, however, that each of these nodes adjoines a major fault zone which may thus be responsible for giving an effective storage coefficient in excess of that normally expected from a confined aquifer.

The transmissibility values used in this final calibration are shown in the form of a contour map in Fig. 7.10 and from this it can be seen that they increase from less than 50,000 GPD/ft in the north-west to 5.0 x 10^6 GPD/ft along the faulted south-eastern boundary of the model. This extremely high value is no doubt due to the presence of the fault zone but, even within the centre of the plains values of 2.1 to 2.7 x 10^6 GPD/ft are required. At the northernend of the plain this falls to 1.5 x 10^6 and 0.4 x 10^6 GPD/ft.

The water balance for the duration of the run indicated that there was a subsurface outflow (including the Cockpit Springs) of 44,537,000 cubic metres and that abstraction (including the Milk River Spring Flow) exceeded recharge by 14,279,000 cubic metres. Thus there was a reduction in storage of 58,591,000 cubic metres.

The directions of cross-flow in the most southerly nodes are shown for each month in Fig. 7.11 and it can be seen that sea water intrusion occurred throughout the 12 month run. This model also successfully simulated this as taking place predominantly to the east of the north-south fault (i.e. in the Kemps Hill - Raymonds area) although it also allows it to take place into node 121 and, for three months, into node 122.

Although a less severe salinity problem does exist in the limestone to the west of Kemps Hill it was said, in an earlier chapter of this thesis, that this was probably due to downward percolation of alluvial water. The fact that the model shows sea water intrusion does not necessarily negate this theory. No component for recharge from the alluvium in this area was included in the model, as the order of magnitude was not known, and thus the model would compensate for this missing recharge by drawing in sea water to make up the deficit.

The net flows across the southern boundary of the model are shown in Table 7.5 and these have been split into the components east and west of the north-south fault zone. From these figures it can be seen that, although some inflow took place in the western half into certain nodes, there was a net discharge to the sea in every month of the simulation period. In contrast to this, there was a net inflow across the eastern half of the southern boundary in eleven out of twelve months. It should be noted here that, although it is depicted as sea water intrusion by the model, it could also be upward movement of saline water as discussed in Chapter 6. The model is unable to distinguish between these two mechanisms.

The actual hydrographs produced by the model, for nodes in which historic water levels are available, are shown in Fig. 7.12.

Nodes	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
110-161	-3.490	-3.106	-2.802	-2.532	-2.355	-2.256	-2.122	-1.938	-1.871	-1.977	-2.170	-2.955
120-160	-2.263	-1.992	-1.841	-1.661	-1.593	-1.547	-1.492	-1.341	-1.284	-1.386	-1.581	-1.902
121-159	0.021	0.318	0.546	0.834	0.811	0.896	0.915	1.243	1.198	0.964	0.567	0.081
122-158	-0.608	-0.613	-0.366	-0.094	-0.245	-0.195	-0.017	-0.297	-0.261	-0.054	-0.391	-0.878
Total	-6.340	-5.393	-4.463	-3.453	-3.382	-3.102	-2.682	-1.739	-1.696	-2.453	-3.575	-5.654
123-157	0.111	0.416	0.460	0.544	0.499	0.606	0.444	0.603	0.583	0.531	0.235	0.015
124-156	1.234	0.761	0.922	1.215	1.007	1.384	1.198	1.411	1.285	1.178	0.882	0.418
125-155	0.490	2.088	2.097	2.745	2.472	2.900	2.542	2.735	2.637	2.536	2.022	1.352
126-154	-0.260	0.322	0.471	0.673	0.712	0.834	0.828	0.881	0.797	0.720	0.574	0.272
127-153	-1.744	-1.585	-1.505	-1.433	-1.387	-1.337	-1.311	-1.285	-1.366	-1.408	-1.454	-1.603
Total	-0.169	2.002	2.445	3.744	3.303	4.387	3.701	4.345	3.936	3.557	2.259	0.454

FLOWS ACROSS THE SOUTHERN BOUNDARY OF THE MODEL.

(In million cubic metres. Negative flow is to the sea)

TABLE 7.5

7.7 Summary of Modelling

The results of the modelling of the White Limestone aquifer of the Rio Minilo - Milk River Basin indicate that this type of karstified aquifer, with its high secondary permeability, can be successfully simulated by means of finite difference approximations using digital computers. The results also indicate, however, that the effective regional transmissibilities are considerably greater than the values derived from pumping tests. As discussed earlier, there is much evidence to suggest that two flow systems exist within the aquifer. Although this concept is difficult to demonstrate conclusively, it would appear that a regional system, probably related to faults and solution cavities, allows large volumes of water to move rapidly through the system, whereas water level measurements and pumping tests on individual boreholes reflect a more normal type of groundwater regime.

In the case of the Clarendon Plains the program KRGW appears to have been particularly successfully in quantitatively simulating the intrusion of saline water. This was apparently due to the fact that the Ghyben-Herzberg relationship does not occur, as such, and that hence the saline water moves laterally away from the fault zone through fissures and solution cavaties,rather than vertically upwards beneath pumping wells.

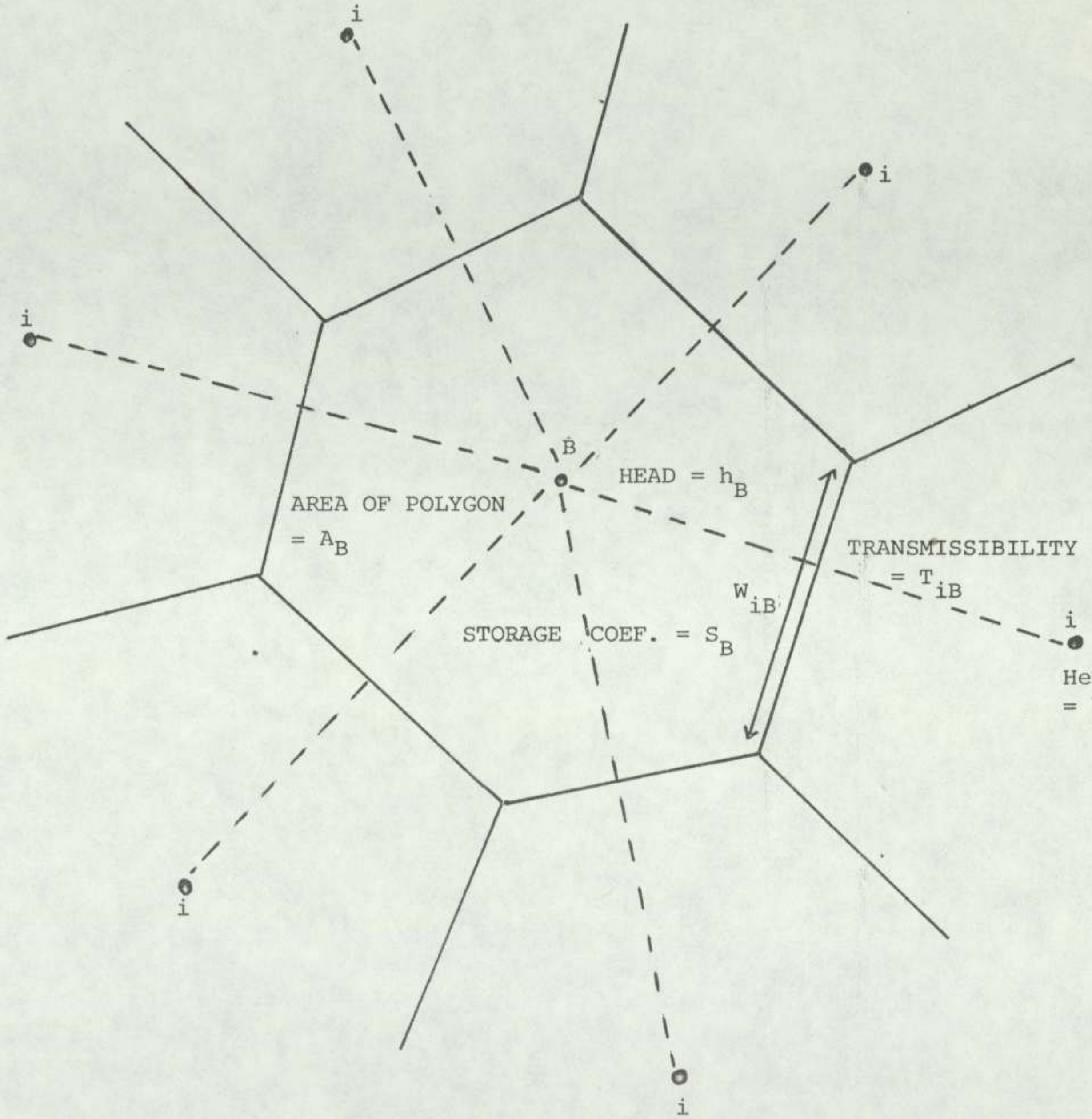


FIG. 7.1 POLYGONAL UNIT OF UNCONFINED AQUIFER

STORAGE COEFFICIENTS

NODE	S
1	.04
2	.04
3	.10
4	.05
5	.05
6	.05
7	.10
8	.08
9	.10
10	.12
11	.08
12	.08
13	.08
14	.05
15	.08
16	.11
17	.001
18	.02
19	.10
20	.10
21	.12
22	.14
23	.001
24	.11
25	.12
26	.12
27	.12
28	.12
29	.06
30	.001
31	.06
32	.08
33	.06

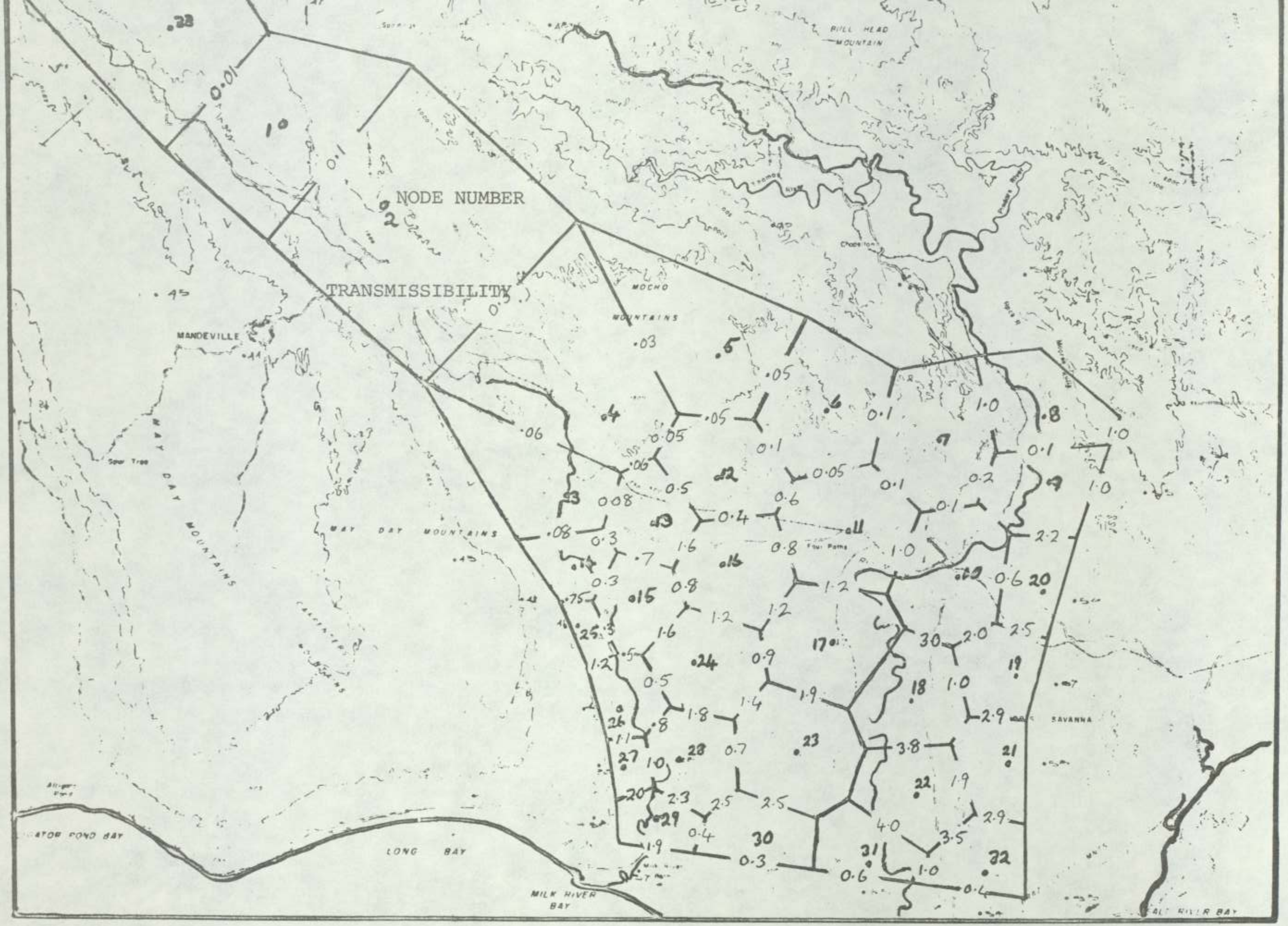


FIG. 7.2

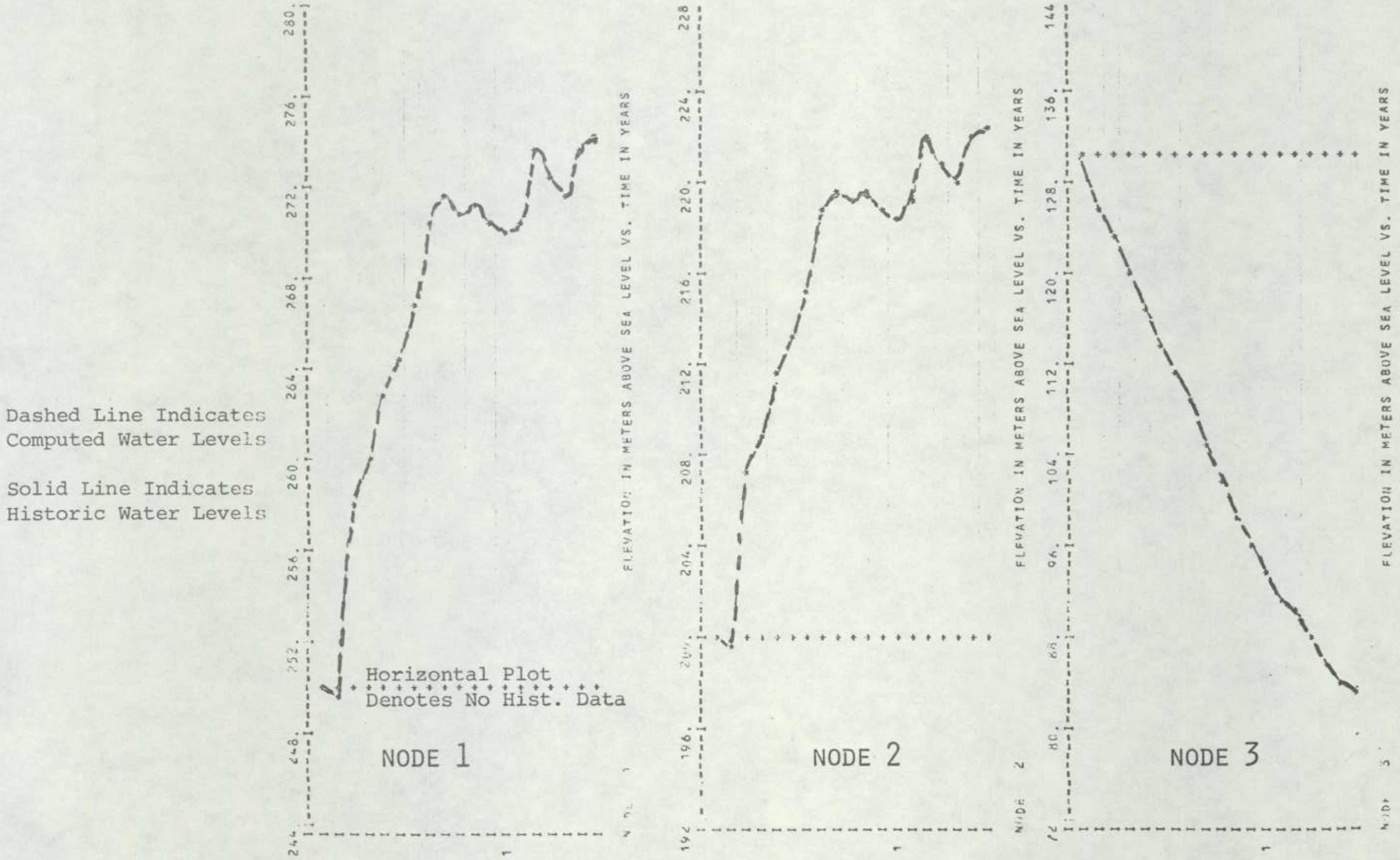


FIG 7.3 HYDROGRAPHS FROM 33-NODE MODEL

Cont. on following pages

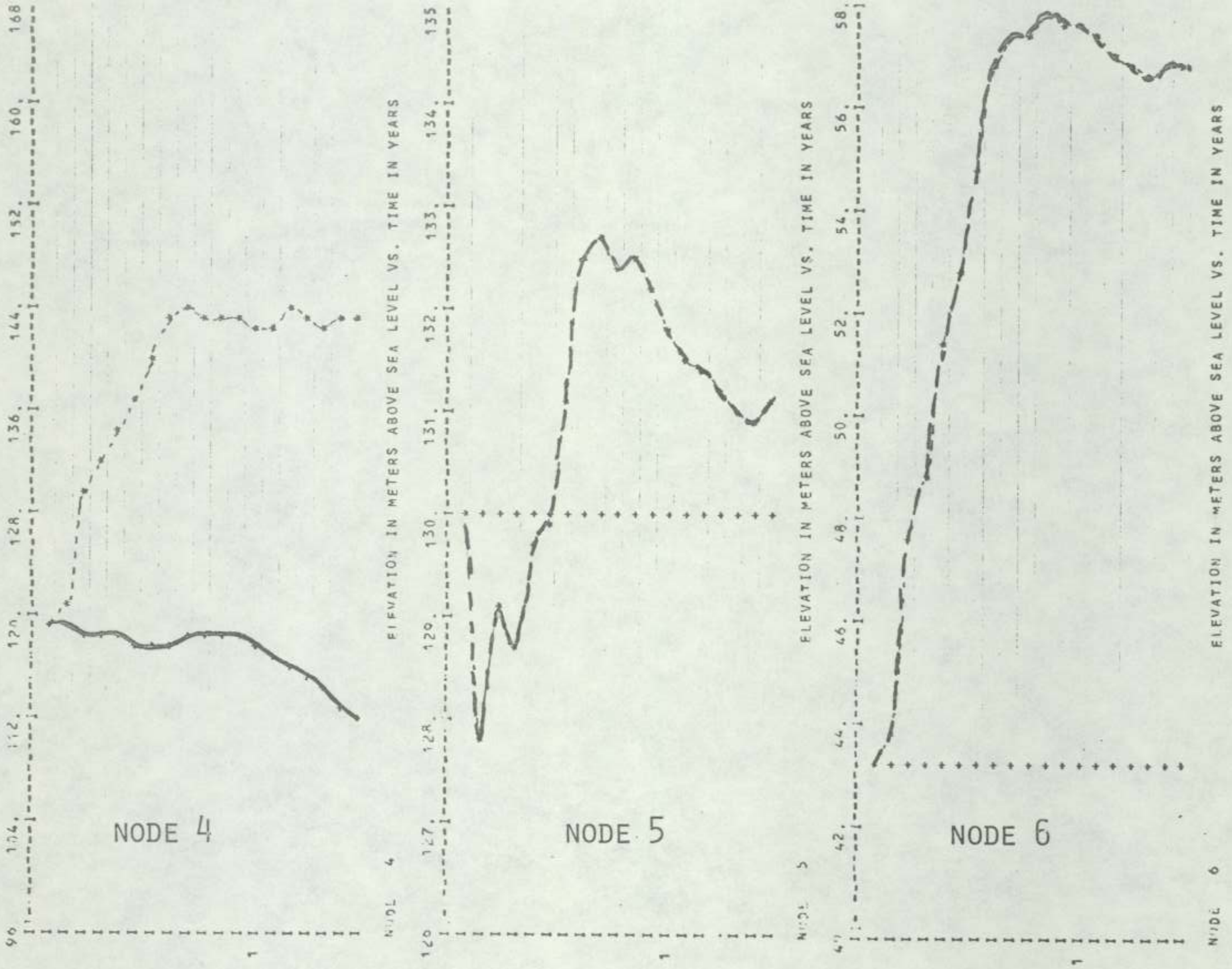
96
104.
112.
120.
128.
136.
144.
152.
160.
168
NODE 4
NODE 4
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
126
127.
128.
129.
130.
131.
132.
133.
134.
135
NODE 5
NODE 5
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
40
42.
44.
46.
48.
50.
52.
54.
56.
58.
NODE 6
NODE 6
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
1
1
1

FIG. 7.3 (CONT)

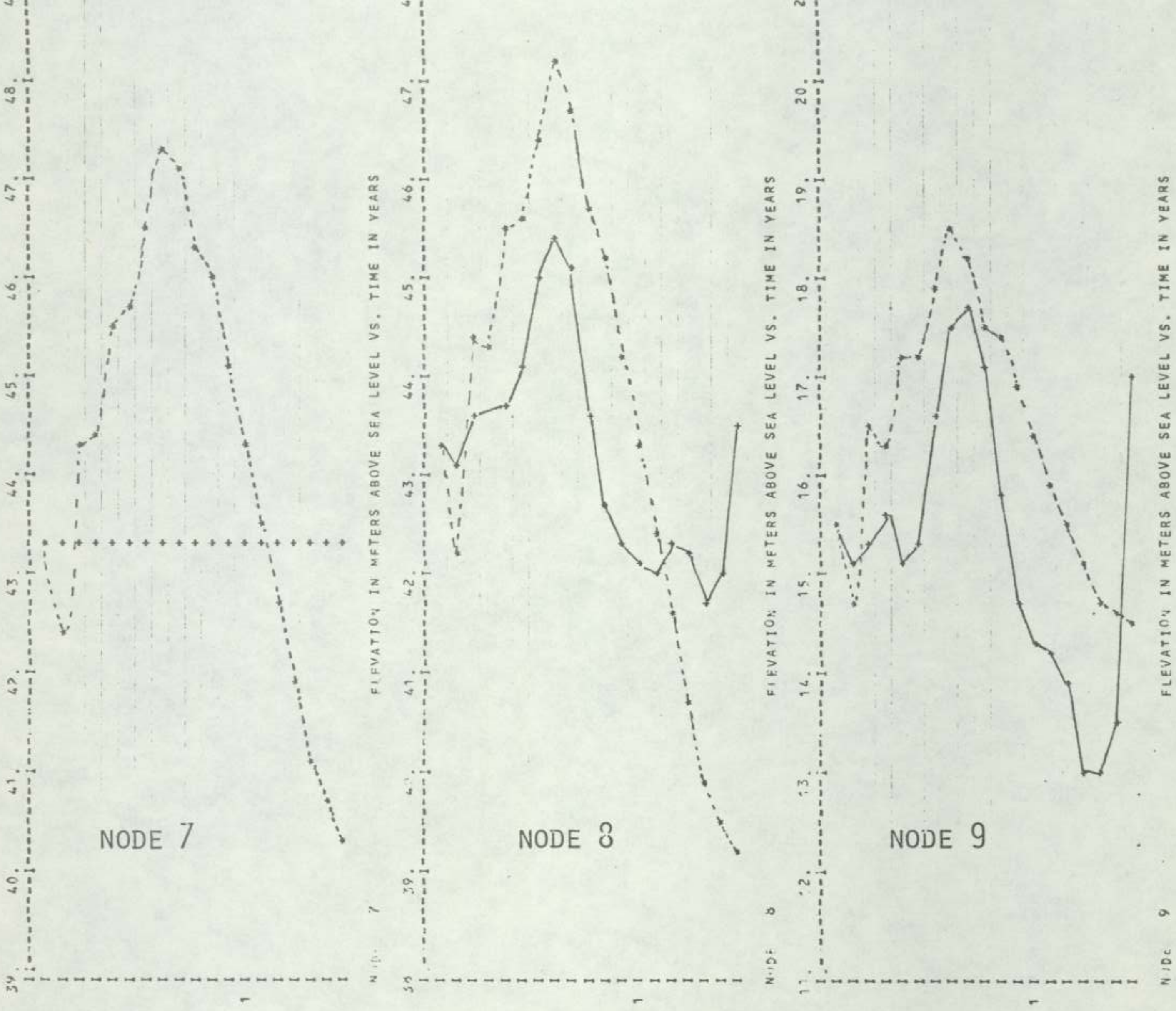

39.
40.
41.
42.
43.
44.
45.
46.
47.
48.
NODE 7
NODE 7
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
39.
40.
41.
42.
43.
44.
45.
46.
47.
NODE 8
NODE 8
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
11.
12.
13.
14.
15.
16.
17.
18.
19.
20.
NODE 9
NODE 9
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS

FIG. 7.3 (CONT)

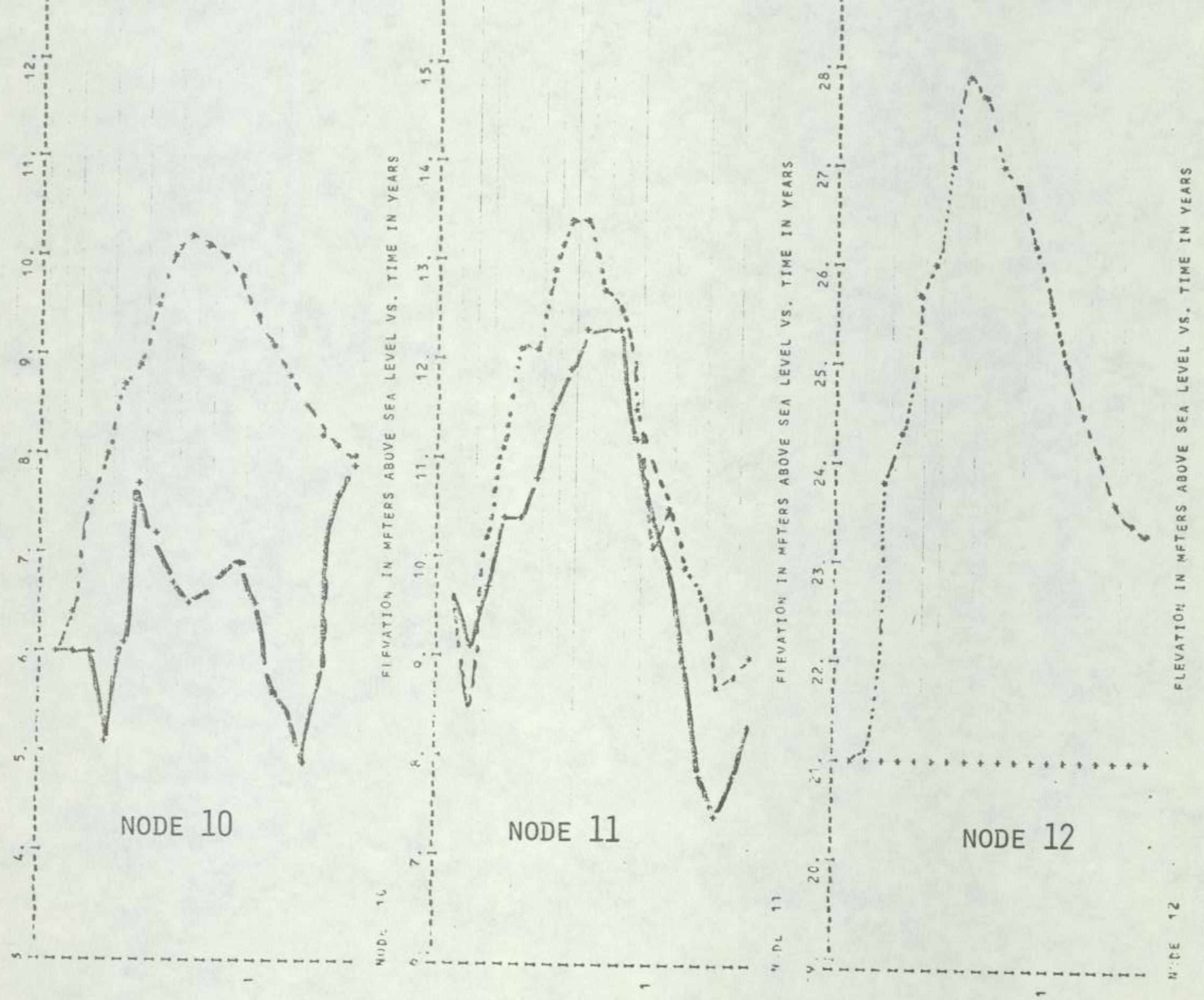

ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
4.
5.
6.
7.
8.
9.
10.
11.
12.
NODE 10
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
7.
8.
9.
10.
11.
12.
13.
14.
15.
NODE 11
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
20.
21.
22.
23.
24.
25.
26.
27.
28.
NODE 12

FIG. 7.3 (CONT)

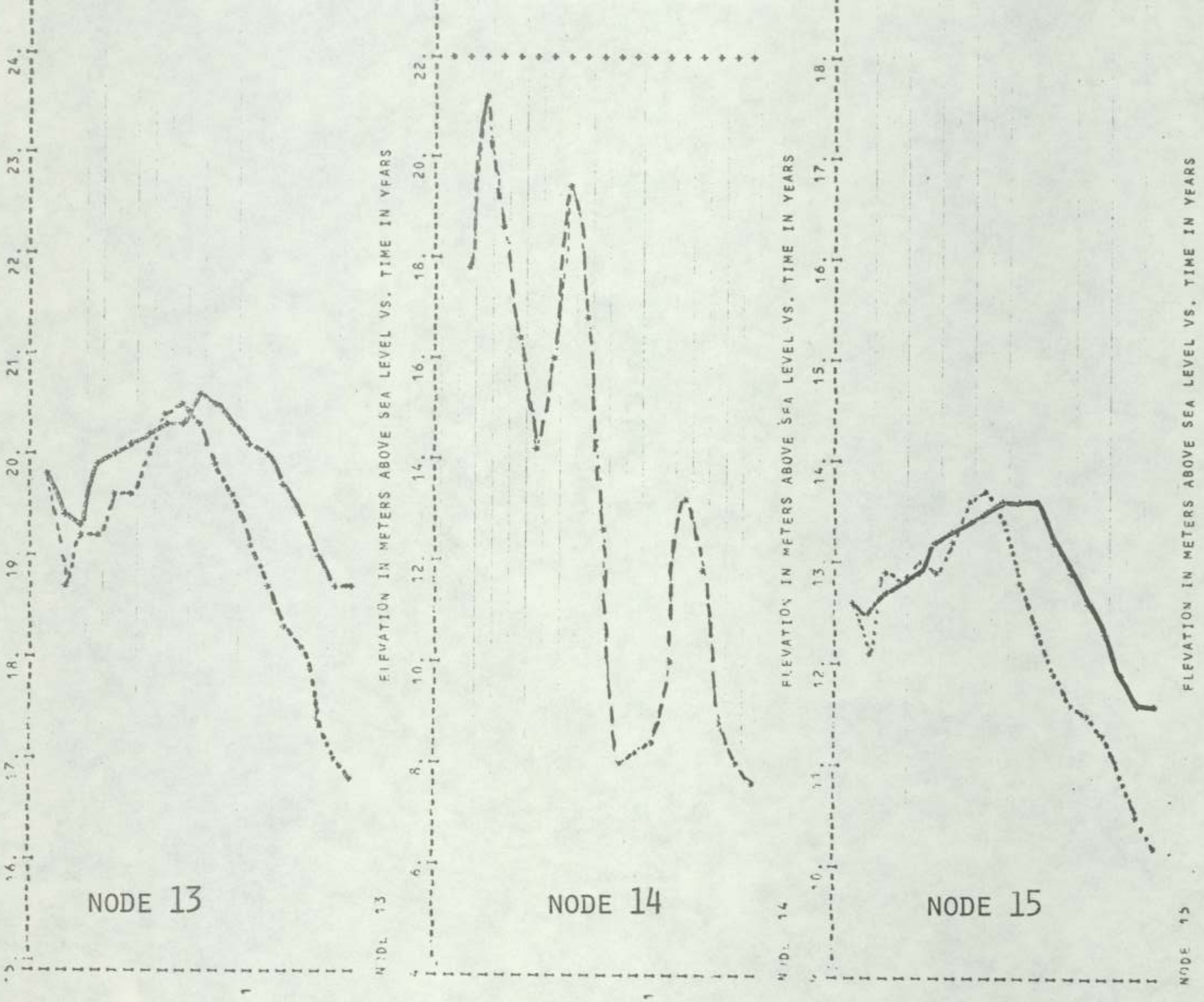

24.
23.
22.
21.
20.
19.
18.
17.
16.
NODE 13
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
NODE 13
22.
20.
18.
16.
14.
12.
10.
8.
6.
NODE 14
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
NODE 14
18.
17.
16.
15.
14.
13.
12.
11.
10.
NODE 15
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
NODE 15

FIG 7.3 (CONT)

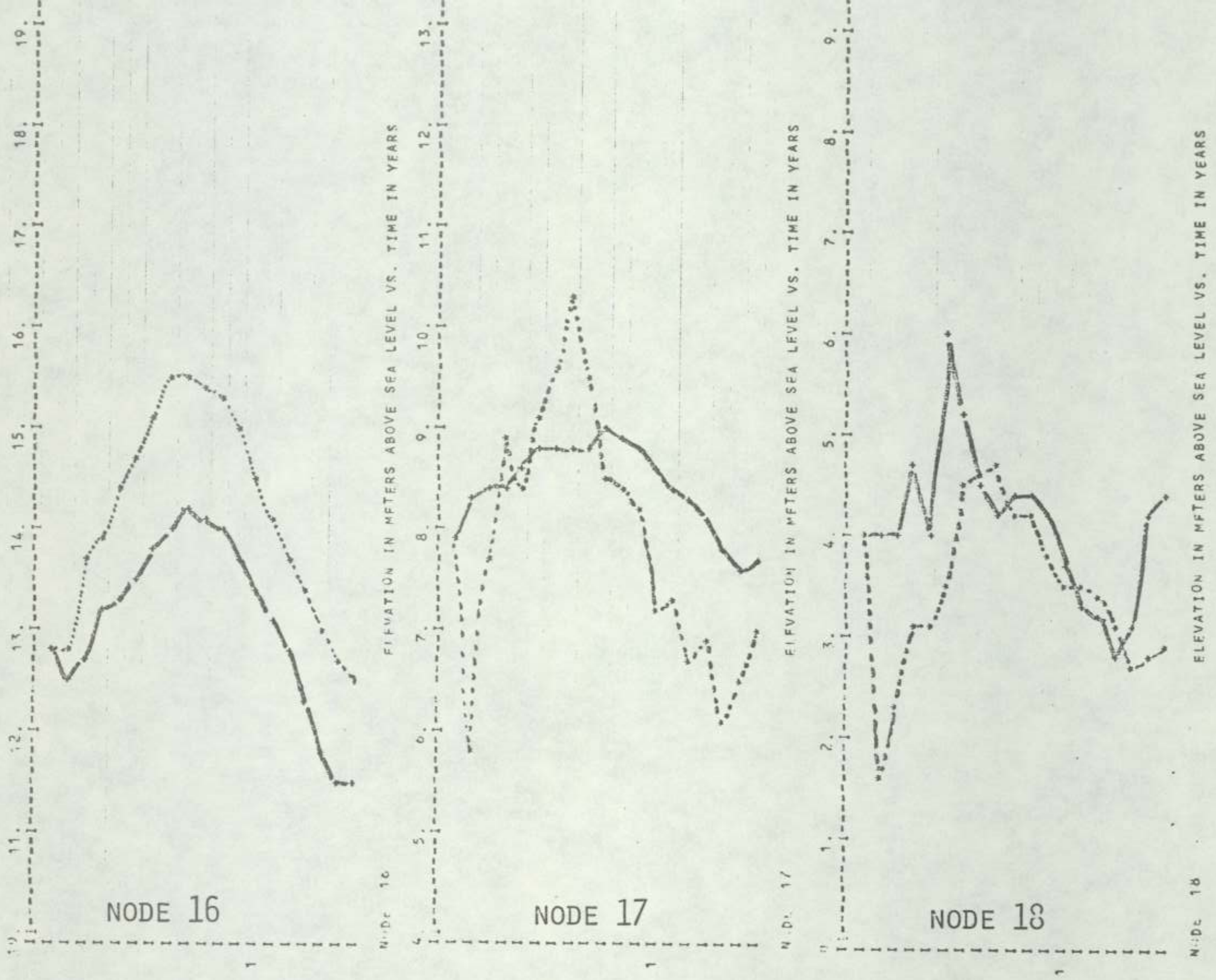

NODE 16
NODE 17
NODE 18
NODE 16
NODE 17
NODE 18
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
11.
12.
13.
14.
15.
16.
17.
18.
19.
5.
6.
7.
8.
9.
10.
11.
12.
13.
1.
2.
3.
4.
5.
6.
7.
8.
9.

FIG. 7.3 (CONT)

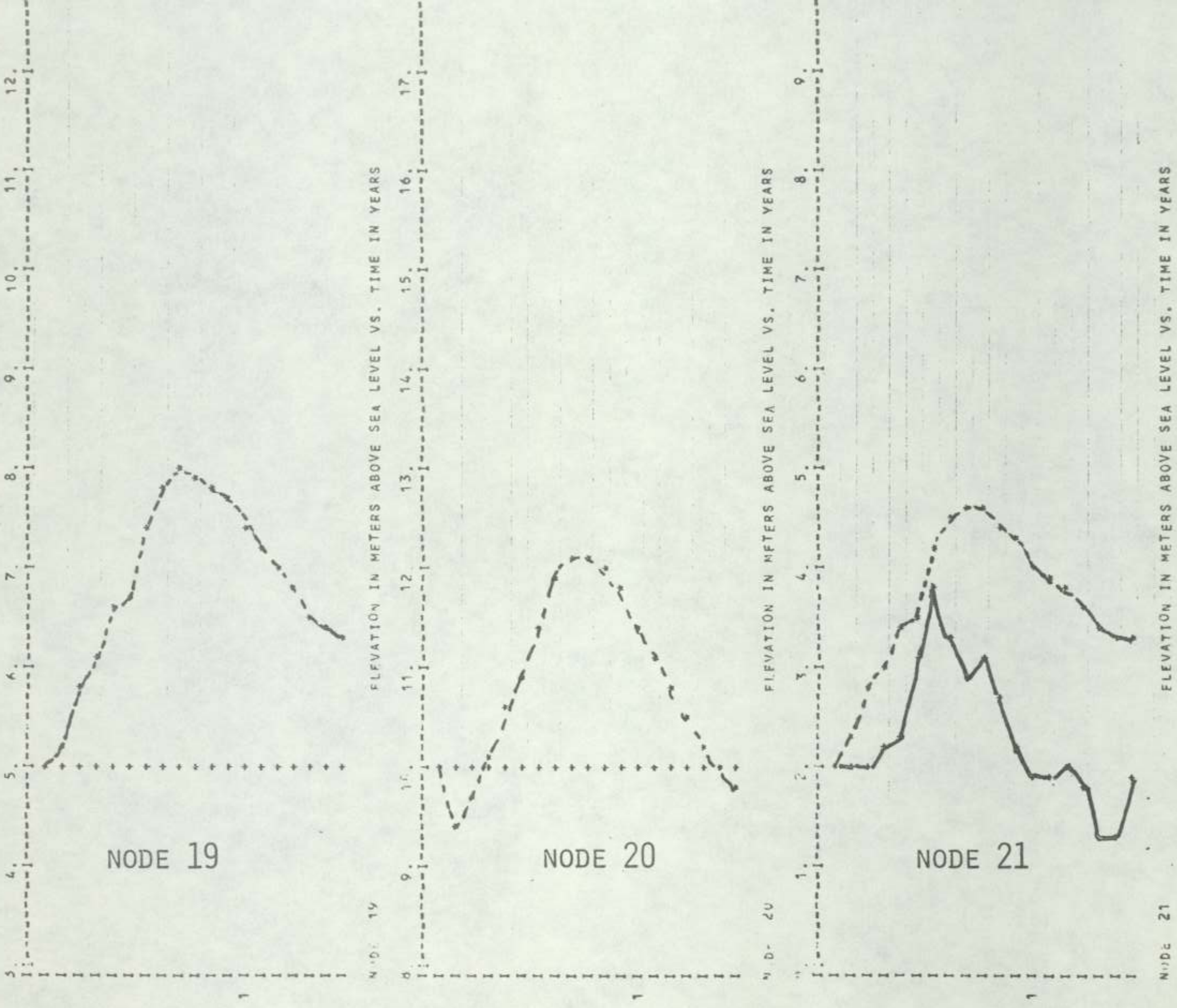
3.
4.
5.
6.
7.
8.
9.
10.
11.
12.
NODE 19
1
NODE 19
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
8
9.
10.
11.
12.
13.
14.
15.
16.
17.
NODE 20
1
NODE 20
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
0
1.
2.
3.
4.
5.
6.
7.
8.
9.
NODE 21
1
NODE 21
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS

FIG. 7.3 (CONT)

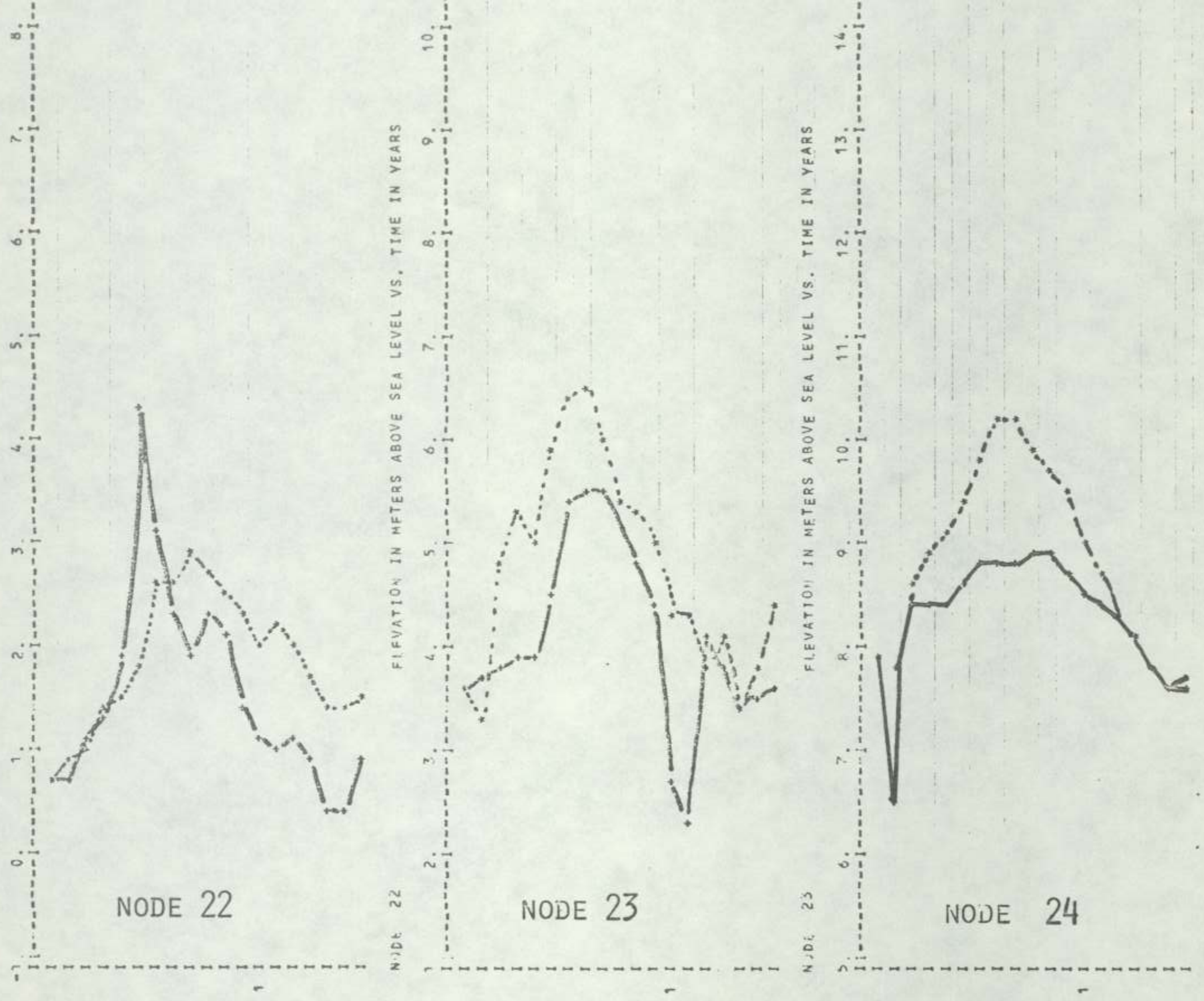

NODE 22
NODE 23
NODE 24
NODE 22
NODE 23
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
-1.
0.
1.
2.
3.
4.
5.
6.
7.
8.
1.
2.
3.
4.
5.
6.
7.
8.
9.
10.
5.
6.
7.
8.
9.
10.
11.
12.
13.
14.

FIG 7.3 (CONT)

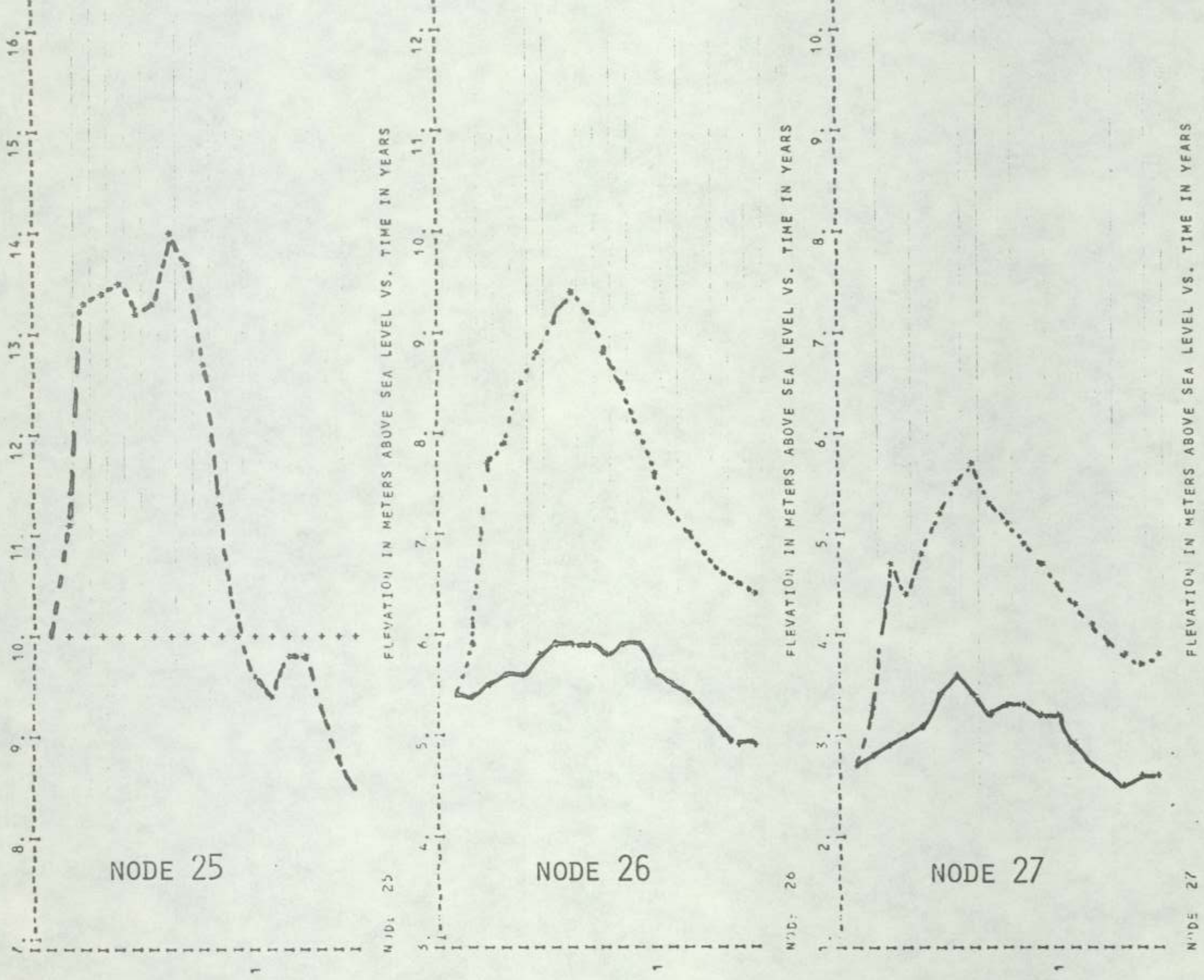
FLEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
NODE 25
NODE 26
NODE 27
7.
8.
9.
10.
11.
12.
13.
14.
15.
16.
5.
4.
6.
1.
2.
3.

Fig 7.3 (cont)

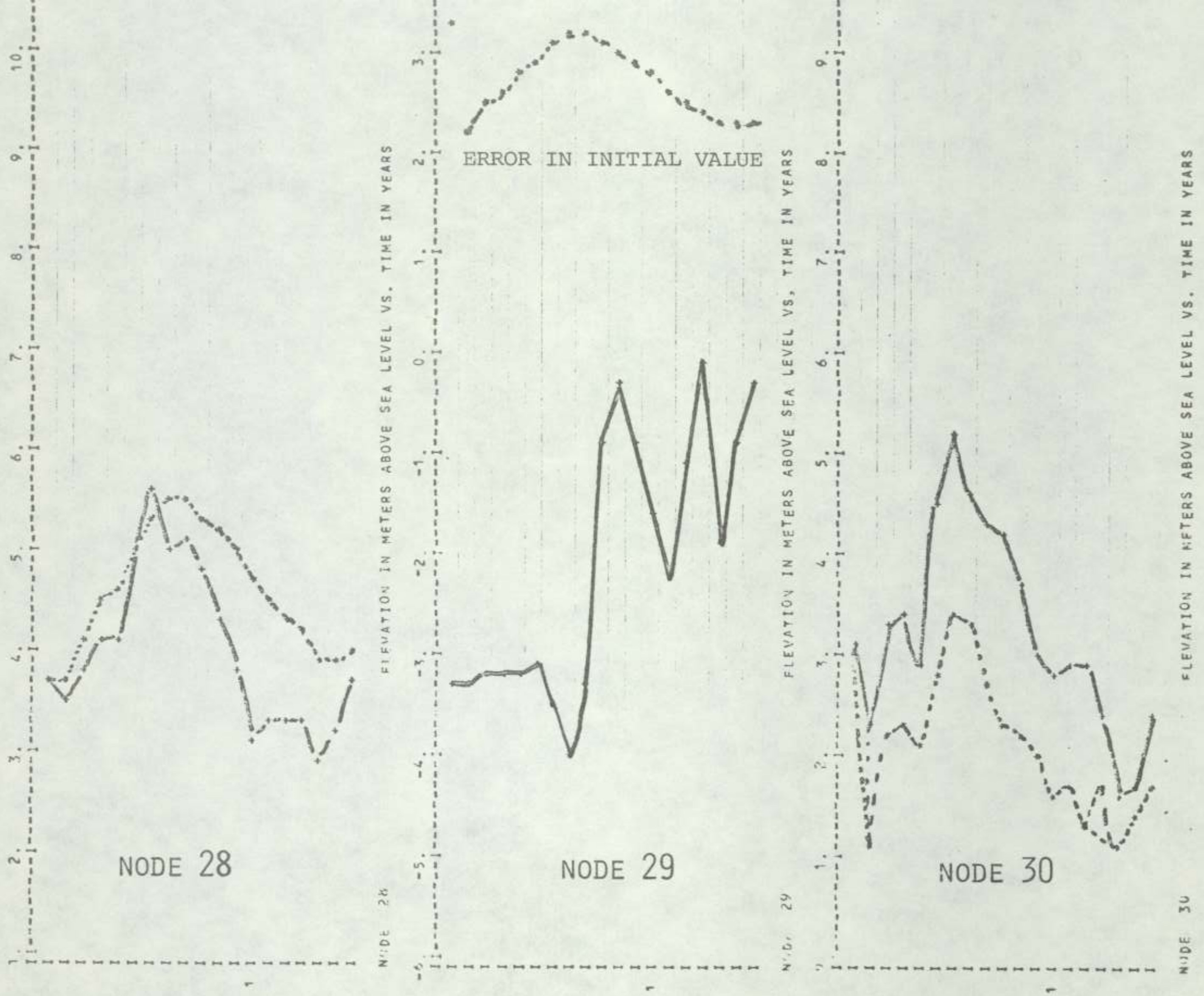

1.
2.
3.
4.
5.
6.
7.
8.
9.
10.
NODE 28
FLEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
NODE 28
-6.
-5.
-4.
-3.
-2.
-1.
0.
1.
2.
3.
ERROR IN INITIAL VALUE
NODE 29
FLEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
NODE 29
0.
1.
2.
3.
4.
5.
6.
7.
8.
9.
NODE 30
FLEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
NODE 30

FIG 7.3 (CONT)

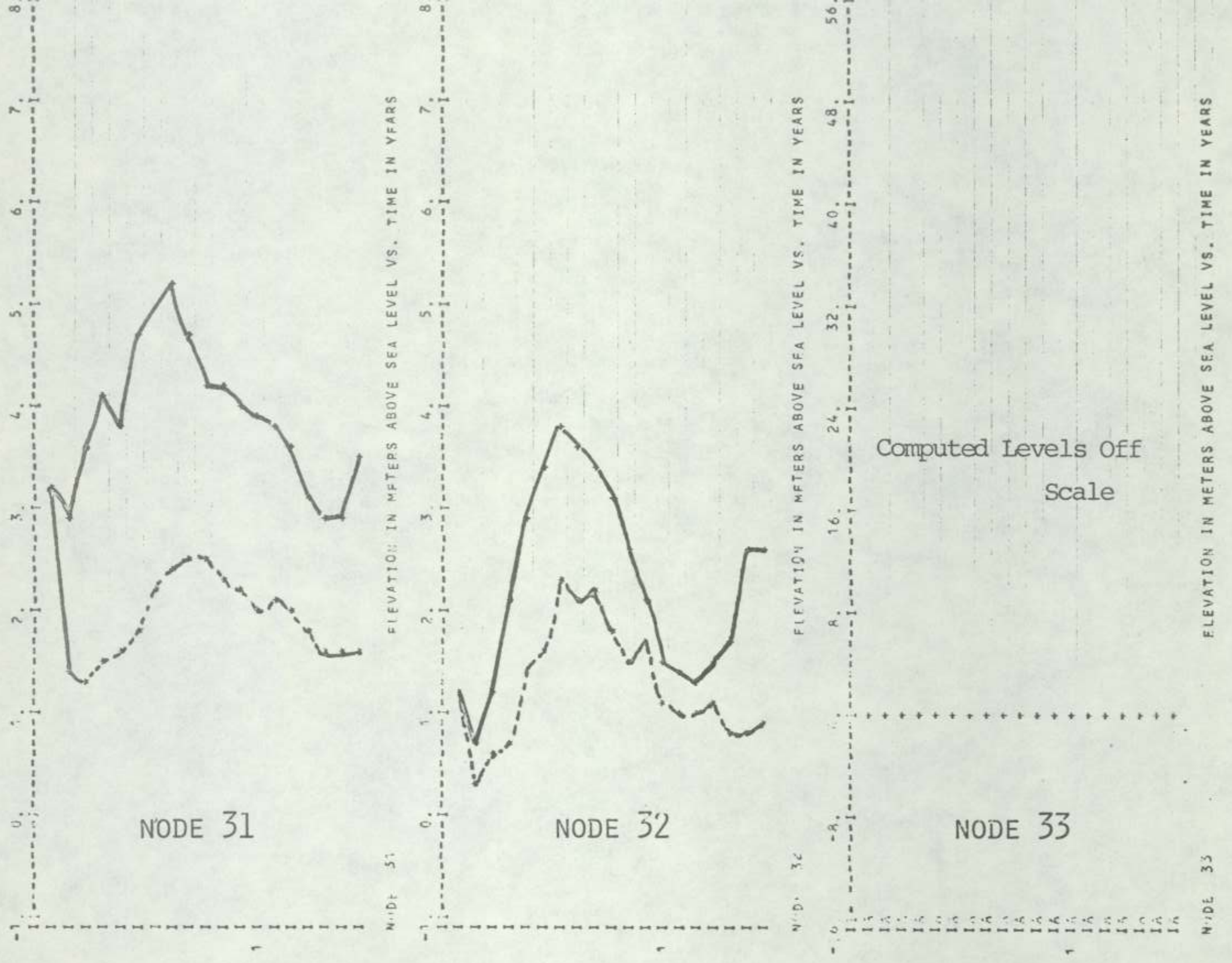
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS
NODE 31
-1.
0.
1.
2.
3.
4.
5.
6.
7.
8.
NODE 32
-1.
0.
1.
2.
3.
4.
5.
6.
7.
8.
NODE 33
-16.
-8.
0.
8.
16.
24.
32.
40.
48.
56.
Computed Levels Off Scale

FIG 7.3 (CONT)

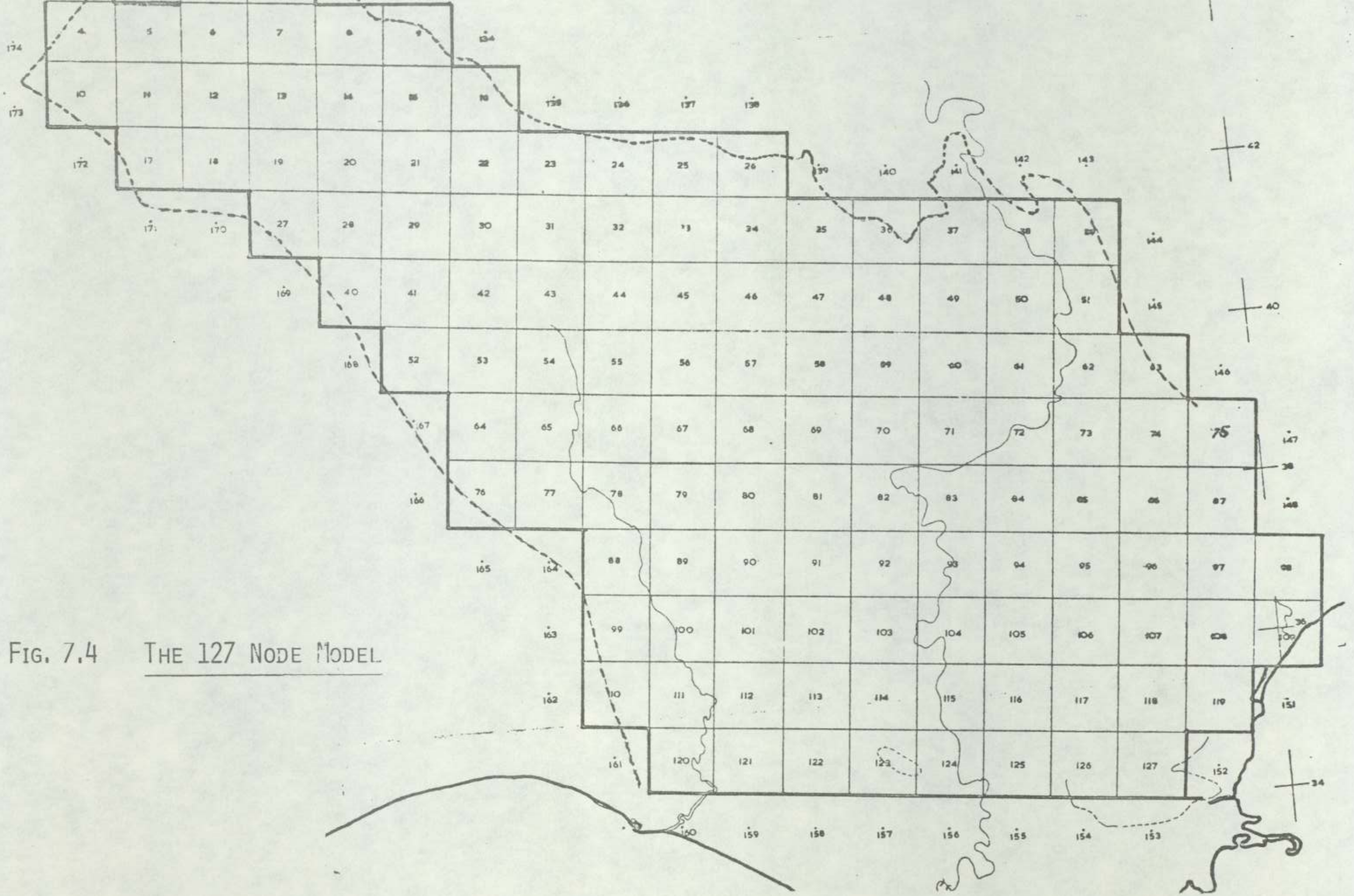
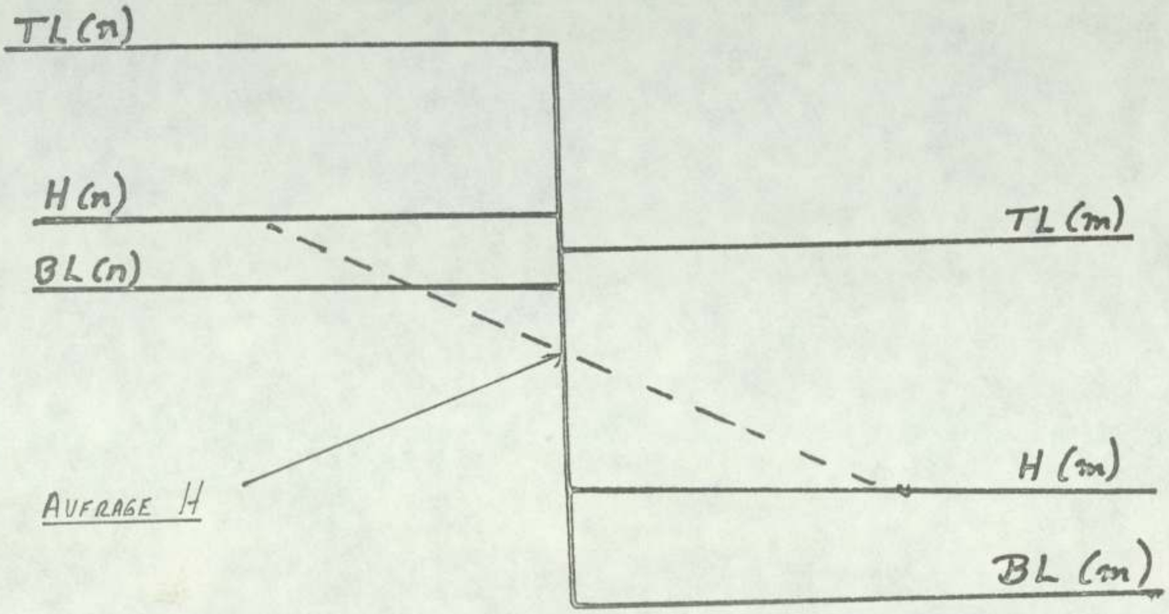


FIG. 7.4 THE 127 NODE MODEL



TL = TOP LEVEL
BL = BOTTOM LEVEL
H = WATER LEVEL

IF THE AVERAGE WATER LEVELS BETWEEN A SIGNIFICANT A SIGNIFICANT NUMBER OF ADJACENT NODES ARE LOWER THAN THE BOTTOM LEVELS OF ONE OF THOSE NODES THEN THE MODEL WILL NOT CONVERGE.

FIG. 7.5

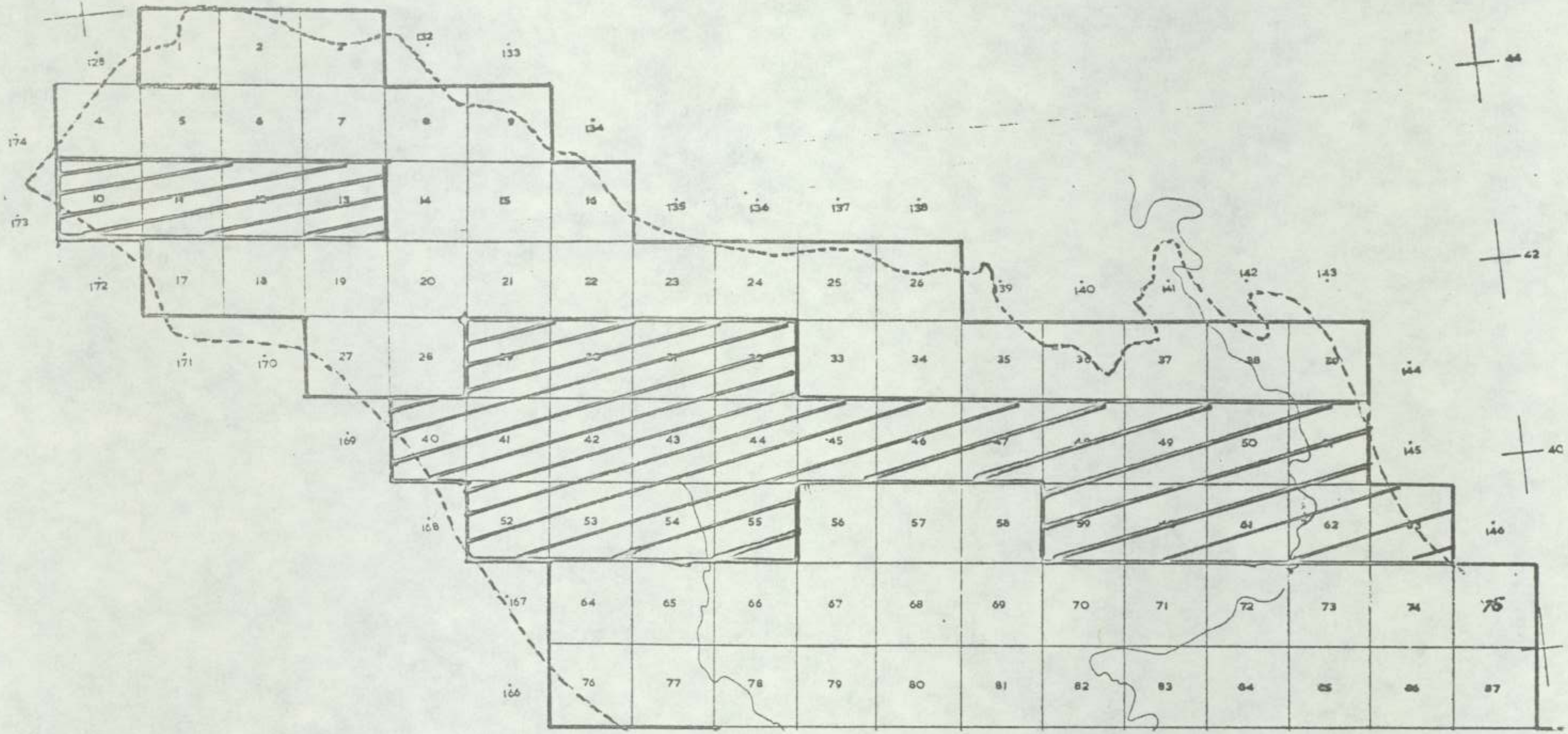


FIG. 7.6 NODES WITH RISING WATER OR SURFACE FLOW IN THE INITIAL RUN

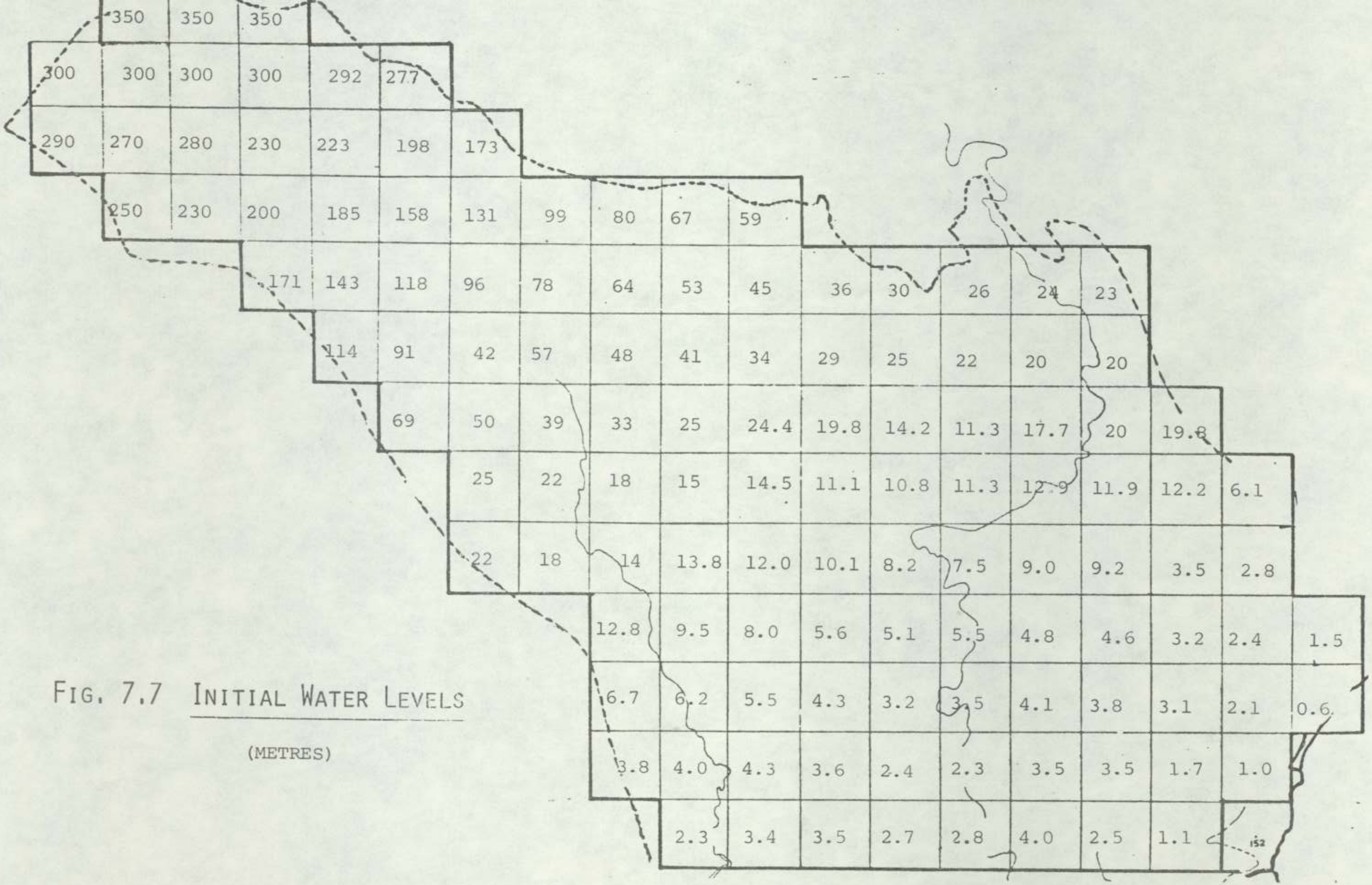
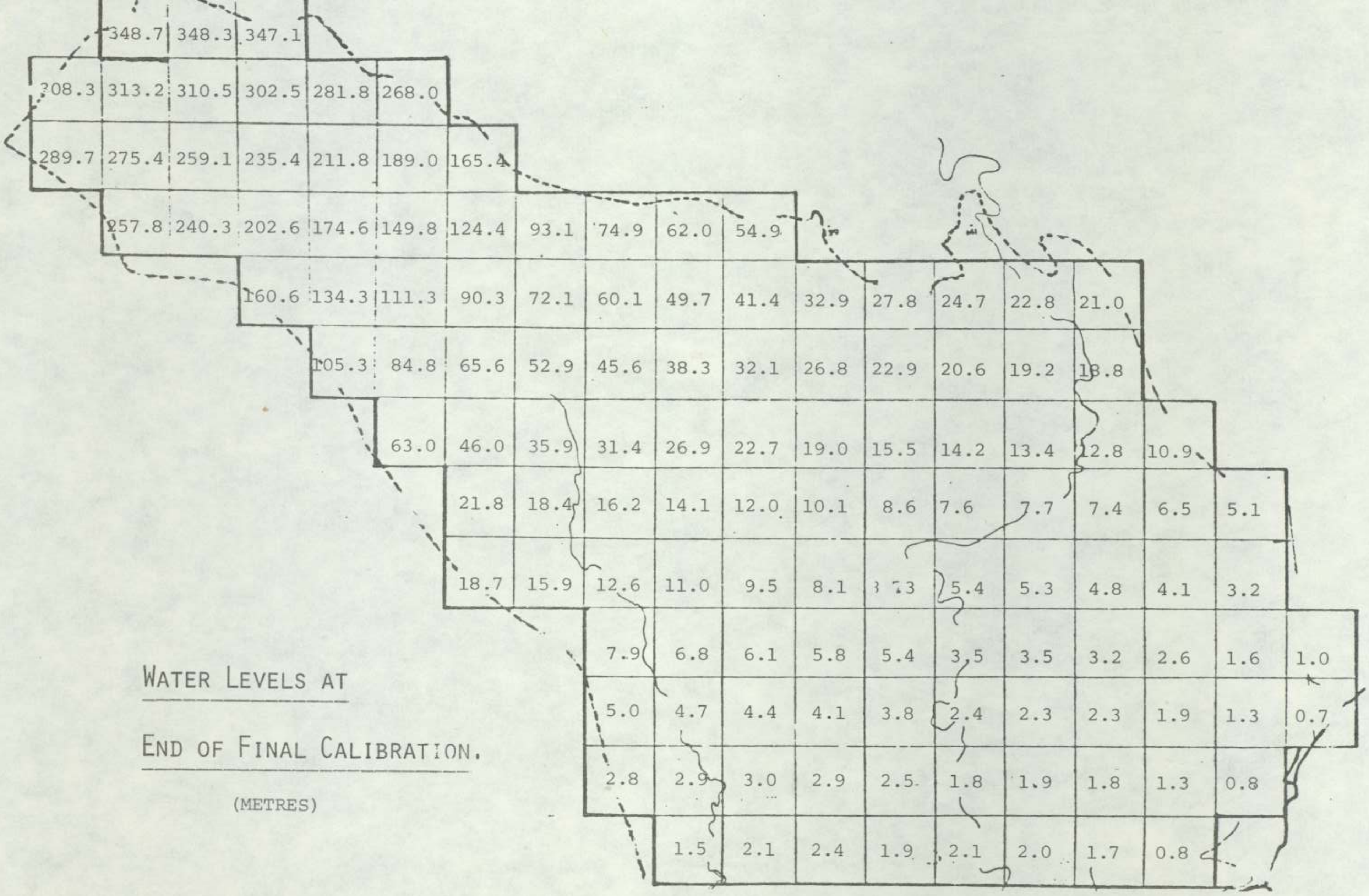


FIG. 7.7 INITIAL WATER LEVELS

(METRES)

(Whole numbers estimated : Decimals from field measurements)

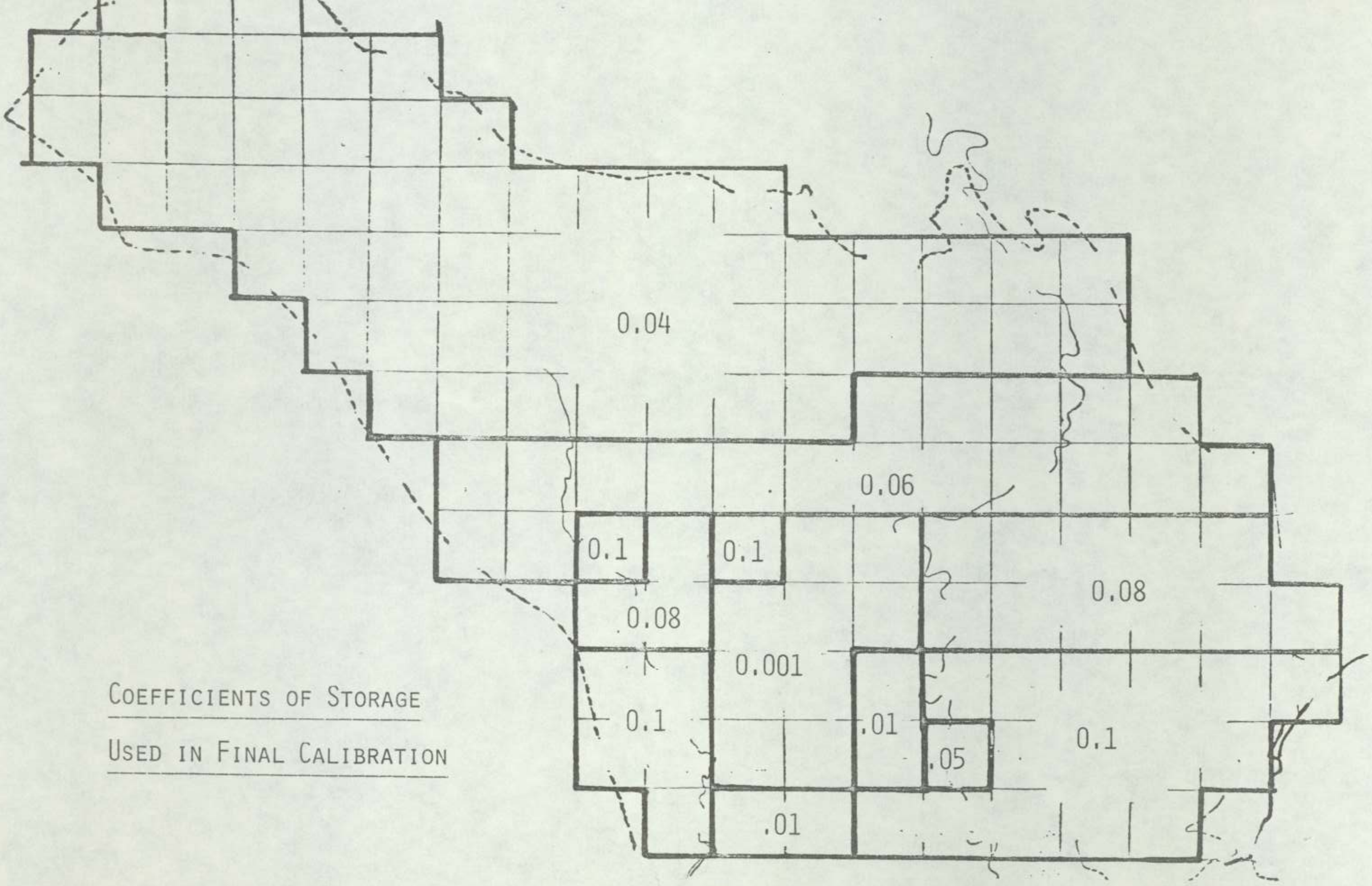


WATER LEVELS AT

END OF FINAL CALIBRATION.

(METRES)

FIG 7.8



COEFFICIENTS OF STORAGE

USED IN FINAL CALIBRATION

FIG. 7.9

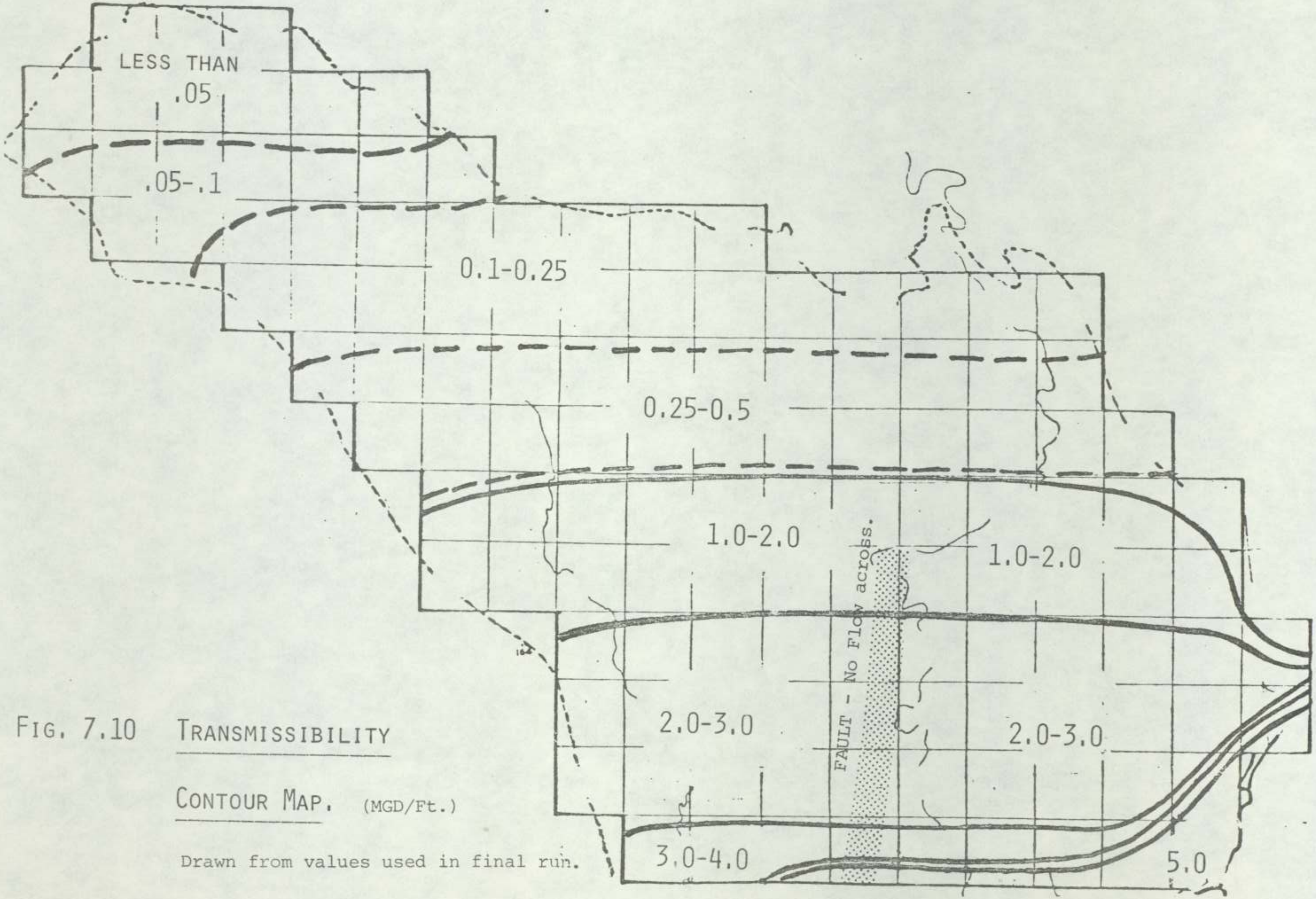
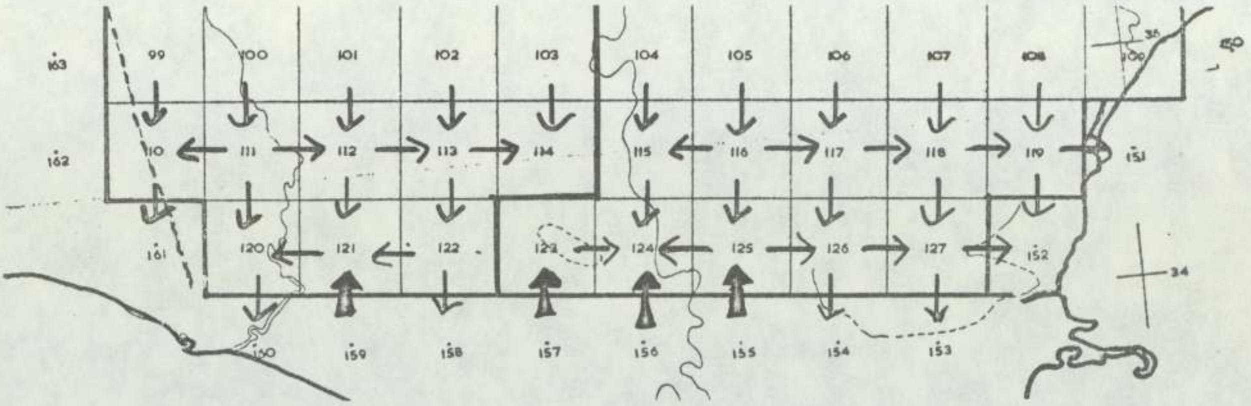


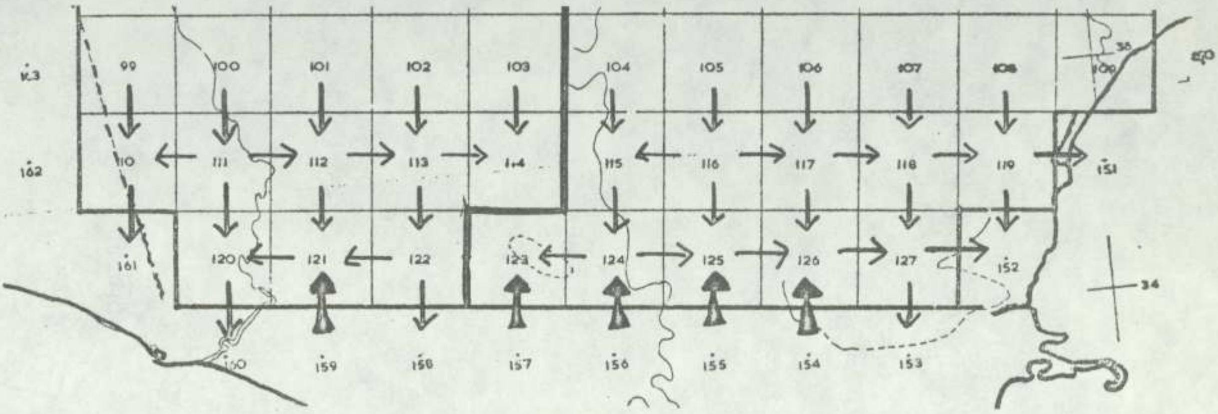
FIG. 7.10 TRANSMISSIBILITY

CONTOUR MAP. (MGD/Ft.)

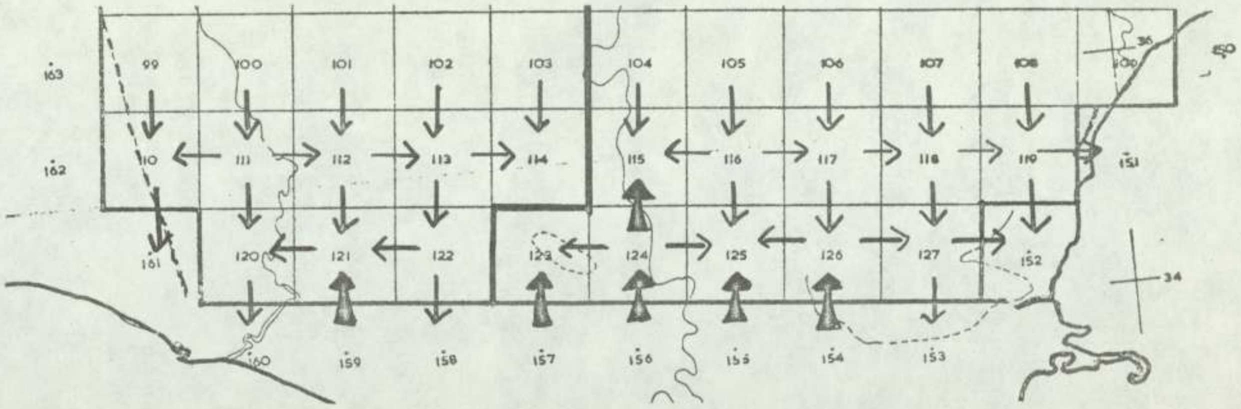
Drawn from values used in final run.



DECEMBER 1970



JANUARY & FEBRUARY 1971

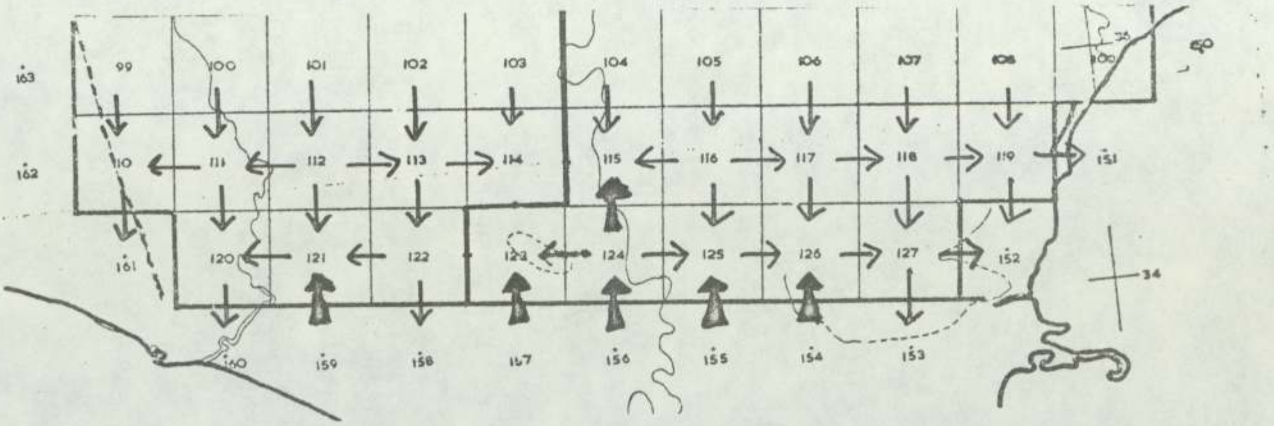


MARCH 1971

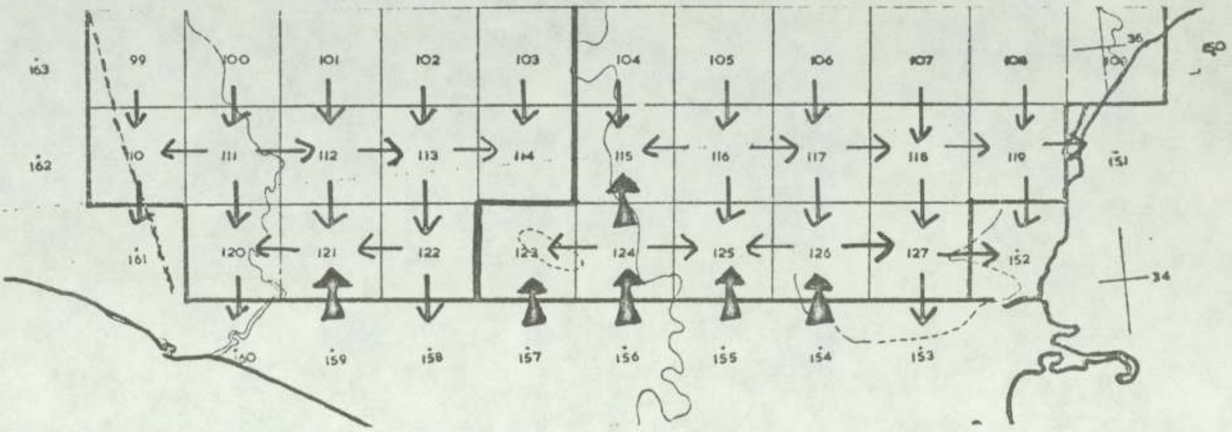
MONTHLY CROSS-FLOW DIRECTIONS AT LOWER END OF MODEL. (Sea Water Intrusion shown by heavier arrow)

FIG. 7.11

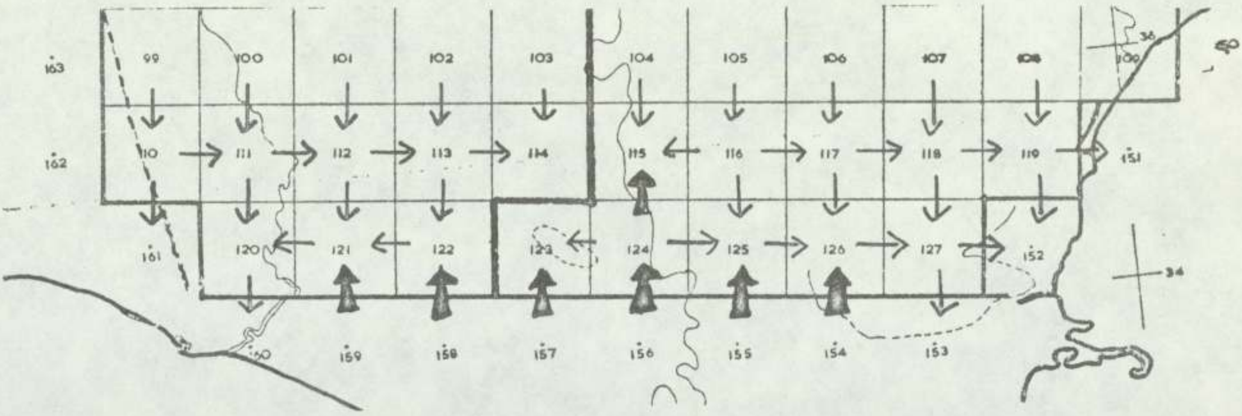
cont./



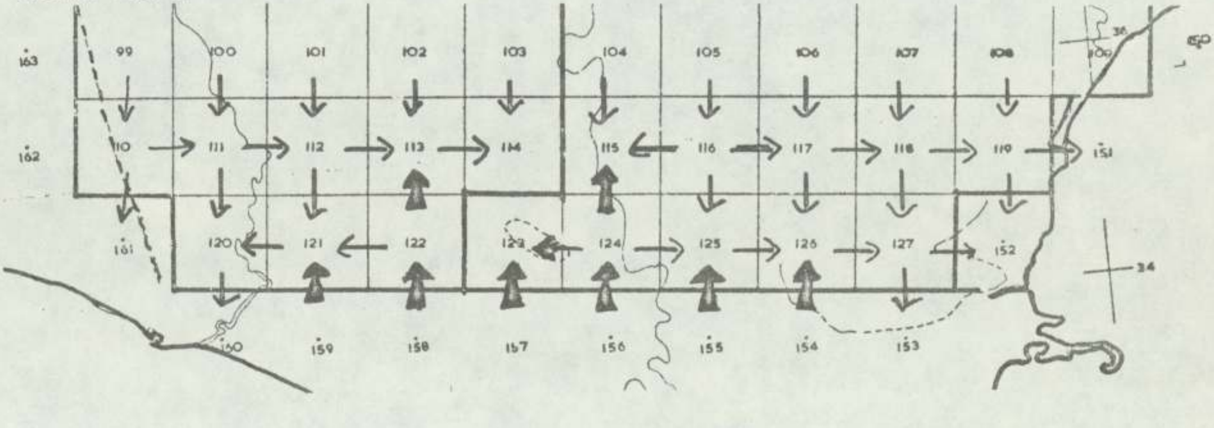
APRIL 1971



MAY 1971

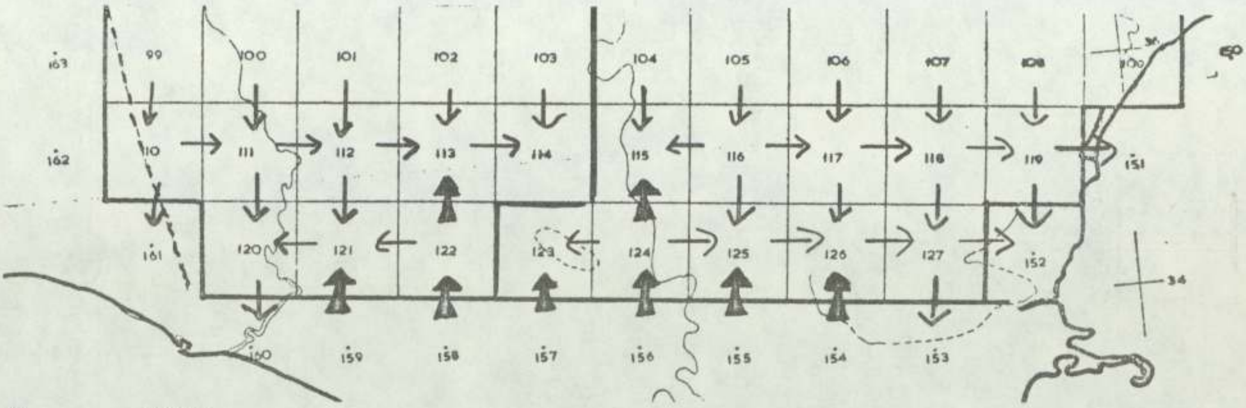


JUNE 1971

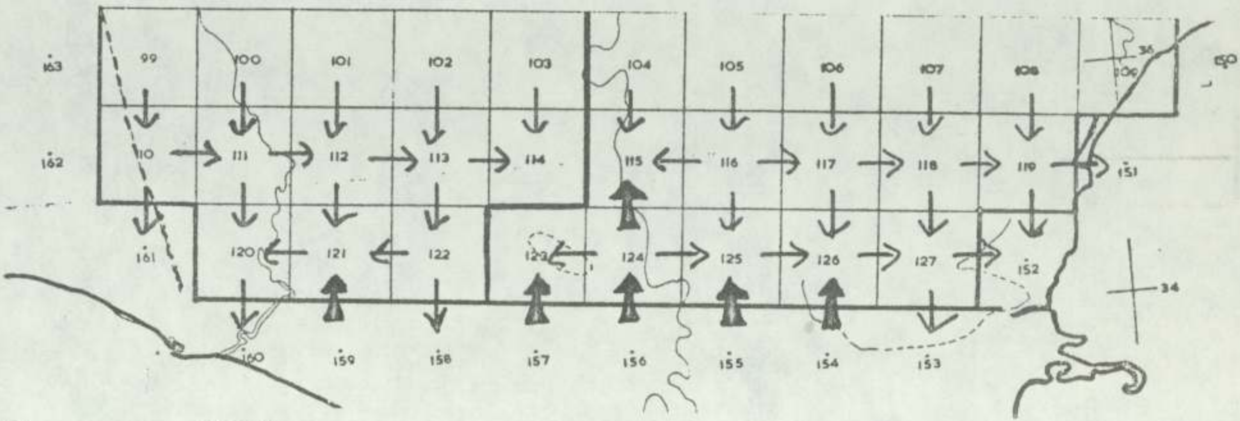


JULY 1971

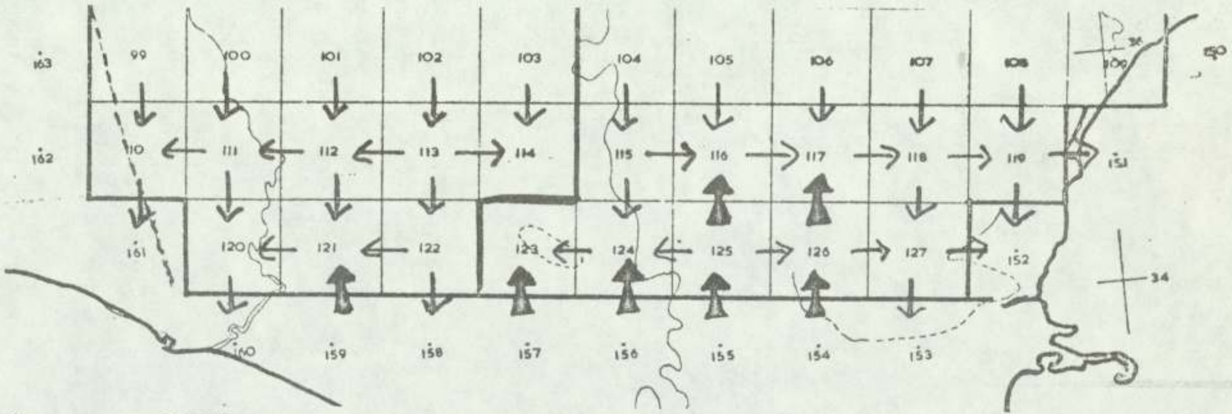
7.11 (CONT)



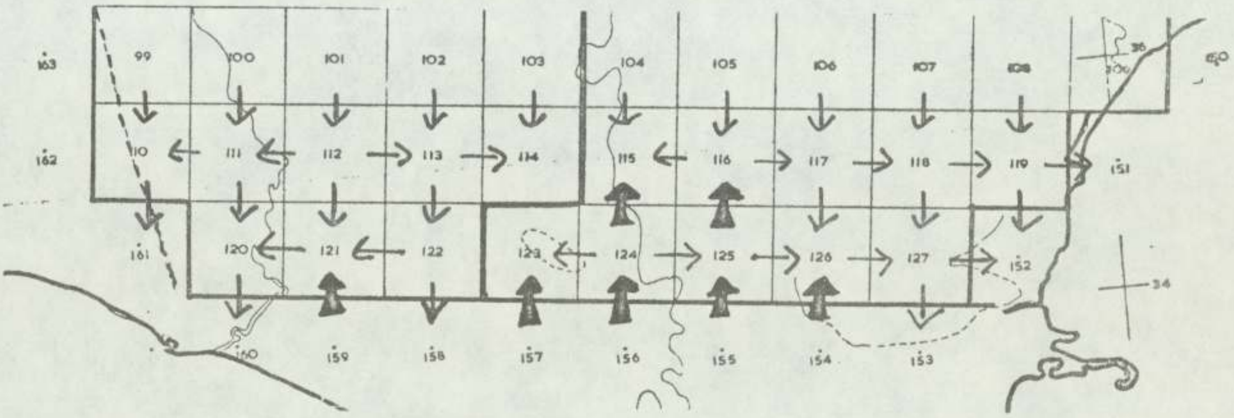
AUGUST 1971



SEPTEMBER 1971

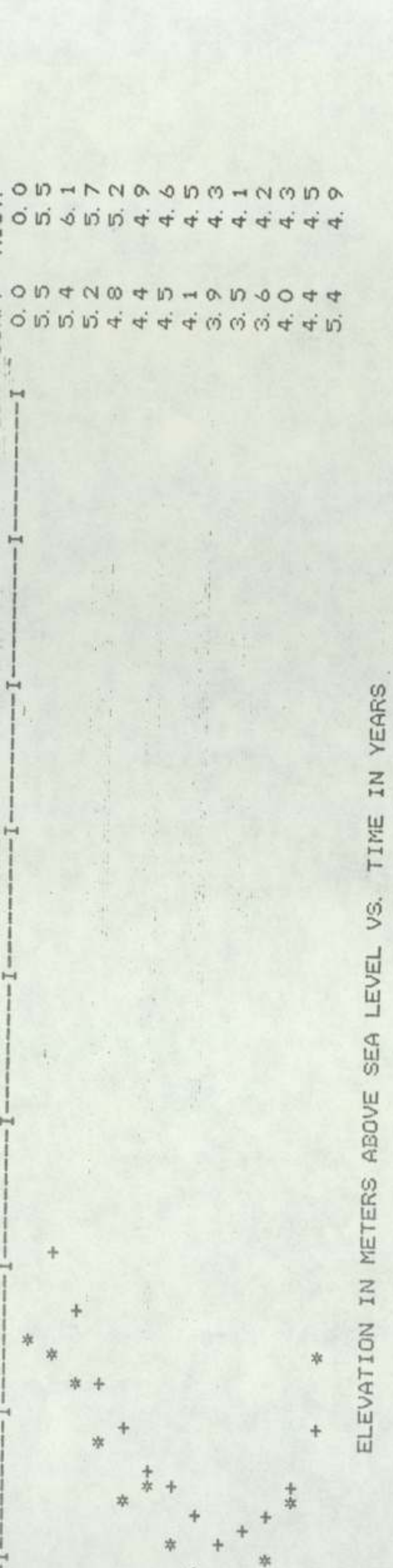


OCTOBER 1971

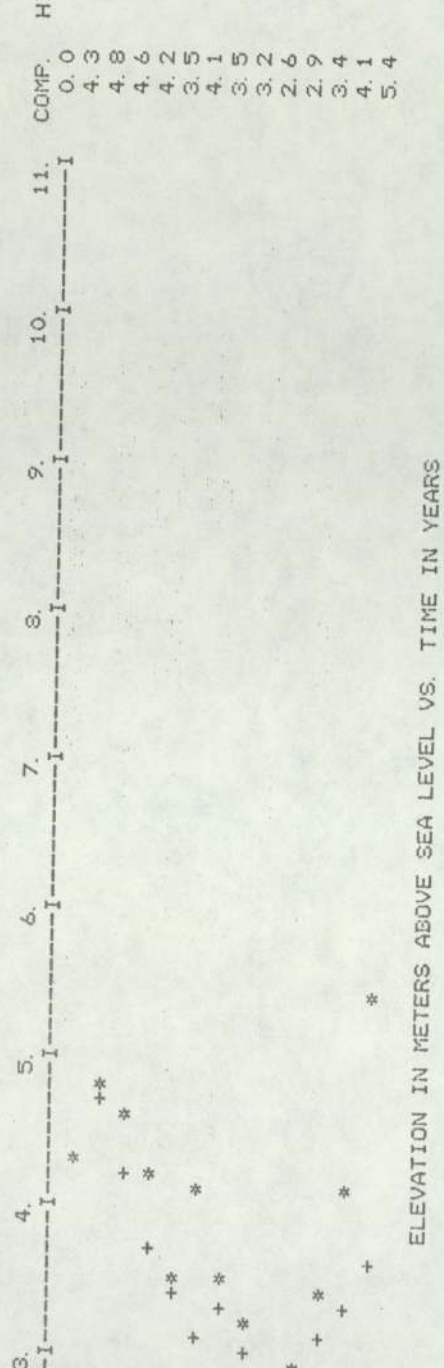


NOVEMBER 1971

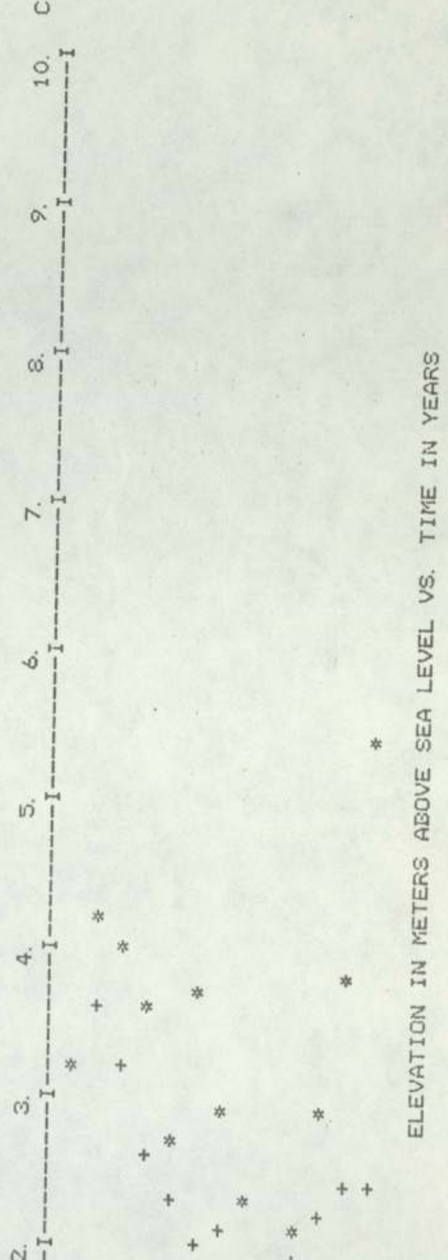
FIG. 7.11 (CONT)



0.0	0.0
5.5	5.5
5.4	6.1
5.2	5.7
4.8	5.2
4.4	4.9
4.5	4.6
4.1	4.5
3.9	4.3
3.5	4.1
3.6	4.2
4.0	4.3
4.4	4.5
5.4	4.9



COMP.	HIST.
0.0	0.0
4.3	4.3
4.8	4.7
4.6	4.2
4.2	3.7
3.5	3.4
4.1	3.1
3.5	3.3
3.2	3.0
2.6	2.7
2.9	2.8
3.4	3.1
4.1	3.3
5.4	3.6



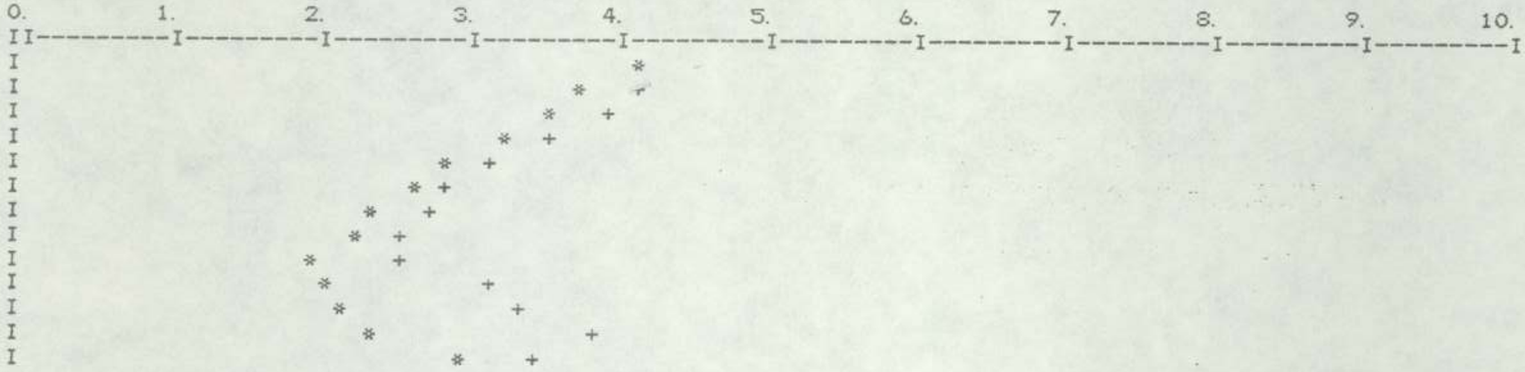
COMP.	HIST.
0.0	0.0
3.2	3.2
4.2	3.6
4.0	3.2
3.6	2.6
2.7	2.3
3.7	2.0
2.9	2.1
2.3	1.8
1.7	1.7
2.1	1.9
2.9	2.2
3.8	2.4
5.4	2.4

* Denotes Computed Water Level
\+ Denotes Historic Water Level

FIG 7.12 HYDROGRAPHS FROM 127 NODE MODEL

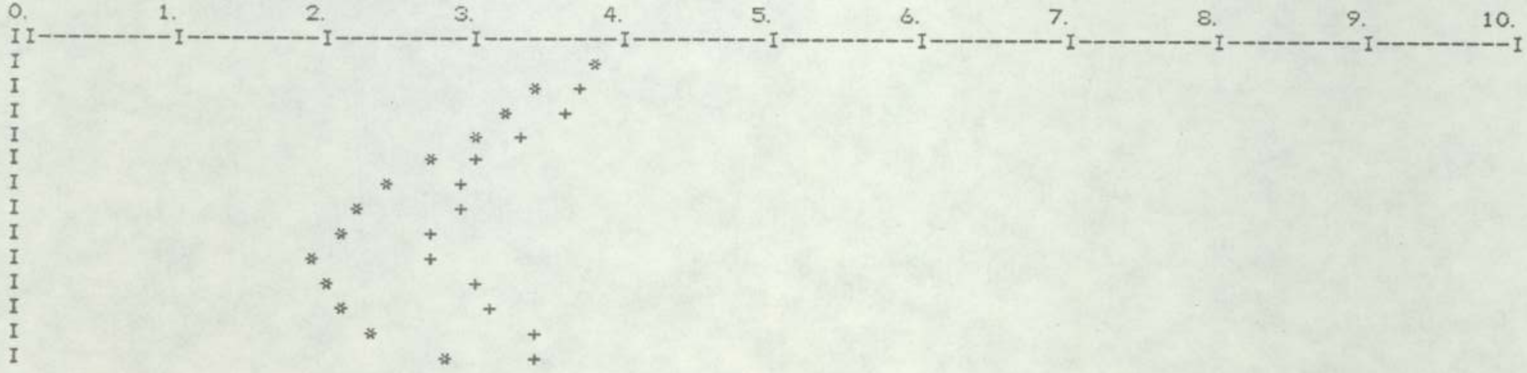
3.5	3.5
3.7	3.6
3.6	3.4
3.2	3.0
2.8	2.7
2.6	2.3
2.3	2.3
2.2	2.0
1.9	2.1
2.0	2.5
2.2	2.8
2.4	3.1
3.0	2.6

NODE 104 ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS



COMP.	HIST.
0.0	0.0
4.1	4.1
3.7	4.1
3.5	3.9
3.2	3.5
2.8	3.1
2.6	2.8
2.3	2.7
2.2	2.5
1.9	2.5
2.0	3.1
2.1	3.3
2.3	3.8
2.9	3.4

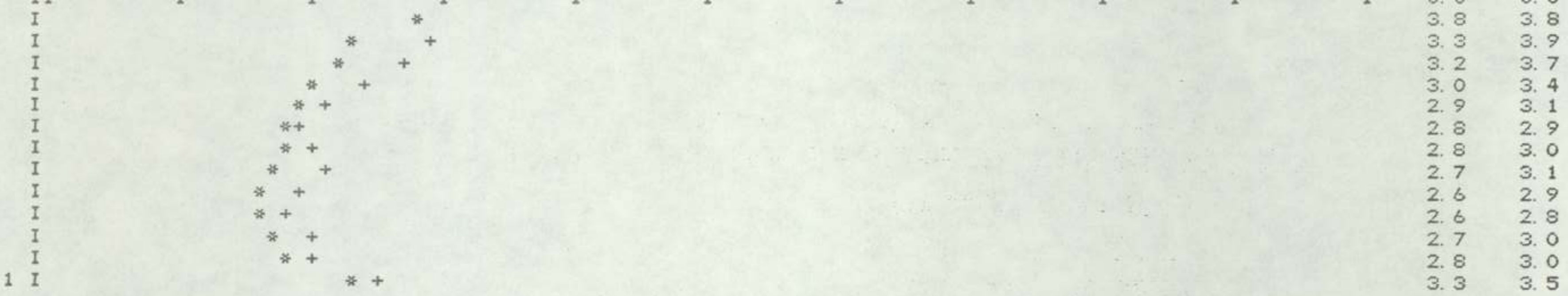
NODE 105 ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS



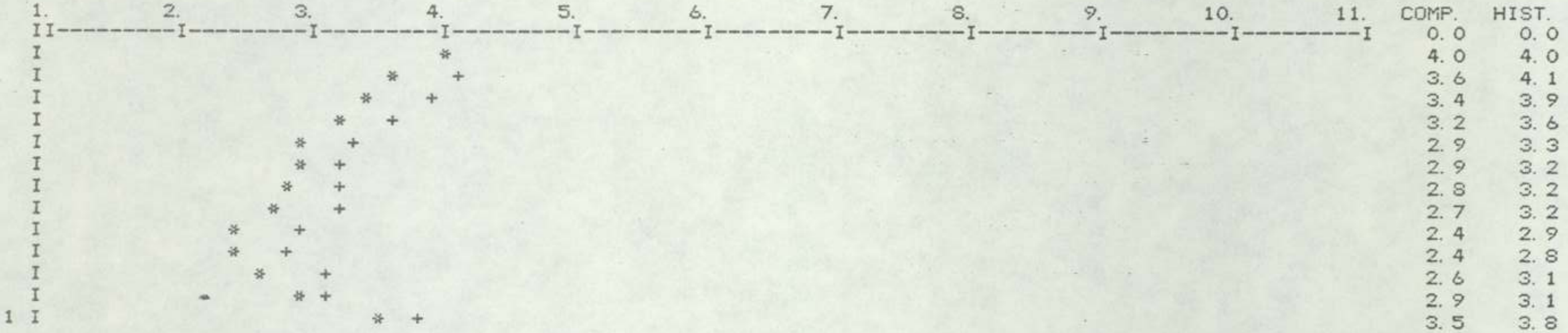
COMP.	HIST.
0.0	0.0
3.8	3.8
3.4	3.7
3.2	3.6
3.0	3.3
2.7	3.0
2.4	2.9
2.2	2.9
2.1	2.7
1.9	2.7
2.0	3.0
2.1	3.1
2.3	3.4
2.8	3.4

NODE 106 ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS

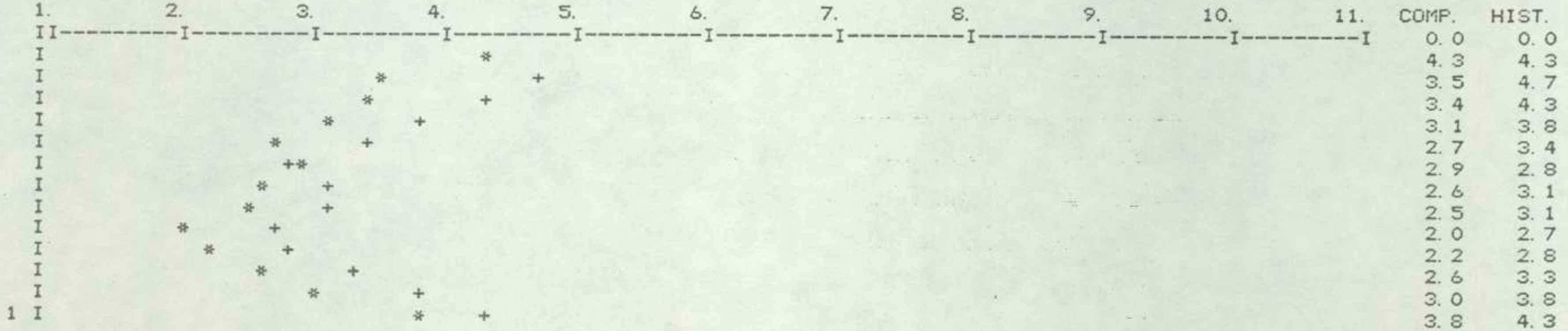
FIG. 7.12 (CONT)



NODE 110 ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS



NODE 111 ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS

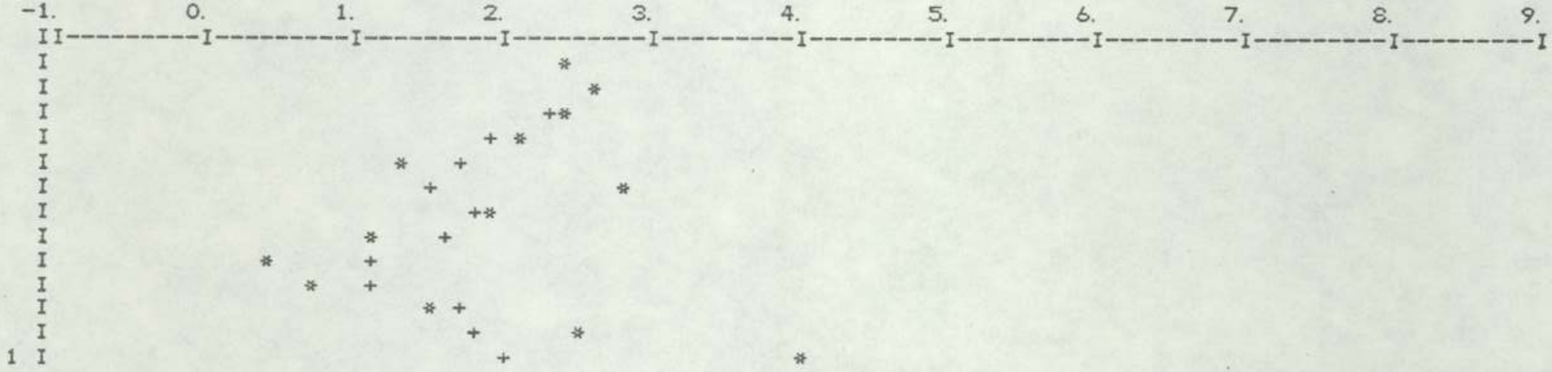


NODE 112 ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS

FIG. 7.12 (CONT)

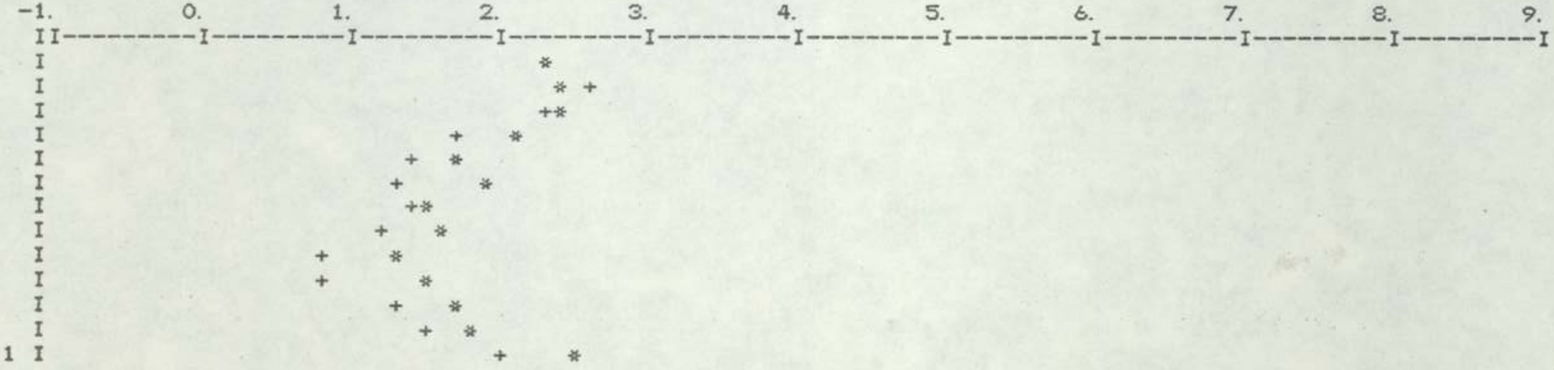
```
 0. 0   0. 0
 3. 6   3. 6
 3. 2   3. 8
 3. 1   3. 5
 2. 8   3. 2
 2. 3   3. 0
 2. 9   2. 7
 2. 4   3. 1
 2. 1   2. 9
 1. 6   2. 4
 1. 8   2. 4
 2. 3   3. 0
 2. 9   3. 2
 3. 9   3. 3
```

NODE 113 ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS



```
COMP.  HIST.
 0. 0   0. 0
 2. 4   2. 4
 2. 6   2. 6
 2. 4   2. 3
 2. 1   1. 9
 1. 3   1. 7
 2. 8   1. 5
 1. 9   1. 8
 1. 1   1. 6
 0. 4   1. 1
 0. 7   1. 1
 1. 5   1. 7
 2. 5   1. 8
 4. 0   2. 0
```

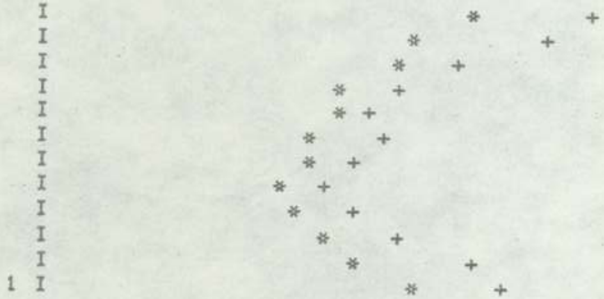
NODE 114 ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS



```
COMP.  HIST.
 0. 0   0. 0
 2. 3   2. 3
 2. 4   2. 6
 2. 4   2. 3
 2. 1   1. 7
 1. 7   1. 4
 1. 9   1. 3
 1. 5   1. 4
 1. 6   1. 2
 1. 3   0. 8
 1. 5   0. 8
 1. 7   1. 3
 1. 8   1. 5
 2. 5   2. 0
```

NODE 115 ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS

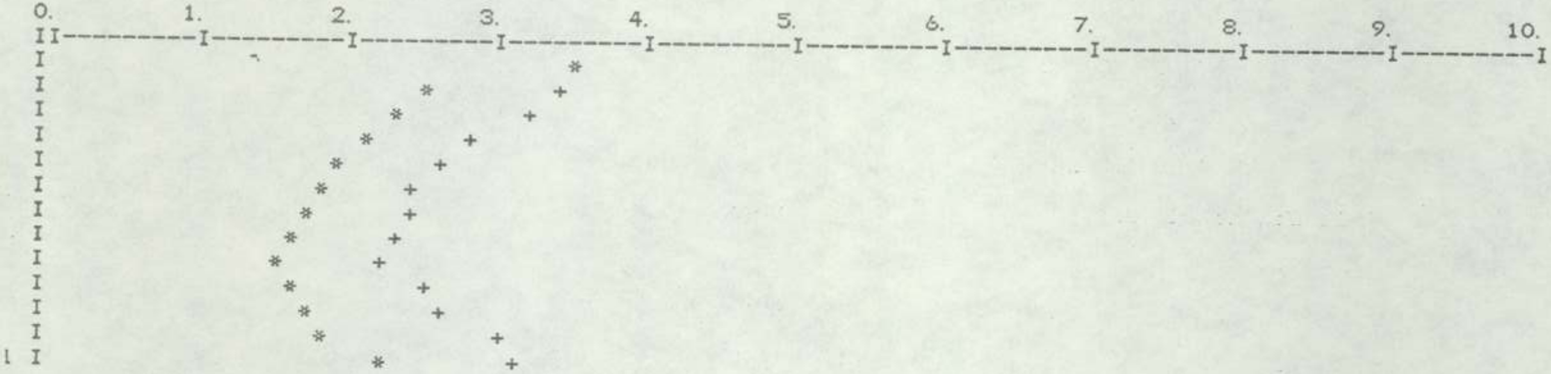
FIG. 7.12 (CONT)



3.5	3.5
2.8	3.6
2.4	3.3
2.3	2.7
1.9	2.3
1.9	2.1
1.7	2.2
1.7	2.0
1.5	1.8
1.6	2.0
1.8	2.3
2.0	2.8
2.4	3.0

NODE 116

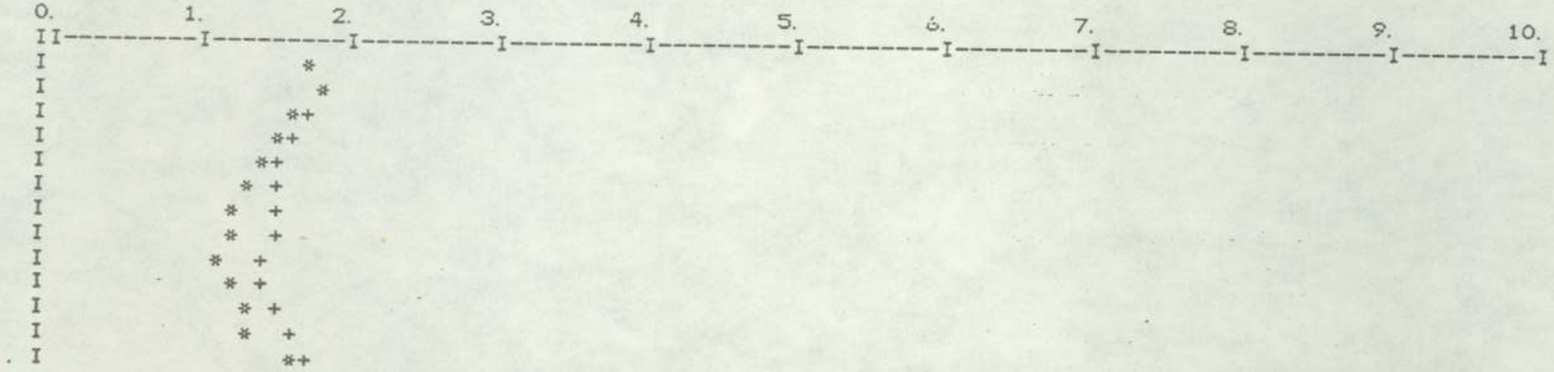
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS



COMP.	HIST.
0.0	0.0
3.5	3.5
2.5	3.4
2.3	3.2
2.1	2.8
1.9	2.6
1.8	2.4
1.7	2.4
1.6	2.3
1.5	2.2
1.6	2.5
1.7	2.6
1.8	3.0
2.2	3.1

NODE 117

ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS

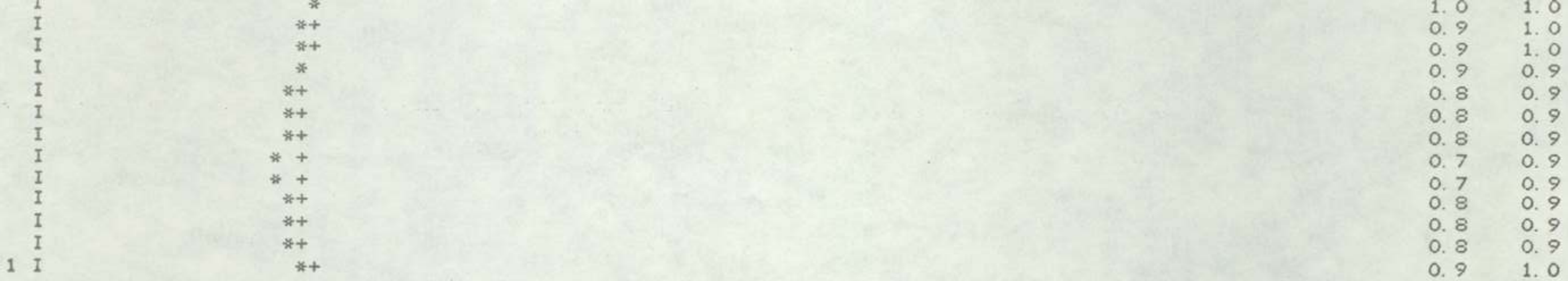


COMP.	HIST.
0.0	0.0
1.7	1.7
1.8	1.8
1.6	1.7
1.5	1.6
1.4	1.5
1.3	1.5
1.2	1.5
1.2	1.5
1.1	1.4
1.2	1.4
1.3	1.5
1.3	1.6
1.6	1.7

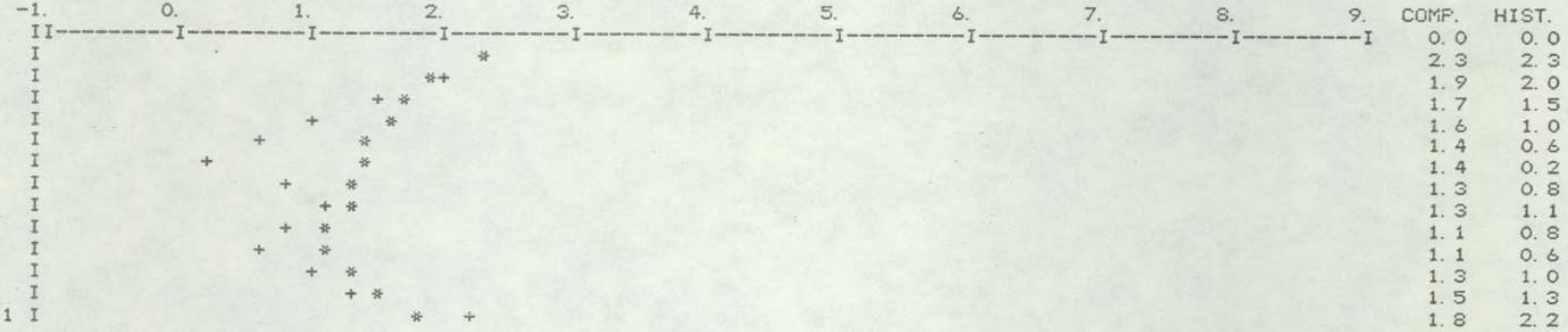
NODE 118

ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS

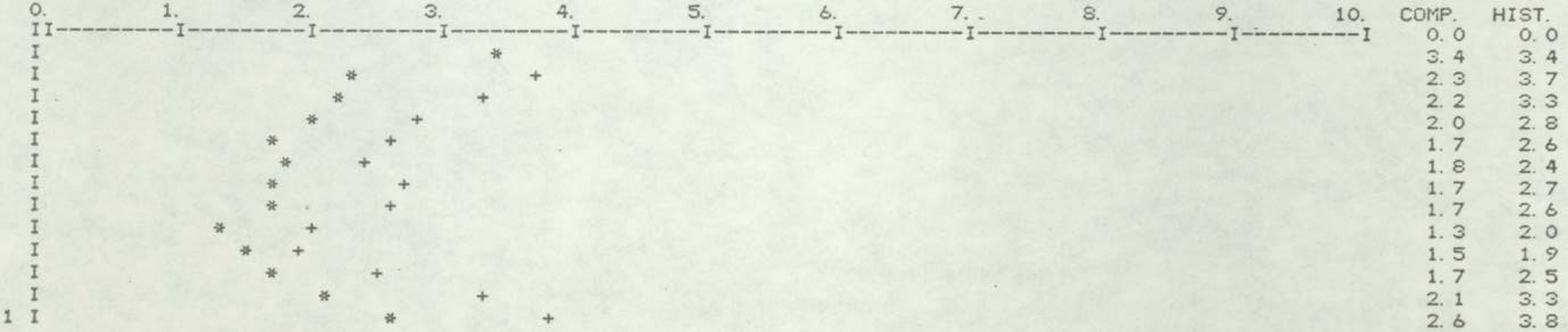
FIG. 7.12 (CONT)



NODE 119 ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS



NODE 120 ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS



NODE 121 ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS

FIG. 7.12 (CONT)

```
  II---------I---------I---------I---------I---------I---------I---------I---------I---------I---------I    0.0    0.0
  I                                   *                                                                     3.5    3.5
  I                        *             +                                                                  2.4    3.8
  I                         *         +                                                                     2.5    3.5
  I                       *       +                                                                         2.3    3.1
  I                    *        +                                                                           2.0    2.9
  I                       *     +                                                                           2.3    2.9
  I                     *         +                                                                         2.1    3.1
  I                    *       +                                                                            2.0    2.8
  I                 *    +                                                                                  1.7    2.2
  I                  *   +                                                                                  1.8    2.2
  I                     *       +                                                                           2.1    2.9
  I                        *        +                                                                       2.4    3.3
1 I                             *      +                                                                    2.9    3.6

  NODE 122                     ELEVATION IN METERS ABOVE SEA LEVEL VS.  TIME IN YEARS

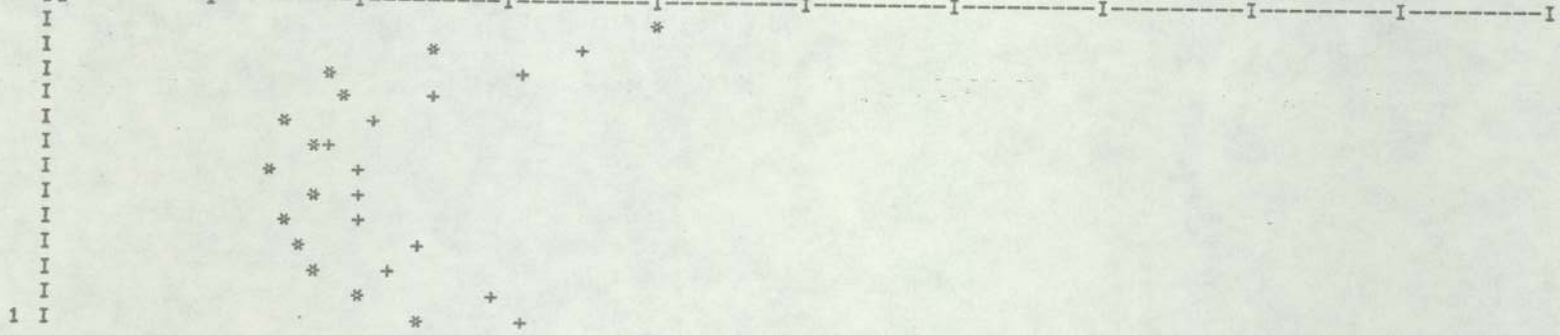
  0.        1.        2.        3.        4.        5.        6.        7.        8.        9.       10.  COMP.  HIST.
  II---------I---------I---------I---------I---------I---------I---------I---------I---------I---------I    0.0    0.0
  I                           *                                                                             2.7    2.7
  I                  *           +                                                                          1.8    3.0
  I                  *        +                                                                             1.8    2.7
  I                 *   +                                                                                   1.7    2.1
  I                 * +                                                                                     1.7    1.9
  I                 *+                                                                                      1.7    1.8
  I                 *  +                                                                                    1.7    2.0
  I                 +*                                                                                      1.8    1.7
  I            +    *                                                                                       1.7    1.2
  I            +    *                                                                                       1.7    1.2
  I                 *                                                                                       1.7    1.7
  I                   *   +                                                                                 1.9    2.3
1 I                    *     +                                                                              2.0    2.6

  NODE 123                     ELEVATION IN METERS ABOVE SEA LEVEL VS.  TIME IN YEARS

  0.        1.        2.        3.        4.        5.        6.        7.        8.        9.       10.  COMP.  HIST.
  II---------I---------I---------I---------I---------I---------I---------I---------I---------I---------I    0.0    0.0
  I                            *                                                                            2.8    2.8
  I                 *           +                                                                           1.7    2.9
  I                     *    +                                                                              2.1    2.6
  I                    *                                                                                    2.0    2.0
  I                 +*                                                                                      1.8    1.7
  I               +    *                                                                                    2.0    1.5
  I                 *                                                                                       1.7    1.7
  I               +   *                                                                                     1.9    1.5
  I           +     *                                                                                       1.7    1.1
  I            +     *                                                                                      1.8    1.2
  I                +  *                                                                                     1.9    1.6
  I                    +*                                                                                   2.1    2.0
1 I                       *+                                                                                2.3    2.4

  NODE 124                     ELEVATION IN METERS ABOVE SEA LEVEL VS.  TIME IN YEARS
```

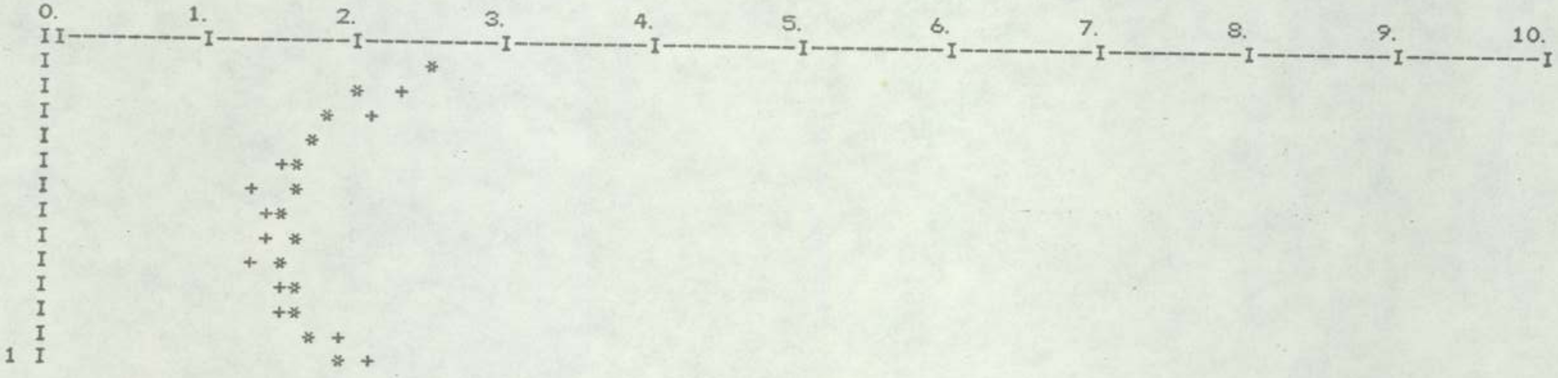
FIG. 7.12 (CONT)



0.0	0.0
4.0	4.0
2.5	3.5
1.8	3.1
1.9	2.5
1.5	2.1
1.7	1.8
1.4	2.0
1.7	2.0
1.5	2.0
1.6	2.4
1.7	2.2
2.0	2.9
2.4	3.1

NODE 125

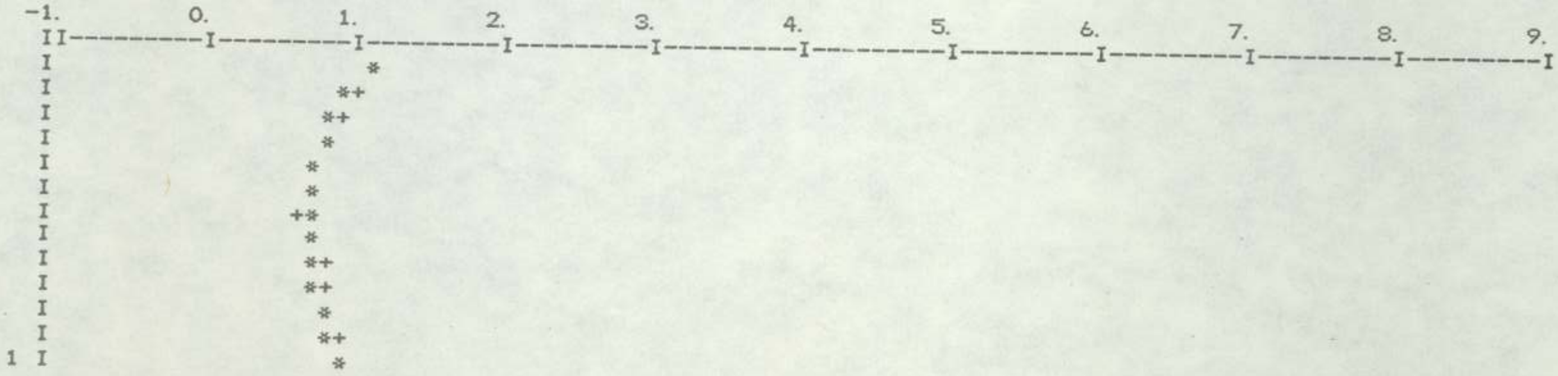
ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS



COMP.	HIST.
0.0	0.0
2.5	2.5
2.0	2.3
1.8	2.1
1.7	1.7
1.6	1.5
1.6	1.3
1.5	1.4
1.6	1.4
1.5	1.3
1.6	1.5
1.6	1.5
1.7	1.9
1.9	2.1

NODE 126

ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS



COMP.	HIST.
0.0	0.0
1.1	1.1
0.9	1.0
0.8	0.9
0.8	0.8
0.7	0.7
0.7	0.7
0.7	0.6
0.7	0.7
0.7	0.8
0.7	0.8
0.8	0.8
0.8	0.9
0.9	0.9

NODE 127

ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS

FIG. 7.12 (CONT)

8 COMPUTER TECHNIQUES

8.1 Introduction

During the course of this research project considerable use was made of digital computers. In many of these cases the actual application has been described in the appropriate section of this thesis. For others, however, the results have been used without any detailed description of the programs or the computational techniques used. Thus, in order to cover any gaps which might otherwise exist, this chapter is included.

The depth of discussion will vary as a function of the amount of coverage given to the respective subjects in other chapters. Thus the discussion of groundwater modelling and cluster analysis in this chapter, will be essentially limited to a description of the programs used, whereas in the case of computer contouring, an evaluation of different techniques will be included.

The attitude of a large, but diminishing, number of hydrogeologists to the use of computers in groundwater studies is to ask "Why bother?". Those who are fully committed to their use see this as a negative and reactionary attitude. The present writer, however, believes that every worker in this field should ask the question of himself, in order to avoid believing too implicitly in the ability of the computer.

In the case of the present research work, one of the objectives was to evaluate the merits of just such an approach and thus, in some cases, the computer was used for a particular task and results compared to a manual approach.

8.2 Computer Contouring

8.2.1 General

Any regional geological or groundwater investigation is likely to involve, at some stage of the study, the preparation of maps which serve as an aid in expressing dimensional relationships. Most maps are estimates of continuous functions which have been based on discrete observations at specific points. In the case of a topographic map, the ground surface can be seen to be continuous whereas subsurface features, based on observations from boreholes, are only assumed to be continuous. Nevertheless, an estimate of the form of the feature is made, although it is recognized that it is inaccurate due to the lack of information between the boreholes or control points.

The traditional method of producing a contour map is by hand, in which case artistic talent is frequently combined with professional judgment to produce a somewhat subjective result. In some cases this may be desirable and the final product may benefit from the added interpretation that the geologist or hydrogeologist is able to give. Conversely, the judgment may be biased and the personal influence may lead to an inferior final interpretation.

Where the number of data points is relatively small and the area to be studied large, then the manual process is often found to be preferable. Where there are many data points, however, it is frequently better to use a computer contouring method. Thus, in addition to being consistent and preventing overly interpretive mapping, the computer will facilitate the manipulation of large quantities of data.

The methods of computer contouring fall into two broad categories; those which attempt to fit a trend surface to the point and those which produce a regular grid based on averages of the nearest data points. The trend surface methods produce smooth maps that possess the distinct disadvantage that most of the actual observed data will not lie on the final computed surface. On the other hand, maps produced by the grid method are likely to be less smooth and to have some discontinuities, although all the data points will lie on the surface.

Much has been written on the general topic of computer contouring and many different programs and commercial packages are available. It was felt, however, that many of these are applied by scientists in various disciplines without a real understanding of the methods or the shortcomings of the respective programs. Thus it was decided to compare two contouring programs, a trend surface method and a grid method, using a set of data which had been derived by hand from an idealised contour map.

8.2.2 Trend Surface Methods

The fundamental concept of trend analysis in the Earth Sciences is to separate large scale trends from minor local variations. Consequently, it would seem to be a potentially useful tool for the hydrogeologist faced with studying a groundwater basin. If, as in the case of the present study area, there are numerous pumping wells which may be influencing the water levels in some monitoring holes, then trend surface analysis appears promising as a potential tool for producing regional maps and overlooking the localized cones of depression.

Trend surface analysis in the Earth Sciences has invariably involved the least-squares criteria, in which the sum of the squared residuals between computed values of the surface and observed values are minimised, Harbaugh and Merriam (1968).

The surface which is to be fitted to the data points can be described by an equation with three variables and a particular number of terms. Thus a plane would be defined by $z = A + Bx + Cy$, where z is the dependent variable; and a paraboloid by $z = A + Bx + Cy + Dx^2 + Exy + Fy^2$. This last equation is known as a second degree polynomial.

In natural conditions, the minimum number of terms necessary to describe a surface such as a water table is likely to be a third degree polynomial as shown below.

$$z = A + Bx + Cy + Dx^2 + Exy + Fy^2 + Gx^3 + Hx^2y + Ixy^2 + Jy^3$$

The method of solving the equation for the coefficient A to J, so that the sum of the squared deviations is a minimum, depends on deriving linear equations which can be solved by matrix algebra.

An alternative method of trend surface analysis is the use of double Fourier series in which the surface is represented by means of a composite of sine and cosine wave forms.

The way in which a complex surface can be built up from a number of two-dimensional sinusoidal wave forms is described by Davis (1973) and illustrated in Fig. 8.0.

Fourier analysis assumes that there is a harmonic pattern to the data, which may be the case with many natural phenomena. If this assumption is accepted then the method can be used to extrapolate beyond the data points, a task which cannot be done with polynomial methods. In that case however, the fundamental wave lengths, which have to be selected prior to the analysis, must be longer than the dimensions of the map, otherwise the Fourier surface will repeat with the map area. (In practice it was found that they need to be longer in all cases).

A detailed description of the mathematics of double Fourier analysis will not be included here, but rather a description of the practical tests carried out with an available program.

The program used was that described by James (U.S. Office of Naval Research) in which the coefficients of the double Fourier series are linearly combined. The series is expanded into a set of simultaneous normal equations and solved for the unknown coefficients. Irregularly spaced map data are fitted by an approximating function based on the coordinates of the data points. The number of required harmonic trends is selected, depending on the number of data points and the program produces a trend map, a complete fit and a residual map showing the difference between the calculated and recorded data. The maps are output on a line printer using characters to depict the calculated values of the dependent variable at those points.

The test data was taken from the idealised map of a coastal aquifer suffering sea water intrusion (Fig. 8.1). The map shows hypothetical lines of equal chloride content and values at 26 irregularly spaced points, corresponding to boreholes, were extracted. These data were then used as input to the program Fourfit in three different ways (tests A - C).

Test A_1

The 26 data points were used and initial wavelengths corresponding to the size of map were put in.

Test B_1

Four additional data points were added with high chloride values representing the sea, which occurs in the southwest corner of the map. The same wavelengths as in A were used.

Test C_1

The 26 data points, as in A, were used but with initial wavelengths of 10 times the map size.

Initially, in error, wavelengths of 1/10 the map size were put into the program and this demonstrated that the initial wavelength must be at least the same order of magnitude as the map size. In Fig. 8.2 it can be seen that results with the small wavelength were meaningless in terms of sea water intrusion.

With the corrected wavelengths (i.e. equal to the map size in tests A_1 and B_1 and 10 times greater in test C) the resulting maps were an improvement on the first run but were far from ideal (Figs. 8.3 to 8.8). What is more important however is that there was very little difference between the trend surface and the full fit due to the fact that too high a degree of fit was being attempted for the number of data points available. In test B, 30 data points were used with 25 coefficients (i.e. a 2nd degree Fourier fit) and hence the trend was almost a full fit. In the cases of tests A_1 and C_1 however, with only 26 data points and 25 coefficients, the trend was in fact a full fit.

As a major purpose in trend surface analysis is to distinguish regional trends from localised fluctuations, i.e. 'signal' from 'noise', it is obviously important to select the number of coefficients which is commensurate with the number of data points. Consequently, the tests were repeated using 9 coefficients (a first degree Fourier analysis).

Tests A_2 and C_2 (26 data points) produced trend maps which were virtually identical (Figs. 8.9 and 8.13) but in which the full fits were significantly different (Fig. 8.10 and 8.14). The trends were reasonable in that they did indeed indicate a "trend" in the water quality but neither would be acceptable as accurate interpretations of the actual groundwater quality. Similarly, the full fits were not very accurate and test C_2 contained a major error in that it showed a chloride 'high' occurring inland with salinity falling off towards the sea. This last point was no doubt due to the fact that no high values representing the sea were included. It is interesting to note though, that with the same data but different starting wavelength, one map should show high chloride values in the area of the sea and other should show low values.

Test B_2, in which high chloride values were included, was run twice. In the first case the four high values were included and in the second these were reduced to just one datum point in order to avoid an unreasonable bias. This gives a similar but improved trend surface and a somewhat improved full fit (Fig. 8.11 and 8.12).

Having tested the program out on the hypothetical water quality data it was then run using the available limestone water levels from the study area for November 1970. In this case, the major shortcomings of the method were highlighted in that, through its imposition of harmonic trends, there were obvious and major errors in the maps which it produced. An examination of Fig. 8.15 will show that, in the northern part, where water levels are known to rise to a considerable elevation above sea level, the map shows values below sea level.

In summary, it can be seen that none of the maps produced by the Double Fourier Analysis Program were acceptable as accurate groundwater quality or water table maps. In cases where there are large numbers of data points the trend surface maps could be useful in indicating the overall pattern, which might then be used as a basis for hand contouring. The tendency, inherent in the method, of imposing harmonic trends on the data points, does not appear to be appropriate in the case of regional groundwater data. An additional area for concern with this method is the difference in final product which results from selecting different initial wavelengths.

8.2.3 Grid Contouring Method

Most grid contouring methods for irregularly spaced data involve calculating values at points on the grid, from weighted averages of a specified number of nearest data points. The method selected for this study involves the use of a simple algorithm for griding and contouring, a program for which is described by Davis (1973).

The data is fed in as a series of observed values of the parameter to be contoured and the grid coordinates for each of these observation points. A rectangular grid of points is then set up, which corresponds to the characters in 60 x 100 array required to produce the line printer map. The program then considers each of the points in the array and searches for a specified number of nearest data points. Having obtained these, a weighting process is applied to obtain an average value for the grid point itself. This process is repeated for each of the 6,000 grid points and in this way the values of the computed surface are obtained. Finally, a plotting routine assigns characters to each grid point on the matrix and produces a line printer map.

The program was tried out on the test set of chloride data (Fig. 8.16) and also on the limestone water level data (Fig. 8.17) and it can be seen that the results are, at least, acceptable. They are not as aesthetically pleasing as the maps from the trend surface analysis but, on comparison with the original or hand contoured maps, they are shown to be reasonably accurate.

The main drawback with this program was the relatively long computational time required, due to the fact that for each of the 6,000 grid points the input data had to be searched each time to locate the nearest data points. With this in mind the tests were run using both the nearest 4 and 6 data points and it was found to be preferable to opt for the higher number even though this was more expensive in computer time.

In all computer mapping techniques there is a significant "edge effect" unless the input data extends beyond the limits of the map. This effect was noticeable in both the trend surface and the grid based maps. It was particularly significant in the latter when only the 4 nearest points were used.

From this work the general conclusion was drawn that the method employing an algorithm for gridding and contouring gave the most reliable results. The results obtained from a Double Fourier Series Program were found, predictably, to produce smoother maps and, in some instances, to enable reasonable extrapolations to be made into areas with little data. It was observed, however, that when an error did occur, it was likely to be a major one.

In order to generate the water level input data for the groundwater model the gridding method was modified slightly, particularly in the method of output. For the model, the water levels at each node are required for each month of the period to be modelled. Hence, instead of calculating the water level at each point on the grid, only those at the node points were determined. These were then printed out in such a format that they could easily be read off for input into the model. An example for one month is shown in Fig. 8.18.

8.3 Cluster Analysis

The theory of cluster analysis was described in Chapter 6 of this thesis, but little was said about the programs which were actually used in this study.

Cluster analysis was used in an attempt to classify the groundwater on the basis of its chemical constituents. The first program used was part of a suite of library routines available on the I.C.L. 1905E Computer at the University Computer Center.

The chemical parameters of Cl, HCO_3, SO_4, NO_3, Ca, Mg, total dissolved solids and electrical conductivity were read in and then standardized in order to avoid a bias towards those variables with a high variance. Once the data had been standardized, then the following programs were executed:

Program ATCO

ATCO computes the similarity matrix and K-linkage lists from the data. These results are then stored on a disc file. The similarity matrix is a triangular matrix of N*(N-1)/2 coefficients such that each element measures the similarity between two individuals. The K-linkages are the lists of nearest neighbours for all N individuals.

Some 40 criteria are available for the measuring of similarity but most of these are beyond the scope of this thesis. The relevant ones were described in Chapter 6.

Program ATR1

This program prints the computed statistics, the coefficient matrix and the K-Linkage lists.

Program ATHA

The program starts with N clusters, each containing a single individual, which are numbered according to the input order of individuals. In each of (N-1) fusion steps, those two clusters which are most 'similar' are combined and the resulting union cluster is labelled with the lesser of the two codes of its constituent clusters. ATHA completes all the fusions and summarizes the sequence in a dendrogram, which it outputs on the graphplotter. The program uses the disc file created by ATFI and assumes that a similarity matrix has been computed by program ATCO. The fusions are produced by means of a transformation of the similarity coefficients. This transformation is expressed as follows (User's Handbook, Section 1801):-

Let clusters P and Q be fused, then the similarity S(R,P+Q) between any cluster R and the new cluster (P+Q) is obtained from the formula:

$$S(R,P+Q) = AP*S(R,P)+AQ*S(R,Q)+B*S(P,Q)+G*ABS(S(R,P)-S(R,Q))$$

Several runs were attempted with the above suite of programs and these met with varying degrees of success. The results are discussed in Chapter 6. Before this work was completed however, the writer no longer had access to the above mentioned computer and had to resort to facilities on which no such library routine was available. Although this caused some inconvenience, there were also some advantages in terms of experience and understanding. The program selected to complete this work was described by Davis (1973) and was somewhat simpler than the one described above. As a listing was also available it meant that the computations could more easily be followed and also, due to its size, the program could be used on relatively small computers. A fact making it of particular value to the hydrogeologist, who is often working in areas with limited computer facilities.

The program reads an NxM matrix and then offers the option of computing an MxM matrix of similarity or an NxN matrix. The user then selects either correlation or distance as the measure of similarity and these are computed by subroutines RCOEF and DIST respectively.

Subroutine WPGA carries out the weighted pair grouping and forms the clusters and DENDRO prints out the dendrogram. This program does not contain a standardization routine and hence it is desirable to do this before the data is read in. In this way anomalous weighting due to say high total dissolved solids can be overcome.

The main difference between this program and the library program described earlier is in the maximum size of the maps and in the fact that the second program uses the line printer to produce the dendrogram.

The cluster analysis of small data sets is relatively simple but, with increasing sample size, the task becomes significantly more arduous. Similarly, it also becomes more difficult to produce acceptable dendrograms without resorting to advanced graphic routines.

8.4 The Groundwater Model

The theory behind digital groundwater modelling and the application of the model in the present study, were described in Chapter 7. The actual program used is described below.

The Program KRGW was developed in Jordan by Chidley and refined for application in Crete by Goodwill (1971). The program consists of a master segment and twelve subroutines as shown in Fig. 8.19. The various steps of the computation are covered in the description of each subroutine. In summary, however, the main arithmetic calculations involved in the iterative procedure are contained in one subroutine and the checking of the results against the known parameters is carried out elsewhere.

The program utilizes five 'scratch' files as temporary storage and all output is on the line printer.

KRGW - Main Segment

This segment defines the array sizes and storage facilities and sets up the five direct access 'scratch' files which are used for temporary storage. It also calls the subroutines KRGW3, KRGW, KRGWP and KRGWG, which control the reading in of data, the execution of the iterative process and the output of the results.

KRGW3

This subroutine reads the basic nodal data and the recharge data and writes it to file. It also calls subroutine KRGW4 which prints out this data. The run number, the simulation period, and the name of the project area or aquifer are printed at the head of each page.

There are 9 switches in the program and a value of 1 or 2 must be given to each. These are used to select various options available in the program with regard to type of data and output of results.

The first three switches (SW(1), SW(2), and SW(3)) select various options with regard to the printing of the results. The remaining six switches function as follows:

SW(4)	If 1 then recharge is read in as the sum of four components (e.g. natural recharge, abstraction by pumping, spring flow etc.); if 2 then net recharge per node is read in.
SW(5)	If 1 then transmissivity is used; if 2 then permeability is used.
SW(6)	If 1 then cross flows between nodes are printed; if 2 then cross flows are not printed.
SW(7)	If 1 then check printing occurs within iterative loop; if 2 then no check printing. (This is used to find out what is happening within the iterative loop when it is suspected that something is going wrong). Normally option 2 is used.
SW(8)	If 1 then run is terminated if more than 50 iterations are used; if 2 then program runs until convergence or time runs out.
SW(9)	If 1 then water levels are printed at the end of each iteration; if 2 then this does not occur.

After the above switches, a further set of control data are read in. These cover various aspects of the computational procedure, including basic time steps and size of the model. These data are summarised in Table 8.1.

The characteristics of the aquifer, as read in, may be considered as three groups. The first group describes the physical shape of each node of the aquifer and its relationship to its neighbours. The second group covers the actual aquifer characteristics (i.e. storage coefficient and permeability or transmissibility) and the third group relates to water levels etc. These sets of parameters are listed in Table 8.2.

CONTROL DATA AND PARAMETERS FOR KRGW

TABLE 8.1

NINO	Number of internal nodes
MAXNO	Maximum number of nodes
NMD	The number of months for which the run is to continue
PCNT	The frequency in basic time steps that printing of results is required (normally the month is divided into PCNT time steps; the smaller the timestep the greater the degree that the finite difference approximation approaches the differential equation)
RCNT	The frequency in basic timesteps that the recharge data is available
NIINT	The number of nodes at which cross flows are required
HCNT	The frequency in basic time steps that boundary head data is read. (This is set to a high value, say 900, if only one set of boundary head data is used. If boundary heads change monthly then this is set to appropriate value)
ERROR	The figure which controls the precision of the iterative process (usually 2.0)
RCOEFF	Relaxation factor normally 1.0 but 0.8 or 1.2 could be tried in an effort to speed results
DIVID	The distance to the bottom of the aquifer below which the program automatically cuts back pumping
K3	Conversion factor for recharge element 1 (converts the recharge to MCM/year from the actual units used)
K4	Conversion factor for recharge element 2
K5	Conversion factor for recharge element 3
K6	Conversion factor for recharge element 4 (multiplies data card figure by K6 x KK to obtain recharge in metres/year over each nodal area)
CHNGP	Conversion factor for permeability or transmissivity. Can be used to convert from actual units to required units or as a means of altering all permeabilities
CHGS 2	Conversion factor for storage coefficient in lower aquifer
CHGS 1	Conversion factor for storage coefficient in upper aquifer
KK	Master conversion factor for recharge to obtain figure in MCM/year
IY	Starting year of calculation
LASTY	Ending year of calculation
MON	Starting month of calculation
RUN	Name of the current run. A different value should be assigned to each run
IBOU	The type of boundary. This can be 0 or 1. If zero then a head controlled boundary is expected at the node referred to.
KONF	This is the type of internal node under consideration. 0 denotes unconfined and 1 denotes confined. Use can be made of dual storage coefficient in the confined aquifer case. A very small value of storage can be assigned if the water level rises above the top level of the aquifer (i.e. the upper level aquifer). When water levels are below this level then a higher value is used
INTNN	The numbers of the nodes at which cross flows are to be printed. Usually there will be a list of numbers 1 to NINO

PHYSICAL PARAMETERS OF AQUIFER

(i) The elevation of the ground surface.
(ii) The elevations of the top and bottom of the aquifer.
(iii) The number of internal and external (boundary) nodes.
(iv) Relationship of each node to its neighbour.
(v) The distance between each adjoining pair of nodes and the width of the groundwater flow path between them.
(vi) The position of any horizon that separates zones of different storage capacities.

AQUIFER CHARACTERISTICS

(i) The storage coefficient.
(ii) The permeability and/or transmissibility between each node.

GROUNDWATER CHARACTERISTICS

(i) The initial water level at each internal node.
(ii) Whether the node is confined or unconfined.

TABLE 8.2- INPUT PARAMETERS DESCRIBING HYDROGEOLOGY OF EACH NODE

The remaining essential data to be read in before compution can proceed is the recharge data. As described above, switch SW(4) enables the choice to be made as to whether this should be read in as a net value or as four components. The actual components will depend on the particular area being modelled but, for example, they could be direct recharge from precipitation, spring flow, pumping and base flow in streams.

Within this subroutine some computations are carried out such as the calculation of total recharge per time step for each node and the total surface area for the model. Many of the data arrays are initialised and some are read onto the scratch files. Checks on the data are carried out and, if necessary, error messages are printed and the run terminated. Subroutine KRGW4 is then called and this prints out the basic data.

Subroutine KRGWM

This subroutine is essentially the main program, in which the backward difference equations are formed and then solved by the Gauss-Siedel Relaxation Technique. The theory for this was discussed in Chapter 7. KRGW6 is called by KRGWM and fetches the boundary head control data, if any, off the cards. It incorporates a checking routine and, if necessary, prints out an error message.

Once the boundary head data has been checked, control is transferred back to KRGWM, which then carries out the interative procedure. ERROR is a selected tolerance used to test for convergence of the relaxation. The calculation of the nodal heads for any given time step is complete when the sum of the absolute values of the residuals for all the nodes is less than ERROR. The residual for each node is the sum of subsurface flow rate, recharge rate and rate of change of storage. The choice of a value for ERROR is important because it controls the accuracy of the final results and influences the amount of time taken to complete the relaxation process.

A check on water levels approaching the base of the aquifer, or on spring flow occurring, is carried out by subroutine KRGW1 at the end of each time increment. If the water levels are approaching the base of the aquifer then the program progressively reduces the abstraction rates and, if necessary, stops abstraction completely. If this fails to prevent the water levels "going through the bottom of the aquifer" then the run is terminated. If the convergence has been successfully completed then KRGW1 checks to see if any water levels in unconfined nodes have risen above the top of the aquifer. If this has happened then they are adjusted back to ground level and, on re-calculation of the water balance, the residuals are given as surface flow. This is achieved by setting the relaxation coefficients to zero.

There is an option for printing out data within the iterative loop, in order to enable an analysis of the convergence procedure to be made. This option is controlled by switch SW(7).

If the computed water levels are required after each time step then switch SW(9) is set to 1 and subroutine KRGW2 is called. This option is useful during the calibration of the model, although the time interval between printed water levels is too short to allow close correlation with the historic water levels.

Boundary conditions are updated at the end of each time interval by recalling KRGW6. This is necessary in order to maintain the required hydraulic gradient across the boundaries.

A monthly water balance summary is prepared by subroutine KRGW5 from the balance kept at the end of each time step. This data, which includes recharge, surface flow, change in storage and net subsurface flow is then stored on a scratch file, as are the computed water levels. If it is required to know the subsurface flows between some or all of the nodes then these are printed out at this stage.

At this point control is transferred back to KRGW which, in turn calls KRGWP.

Subroutine KRGWP reads the data off the scratch files and sorts it into an appropriate format. It prints out the water balance summaries and tabulates the computed water levels. Control is then returned to KRGW.

At this point all the computation has been completed and the results displayed on the line printer. In order to facilitate the evaluation of these results however and, in particular, to enable a comparison of the computed and historical water levels to be made, a number of subroutines to produce graphs are included. These make use of the line printer.

Subroutine KRGW6 plots the graphs and makes use of the following routines as indicated:

Subroutine HPLOT

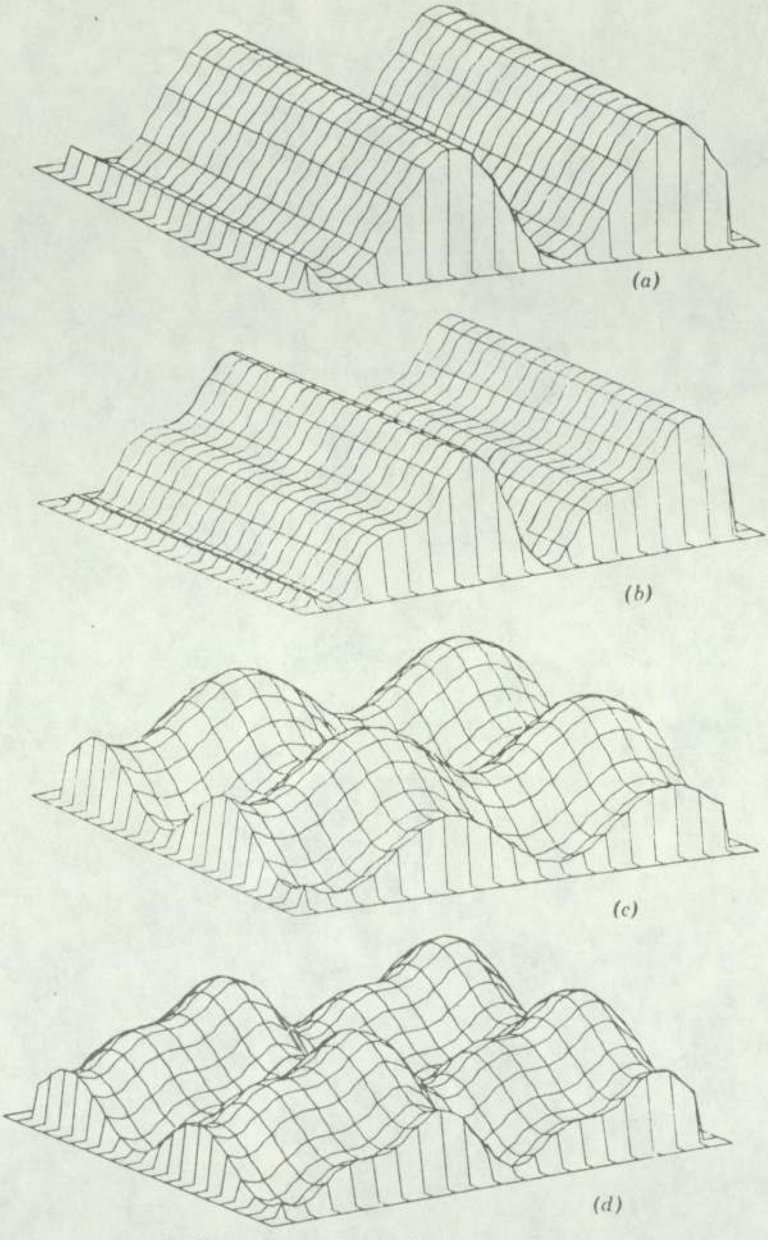
This finds the highest and lowest water levels for each node.

Subroutine HEADG

This routine heads the graphs and selects appropriate scales based on the values determined by HPLOT.

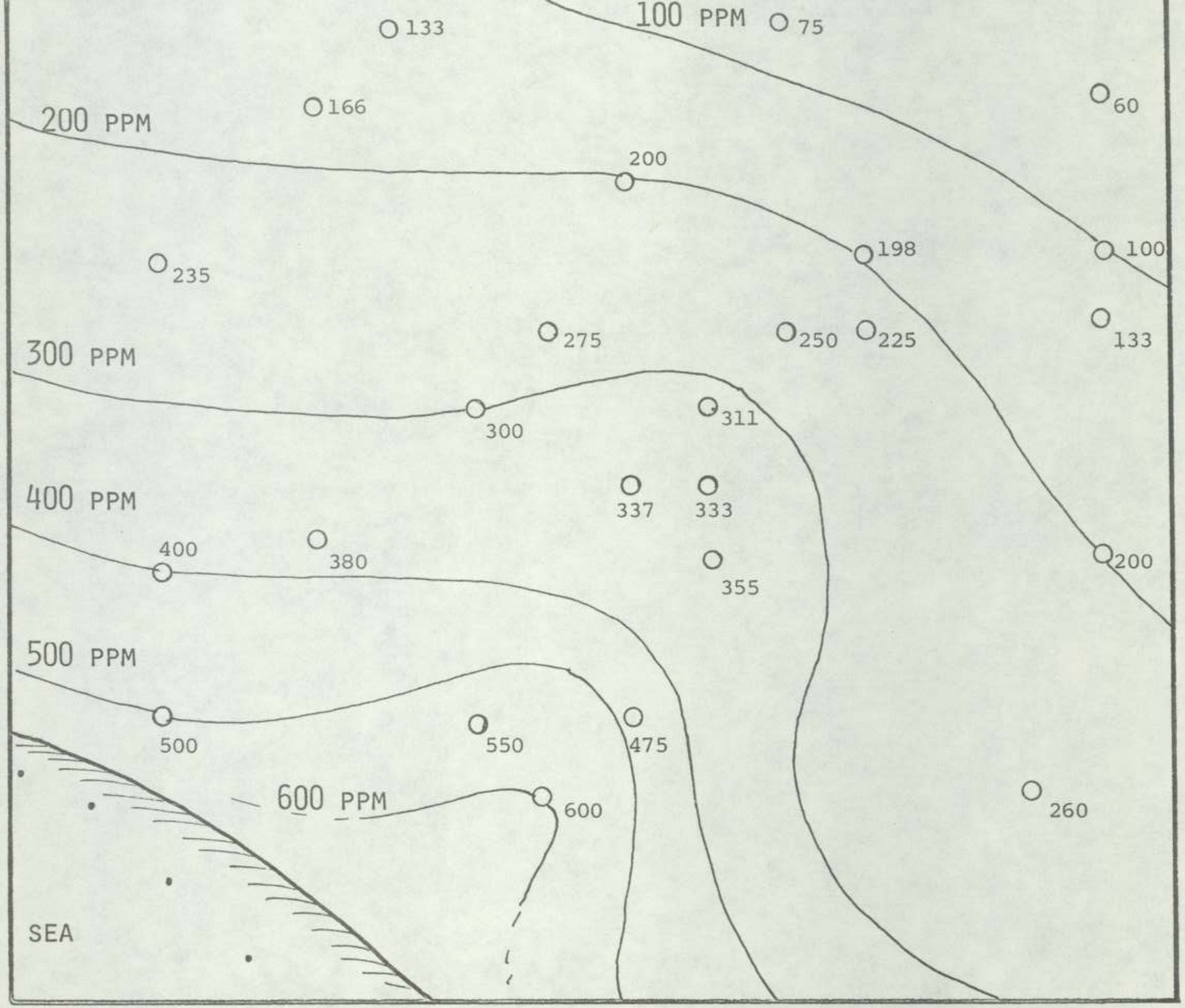
Subroutine PRINT

This routine plots the points using different symbols for the historical and computed water levels. It also plots one axis and, if the water lever goes beyond the range of scale, it indicates this with either an A or B.



Two dimensional sine waves. (*a*) Single harmonic in X_1 direction. (*b*) Two harmonics in X_1 direction. (*c*) Single harmonics in both X_1 and X_2 directions. (*d*) Two harmonics in both directions.

FIG. 8.0 (AFTER DAVIS, 1973)



IDEALISED MAP SHOWING SEA WATER INTRUSION.

FIG. 8.1

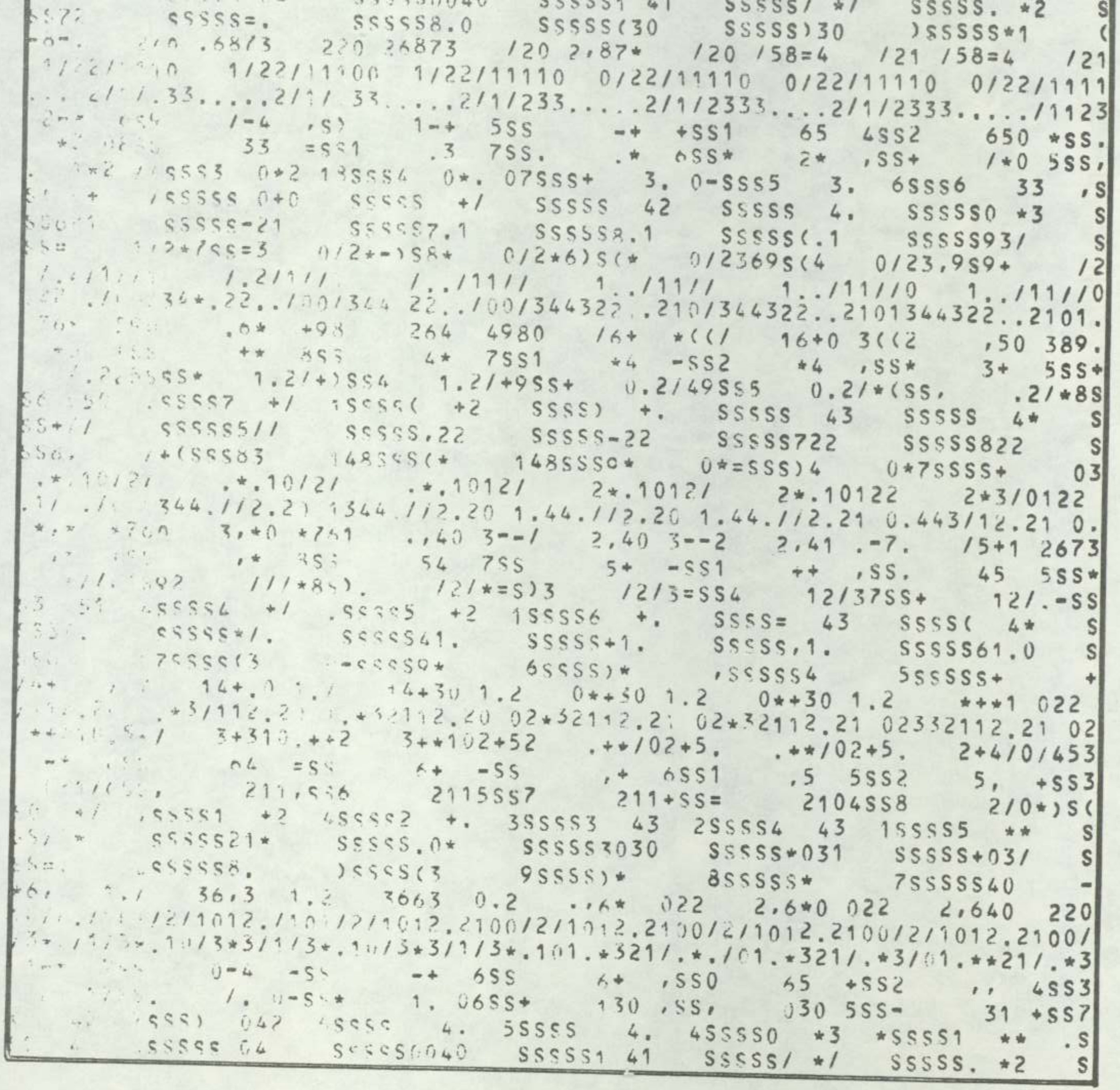
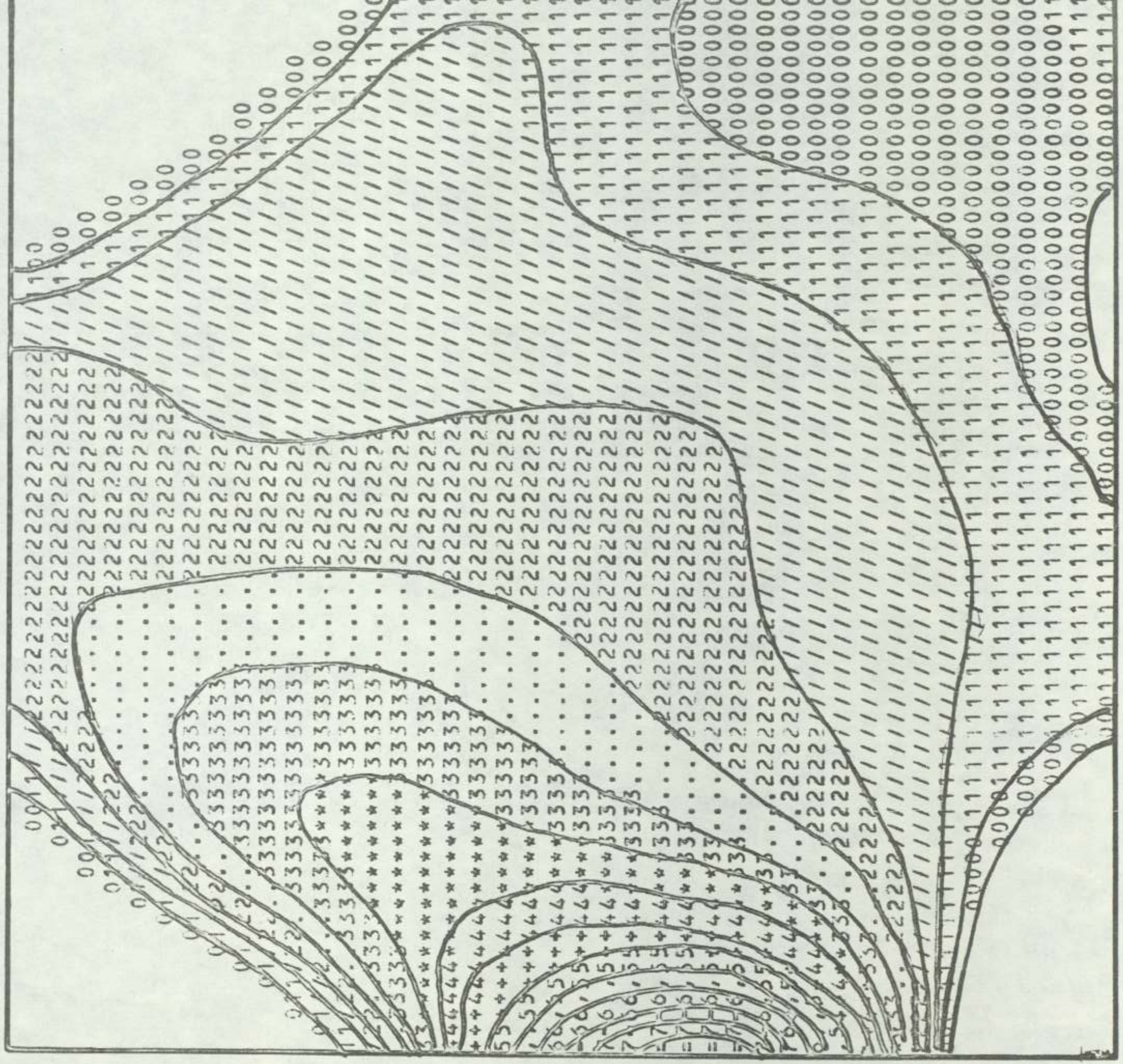


FIG. 8.2 TREND SURFACE MAP WITH ORIGINAL WAVELENGTH 1/10 OF MAP WIDTH.

SYMBOL MEANINGS

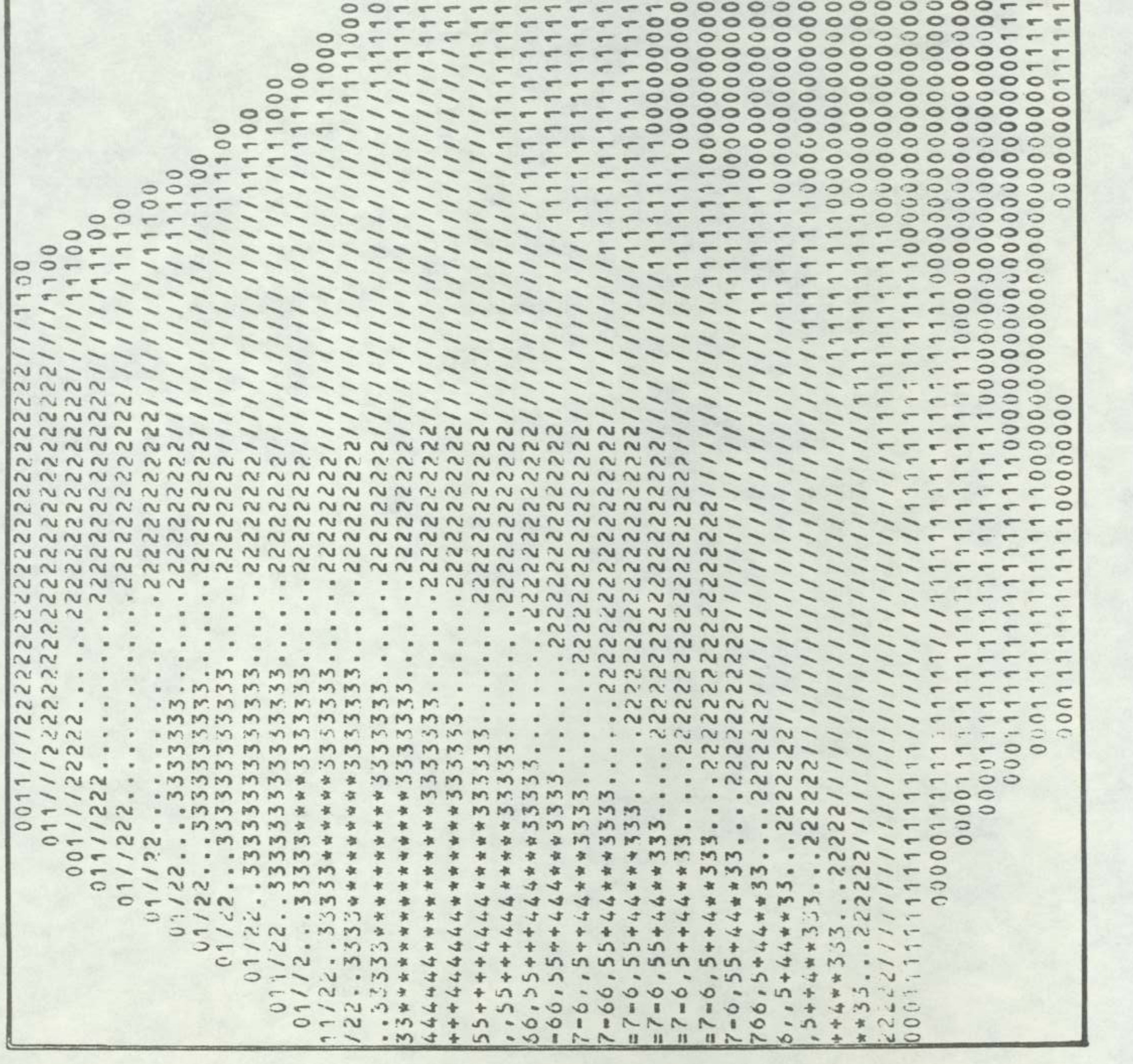
SYMBOL	MAX VAL
0	100.0000
1	200.0000
/	300.0000
2	400.0000
.	500.0000
3	600.0000
*	700.0000
4	800.0000
+	900.0000
5	1000.0000
,	1100.0000
6	1200.0000
-	1300.0000
7	1400.0000
=	1500.0000
8	1600.0000
(	1700.0000
9	1800.0000
)	1900.0000



TEST A,

FOURIER ANALYSIS - TREND SURFACE

FIG. 8.3



TEST A,

FOURIER ANALYSIS - FULL FIT

FIG.8.4

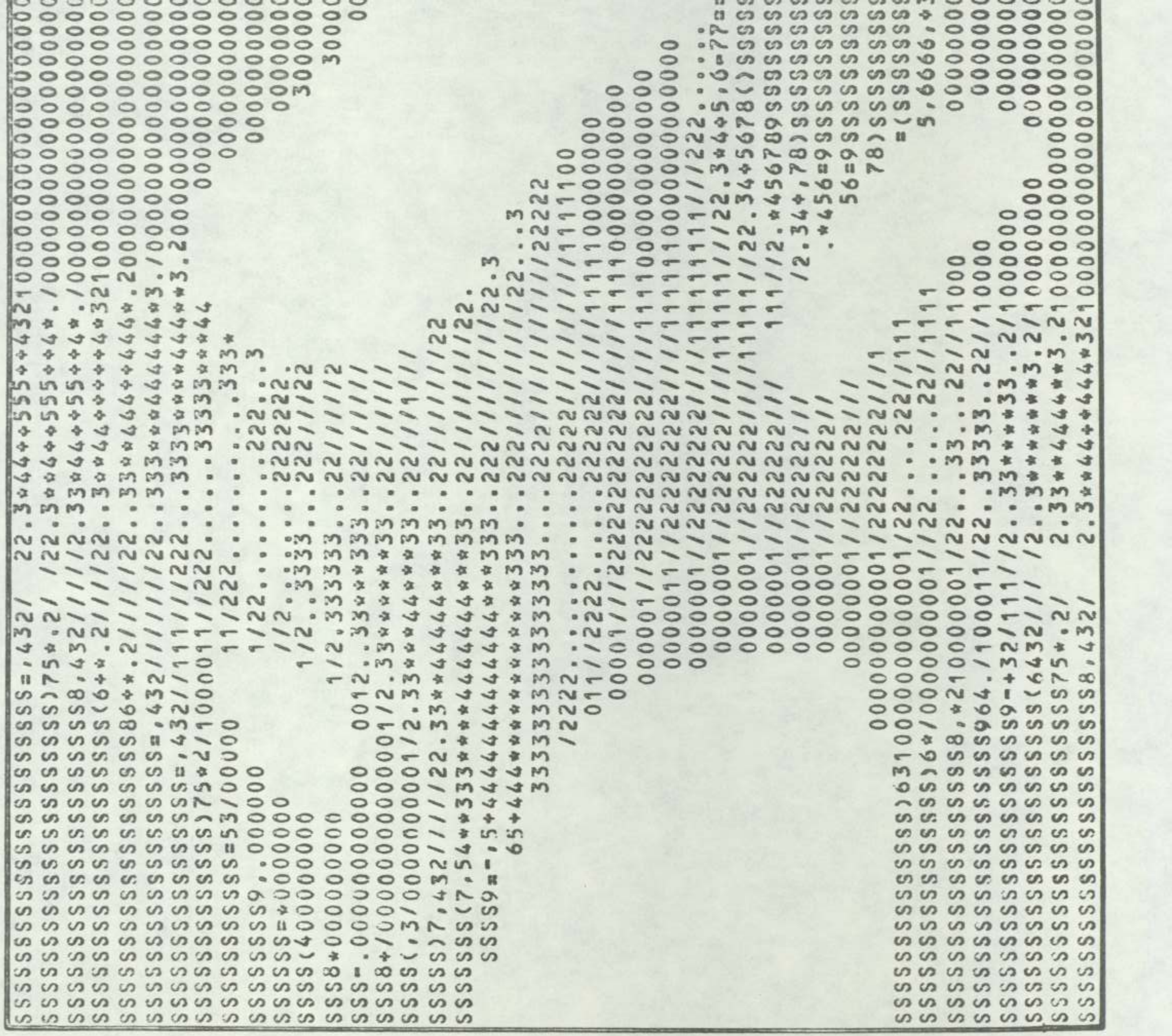
SYMBOL MEANINGS

SYMBOL	MAX VAL
0	100.0000
1	200.0000
/	300.0000
2	400.0000
.	500.0000
3	600.0000
*	700.0000
4	800.0000
+	900.0000
5	1000.0000
,	1100.0000
6	1200.0000
-	1300.0000
7	1400.0000
=	1500.0000
8	1600.0000
(	1700.0000
9	1800.0000
)	1900.0000

TEST B₁

FOURIER ANALYSIS - TREND SURFACE

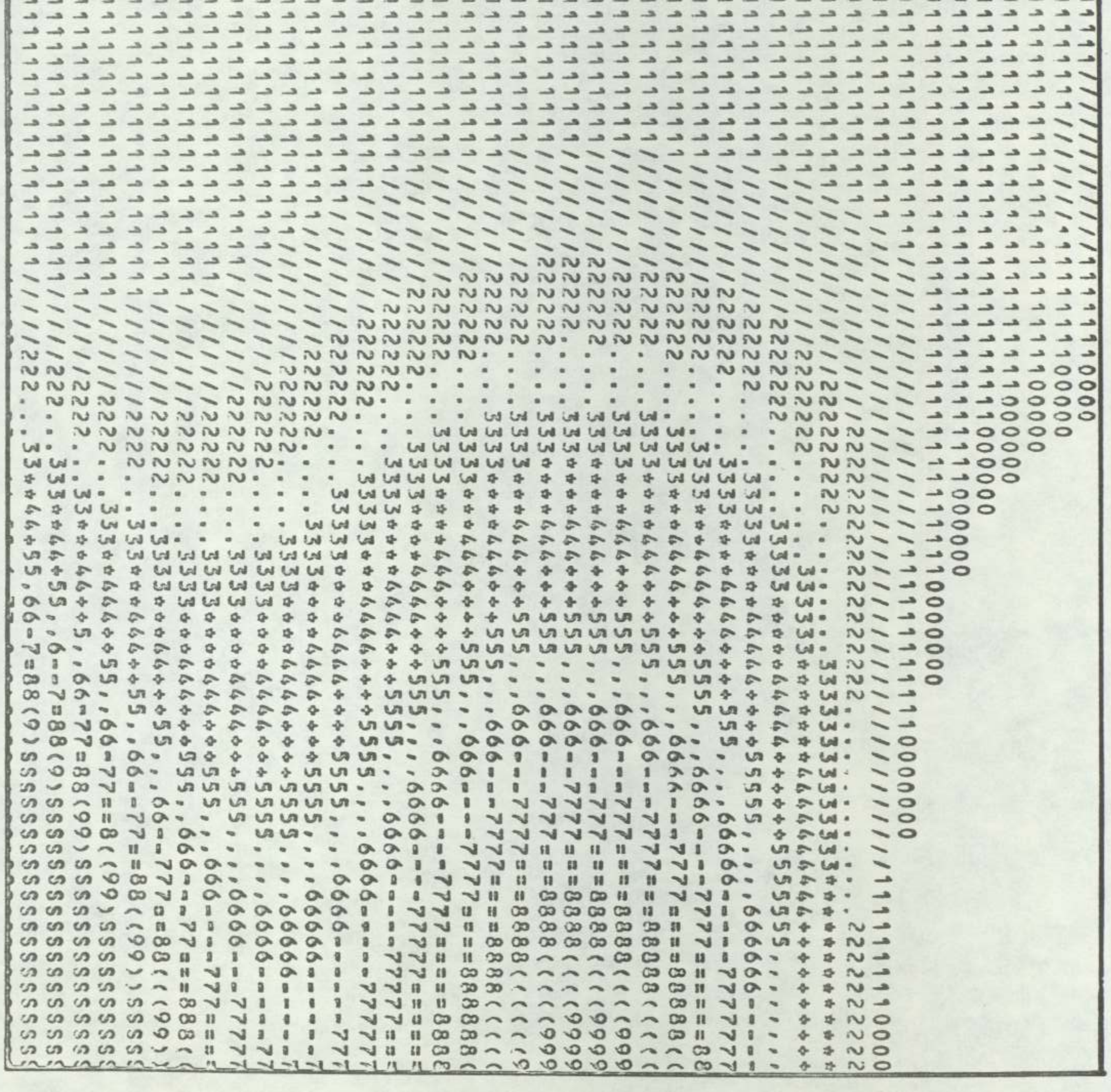
FIG. 8.5



TEST B1

FOURIER ANALYSIS - FULL FIT

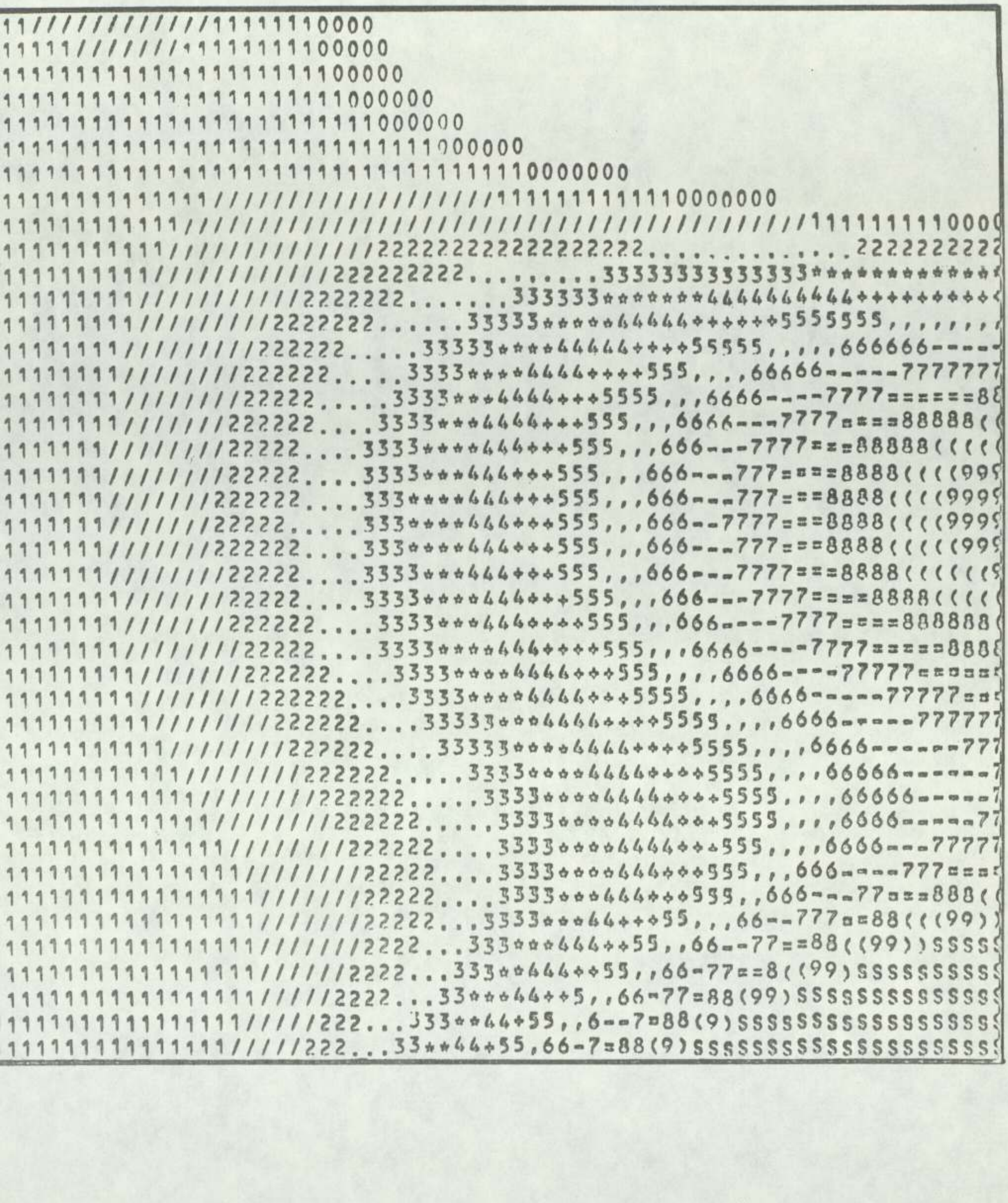
FIG. 8.6



Test C_1

Fourier Analysis - Trend Surface

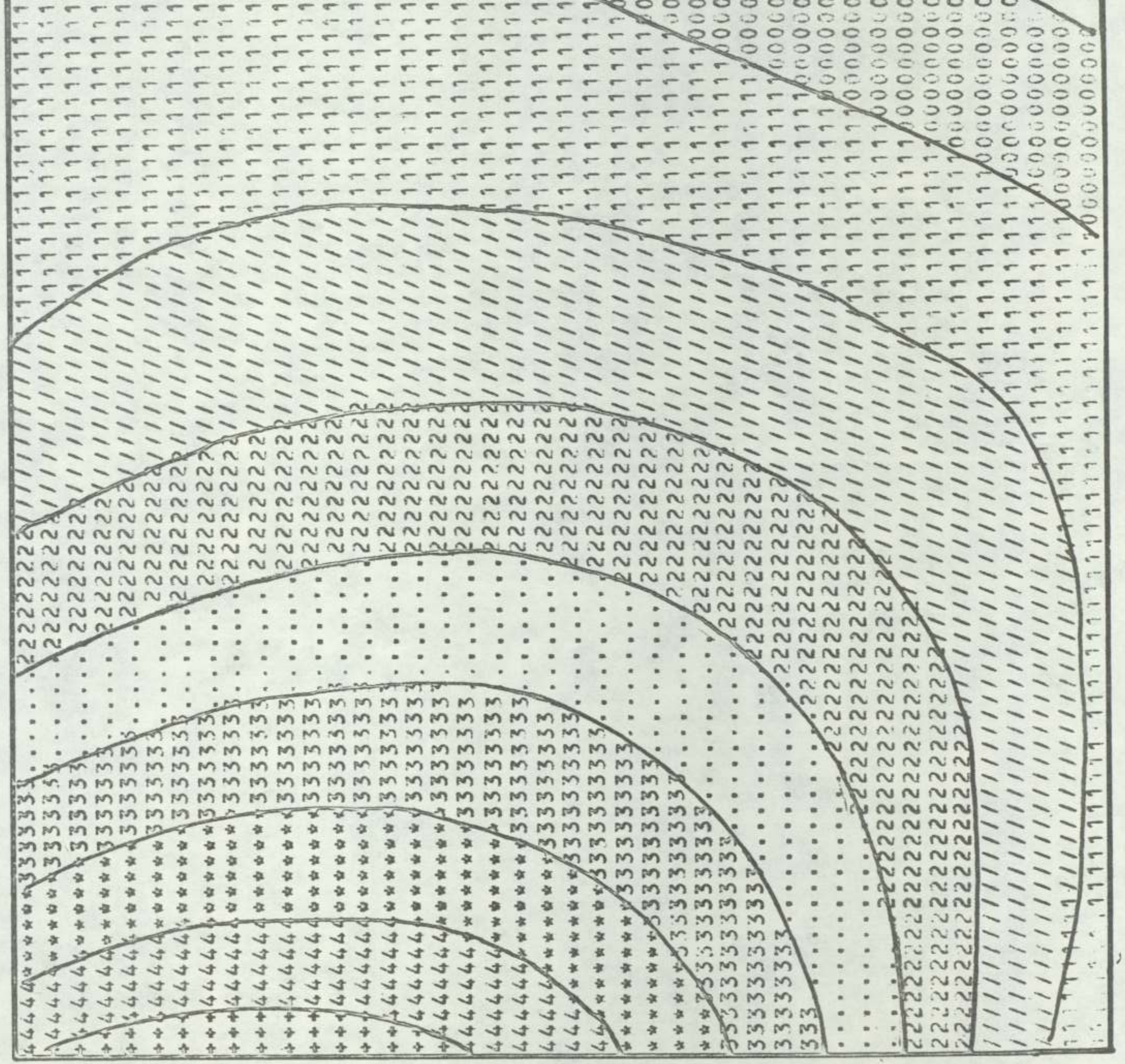
Fig. 8.7



TEST C_1

FOURIER ANALYSIS - FULL FIT

FIG. 8.8

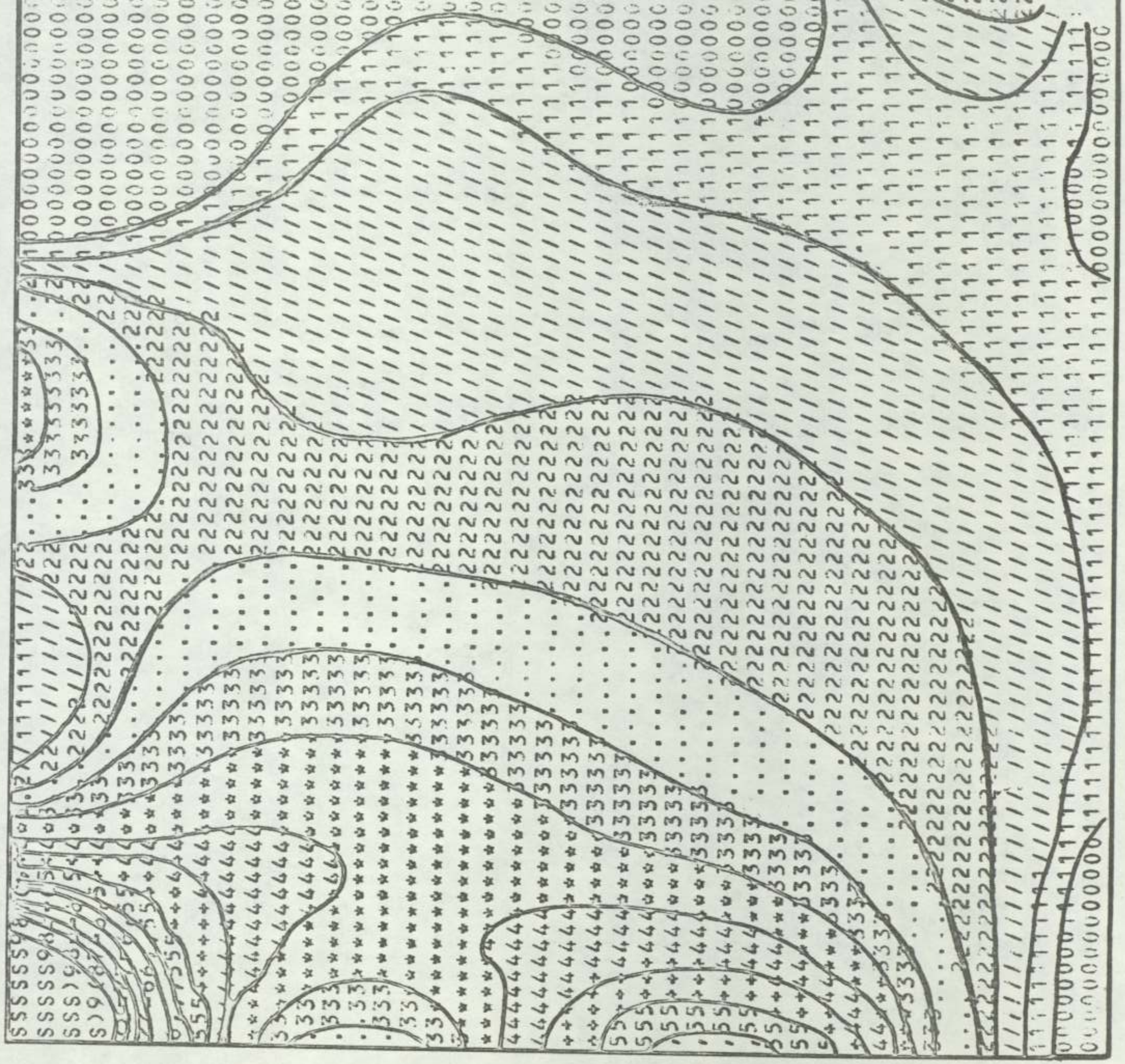


Test A_2

Fourier Analysis - Trend Surface

Fig. 8.9

0	100.0000
1	200.0000
/	300.0000
2	400.0000
.	500.0000
3	600.0000
*	700.0000
4	800.0000
+	900.0000
5	1000.0000
,	1100.0000
6	1200.0000
-	1300.0000
7	1400.0000
=	1500.0000
8	1600.0000
(	1700.0000
9	1800.0000
)	1900.0000

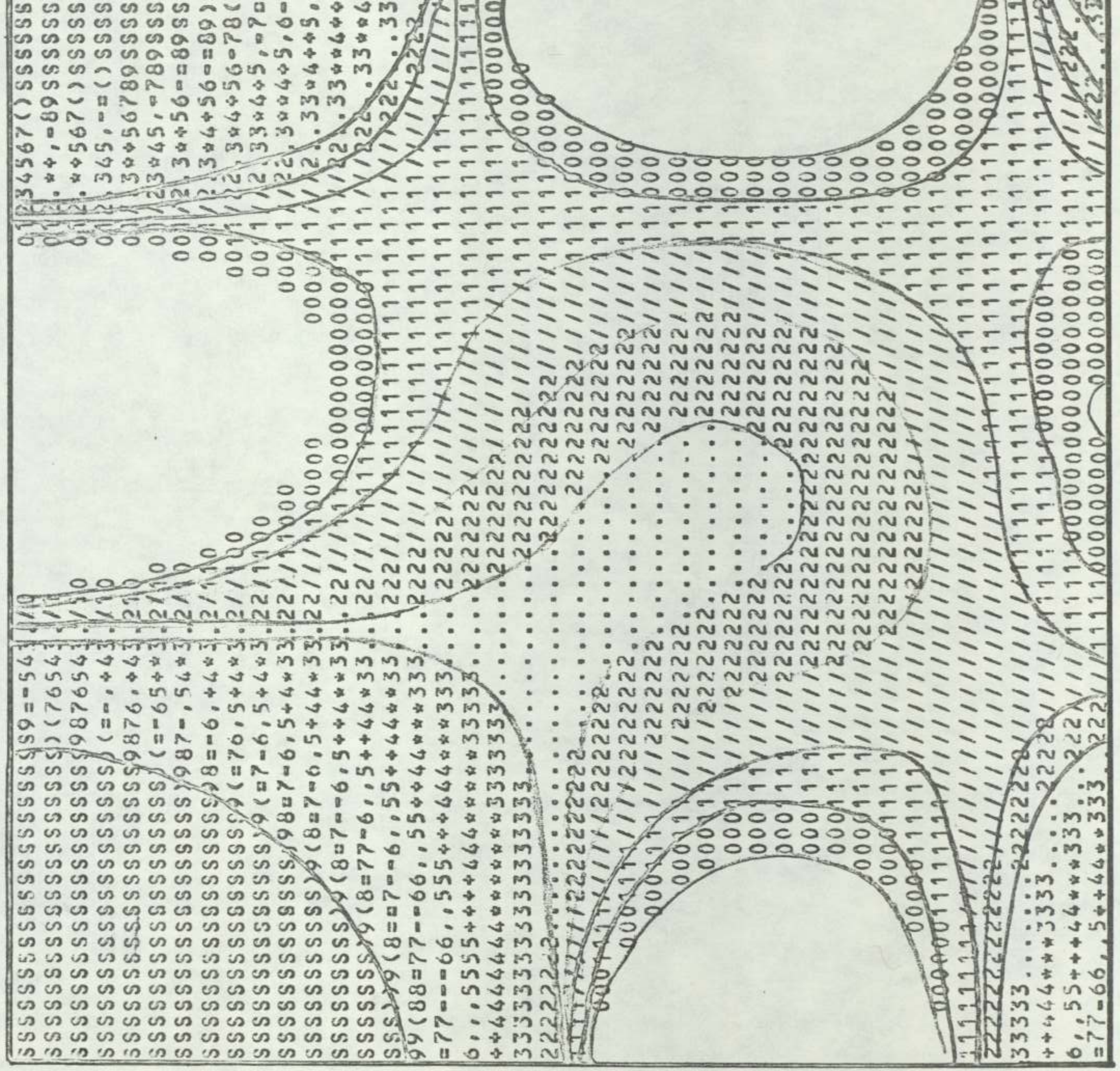


TEST A_2

FOURIER ANALYSIS - FULL FIT

FIG. 8.10

SYMBOL	MAX VAL
0	100.0000
1	200.0000
/	300.0000
2	400.0000
.	500.0000
3	600.0000
*	700.0000
4	800.0000
+	900.0000
5	1000.0000
,	1100.0000
6	1200.0000
-	1300.0000
7	1400.0000
=	1500.0000
8	1600.0000
(	1700.0000
9	1800.0000
)	1900.0000



TEST B_2

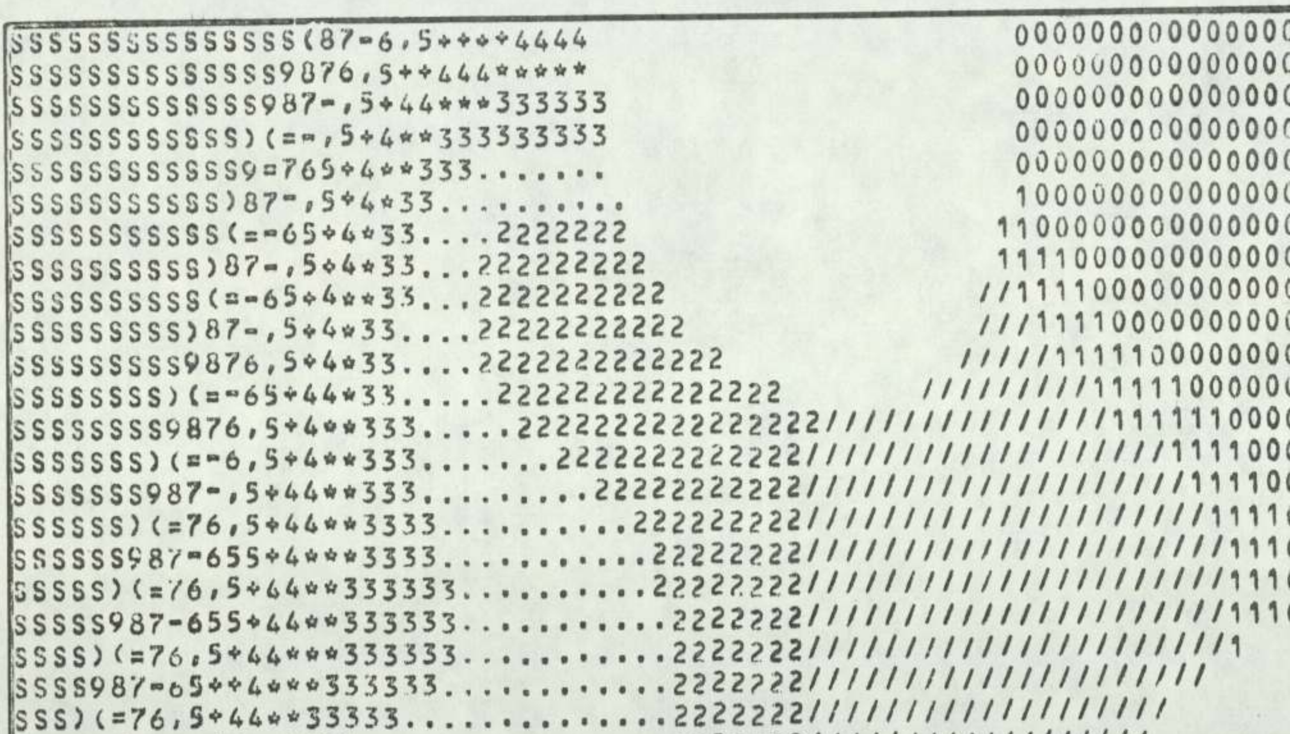
FOURIER ANALYSIS - TREND SURFACE

FIG. 8.11

Test B_2

Fourier Analysis - Full Fit

Fig 8.12



```
SSSSSSSSSSSSSSS(87-6,5+++4444                   00000000000000
SSSSSSSSSSSSSS9876,5++444*****                  00000000000000
SSSSSSSSSSSSS987-,5+44***333333                 00000000000000
SSSSSSSSSSSS)(=-,5+4**333333333                 00000000000000
SSSSSSSSSSSS9=765+4**333.......                 00000000000000
SSSSSSSSSSS)87-,5+4*33..........                10000000000000
SSSSSSSSSSS(=-65+4*33....2222222               110000000000000
SSSSSSSSSS)87-,5+4*33...222222222              111100000000000
SSSSSSSSSS(=-65+4**33...2222222222            //11110000000000
SSSSSSSSS)87-,5+4*33....22222222222           ///1111000000000
SSSSSSSSS9876,5+4*33....222222222222         /////111110000000
SSSSSSSS)(=-65+44*33.....22222222222222     /////////111110000
SSSSSSSS9876,5+4**333.....22222222222222////////////////1111110000
SSSSSSS)(=-6,5+4**333.......222222222222////////////////////111100
SSSSSSS987-,5+44**333.........2222222222////////////////////11110
SSSSSS)(=76,5+44**3333.........22222222/////////////////////1111
SSSSSS987-655+4***3333..........2222222/////////////////////111
SSSSS)(=76,5+44**333333.........2222222/////////////////////111
SSSSS987-655+44**333333..........222222/////////////////////111
SSSS)(=76,5+44***333333..........222222/////////////////////1
SSSS987-65++4***333333...........222222////////////////////
SSS)(=76,5+44**33333.............222222///////////////////
   987-,5+44**3333...............2222222//////////////////
       ,5+4**333................22222222//////////////////
         4**333.................2222222//////////////////
           33..................222222222/////////////////
             ....222222222222222222222///////////////////
              .222222222222222222222////////////////////
              2222/////222222222222222//////////////////
              22///////////////2222/////////////////////
              //////////////////////////////////////////
              ///1111111///////////////////////////////
             ///11111111111111/////////////////////////
           2//11111111111111111/////////////////////////
        *3.2//11111101111111111111111111//////////////////
   (765+*3.2//1111000000111111111111111111111///////////////1
SSS9=-,+4*..2//111000000000111111111111111111111111///////////////1110
SSS)(765+*3.22/11111000000011111111111111111111111111//////////111100
SSSS98-,54*3.2///1111111111111111111111111111111111111///11111000
SSSSS(=-,+4*3.22//11111111111111111111111111111111111111111110000
SSSSS)(76,+4*3..22///111111111111111111111111111111111111111000000
SSSSSS)876,+4*33..22//////////1111111111   111111111110000000000000
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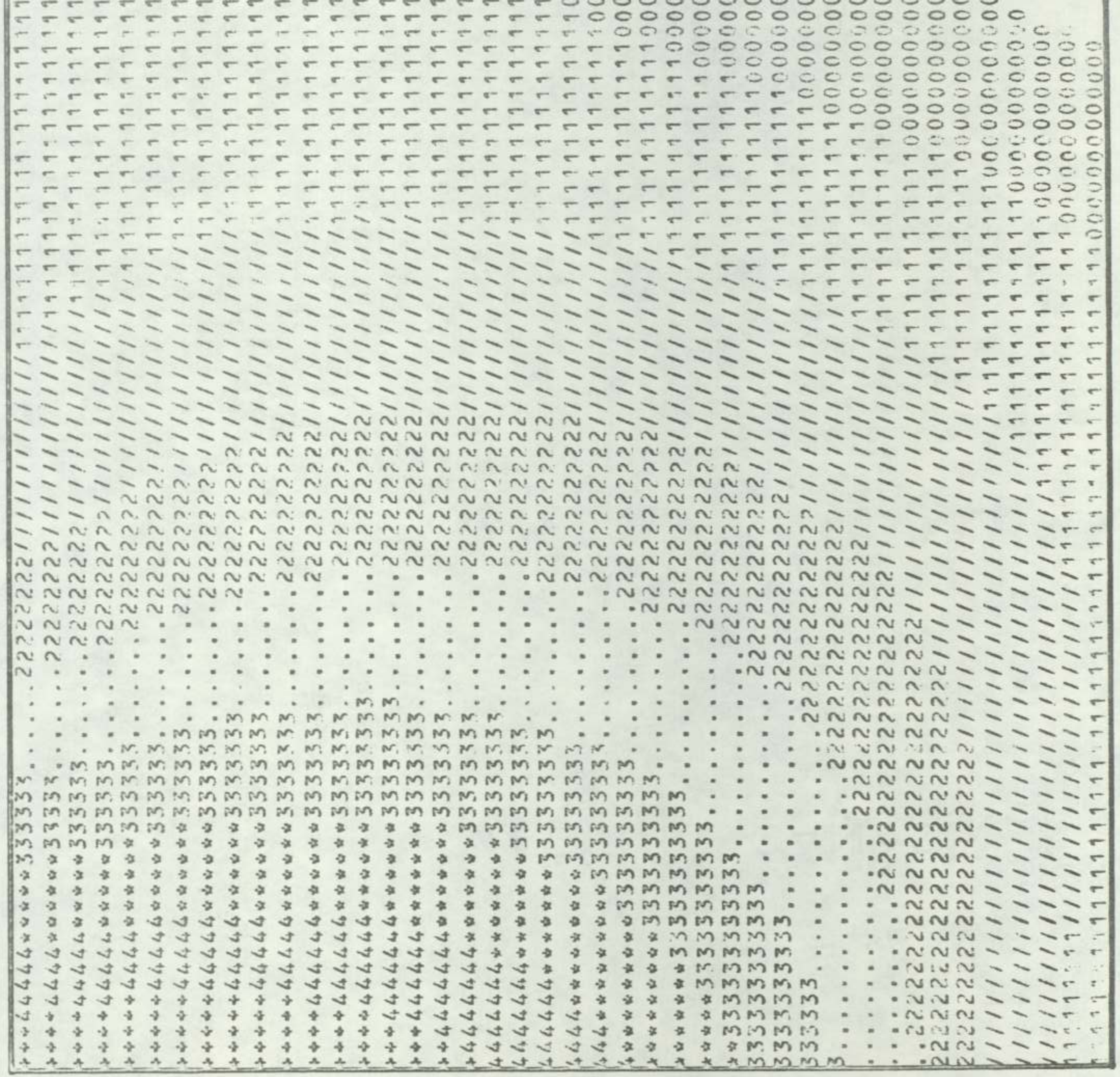
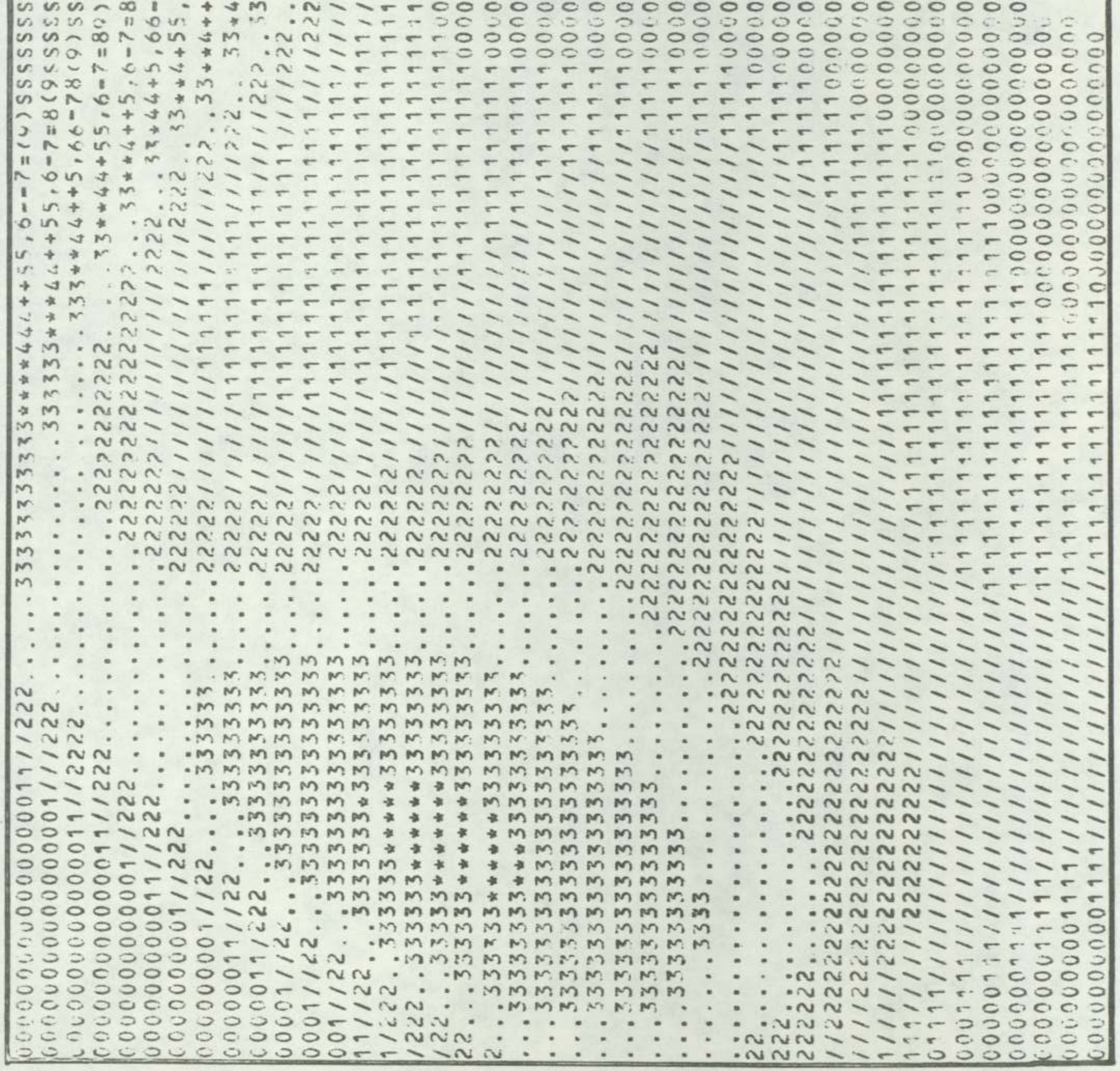


Test C_2

Fourier Analysis - Trend Surface

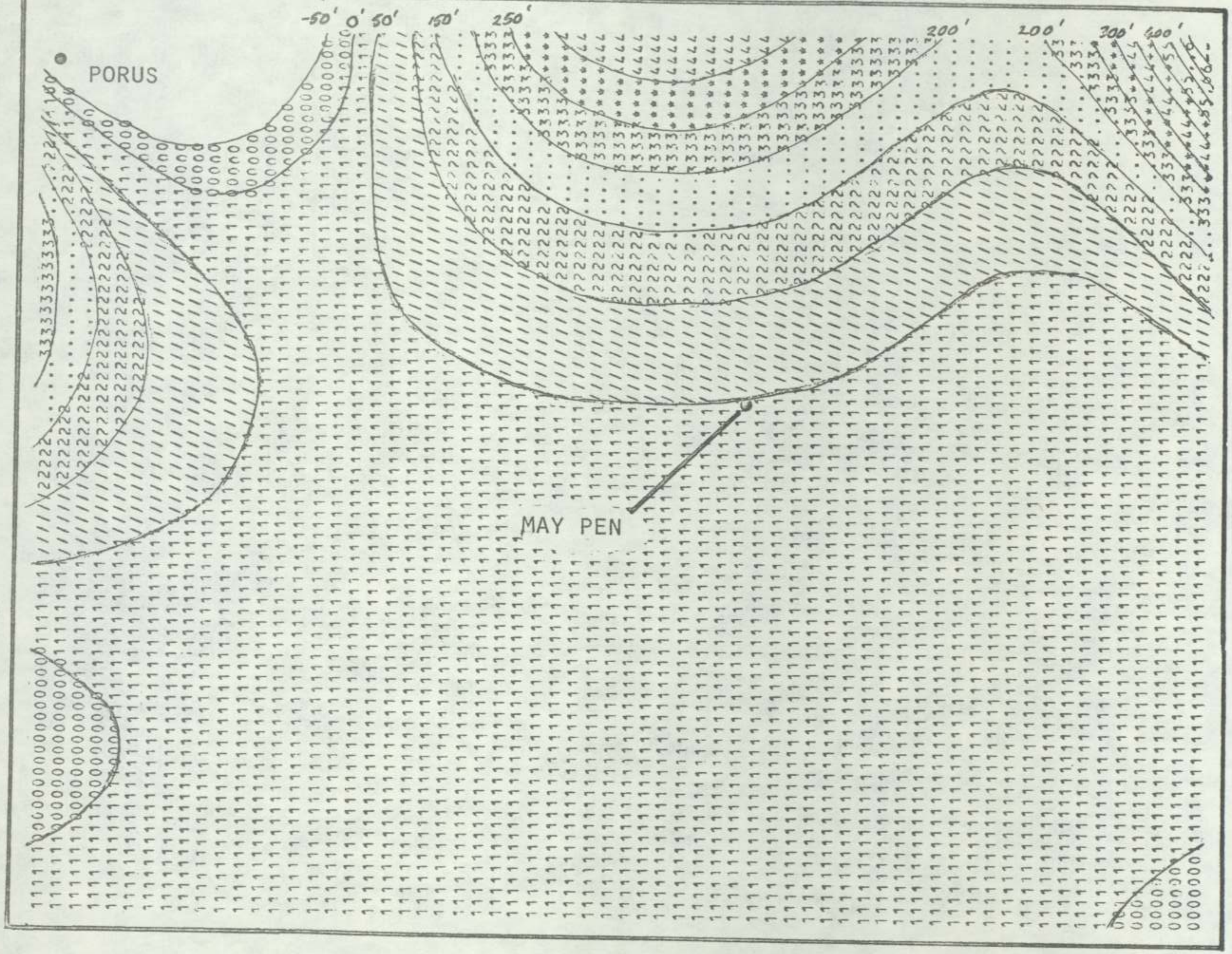
Fig. 8.13



Test C_2

Fourier Analysis - Full Fit

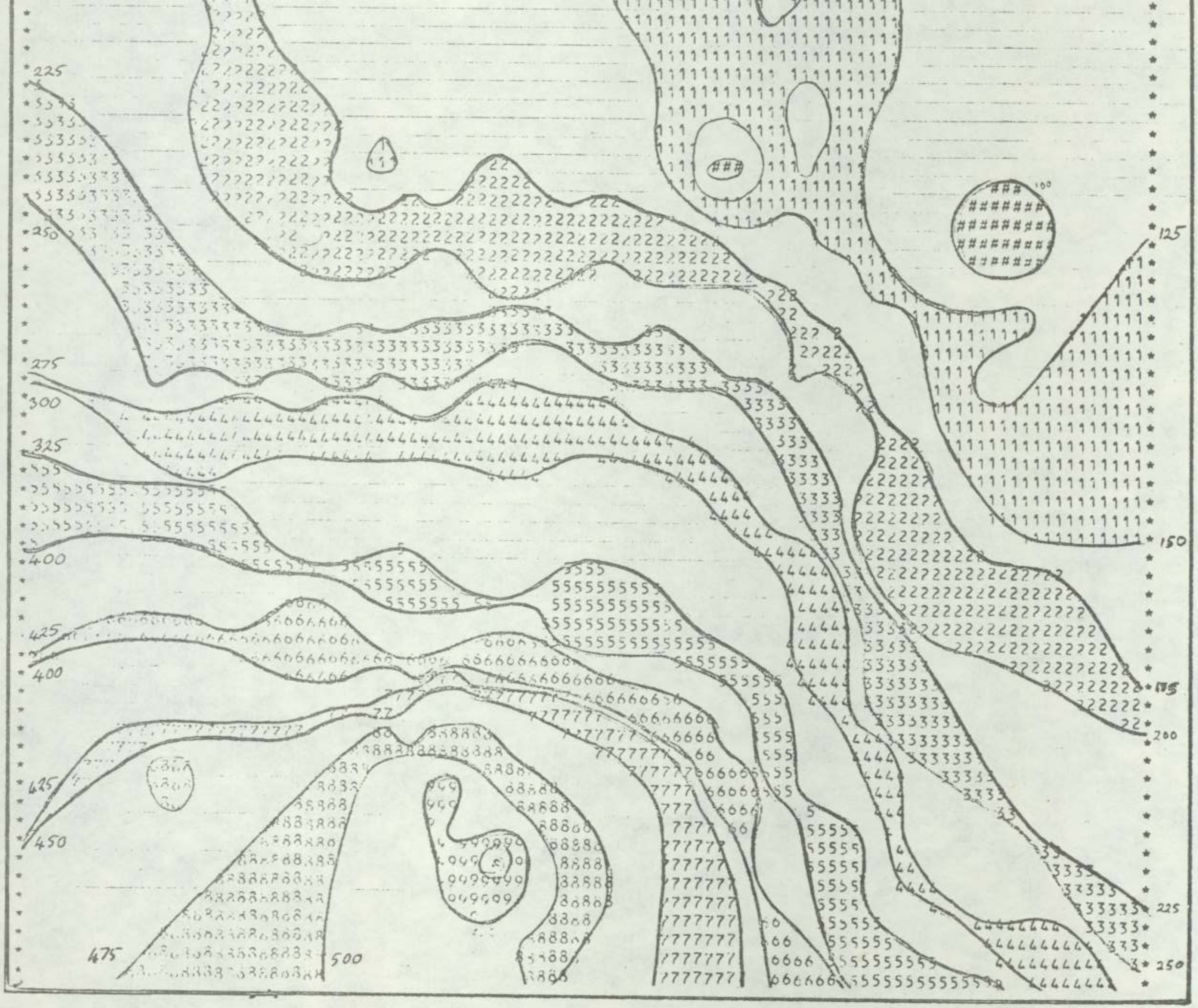
Fig. 8.14



TREND SURFACE MAP OF
LIMESTONE WATER LEVELS
IN CLARENDON PLAINS,
PRODUCED BY FOURIER
ANALYSIS.

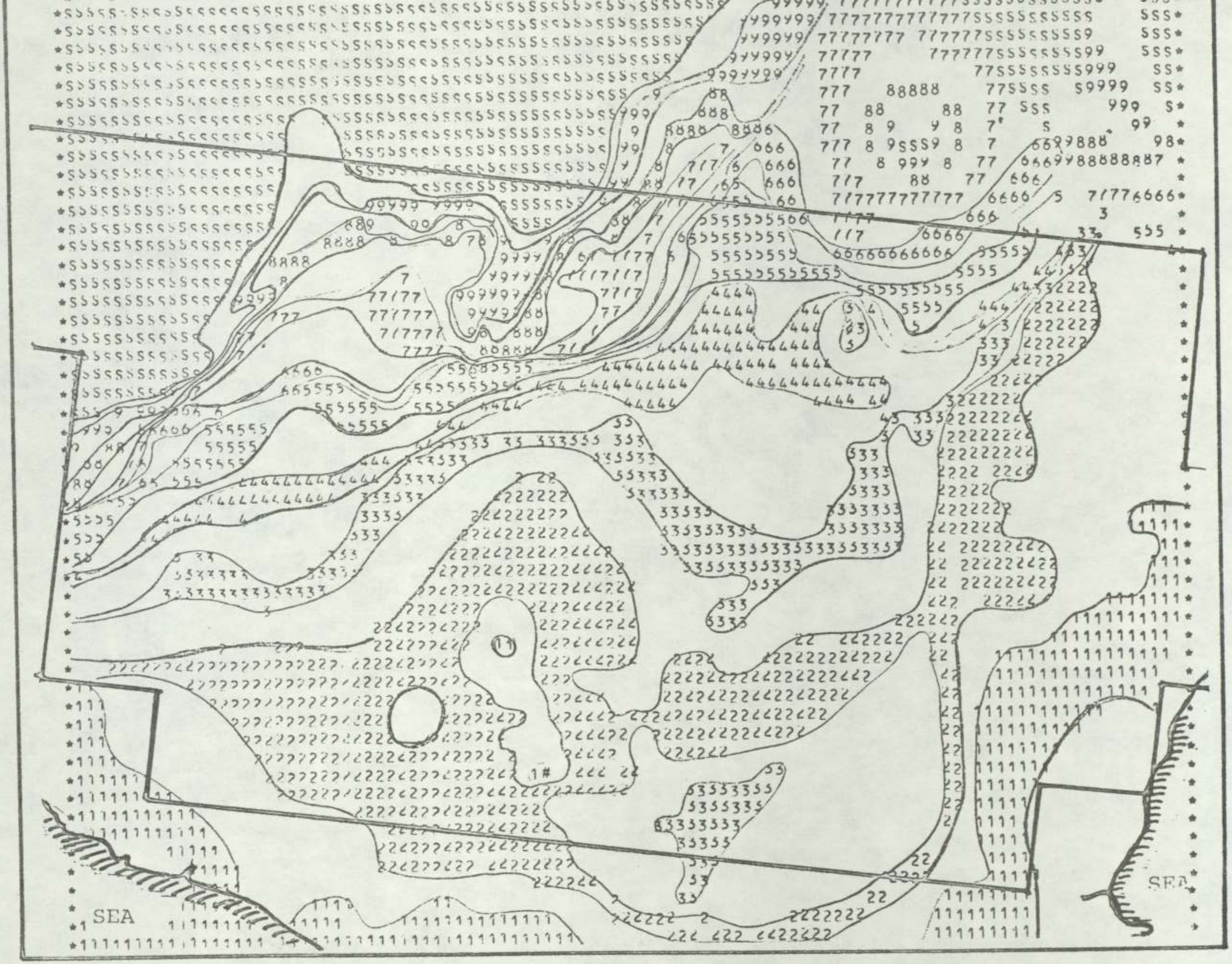
Contour interval 50 Ft.
Scale 1:200,000

FIG. 8.15



MAP OF CHLORIDE CONTENT
PRODUCED BY GRID METHOD
CONTOURING PROGRAM

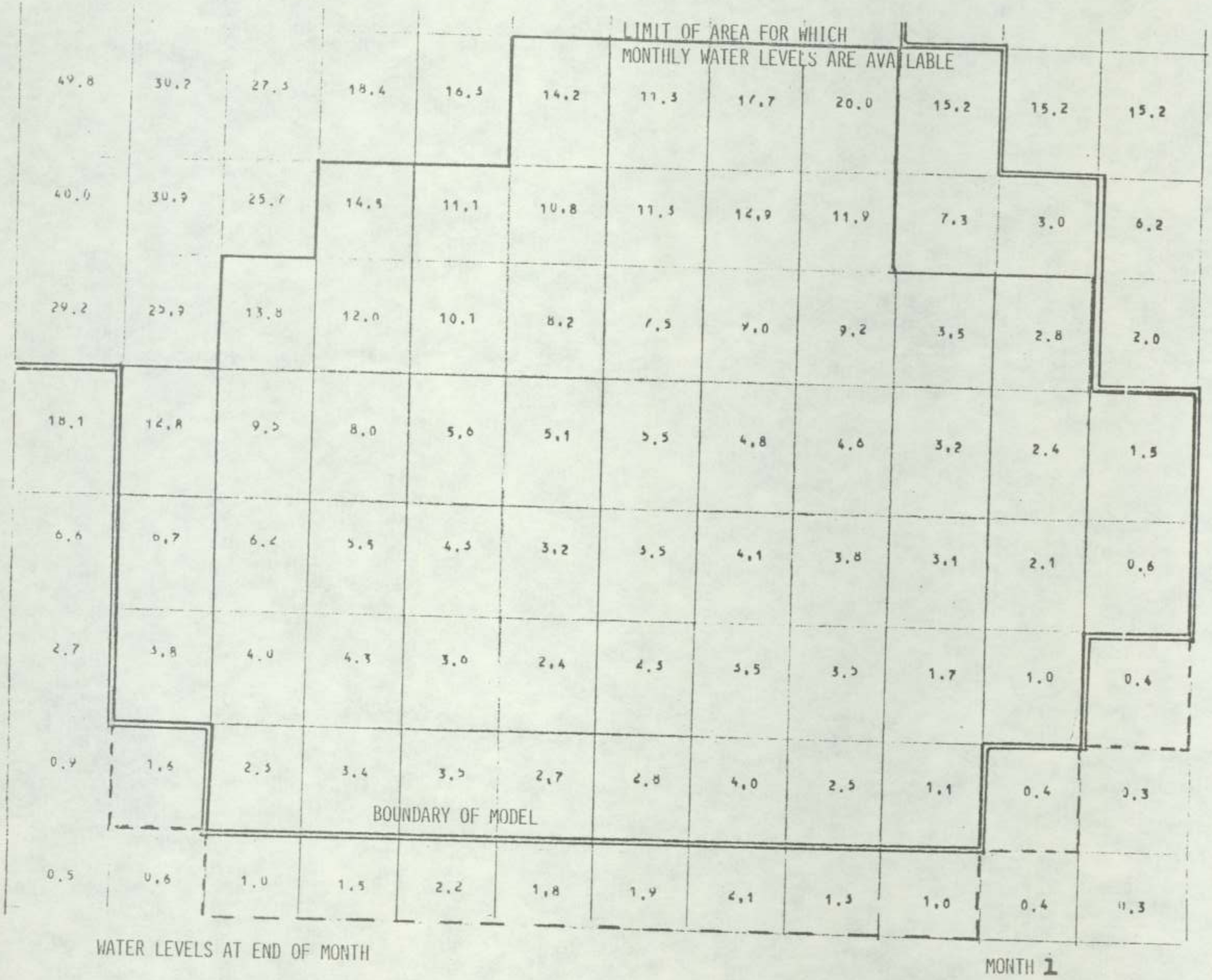
FIG. 8.16



LIMESTONE WATER LEVELS
FOR CLARENDON PLAINS,
PRODUCED BY COMPUTER
CONTOURING PROGRAM
(GRID METHOD)

Contour intervals 3 Ft.
Scale 1:200,000
Outline of southern
nodes of GW model shown

FIG 8.17



49.8	30.2	27.5	18.4	16.5	14.2	11.5	17.7	20.0	15.2	15.2	15.2
40.0	30.9	25.7	14.9	11.1	10.8	11.5	12.9	11.9	7.3	3.0	6.2
29.2	25.9	13.8	12.0	10.1	8.2	7.5	9.0	9.2	3.5	2.8	2.0
18.1	12.8	9.5	8.0	5.6	5.1	5.5	4.8	4.6	3.2	2.4	1.5
6.6	6.7	6.2	5.5	4.5	3.2	3.5	4.1	3.8	3.1	2.1	0.6
2.7	3.8	4.0	4.3	3.0	2.4	2.5	3.5	3.5	1.7	1.0	0.4
0.9	1.6	2.5	3.4	3.5	2.7	2.8	4.0	2.5	1.1	0.4	0.3
0.5	0.6	1.0	1.5	2.2	1.8	1.9	2.1	1.3	1.0	0.4	0.3

WATER LEVELS CALCULATED BY CONTOURING PROGRAM FOR INPUT TO GROUNDWATER MODEL.

FIG. 8.18

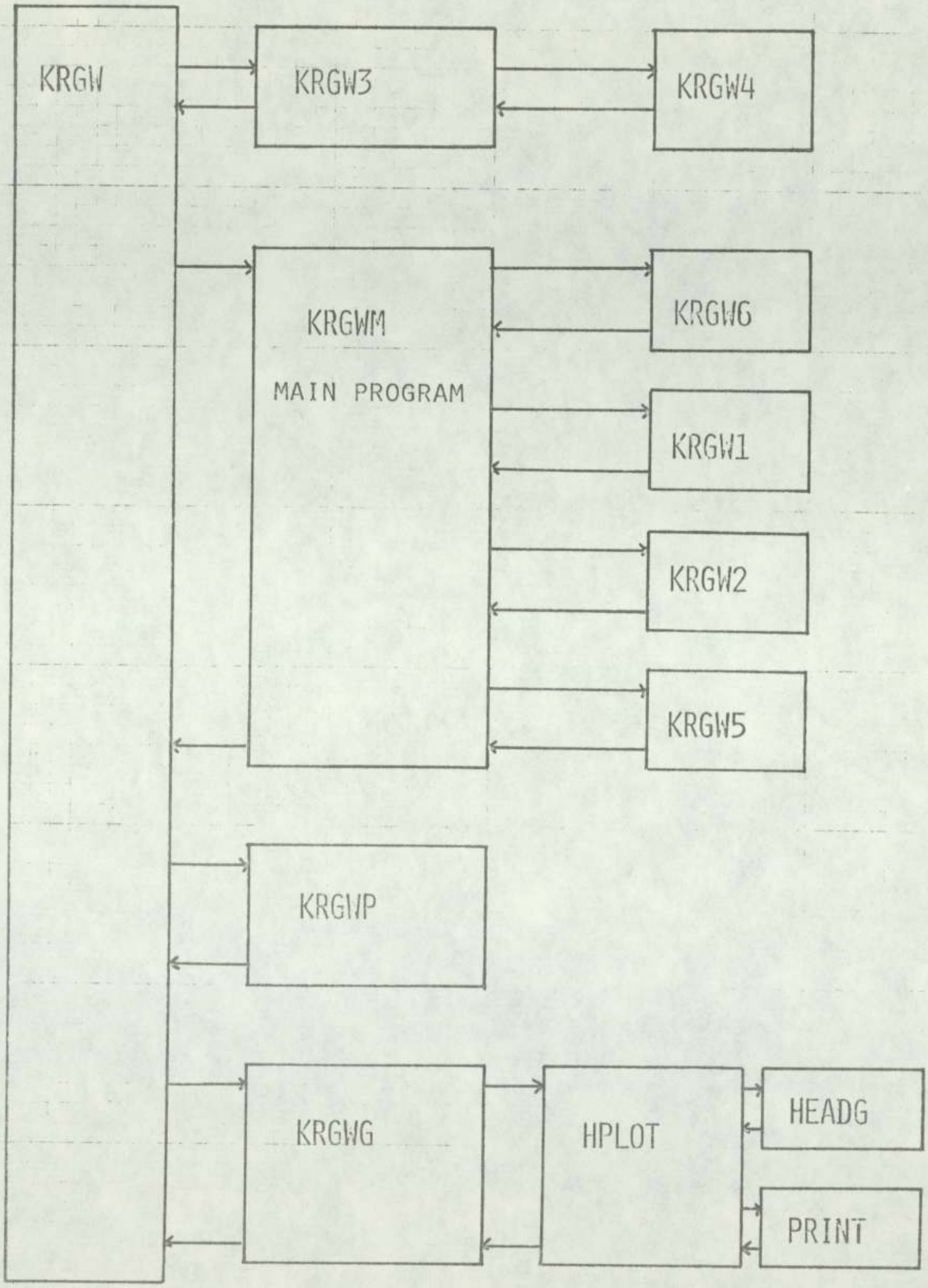


FIG. 8.19 PROGRAM KRGW

9 WATER RESOURCES APPRAISAL

9.1 Introduction

In earlier sections of this thesis it was shown that a salinity problem exists in the limestone aquifer of the Clarendon Plains. It was further shown that this problem is more severe in the eastern half of the southern plains and that the north-south fault probably plays a part in restricting the flow of fresh groundwater.

The computer simulation confirmed this theory and indicated that, whereas the eastern half is overdeveloped, there appears to be surplus groundwater in the western half of the plains. As the model only covered a 12-month period, however, it was decided to carry out a manual calculation covering the 16-year period for which recharge data is available.

9.2 Groundwater Balance

Within the plains where the main limestone aquifer is found, it can be considered as consisting of three units which, though not entirely separate, are at least distinct. The units are shown in Fig. 9.1 and have been labelled A, B and C.

Unit A is by far the largest and is separated from B by the supposed fault which runs NNW from Kemps Hill to west of May Pen. Unit B is, in turn, separated from unit C by the groundwater divide which runs southward along the western edge of Harris Savannah and the Brazilletto Hills.

The direction of groundwater flow can be determined from the groundwater contour map and thus the catchments which contribute to each unit can be defined. It can be seen that all of catchments 2 and 5, and virtually all of catchment

6, contribute to unit A, along with most of catchment 4. It is unlikely, however, that much infiltration takes place over catchment 6, due to the fact that most of the area is covered by clayey alluvium. Consequently, the catchment will be omitted from the calculations of recharge to unit A, but compensated for by including all of catchment 4, although some of this contributes to unit B.

Unit B is supplied from catchment 10, plus a small area of catchment 4, and in addition some of the water lost from the Rio Minho above May Pen flows into this unit. The annual contribution from catchment 10 is given in Table 9.1. Based on area and precipitation a rough estimate of 16% was made for the proportion of catchment 4 which contributes to unit B and, with a 16-year mean recharge of 56,000 acre-feet over the whole catchment, this represents about 9,000 acre-feet to unit B. In addition, an estimate of losses from the Rio Minho gave a figure of about 20,000 acre-feet per annum, which is divided between units B and C. Assuming this to be about "half and half" will give an additional 10,000 acre-feet to unit B. It is also possible that some water recharges the limestone in this unit from the Rio Minho below May Pen, by way of the alluvium. From Table 9.1 it can be seen that the average recharge from catchment 10 is 8,000 acre-feet and, added to the other factors outlined above, this gives a total recharge to unit B of more than 30,000 acre-feet, but certainly less than 40,000 acre-feet.

The annual recharge to unit A is also given in Table 9.1 and it can be seen that over the 16-year period, the average recharge was 225,000 acre-feet, the actual totals varying from 130,000 acre-feet in 1968 to 449,000 acre-feet in 1969.

Unit C is not covered in detail in this assessment as it appears to be capable of sustaining the present demand, and is not considered as a source of increased supply to the

YEAR	CATCHMENTS					TOTALS		
	2	4	5	10	6	2+4+5	2+4+5+6	All catch.
1956	150	59	21	7	14	230	244	251
1957	157	41	30	3	14	228	231	245
1958	256	107	69	19	55	432	451	506
1959	109	28	16	2	10	153	155	165
1960	141	61	29	16	33	231	247	280
1961	139	57	20	10	25	216	226	251
1962	141	26	19	2	11	186	188	199
1963	244	70	35	12	15	349	361	376
1964	109	44	23	8	14	176	184	198
1965	127	36	21	5	26	184	189	215
1966	181	47	29	7	20	257	264	284
1967	122	19	14	7	13	155	162	175
1968	105	14	11	3	7	130	133	140
1969	266	131	52	13	31	449	462	493
1970	202	79	36	8	22	317	325	347
1971	107	48	10	3	8	165	168	176
MEAN		54		8		241	249	269

RECHARGE TO LIMEST.
AQUIFER.
THOUSAND ACRE-FEET.

TABLE 9.1

Clarendon Plains.

The annual abstraction of groundwater from the three units are given in Table 9.2 for the years 1969 - 1972 and the mean abstraction from each unit is calculated. It can be seen that the greater proportion of the groundwater is abstracted from unit B whereas the larger unit A contributes significantly less to the overall abstraction figures for this basin. Thus it is obvious that unit B is, at present, overdeveloped, with the mean annual abstraction exceeding the recharge by some 28,000 acre-feet, a fact which explains the decline in quality of the groundwater in the southern part of this unit, as compared with that in unit A.

9.3 Recommendations

From the above calculations, and the results of the computer simulation, it would appear that production from groundwater unit B should be reduced by some 30,000 acre/feet per year. In order to maintain agricultural production, however, it will be necessary to obtain this water from alternative sources. Here again, both the manual calculations and the computer simulation indicate that this water can be obtained by drilling additional boreholes in the northern part of groundwater unit A.

9.4 Conclusions

The salinity problem in the White Limestone Aquifer of the Clarendon Plains, severe though it is, does not present a hopeless picture. The available evidence suggests that the problem, on a regional scale, is one of bad development rather than overdevelopment. Part of the available surplus of water can, given a sound basin management policy, be utilized to make up any deficit arising from the abandonment of saline wells. With regard to this abandoning of wells, it

GROUNDWATER UNIT	1969-70	1970-71	1971-72	MEAN
	Million U.S. Gallons			Acre-Ft.
A	13,482	13,806	18,827	48,000
B	17,408	20,374	22,824	68,000*

*New wells allowed for.

Table 9.2 Abstraction of Ground Water

is suggested that those shown in Fig. 9.2, if still in operation, be shut down as soon as possible.

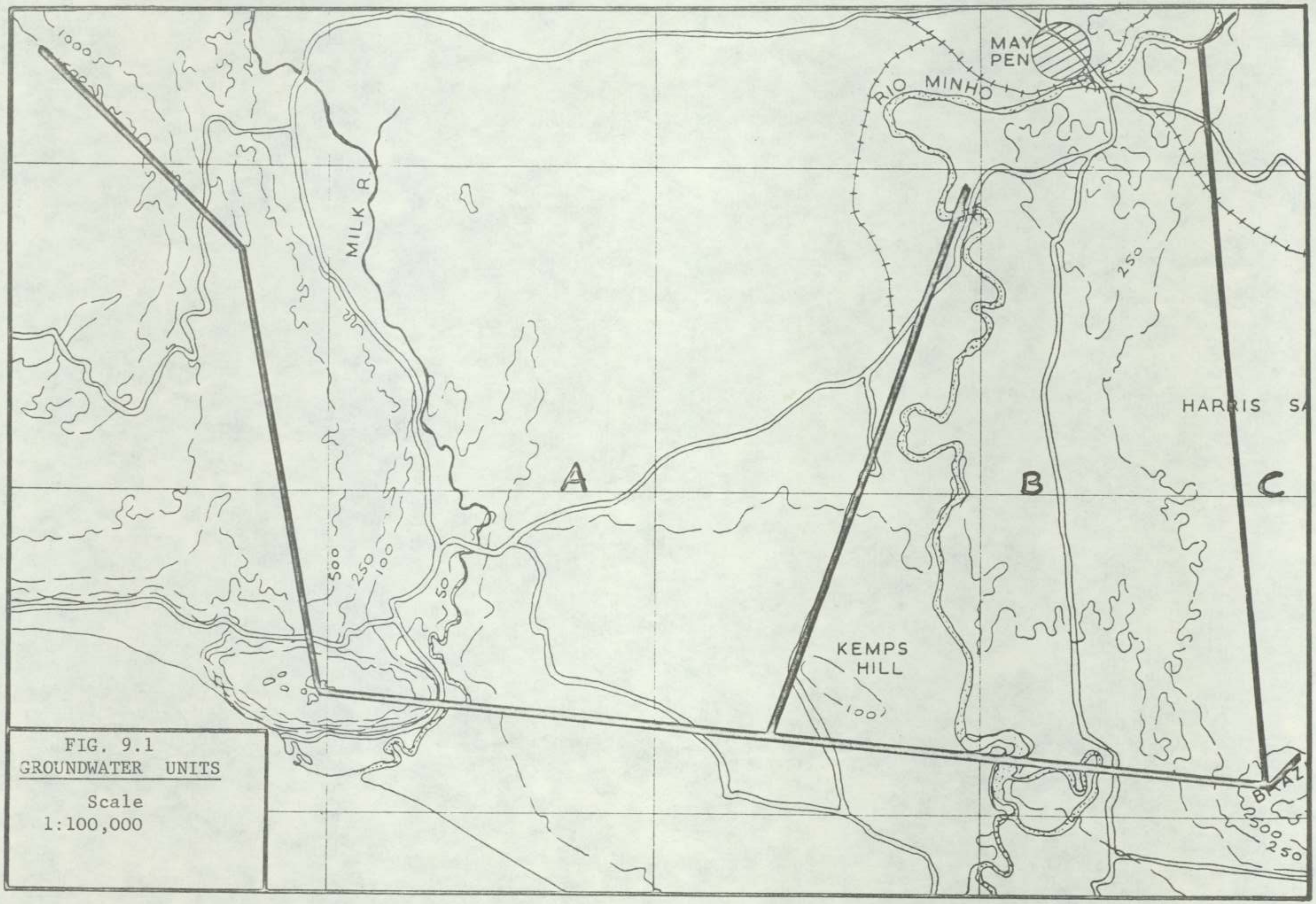
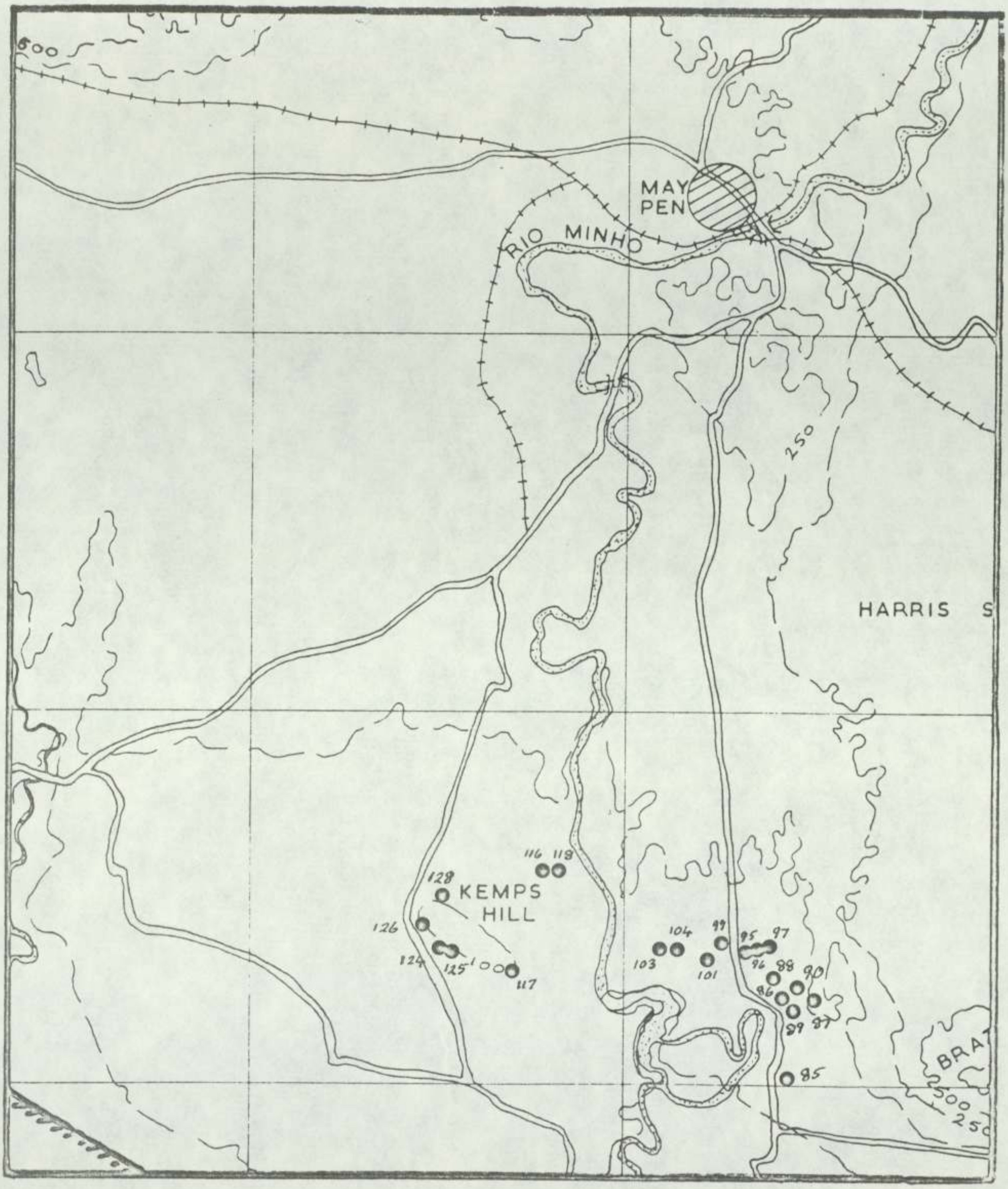


FIG. 9.1
GROUNDWATER UNITS

Scale
1:100,000



LIMESTONE WELLS WHICH SHOULD BE ABANDONED.

FIG. 9.2

BIBLIOGRAPHY

Archie, D. (1952), Classification of carbonate reservoir rocks and Petro-physical considerations, Am.Assoc. Petrol Geol. Bull. vol. 70, pp.1019 - 1032.

Atkinson, T.C. and Smith, D.I., Rapid groundwater flow in fissures in the chalk : An example from South Hampshire, Quarterly Journal of Engineering Geology, vol. 7, no. 2, pp. 197-205

Bamber, H.A., (1951), Some factors affecting the solubility of limestone in natural waters, Cave Science, vol. 2, pp. 139 - 161.

Brown, R.H. et al, (1972), Groundwater studies - An international guide for research and practice, The Unesco Press.

Burdon, D.J., and Mazloum, S. (1958), Some chemical types of groundwater from Syria. Salinity problems in arid zones. Unesco Symposium, Teheran.

Cederstrom, D.S. (1946), Genesis of groundwater in the coastal plains of Virginia, Economic Geology, no. 41, pp. 218 - 245.

Chidley, T.R.E. (1971), Report on computer procedures and programs for the analysis of project data, Raikes and Partners, Report to the sandstone aguifers project of East Jordan. UNDP/FAO Project no. 212.

Chilingar, G.V. (1956), Durov's classification of natural waters and chemical composition of atmospheric precipitation in U.S.S.R. Trans. Am. Geophys. Un. 37, pp. 193 - 196.

Cole, A.J. (1969), Proceedings of St. Andrews Colloquium in Numerical Toxonomy 1968, Academic Press.

Davis, J.C. (1973), Statistics and data analysis in geology, John Wiley & Sons.

Davis, S.N. (1966), Initiation of groundwater flow in jointed limestone, Nat. Speleol. Soc. Bull, vol.28, no. 3, pp. 111 - 117.

Davis, S.N. and de Weist, R.J.M. (1966), Hydrogeology, John Wiley & Sons,p.463.

De Weist, R.J.M. (1965), Geohydrology, John Wiley & Sons, p. 366.

Downing, R.A. and Williams, B.P. (1969), The groundwater hydrology of the Lincolnshire limestone, Water Res. Board PVB, no.9, p.160.

Durov, C.A. (1948), Proceedings of Academic Science, U.S.S.R., vol. 59, no.1, p. 87.

FAO - UNDP, (1971), A groundwater investigation in two areas of the interior - Jamaica, FAO - UNDP Special Fund Project.

Foster, M.D. (1967), Base exchange and sulphate reduction in salty groundwater along Atlantic and Gulf coasts, Am. Ass. Petr. Geol. vol. 26, no. 5, pp.838 - 851.

Fox, I.A. and Rushton, K.R., Rapid recharge in a limestone aguifer, Groundwater, vol. 14, pp. 21 -27.

Goodwill, I.M. (1971), Study of the water resources and exploration for irrigation in Eastern Crete, Greece, Raikes and Partners for FAO, FAO/SF 166/6RE.

Grund, A. (1914), Der Geographische Zyklus im Karst, Z. Ges. Frdk d. Berlin, pp. 621 -640.

Hall, A.V. (1969), Group forming and discrimination with homogeneity functions, Proceedings of St. Andrews Colloquium in Numerical Toxonomy (1968) Academic Press.

Harbaugh, J.W., and Merriam, D.F. (1968), Computer Applications in Stratigraphic Analysis, John Wiley and Sons.

Hem, J.D., (1959), Study and interpretation of the chemical characteristics of natural water, U.S.G.S. Water Supply Paper, 1473.

Herak, M., and Stringfield, V.T., (Editors) Karst, important regions of of the Northern Hemisphere, Elsevier, Amsterdam.

Herbertson, (1972), Surface water hydrology of the Rio Minho - Milk River Basin, Internal report of FAO-UNDP Water Resources Project, Government of Jamaica.

Hose, H.R. and Versey, H.R. (1956), Paleolontogical and lithological divisions of the lower tertiary limestones of Jamaica, Colloquium Geol. Min. Res. no. 6, pp. 19 - 39.

Hubbert, M.K. (1940), The Theory of groundwater movement , Journal of Geology vol. 48, no. 8, Part 1, Nov. Dec., 1940.

Hubbert, M.K.(1957), Darcy's law and field equations of the flow of underground fluids, Bulletin de l'Association d'Hydrologie Scientifique, no. 5.

Huie, and Ramdial (1971), Internal Irrigation Report, West Indies Sugar Co. Unpublished.

Ineson, J. and Downing, R.A. (1963), Changes in the chemistry of groundwater of the chalk passing beneath argillaceous strata, Bull of Geol.Soc. of G.B. no. 20, pp 176 - 192.

James, W.R., The Fourier Series Model in Map Analysis, U.S. Office of Naval Research, Geog. Branch, Tech. Rep. no. 1.

Law, J.P. et al,(1970), Degradation of water quality in return flows, Bulletin B-684, Water Research Center, Oklahoma State University.

Lawrence, A.R., Lloyd, J.W., and Marsh, J.M. (1976), Hydrochemistry and groundwater mixing in part of the Lincolnshire limestone aguifer, England. Groundwater, vol. 14, no. 5, pp. 320 - 327.

Le Grand, H.E. and Stringfield, V.T. (1973), Karst Hydrology - A Review , Journal of Hydrology, vol. 20, no. 2, pp.97 - 120.

Leonard, R.B., (1970), Effects of irrigation on the chemical quality of ground- and surface waters, Cedar Bluff Irrigation District, Kansas, Cornell University Conf. on Agriultural Waste Management pp. 147 - 163.

LLoyd, J.W. (1965), The Hydrochemistry of the Aguifers of Nort-Eastern Jordan, Journal of Hydrology, no. 3, pp. 319 - 330.

Logan, J. (1961), Estimation of Electrical Conductivity from Chemical Analysis of Natural Waters, Jour. of Geophys. Res. vol.66, pp. 2479 - 2483.

MacFarlane, N. (1972), Report on the geology of the Rio Minho - Milk River Basin, Internal Report, FAO - Govt. of Jamaica, Water Res. Proj.

Matley, C.A. (1924), Report by the Government Geologist, Supplement to the Jamaica Gazette, no. 47.

Meinzer, O. (1923), Outline of groundwater hydrology with definitions, U.S.G.S. Water Supply Paper 494 p. 71.

Miller, J.P. (1952), A portion of the system Calcium Carbonate- Carbon Dioxide- Water with geological implications, Am. Jour. of Sc. vol. 250 pp. 161 - 203.

Palker, G.G. and Stringfield, V.T. (1950), Effect of earthquakes, trains, tides, winds and atmospheric pressure changes on water in the geologic formations of Southern Florida, Econ. Geol. vol. 45, pp. 441 - 460.

Parks, G.M. (1972), Cluster analysis applied to multivariate geologic problems,.

Piper, A.M. (1944), A graphic procedure in the geochemical interpretation of water analyses, Trans. Am. Geophys. Union, vol. 25, pp. 914 - 923.

Robinson, T.W. (1939), Earth tides shown by fluctuations of water levels in wells in New Mexico and Iowa, Am. Geophys. Union Trans. vol. 20, pp. 656 -666.

Rushton, K.R., and Booth, S.J., Pumping test analysis using a discrete time-discrete space numerical method, Jour. of Hydr. vol. 28, pp.13 - 28.

Rushton, K.R. and Tomlinson, L.M. (1971), Digital Computer Solutions of Groundwater flow , Jour. of Hydrol. no. 12, pp. 339 - 362.

Rushton, K.R., (1973), Discrete time steps in digital computer analysis of aguifers containing pumping wells, Jour. of Hydrol. no. 18, pp. 1-19.

Rushton, K.R. and Wedderburn, L.A. (1973), Starting conditions for aguifer analysis, Ground Water no. 11, pp. 37 - 42.

Shuster, E.T. and White, W.B. (1971), Seasonal fluctuations in the chemistry of limestone springs : A possible means for characterising carbonate aguifers, Jour. of Hydrol. no. 14, pp. 93 - 128.

Sweeting, M.M., (1958), The Karstlands of Jamaica, Geograph. Jour. no. 124, pp. 184 - 199.

Sweeting, M.M. (1972), Karst Landorms, The Macmillan Press, p. 362.

Taylor, S.A.G. (1939 and 1944), Irrigation of the Plains of Clarendon by Borehole Wells, Internal Reports, Government of Jamaica.

Taylor, S.A.G. (1954), An account of the development of the water resources of the Clarendon Plains, Internal Report, Government of Jamaica.

Taylor, S.A.G. (1965), The early development of underground water in Jamaica, Bull of Science Research Council, Jamaica, vol. 6, no.1.

Todd, D.K., (1966), Ground water hydrology, John Wiley & Sons, p.336.

Tyson, H.N. and Weber, E.M. (1963), Use of electronic computers in simulation of the dynamic behaviour of groundwater basins, Am. Soc. Civ. Eng., Water Res. Eng. Conf. Milwaukee.

Versey, H.R. (1956), The Ipswich limestone of Jamaica and its structural significance, Contribution to the XX Jnt. Geol. Congress, Mexico.

Versey, H.R. (1959), The hydrologic character of the white limestone formation of Jamaica, Trans. of the 2nd. Caribbean Geol. Conf.,P.Rico.

Versey, H.R. (1962), Older Tertiary Limestones, in Synopsis of the Geol. of Jamaica, Geol. Survey Dept. Kingston.

Versey, H.R. (1971), Report of the National Water Authority on the Selection of a Borehole Location in South Manchester (Unpublished).

Versey, H.R. (1972), Karst of Jamaica, See Herak & Stringfield, 1972.

Versey, H.R. and Prescott, G.C. (1956), Progress report on geology and groundwater resources of the Clarendon Plains Jamaica, W.I., Geol. Survey Dept. Occ. Paper No. 1.

Vincenz, S.A. (1959), Some observations on gamma radiation emitted by a mineral spring in Jamaica, Geophys. Prospecting, vol.VII, no. 4.

Whittaker and Thresh (1916), Water Supply of Essex, Memoir of Geol. Survey (Great Britain).

Wirtz, R. (1970), Final Report to FAO on Completion of Assignments to Jamaica, Unpublished.

Wishart, D. (1969), Mode Analysis : A generalisation of nearest neighbour which reduces chaining effect, Proceedings of St. Andrews Colloquium in Numerical Taxonomy, 1968. Academic Press.

Wozab, D. et al (1972), Report on the Water Resources of the Pedro Plains, Jamaica, FAO-UNDP Special Fund Project.

Zans, V.A. (1955), Water supply conditions in the Karstlands of Jamaica, Proceedings of the 1st. Caribbean Geol. Conf. Antigua.

APPENDIX

Well	Date	EC	pH		Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	Hard	Alk.	TDS
96	3/68	1350.	7.1	PPM	101.0	38.0	125.0	9.0	390.1	25.0	210.0	4.0	408.0	320.0	801.0
				EPM	5.03	3.12	5.43	0.23	6.39	0.52	5.92	0.06			
100	3/68	1560.	7.2	PPM	142.4	27.4	162.0	8.0	412.0	49.0	305.0	1.8	468.0	338.0	1109.0
				EPM	7.10	2.25	7.04	0.20	6.75	1.02	8.60	0.02			
103	3/68	1138.	7.2	PPM	112.0	31.0	120.0	8.5	412.0	28.4	148.0	3.9	406.0	338.0	647.0
				EPM	5.58	2.54	5.22	0.21	6.75	0.59	4.17	0.06			
119	3/68	7680.	6.7	PPM	288.0	136.7	1250.0	24.5	329.1	163.3	2450.0	3.2	1278.0	270.0	5197.0
				EPM	14.37	11.24	54.37	0.62	5.39	3.39	69.08	0.05			
122	3/68	5700.	6.9	PPM	252.0	91.1	687.0	15.5	336.5	98.6	1630.0	4.6	1002.0	276.0	3770.0
				EPM	12.57	7.49	29.88	0.39	5.51	2.05	45.96	0.07			
122	10/68	4650.	[illegible]	PPM	224.0	82.3	{84.0}	12.5	226.7	120.0	1523.0	1.0	896.0	186.0	3654.0
				EPM	11.17	6.76	{3.65}	0.31	3.71	2.49	42.94	0.01			
151	3/68	1440.	7.2	PPM	88.0	67.8	70.0	5.3	338.9	85.0	234.0	0.0	516.0	278.0	1106.0
				EPM	4.39	5.57	3.04	0.13	5.55	1.76	6.59	0.00			
202	3/68	930.	7.2	PPM	9.3	23.5	140.0	6.5	402.3	22.0	95.0	5.0	330.0	330.0	540.0
				EPM	0.46	1.93	6.09	0.16	6.59	0.45	2.67	0.08			
204	3/68	965.	7.1	PPM	100.0	2.4	110.0	7.5	412.0	23.0	107.0	4.9	346.0	338.0	571.0
				EPM	4.98	0.19	4.78	0.19	6.75	0.47	3.01	0.07			
207	3/68	930.	7.1	PPM	93.0	23.5	48.0	7.5	380.3	16.8	87.0	5.1	328.0	312.0	481.0
				EPM	4.64	1.93	2.08	0.19	6.23	0.34	2.45	0.08			
230	3/68	560.	7.4	PPM	76.0	15.2	6.0	6.0	297.4	3.5	20.0	4.9	252.0	244.0	280.0
				EPM	3.79	1.25	0.26	0.15	4.87	0.07	0.56	0.07			
270	3/68	432.	7.4	PPM	73.6	10.3	8.0	5.5	234.0	0.6	11.0	3.4	226.0	192.0	228.0
				EPM	3.67	0.84	0.34	0.14	3.83	0.01	0.31	0.05			

GROUNDWATER QUALITY DATA (ANALYSES BY N.W.A.)

(THE FIGURES IN BRACKETS WERE SUBSEQUENTLY ADJUSTED
IN THE LIGHT OF THE DATA CHECKING PROGRAM)

Well	Date	EC	pH		Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	Hard	Alk.	TDS
271	3/68	400.	7.5	PPM	72.0	14.2	3.0	6.5	248.7	1.6	11.0	3.2	238.0	204.0	227.0
				EPM	3.59	1.16	0.13	0.16	4.07	0.03	0.31	0.05			
323	3/68	435.	7.3	PPM	73.6	13.3	{N.D.	{N.D.	256.0	0.0	10.0	3.3	238.0	210.0	245.0
				EPM	3.67	1.09	0.00}	0.15}	4.19	0.00	0.28	0.05			
500	3/68	1585.	7.0	PPM	93.6	32.8	{N.D.	{N.D.	326.7	30.0	350.0	3.5	370.0	268.0	975.0
				EPM	4.67	2.69	0.00}	0.00}	5.35	0.62	9.86	0.05			
102	5/69	3498.	7.1	PPM	184.0	53.9	340.0	30.0	390.1	110.0	1023.0	2.4	680.0	320.0	2375.0
				EPM	9.18	4.43	14.79	0.76	6.39	2.29	28.84	0.03			
116	5/69	1166.	7.7	PPM	100.0	25.5	120.0	3.8	207.2	30.0	220.0	4.1	354.0	170.0	741.0
				EPM	4.98	2.09	5.22	0.09	3.39	0.62	6.20	0.06			
122	5/69	7314.	7.0	PPM	352.0	113.0	880.0	37.0	280.4	164.0	2772.0	4.4	1340.0	230.0	5550.0
				EPM	17.56	9.29	38.28	0.94	4.59	3.41	78.17	0.07			
125	5/69	4134.	7.9	PPM	208.0	64.0	62.0	12.0	341.3	104.0	1177.0	3.6	780.0	280.0	2845.0
				EPM	10.37	5.26	2.69	0.30	5.59	2.16	33.19	0.05			
126	5/69	1484.	7.5	PPM	94.0	36.3	100.0	5.2	390.1	61.0	165.0	5.3	384.0	320.0	886.0
				EPM	4.69	2.98	4.35	0.13	6.39	1.27	4.65	0.08			
128	5/69	710.	7.8	PPM	78.0	14.2	20.0	3.7	292.6	10.7	74.0	2.2	254.0	240.0	289.0
				EPM	3.89	1.16	0.87	0.09	4.79	0.22	2.08	0.03			
151	5/69	1590.	7.5	PPM	120.0	83.3	110.0	21.0	316.9	128.0	182.0	1.5	640.0	260.0	1242.0
				EPM	5.98	6.85	4.78	0.53	5.19	2.66	5.13	0.02			
157	5/69	1802.	7.7	PPM	192.0	44.1	180.0	46.0	536.4	97.6	396.0	7.9	660.0	440.0	1227.0
				EPM	9.58	3.62	7.82	1.17	8.79	2.03	11.16	0.12			
164	5/69	1272.	7.7	PPM	96.0	49.0	170.0	32.0	256.0	56.4	528.0	3.8	440.0	210.0	1221.0
				EPM	4.79	4.02	7.39	0.81	4.19	1.17	14.88	0.06			
172	5/69	965.	7.8	PPM	112.0	29.4	53.0	2.6	390.1	16.7	111.0	2.5	400.0	320.0	617.0
				EPM	5.58	2.41	2.30	0.06	6.39	0.34	3.13	0.04			
188	5/69	636.	8.1	PPM	103.0	15.2	5.0	2.2	365.7	2.2	18.0	3.2	320.0	300.0	{0.0}
				EPM	5.13	1.25	0.21	0.05	5.99	0.04	0.50	0.05			
207	5/69	922.	7.4	PPM	96.0	22.1	62.0	3.7	377.9	17.5	167.0	2.4	330.0	310.0	471.0
				EPM	4.79	1.81	2.69	0.09	6.19	0.36	4.70	0.03			

Well	Date	EC	pH		Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	Hard	Alk.	TDS
228	5/69	721.	7.9	PPM	80.0	24.5	230.0	2.5	292.6	4.9	65.0	3.5	300.0	240.0	407.0
				EPM	3.99	2.01	10.00	0.06	4.79	0.10	1.83	0.05			
230	5/69	615.	7.8	PPM	81.6	6.9	6.0	2.6	316.9	5.0	20.0	0.0	244.0	260.0	251.0
				EPM	4.07	0.56	0.26	0.06	5.19	0.10	0.56	0.00			
236	5/69	615.	7.8	PPM	94.0	8.3	10.0	2.0	280.4	10.0	26.0	6.6	168.0	230.0	248.0
				EPM	4.69	0.68	0.43	0.05	4.59	0.20	0.73	0.10			
262	5/69	498.	7.9	PPM	78.0	13.7	6.0	1.4	170.6	9.0	176.0	8.0	206.0	140.0	215.0
				EPM	3.89	1.12	0.26	0.03	2.79	0.18	4.96	0.12			
265	5/69	530.	8.1	PPM	88.0	9.8	12.0	1.8	316.9	4.5	22.0	4.4	260.0	260.0	385.0
				EPM	4.39	0.80	0.52	0.04	5.19	0.09	0.62	0.07			
270	5/69	435.	8.2	PPM	66.0	9.8	6.0	1.8	231.6	6.7	18.0	5.5	138.0	190.0	173.0
				EPM	3.29	0.80	0.26	0.04	3.79	0.13	0.50	0.08			
273	5/69	403.	7.8	PPM	53.6	12.3	10.0	1.8	219.4	6.6	13.0	6.3	182.0	180.0	213.0
				EPM	2.67	1.01	0.43	0.04	3.59	0.13	0.36	0.10			
274	5/69	604.	7.7	PPM	144.0	54.0	9.0	2.4	182.8	5.7	25.0	1.2	580.0	150.0	0.0
				EPM	7.18	4.44	0.39	0.06	2.99	0.11	0.70	0.01			
276	8/69	595.	7.4	PPM	70.0	14.7	18.0	1.6	270.6	20.0	33.0	2.6	236.0	222.0	217.0
				EPM	3.49	1.20	0.78	0.04	4.43	0.41	0.93	0.04			
281	8/69	1270.	7.4	PPM	80.8	24.0	98.0	7.5	292.6	32.0	222.0	0.0	300.0	240.0	680.0
				EPM	4.03	1.97	4.26	0.19	4.79	0.66	6.26	0.00			
283	8/69	1165.	7.3	PPM	83.0	32.3	98.0	8.2	329.1	34.0	215.0	0.0	340.0	270.0	720.0
				EPM	4.14	2.65	4.26	0.20	5.39	0.70	6.06	0.00			
289	5/69	1590.	7.6	PPM	136.0	74.0	159.0	9.0	365.7	37.0	407.0	6.2	640.0	300.0	1500.0
				EPM	6.78	6.08	6.91	0.23	5.99	0.77	11.47	0.10			
295	5/69	1060.	7.3	PPM	81.6	24.0	78.0	4.0	290.1	25.5	194.0	2.8	302.0	238.0	629.0
				EPM	4.07	1.97	3.39	0.10	4.75	0.53	5.47	0.04			
296	5/69	1165.	7.2	PPM	73.6	29.4	86.0	5.0	282.8	24.9	224.0	2.4	304.0	232.0	668.0
				EPM	3.67	2.41	3.74	0.12	4.63	0.51	6.31	0.03			
297	11/69	0.	7.6	PPM	84.0	20.4	51.0	1.4	320.6	24.0	62.0	7.0	295.0	263.0	411.0
				EPM	4.19	1.67	2.21	0.03	5.25	0.49	1.74	0.11			
323	5/69	445.	7.6	PPM	80.0	0.0	12.0	2.1	256.0	0.0	77.0	2.9	166.0	210.0	221.0
				EPM	3.99	0.00	0.52	0.05	4.19	0.00	2.17	0.04			

Well	Date	EC	pH		Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	Hard	Alk.	TDS
504	6/69	1590.	7.7	PPM	77.6	26.0	196.0	3.5	246.2	407.0	347.0	5.8	300.0	202.0	811.0
				EPM	3.87	2.13	8.52	0.08	4.03	8.47	9.78	0.09			
126	4/70	1380.	7.1	PPM	93.2	34.0	N.D.	N.D.	382.8	11.0	115.0	1.6	262.0	314.0	739.0
				EPM	4.65	2.79	0.00	0.00	6.27	0.22	3.24	0.02			
126	4/70	1590.	7.2	PPM	87.1	27.3	N.D.	N.D.	321.8	52.0	200.0	2.1	374.0	264.0	1075.0
				EPM	4.34	2.24	0.00	0.00	5.27	1.08	5.63	0.03			
128	4/70	1060.	7.5	PPM	40.0	39.2	91.0	3.4	295.0	22.0	100.0	2.5	270.0	242.0	604.0
				EPM	1.99	3.22	3.95	0.08	4.83	0.45	2.81	0.04			
151	4/70	1165.	7.5	PPM	70.4	50.2	30.0	4.0	321.8	48.0	77.0	0.7	381.0	264.0	297.0
				EPM	3.51	4.12	1.30	0.10	5.27	0.99	2.17	0.01			
164	4/70	2330.	7.4	PPM	52.8	34.0	200.0	20.0	104.8	85.0	340.0	0.2	271.0	86.0	1443.0
				EPM	2.63	2.79	8.70	0.51	1.71	1.76	9.58	0.00			
168	4/70	795.	7.2	PPM	88.0	16.2	38.0	0.9	309.6	22.0	38.0	2.0	286.0	254.0	404.0
				EPM	4.39	1.33	1.65	0.02	5.07	0.45	1.07	0.03			
229	4/70	670.	7.7	PPM	184.0	36.3	62.0	1.4	434.0	30.0	45.0	6.8	300.0	356.0	427.0
				EPM	9.18	2.98	2.69	0.03	7.11	0.62	1.26	0.10			
262	6/70	260.	8.0	PPM	36.0	26.5	N.D.	N.D.	148.7	3.0	7.0	2.1	198.0	122.0	173.0
				EPM	1.79	2.17	0.00	0.00	2.43	0.06	0.19	0.03			
270	4/70	308.	7.9	PPM	56.0	1.0	N.D.	N.D.	209.7	5.0	5.0	6.0	144.0	172.0	210.0
				EPM	2.79	0.08	0.00	0.00	3.43	0.10	0.14	0.09			
273	5/70	510.	7.3	PPM	32.6	9.7	19.0	0.9	256.0	9.4	6.0	0.1	121.0	210.0	251.0
				EPM	1.62	0.79	0.82	0.02	4.19	0.19	0.16	0.00			
311	4/70	435.	7.6	PPM	76.0	3.4	N.D.	N.D.	256.0	8.0	7.0	1.4	204.0	210.0	244.0
				EPM	3.79	0.27	0.00	0.06	4.19	0.16	0.19	0.02			
345	12/70	1985.	7.2	PPM	65.6	34.3	N.D.	N.D.	199.9	41.0	0.0	40.0	304.0	164.0	1452.0
				EPM	3.27	2.82	0.00	0.00	3.27	0.85	0.00	0.64			
345	12/70	0.	7.1	PPM	800.0	1519.0	N.D.	N.D.	438.9	1900.0	850.0	665.0	8200.0	360.0	0.0
				EPM	39.91	*****	0.00	0.00	7.19	39.55	23.96	10.72			

Well	Date	EC	pH		Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	Hard	Alk.	TDS
345	12/70	0.	7.1	PPM	584.0	901.0	N.D.	N.D.	263.3	2850.0	0.0	576.0	5140.0	216.0	0.0
				EPM	29.14	74.09	0.00	0.00	4.31	59.33	0.00	9.29			
345	12/70	0.	7.3	PPM	640.0	980.0	N.D.	N.D.	277.9	2950.0	0.0	1108.0	5600.0	228.0	0.0
				EPM	31.93	80.59	0.00	0.00	4.55	61.41	0.00	17.87			
347	7/70	0.	7.3	PPM	86.4	1.7	7.0	0.2	0.0	0.0	12.0	10.0	223.0	0.0	246.0
				EPM	4.31	0.13	0.30	0.00	0.00	0.00	0.33	0.16			
99	7/71	1123.	7.2	PPM	86.4	29.4	N.D.	N.D.	402.3	21.0	190.0	4.4	336.0	330.0	647.0
				EPM	4.31	2.41	0.00	0.00	6.59	0.43	5.35	0.07			
115	7/71	1005.	7.1	PPM	88.0	17.6	N.D.	N.D.	414.5	19.0	170.0	2.6	364.0	340.0	632.0
				EPM	4.39	1.44	0.00	0.00	6.79	0.39	4.79	0.04			
125	6/71	1365.	7.0	PPM	92.8	10.7	N.D.	N.D.	370.6	28.0	310.0	15.5	320.0	304.0	753.0
				EPM	4.63	0.87	0.00	0.00	6.07	0.58	8.74	0.25			
125	7/71	1916.	7.0	PPM	105.6	13.2	80.0	22.0	341.3	61.5	510.0	10.0	372.0	280.0	1365.0
				EPM	5.26	1.08	3.48	0.56	5.59	1.28	14.38	0.16			
128	6/71	870.	7.0	PPM	72.0	0.9	N.D.	N.D.	292.6	19.2	236.0	2.2	188.0	240.0	555.0
				EPM	3.59	0.07	0.00	0.00	4.79	0.39	6.65	0.03			
128	7/71	1178.	7.1	PPM	80.0	27.4	N.D.	N.D.	312.1	35.5	250.0	1.1	312.0	256.0	710.0
				EPM	3.99	2.25	0.00	0.00	5.11	0.73	7.04	0.01			
163	7/71	1674.	7.0	PPM	84.0	13.2	N.D.	N.D.	224.3	19.0	420.0	2.2	264.0	184.0	932.0
				EPM	4.19	1.08	0.00	0.00	3.67	0.39	11.84	0.03			
164	7/71	1674.	7.0	PPM	84.0	13.2	N.D.	N.D.	224.3	19.0	420.0	2.2	264.0	184.0	932.0
				EPM	4.19	1.08	0.00	0.00	3.67	0.39	11.84	0.03			
168	7/71	682.	7.0	PPM	81.6	11.2	N.D.	N.D.	329.1	11.8	84.0	10.2	250.0	270.0	432.0
				EPM	4.07	0.92	0.00	0.00	5.39	0.24	2.36	0.16			
213	7/71	819.	7.1	PPM	73.6	21.0	N.D.	N.D.	292.6	53.0	130.0	4.4	270.0	240.0	448.0
				EPM	3.67	1.72	0.00	0.00	4.79	1.10	3.66	0.07			
220	6/71	2045.	7.0	PPM	163.2	12.2	N.D.	N.D.	407.2	17.0	540.0	3.5	508.0	334.0	1298.0
				EPM	8.14	1.00	0.00	0.00	6.67	0.35	15.22	0.05			
229	7/71	868.	7.0	PPM	77.6	24.5	N.D.	N.D.	341.3	9.8	88.0	8.0	294.0	280.0	419.0
				EPM	3.87	2.01	0.00	0.00	5.59	0.20	2.48	0.12			
262	6/71	485.	7.0	PPM	78.0	0.9	N.D.	N.D.	370.6	0.0	13.0	4.8	200.0	304.0	246.0
				EPM	3.89	0.07	0.00	0.00	6.07	0.00	0.36	0.07			

Well	Date	EC	pH		Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	Hard	Alk.	TDS
269	6/71	460.	7.0	PPM	80.0	0.0	N.D.	N.D.	275.5	0.0	13.0	5.3	198.0	226.0	219.0
				EPM	3.99	0.00	0.00	0.00	4.51	0.00	0.36	0.08			
318	6/71	460.	7.0	PPM	73.6	7.8	N.D.	N.D.	256.0	0.0	13.0	8.0	216.0	210.0	326.0
				EPM	3.67	0.64	0.00	0.00	4.19	0.00	0.36	0.12			
341	2/71	930.	7.0	PPM	9.6	40.2	N.D.	N.D.	316.9	13.5	200.0	4.0	188.0	260.0	1419.0
				EPM	0.47	3.30	0.00	0.00	5.19	0.28	5.63	0.06			
341	2/71	635.	7.4	PPM	72.8	5.4	N.D.	N.D.	268.2	0.7	54.0	8.7	204.0	220.0	325.0
				EPM	3.63	0.44	0.00	0.00	4.39	0.01	1.52	0.14			
341	2/71	620.	7.3	PPM	87.0	8.3	N.D.	N.D.	277.9	1.9	58.0	8.7	252.0	228.0	373.0
				EPM	4.34	0.68	0.00	0.00	4.55	0.03	1.63	0.14			
501	4/71	396.	7.0	PPM	72.0	0.0	N.D.	N.D.	221.8	1.5	12.0	7.5	162.0	182.0	194.0
				EPM	3.59	0.00	0.00	0.00	3.63	0.03	0.33	0.12			
502	4/71	1550.	7.0	PPM	115.0	63.0	N.D.	N.D.	243.8	160.0	1600.0	0.0	548.0	200.0	2648.0
				EPM	5.73	5.18	0.00	0.00	3.99	3.33	45.11	0.00			
502	6/71	3535.	7.0	PPM	91.2	28.0	N.D.	N.D.	268.2	150.0	1300.0	4.4	456.0	220.0	2101.0
				EPM	4.55	2.30	0.00	0.00	4.39	3.12	36.65	0.07			
503	4/71	1364.	7.2	PPM	88.0	22.5	N.D.	N.D.	243.8	144.0	290.0	23.1	312.0	200.0	779.0
				EPM	4.39	1.85	0.00	0.00	3.99	2.99	8.17	0.37			
503	6/71	1365.	7.0	PPM	768.0	10.2	N.D.	N.D.	273.1	28.8	400.0	2.7	276.0	224.0	805.0
				EPM	38.32	0.83	0.00	0.00	4.47	0.59	11.27	0.04			
85	7/72	1798.	7.1	PPM	220.0	49.0	N.D.	N.D.	492.5	32.8	370.0	8.9	750.0	404.0	1337.0
				EPM	10.97	4.02	0.00	0.00	8.07	0.68	10.43	0.14			
86	7/72	1736.	7.0	PPM	180.0	245.0	N.D.	N.D.	414.5	28.0	335.0	6.6	550.0	340.0	1168.0
				EPM	8.98	20.14	0.00	0.00	6.79	0.58	9.44	0.10			
87	7/72	2604.	7.0	PPM	180.0	105.3	N.D.	N.D.	455.9	35.2	610.0	6.6	880.0	374.0	1865.0
				EPM	8.98	8.65	0.00	0.00	7.47	0.73	17.20	0.10			
89	7/72	1922.	7.0	PPM	160.0	61.2	N.D.	N.D.	448.6	31.2	345.0	4.4	650.0	368.0	1082.0
				EPM	7.98	5.03	0.00	0.00	7.35	0.64	9.72	0.07			
95	7/72	2046.	7.0	PPM	152.0	73.5	N.D.	N.D.	463.3	29.2	425.0	8.9	680.0	380.0	1202.0
				EPM	7.58	6.04	0.00	0.00	7.59	0.60	11.98	0.14			

Well	Date	EC	pH		Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	Hard	Alk.	TDS
96	7/72	1240.	7.0	PPM	128.0	68.6	N.D.	N.D.	448.6	20.4	220.0	3.5	600.0	368.0	790.0
				EPM	6.38	5.64	0.00	0.00	7.35	0.42	6.20	0.05			
97	7/72	1054.	6.9	PPM	140.0	73.5	N.D.	N.D.	436.4	23.6	165.0	8.9	650.0	358.0	674.0
				EPM	6.98	6.04	0.00	0.00	7.15	0.49	4.65	0.14			
99	7/72	1054.	7.1	PPM	128.0	56.3	N.D.	N.D.	465.7	24.0	270.0	7.1	550.0	382.0	683.0
				EPM	6.38	4.63	0.00	0.00	7.63	0.49	7.61	0.11			
101	7/72	1426.	6.9	PPM	136.0	88.2	N.D.	N.D.	468.1	40.0	275.0	17.7	700.0	384.0	892.0
				EPM	6.78	7.25	0.00	0.00	7.67	0.83	7.75	0.28			
103	7/72	1054.	7.0	PPM	112.0	53.9	N.D.	N.D.	463.3	23.6	165.0	8.0	500.0	380.0	657.0
				EPM	5.58	4.43	0.00	0.00	7.59	0.49	4.65	0.12			
104	7/72	1023.	7.1	PPM	120.0	68.6	N.D.	N.D.	470.6	18.0	128.0	13.3	580.0	386.0	633.0
				EPM	5.98	5.64	0.00	0.00	7.71	0.37	3.60	0.21			
105	7/72	1116.	7.1	PPM	96.0	93.1	N.D.	N.D.	356.0	18.0	120.0	11.1	620.0	292.0	634.0
				EPM	4.79	7.65	0.00	0.00	5.83	0.37	3.38	0.17			
116	7/72	1116.	7.2	PPM	96.0	88.2	N.D.	N.D.	468.1	17.2	160.0	10.6	600.0	384.0	576.0
				EPM	4.79	7.25	0.00	0.00	7.67	0.35	4.51	0.17			
118	7/72	1054.	7.1	PPM	112.0	66.1	N.D.	N.D.	453.5	19.2	148.0	8.0	550.0	372.0	687.0
				EPM	5.58	5.43	0.00	0.00	7.43	0.39	4.17	0.12			
125	7/72	1675.	7.2	PPM	140.0	73.5	156.0	5.6	{370.6}	31.2	450.0	6.6	650.0	304.0	1325.0
				EPM	6.98	6.04	6.78	0.14	{6.07}	0.64	12.68	0.10			
126	4/72	1023.	7.2	PPM	32.0	19.6	N.D.	N.D.	173.1	17.0	214.0	0.1	160.0	142.0	578.0
				EPM	1.59	1.61	0.00	0.00	2.83	0.35	6.03	0.00			
126	7/72	1240.	7.2	PPM	112.0	53.9	N.D.	N.D.	421.8	26.4	220.0	5.3	500.0	346.0	696.0
				EPM	5.58	4.43	0.00	0.00	6.91	0.54	6.20	0.08			
128	7/72	906.	7.3	PPM	96.0	46.5	N.D.	N.D.	343.8	7.6	164.0	6.2	430.0	282.0	485.0
				EPM	4.79	3.82	0.00	0.00	5.63	0.15	4.62	0.10			
192	7/72	682.	7.2	PPM	96.0	63.7	N.D.	N.D.	370.6	14.0	89.0	4.4	500.0	304.0	474.0
				EPM	4.79	5.23	0.00	0.00	6.07	0.29	2.50	0.07			
193	7/72	744.	7.2	PPM	96.0	33.2	N.D.	N.D.	402.3	21.2	116.0	5.3	376.0	330.0	586.0
				EPM	4.79	2.73	0.00	0.00	6.59	0.44	3.27	0.08			
194	7/72	682.	7.4	PPM	108.0	19.6	N.D.	N.D.	343.8	21.2	82.0	4.4	175.0	282.0	459.0
				EPM	5.38	1.61	0.00	0.00	5.63	0.44	2.31	0.07			

Well	Date	EC	pH		Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	Hard	Alk.	TDS
196	7/72	930.	7.3	PPM	99.2	37.2	N.D.	N.D.	443.7	20.4	132.0	8.0	400.0	364.0	680.0
				EPM	4.95	3.05	0.00	0.00	7.27	0.42	3.72	0.12			
197	7/72	837.	7.4	PPM	88.0	44.1	N.D.	N.D.	387.7	18.0	118.0	4.0	400.0	318.0	566.0
				EPM	4.39	3.62	0.00	0.00	6.35	0.37	3.32	0.06			
199	7/72	837.	7.2	PPM	108.8	31.3	N.D.	N.D.	477.9	22.4	104.0	4.4	400.0	392.0	566.0
				EPM	5.42	2.57	0.00	0.00	7.83	0.46	2.93	0.07			
201	7/72	868.	7.1	PPM	110.4	35.2	N.D.	N.D.	419.4	18.0	112.0	6.2	420.0	344.0	566.0
				EPM	5.50	2.89	0.00	0.00	6.87	0.37	3.15	0.10			
202	7/72	806.	7.3	PPM	99.2	36.2	N.D.	N.D.	402.3	18.0	110.0	3.1	396.0	330.0	532.0
				EPM	4.95	2.97	0.00	0.00	6.59	0.37	3.10	0.05			
203	7/72	682.	7.5	PPM	88.4	44.1	N.D.	N.D.	399.9	18.6	71.0	4.0	396.0	328.0	450.0
				EPM	4.41	3.62	0.00	0.00	6.55	0.38	2.00	0.06			
204	7/72	744.	7.2	PPM	96.0	29.4	N.D.	N.D.	438.9	18.6	116.0	4.4	360.0	360.0	540.0
				EPM	4.79	2.41	0.00	0.00	7.19	0.38	3.27	0.07			
206	7/72	837.	7.3	PPM	92.8	48.0	N.D.	N.D.	429.1	17.8	108.0	8.9	428.0	352.0	621.0
				EPM	4.63	3.94	0.00	0.00	7.03	0.37	3.04	0.14			
207	7/72	899.	7.3	PPM	100.8	43.1	N.D.	N.D.	438.9	24.6	112.0	4.4	448.0	360.0	556.0
				EPM	5.02	3.54	0.00	0.00	7.19	0.51	3.15	0.07			
211	7/72	744.	7.1	PPM	92.8	41.1	N.D.	N.D.	382.8	16.4	96.0	5.3	400.0	314.0	538.0
				EPM	4.63	3.38	0.00	0.00	6.27	0.34	2.70	0.08			
212	7/72	744.	7.4	PPM	99.2	31.3	N.D.	N.D.	429.1	16.4	74.0	8.9	376.0	352.0	528.0
				EPM	4.95	2.57	0.00	0.00	7.03	0.34	2.08	0.14			
213	7/72	682.	7.2	PPM	83.2	42.1	N.D.	N.D.	353.5	13.4	85.0	8.9	376.0	290.0	455.0
				EPM	4.15	3.46	0.00	0.00	5.79	0.27	2.39	0.14			
215	7/72	1240.	7.1	PPM	115.2	37.2	N.D.	N.D.	377.9	18.8	240.0	6.2	440.0	310.0	867.0
				EPM	5.74	3.05	0.00	0.00	6.19	0.39	6.76	0.10			
218	7/72	992.	7.3	PPM	120.0	26.4	N.D.	N.D.	392.5	18.8	160.0	4.4	408.0	322.0	665.0
				EPM	5.98	2.17	0.00	0.00	6.43	0.39	4.51	0.07			

Well	Date	EC	pH		Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	Hard	Alk.	TDS
219	7/72	415.	7.6	PPM	76.8	28.4	N.D.	N.D.	312.1	1.0	14.0	7.5	308.0	256.0	237.0
				EPM	3.83	2.33	0.00	0.00	5.11	0.02	0.39	0.12			
221	7/72	508.	7.5	PPM	{172.0}	19.6	N.D.	N.D.	295.0	1.9	27.0	7.9	260.0	242.0	260.0
				EPM	{8.58}	1.61	0.00	0.00	4.83	0.03	0.76	0.12			
222	7/72	2542.	7.2	PPM	200.0	61.2	N.D.	N.D.	419.4	54.0	680.0	8.9	750.0	344.0	2007.0
				EPM	9.97	5.03	0.00	0.00	6.87	1.12	19.17	0.14			
224	7/72	428.	7.6	PPM	78.4	21.0	N.D.	N.D.	353.5	2.5	18.0	3.9	282.0	290.0	311.0
				EPM	3.91	1.72	0.00	0.00	5.79	0.05	0.50	0.06			
225	7/72	474.	7.3	PPM	73.6	18.6	N.D.	N.D.	321.8	3.8	21.0	7.1	260.0	264.0	371.0
				EPM	3.67	1.52	0.00	0.00	5.27	0.07	0.59	0.11			
226	7/72	310.	7.7	PPM	72.0	20.8	N.D.	N.D.	314.5	2.7	21.0	6.2	264.0	258.0	258.0
				EPM	3.59	1.71	0.00	0.00	5.15	0.05	0.59	0.10			
230	7/72	459.	7.5	PPM	74.4	18.1	N.D.	N.D.	307.2	6.0	27.0	6.2	260.0	252.0	222.0
				EPM	3.71	1.48	0.00	0.00	5.03	0.12	0.76	0.10			
266	4/72	393.	7.4	PPM	26.4	5.8	N.D.	N.D.	156.0	9.0	34.0	0.0	90.0	128.0	274.0
				EPM	1.31	0.47	0.00	0.00	2.55	0.18	0.95	0.00			
345	4/72	{0.}	7.0	PPM	320.0	76.0	N.D.	N.D.	241.4	520.0	5200.0	1.7	2350.0	198.0	0.0
				EPM	15.96	6.25	0.00	0.00	3.95	10.82	*****	0.02			
350	4/72	418.	7.6	PPM	60.0	14.7	N.D.	N.D.	285.2	3.1	14.0	0.1	210.0	234.0	367.0
				EPM	2.99	1.20	0.00	0.00	4.67	0.06	0.39	0.00			
350	4/72	291.	7.6	PPM	40.0	4.9	N.D.	N.D.	163.3	0.3	14.0	0.1	120.0	134.0	143.0
				EPM	1.99	0.40	0.00	0.00	2.67	0.00	0.39	0.00			
352	4/72	620.	7.5	PPM	59.2	9.3	N.D.	N.D.	260.9	7.4	69.0	4.4	186.0	214.0	313.0
				EPM	2.95	0.76	0.00	0.00	4.27	0.15	1.94	0.07			
352	4/72	589.	7.5	PPM	59.2	9.3	N.D.	N.D.	265.7	12.1	69.0	3.1	186.0	218.0	323.0
				EPM	2.95	0.76	0.00	0.00	4.35	0.25	1.94	0.05			