GROUNDWATER INVESTIGATION IN PAPHOS REGION

by

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Thesis submitted in fulfilment
of the requirements for the degree of
Master of Philosophy to the
Loughborough University of Technology

Cyprus October 1994

ABSTRACT

Cyprus is a semi-arid island. Its water resources rely on winter rainfall which supply the impounding reservoirs constructed on the dry river courses and replenish the groundwater resources within the river gravels or the plain aquifers.

Water requirements for domestic use and irrigation have been increasing considerably for the last ten years. The potential of the conventional water resources have been developed according to techno-economic factors. Also, the unconventional sources (treated domestic effluents and desalinating sea water) are receiving particular attention to support water requirements throughout the island.

The current study deals partly with the calcarenite aquifer of the Paphos Coastal Plain. It has been investigated whether this resource is offered for an integrated exploitation program. In addition the domestic effluent of the Paphos urban zone is considered as a promising resource for providing reliable and continuous quantities for irrigation use after treatment.

The calcarenite aquifer of the Paphos Coastal Plain has shown to be poor. Its potential capacity is limited due to the aquifer geometry and configuration. It cannot serve as an all year reservoir. The water quality has been found to cause problems. Generally it can be used for irrigation but with caution and where the salinity is very high, special management must be used. A development program has been proposed to minimise losses to the sea, as an alternative option for groundwater exploitation.

The domestic effluents of the Paphos urban zone, after proper treatment can be used for irrigation purposes to save raw water from the Asprocremmos dam. The raw water can be used after treatment for potable supply. In order to overcome environmental as well as socio-economic concerns a new concept of effluent treatment must be initiated. The soil-aquifer treatment (S.A.T.), is proposed. The Ezousa gravel aquifer will be used for this purpose.

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ACKNOWLEDGEMENT

I wish to thank all those who have assisted in producing this thesis.

Among those to whom I am most indebted are:

Dr R. Allwood for providing the guide lines of the research and supervising the thesis.

Mr W. S. Moffat for his invaluable discussions of the approach and results of the study.

Mr I.K. Smout for his critical review helping to clarify the ideas and improving the presentation.

Special acknowledgement is due to Mr L.G. Hutton for his continued advice even after having left the Loughborough University.

I also thank Dr G. Michaelides for his external supervision and advice throughout the course in Cyprus and Mrs Dianne Pyper for her patience while typing the thesis.

PART A

BACKGROUND TO THE STUDY

CHAPTER 1

INTRODUCTION

1.1 FOREWORD

Through out the history of Cyprus, it has been apparent that the use of extensive areas of productive lands, with an all year growing season is dependent upon control and utilization of available water resources.

Water, as a renewable resource has kept the economy alive and flourishing not only through agriculture but has allowed tourism and industrial development to expand.

As a result phenomenal growth in population, tourism, and agriculture of the last two decades, the island is in need of large additional continuous supplies of water. A benefit/cost analysis, from the standpoint of the economy of Cyprus has acquired urgency and new dimensions.

Already utilized water and management control are the most important factors for assuring continued population prosperity.

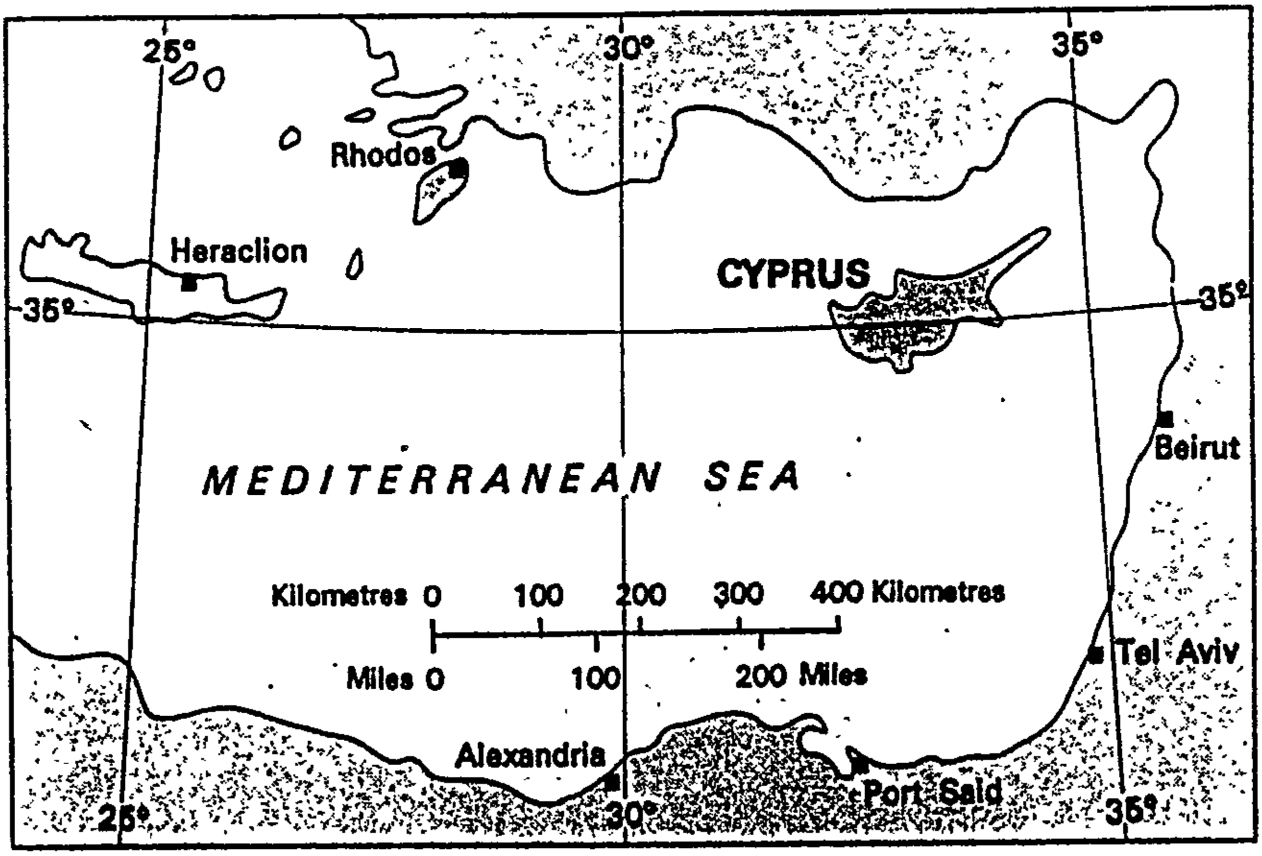
The present study deals partly with the groundwater resources of the region of Paphos as an option for development, but the lessons learnt could be expanded to other regions to improve the acute problem of water resources of Cyprus.

1.2 GEOGRAPHIC BRIEFING OF CYPRUS

1.2.1 Area and situation

Cyprus is situated in the North East of the Mediterranean sea, between 34° 33′ and 35° 41′ N. latitude and 32° 20′ and 34° 35′ E. longtitude, (Fig.1.1). The island has an area of 9,251 km^2 being smaller than Sicily or Sardenia but larger

Fig.1.1 Cyprus in the Eastern Mediterranean



than that of Crete. It extends in a N.E., S.W. direction to a length of 225 km. and breadth of 96 km., and with a coastline of 781 km.

1.2.2 Geological setting

The geology of the island has long been studied, from the pioneer researchers of Gaudry, Unger and Kotschy, and Bellamy to the synthesis of Henson et al (described by Price, 1979) and the detailed mapping by the Geological Survey Department (G.S.D.). An explanation of the geological origin of Cyprus has recently been proposed by means of a model based on sea-floor spreading and plate tectonics, (Gass, 1968, Robinson and Malpas, 1987). According to this model, the main southern mountain range of the island, the Troodos Massif, was formed on mid-Tethyan oceanic ridge and then exposed sub-aerially when the African underthrust the European plate during a phase of the Alpine Orogeny. Exceptional differential uplift, followed by heavy erosion, has resulted in the roughly annular structure which the Troodos Massif takes today. The Massif covers between one quarter and one third of the island's surface, consisting of the main block with two inliers to the east (Troulli) and west (Akamas). The greater part of the Southern range is surrounded by undeformed, largely calcareous sediments of the Upper Cretareous-Miocene Age.

In the North of the island the brecciated and recrystallized limestone of the Kerynia or Northern Range represent the most southernly fold arc of the Taurus which has been thrust southwards and deformed during Alpine orogenic movements, (McCallum and Robertson, 1987).

Between the two Ranges, the Plio-Pleistocene sediments of the central low lands conceal the contact between the deformed and undeformed formations.

Early Miocene to early Pliocene sedimentation around the north and southeast, and southwest area was influenced by localized uplift in a dominantly tensional setting (Follows and Robertson, 1987) . These form the present coastal terrace and planations, clearly evident over the study area of Paphos.

An outline geological map of Cyprus is provided in Fig.1.2.

1.2.3 Physical features

The main features one can be distinguised over the island as in Fig.1.3 are the following:

a.) In the north - Kerynia Range.
b.) The central lowlands of Messaoria, (Messaoria Plain)
c.) In the south and southwest, the Troodos Massif.
d.) The narrow coastal plain.

a.) The Kerynia Range extends along almost the whole of the northern coast, in a narrow anticline, to a length of over 160 km. and out a distance never more than 5 km from the sea. It is composed of grey-pink limestones rising into several peaks exceeding 914m.
b.) The central lowlands of Messaoria stretch between the two ranges, from Morphou Bay in the west to Famagusta Bay in the east. It is an alluvial plain formed by streams from both ranges. The alluvium cover of about 30 m at places, is the most fertile region of the island.
c.) Central Cyprus is dominated by the Troodos Massif which forms a structural and morphological backbone to the island. Its mount Olymbos, otherwise called Chionistra, is the highest in the island at 1953 metres. The Massif is a rugged region characterised by forest-covered steep valleys and deep river gorges, fast streams and rock slides.
d.) The narrow coastal plains are clearly defined within the Polis-Khrysochou region, the Paphos region and the Limassol region too. These include narrow coastal plains and higher terraces all of which were developed between Plio-Pleistocene time. These

Fig. 1.2 Geology of Cyprus

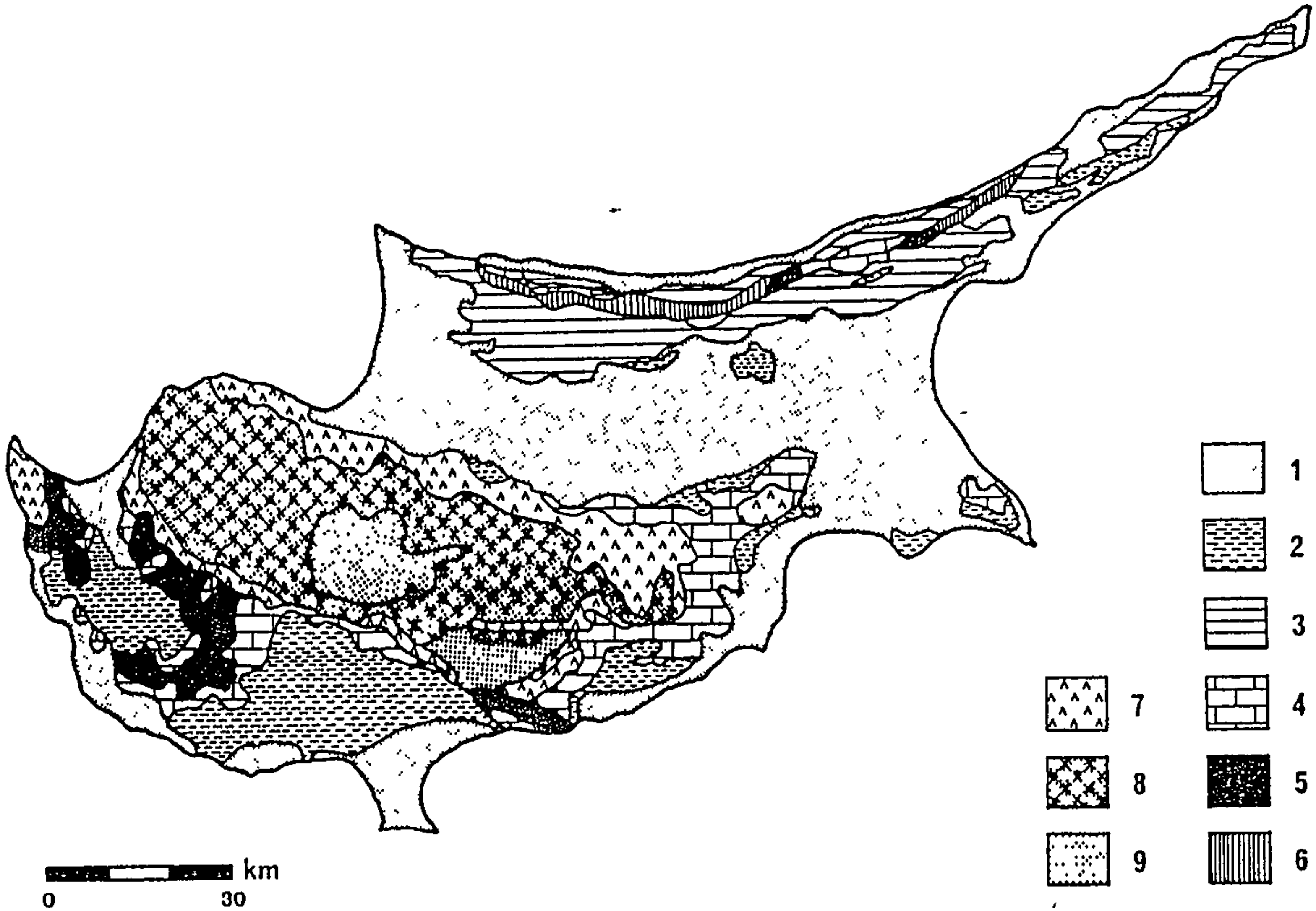


Fig.1.2 Cyprus geology

Sedimentary rocks

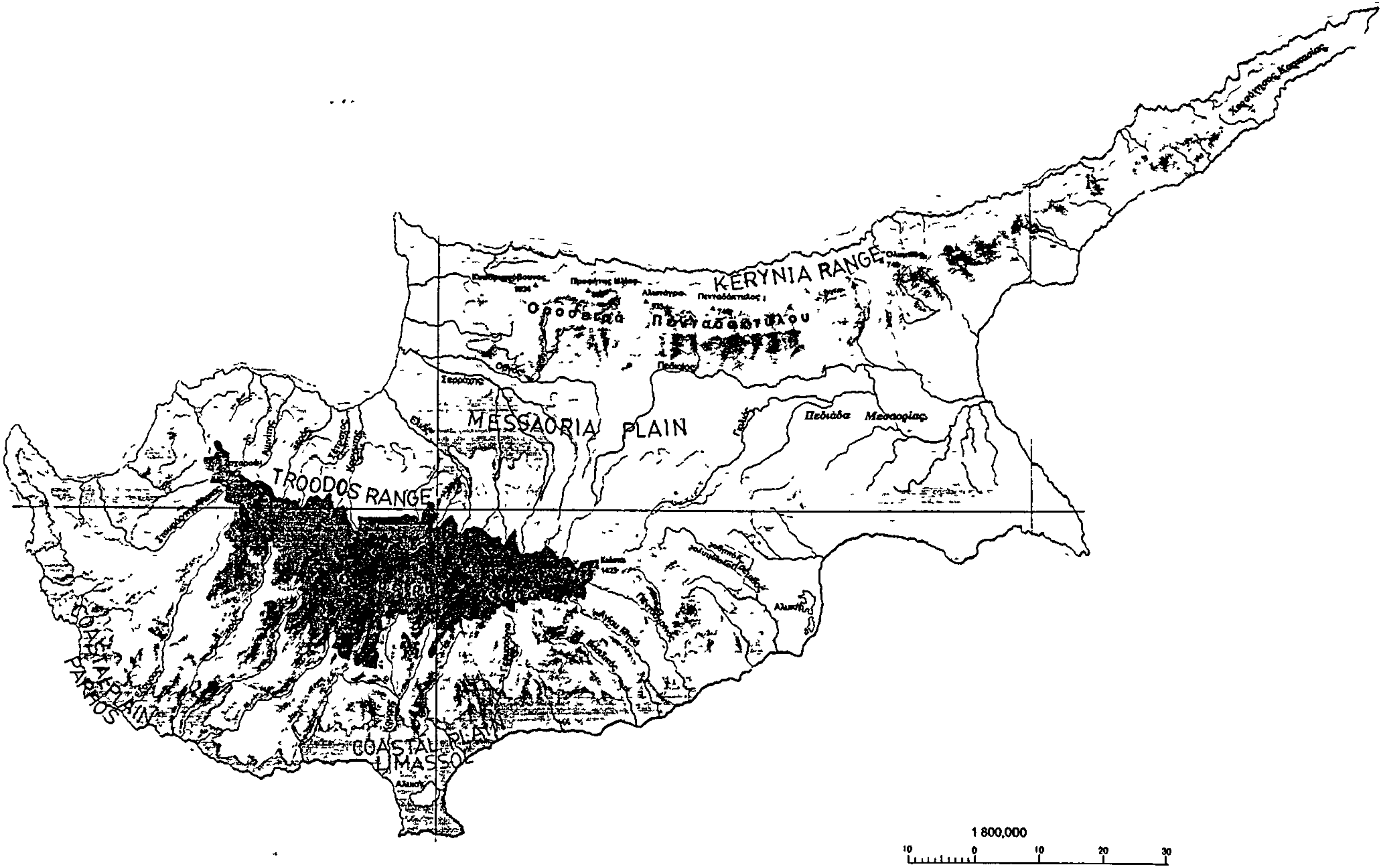
1.	Alluvium, Terrace deposits, Fanglomerates and Mesaoria Group	Recent to Upper Miocene
2.	Koronia Limestones, Kalavasos and Pakhna Formations	Middle Miocene
3.	Kythrea Formation	
4.	Lefkara Group, Lapithis, Moni, Perapedhi and Kannaviou Formations	Lower Miocene to Upper Cretaceous
5.	Mamonia Complex	Cretaceous-Triassic
6.	Hilarion, Sykhari and Dhikomo Formations	Upper Cretaceous to Carboniferous

Igneous rocks

7.	Upper and Lower Pillow Lavas	Troodos Pillow Lavas
8.	Basal Group and Diabase	Sheeted Intrusive Complex
9.	Gabbro-Granophyre Suite, Ultramafic Suite	Troodos Plutonic Complex

Source: Pantazis (adaptation),1973

Fig. 1.3 Geomorphology of Cyprus



geomorphological features are of marine origin and are locally significant because they contain important aquifers which have been supporting of irrigated agriculture over the good fertile soils which cover these lowlands.

1.2.4 Climate

The climate of Cyprus is characterised by the mild wet winters with a high inter-annual variations and hot dry summers separated by short transitional seasons. The rainfall is produced by depressions passing through the Mediterranean region in winter. The rainfall confined to the months from November to April averages 500 mm per year, varying from 350 mm in the central Messaoria plain to 1000 mm on the Troodos mountains, and with isohyets following topograhic contours as in Fig.1.4.

The 30 year moving averages of the annual precipitation for Cyprus as a whole as from 1916 reveal a decreasing trend in the precipitation regime. The average precipitation for the period of 1916-50's is 503mm, for the period 1941-70's is 489mm and for the period of 1951-80's is 477mm, (Fig.1.5).

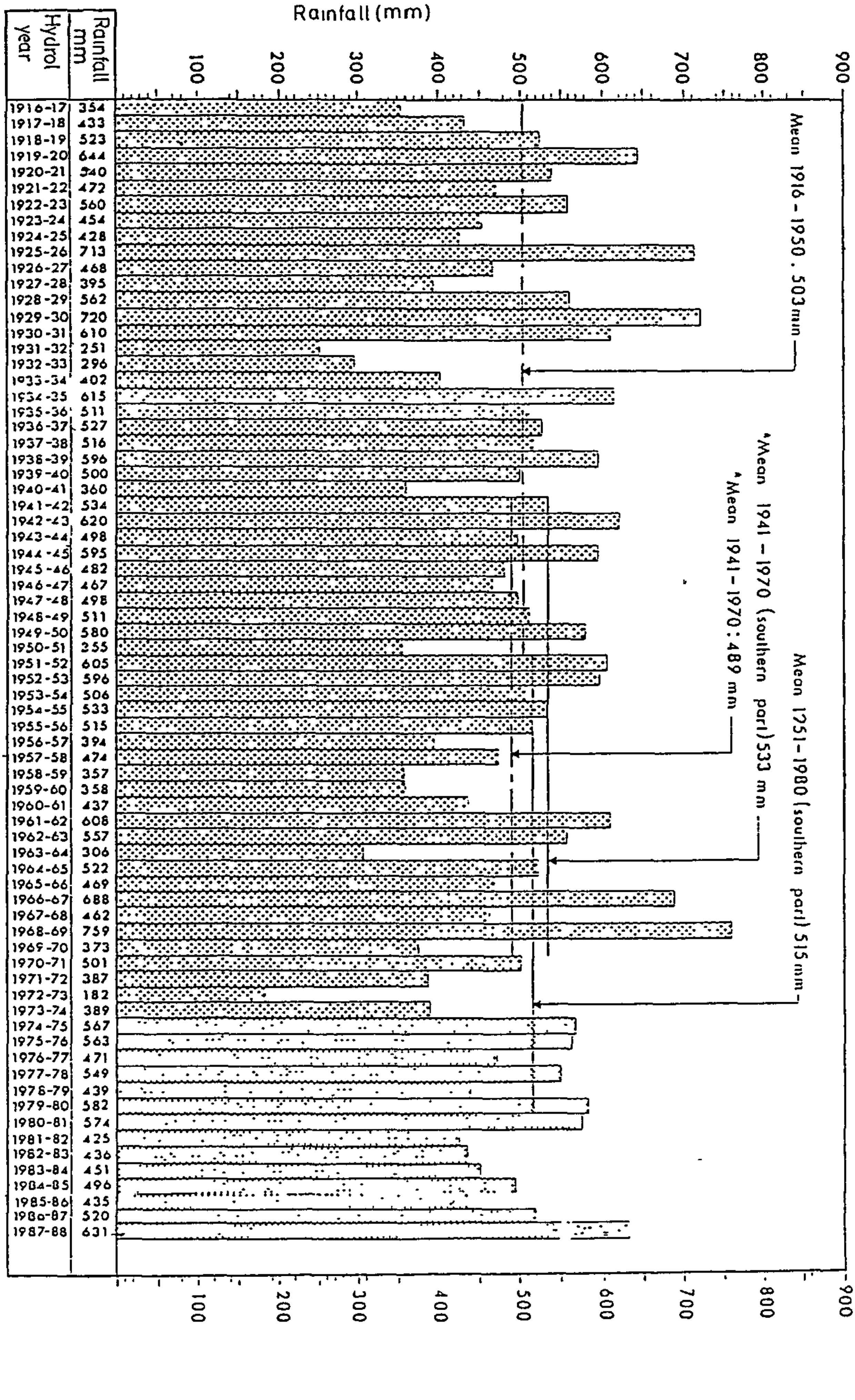
The first and second order 5 year moving averages of the precipitation on the island as from 1916 give a more enlightening picture of the annual variability of the precipitation and the different patterns of the precipitation regimes in different periods,(Fig.1.6). In the last 30 years, the average precipitation is lower and its variability is greater than in the preceeding periods except for two short periods in the early 1930's and 1970's when severe droughts were experiences. Recent drought of 1990-92 is not included.

1.2.5 Water availability

A. Georgiou (1991) has estimated that of the total annual average rainfall of approximately $4625x10^6m^3$ falling over the island, 60% is lost through evaporation and evapotranspiration

Fig. 1.4 Isohyetal map of Cyprus 1941–1990

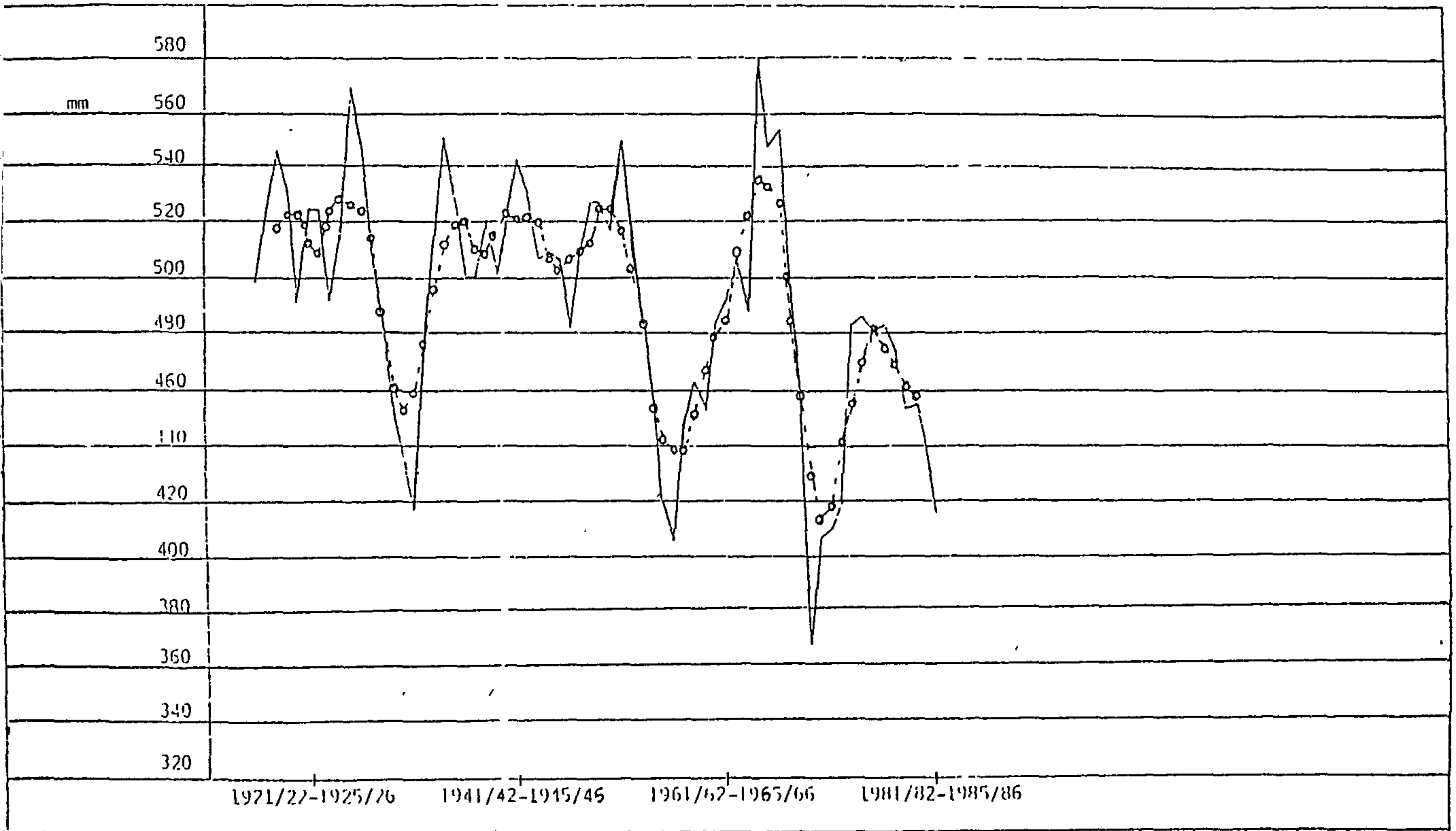
Source: Meteorological Service, 1992



Source: Kypris et al, 1989

Fig.1.6 Cyprus: First- and second order 5 year moving averages of annual rainfall 1916-85

Source: Meteorological Service, 1992



from non-cultivated areas, 20% is used up by crops in cultivated areas, thus, there remains on an average annual basis 100mm which amounts to $925x10^6m^3$ for recharge and runoff. Approximately two thirds of this leaves the area or sub-surface run-off and the remainder replenish naturally, (under gravity action), the groundwater most of which are contained in the plains and coastal aquifers and which in turn are pumped and utilized mainly for irrigation.

C. Lytras (1990) reported that $150x10^6m^3$ of the surface flows are diverted during winter and early spring and are used for spate irrigations, whilst $190x10^6m^3$ are controlled through retaining dams and the remainder of $260x10^6m^3$ are lost by flowing to the sea. Since the early 1960's 104 retaining dams of total maximum capacity approximately $297x10^6m^3$, have been constructed (Kypris and Neophytou, 1989).

Under the projected water developments within the Ezousa and the Diarizos rivers in the Paphos region and within the Karkotis river in the Nicosia region, new impounding reservoirs is expected to be constructed soon. Therefore, total losses should further be decreased upto $60x10^6m^3$ in a wet year, which is the storage capacity of the proposed dams.

Due mainly to geographical, geological and financial constraints the prospect to set up new impounding reservoirs does not seem feasible in the near future, (Christodolou et al., 1991).

Groundwater resources play an important role in water management particularly for domestic supply. The most significant resources have been defined within the major river alluvium depositional environment. Some other depositional fan facies and consolidated sediments of sandstones and limestones also form reasonable aquifers.

S. Kramvis (1987) has designated Cyprus aquifers as first and second class aquifers on the basis of their extents and specific yields.

A generalized map of the aquifers of Cyprus is shown in Fig.1.7.

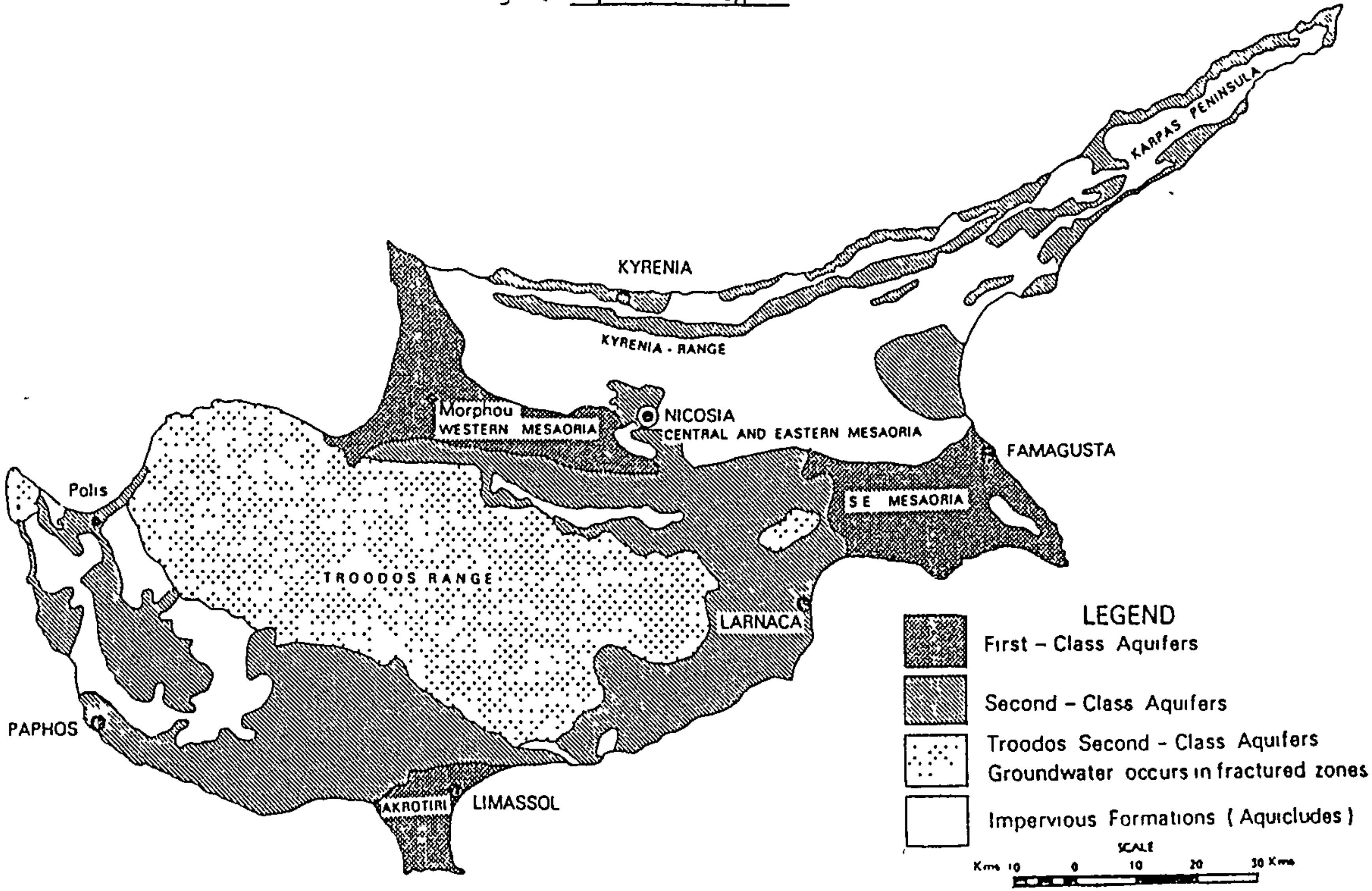
The first class aquifers are defined the western and south eastern Messaoria aquifers and the Akrotiri aquifer. The western Messaoria aquifer covers an area of about 400 km^2 and has a maximum thickness of over 100m at places (Morphou Bay) with specific yields of 6-9%. The southeastern Messaoria aquifer extends over an area of 500 km^2 and its base is undulating varying in depth from 20m-80m. The Akrotiri aquifer extends almost 42km^2 (it is the third larger in the island) with an average thickness of 40-45m. Its specific yields vary from 3-6% and 10-15% in the calcarenite and in the gravels respectively.

Second class aquifers consist of pervious layers of highly variable thickness and limited lateral extent. They are associated with the fracture and karstic limestones of the Kerynia Range and the reef limestone gypsum and calcareous rocks which surround the Troodos Massif. The calcarenites and marine deposits of the narrow coastal plains and the river's fluvial deposits are considered as second class aquifers.

Unfortunately, the aquifers encountered in the study area fit into the second class. These are, the Paphos coastal plain calcarenite aquifer, and the Dhiarizos, Xeros, and Ezousa river gravel beds of some 6 to 13km from the sea, (Mero, 1969; Kramvis, 1987).

Evidence shows that underground water resources have been over-exploited as early as the 1940's. Average pumpages have been estimated to come up to $270x10^6m^3$ on an average year basis for the last ten years or 46% of the current total consumption. An investigation of the underground reserves

Fig. 1.7 Aquifers of Cyprus



Source: Kramvis 1987

which has been conducted by the Water Development Department (W.D.D.)-Hydrological Division in 1992 pointed out that an amount approximately $70x10^6m^3$ drains annually to the sea. It was also found out a negative balance of approximately $40x10^6m^3$ which was realized as over-pumping.

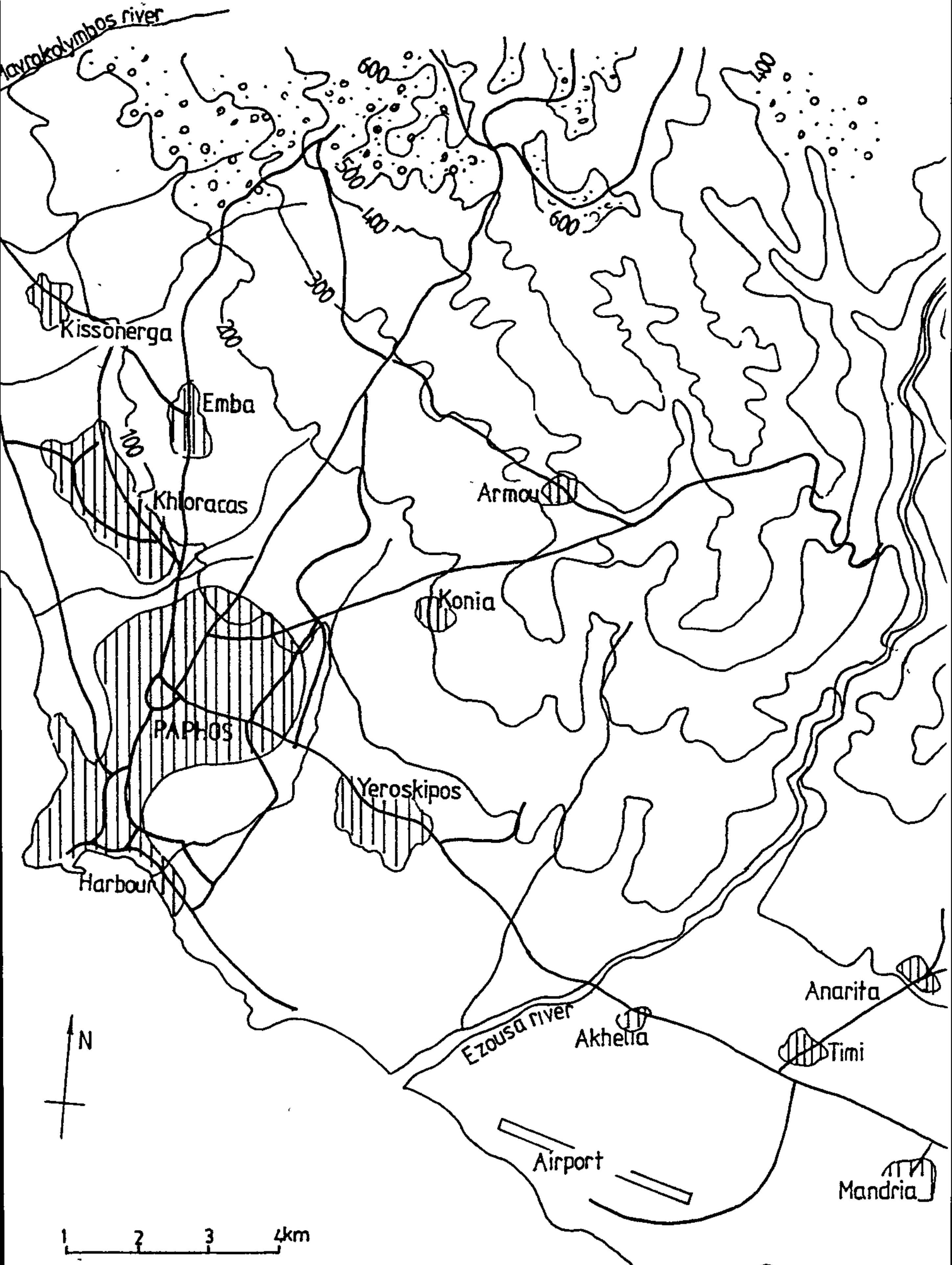
Uncontrolled pumping is, in fact, the main cause of the encroachment of the sea water into many coastal parts of the island. For instance, sea intrusion problems have been encountered for the last ten years on the Kokkinochoria region at the southeast of Cyprus. There, the sandy calcarenite aquifer has been over-pumped down 15% of its original reserves, and sea water intrusion has reached up to 2 kms. inland. The available storage for recharge is in excess of $250x10^6m^3$. The water table is down to 50 m below mean sea level and the water table lies between 60 and 100 m from the ground surface, (W.D.D., 1992).

Water utilization is currently risen up to $590x10^6m^3$. Irrigated agriculture is the largest water consumer with approximately $525\text{-}30x10^6m^3$, but also towns, industrial centres and tourist resorts need large quantities of fresh water with high seasonal water demand peaks. There are already restrictions on the water supply in the largest towns and villages, and tourist projects place new heavy burdens on the water demand.

1.3 THE STUDY AREA

The study area is demarcated in the southwestern part of the island and covers a geographical area of some $300km^2$. It is bounded by the Mediterranean Sea on the south and west by the Dhiarizos catchment on the east and the Mavroukolymbos catchment on the northwest. Over the northern side low hilly country prevails, marking the beginning of the mountainous inland, (Fig.1.8).

Fig. 18 Paphos region



The town of Paphos is situated almost near the middle of the study area and therefore two sub-areas can be outlined, the eastern and western areas. The eastern site covers a large area rather regular with foothills having a relatively uniform slopes towards the sea; it is dissected by three perenial rivers, the Diarizos, the Xeros, and the Ezousa, the resources of which provide the major potable and irrigation water supply of the area. Much more irregular topography and higher elevations characterised the western side of the Paphos town.

The study area is also characterised by the coastal plain and the higher terraces which form the main geomorphological features in the region. The low lying coastal plain comprises the most fertile soils and has yet been developed agriculturally with the construction of the Paphos Irrigation Project (P.I.Project) in 1985. In the middle of this plain and around the small Paphos harbour, the tourist zone is developed. The habitation of the population has traditionally been gathered over the higher planations overlooking the Mediterranean Sea and coastal plain. Half the population (32,000) of the district lives and works over this area.

Paphos has a long history of human settlement, since 8th century B.C. The area is rich in ancient monuments, archeological and historical sites which has eventually acquired a worldwide respect after UNESCO included them in the "World Heritage List" in 1985. During Roman rule (60 B.C.-400 A.D.), Paphos became the principal town of the island with a well developed commercial and political influence in the region. Unfortunately, after some centuries of flourishing it slowly declined to a minor regional town. This was due chiefly to the inadequate road service and the absence of infrastructure in the region.

Throughout the 1960's and early 70's the rest of Cyprus was prospering and developing economically but the Paphos region remained the poor relative. This situation continued until 1974.

The Turkish invasion in 1974 and subsequent events caused sharp changes in the economic and social life of the region. The urgency for the reconstruction of the country's economy prompted large investment in both tourism and agriculture. These two factors boosted economic growth in the area and Paphos has benefited extensively.

Paphos, the former "fishing village" until the late 1970's, has therefore, grown into a major tourist centre. Several luxurious hotels and developments in tourist infrastructure have taken place here. The number of visitors has since, considerably, been increased at a rate of 25% per annum over this period by reaching, in 1990, 2.2 million overnight stays, (C.T.O.,1990).

Agriculture has traditionally been the main activity of the local population. The uniform temperatures and the relatively humidity (see section 2.4) are conducive to the production of very early fruit and vegetables and the reputation of Paphos for early producer is well known. Agriculture till 1970's was based on rainfed crops-cereals and legumes over 60% of the entire area and crops irrigation from wells and river spates is approximately 20%, the rest of the area was remaining uncultivated (Agric. Dept.,1970).

The construction of the Paphos Irrigation Project (P.I.Project) which extends almost all over the coastal plain has given a new dimension to agriculture. It was designed for growers of traditional farming to shift over new and modern cropping patterns resulting into increasing their income and productivity with cash crops such as citrus, bananas, avocados, potatoes, nuts, carrots, etc. (see section 3.2.3).

Agriculture has been developed so far but the region's main economic growth throughout Cyprus is tourism. Due to tourism building construction industry, trading, banking, entertainment and several other occupations have been expanded in such a degree so that labour deficiency is in fact a problem. Rural population moved to the urban development areas, abandoning their properties. However, there is a great concern about the possible effects of such a rapid development.

Among the other adverse effects encountered in the area, the most serious are the effects on the natural environment. The erection of large buildings such as hotels and tourist complexes along the fringe line destroy, the landscape and threaten the marine environment, due to the malfunction of the wastewater treatment facilities.

1.4 OBJECTIVES OF THE STUDY

This study has been initiated to investigate possible aquifers for further water resource development in Paphos region. This is particularly topical after the recent consecutive dry years between 1989-1991.

Also it encouraged by the specific costly solutions being proposed from various government agents to overcome water requirements particularly during peak seasons of June to September. The first proposal consists of shipping water from nearby countries i.e. Greece (from the island of Crete) and Syria. Because of political uncertainties, shipping may not be given a long term availability as a water resource. The second proposal is the introduction of disalinisation developments. The disalting of sea water by means of reverse osmosis is estimated to cost approximately C£0.60 per m^3 (CH2M Hill, 1993).

There is however, a growing concern over this approach to the problem. The author believes that there are still possibilities for further developments by reviewing conventional and unconventional available resources. In respect to the latter source, modern technology can and should be used in an effort to increase water availability.

In recent years, the developments of the surface and groundwater resources of Cyprus has reached a very high degree of available water utilization. This development together with the projects now under consideration will bring Cyprus to the point where any additional water development will either require high investment or such quantities will be involved that they will make little contribution to the overall water availability.

The author has identified two aquifers to be considered for possible water resources development.

1. The Paphos Coastal Plain aquifers with its groundwater resources.
2. The Ezousa river gravel with artificial recharge using treated sewarage effluent from Paphos town and its environs.

The first of these is to be the main focus of the study, but the second one is considered in less detail. The available data on these aquifers are inadequate for assessing the potential for water resource development and the main aim of this research is to obtain the necessary hydrogeological information.

The specific objectives of the research are:

1. For the Paphos Coastal Plain Aquifer.
   1.1 To determine the extent of the Athalassa Calcarenite Aquifer in the Paphos Coastal Plain.
   1.2 To estimate the saturated volume and the hydraulic parameters of the aquifer.

1.3 To determine the quality of the groundwater and its suitability for irrigation.

1.4 To estimate existing uses of the aquifer.

1.5 To identify possible methods of increasing utilization of the aquifer.

2. For the Ezouza river gravel aquifer.

2.1 To identify the potential of the gravel aquifer for treatment and storage of the reclaimed domestic effluents derived from the Paphos urban zone.

2.2 To determine to extent of the river aquifer and its hydraulic parameters that is associated with the proposed role of the gravel bed as a discharge basin.

1.5 SUMMARY OF INVESTIGATIONS (STRUCTURE OF THE THESIS)

1.5.1 Paphos Coastal Plain aquifer

Local farmers were interviewed to provide information on crops being cultivated and private abstractions from the Paphos Coastal Plain aquifer (P.C.Pl.aquifer) and the major river gravel aquifers in the region. The findings are discussed in Chapter 5,6,9(9.6) and 12.

Existing boreholes were located in the P.C.Pl. aquifer and levelled in where necessary, borehole logs were retrieved and exposed rocks were identified. From these data maps were prepaired for the borehole positions and the hydraulic basement of the aquifers. The type of aquifer (confined or unconfined) was inferred from the geological stratification. Electrical resistively logging was also used in the case of the Ezouzas river basins (section 14.7). Pumping test records were retrieved and additional pumping test and recovery test were carried out in areas not previously covered. These were used for estimation of aquifer parameters, particularly transmissibility, as detailed in Chapter 9.

Water levels were measured in boreholes and wells, from which hydrographs and water table contour maps were prepaired. Using these and the maps of the hydraulic basement of the aquifer, computer analysis were undertaken to estimate the saturated volume of the aquifer per season. (Chapter 12).

Groundwater samples were collected from several operating boreholes in the P.C.Pl. aquifer and sent for chemical analysis. The water quality for irrigation was assessed. (Chapter 10).

Drilling was carried out to determine water levels, near the sea, and trenches were excavated for assessment of the potential of trench collectors, (Chapter 13).

1.5.2 Ezousa River gravel aquifer

Survey work was undertaken to determine the extent of the Ezouza river gravels, and hydraulic parameters were estimated. These were interpretted for potential storage of Paphos wastewater, (Chapter 14).

1.5.3 Structure of Thesis

The thesis is devided into 4 parts. Part A (Chapter 1 to 6) provides background to the thesis and the study area. Part B (Chapter 7 to 13) covers the P.C.Pl. aquifer. Part C (Chapter 14) describes investigations of the Ezouza river gravel as a recharge basin of the Paphos effluent. Part D (Chapter 15) presents the conclusions of the study.

References and Appendices are given at the end of the thesis.

CHAPTER 2

CHARACTERISTICS OF THE STUDY AREA

2.1 GEOMORPHOLOGY

The broken topography of the study area includes the low lying coastal plain (that is the longer strip-plain in the region) a series of long area terraces backed by scarps which run east-north western and a plateau surface over an abruptly rising at the north eastern site of the areas concerned. All of these were identified as Plio-Pleistocene raised beaches.

At the east of the region the three river valleys (Dhiarizos, Xeros, and Ezousa) form a different physiographic unit.

The above configuration can be observed within the maps as in Fig.1.3. and in Fig.1.8.

2.1.1 The Coastal Plain

The low lying coastal plain, hereafter will be referred to as the coastal plain, stretches between the Dhiarizos river to the east and the Mavrokolymbos river, to the west repectively and along the coast for some 25 km and is nowhere more than 3km wide.

The eastern plain is a very regular surface with a uniform seaward slope of about 5%. Some minor very low plateau like interruptions outcrop. The soils are relatively homogeneous and made up of old fine deposits between more recent river alluvium. The majority of the soils are heavy and clayey with low permeability. These soils are subject to waterlogging and water pounding in places where the land is flat (Sotiriades et al.,1968).

The western plain is very broken with undulating relief of varying slopes. A mosaic of different formation is found with red Mediterranean soils overlying limestone crust throughout the area down the shore line.

The coastal plain contains the main outcrop of the Athalassa calcarenite formation. This is the most significant water bearing formation encountered all over the region. It has so far become established as a traditional groundwater resource for the area, but it is importance downgraded since the implementation of the P.I. Project in 1985.

2.1.2 The terraces

The northern boundary of the coastal plain is well marked by the Kissonerga-Kouklia escarpment of about 60m high ± 5-12m. Immediately above the escarpment there is a terrace wide spread and extensive. It is quite an irregular surface with undulating relief of varying slopes inclining towards the sea at 5-8%. Few kilometers north the land slopes sharply upwards at an elevation of approximately 140m contour. Above this contour a second terrace can be seen. This terrace is of limited extent and ends at the foot of the higher hills. The 400m high surface is clearly distinct. This plateau is deeply incised by numerous streams with deep and steep valleys.

2.1.3 The river valleys

The eastern part of the region is drained by three of the major river in the island, the Dhiarizos, Xeros, and the Ezousa. These rivers run parallel with each other in a north-north-east to south-south-west direction for distance up to 50km from their head waters on the Troodos Range to the coast. The rivers are often deeply entrenched between steep wall valleys with width of 100 and 300m in places. Where the river basins are somewhat larger, small irrigation farming can be seen. By breaching the Kissonerga-Kouklia escarpment have their basins expanded over the coastal plain forming flat valley floors.

A fourth river, the Mavrokolymbos, drains the western edge of the coastal plain within a very limited catchment.

Besides the four rivers above, the area is drained by few small streams, short creeks and a number of short coastal water courses all of which have contributed in the formation of the present landscape, the deposition of soils and their development. A number of short creeks running steeply in the north-west disappear when they reach the lower and middle planation.

2.2 REGIONAL GEOLOGY

The Southwestern Foothill Belt in the southwestern part of the island consists essentially of gently folded Upper Cretaceous to Middle Miocene calcareous sediments containing large inliers of the allochtonous Mamonia Group. The Mamonia Group was originated elsewhere and was emplaced at its present situation after grading, sliding and thrusting (Roberston and Woodcock,1979; Murton,1987).

A marine planation extending alongside the Foothill Belt marks the present form Cyprus obtained after a considerable uplifting in the Pliocene-Pleistocene period.

Therefore, the rocks of the region can be distinguished in two main sequences; the allochtonous sequence belonged to the Mamonia Group and the autochotonous which was formed in-situ.

The Mamonia terrain is structurally complex, comprising a late Palaeozoic to late Cretaceous assemblage of sedimentary, igneous and minor metamorphic rocks. The sedimentary deposits are of late Triassic to early Cretaceous and consist of deltaic and turbitic sandstones and sillstones, cherts, mudstones and radiolarites and pelagic limestones. The igneous group are of Triassic to Early Cretaceous and comprises alkali volcanics, volcanics breccias, shallow water carbonates, calcitutites, cherts and siltstones (Evans,1988 and Hamilton,1990).

This terrain is well defined in a geological map produced by Dr H. Lapierre, which is the official map (Geological map of the Polis-Paphos area,1971).

The autochthonous group include the Troodos igneous rocks and the sedimentary which ages from Upper Cretaceous to Recent.

The Troodos igneous rocks outcrop off the study area further north inland. The sedimentary group is restricted within the study area into the three main formations, the Lefkara, the Pakhna and the Athalassa.

The Lefkara group comprises the first cycle of chalk sedimentation following the extrusion of the Troodos pillow lavas. Its age ranges from the Upper Upper Cretaceous (Mastrician) to the Lower Miocene and has been split into three divisions on presence of partial unconformities, lithological differences and paleonthological evidence. These units are the Lower, Middle and Upper Lefkara. Lithologically are composed of clay and pinkish marly chalk at the base followed by white chalks with bands of chert topped by flaggy and massive chalks. Within this group and during the lower Miocene, the Terra-Limestone was developed. This consist of massive bedded fossiliferous limestones which interfingers with the surface of the lower marine terrace and partly on the higher, (Hadjistavrinou, 1977).

However, the biggest part of the region is covered with the Pakhna formation (M.Miocene). This consist of alternating layers of limestones, chalky marls amd marls giving genesis to a very or extremely calcareous light, pale grey raw soils. By the washing of the soils to the lower parts of the area, extremely calcareous deposits called "havara" were formed. Such deposits are found at a certain depth in almost every part of the coastal plain and it rests mostly unconformably on the underlying formation of the Lefkara.

The Lefkara and Pakhna formations are of limited permeability and for most purposes can be treated as aquicludes. However, the Lefkara are sometimes jointed and fractured allowing water to disperse through them by dissolving calcium carbonate ($CaCO_3$). Their secondary permeability increases the porosity and in places this forms aquifers. This is not the case in the coastal plain because Pakhna formation contains marls and by overlying the Lefkara formation forms an aquiclude.

The Athalassa calcarenite is well developed in the upper and lower coastal plains but it is more extensive in area in the former one. This contains an old marine planation which was formed during the Pleistocene. It consists of several beds of medium to coarse grained fossiliferous current bedded calcarenite interbedded with sandy fossiliferous marls. Calcarenite predominates over the marls and in places forms the bulk of the formation.

The Athalassa calcarenites of the lower coastal plain is an extensive aquifer, traditionally used as a water resource to local farmers. The upper one is floored by Terra-Limestone which has a shallow weathered zone. This is a very poor aquifer and only occasionally was found to contain some reasonable quantities of water.

However, the Athalassa calcarenite water resources of the lower coastal plain has been a matter of long discussion. This will be the subject of the current study and therefore detailed investigation has been conducted.

Generalized geological map showing the Paphos region is given in Fig.2.1.

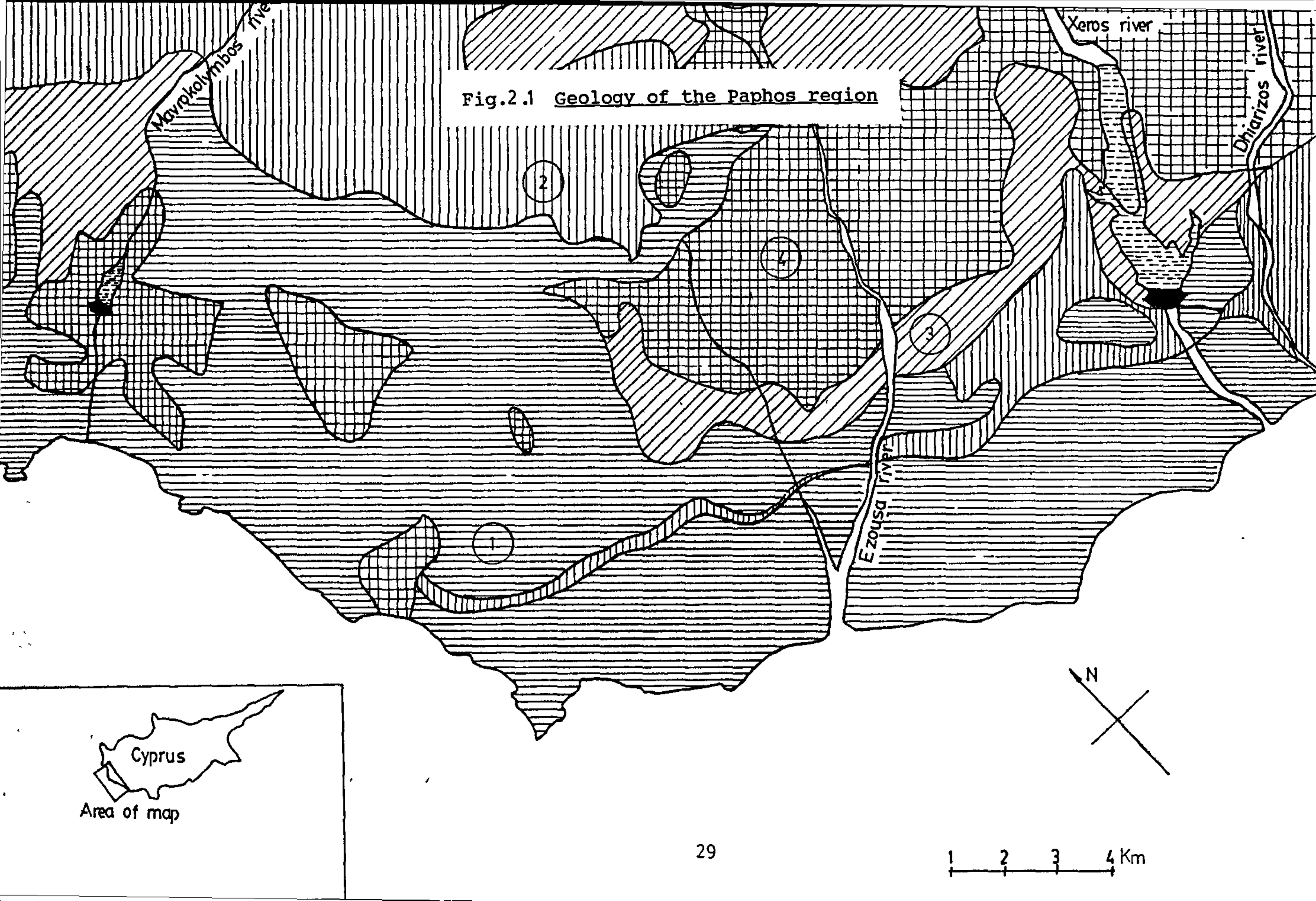


Fig.2.1 Geology of the Paphos region

Fig.2.1 Geology of the Paphos region

Legend

1- Plio-Pleistocene :	Terrace deposits (calcarenite, sand, gravels, conglomerates) Athalassa formation (biocalcarenite, sandstones, sandy marls)
2- Middle Miocene :	Pakhna formation (marls interbedded with chalks)
3- Lower Miocene :	Lefkara formation (limestone, chalk marl, marly chalk, marl with cherts)
4- Cretaceous-Triassic :	Mamonia formation (clays and serpentines)

Source: Tullstrom,1970; Lapierre, 1971

2.3 SEISMICITY

Cyprus has long history of severe earthquakes, with reference to destruction of towns, going back to 4th and 5th centuries BC. This seismicity is related to continuing tectonic activity of the Mediterranean region where the African continental plate or part of the earth mantle, has come in contact with the Eurasian continental plate. The continental plate boundaries are complex in the region of Cyprus, but it appears that Cyprus lies very close to the southern boundary of the Anatolia plate where the present tectonic activity is occuring, (Williams Halcrow,1981; Haimson et al,1987), (see Fig.2.2).

The area of greatest tectonic flux during the present century has in fact been in southeast Cyprus, declining westwards, but the Mamonia Group of the Paphos district is the area most geologically unstable and prone to earthquakes, (Price,1979). A map of the area affected by the most recent severe earthquake in Cyprus (i.e. 1953) showing the correlation between the Mamonia Group and sites damaged by it, is given in Fig.2.3.

2.4 CLIMATE

Paphos weather conditions have been observed and recorded since 1961. Meteorological data is available for three recording stations serving the Paphos area. These stations and their dates of operations are summarized below.

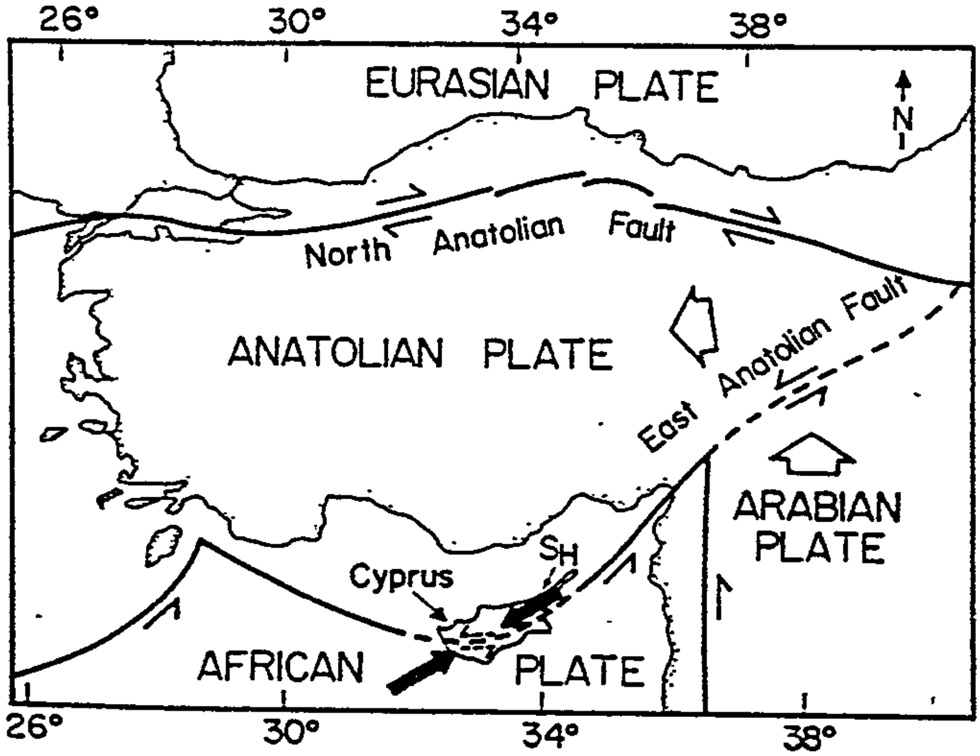
a.) Kato Paphos, records available for 1961-1983.
b.) Akhelia, records available since 1967.
c.) Paphos Airport, records available since 1983.

The old Kato Paphos station is no longer in service, it has been substituted with the one in the airport.

These places can be seen in map, Fig.1.8.

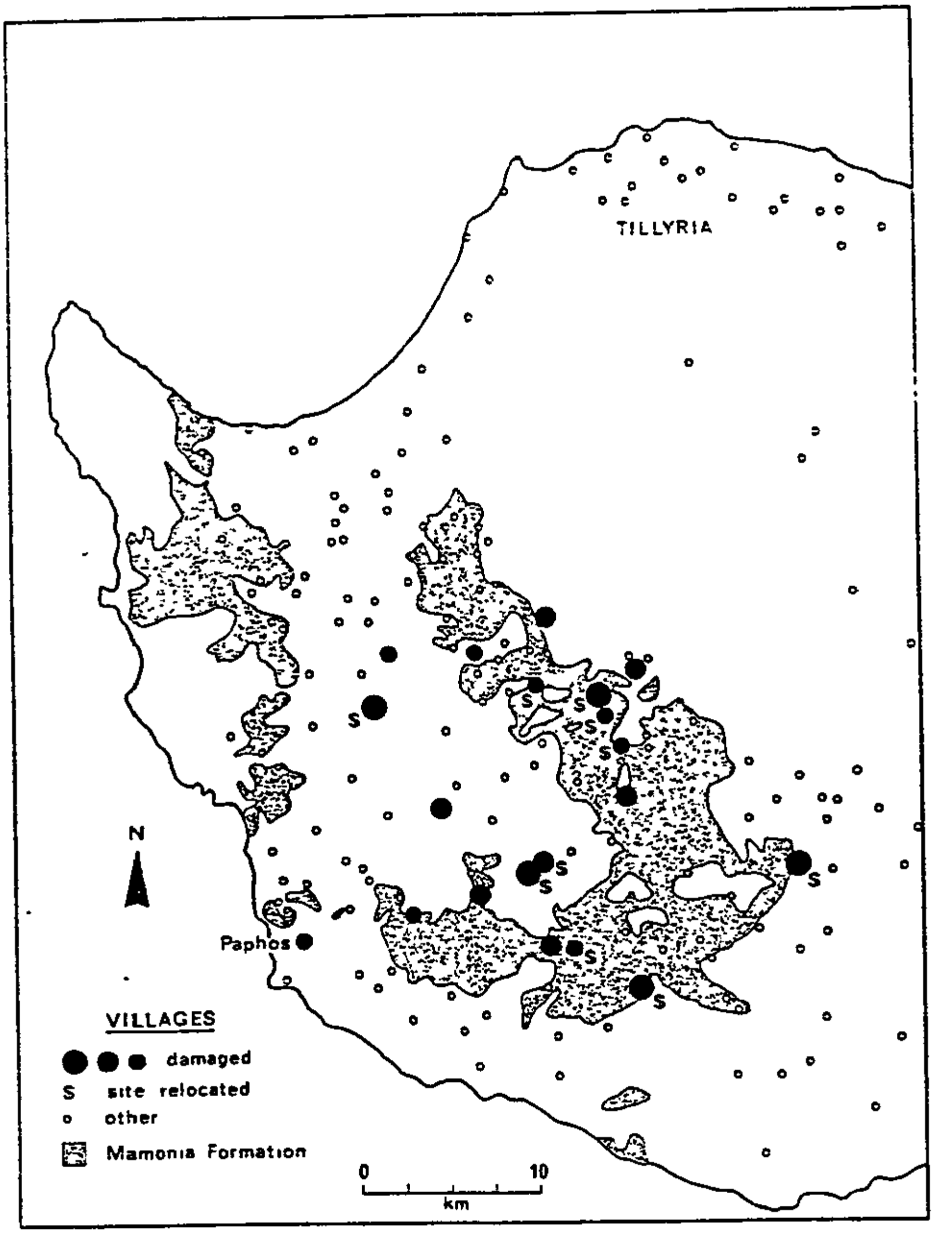
The following is based on information and data collected

Fig. 2.2 Cyprus within the African and Eurasian Plates



Source: Haimson et al, 1990

Fig. 2.3 Major earthquake in Cyprus, 1953



Source: Price, 1979

from the Cyprus Meteorological Service in Nicosia and W.D.D. sources.

The climate of the area is most coastal Mediterranean and the influence of the marine environment give cooler summers and warmer winters. The mean daily temperature ranges from 12.5°C in February to 25.9°C in August. The area can thus be considered as frost free, while ground frost occurs on average 0.5 to 1 day a year.

The mean daily temperature, the mean number of days with ground frost and the mean daily sunshine duration as these recorded at the Akhelia station (Akhelia O.N.S.,1993) are cited on Table 2.1.

The mean annual rainfall in the region ranges from 400-500mm. The largest amount of rainfalls during the winter months, some during spring and autumn and hardly any during the summer (Fig.2.4). The rainfall of the area is insufficient for intensive agriculture and supplementary irrigation from run-off water wells or boreholes is necessary.

The winds blowing mainly from the west to southwest usually defines the direction of the rainfall.

The mean average humidity ranges from 60-68%, varies little, ranging from 57% in October to 75% in January. Class A evaporation pan are observed all over Cyprus, in particular at Asprocremmous dam and Paphos Airport. The average evaporation in the study area is 1,759m distributed as on Table 2.2.

Table 2.1 Mean daily temperature, mean number of days with ground frost and mean daily sunshine duration for the period 1967-1992

Month	Temp. °C	Mean number of days with ground frost	Mean daily sunshine duration, hours
January	12.7	0.6	5.3
February	12.5	0.2	6.4
March	13.9	0	7.1
April	16.7	0	8.8
May	20.0	0	10.7
June	23.2	0	12.3
July	25.6	0	12.5
August	25.9	0	11.9
September	24.3	0	10.5
October	21.4	0	8.9
November	17.7	0	7.4
December	14.3	0	5.6

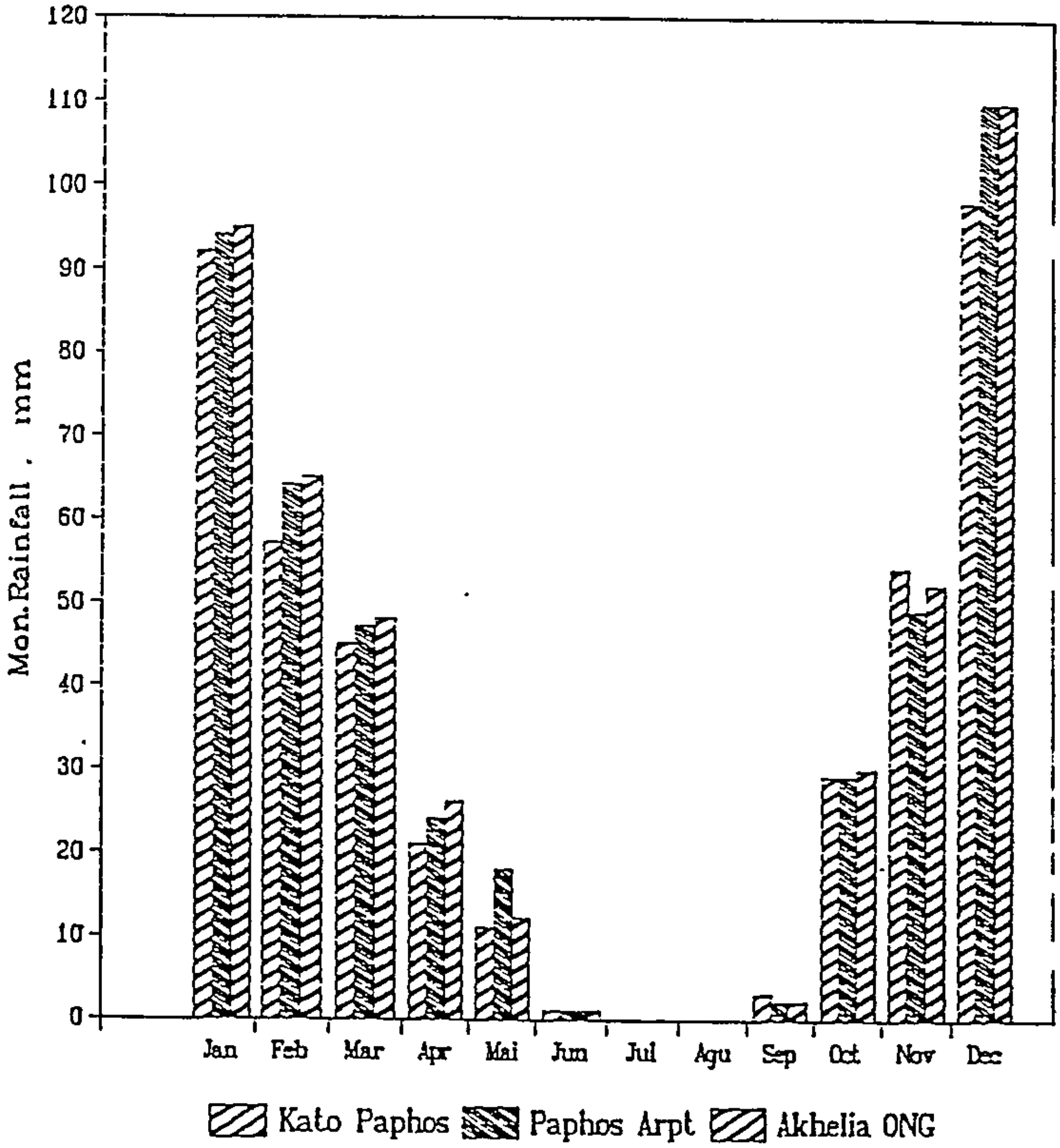
Source: Meteorological Service, 1992

Table 2.2 Mean monthly and annual Class A Pan Evaporation at Paphos Airport and Asprocremmos dam for the period 1983-1992

Month	% of annual	Evaporation (mm)
January	4.0	71
February	4.1	72
March	5.6	97
April	8	140
May	10.7	189
June	12.6	222
July	13.4	236
August	12.8	225
September	10.6	187
October	8.2	144
November	5.7	100
December	4.3	76
	100.0	1759

Source: W.D.D., 1992; Meteorological Service, 1992

Fig. 2.4 Paphos Norm. Rainfall
Period 1951-92



Source: Meteorological Service, 1992

CHAPTER 3

WATER SUPPLY AND IRRIGATION PROJECTS

3.1 DOMESTIC WATER SUPPLY

3.1.1 Historical review

Since the beginning of civilization human settlements were located in areas of easy access to water such as stream, springs, and eventually in areas where drinking water could be drawn from shallow wells. Although the abundant quantities of groundwaters existed then in the area could not at the time be exploited because of the absence of pumping technology.

However, with the introduction of modern hygiene in the 1940's it became necessary to convey water to villages from far away sources to substitute the use of groundwater drawn from shallow wells in the yard of each village home as the introduction of toilet pits posed a pollution threat for these shallow wells.

During the 1950's a start was made on regional water supply schemes. Originally water conveyed to villages was distributed through public fountains which were placed in strategic spots throughout the village for easy access to as many homes as possible. In some instances these fountains were combined with troughs for watering animals.

Towards the end of the 1950's some villages were provided with metered house to house water supply schemes through the use of distribution boxes. As from 1960 all new schemes provide for house to house supply of water and by early 1970's, practically all villages had piped water in the home. Since all domestic water supply sources were from natural springs, wells and chain-of-wells and sub-surface dams in river beds, the water was pure enough needing only chlorination at the reception storage tanks.

Nowadays, two different schemes supply the area under consideration with fresh water. These are the Paphos Municipality Water Supply Scheme (P.M.W.S.Scheme) and the Lower Village Water Supply Scheme (L.V.W.S.Scheme). Both were constructed between mid-1970's. These are showed diagrammatically in Fig.3.1.

3.1.2 The P.M.W.S. Scheme

The P.M.W.S. Scheme and the L.V.W.S. Scheme as well are based their water supplies on the same wellfield located upstream of the Asprocremmos dam in the Xeros river gravel aquifer (Fig.3.1). A main conveyor with a diameter of 300 mm supplies the Vasilico storage tank, sited over the eastern hights of Paphos town from which the greater part of the town is supplied by gravity. From there water is boosted towards two tanks which supply the higher boroughs.

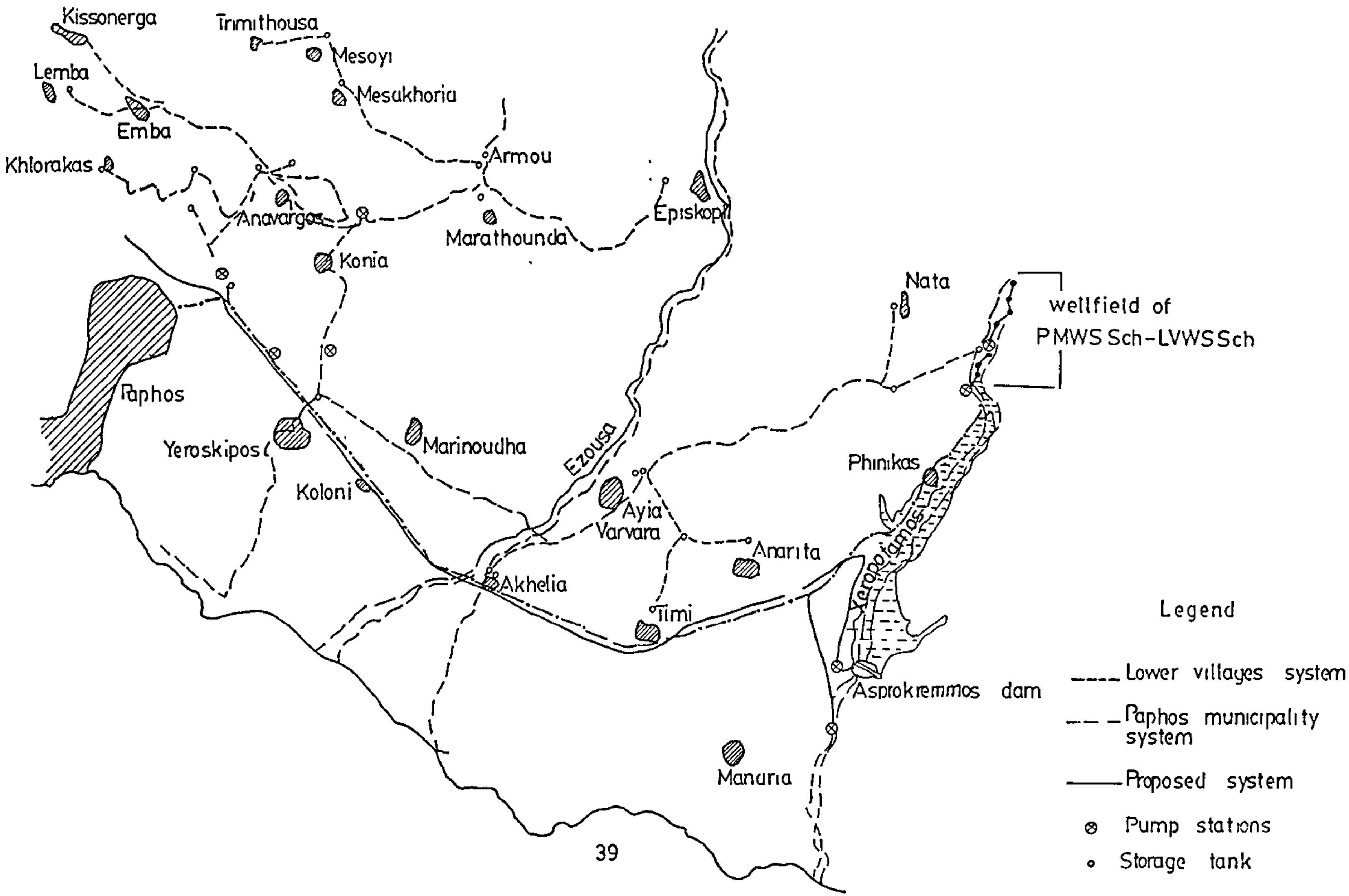
Recent developments and tourism expansion, (this will be discussed in the following Chapter-4) resulted in augmenting water demand, particularly during peak seasons from July to September. The main conveyance system was proved inadequate and therefore a new one was required. Thus, a new 600mm pipeline was laid alongside the existing one to increase water supply from the Xeros wellfield.

3.1.3 The L.V.W.S. Scheme

This scheme encompasses 22 communities with population of 9800 according to the 1990 statistical data. This Scheme also assists Paphos town water supply whenever there is insufficient supply from P.M.W.S.Scheme and during peak seasons demands.

A main conveyor with diameter of 300 mm, several tanks of capacities varying from 9 to 450m^3 and a distribution network ensure the water supply to the villages. The operation and maintenance is carried out by the W.D.D. but the control and management of the house to house supply is the task of the village boards. Water meters are installed to each residence

Fig. 3.1 Paphos water supply system. Layout of existing and proposed facilities



and the village board charges them a constant tariff C£0.16 per m^3 for every two months.

3.1.4 The Prospective Developments

The reliance on the groundwater makes water supplies critical especially in the case of the Xeros river where the gravel aquifer is of limited extent due to its physical size.

Therefore, alternative options had to be investigated. For this reason, the Cyprus government requested to Howard Humphreys consulting engineering firm to review the preliminary studies conducted by the W.D.D. in 1991. Within this study the Ezouza river surface flows have been considered as the source to which the newly established Greater Paphos Water Supply Scheme (G.P.W.S.Scheme) which includes the P.M.W.S.Scheme and the L.V.W.S.Scheme will have to be relied upon. This project may cover the water requirements for the Greater Paphos for a period of up to the year 2020. The above firm has finally recommended a multi-functional system in order to secure the maximum, possible water from surface and sub-surface flows. This as was envisaged by Howard Humphreys, is summarized below from their report (1993).

An impounding reservoir of total storage capacity $15x10^6m^3$ and reliable yield of $5-6x10^6m^3$ must be the main source of the G.P.W.S.Scheme. This can be ensured with the erection of the dam far upstream about 30km on the Troodos mountains. This reservoir should be associated with the treatment plant which will be situated near the Asprocremos dam (Aprocremmos dam is described in section 3.2.3) to provide an alternative source of supply. When diverted flows exceed the demand, the excess can be stored in the Asprocremmos reservoir for later use. However, between the proposed dam and the lower river valley there is a significant catchment. The surface and subsurface flows in this portion will be controlled by the construction of the Episkopi dam. It was estimated by the same firm above, that $2.3x10^6m^3$ per annum can be secured at the minimum. This source will be supporting the Mavrokolymbos scheme, provided that a good wet season occurs, by conveying as much water through the pumping facilities of the P.I. Project, (see section 3.2.2). Hence, the downstream wellfield is to be completely dependent on releases from the Episkopi impounding reservoir or otherwise it may be considered.

3.2 IRRIGATION PROJECTS

3.2.1 General Consideration

If water cannot be stored it can at least be utilized at the brief periods when it is abundantly available, that is, in winter and spring. Thus water from the streams has been taken on the land since very early days, but nowadays this practice is not used anymore. Modern agriculture certainly depends on the reliability of the water supply throughout the year. However, water resources reliability is a function of extreme events and not simply of average conditions.

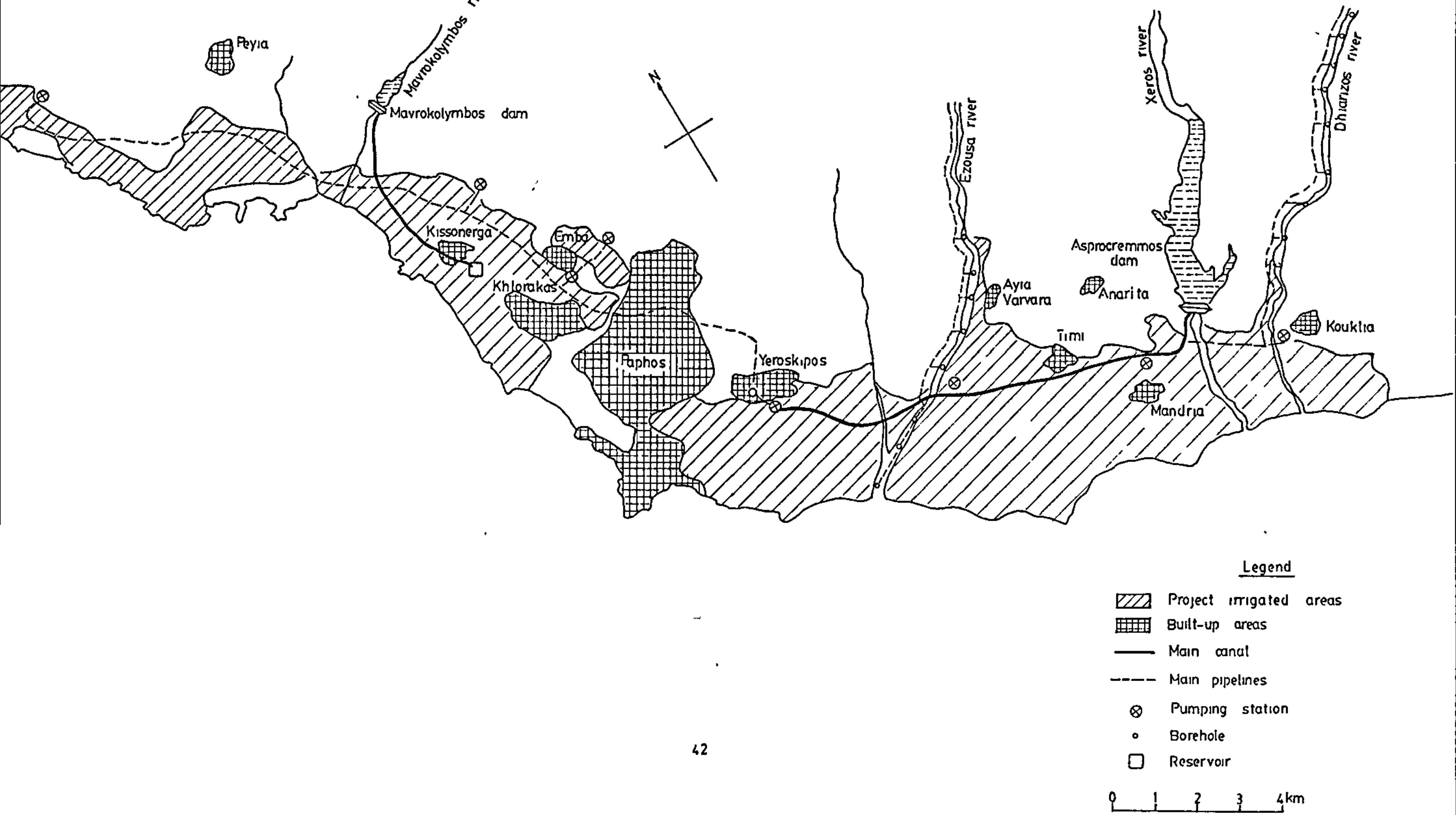
It was therefore necessary to execute the water developments works quickly. With the establishment of the Cyprus Republic in 1960 this was fully recognized by the various governments, and as a matter of policy to construct large dams for impoundment of water for irrigation. It is worth noting that the technical assistance and the financial support which recieved from the United Nations FAO and UNDP and the World Bank allowed to Cyprus government for the execution of this programme successfully.

According to this programme among others had been constructed the Mavrokolymbos Irrigation Scheme and the Paphos Irrigation Project which have together been covering the irrigation requirements over the lowlands of Paphos (i.e the coastal plain and the higher planations nearby). The two projects and the area irrigated is described in Fig.3.2.

3.2.2 The Mavrokolymbos Irrigation Scheme

This scheme was constructed in 1967 with the assistance

Fig 32 Paphos irrigation project — General plan



of FAO and UNDP and consists one of the earliest attemps to control the river flows. The scheme includes a small dam of maximum capacity of $2.1x10^6m^3$ constructed on the Mavrokolymbos river 2.4km from its reach. The dam is founded at 110m elevation allowing distribution of the irrigation water to be performed by gravity. A conveyance cum distribution network commands a net area of 279ha along the coastal strip, western of Paphos town.

The Mavrokolymbos river flow doesn't fill the increasing irrigation demand of this Scheme (see also section 5.2.4) and therefore, supplementary quantities are provided by the P.I.Project.

3.2.3 <u>The Paphos Irrigation Project</u>

This project is the second largest in the island, after the Southern Conveyor Project. The feasibility study was completed by consulting firms under the supervision of the UNDP-FAO and was financed partly by the Cyprus Government and partly by the World Bank (SOGREAH,1976). It covers an area of 5,086 ha which extends over the entire coastal plain of Paphos. This area stretches between the Dhiarizos river and the Ayios Yeorgios at the east and west respectively. The whole area is sub-divided, due to design operation purposes, into 17 sections which are supplied separately.

Supply was designed on the following assumptions:

* Daily irrigation time: 16 h / 24 h;
* Operation frequency of one outlet 1/3, and average;
* Probability of satisfactory supply 95%;

The main components of the project are described below.

Asprocremmos dam. This is the principal water resource of the project. It is an earthfilled retaining reservoir of maximum capacity $52x10^6m^3$ and 53m high. It was erected where Xeros river breaches the Kissonerya-Kouklia escarpment only near as 3km from the sea.

Main Canal. A 12km. long main canal extending from Asprocremmos to Yeroskipos being supplied by the dam it commands the major irrigation area of the eastern plain.

Western conveyance system. It originates from the large pumping station located at Yeroskipos; the water rises by nearly 100m, then conveyed by a gravity pipeline over some 19km down to Ayios Yeorgios.

Pumping Stations. Pressurisations of the water supplied by the main canal and the pipe conveyors is achieved by 14 automatic pumping plants having a mere pump regulations (eastern part) or a regulation cum storage function (western part).

Distribution System. In order to promote sprinkler and drip irrigation a pressurised network was installed providing approximately 3.5 bars pressure at each hydrant. The network consist of asbestos cement (A.C.) pipes range between 80mm and 300mm of cumulative length 540km.

Eight years after the completion of the P.I.Project, agricultural practice has shifted to more irrigated crops but still remains below the potential of the Project. This is rather exceptional considering the efficiency in readily available water on fertile soils. However, the current situation doesn't favour agricultural expansion because the avalablility of the produced crops encounters many difficulties in the local market as well as abroad. The local market orientation limits certain production, but, exports also face hard competition because of the increase in the production costs due to mainly to labour expenses.

According to Project source irrigated agriculture covers almost 70% of the arable land which includes the permanent plantations of 30% (citrus, bananas, vines, avocado etc.) and the seasonal plantations of 40% (potatoes, nuts, beans, carrots, etc.) the rest of the area has either been cultivated with rainfed crops mainly cereals and legumes or otherwise remains uncultivated (W.D.D.,1993).

CHAPTER 4
WATER REQUIREMENTS.

4.1. GENERAL CONSIDERATION

Water requirements particularly in domestic use have increased tremendously during the last ten years due to the unprecedented growth, up to 25% per annum in the tourist industry. The resident population has increased over the same period but at a lower rate, 3.3%.

Irrigated agriculture has been performed satisfactorily under the P.I.Project but when the area is to be fully developed, it is questionable whether the Asprocremmos reservoir, alone, can ensure adequate water demands, especially in dry years. Also, new areas over the P.I. Project boundaries are claiming irrigation supplies, resulting in the over-all demand of fresh water within the coming years.

For the purpose of the current study, a period of up to the year 2020 is considered as more functional; because certain difficulties often arise which may complicate a longer period projection. The estimation of the domestic water needs is proceeded by considering the population increasing trends as these were available from the various official reports. However, growth rate must be distinguished between tourist and residential population because of the different trends and great variance in consumption rate.

4.2 TOURIST DEVELOPMENTS

The tourist sector has realized substantial growth in recent years as the number of arrivals in the island has been swelled from 350,000 to 1,900,000 per year since 1982 to 1992, (Department of Statistics,1992, Cyprus Tourism Organization, (C.T.O.,1992).

Paphos a major tourism centre, has been sharing in a higher rate of growth. An indication of the tourist growth in the Paphos area to that of Cyprus are the increasing number of the licenced beds provided by the Hoteliers Association of Cyprus, 1992 (Table 4.1).

Tourist overnights stays figures, have been adopted in order to calculate water requirements in this potential sector of water users. Overnight stays represents the more realistic approach to the problem instead of considering the licensed bed figures along with the figure of numbers of arrivals.

The projected overnight stays are given in Table 4.2

The growth rate was found to be 23% per annum by the year 1993, but thereafter, this rate should be decreased at lower rate. The government of Cyprus has formulated a long term strategy of controlled development of the tourist industry but improving infrastructure in order to increase the tourist revenue.

Due to the current uncertainties relating to future tourist development and the present moratorium on hotel construction, the author is unable to revise growth projections as mentioned previously. These figures are broadly accepted and have been used by the Ministry of Commerce and Industry, Paphos Municipality, Water Development Department of Ministry of Agriculture.

4.3 RESIDENT POPULATION INCREASE

The population data which is presented hereafter (Table 4.3) is for the study area of the urban zone of Paphos and 22 other villages. The population figure is based in the past official census carried out in 1976 and 1982 by the Department of Statistics, the 1990 elections data and the projections made by the same department and the Town Planning Bureau up to the year 2020 which have been borne out by the actual developments during the last ten years.

Table 4.1 Licensed beds of Cyprus and Paphos

	Cyprus	Paphos	%
Number Of Licenced Beds in 1988:	48,458	7,070	14.6
Number Of Licenced Beds in 1992:	69,800	18,400	26.4

Source: Hoteliers Association, 1992

Table 4.2 Projected overnight stays

Year	Overnight stays	% Increase per annum
1982	544,200	--
1987	1,461,700	21.8
1990	2,759,500	23.4
2000	4,491,400	5.0
2010	6,089,000	3.1
2020	8,183,100	3.0

Source: C.T.O., 1992

The growth rates are quite high compared to that of the other parts of the island and this is due to the fact that the rural population has been moving to the urban zone of Paphos because of the increasing labour demand by tourist industry. The urban-rural growth ration within the Paphos district is given below (Table 4.4) and also that of the rest of the Cyprus for comparison.

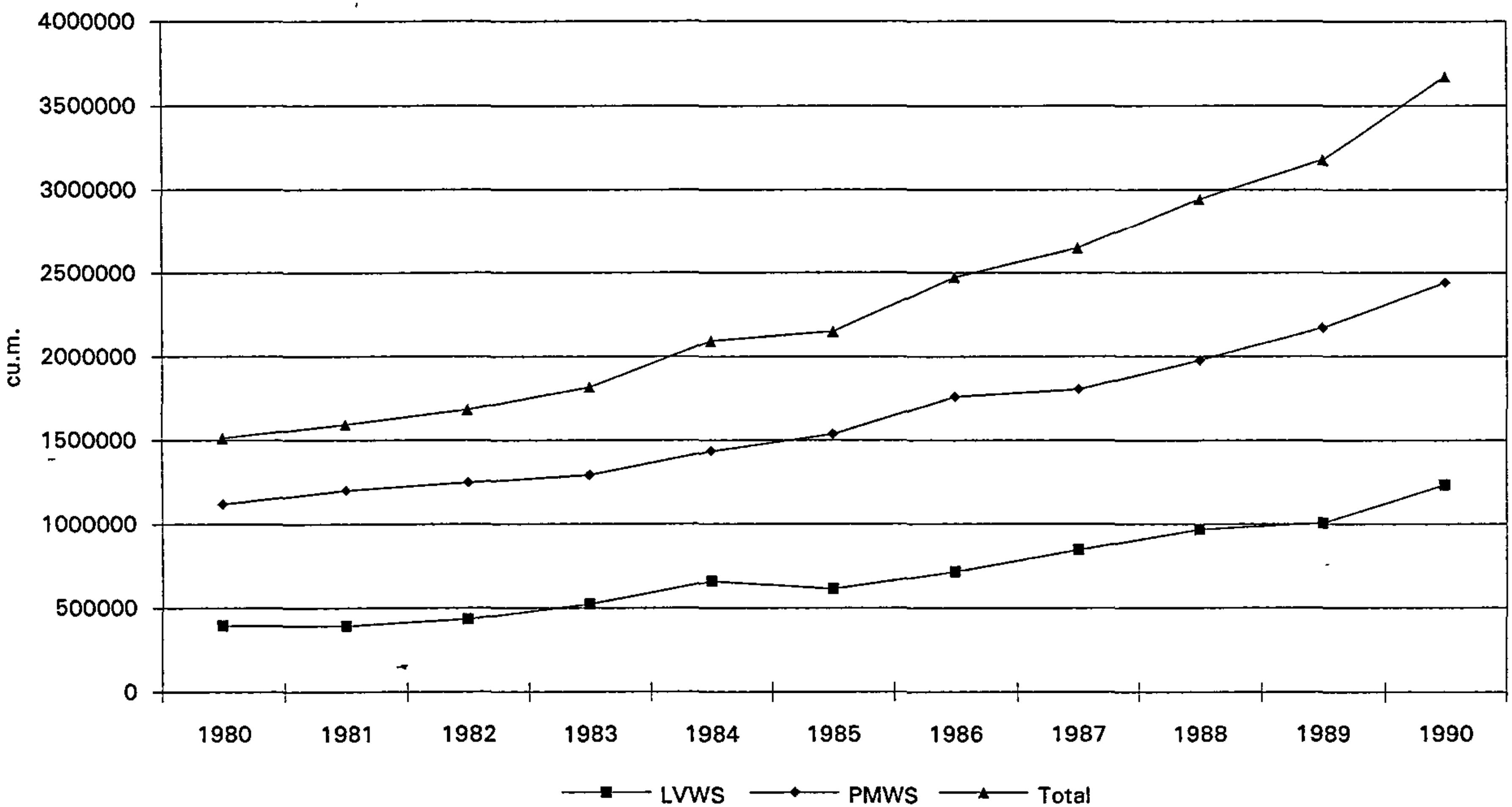
Its apparent that growth rate and development does not always progress in a uniform and orderly manner, on the contrary a decreasing trend will be expected, otherwise no people will remain in the remote villages. Gradually, the growth rate within the region may reach the average national growth rate and remain constant at 1%.

4.4 WATER DEMAND FOR DOMESTIC USE

The evolution of water demand within the study area from 1980 to 1990 is shown in Fig.4.1 and demonstrates an mean average growth rate for this period approximately of 13% per year. Considering that the population consumption trends between 1980 and 1990, the average water consumption was estimated to be 170 litres per capita per day and 320 litres per capita per day respectively. This later considerable increase in the per capita water consumption is, mainly, due to the expansion of the tourism within the study area over this period and the improving of the living standards of the local population.

The use of the proposed per capita water consumption figures to forecast future consumption can be justified by comparing the results of a calculation based on per capita figures with the historical statistics actually recorded for the same area and period either by the W.D.D. or the Paphos Municipality Water Division. Thus the 1990 records will be considered for this purpose as the most recently available.

Fig.4.1 Paphos water consumption (1980-1990)



Source: Municipality of Paphos, 1990; WDD, 1990

Table 4.3 Residential population increase in the Paphos urban area

Year	Residential population	% Increase per annum
1976	20,300	--
1982	24,400	3.1
1987	28,500	3.1
1990	31,400	3.3
2000	39,600	2.35
2010	44,900	1.3
2020	49,600	1.0

Source: Town Planning Bureau, 1990; Dept. of Statistics, 1992

Table 4.4 Urban and rural population of Cyprus and Paphos

		1982	1990	% per annum
Paphos :	Urban :	20,824	28,800	4.14
	Rural :	24,821	19,200	-3.28
Cyprus :	Urban :	325,386	397,800	2.54
	Rural :	186,712	177,200	-0.66

Source: Dept. of Statistics, 1992

TOURIST

Number Of Overnight stays	:	2,759,500
Per capita demand	:	480 liters per day
Total	:	1,324,560 per annum

RESIDENT

Number	:	31,400
Per capita demand	:	240 liters per day
Total	:	2,750,640 per annum
Total by calculation	:	4,075,200
Total by statistics	:	3,673,841
Difference	:	10.9 %

These figures include consumption by industries and institutions such as offices, hospitals, and schools.

The method has produced results varied only 10.9% from the actual consumption. C. Marcoullis (1990) determined the same rates for both categories of consumers for the Paphos water supply. Similar studies in other parts of the island, such as the Limassol Sewerage Scheme (Luis Berger Int.,1985), it was assumed that the ultimate demand will be reached by the same time, the year 2000, after running consumption of 225 litres/h/day for residents, and 500 litres/h/day for tourists. As one can see these rates are very similar to those above.

These rates of per capita demand will be used to make a projection of the total water demands up to the year 2020. If however, tourist developments increased as will be expected, the foreseen demand by the year 2020 will be increased up to $8.3x10^6m^3$. Monthly demand of course varies considerably but peaks during summer season, particularly between July and September. For these three months demand would range between 11 and 13% to that of the total annual demand, but W.D.D. is adopting higher values for design purposes to coastal-tourist areas as 15%. In Table 4.5 is shown the monthly pattern demand for the year 2000 and 2020 and the projected demands for these years. The monthly pattern is made up by combining statistics produced by different agents (Town & Planning Bureau,1990; C.O.T.1992; W.D.D.,1992; Luis Berger Int.,1993; H. Humphreys,1993).

4.5 IRRIGATION WATER DEMAND

Irrigation demand is difficult however to predict because of uncertainties, such as the shift of the local population to the tourist area and the limited market orientation for irrigated crops. Athough there is an increase demand of irrigation for amenity areas around tourist developments. For instance, $2 \times 10^6 m^3$ per year are to be provided for a certain golf course.

Meanwhile, there is a need for more water than is provided by the Asprocremmos dam, especially in dry years, but this is likely to be satisfied by new supplementary supplies from the proposed development in Ezousa and Dhiarizos river (sections 3.1.4 and 5.2.1). This problem has been very acute during the recent drought of 1989-91 where tough control measurements were implemented. Irrigation provisions were limited to the actual requirements of the permanent plantation and for the seasonal crops. The water was provided by taking into account the farmers actual income while for the other users there were even further tighter restrictions. These restrictions included the irrigation of a small percentage of the land use and this was allowed for only gardens of low water requirements.

Table 4.5 Projected monthly water demand for the years 2000 and 2020

Month	Year 2000		Year 2020	
	%	Total (m^3)	%	Total (m^3)
January	5.2	292,500	5.0	415,000
February	4.9	275,625	4.8	398,400
March	6.8	382,500	6.3	522,900
April	7.4	416,250	7.3	605,900
May	8.3	466,875	8.3	688,900
June	10.8	607,500	10.4	863,200
July	11.9	669,375	11.4	946,200
August	13.0	731,250	13.5	1,120,000
September	11.6	652,500	12.0	996,000
October	8.8	495,000	9.2	763,600
November	6.0	337,500	6.3	522,900
December	5.3	298,125	5.5	456,500
Total		5,625,000		8,300,000

Source: Town Planning Bureau, 1990; C.O.T., 1992; W.D.D., 1992; Luis Berger International, 1993; H. Humphreys, 1993; Author's research, 1993

CHAPTER 5

THE RIVER RESOURCES AND THE SCHEDULED DEVELOPMENTS

5.1 GENERAL VIEW

The water resources, are highly vulnerable to the climatic interannual variations and this has been the cause of a long suffering throughout the Cyprus history.

Paphos region is drained by three of the major rivers in the island. These are the Dhiarzos, Xeros, and Ezousa rivers, (see Fig.4.1). These rivers have, so far, been providing an essential source for long term utilization.

The three rivers are rather perennial and they emanate from the Troodos mountains as the other rivers in the island. Their catchment characteristics are very similar and therefore they respond almost the same during the major storm events. They receive approximately the same amount of rainfall. Rainfall over the Dhiarizos basin is slightly higher since the altitude of its higher part is greater than the other two rivers. The average annual precipitation for the period 1951-1990, over the three river catchments can be illustrated by isohyets as in Fig.5.1.

The mean inflows at the gauging stations sited a few kilometers from the sea, over the years up to and including the year 1991 and the catchment characteristics can be along the following lines (Table 5.1). The catchment characteristics are based on flows simulated using the Mero model. A rainfall/run-off model was developed in 1967 by Mero of Tahal-Israel, to suit conditions in Cyprus (W.D.D.,1992).

The three rivers by passing through deeply entrenched valleys of steep gradients over the mountains and eventually in wide flood plains in the coastal zone, have been actively depositing materials particularly within their lower courses over some distance from the sea. These portions of the river

Fig 51 Isohyetal map of the Ezousa, Xeros and Dhiarizos catchment areas

Sourse: Kypris et al, 1989

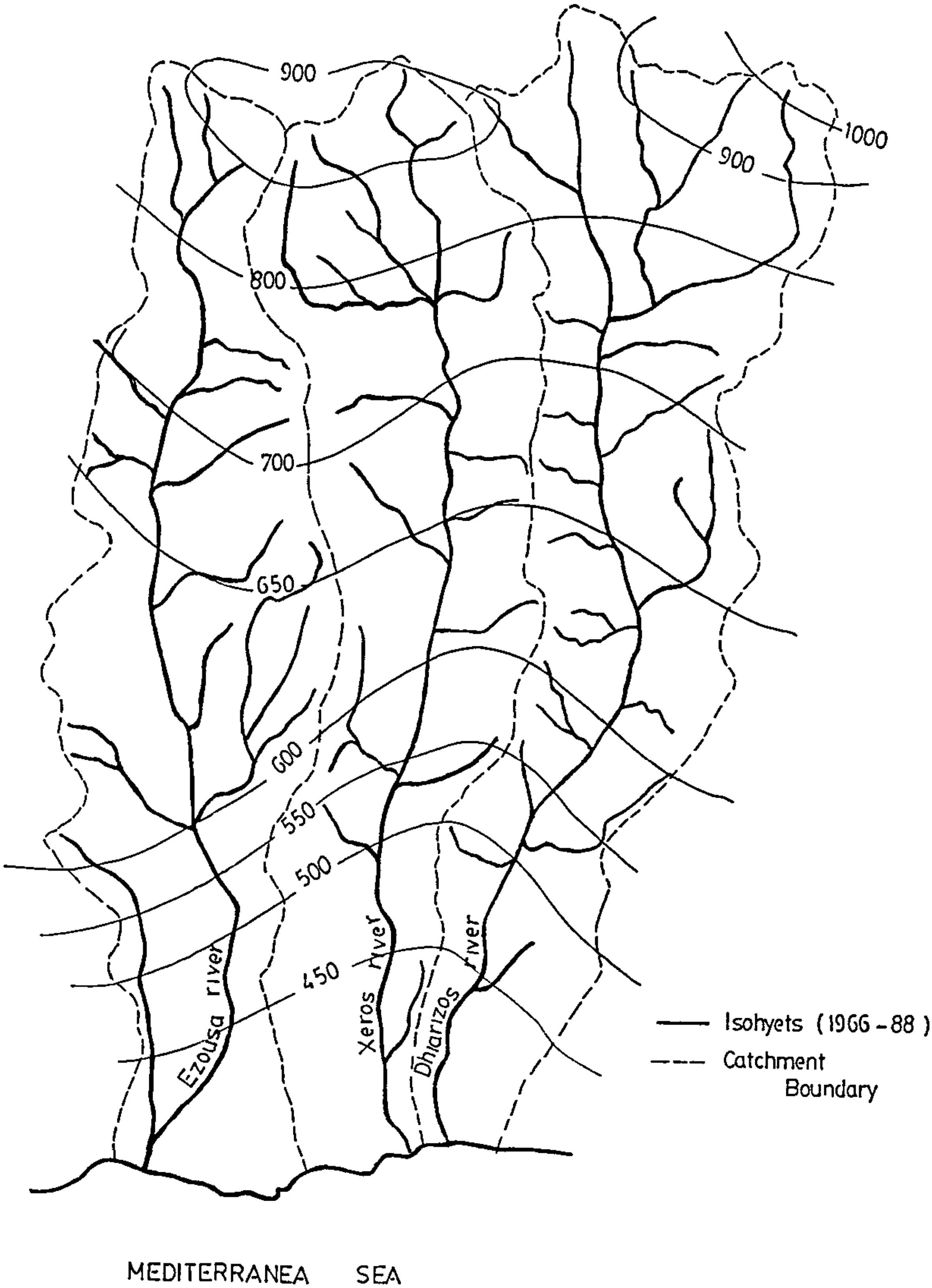


Table 5.1 River characteristics

Rivers	Gauging st.	Distance from the sea	App. Mean Annual Flow	Catchment Area	Arith. Mean of annual depth-area precipitation	Run-off factor
Dhiarizos	Kouklia	1.5km	$25x10^6m^3$	$263.7km^2$	711.4mm	0.208
Xeros	* Phinikas	4.5km	--	$218.9km^2$	710.7mm	0.209
Ezousas	Akhelia	2.3km	$15x10^6m^3$	$211.3km^2$	668.2mm	0.180

* Terminated after the construction of the Asprocremos Dam.

Source: W.D.D., 1992.

valleys contain important gravel aquifers which have heavily been exploited for the last 40 years, (W.D.D., 1992)

The river gravel aquifers are supplied from October to April by infiltration of the surface river flows, the time dependent variations of which are fairly similar for the three rivers; in addition recent piezometric data (Fig.5.2) show that the groundwater level fluctuations are closely related to the surface flow variations.

However, the prospects of the gravel aquifers are closely related to the surface flow developments scheduled further upstream. These developments as have been projected by the W.D.D. should affect the natural regime of the Dhiarizos and Ezousa river basins in a similar way to the Xeros river after the construction of the Asprocremmos dam. When the proposed works have finished, the downstream river courses should dry unless impounded water is released or spilled over after very wet years. This has been subject of long discussion between local environmentalist groups, the communities which are sited along the river basins and the government agents.

5.2 THE CURRENT SITUATION AND THE PROPOSED DEVELOPMENTS

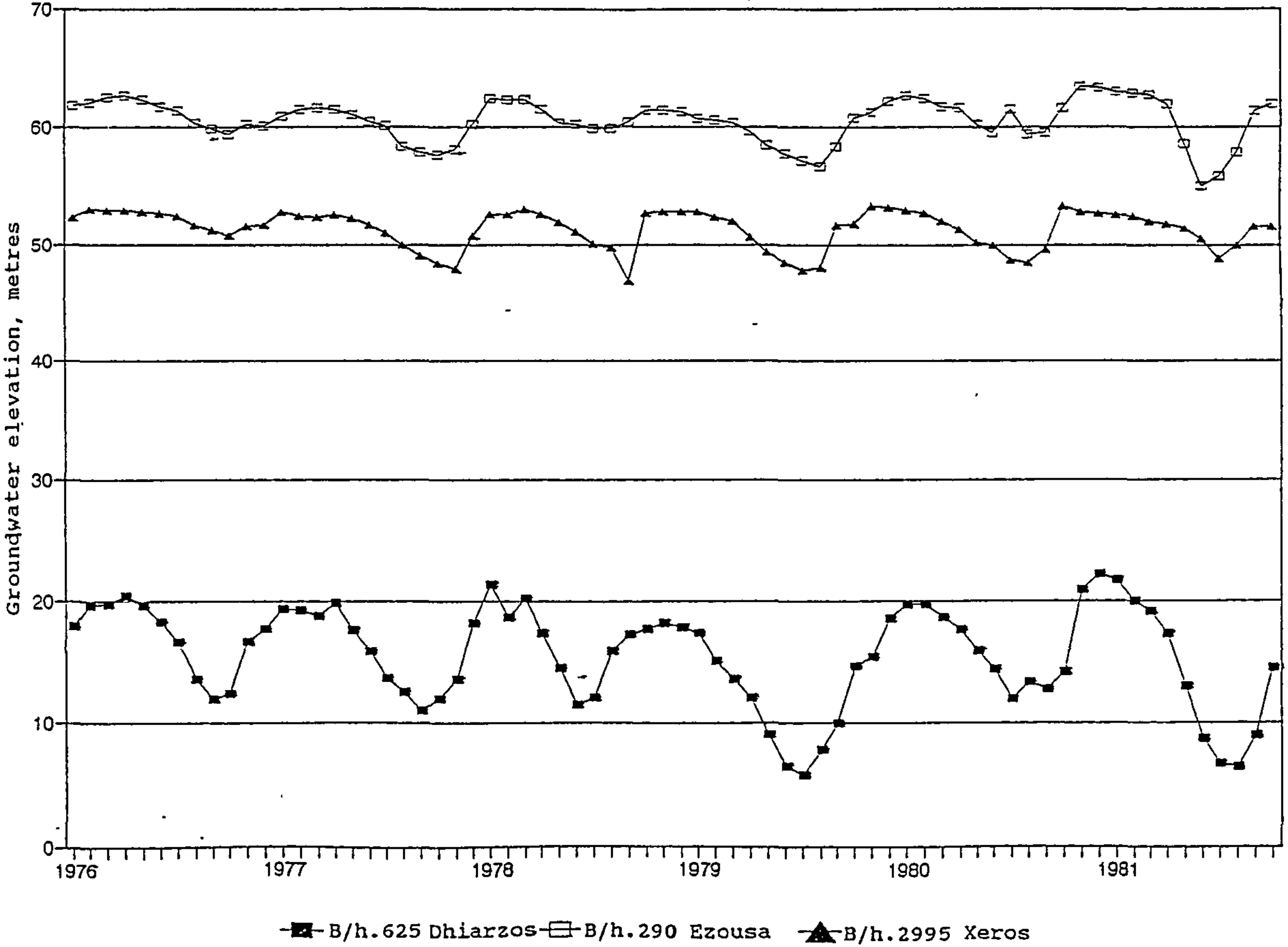
5.2.1 The Dhiarizos river

The alluvium of the river forms an aquifer of 13km, which is the longest in the area. Numerous drilling operations were carried out by the private and public sector. After a field survey was conducted by the author it was found that only 29 boreholes are regularly in service. Nine of them are used by the P.I.Project (see Fig.3.2) and it is estimated that they produce over half the total annual water yielded from this aquifer.

An indication of the pumpage occurred, may be provided by citing years data. The data concerning private abstractions, were selected through information taken from farmers. But these referred to the P.I. Project's boreholes based on water

Fig. 5.2 Hydrographs from wells in river gravel aquifers

Source: WDD,1990



meter records, where these were available by W.D.D. These records do not appear to be very accurate, due to usual discontinuities of the water meter records. All information collected and data used has been processed to conclude a rough estimate of the extraction potential of the river aquifers. This also applies to the other two rivers studied.

The following table (Table 5.2) includes recent past yields and can provide some indication of the operational requirements.

The Dhiarizos river is a major potential water resource in the island. Now large volumes flow freely to the sea but soon large amounts of the winter flows will be available for the Southern Conveyor Project through especially designed tunnel. These development along with the proposed ones are described below and are shown schematically in Fig.5.3, (H.Humphreys,1993).

Arminou Dam. Closed to Arminou village where is the narrowest section of the river valley, an impounding reservoir of maximum capacity $5x10^6m^3$ will be constructed in order to ensure irrigations and potable requirements within the Higher Villages Development Programme.

Diversion Tunnel. Downstream, about 1.6km. from the proposed dam site, a 15km long diversion tunnel of maximum capacity $6.5m^3/s$ has been constructed. Its role is to discharge through it as much as $20x10^6m^3$ per annum of the winter flows into the Kourris dam which is the largest water resource of the Southern Conveyor, multi-purpose project.

Souskiou Dam. A regulation-recharge dam of maximum capacity of $2.5x10^6m^3$ has also been proposed within the optimum utilization of the Dhiarizos resources. This dam will be set up at the nearest point to the Asprocremmos basin which is sited about 7km from the Dhiarizos reach. It will serve dual

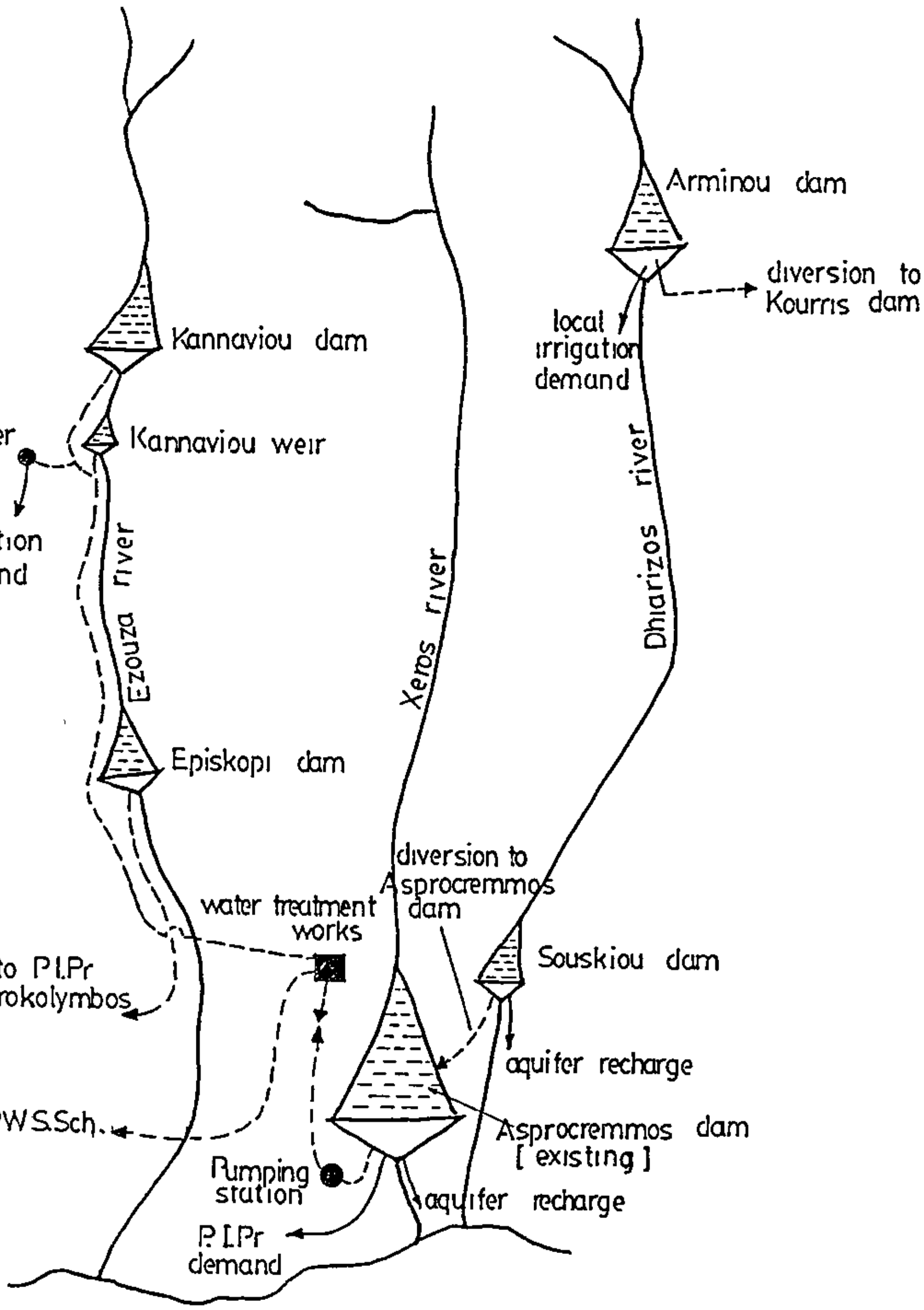
Table 5.2 Abstraction from Dhiarizos river gravel resources

Year	P.I. Pr. Supplies	Private Pumpages	Total
1983	$1.8x10^6(m^3)$	$1.3x10^6(m^3)$	$3.1x10^6(m^3)$
1984	$1x10^6(m^3)$	$1.2x10^6(m^3)$	$2.2x10^6(m^3)$
1985	$1.5x10^6(m^3)$	$1.4x10^6(m^3)$	$2.9x10^6(m^3)$
1986	$3.6x10^6(m^3)$	$0.9x10^6(m^3)$	$4.5x10^6(m^3)$
1987	$2.9x10^6(m^3)$	$1.5x10^6(m^3)$	$4.4x10^6(m^3)$
1988*	$0.02x10^6(m^3)$	$1.3x10^6(m^3)$	$1.32x10^6(m^3)$
1989*	$0.15x10^6(m^3)$	$1.7x10^6(m^3)$	$1.85x10^6(m^3)$
1990	$4.3x10^6(m^3)$	--	$4.3x10^6(m^3)$

* Dry years occurred

Source: W.D.D., 1992; Autohor's Research, 1992

Fig 5.3 Schematic diagram of the proposed developments of the Dhiarizos, Xeros and Ezousa river



purposes: a.) to divert surplus winter flows to storage in the Aprocremmos reservoir and b.) to maintain aquifer yields after the reduction of inflow due to the construction of the Arminou dam and diversion weir upstream.

5.2.2 The Xeros river

The water resources of the Xeros river were assessed under the Paphos Irrigation Project in 1970 and had led to the construction of the Asprocremmos dam with its maximum capacity $52x10^6m^3$ in 1982. The dam is sited about 3 km from the sea or where the river breaches the Kissonerga-Kouklia escarpment. Asprocremmos dam is the principal water source of the P.I.Project. In the ultimate development of the project area with total irrigation demand of $32x10^6m^3$ per annum, Asprocremmos reservoir would be fully utilized, there might be some curtailment of irrigation supplies in particularly dry years. The maximum and minimum inflows recorded each year are shown in Table 5.3.

Paphos Municipality and Paphos Lower village Scheme depend completely their water supplies on the wellfield located upstream of the Asprocremmos dam (Fig. 3.1). Ten boreholes five for each scheme were constructed in the river gravel bed. The drillings had an average depth of 18m and their casing are of steel pipe of 12" in diameter. They are equipped with electric-submersible pumps of 20-25kw and have various discharge range from 60 to $85m^3/h$.

It is worth noting that due to the normal ageing of the pumping and drilling facilities during the operating period, clogging of screens, wear equipment, possibility of momentary break-downs etc. the average discharge has been declining considerably, up to as much as 50% at times.

Within the upstream portion of the above wellfield, thirty-three boreholes were found, irrigating small properties off the river bed. Also, as matter of the pressure exerted

Table 5.3 Asprocremmos reservoir operation

Year	Maximum Storage		Minimum Storage	
	Volume (m^3)	Month	Volume (m^3)	Month
1982	$6.28x10^6$	May	$1.90x10^6$	December
1983	$20.03x10^6$	June	$2.13x10^6$	January
1984	$25.69x10^6$	May	$14.27x10^6$	November
1985	$28.97x10^6$	April	$15.83x10^6$	December
1986	$21.71x10^6$	April	$9.46x10^6$	December
1987	$43.15x10^6$	May	$33.43x10^6$	December
1988	$52.38x10^6$	March	$41.67x10^6$	December
1989	$52.38x10^6$	January	$36.37x10^6$	December
1990	$38.76x10^6$	March	$21.98x10^6$	December
1991	$21.65x10^6$	January	$13.06x10^6$	December

Source: W.D.D., 1992

by the local population, minor government schemes are being planned by the W.D.D.

The total yield from the Xeros aquifer was estimated after following the same approach as in the case of the Dhiarizos aquifer. The findings for the years 1985 to 1990 are tabled below (Table 5.4).

The Xeros lower basin which cross the coastal plain has been cut-off from the river course after the construction of the Asprocremmos Dam.

5.2.3 The Ezousa River

As shown in the Table 5.1 the mean annual flow approximately $15x10^6m^3$ yet remain unexploited and flows freely to the sea. Although some minor surface flows are boosted into the Mavrokolymbos reservoir. These supplies are shown in Table 5.6 and vary between $0.5x10^6m^3$ and $2.0x10^6m^3$ per year depending upon the contribution of the Mavrokolymbos river.

The lower river course 7 km from the sea is an important aquifer. It has undergone heavy exploitation particularly since the implementation of the P.I.Project by the development of eight boreholes over the end portion of the channel (see Fig.4.1). The total annual yields for the last ten years are given below, in Table 5.5.

Some minor extractions occured along the rest of the river gravel upstream but because of the river narrow valley the potential yield is limited and only some localized spots exhibits higher yields. It was found, through field inquiry, that $0.6x10^6m^3$/an was used for local irrigation requirements over the last few years.

As referred to the prospective development of the surface flows of the Ezousa river, these are being considered now within the projected C.P.W.S.Scheme that is discussed in

Table 5.4 Abstraction from Xeros river gravel resources

Year	P.M.W.S. & P.L.V.S. Supplies	Private Pumpages	Total
1985	$1.72 \times 10^6 m^3$	$0.06 \times 10^6 m^3$	$1.78 \times 10^6 m^3$
1986	$1.86 \times 10^6 m^3$	$0.56 \times 10^6 m^3$	$2.42 \times 10^6 m^3$
1987	$2.04 \times 10^6 m^3$	$0.86 \times 10^6 m^3$	$2.90 \times 10^6 m^3$
1988	$2.25 \times 10^6 m^3$	$0.78 \times 10^6 m^3$	$3.03 \times 10^6 m^3$
1989	$2.45 \times 10^6 m^3$	$0.72 \times 10^6 m^3$	$3.17 \times 10^6 m^3$
1990	$2.84 \times 10^6 m^3$	$0.66 \times 10^6 m^3$	$3.50 \times 10^6 m^3$

Source: W.D.D., 1992; Author's Research, 1992

Table 5.5 Abstraction from Ezousas river gravel resources

Year	Total Extractions
1981	$1.3 \times 10^6 m^3$
1982	$1.7 \times 10^6 m^3$
1983	$1.8 \times 10^6 m^3$
1984	$1.8 \times 10^6 m^3$
1985	$1.9 \times 10^6 m^3$
1986	$2.7 \times 10^6 m^3$
1987	$2.9 \times 10^6 m^3$
1988	$1.1 \times 10^6 m^3$
1989	$1.3 \times 10^6 m^3$
1990	$3.0 \times 10^6 m^3$

Source: W.D.D., 1992; Author's Research, 1992

section 3.1.4. The proposed developments of the Ezousa river is shown in Fig.5.3.

Because the gravel bed of the Ezousa river is to be of great importance for the current investigation not merely as an aquifer system but as a recharge and storage system of the domestic effluents of the Paphos town as well. This will be proceeded apart of the coastal plain calcarenite aquifer when it is to be studied the role of the Paphos domestic effluents, in Chapter 14.

5.2.4 The Mavrokolymbos River

The Mavrokolymbos river is a small river flowing through a small catchment area of $39.9km^2$.

This catchment experienced very little flow in the recent past; this is primarily due to the recession in the surface run-off corresponding on the one hand to the sustained decrease in rainfall and on the other hand to the reclamation of the land use over the river valley, (viz. the rugged terrain turned out to vineyards). Therefore the river is unable to fill the dam itself. This problem has finally been overcome by conveying winter flows through the pumping facilities of the P.I.Project from the Dhiarizos and the Ezouza river. Also with this arrangement the flow to the sea has been reduced. The limited potential of the river can be assessed through citing information of the inflows into the dam as in Table 5.6.

The Mavrokolymbos dam will be considered as the optimum development allowed for that resource.

Table 5.6 Mavrokolymbos reservoir operation

Year	Maximum storage		Minimum storage		Supplies from the Asprocremmos Dam m^3
	Volume (m^3)	Month	Volume (m^3)	Month	
1980	1,350,000	April	90,000	Oct.	--
1981	1,750,000	"	116,000	Nov.	--
1982	649,000	"	100,000	Aug.	--
1983	678,000	"	110,000	Oct.	--
1984	448,000	"	170,000	Sept.	--
1985	764,000	"	268,000	Oct.	--
1986	533,000	"	244,000	Oct.	--
1987	877,000	"	150,000	Oct.	--
1988	2,164,000	"	227,000	Dec.	1,114,000
1989	2,082,000	March	120,000	Nov.	500,000
1990	2,070,000	April	127,000	Oct.	1,846,300
1991	1,890,000	"	175,000	Nov.	1,927,050
1992	2,180,000	March	310,000	Nov.	1,460,850

Source: W.D.D., 1993.

CHAPTER 6

GROUND WATER DEVELOPMENTS AND IRRIGATED AGRICULTURE OVER THE COASTAL PLAIN.

6.1 HISTORICAL REVIEW OF IRRIGATED AGRICULTURE

Paphos was once the principal town of the island (see section 1.3) has experienced commercial successes, in both navigation and agriculture. The evergreen had been found here was led to the name of the Yeroskipos nearby, (literally in Greek, the Holy Gardens) which was also regarded in the ancient times, as the gardens of the Goddess of Aphrodite (Mangoian et al.,1947). There is little knowledge of what was planted or cultivated in the area, but it is believed that hemps, cereal, vines, orchards, summer crops might have been cultivated throughout the island (Grecos,1991). The irrigation water was provided from the rivers through earth canals networked where the elevation allowed it. Spate irrigation had been practiced extensively in the island, (Peristianis,1930). Chain-of-wells was found to perform so far, (this is described in section 6.2.2). These structures are similar to that of the Persian ganats but here was found to distribute in lesser area, (Christodoulou, 1959). Unfortunately there is no information as to the extent that they had used over this period or how much water it was providing. Remains within the ancient settlements show that it was used for domestic purposes as well as irrigation.

During the Middle Ages, visitors to the region described the coastal plain with an emphasis of the gardens they found here (Pavlides,1993). They reported seeing evidence of extensive cultivations of onions, beans and other seasonal crops. Ruins of the workshops for sugar processing have been found in the Kouklia, Yeroskipos (Mitjia), Kato Paphos. Similarly, there is evidence for hemp manufacturing in Kissonerga, Tala, Yeroskipos.

Irrigation practice during this period was continued as before, and relied almost completely on the river spates and lesser on groundwaters. This later source was chiefly being used for potable supplies and was being obtained from shallow dug-wells by employing simple lifting devices.

During the Turkish occupation from 1570/71 to 1878 these schemes were abandoned but in its last decade private enterprises brought about some development. Chain-of-wells had been developed and dug-wells equipped with similar to "Persian wheels" arrangements made their appearance.

The chain-of-wells, were usually developed by the larger estates of the area, the Yerotjipia, the Akhelia, the Lisatto, Mandria, and Kouklia. The conditions, herein, were favourable for these excavations because of the existence of shallow aquifers and the presence of easily excavated calcarenite rocks.

Hemp and cotton yet remained important crops and tobacco was taken-up. Sugar cane cultivation came an end by the early years of the seventeenth century due chiefly to the shift to the most profitable cultivations as the cotton (Aristidou, 1986). In the 1850's the main cultivations were cotton, hemp, tobacco, sesame, linseal, cereals, and onions, and course of cereals.

Much the same pattern of cultivations mentioned above, were continued until the post World War II days. The introduction of mechanical pumpings initiated farmers to make more intensive land use with wider choice of crops and higher yields. Thus traditional crops as cotton, hemp, sesame, eventually were replaced with higher value crops as citrus, bananas, potatoes, ground-nuts,etc.

Unfortunately, no analytical statistics of water supplies and irrigated crops were found. Although some figures were available (Christodolou,1959) which demonstrated irrigated areas with perennial flows from the Dhiarizos, Xeros, Ezousa for the year 1946 (Table 6.1). These figures with maps illustrated perennial irrigations with or without mechanical means. This later map referred to the perennial irrigation with the use of mechanical means may indicate the exploitation occurring at this time across the coastal plain calcarenite aquifer. These maps are shown on Fig. 6.1a and 6.1b.

A census which was later carried out, in 1962 by the Agricultural Department revealed that crop irrigation distribution over the coastal plain was as follows:

Crops Irrigated by river's spate	:	18%
Crops Irrigated from wells or boreholes .	:	13%
Rain-fed crops	:	38%
Uncultivated land	:	31%

Nowadays, groundwater yields consist only a small fraction of the total irrigation water provided along the coastal plain. An estimate based on evapotranspiration computations showed that this ranges between 7-10% (see section 6.3).

6.2 OLD PRACTICES IN GROUND WATER EXPLOITATION

6.2.1 General

Ground water developments go back to ancient times. Chain-of-wells or qanats have been set up for delivering continuous quantities of water. These persist to the present day and can be found in a band across the arid regions of Southwestern Asia and North Africa extending from Afghanistan to Morocco, (Todd,1980).

In Cyprus and in Paphos regions as well, there are many evidence visible in the field which determines early historic groundwater developments. However, it is much later in the second half of the 17th century, when such developments as chain-of-wells and dug-wells had been widely employed in the

Fig 61a Cyprus perennial irrigation. water drawn mechanically 1946

Fig 61b Cyprus perennial irrigation: free water 1946

Each dot represents 3.3ha

0 10 20 40

Source Christodoulou, 1959

Table 6.1 Irrigated areas from perennial flows (1946)

River	Basin section-ha	Plain section-ha	TOTAL-Ha
Dhiarizos	480	230	710
Xeros	187	356	543
Ezousas	107	140	247

Source : Christodoulou, 1959.

region (Christodoulou,1959).

Chain-of-wells have been the most ever compatible invention to draw-off groundwater. It was needing only some technical skilling as in building sub-surface tunnelling and nothing mechanical device was required to force the water out. Dug wells, in contrast to the chain-of-wells, were much easier in construction but there it was necessary a mechanical provision to tap the groundwater on the surface.

Both developments have been well established over the study area. The description below is based on the author's information received from farmers involved in this task.

6.2.2 The chain-of-wells

"Chain-Of-Wells" is the term used by the British for the traditional "fotistica" which literally means that they carry "fos" (in English light) into the tunnelling.

Chain-of-wells were favoured where shallow aquifers prevail. The maximum depth founded was 2.5 to 4m from the ground. It was near horizontal tunnel which started below the saturated zone at the beginning of the excavation and emerged at the surface at the other end. Water infiltrated into the tunnel and flowed out by gravity to the surface. Usually a storage reservoir was built at the outlet. The tunnel was linked to the surface by vertical shafts excavated 20-25 metres apart. The shafts provided light and ventilation during the construction and maintenance works. They also facilited the disposal of the excavated materials. The opening of the shafts to the surface was used to be sealed with slabs of concrete, metal caps or flat rocks. The tunnel and shafts were subject to caving-in. Affected sections were braced by lining the walls with rocks, wood or concrete.

The construction pattern varied from place to place. It was dependent upon the physical site (landforms, rocks easily excavated, ground-water table etc.) and irrigation requirements. The excavation of the tunnels, most usually, followed normal directions to the flowlines but combining patterns were also very common. With this way multi-directional functioning of the system was allowed . As recorded in 1971 on Catastral Map No. 51, a distribution of a typical chain-of-wells is illustrated in Yerojipia location (see Fig.13.1).

The performance of this development could not be appraised through statistics because there are not as such elsewhere. Nevertheless, local resources argue that the system has been very effective after a preceeding wet year, but whenever drought occured their yields were obviously lower. They said that during the dry years of 1931-32 and 1972-73 most of them provided no water. However, chain-of-wells having been excavated in shallow deposits yield effects are often short term.

Most of the chain-of-wells were destroyed during the construction of the pipeline network for the P.I. Project and consequently reclamation of the fields made with heavy tractors. The only existing chain-of-wells which remains as evidence of the past is a section of the Yerojipia's location.

6.2.3 The dug-well equipped with "persian wheels"

This fashion of groundwater extraction were widely employed by the introduction of a similar to "Persian Wheels" arrangement in mid-ninetieth century, (Christodoulou,1959).

Dug-wells are hand made excavations of various depth but usually laying bitween 3-7 m along the coastal plain and 8-13m over the higher elevations. The depth, however, is always dependent on the levels of the water table in place.

The rectangular hole of the wells were about no standard size but near 1.5x1.3m was common. The bottom of the well was used to be enlarged considerably for increasing storage. The upper part from 1.5 to 2m depth usually occured in alluvium, was used to be lined with concrete or was braced with stones.

The "Persian Wheels" arrangement, usually was driven by donkeys or mules and rarely by cows. The drawn water was stored in stone built reservoirs sited beside the well. Irrigation was being based on furrow method, whilst the size of the irrigated area was being limited between 0.2 and 0.7 hectare, the maximum. The most usual plantations were gardens orientated to the local market capacity. These were green vegetables, tomatoes, melons, potatoes, beans, onions, citrus, orchards, etc.

With the appearance of the mechanical pumpings in the area in the early days of 1940's, Persian Wheels were replaced them with mechanical pumping devices. The shift from the old system to the modern was eventually achieved in the 1960's.

6.3 RECENT DEVELOPMENTS IN GROUNDWATER EXTRACTIONS

It was estimated that, between 1950 and 1970, about 270 wells were equipped with pumps or turbines, (W.D.D.,1970). These were powered by diesel engines and rarely by tractors to supply water directly for irrigation. Thus, the furrow methods of irrigation gradually was replaced by the pressurized systems which give wider options and larger cultivations. The local farming population have been very receptive to modern irrigation techniques as well as to new methods of agricultural practice like green houses and plastic tunnels, etc.

Where shallow wells occured the centrifugal pumps were commonly employed. The usual diameter used was 2" and 2 ½" but sometimes larger diameter as 3" can be seen. In deep-wells requiring high lifts shaft-driven turbines were employed. Suction pipe diameters ranges between 18 and 20cm. The pumping system is usually connected directly to the irrigation system. Application of fertilizers takes place sometimes during the pumping into the water distribution system.

The most common irrigation systems are sprinklers and trickles. The sprinkler nozzles are of 140 l/h and 200 l/h connected with a network of 1" PVC pipe diameters. Those sprinklers with 1000 l/h nozzle are fitted with aluminium galvanized laterals of 3". The 140l/h and 200 l/h are used to irrigate banana plantations, or some cultivations as potatoes, peanuts, beans, etc. The 100 l/h are exlusively used for seasonal cultivations. Trickle drips are the favoured irrigation system for bananas and green house applications because of its high efficiency.

Despite the readily available irrigation water through the P.I. Project, often the dug-wells are well maintained and are used as the supplementary irrigation source. Farmers sometimes resort to private pumpage to the fields because of the following restrictions at the P.I.Project.

a) The P.I.Project supplies water at constant pressure about 2.3 atm and 16-18m^3/h of water per outlet per 2.6-3.0 hectares. Farmers who have 0.6-1.0 ha use this water from one outlet by rotation.

b) The supplied water by the P.I.Project is interrupted between 5pm and 11pm because of the constrain of the Electric Authority. At this time the electricity requirement is it's peak and therefore costly to use it to pump irrigation waters.

c) The above constrains led the farmers to utilize pumping water from the dug-wells, using diesel, engines than the supplied water so they do the private pumping. It is only benefitting those with their own pumping systems.

d) Using the combinations of the two sources, particularly the water consumers who are fully occupied in agriculture to save time and decrease expenses.

An estimation of the irrigated agriculture over the coastal plain is provided in Table 6.2. Within the same table irrigation water is distinguished in the water supplied from the P.I.Project and in the extractions made from the calcarenite aquifer. Because the farm pumping systems are not fitted with water meters, extraction figures have been estimated by considering the crop water requirements with the evaporation loses (i.e. evapotranspiration). This estimation has partly been based on the irrigation pattern available from the Institute of Agriculture (Metochis,1988) and the local field experience of the author on the operation of the P.I.Project.

It is apparent from the table mentioned above that groundwater extractions has remained quite constant at least for the six years concerned. This amount approaches 9% to that of the irrigation water provided by the P.I.Project.

The shift of the groundwater extractions from the coastal plain calcarenite aquifer as from 1980 is shown in Table 6.3.

It is possible to estimate yield from the size of the pumps, pipes and hours of pumping. But because of lack of information this estimate could be very variable.

Table 6.3 may have errors in estimation ±30% for better water management for future realistic groundwater extractions quantities must be determined, possibly by fitting water meters on boreholes.

Table 6.2 Irrigated agriculture in the Paphos Irrigation Project area

Year	1985	1986	1987	1988	1989	1990
Plantations ($*10^3 m^2$)						
Citrus	4612	5356	7698	8225	8301	8436
Vines	3072	2979	3957	3915	3631	3273
Bananas	2904	3449	3905	3200	2444	2503
Avocados	415	298	438	500	475	485
Walnuts	144	198	407	479	547	687
Various trees	507	319	739	791	762	809
Nuts	4454	4126	4289	4740	6013	6981
Beans	2884	5229	8072	5159	5034	5056
Potatoes	2718	3346	5169	5460	5125	5028
Onions	323	492	478	499	492	392
Greenhouse	295	243	388	429	683	980
Melons	611	561	1040	677	789	560
Clover	624	626	648	967	381	386
Various greens	1693	1507	2026	2185	1975	1751
P.I. Project Supply $*10^6 m^3$	21.2	23.2	20.1	16.2	17.6	20.8
Groundwater pumpages $*10^3 m^3$	1746.8	1800.4	1741.2	1857.2	1740.1	1798.9
(Total irrigation)/pumpages	7.6%	7.2%	7.9%	10.3%	8.99%	7.9%

Source: W.D.D., 1992; Author's Research, 1992

Table 6.3 The shift of the groundwater extractions in the P.I.Project area 1980-1990

Year	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
Groundwater pumpages ($*10^3 m^3$)	3242.7	3126.7	3426.9	2083.5	1448.2	1746.8	1800.4	1741.2	1857.2	1740.1	1798.9

Source: W.D.D., 1992; Author's Research, 1992

PART B

INVESTIGATION OF THE COASTAL PLAIN AQUIFER

CHAPTER 7

THE PAPHOS COASTAL PLAIN AQUIFER.

7.1 INTRODUCTION

The role of the P.C.Plain groundwater resources have been a challenging issue by those concerned with water management aspects as the W.D.D. and the regional authorities. After the implementation of the P.I.Project since 1982 which covers all the lowlands of the region, officials of the W.D.D. and the G.S.D. believed that the calcarenite aquifer which underlains the Project area could have been constantly enriched due to infiltration losses.

The review of the feasibility study of the P.I.Project prepaired by SOGREAH consulting engineers of the Project (1976) has assumed increasing losses on the groundwater reserves to such extent that the need of anti-drainage works might have been necessary after some years of intensive irrigation. They suggested such preventive measures by encouraging farmers to exploit their existing pumping facilities or sink new wells, in order to retain water table level untimely rising by extracting certain volumes of groundwater.

In formulating the current investigation, the author has considered the parameters required in order to define the hydrologic conditions which prevail after ten years of the P.I.Project in service.

7.1.1 The approach to the study

It is apparent that the extent and the nature of the aquifer (i.e. whether it is confined or unconfined, etc.) can rarely be assessed from surface evidence alone and therefore initial geotechnical investigation has to be carried out. The investigation has exploited techniques such as geological archives searches, records of borehole logs, geophysical survey, etc. back up by extensive amount of corroborative fieldwork. By combining the analysis of historical data and art studies along with geotechnical engineering exercise and the results of detailed in-situ investigation the hydrogeological environment of the coastal plain calcarenite aquifer can be predicted with confidence.

7.1.2 The Coastal Plain aquifer division of zones

Groundwater basins may be defined as a hydrogeological unit containing one large aquifer or several connected and interrelated aquifers. It can be defined on general geomorphological grounds, i.e. landforms and drainage and as geographical units can be subdivided in the light of evidence visible in the field.

Considering the existing physiography of the area and the interrelation of the unit areas the following sub-division of the coastal plain aquifer has been outlined. The sub-areas are named here, zones and are listed below, (Table 7.1) and shown on plate, (Fig.7.1).

This zone division has the merit of simplicity and brevity, each zone being clearly identifiable on topographic grounds although merging into each other or to the most of the area without always clear boundaries between them.

7.2 DATA COLLECTION AND UTILIZATION OF FIELD EVIDENCE

7.2.1 Topographic data

Catastral map series of scale 1:25000 cover the entire island. These maps provide good information of the landforms, terrace, natural environment and elements of land use. The last edition dates back to 1971 and therefore some significant changes have occurred over the study area. Nevertheless, the map with Serial No. 45 and 51 were used as the base maps during the reconnaisance stage of the current investigation. Field survey information and other pertinent references obtained has allowed the updating of these maps or otherwise to adapt them according to the study requirements. Also, much

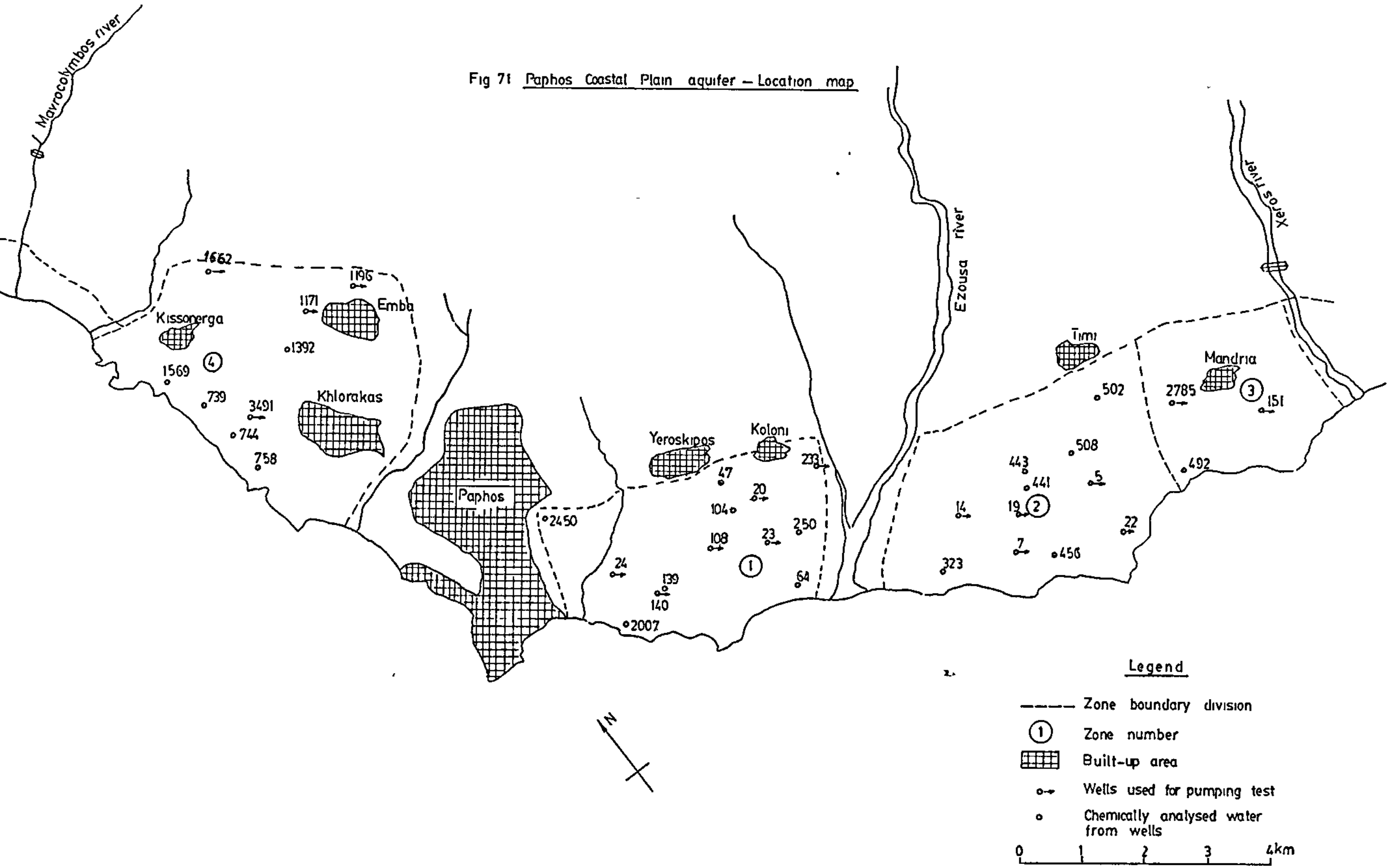
Table 7.1 Hydrogeological zones

Zone	Area of zone	Village Areas within the zone	Aquifer
1	12.04km^2	Yeroskipos-Koloni	Calcarenite
2	14.40km^2	Akhelia-Timi	"
3	6.76km^2	Mandria	"
4	12.25km^2	Khlorakas-Emba-Kissonerga	"

Table 7.2 Water bearing formation capacity of the calcarenite aquifer (m^3)

Zone	For November 1980	For March 1981	For October 1981	For November 1987	For March 1988	For October 1988
1	3.9x10^7	5.73x10^7	5.11x10^7	4.68x10^7	5.64x10^7	5.35x10^7
2	9.07x10^7	11.21x10^7	10.20x10^7	6.28x10^7	9.42x10^7	8.88x10^7
3	4.20x10^7	5.30x10^7	4.65x10^7	3.92x10^7	4.56x10^7	4.32x10^7
4	2.02x10^7	3.61x10^7	3.01x10^7	2.88x10^7	3.58x10^7	3.15x10^7

Fig 71 Paphos Coastal Plain aquifer – Location map



time was spent to plotting the several drillings and wells having a lithological and hydrogeological interest.

Specific topographic survey was undertaken for the drawing of the various maps (hydraulic basement of the aquifer, groundwater contouring, groundlevel maps) and the several hydrogeological sections. This task included extensive levelling of the numerous reference points, (i.e. boreholes, wells, and some other intermediate auxiliary points), which were later used for the drawing of the various maps mentioned above.

7.2.2 Hydrologic data

Water balance consideration has been based on the classical method of estimating inflow-outflow quantities and groundwater head difference, (section 12.1). As regard inflows precipitation records were available from the Meteorological Department (section 2.3), which maintains two gauging stations in the area. Percolation due to infiltration losses of the irrigations were not readily available. The assessment of these losses have been based on water balance computations by considering evapotranspiration requirements to estimate groundwater extractions from the calcarenite aquifer (which is detailed in Chapter 12).

A network of wells and boreholes were set-up by the W.D.D. Hydrogological Division with the establishment of the regional office in 1969. Water table levels have since then been recorded regularly on monthly and six-months interval. The networks covers the entire coastal plain and the major rivers, Dhiarizos, Xeros, and Ezousa gravel aquifers. From the available record book it was found that some sets of readings were incomplete whilst in other cases measurements were terminated some time later because of the closing up of the wells. Also, some measurements were taken while in the well or nearby pumping was in operation. The latter used to produce hydrographs to show the influence exerted by pumpage in this particular aquifer (see section 11.3). All the measurements seem reliable and have been used officially for relevant studies. These measurements have been used to produce representative hydrographs to the calcarenite aquifer conditions as well as groundwater table level contouring maps. The provided measurements have not been used immediately but incorporated with the mean sea level in places and expressed as absolute water level records. This data is used everywhere within this study.

All survey data have been developed on three dimensional coordinate system and together with the other pertinent information from the topographic survey were inserted into a computer programme, Quick-Serf (Q.S.), Version 2. This programme in conjuction with the AutoCad was capable of fitting contours and calculating the resulting capacity with respect to a fixed datum. For proceeding more approximation to the reality it was allowed to the programme to run the smaller grid scale of 200mx200m.

The resulted water bearing formation capacities are provided in Table 7.2.

It was realized that the produced contour maps had marked the actual situation and only a few distortions had been recognized. This drawback, though of insignificant importance was immediately corrected by hand.

For the purpose of this study (Chapter 11 and 12) have been produced several groundwater table level contour maps which respond to the commencing and ending of the hydrological year (i.e from 1st of November to 30th of October), and an intermediate map respond to the hydrological conditions before the commence of the irrigated season (i.e. end of March). Therefore, the groundwater level fluctuations and groundwater gradients are revealed within the water table maps, that is described in section 11.3. The capacities associated with these maps as produced by the Q.S. programming, are to be used later on in this thesis to carry out storage computations (section 12.3). Some other assessments regarding the groundwater flow regime was also possible and are found elsewhere in this study.

These groundwater table level contour maps are of 1:25000 scale in all zones. The contour interval is basically 5m interval, for the zones 1,2,3 and 20m for the zone 4 but 10m were also drawn where this was considered necessary.

These maps respond to the following seasons/years:

Ground water table level contour map for	November	1980.
- do -	March	1981.
- do -	November	1981.
- do -	November	1987.
- do -	March	1988.
- do -	November	1988.

The hydrographs are provided in Fig. 11.1a and 11.1b whereas the maps above are provided in Appendix I.

7.2.3 Geologic data

Surface and sub-surface geological mapping provides the framework for the occurence and movement of the groundwater and hence is essential for groundwater management studies.

Most of the maps which have been available are surface maps and illustrate the main geological features and the principal formations outcrop over the area concerned. Although, many institutions and individuals which had been working on various areas of particular interst either for academic purposes or for regional developments, produced some detailed maps also. Dr. H. Lapierre, for example, produced a geological map covering the region of Polis-Paphos on scale 1:50000. Within this map more emphasis was given to the Mamonia formation while the rest of the area was roughly covered being divided to the main formations encountered on the region, the Pakhna and Lefkara and the calcarenite over the entire southwestern coastal plains of Paphos.

Hydrogeological maps are also available. The official map dated in 1970, has scale 1:250000 and covers the island in large. On this map is provided all the spectrum of the aquifers encountered in Cyprus, but with some generality. Also, Dr. H.O. Tullstrom, (1970) working on behalf of the Cyprus goverment produced a very comprehensive hydrogeological map of the Paphos region. Over this map is shown the extent of the Athalassa calcarenite aquifer as well as the other aquifers though of minor importance and the aquicludes of the region. Another map concerning the different formations outcrop on the Paphos region was produced by Ingledow, (1969).

It can be noted that the general accuracy of the maps is rarely in question, because it is usually a matter of local detail.

Sub-surface geological maps were not available. However the numerous borehole and well logs which have been constructed since 1946 provided an excellent source of information including the depth of the permeable/impermeable rocks. The majority of this boreholes were drilled by the G.S.D. using the cable tool rig which is broadly acknowledge as giving the more accurate formation logging. The collection, collation and identification of the available information as well as the interpretation of the borehole logs, allowed to produce the hydraulic basement contour map and several cross-sections of the coastal plain. Regarding the hydraulic basement of the aquifer, this was drawn by using the same procedure as in the case of the water table contour maps and the same computer programming (see the preceeding section, 7.3.2). The difference here is, however, the coordinated system which responded to different spots and also instead of the water table records here was provided the absolute depth of the impermeable rocks (i.e. the clay or marls depth in repect to the sea mean level). The contour interval followed basically 10m interval but often 5 and 15m contour where were necessary, have been shown. The scale was 1:25000 for all zones. These maps are being further discussed in section 8.4. The longitudinal and lateral cross-sections are also discussed separately in section 8.3. The various cross-sections are provided in Fig.8.1, whereas the hydraulic basement contour map is shown in Fig.8.2a, 8.2b and 8.2c.

Using this approach has been possible to reveal the actual physical extent of the calcarenite aquifer and even to define, accurately, the type of the aquifer in place i.e whether the aquifer is confined/unconfined or it is an intermediate stage. This however, is dependent upon the stratification of the bounding layers. The stratification can be recognised in the legend following the cross-sections in Fig.8.1.

Further to the geological maps, the borehole logs, the in-situ survey etc., a geophysical investigation was also employed to bridge the gap between the boreholes in the Ezousa river gravel aquifer, (this discussed in section 14.7). The original electrical sounding figures and the interpretation made were available from the G.S.D. which carried out the survey in 1976.

Knowledge of the physical evolution over the island and the study of the geology of the region in particular, have strengthened the background information which was required to recognise the geomorphological phenomena which occured within the study area. Several reports and papers, though some of them had had different aims, included very useful information and references over this aspect. Most of them were available from private sources but some of them provided from the G.S.D. source and the W.D.D. library, (Christodoulou,1959; Soteriades and Koudounas,1968; Ingledow and the Associates Ltd.,1969; Proceedings of the International Ophiolite Symposium - Cyprus

1979; Proceedings of the Symposium "Troodos 1987"; Evans,1988; Hamilton, 1990).

CHAPTER 8

THE PROFILE OF THE UNDERLYING FORMATIONS WITHIN THE COASTAL PLAIN

8.1 GEO-HISTORICAL OUTLINE AND STRATIFICATION

The Lower Miocene sediments which are encountered in the study area belongs to the Lefkara group and are mainly composed of marine marls. The Lefkara marls herein underlay the Pakhna formation of the Middle-Miocene which are mainly of marly content and back the allocthonous Mamonia serpentine within the north western section of the study area. The Late-Miocene setting of the area had provided the background to the Plio-Pleistocene evolution of the basin under consideration. During the Plio-Pleistocene the Troodos ophiolite was gradually uplifted while the surrounding areas underwent tension and subsidence causing the formation of the present marine planations (Section 1.2.2). The uplift of the Troodos Massif is attributed to a combination of underthrusting of continental crust and serpentinite diapirism (Robertson, 1987). The Plio-Pleistocene sediments overlie a marked unconformity surface. Moreover, this unconformity was generated during phases of lowered sea level associated with the Messinia salinity crisis (McCallum & Robertson,1987). The calcarenite formation outcropping in the area is ascribed to the Plio-Pleistocene and include a variety of lithofacies of marine coastal origin.

With background information, the history of the geological evolution and the knowledge of the depositional and erosional events in the study area, the nature of the coastal aquifer, the continuity and interconnection of certain aquifers and the important aquifer boundaries are revealed .

8.2 THE ATHALASSA CALCARENITE AND THE LITHOLOGY REVEALED BY THE BOREHOLE LOGS

The generalised lithological section in the coastal plain from the top down to about 40m may be as follow:

In most cases all alluvial material of average thickness 3m find a layer of secondary limestone (locally named havara) developed on top of marly layers. However, there are cases in which sandy marl is present. At depths greater than 3m it is common to find an interchanging series of marly calcarenites and shelly calcarenites as well as calcarenite to calcareous sandstones. These later biocalcarenites in origin, constitutes the actual Athalassa water bearing formation. The interchanging marly beds swell and pinch rapidly so that the proportion of the pervious to non-pervious layers varies rapidly from place to place. At the bottom of the calcarenite in a number of drillings a conglomerate in clay matrix was developed. At greater depth alternating bands of chalky marls and clayey marls predominate. These usually denote the presence of the Pakhna formation. For the purpose of this study this defines the hydraulic basement of the aquifer.

In the western part of the coastal plain because of the occurrence of the Mamonia Group, beds of serpentinite and loose lavas and also clay matrix have been found to underlay the Athalassa calcarenite formation.

A summary of the geology and hydrogeology in the Paphos coastal plain is provided within the Table 8.1.

8.3 THE CROSS-SECTIONS OF THE COASTAL PLAIN

The study of the surface marks along with the borehole logs enable the author to produce various cross-sections, to show the distribution of the different rock formations which underlay the coastal plain. By completing this work it has been possible to estimate the actual physical extent of the Athalassa calcarenite aquifer and to define its thickness in place and the regularity of the water bearing rock.

This task, however, involved many complexities such as to distinguish rocks of similar marly matrix as those found within the Pakhna and Lefkara formation.

Table 8.1 Summary of the geologic and hydrologic setting occurred within the Paphos coastal plain

Age	Group	Formation	Lithology	Thickness	Aquifer
Recent		Alluvium		1-3m	No aquifer above water table
Pleistocene		Fanglomerates	Gavel, breccia, sand and silt well cemented	1-3m	?
Pliocene	Nicosia	Athalassa	Shelly calcarenite with marls intercalations	8-15m	Good aquifer with variable permeability and yields;
U. Miocene		Myrtou-Nicosia			
M. Miocene	Pakhna (Dhali)	Pakhna	Marls, marly chalk and paper shales		quite-impermeable
L. Miocene	Lefkara	Terra Limestone Upper Lefkara Middle Lefkara Lower Lefkara	Fossiliferous limestones, occasionally calcarenite and marl		limited aquifer
Up. Triassic L. Triassic	Mamonia	Sedimentary	Sandstones, pelagic limestones shales and cherts	?	Under-favourable conditions slightly aquifer
		Igneous	Pillow laves, Serpentines	?	Generally aquiclude

Source: G.S.D.,1970

Fieldwork performed so far by the author, has been inadequate to clarify such complexities encountered in-situ. Therefore, lithological analysis together with paleontological evidence from the formations should have proved valuable source of information. Nevertheless, the problem was finally overcome by retrieving available borehole lithological reference and historical data provided by the G.S.D. and W.D.D. sources.

The drawn sections revealed that the calcarenite aquifer is widely spread throughout the coastal plain and in particular between the Kissonerga and Mandria sector in east and west direction, while the Kissonerga-Kouklia escarpment marks the north boundary of the aquifer. This is approximately in line with the mapping of the former investigator S. Afrodisis (1969) and Dr. H.O. Tullstrom (1970). It contains an essential unconfined aquifer which is extensive in area though rather thin. Occasionally semi-unconfined or leaky conditions prevail, due mostly to the intercalation of the calcarenite with impermeable marls. Some localised spots can be reported as artesian as in the case of borehole No.24 between K. Paphos and Yeroskipos (see Fig.7.1). The thickness of the calcarenite marl sequence usually ranges between 7 and 13m. Field evidence showed that some 30 to 50 percent of this sequence may consist of impermeable marls.

The Pakhna formation has various thickness ranging from 10m to 160m the maximum. The Lefkara formation has thickness reaching greater depth even more that 250m. The allochthonous Mamonia formation were juxtaposited elsewhere irregularly. All these are considered as impermeable for most purposes (Toufexis and Joannou,1976).

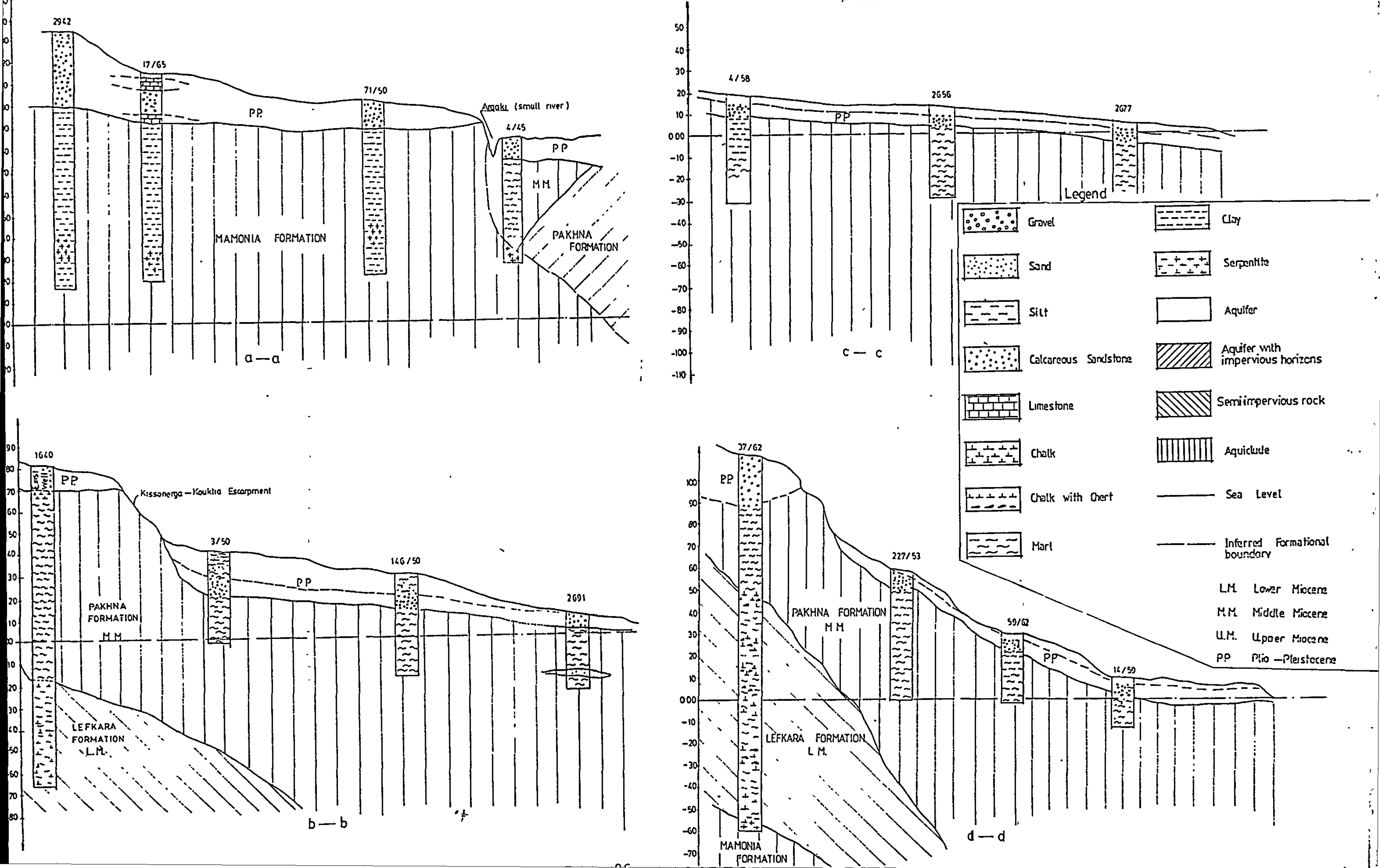
The drawn sections are illustrated in Fig.8.1.

8.4 THE HYDRAULIC BASEMENT CONTOUR MAP

This map is considered to be the principal map to which

Fig 8.1 Cross sections of the Paphos Coastal Plain aquifer

Source: GSD,1970; Author's research,1992



the assessment of the various seasonal ground water storages along with the relevant water table maps will be based on (section 12.2).

The hydraulic basement of the Athalassa calcarenite aquifer and the Ezousa river gravel aquifer (see section 14.7.2), have been defined by considering the underlying formations. These formations have low permeability due to the presence of marly and clayey beds of the Pakhna and Lefkara formation which extends from the middle to the eastern sector of the coastal plain (i.e. zone 1,2 and 3). The serpentinite and clay layers of the Mamonia Group which underlies the western sector (i.e. zone 4) form the impermeable basement of the overlying water bearing strata.

Several boreholes have been identified in the field using the available borehole record books . After careful interpretation of their logs was made possible to find out the depth of the various lithology encountered in the plain. It had been apparent from the early stage of this survey that many locations lacked certain information necessary for the drawing of this map. Therefore, an alternative method was used to proceed. Instead of attempting an extrapolation technique in order to overcome the problem, because of the risk involved, it was realised that a new round of field survey was required. This stage of investigation was practised by combining verbal information received from many individuals and farmers experienced in excavating of dug-wells. This information has been identified by personal inspection of the evidence remained in the field. However, experience shows that all information must be cross checked; particularly verbal ones involves high risk of misleading, among others.

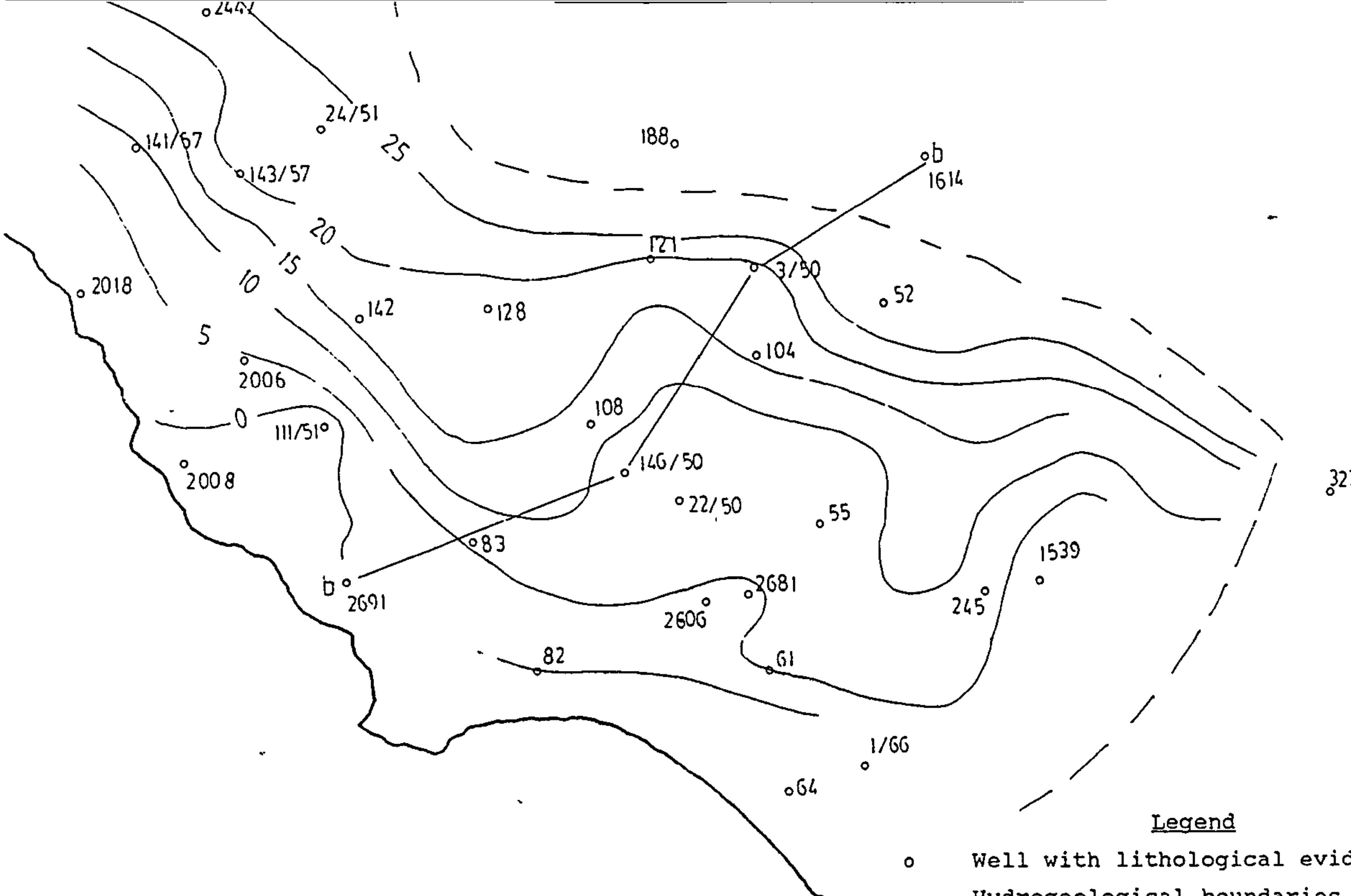
This method has allowed to extend information over many locations where there was a gap of borehole logs. Thus the depth of the marl clay in place and the depth of the water bearing horizons of the Athalassa formation were pointed out at many instances over the coastal plain. Based on this information it has been possible to complete the framework of the co-ordinate system which was used to produce the hydraulic basement contour map (see section 7.3.3). This map depicts the actual size and the geometry of the aquifer but also the following are well revealed.

- The zero contour of the base of the aquifer in respect to mean sea level from west of Paphos travels gently along the sea shore and on reaching Xeros river, it goes along the reaches of the unit inland for about 2.8km in the Kouklia-Kissonegra escarpment, comes back to the coast line and again inwards to the same escarpment in the east for a distance of roughly 1.5km.

  This configuration may be attributed to the late formation of the lower plane and alluvials deposited by the major rivers above the underlying formation of Pakhna Group. To the eastern side of Paphos town the 40m contour defines the northern boundary of the basin which coincides with the foot of the above escarpment. Some localities along the coastal fringe and even more inland and the Xeros river lower basin are endangered by sea intrusion due to the fact that the basement lies below the sea level (Fig.8.2a and 8.2b). To the north-western part of Paphos town contours as high as 130m and even 140m limit the calcarenite aquifer. Along the shore line the 5m contour is well drawn.

- The Athalassa calcarenite formation in contact with the underlying formation is irregular but has general slope towards the sea with gradients varying between 1 in 60 and 1 in 75 over south-south-east of Paphos and higher gradients of 1 in 20 and 1 in 30 over the north western side.

Outline contour map is passing the hydraulic basement of the coastal plain calcarenite aquifer as follows: a) the map in Fig.8.2a and 8.2b which covers the eastern block area (zones 1,2,3 respectively) and b) the map in Fig.8.2c which covers the western block area (zone 4).

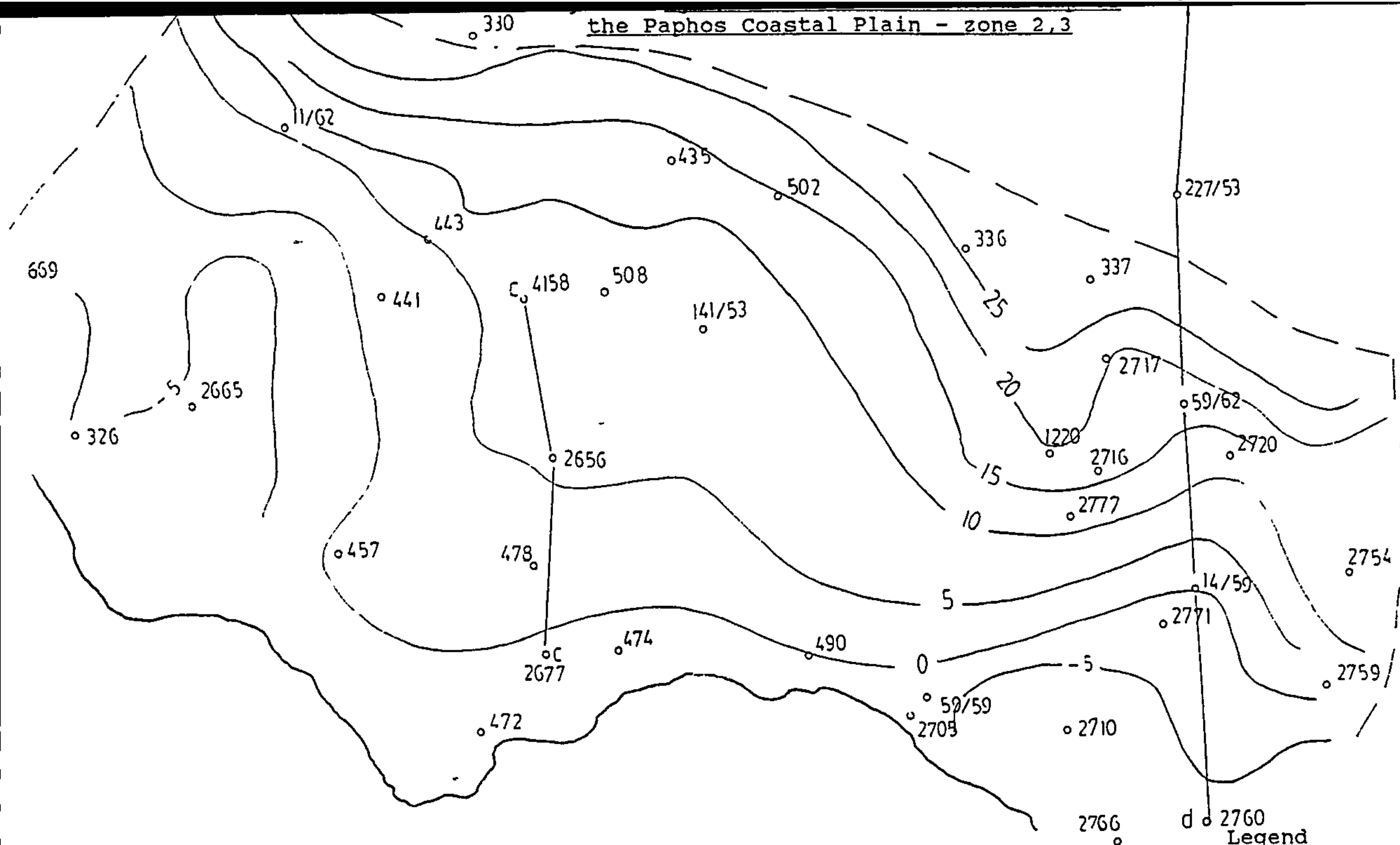


Legend

o	Well with lithological evidence
— —	Hydrogeological boundaries
——	Hydrogeological section line
—5—	Hydraulic basement contours in metres above sea level

Scale, 1:25000

the Paphos Coastal Plain - zone 2,3



Legend

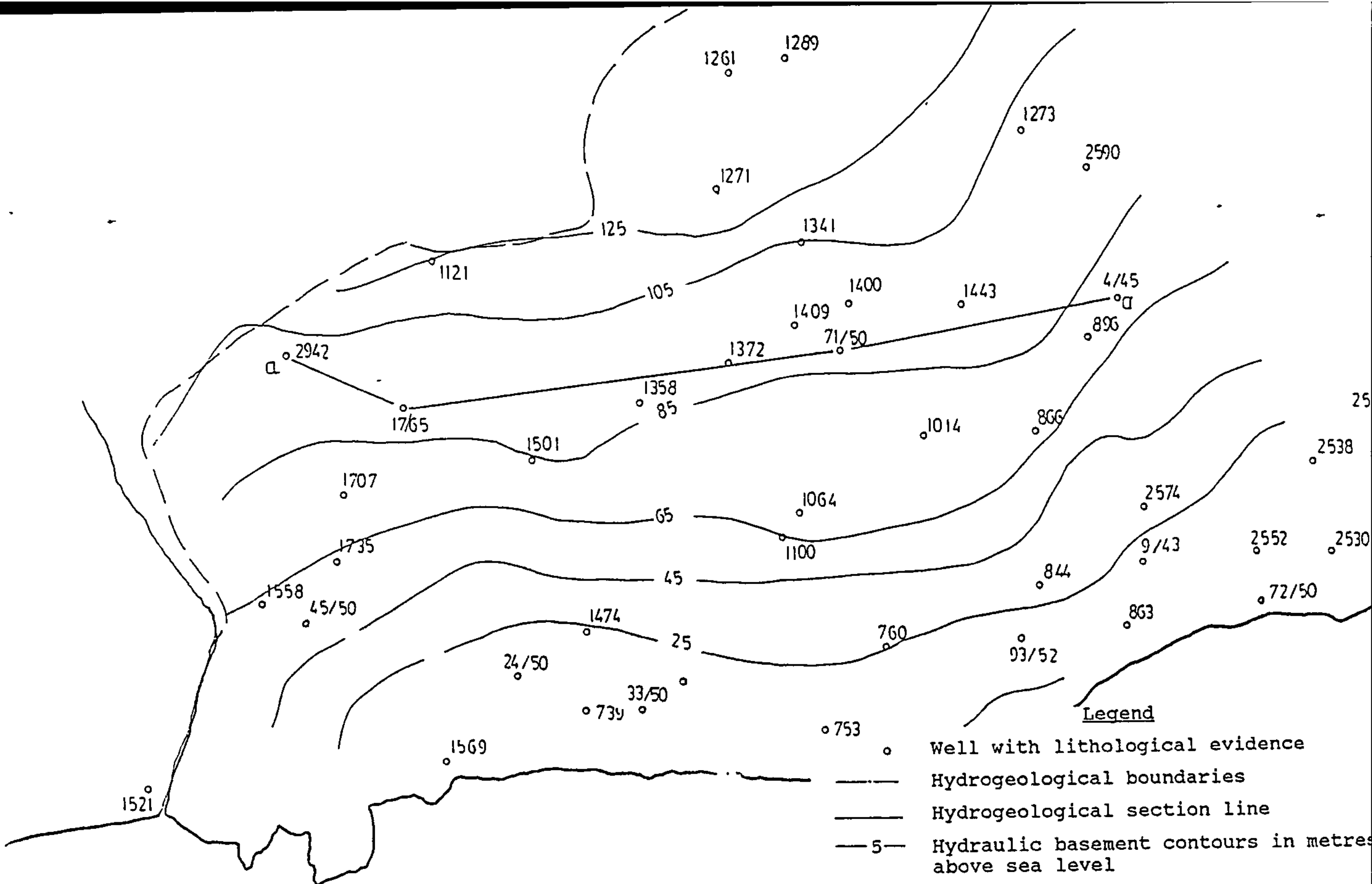
o Well with lithological evidence

— — Hydrogeological boundaries

—— Hydrogeological section line

—5— Hydraulic basement contours in metres above sea level

Scale, 1:25000


1289
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1372
2942
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1358
85
17/65
1014
866
25
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2538
1707
1064
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2574
1735
1100
2552
2530
9/43
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1558
72/50
45/50
863
1474
760
25
93/52
24/50
33/50
739
753
1569
1521
Legend
Well with lithological evidence
Hydrogeological boundaries
Hydrogeological section line
5 Hydraulic basement contours in metres above sea level
Scale, 1:25000

CHAPTER 9

THE HYDRAULIC CHARACTERISTICS OF THE ATHALASSA CALCARENITE AQUIFER

9.1 INTRODUCTION

The geologic origin of the aquifer as well as the degree of consolidation of the various rocks of the formation area and the development of the permeable zones are key factors influencing the aquifer hydraulic characteristics.

The predominant aquiferous stratum here is the Athalassa calcarenite of Plio-Pleistocene age. This is made up by sandy marls, calcareous sands and conglomerates, capped by hard limestone. This limestone consists mainly of calcarenite deposits containing many fossiliferous and hard ground horizons. The calcarenite consists of micro-fossil grains and fragments. The thickness and the boundary of the aquifer have been determined during this study by drawing sub-terranean cross sections already discussed in the preceding section. Prior to the performance of an aquifer test, this information could be used to obtain an initial impression of the hydraulic characteristics of the aquifer.

Outcrops of the formation show that it has generally low primary porosity which consists of void space between clastic carbonate fragments and shell fragments. In place secondary porosity has developed by the solution of the calcarenite especially along joint lines and fractures and therefore karstic features occurred from sinkholes to cavities.

9.2 THE AQUIFER PARAMETERS

However, field evidence will provide some knowledge of the areal distribution of the aquifer characteristics but for optimum results hydrogeological investigation is necessary to determine the most decisive parameters which mark the groundwater system. These are the hydraulic conductivity, the transmissibility and the storage coefficient and specific yield. A definition of these aquifer parameters is given below (Fair,et al,1966; Cedergen,1968; Blyth et al.,1987; Todd,1980; Bowen,1980; Bedient et al,1988).

Hydraulic conductivity (K) is defined as the rate of flow of groundwater through a unit cross sectional area of the aquifer under a hydraulic gradient equal to unity. It is expressed in m/day.

Transmissibility (T) was first introduced by Theis (1935) to define the rate of flow of water through a vertical strip of the aquifer of unit width and extending the full saturated thickness under a hydraulic gradient equal to unity. It is expressed in m^2/day and can be the product of the permeability and the thickness of the relevant water bearing layer, "KD".

Storage coefficient and Specific yield are both denoted with S and define the volume of water released from or taken into storage per unit surface of the aquifer per unit change in the component of head normal to that surface. Storage coefficient refers only to the confined aquifers and depends on the elasticity of the aquifer material and the fluid. Specific yield refers only to unconfined conditions. They are both, of course, dimensionless.

These are determined through the so called " the aquifer test" because it is the aquifer rather than the pump or well which is tested. Other methods for determining the hydraulic characteristics of an aquifer are laboratory methods (for example constant head and falling head parameters are used for measuring permeability values) and methods based on the water balance and the natural groundwater flow regime. Field methods generally yield significantly different values of permeability than that corresponding laboratory tests performed on cores removed from the aquifer and are preferable for the accurate determination of aquifer parameters. Tracer test method is also used to be employed; in Cyprus its use is restricted in special cases. For instance, tracer tests had been used to define the source which contaminated an aquifer or to draw the influence of a certain water resource in an aquifer as in the case of the Yermasoyia aquifer (section 14.4.1). It is, however, broadly accepted that the most important technique for assessing the aquifer hydraulic properties remains the pumping test. Although, storage coefficient is broadly calculated by considering water balance computation for a particular aquifer.

9.3 THE AQUIFER TEST

9.3.1 The pumping test

A pumping test in conjunction with the installation of piezometers and monitoring of drawdown, can provide direct information as to groundwater lowering and quantities of water extracted. An analysis of pumping test data provides combined data on hydraulic conductivity and thickness of water bearing layers via "KD" values. Also storage coefficient or specific yields can accordingly be estimated by applying in an appropriate formula. The pumping tests which were conducted over the coastal plain aquifer, both before and during this study, were of two types; the drawdown and the recovery test.

9.3.1.1 The Drawdown Test. In this type of test drawdown is recorded versus time at least at one observation well located at known distances from another well which is pumped at a uniform rate. For solving the problem radial flows towards the well are considered; these form "the cone of depression", and the subsequent drawdown effects are calculated with respect to a fixed datum. The equations govern the groundwater flows are based on Darcy's Law which states that the velocity of flow (v) in a given direction is proportional to the hydraulic gradient ($\Delta H/ L$) in that direction and the continuity equation.

Darcy's Law: $v=Ki$ (9.1)

where $i=\Delta H/L$

Continuity $Q=Q_o$ (9.2)

where Q_o is the discharge rate.

For growndwater lowering by pumping in an unconfined or confined aquifer and under steady-state conditions (ie variations of head occurs only in space and not in time), the aquifer hydraulic characteristics can be determined. The mathematic approach below based on an arrangement such as that shown in Fig.9.1a and 9.1b let to the formula enables to determine the hydraulic conductivity and transmissibility of an aquifer(Todd,1980; British Standards,1981; Whitlow,1983; Dake,1983).

For unconfined conditions; after a steady-state conditions develop, the quantity of water flowing towards a well in unit time (Darcy's Law) is

$Q=KiA$ (9.3)

At a distance r from the well, the area A through which the water is flowing

$A=2\pi rh$ (9.4)

Applying Dupuit's assumption that $i=dh/dr$

giving $Q=2\pi rhKdh/dr$

so $Qdr/r=2\pi hKdh$ (9.5)

rearranging and integrating for the boundary conditions $h=h_w$ at $r=r_w$ (that is, constant drawdown in the well) and $h=h_o$ at $r=r_o$ (that is, zero drawdown at some radial distance from the well)

$$\int_{r_w}^{r_o} dr/r = 2\pi K/Q \int_{h_w}^{h_o} hdh$$

$\ln r_o/r_w = 2(\pi K/Q)(h_o^2-h_w^2)$ (9.6a)

hence $K=(Q/\pi(h_o^2-h_w^2))\ln r_o/r_w$ (9.6b)

For confined conditions; in an aquifer confined above and below by impermeable strata the test conditions are as shown

Fig. 9.1a Steady flow in an unconfined aquifer

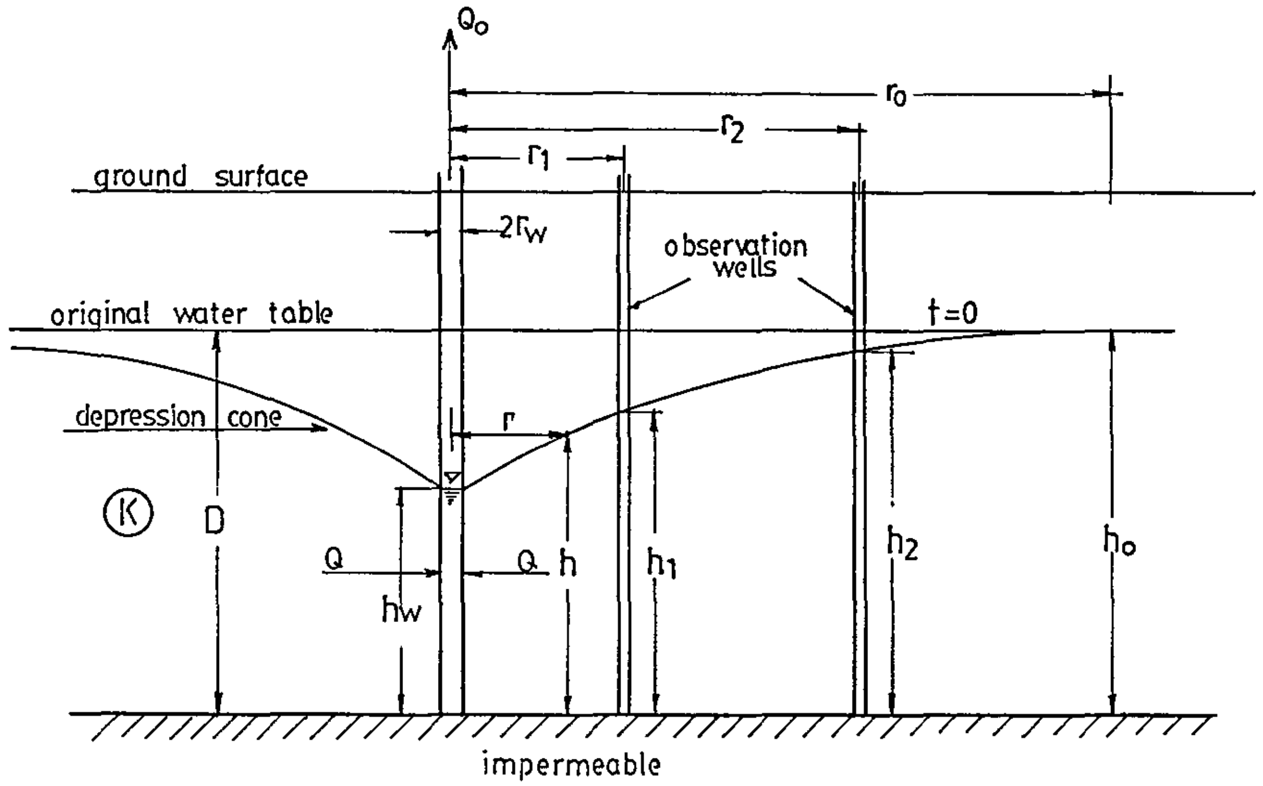
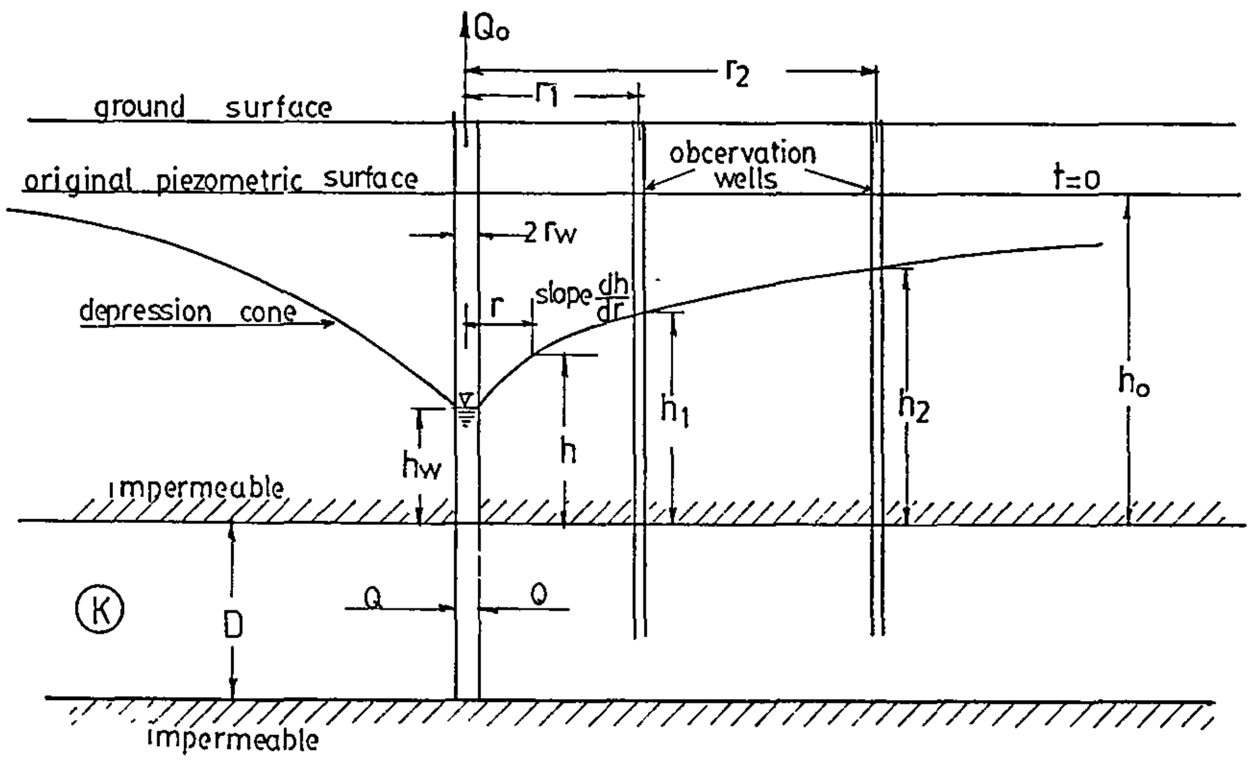


Fig. 9.1 b Steady flow in a confined aquifer



Source: Todd, 1980; British Standards, 1981; Whitlow, 1983; Dake, 1983 in Fig.9.1b, providing the piezometric surface is above the upper surface of the aquifer at all radii, both before and during the test. Pumping is maintained at a constant rate (Q) until a steady state has been achieved. Then at a given radius r the hydraulic gradient is

$$i=dh/dr$$

The area through which flow occurs

$$A=2\pi rDK \qquad (9.7)$$

Then applying Darcy's Law (Q=KiA)

and $Q=2\pi rDKdh/dr$

so $Qdr/r=2\pi DKdh$ (9.8a)

or $dr/r=(2\pi DK/Q)dh$ (9.8b)

integrating the equation (9.8b) between the limits $h=h_w$ to $h=h_o$ and $r=r_w$ to $r=r_o$

$$\int_{r_w}^{r_o} dr/r=(2\pi Dk/Q)\int_{h_w}^{h_o} dh$$

$$\ln r_o/r_w=(2\pi Dk/Q)(h_o-h_w) \qquad (9.9a)$$

giving $K=(Q/2\pi D(h_o-h_w))\ \ln r_o/r_w$

By transposing terms it can be used in estimating the yield of wells

$$Q=2\pi DK(h_o-h_w)/\ln r_o/r_w \qquad (9.9b)$$

Since h increases indefinitely with increasing r, yet the maximum head is h_o for Fig.9.1b. Near the well the relationship holds and can be rearranged to yield an estimate for transmissibility T

$$T=Kb=(Q/2\pi(h_2-h_1))\ \ln r_2/r_1 \qquad (9.10)$$

by observing heads $h_1$and h_2 at two adjacent observation wells located at distances $r_1$and r_2, respectively, from the pumping well. In practice, it is often necessary to use unsteady-state analysis because of the long times required to reach steady-state (Bedient et al,1988).

Equations 9.9b and 9.10 are known as equilibrium or Thiems equation and enables the aquifer permeability and transmissibility to be determined from a pumping test data. The derivation assumes that the aquifer is homogeneous, isotropic, has infinite areal extent, flows are laminar, and the well penetrates the entire aquifer.

In nature, non-steady state flow conditions are encountered and for them C.V. Theis (1935) developed a formula by which the unsteady radial flow conditions in which the head continues to decline with pumping at a constant rate was taken into account for the first time. This is known as the non-equilibrium or Theis equation and can be used for determining S and T parameters of an aquifer by means of pumping test of wells.

The non-equilibrium or Theis equation is

$$h_0-h=Q/4\pi T\int_u^\infty (e^{-u}/u)du=QW(u)/4\pi T \text{ where} \qquad (9.11)$$

$u=r^2S/4Tt$ and

$W(u)=-0.577216-\ln(u)+u-u^2/2x2!+u^3/3x3!-u^4/4x4!$ ....

Theis method is a graphical method utilising a "type curve" i.e. a plot of W(u) versus u on logarithm paper. Drawdown measurements are plotted too, against distance square divided by time (i.e. r^2/t). When superimposed over the type area values of W(u),u,h_0-h, and r^2/t may be selected at any desired point (match point) and substitute in Theis equation. For details of this see Todd (1980) and Kruseman et al, (1983).

Because of the mathematical difficulties encountered in applying the Theis equation in its original form several investigators have developed approximate solutions which can be readily applied to obtain required answers.

Cooper and Jacob (1946) modified the non-equilibrium

(Theis) equation which relates drawdown-s to discharge-Q and pumping time-t to that form

$$s=(2.30\ Q/4\pi T)\ \log 2.25Tt/r^2S \qquad (9.12)$$

A plot of drawdown-s versus the logarithm of t produces a straight line. This line is extended until it intercepts the time-axis where s=0 thus the interception has the coordinates s=0 and $t=t_o$. Substituting of these values into the above equation gives

$$0=(2.30\ Q/4\pi T)\log 2.25Tt_o/r^2S \qquad (9.13)$$

and because $2.30\ Q/4\pi T \neq 0$

it follows that $2.25Tt_o/r^2S=1$ (9.14a)

or $S=2.25Tt_o/r^2$ (9.14b)

if $t/t_o=10$ and hence $\log t/t_o=1$, drawdown s can be replaced by Δs, viz the drawdown difference per log cycle of time and it follows that

$$T=2.30\ Q/4\pi\Delta s \qquad (9.15)$$

The assumption and conditions which should be satisfied with employing of the Cooper and Jacob method are those considered for the former methods in addition to that: the r-value is small and t is large.

This method has extensively been used by the G.S.D. and W.D.D. because of its simplicity to determine reliable aquifer constants T and S.

Also, N. S. Boulton (1963) treated the non-equilibrium case for unconfined aquifer affected by delayed yield. He observed that in some aquifers water is not released from storage instantaneously with declining head (as assumed by most other non-equilibrium methods, for example Theis) but this process takes some finite and often appreciable time. This has the effect of increasing the apparent storage coefficient with time. Eventually this delayed yield reaches a maximum, as the rate of change of drawdown declines, which is equal to the specific yield of the material in the water-bearing zone.

The solution of the flow equation which applies to certain conditions is rather a complicated differential equation because of the difficulties in defining analytically the upper boundary condition of the equation and as a consequence the continuity equation and its solution becomes complex in the extreme (McDonald et al.,1973).

However, graphical representation of Boulton's solution is available in the form of a series of type curves to which pumping test data plots may be fitted and the coefficiency of transmissibility and storativity calculated. Drawdown data from an observation well some distance from the pumping well are required for the data plot.

Applicability of the Boulton method is sometimes difficult to decide but if a complete pumping test data is plotted (i.e. time-days vs drawdown-m) this may have the characteristic S shape, and so it is a very good reason to consider Boulton's method.

9.3.1.2 The recovery test. When pumping of a well is stopped, water levels in pumping and observation wells begin to rise (recover) until they reach pre-pumping static water level. This is the residual drawdown s' and is measured at close intervals.

The recovery test data from an observation well enable the accurate determination of the aquifer constants T and S and whereas pumping and observation data are recorded in the same well, only T will be calculated (Kramvis, 1987). In any case it is assumed that the pumping is performed at a constant rate.

As with drawdown test data a plot of recovery s-s' versus the logarithm of time taken to recovery will be a straight line except for a small ini al and a final portion of the curve. However, the determination of the recovery s-s′ from an extension of the time-drawdown curve is rather difficult to obtain accurately if an observation well is not available. This problem is overcome by making direct use of the residual drawdown s′ which, according to Theis is given by

$$s'=(2.30\ Q/4\pi kD)\log t/t' \qquad (9.16)$$

From this equation it is apparent that a straight line for the residual drawdown curve will be obtained when values s′ are plotted on a linear scale versus corresponding values of the ratio t/t′ on a logarithmic scale. The transmissibility is then calculated from the formula

$$T=2.30\ Q/4\pi\Delta s' \qquad (9.17)$$

where $\Delta s'$ is the change in residual drawdown per logarithmic cycle of values of t/t′.

Storetivity values cannot be determined with this approach.

9.3.1.3 <u>The application of the method analysis of the pumping test data.</u> All the formulas available for calculation of the aquifer hydraulic characteristics have to be confined to some theoretical conditions and assumptions the basic of which are: (1) the homogeinity (isotropism) of the aquifer and the infinity in areal extent; (2) the well penetrates the entire thickness of the aquifer; (3) the coefficient of transmissibility and storage are constant at all times and places; and (4) water is released from the storage as soon as the cone of depression develops (Fair et al.,1966). In nature, however, other large deviations occur from these conditions and assumptions and therefore the application of a certain formula as well as the acceptability of the determined constants should be subjected to a great extent on personal judgement. Information including the subsurface geology, the hydrology and the history art of the area in general and the concerned aquifer in particular help to this understanding in order to approximate conditions and adjust results with confidence. Nevertheless, the formulas are applied with success and the calculated hydraulic characteristics are proved to be reliable for most purposes (Kruseman and De Ridder,1983).

9.4 PREVIOUS INVESTIGATIONS

In 1969 the G.S.D. initiated a geo-hydrological investigation of the southwestern region of the island. Within this program the most comprehensive survey had been linked to the middle-eastern part of the Paphos Coastal Plain covering in particular the zones 1 and 2 and the three major river gravel bed resources, (i.e. Dhiarizos, Xeros and Ezousa).

An electrical resistivity sounding had been carried out by which it was allowed to select the most promising locations for drilling boreholes. Several sets of boreholes (i.e. pumping and observation boreholes) were constructed along a coastal strip of 7-8km long, between zone-1 and zone-2. Through the pumping tests which followed, it was provided, for the first time, information necessary to extract numerical values of the aquifer hydraulic characteristics. By employing the Theis "type curve" method of analysis (described in section 9.3.1.1) the most significant hydraulic properties of an aquifer it was determined i.e. the hydraulic conductivity, the transmissibility and the coefficient of storage. The determined constants are shown in Table 9.1.

It should be noted that the hydraulic year 1968/1969 has been an extensively wet year, with an average precipitation exceding 740mm (Akhelia Met. St.) or 170% of the mean average. The pumping tests were completed early summer of this year when the water-table was abnormally high (see Fig.11.2) and

Table 9.1 Determined calcarenite aquifer hydraulic parameters

Testing B/H		Transmissibility-T(m^2/day)					Specific yield-S(%)		
		Theis	Equilibrium	Boulton	Cooper-Jacob	Recovery	Theis	Boulton	Cooper-Jacob
Zone: 1	No.20	388	194.0	197.0	396	220	1.630	3.7	1.440
1	23	1600	118.0?	269.0	1254	416	0.126	13.2	1.421
1	24	14	53.7	--	294	98	0.022	0.06?	0.442
Zone: 2	No. 5	110	17.2	18.2	108	152	0.064	2.8	0.500
2	7	682	155.0	165.0	654	425	0.00147	3.4	0.540
2	14	816	64.0	--	692	189	0.031	--	1.430
2	22	290	78.2	90.0	241	162	0.114	4.0	0.248
2	19	1970	53.10	808	1246	964	0.15	5.5	0.22

Source: Afrodisis, 1969; McDonald et al, 1973; Author's Research, 1993 therefore the resulted values of transmissibility might not respond to the conditions of a normal rainy year.

The same pumping test data was re-analysed for the purpose of the feasibility study of the P.I. Project (McDonald et al, 1973). For determining the aquifer parameters, in this case, the equilibrium equation and the Boultons graphical method were employed (that were described in section 9.3.1.1).

McDonald observed that the rate of change of drawdown at the end of the pumping had been very small and in most cases the water level in the pumping well remained steady. Thus, there were arguments to analyse the pumping test data with the equilibrium formula. The findings are shown in Table 9.1 as well.

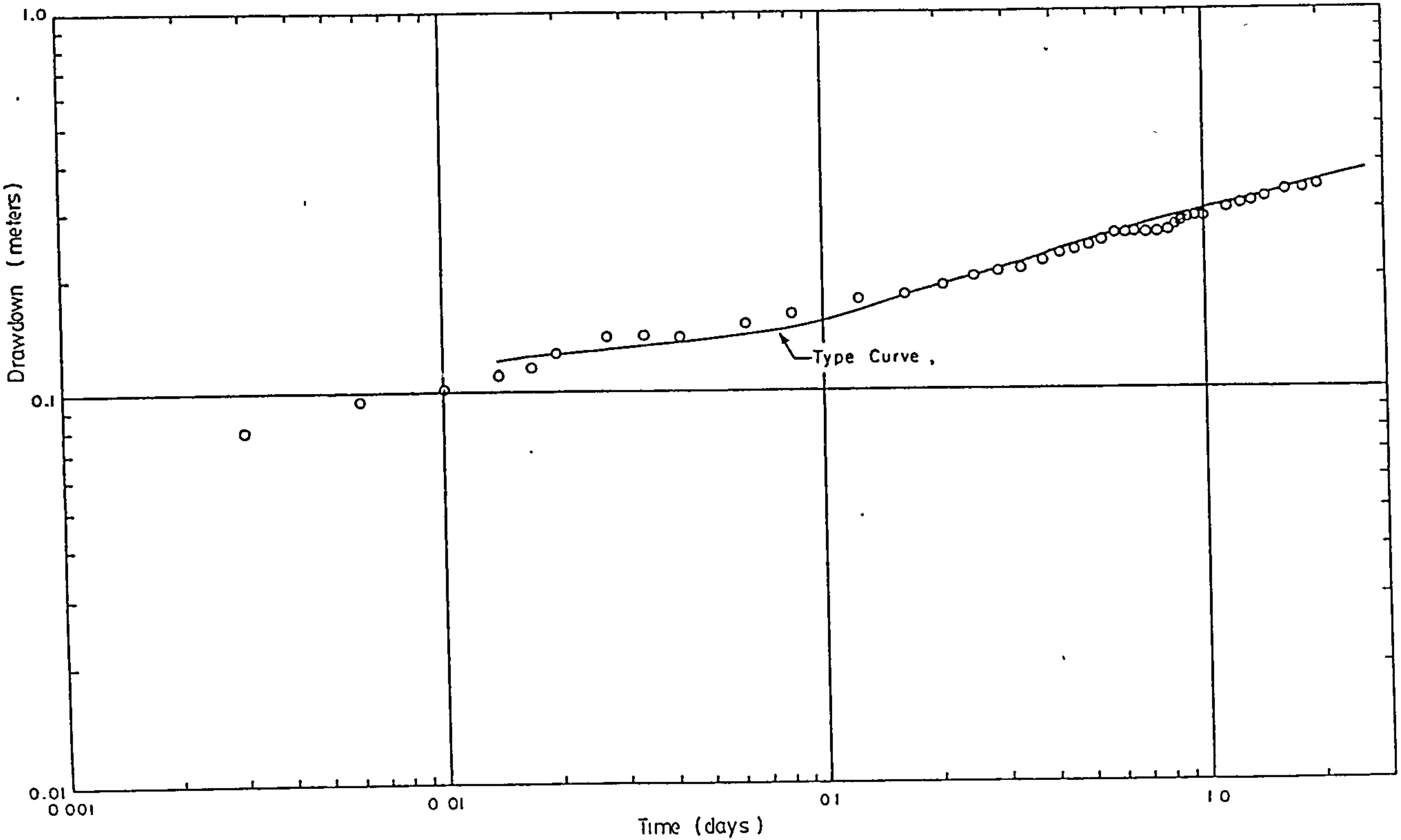
Concerning Boulton's graphical solution, this may suit the geologic and the hydrologic conditions encountered in many cases in the Athalassa calcarenite aquifer. The intercalation of the various beds with the different lithology and the degree of consolidation could be realised as a function of delayed fields, i.e. conditions favour the application of the Boulton's formula. The pumping test plot of the b/h 19, having been fitted to one of the Boulton's type curves might have been an indication of its applicability (Fig.9.2). The determined constants are also cited in Table 9.1.

In spite of the fact that the data used in both cases are the same, the transmissibility determined by the Theis approach is much higher than those determined by the application of Boulton's. The opposite happened by determining the storage co-effecient. Theis application determined very low values to that of Boulton's analysis results.

With regard to the values of transmissibility through the equilibrium method these seem rather closed to those found by

Fig. 9 2 Boulton method of pumping test analysis, B/h 19

Source. Mc Donalds et al, 1973



the Boulton's method. These constants as well as these ones which have been determined by using different methods of analysis for the purpose of the present study are to be discussed, to some extent, afterwards.

E. Dahmen and F. Mero (1970) had designed a different methodology to carry out the study of the aquifer characteristics. They considered an area of 10km^2 in Timi-Mandria groundwater basin (zone-3) as a typical calcarenite of the area and they tested a special "Geo-Hydrometeorological" mathematical model to investigate the properties and the behaviour of the aquifer under various conditions. As basic assumptions, use was made of the findings by S. Afrodisis of G.S.D. in 1969. In the simulations run on the computer programming, several calibrations were made in such a way as to obtain the closest fit between calculated and observed water levels in a certain group of wells representing a certain aquifer.

A summary of their estimations is as follows:

- A storage coefficient of 4-5% and "return flow coefficient" of 15% over the irrigated area will be assumed for future irrigation practice.
- The average annual replenishment from rainfall is about 135mm ranging from 0 in dry years to 280mm in a very wet year.
- The average depletion time (i.e. when "live storage" depletes to 36% of its initial content) ranges between 120 and 180 days. Therefore the aquifer is not capable of serving as a long-term storage reservoir being constantly discharged to the sea.

This model work is, however, an advancement to the general consideration of the investigation of the calcarenite aquifer. Nevertheless, it has to be emphasized that the aquifer under study is most complex due to their physical, geometrical as well as lithological characteristics.

Therefore, the above determined aquifer properties have to be used with particular care or otherwise for comparison with other source information and consultation for such investigations.

9.5 THE ASSESSMENT OF THE CALCARENITE AQUIFER HYDRAULIC CHARACTERISTICS

The former studies dealt with the Paphos Coastal plain aquifer were available from the W.D.D. and the G.S.D. resources. Together with these studies the basic information and the original data which had been produced during the in-situ work were available. The material which has been researched is found to contain very essential information which is necessary to the present study, the borehole logs and the original pumping test data in particular. The author proceeded his investigation by analysing the data of the pumping test with different methods making comparable assessments. In this way, it has been possible to indentify the information which needs to be brought together in order to produce realistic estimates of the potential capacity of the calcarenite aquifer.

Also, a supplementary investigation was carried out in order to cover the areas which lacked certain information. Within this stage of field work, additional pumping tests were carried out. This is discussed in section 9.5.1.2.

9.5.1 Analysis of pumping test data

9.5.1.1 Data available from previous investigations. As referred to in the preceding section, the G.S.D. , conducted the first comprehensive geohydrological survey over the middle-eastern part of the coastal plain in 1969. The reported information and data were acknowledged by the later investigators for its merit (Mero,1969; McDonalds et al.,1973). From the constructed boreholes, an excellent source of geological information was provided, while the observation boreholes allowed classical pumping tests to be performed.

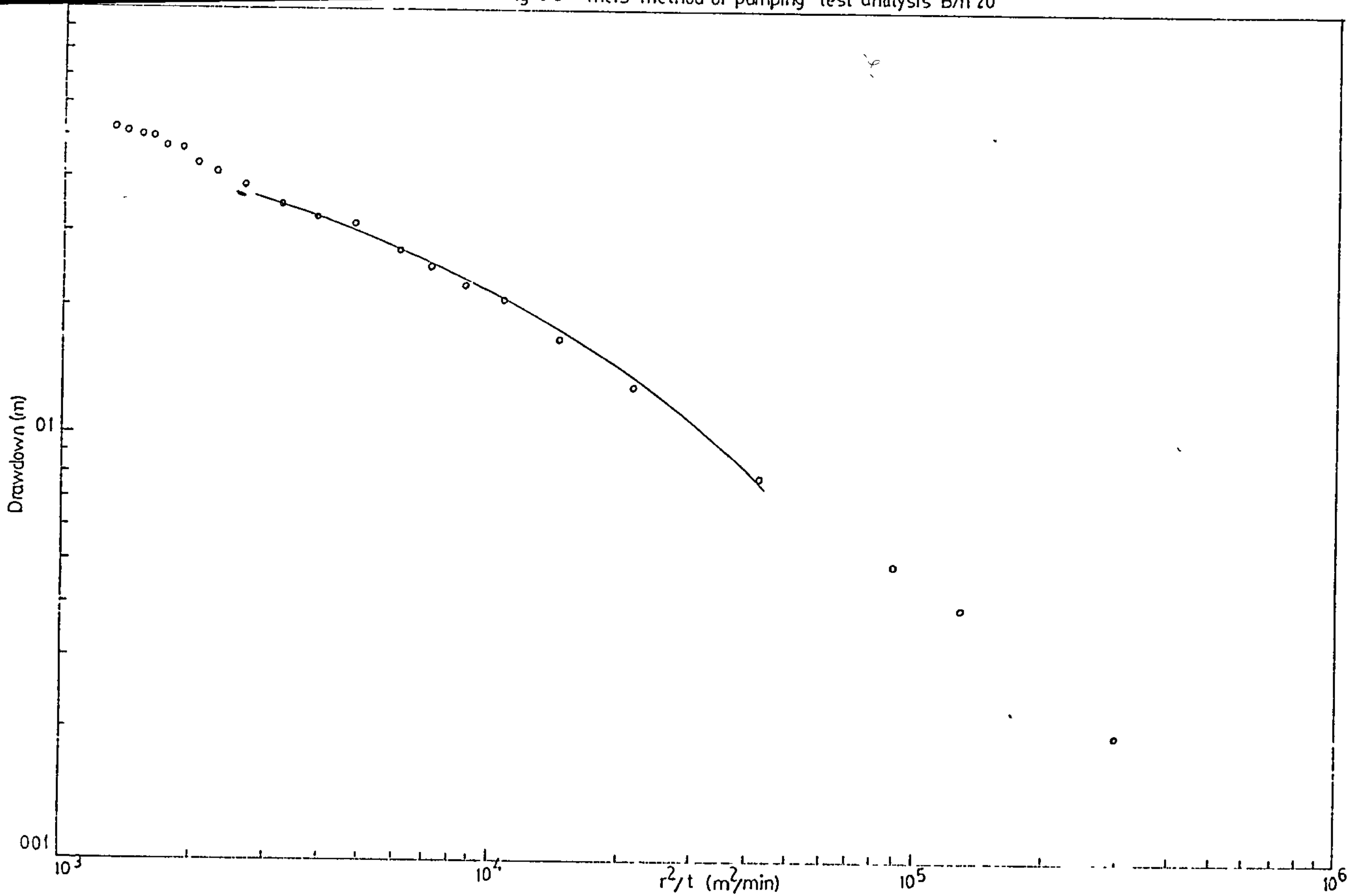
The reported pumping test data was available from the G.S.D. pumping test record files. Because these were provided in the original form, as it was written on the site, it has had to be interpreted and adapted accordingly in respect to the requirements of the method of analysis which is to be used.

S. Afrodisis of the G.S.D. employed the Theis "type curve" method for the survey carried out in 1969. Figure 9.3 demonstrates a pumping test analysed by the Theis method as in the case of b/h 20. Later on and during the P.I. Project feasibility study (1973) the Boulton's graphical solution, in addition to the equilibrium formula, were employed (McDonald et al,1973). In the light of this evidence it has been considered useful to treat with other methods than that already applied. Therefore, the Cooper-Jacob and recovery (Theis recovery) methods have been applied.

Even though the conditions for the application of the Cooper-Jacob method are somewhat more restricted than that of the Theis method, by assuming moreover, small values of u (u<0.01) i.e. (small values of -r- and large values of -t-) to avoid large errors (section 9.3.1.1). This assumption, for unconfined conditions may be satisfied by pumping of 12 hours or more (Kruseman, and De Ridder,1983).

As it was mentioned before, the Cooper-Jacob method has long been applied, along with the other methods above, by the hydrogeologists in W.D.D. and G.S.D. Although, it has been considered under variable conditions, despite the fact that within the several textbooks (Todd,1980, Bedient et al, 1988) it is emphasized that its application is most stringent. For the purpose of this study, the reformed assumptions above may be satisfied sufficiently; the -r- value was at moderate distances of about 24m and the pumping was exceeding the 12

...ig ... ...ers method of pumping test analysis B/h 20



Source: Afrodisis, 1969

hour duration in each case. The determined values of T are illustrated in Table 9.1. An analysis of the pumping test data with the Cooper-Jacob is shown in Fig. 9.4.

Regarding the recovery method, this is an easy and rather straight forward method without complicated prerequisites for its application. Although its application limits to determining only values of transmissibility (see section 9.3.1.2), it is, however, considered much reliable and is used extensively. The recovery data of the available pumping tests have been analysed and the determined values are presented in the same table as well, i.e. Table 9.1. The use of the recovery method in the case of the borehole pumping test is demonstrated in Fig. 9.5.

It is apparent from Table 9.1 that the former determined values together with the new ones resulted from the same pumping test data analysis by using the Cooper-Jacob and recovery method, have all shown large differences between those reported either to the same pumping well or to the same catchment unit.

As one can see in the case of the specific yield constants, the findings are varying so much with each other so that it is difficult to extract over any relationship.

The transmissibility parameters determined by applying the equilibrium and the Boulton's formula were, to some extent, close to each other in most cases. Almost the same happens between the parameters determined through the Theis and the Cooper-Jacob methods. On the other hand, the results of the recovery method vary considerably from all of the others.

It has been noted that assumptions and conditions are to be satisfied in any method employed to analyse pumping test data, but this prospect is usually ruled out because some of

Fig. 9.4 Cooper–Jacop method of pumping test analysis B/h 23

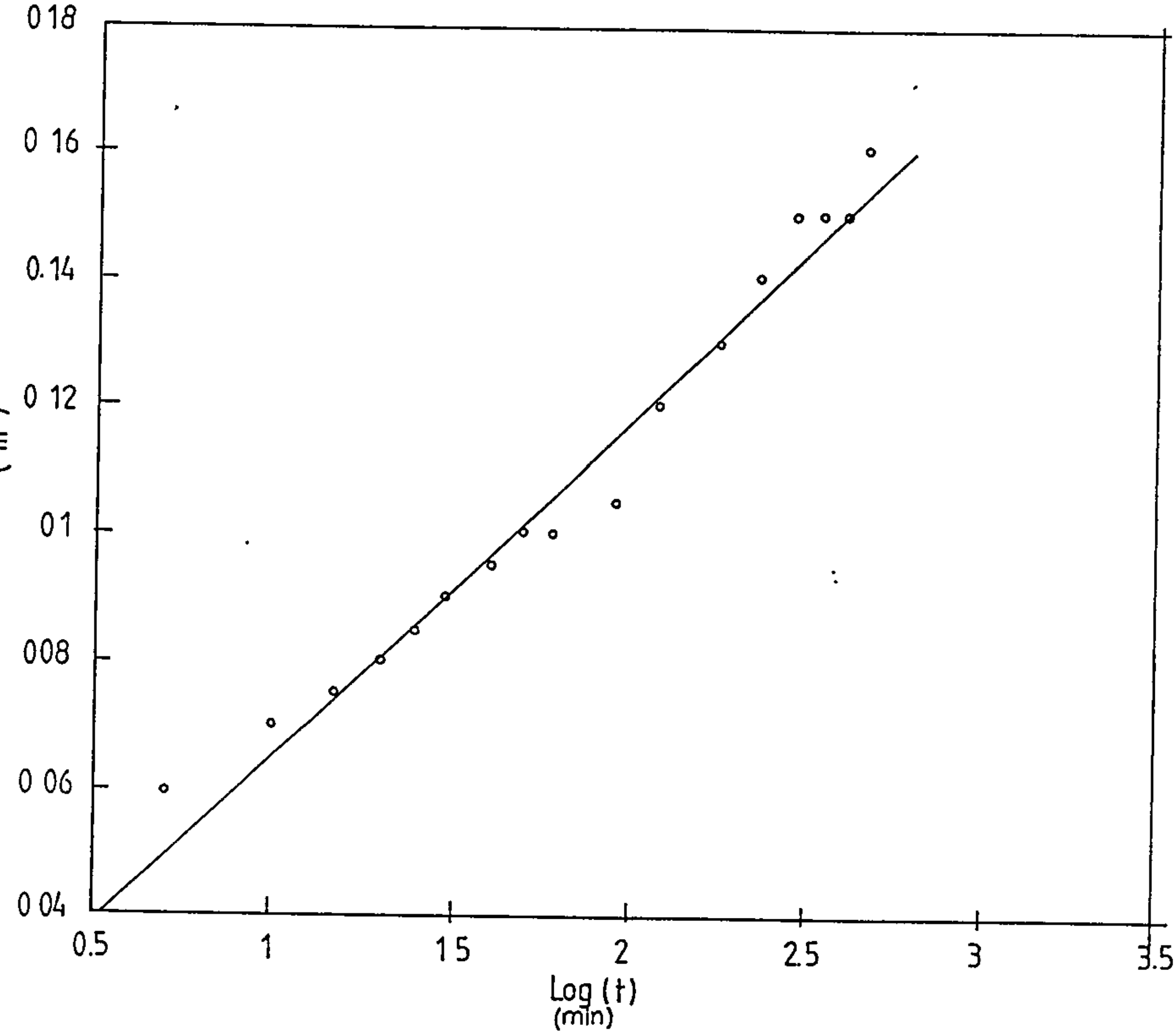
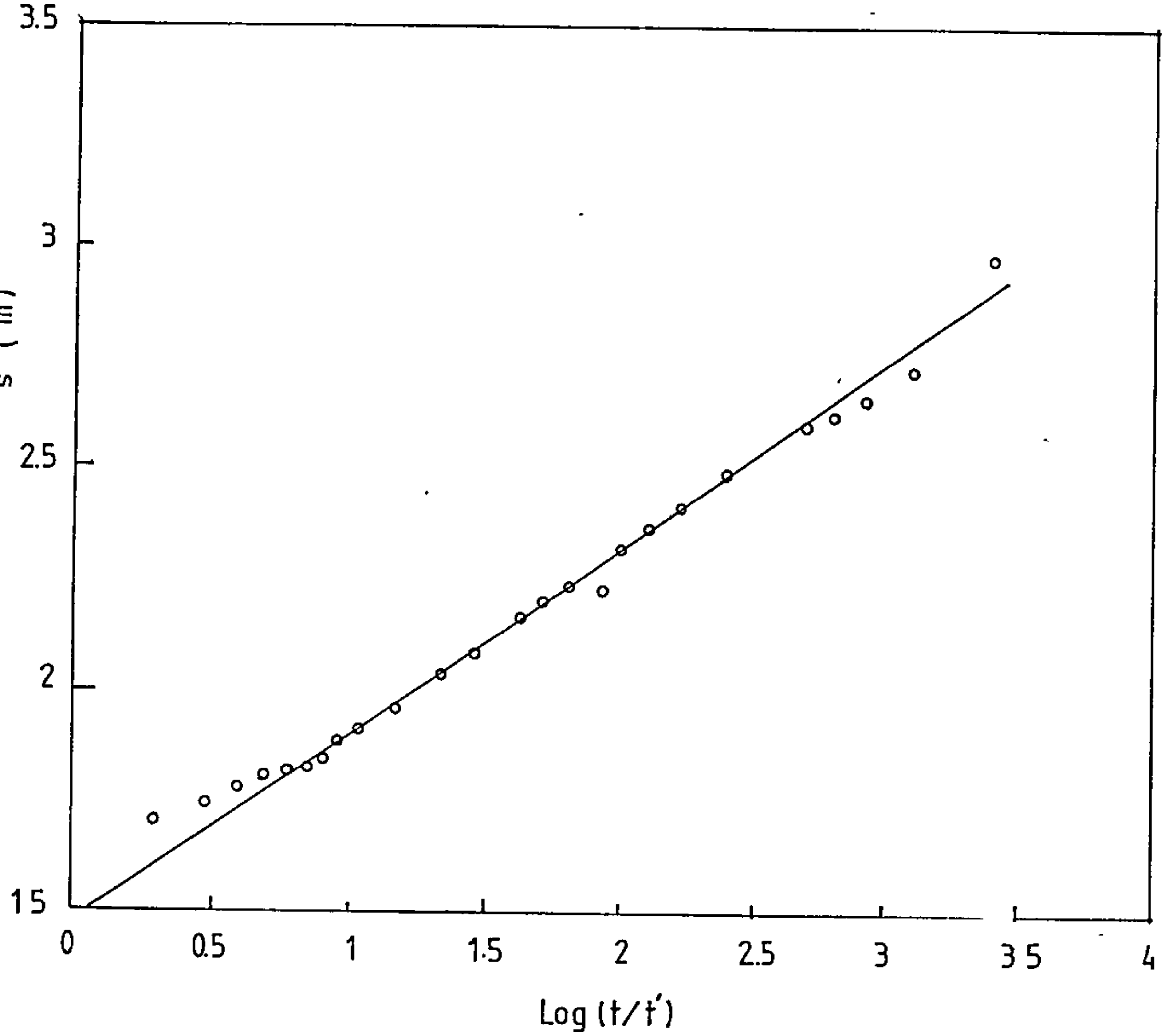


Fig. 9.5 Recovery method of pumping test analysis B/h 22



the basic assumptions as the "infinite areal extent" of the aquifer etc. may not exist in reality and therefore are to be approximated to human terms. On the other hand particular provisions which are often required for the applicability of such a formula like the equilibrium conditions of the relevant equation delayed yields in the case of the Boulton's method etc., led to more constraints, which also strictly speaking, can never be defined precisely.

It is recognised, however, that both the steady flow, based on the Dupuit-Forchheimer assumptions, as well as the non-steady flow encountered in unconfined non-homogeneous and anisotropic aquifers contain many uncertainties and approximations (Bouwer,1978; Todd,1980). Therefore, many complexities of the groundwater movement have been demonstrated in the application of the various methods which have been derived to deal with this problem (Shaw,1984).

In nature, stratification of sediments occur and this may greatly affect the response of groundwater movement during the course of the pumping test.

However, there are in fact, man-made functions involved in interpreting the pumping test data. Therefore, the determined values by any method are a marked bearing of judgement, experience and the restraints of the study. The Paphos Coastal Plain as it was revealed from the several borehole logs, overlies a variety of sediments of different origins, grain size and consolidation. For instance, the Athalassa calcernite, the most water bearing formation, consists of bands of fine to medium soft shelly calcareous sandstones, shelly medium to course grained sandstones, loosely cemented calcareous stones etc. which exhibit different porosity. These rock layers do not extend regularly and are interbedded elsewhere and at various depths with horizons of marly matrix etc. which are of restricted permeability. This configuration led to the development of semi-unconfined conditions at some extent and at lesser extent semi-confined and rarely confined conditions in place only. On the other hand, fissured and carstic phenomena might be locally produced closed depressions which also worsened the designation of the aquifer conditions.

The discord found regarding the resulted values by the five methods employed is not an occasional matter, this has been experienced by hydrogeologists elsewhere. Therefore, local experience showed that pumping tests conducted within first-class aquifers as in the case of the Kokkinochoria sandstone aquifer and Akrotiri alluvium aquifer (which is designated as quite homogeneous vertically and horizontally) both showed results with large deviations of some order either in transmissibility or storage coefficients, (Georgiou,1992; Afrodisis,1992). In this case, appraisal of the findings was based on local information along with the formula processed.

Concerning the results tabled above, S. Afrodisis (1992), who conducted the former pumping test on the coastal plain and his findings have been used as the background of the later investigators (see section 9.4), had expressed some reservations on the use of the equilibrium formula because the equilibrium conditions in nature, make it quite difficult to occur, moreover in this aquifer . In his opinion, with respect to the Boulton's conditions application because of the thin aquiferous horizons, minor delayed yields were produced, so that the flow components in the well might not be affected to such an extent, as the plotted data had mentioned in the S figuration proposed by Boulton's approach (section 9.4). He has yet recommended the use of the Theis method of analysis plus the recovery method, under such circumstances and the use of Cooper-Jacob but with some conditions being satisfied. His view is also shared by the W.D.D. sources which further stressed on the difficulties encountered to make generalized assessment, by relying merely on pumping test data analysis.

Under these circumstances it is difficult to decide certainly over the resulted values which are the best fitted to the calcarenite aquifer.

Although the storetivity values determined by Boulton's methods look more realistic than those resulted by the Theis and Cooper-Jacob methods, however, the arguments mentioned above seem very consistent and are largely agreed with in this study.

It was found necessary to proceed with supplementary pumping test before concluding over certain parameters . In addition to this, a particular field survey was designed to meet some original information over this issue by interviewing people being experienced on the matter either by constructing of wells or extracting groundwaters in the area.

9.5.1.2 Supplementary pumping tests. Within this later course and with the assistance of the farmers who still utilise groundwater, a large number of wells and boreholes were inspected to see whether these facilitated some sort of pumping testing. Attention was given: a) to the availability of the existing pumping systems and their suitability to function for pumping test in order to carry out particular measurements; b) to the likely interference from other pumpages taken place in the vicinity of the proposed pumped well which for any reason could have been disturbing the test under way.

At last, only a few wells were identified as the most suitable between the available number of wells to perform a pumping testing. These are provided in Table 9.2 and are shown in map in Fig.7.1.

Many difficulties were encountered with the preparation of these pumping tests. The main problems which were to be overcome were that; (a) the lack of an observation well, (b)

Table 9.2 Aquifer constants determined from supplementary pumping tests

Zone	Well No.	Hydraulic conductivity-K	Transmissibility-T
1	108	203m/day	705.m^2/day
	140	7.3 "	176. "
	233	3.5 "	440. "
3	2785	30.4 "	92.3 "
"	151	10.3 "	114.0 "
4	1171	14.4 "	57.8 "
	1196	6.2 "	80.76 "
	1662	14.0 "	1483.7 "
	3491	19.0 "	19.6 "

the lack of monitoring facilities, and (c) the lack of personnel to assist the pumping testing. The first problem was tackled with the conforming of the pumping test to the conditions that responded to a certain formula. The other two problems were eliminated with the employment of a self-developed apparatus and with the useful help provided by some skilled colleagues of the W.D.D..

It is understood that, classical pumping test models could not have been considered under such circumstances. Furthermore, the lack of observation wells excluded some of the most popular methods of pumping test data analysis, like the Theis, Boulton, Cooper-Jacob etc. and thus detailed analysis of the aquifer behaviour could not have been possible. It was, however, able to adapt, well-established formulas as the equilibrium or Thiem formula, to the conditions referred hereto in order to approximate the solution which led to determine permeability values. Also, recovery (Theis) method can be applied without the need of observation well measurements, but with the use of measurements of residual drawdown in the pumped well only. Hence, transmissibility values may be obtained.

The equilibrium or Thiem equation can be used to express the existing conditions under which the factor $\ln r_2/r_1$ is not known. It can be easily shown that the computed transmissibility is remarkably insensitive to large variations in r_o and r_w. Therefore, any reasonable values for these will produce a good approximation. Muscat (the definitive work on well hydraulics) dealing with oil wells (according to McDonalds, 1973, et al) recommends $r_w={}^1/_4$ft and r_o=500ft; work in West Pakistan by Hunting Technical Services Ltd and Sir MacDonalds and Partners in 1966 has shown that in well-developed water wells the effective well radius is nearer to $r_w={}^1/_2$ft. Therefore, by adopting the values of $r_w={}^1/_2$ft and r_o=500ft, equation 9.6 can be written.

$$h_o^2-h_w^2=3Q_o/\pi K \qquad (9.18)$$

Finally by the use of the adapted equilibrium equation above (9.18), and also the recovery method the following constants (that is, the hydraulic conductivity-K and the transmissibility-T) have been determined (see Table 9.2)

These pumping tests were performed in poorly designed wells and variant conditions and therefore the formula employed for analysis of the pumping test data might not have been satisfied to the extent needed. Nevertheless, the determined values, hydraulic conductivity and transmissibility seem to respond in most cases to the geohydrological conditions of the aquifer. These are in agreement with what, by experience, was expected and the lithological sections persuaded. There are, however, two cases where values are contradictory. This is the case of the pumping well No. 233, where permeability seems quite low and the transmissibility is high and the case of the pumping well No. 3491 where the transmissibility is very low while the permeability is high.

It is worth mentioned that the pumping test took place during the summer of 1991. In this hydrological year, 1990-91, the precipitation was 250mm or approximately half the normal annual precipitation in the coastal area of Paphos. Therefore, the saturated zone was limited to the minimum and transmissibility values reflect the conditions in a dry year.

9.6 AN OVERVIEW OF THE PERFORMANCE OF THE CALCARENITE AQUIFER THROUGH FIELD EXPERIENCE

During the field survey it was found useful to extend relations with the local population who have been experiencing with groundwaters by excavating and maintaining themselves dug-wells or merely they have been involved in groundwater developments. These people provided strong arguments over the aquifer conditions usually encountered in the area. These along with the other evidence and estimates of the aquifer properties allow to set out the actual picture of the aquifer.

Some of this information is summarised below:

a) Farmers in Yeroskipos (zone-1) and Timi (zone-2) reported that in their dug-wells, water disappears after a few hours of pumping, i.e. 2-3 hours, and takes a long time to recover.

b) The pumping at one farmer's plot affects farmers next, which means that the aquifer is interconnected (probably with large karstics) but with relatively low yield capacity.

c) Further in Emba - Kissonerga (zone-4) the situation here is different, because one farmer may get a large amount of water from his dug-well but the next neighbour close by approximately 100 or 500m away might only produce negligible quantities. This may be due to the nature of the aquifer medium which encourages formation of cavaties.

d) These dug-wells are distributed all over the area and the owners reported that during construction, they came across alluvial layers after digging for about 1-3m on average. Physically, these were a mixture of calcareous deposits and claying materials.

However, it is understood that, where the well is unable to intercept sufficient recharge, it could withdraw water from storage in its immediate vicinity. Also, due to the lack of available recharge in the long term (the bulk of which takes place during the winter) there is local dewatering and a decline in the yield of the well. The recharge from rainfall through infiltration percolation is constrained by the lateral limited extent of the contributing area i.e. the coastal plain itself. On the other hand abstraction is also constrained by the permeability of the aquifer, the storage capacity of the well itself and the proximity of other sources.

This survey has yet to be re-ascertained that the dug-wells and drillings have varying rock profiles and depths, water struck levels and water rest levels.

9.7 SUMMARY EVALUATION OF THE CALCARENITE AQUIFER CHARACTERISTICS

This aquifer is a typical second-class aquifer with limited storage capacity and poor yield (in general it ranges between 10 and 16m^3/h), except in a few localised spots, where karstic developments are predominant.

The hydraulic properties have been assessed after analysing old and recent pumping test data by the use of different methods. Due to the complexity of the hydrogeological conditions in the area and the weakness of the available methods of analysis to function within a certain aquifer, the determined values gave rise to uncertainties over their reliability. In order, however, to carry out the constants of the aquifer, the pumping test data analysis was reviewed and adapted accordingly. Some consultation into this was received from the W.D.D. and G.S.D. geohydrologists who have long treated similar functions. Relating to the experience which emerged either from this investigation or from other sources and also from the experience contributed by workers throughout the island, the result is the final constants of the aquifer. The determined constants are tabled below together with the constants adopted by former investigators, for comparison purposes (Table 9.3).

Due to the geometry of the aquifer (i.e. the limited lateral extent and the consistent sloping of the hydraulic basement towards the sea) there is continuous underflow into the sea and therefore the aquifer is not capable to serve as a long-term storage reservoir. However, by the end of the rainy reason the water level peaks and from a hydrological point of view, pumpage from this aquifer should be timed in such a manner as to extract part of the groundwater prior to its depletion; i.e. from March onwards in order to reduce the flow into the sea.

Table 9.3 Adopted calcarenite aquifer hydraulic parameters

Transmissibility-T (m^2/day)				Hydraulic conductivity-K (m/day)		Specific Yield (%)		
Zone	Afrodisis 1969	McDonalds 1973	Current study	McDonalds 1973	Current study	Afrodisis 1969	McDonalds 1973	Current study
1	70	100	80	20	20	8.0	6.0	6.0
2	80	100	80	20	20	8.0	6.0	6.0
3	80	100	80	20	20	8.0	6.0	7.5
4	50	50	50	--	16	8.0	/	5.0

Source: Afrodisis,1969; McDonald et al,1973; Author's Research, 1993

Sea water intrusion should not be a matter of great concern since generally the basement of the aquifer is well above sea level, except in a few locations in the vicinity of the shore line. That is revealed within the hydraulic basement contour map (Fig.8.2,8.3 and 8.4). However, for the threatened areas with sea water intrusion a continuous monitoring of the water-table should eliminate the likely risk.

CHAPTER 10
THE GROUNDWATER QUALITY

10.1 INTRODUCTION

Water quality is a fundamental parameter in water management. It determines if the resource can be used for domestic or agricultural purposes.

In the case of the Paphos Coastal Plain aquifer, the chemical composition is considered for irrigation use by:

1. Its suitability for crop cultivations
2. Its corrosion and incrustation potential

Because of poor yield, the aquifer may not be suitable for domestic supply. Therefore, groundwater quality is not considered for this use.

Only very recently since 1992, the government bodies involved in water management and health have acknowledged the magnitude of the problem and have put a plan forward. The plan consists of regular six monthly base sampling in June and December of fresh, impounded and sea water for complete biochemical analysis. Therefore, reliable information is not yet available.

Some data is available from the W.D.D. such as the chloride, dissolved solids and hardness concentrations.

For the purpose of this study, however, samples were taken from several operating wells and boreholes (Fig.7.1) along the shoreline and some along the northern boundary of the Coastal Plain aquifer closed to the various communities sited there. This combination of the selected samples may be used to indicate the groundwater movement and the probable effects from the nearby communities on the quality of the groundwater.

For the sampling was employed the standard instrument used by the W.D.D. (glass sampler). This task was carried out in August 1992 and the samples were analysed by P.M. Hydrolab in Paphos. The analysis made the following determinations:

PH
Electrical conductivity
Total Hardness
Calcium
Magnesium
Sodium
Chloride
Sulphates
Nitrates
Bicarbonates

The results are given in the Table 10.1. The principal ionic concentrations of the groundwater analysis are illustrated through Schoeller diagrams (Fig. 10.1).

10.2 THE SUITABILITY FOR CROP IRRIGATION

The suitability of groundwater for irrigation purposes is a function contingent upon various parameters of which the most important are the following (Varshney et al.,1985; Ayers and Westcot,1989):

1. Salinity
2. Water infiltration rate
3. Specific Ion Toxicity
4. Miscellaneous effects

Clearly, both total salinities and activities of ions are continually changing. Chemical analysis of a water sample can yield only a composition at one point in time at a particular location. However, general assessment can be made in order to appraise water quality and carry out irrigation management.

FAO Guidelines (Ayers, and Westcot,1989) for these parameters are shown in Table 10.2.

Table 10.1 Chemical analysis of the well samples

Well No.	Conductivity µS/cm	SAR	Total hardness as $CaCO_3$ mg/l	pH	Alkalinity as $CaCO_3$ mg/l	Chlorides mg/l	Sulphates mg/l	Bicarbonates mg/l	Nitrates mg/l	Calcium mg/l	Magnesium mg/l	Sodium mg/l
W.508	1251	1.42	440	7.4	200	225	50	244	20	96	48	68
W.490	2080	4.87	644	7.3	320	320	450	390	18	123	81	283
W.502	1164	2.48	364	7.8	290	150	80	354	16	90	34	109
W.250	1472	3.21	564	7.4	280	200	350	342	15	83	85	175
W.443	2160	5.52	872	6.6	370	275	885	451	0	235	68	373
W.2450	1162	7.85	164	8.9	320	170	91	390	10	24	25	230
W.64	1740	3.92	664	7.3	300	205	540	366	12	120	87	231
W.2007	1420	6.22	400	8.1	460	275	30	561	170	67	56	285
W.323	1324	3.19	600	7.2	210	75	640	256	6	173	40	179
W.456	2280	5.72	920	7.1	290	335	970	354	8	214	92	398
W.104	1940	2.77	780	7.3	400	260	350	488	35	162	90	177
W.139	2100	2.87	784	6.9	410	240	340	500	95	163	90	184
W.744	1360	2.40	452	8.3	250	220	120	305	22	90	55	117
W.739	3520	3.48	752	7.5	320	445	220	390	58	190	66	219
W.758	3210	3.97	636	7.5	350	285	320	427	59	208	28	230
W.1392	2160	1.15	524	8.1	260	180	90	317	55	139	42	60
W.1569	3240	4.08	688	7.6	390	290	320	476	105	168	64	245
W.2951	1590	3.53	464	7.1	340	165	210	415	60	101	51	174
W.441	2000	3.41	661	8.1		266	647	76	12	144	77	204
P.I.Pr.	600	1.8	203	8		49	89	210	4	49	19	16

Fig. 10.1 Schoeller diagrams of groundwater analysis

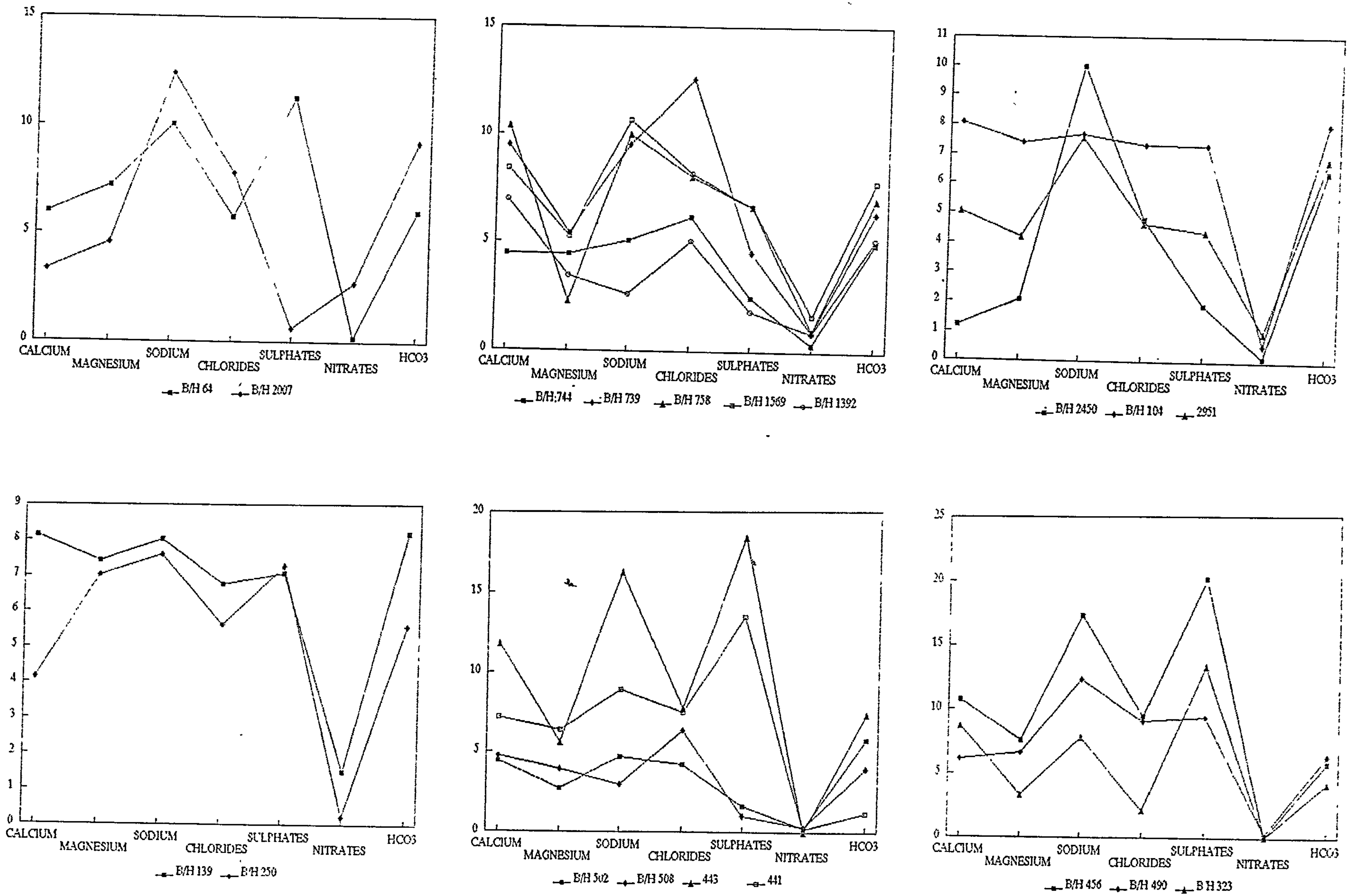


Table 10.2 Guidelines for interpretations of water quality irrigation

Potential Irrigation Problem		Units	Degree of restriction on use		
			None	Slight to moderate	Severe
Salinity					
EC_w		dS/m	< 0.7	0.7 - 3.0	> 3.0
(or)					
TDS		mg/l	< 450	450 - 2000	> 2000
Infiltration					
SAR = 0-3 and EC_w =			> 0.7	0.7 - 0.2	< 0.2
= 3-6 =			> 1.2	1.2 - 0.3	< 0.3
= 6-12 =			> 1.9	1.9 - 0.5	< 0.5
=12-20 =			> 2.9	2.9 - 1.3	< 1.3
=20-40 =			> 5.0	5.0 - 2.9	< 2.9
Specific Ion Toxicity					
Sodium (Na)[4]					
	surface irrigation	SAR	< 3	3 - 9	> 9
	sprinkler irrigation	me/l	< 3	> 3	
Chloride (Cl)[4]					
	surface irrigation	me/l	< 4	4 - 10	> 10
	sprinkler irrigation	me/l	< 3	> 3	
Boron (B)[5]		mg/l	< 0.7	0.7 - 3.0	> 3.0
Miscellaneous Effects					
Nitrogen (NO_3-N)[6]		mg/l	< 5	5 - 30	> 30
Bicarbonate (HCO_3)		me/l	< 1.5	1.5 - 8.5	>8.5
pH				Normal Range 6.5 - 8.4	

Source: F.A.O. (29 Rev.1), 1989

10.2.1 Salinity problems

Irrigation water with increasing salinity hinders plant growth and affects the crop yield mainly due to osmotic stress. In addition they may have indirect chemical effects on the metabolism of the plant and the soil properties as those of infiltration, permeability rate and aeration (Varshney et al.,1983;F.A.O.,1989).

The general accepted limit-criteria to asses the suitability of irrigation water based on electrical conductivity of water (EC_w) or Total Dissolved Solids (T.D.S.) criterion. If a salinity problem is indicated, suitable crops can often be selected that are tolerant to the expected salinity. Crop tolerance table for representative field, forage, vegetable and tree crops are available through many publications (Texas Techn.Un. 1976; Todd 1980; F.A.O.,1989). Based on this data, the Table 10.3 is drawn up with particular selected crops which are being cultivated in Cyprus; the salinity criterion was based on EC_w values. Also, F.A.O. describes salinity problems in terms of T.D.S. criterion. According to this, effects are slight to moderate if it falls into the range of 450 - 2000 mg/l and when it exceeds the 2000mg/l are described as severe. Other researchers give more restricted guidelines but in respect to T.D.S. and pH as in Table 10.4, below. For this study, however, samples have been analysed for the salinity problems in terms of EC_w according to the FAO Guidelines (Table 10.2); the results are shown in Table 10.5.

10.2.2 Water infiltration rate

Most normal soils of arid and semi-arid regions have calcium and magnesium as the principal cations with sodium representing generally less than 5% of the exchangable cations. If the sodium percentage in the soil is increased to 10% or more the aggregation of this soil breaks down and the soil becomes less permeable, crusts when dry and its pH is raised. Since calcium and magnesium replaces sodium

Table 10.3 Relative salt tolerance of agricultural crops

Tolerant	Moderately tolerant	Moderately sensitive	Sensitive
Barley	Wheet	Groundnut	Bean
	Beet, red	Alfalfa	Carrot
	Olive	Brussel sprouts	Onion
	Papayia	Cabbage	Avocado
		Cucumber	Lemon
		Corn, sweet	Orange
		Lettuce	Strawberry
		Pepper	
		Potato	
		Tomato	
		Grape	

Source: FAO (29 Rev 1), 1989

Table 10.4 Suitability of water for irrigation in relation to T.D.S. and pH

T.D.S.	Water suitability	Water doubtful to unsuitable if
up to - 400 ppm	all waters general fit for irrigation	----
400 - 600 ppm	pH < 9.0	pH > 9.0
600 - 800 ppm	pH < 8.5	pH > 8.5
800 - 1000 ppm	pH < 8.0	pH > 8.0
1000 - 1200 ppm	----	doubtful for irrigation
more than 1200 ppm	----	generally unsuitable

Source: Varshney et al,1983

Table 10.5 Interpretation of the Groundwater chemical analysis according to F.A.O. guidelines for irrigation use (1989)

Sample extractions from Well No.	Salinity EC_w (µS/cm)			Infiltration			Specific ion toxicity: Sodium (Na)			Specific ion toxicity: Chloride (Cl)			Miscellaneous effects (HCO_3)		
	None	Slight to moderate	Severe	None	Slight to moderate	Severe	None	Slight to moderate	Severe	None	Slight to moderate	Severe	None	Slight to moderate	Severe
508		*		*				*			*			*	
490		*		*				*			*			*	
502		*		*				*			*			*	
250		*		*				*			*			*	
443		*		*				*			*			*	
2450		*			*			*			*			*	
64		*		*				*			*			*	
2007		*			*			*			*			*	
328		*		*				*		*					*
456		*		*				*			*			*	
104		*		*				*			*			*	
139		*		*				*			*			*	
744		*		*				*			*			*	
739			*	*				*			*			*	
758			*	*				*			*			*	
1392		*		*			*				*			*	
1569			*	*				*			*			*	
2951		*		*				*			*			*	
441		*		*				*			*		*		

* Surface irrigation is not considered because it is not yet practised in the area.

irrigation water with low sodium absorption ration (S.A.R.) is desirable (Linsley et al.,1964).

The S.A.R. indicates the relative activity of the sodium ion exchange reactions with the soil. An irrigation water with a high S.A.R. will cause the soil to tighten-up among other effects. S.A.R was first proposed by the U.S.D.A. Salinity Laboratory (U.S.D.A. Handbook 60, 1954) for studying the suitability of groundwater for irrigation purposes; it is defined according to the formula:

$$S.A.R.= Na/\sqrt{(Ca+Mg)/2}$$

where the constituents are expressed in milliequivalent per litre.

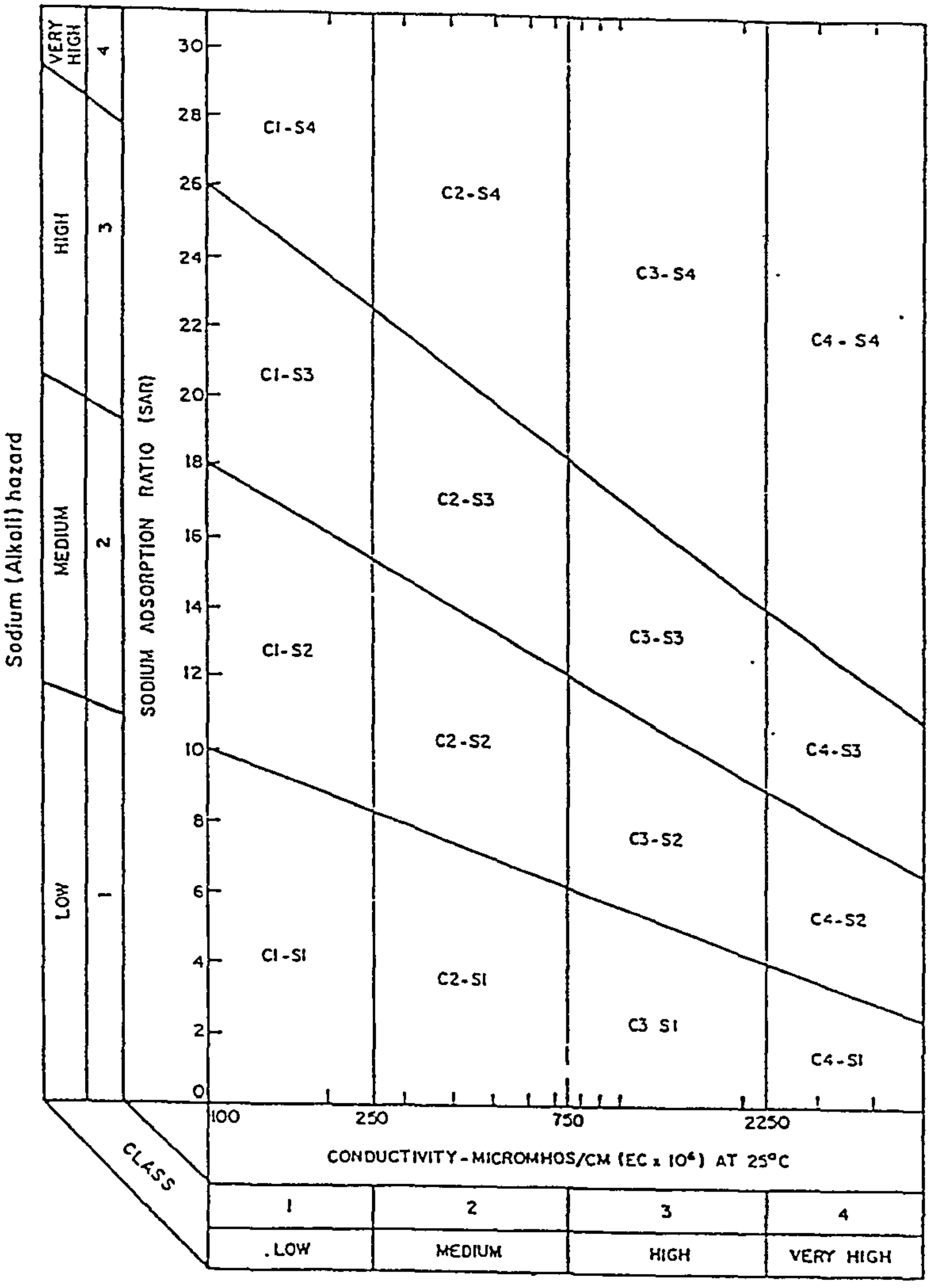
This forms the basis of a classification developed by the U.S. Salinity Laboratory of the Department of Agriculture, U.S.D.A., (1954). Irrigation water is classified by taking into account electrical conductivity, EC_w, and S.A.R. values. A particular diagram was developed by U.S.D.A. to convenience the classification. It consists of sixteen divisions representing various classes from C1-S1 (low salinity and sodium hazards) to C4-S4 (high salinity and sodium hazards), (see Fig.10.2).

The F.A.O. Guidelines (Table 10.2) describe as well the affects of the infiltration rate of water into the soil by considering together EC_w and S.A.R. These guidelines have acquired worldwide acceptance. That is a very good reason, to analyse samples of groundwater according to the guidelines above.

10.2.3 Specific toxicity

Toxicity problems occur if certain constituents in the soil-water are taken up by the plant and accumulate to concentrations high enough to cause crop damage or reduce yield. The most common toxicities referred to are sodium, chloride and boron. The F.A.O. Guidelines above treat a lot

Fig. 10.2 Water quality for irrigation practice
Source: Todd, 1980, Varshney et al, 1985



Salinity Hazards

over this issue. The limitations of such a quality of the irrigation water is shown within the same Table 10.2.

10.2.4 Miscellaneous effects

Several other problems related to irrigation water quality occur with sufficient frequency for them to be specifically noted. These include high nitrogen concentrations in the water, which supplies nitrogen to the crop and may cause excessive vegetable growth, clogging and delayed maturity. Abnormalities often associated with unusual pH of the water are of serious concern. Particular hazards may occur against irrigation and pumping metallic material. High concentration of bicarbonate ions may result in precipitation of calcium and magnesium bicarbonates from the soil solutions, increasing the relative proportion of sodium and causing sodium hazards.

10.3 THE QUALITY OF THE GROUNDWATER IN THE COASTAL PLAIN

The quality of this groundwater is considered for irrigation purposes only because of the reasons explained soon before, (section 10.1).

10.3.1 The suitability for irrigation use

The quality of the groundwater in the calcarenite aquifer varies considerably from location to location. It generally contains high calcium carbonates, $CaCO_3$, and the water may be classified as hard to very hard as it is shown in Table 10.6 (Twort et al.,1974).

The quality of the groundwater was processed/analysed in respect to the salinity problems. The total quantity of salts in the proposed irrigation water, according to the F.A.O. Guidelines (Table 10.2) is such that it falls in the category of slight to moderate and only three of the sampling well waters (W.739, W.758 and W.1569) have been classed as having severe affects, (Table 10.5). This water can be used cautiously if the conditions are favourable. Some of the

Table 10.6 <u>Hardness Classification of Water</u>

Hardness as $CaCO_3$	Water Class
0 - 50mg/l	soft
50 - 100mg/l	moderately
100 - 150mg/l	slightly hard
150 - 200mg/l	moderately hard
Over 200mg/l	hard
Over 300mg/l	very hard

Source: Twort et al, 1974

waters are suitable only for salt-tolerant crops.

According to the same Guidelines above, infiltration problems are not expected. The analysis results are shown in Table 10.5, too.

The specific ion toxicity effects of sodium and chloride were found to be between slight to moderate (Table 10.5). The sodium toxicity is not easily diagnosed but clear cases have been recorded as a result of relatively high sodium concentrations in the water (high Na or S.A.R.). Typical symptoms are leaf burn, scorch and dead tissue along the outside edges of leaves. Particular care in assessment of a potential toxicity due to S.A.R. or sodium is needed with high S.A.R. water because apparent toxic effects of sodium may be due to or complicated by poor infiltration. Crop relatively tolerant to exchangeable sodium are sited in the Table 10.7.

The chloride ranges between 75 and 335 mg/l (Table 10.1) and considered as satisfactory for sprinkler irrigation, exception consists the sample from the dug-well W.739 which indicated 445 mg/l and it is therefore unsuitable for surface irrigation. Plants show variable sensitivity to chloride concentrations with tolerance limits as in Table 10.8.

For the purpose of this study miscellaneous effects are considered along the bicarbonates (HCO_3) alone. Bicarbonate is usually the primary anion in groundwater, it is derived from carbon dioxide released by organic decomposition in the soil. After the analysis through the F.A.O. Guidelines (Table 10.2) such effects are limited to slight to moderate. Severe effects are possible only in the case of the well W.2007 and this is a localised phenomenon. The degree of restrictions due to HCO_3 is determined in Table 10.5 as well.

Further to the analysis proceeded by considering the F.A.O. Guidelines because of local experience in sulphate

Table 10.7 Relative tolerance of selected crops to exchangeable sodium[1]

Sensitive[2]	Semi-tolerant[2]	Tolerant[2]
Avocado	Carrot	Alfalfa
Deciduous fruits	Clover, Ladino	Barley
Nuts		
Bean, green	Dallisgrass	Beet, garden
Cotton (at germination)	Fescue, tall	Beet, sugar
Maize	Lettuce	Bermuda grass
Peas	Bajara	Cotton
Grapefruit	Sugarcane	Paragrass
Orange	Berseem	Rhodes grass
Peach	Benji	Wheatgrass, crested
Tangerine	Raya	Wheatgrass, fairway
Mung	Oat	Wheatgrass, tall
Mash	Onion	Karnal grass
Lentil	Radish	
Groundnut (peanut)	Rice	
Gram	Rye	
Cowpeas	Ryegrass, Italian	
	Sorghum	
	Spinach	
	Tomato	
	Vetch	
	Wheat	

Adapted from data of FAO-Unesco (1973); Pearson (1960); and Abrol (1982).

The approximate levels of exchangeable sodium percentage (ESP) corresponding to the three categories of tolerance are: sensitive less than 15 ESP; semi-tolerant 15-40 ESP; tolerant more than 40 ESP. Tolerance decreases in each column from top to bottom. The tolerances listed are relative because, usually, nutritional factors and adverse soil conditions stunt growth before reaching these levels. Soil with an ESP above 30 will usually have too poor physical structure for good crop production. Tolerances in most instances were established by first stabilising soil structure.

Source: F.A.O. (29 Rev.1), 1989

Table 10.8 Chloride tolerance of some fruit crop cultivars and rootstocks[1]

Crop	Rootstock or cultivar	Maximum permissible Cl-without leaf injury[2] Root zone (Cl_e) (me/1)	Irrigation water (Cl_w)[3 4] (me/1)
Avocado	Rootstocks		
	West Indian	7.5	5.0
	Guatemalan	6.0	4.0
	Mexican	5.0	3.3
Citrus	Sunki Mandarin	25.0	16.6
	Grapefruit		
	Cleopatra mandarin		
	Rangpur lime		
	Sampson tangelo	15.0	10.0
	Rough lemon		
	Sour orange		
	Ponkan mandarin		
	Citrumelo 4475	10.0	6.7
	Trifoliate orange		
	Cuban shaddock		
	Calamondin		
	Sweet orange		
	Savage citrange		
	Rusk citrange		
	Troyer citrange		
Grape	Salt Creek, 1613-3	40.0	27.0
	Dog Ridge	30.0	20.0
Stone fruits	Marianna	25.0	17.0
	Lovell, Shalil	10.0	6.7
	Yunnan	7.5	5.0
	Cultivars		
Berries	Boysenberry	10.0	6.7
	Olallie blackberry	10.0	6.7
	Indian summer raspberry	5.0	3.3
Grape	Thompson seedless	20.0	13.3
	Perlette	20.0	13.3
	Cardinal	10.0	6.7
	Black rose	10.0	6.7
Strawberry	Lassen	7.5	5.0
	Shasta	5.0	3.3

Source: F.A.O. (29 Rev.1),1989

problems this is considered as well. Sulphates range from a maximum of 97 mg/l to a minimum of 30 mg/l, (Table 10.1). According to Chr. Metochis (1989) the use of high sulphate water for irrigation of citrus such as grapefruit and oranges, although high in salinity (4.1 dS/m) seems not to present a serious problem. The constant non-leachable salinity created in the soil profile is rather low, as accumulation of Ca^{++} and SO_4 above gypsum solubility product is prevented by its precipitation. The trees grow less, but as yield per tree volume is similar to that of trees irrigated with low salinity water under Cyprus conditions, more dense planting could result in high yields.

The groundwater in the coastal plain calcarenite aquifer generally can be used for irrigation but with caution. Although, suitable water management needs to be developed for extensive use.

The recommended management of this water is summarised below for proper utilization of the groundwater.

1) Mixing the groundwater with the water provided by the P.I.Project.
2) Control on the private extractions.
3) Encourage farmers to practice shift cultivation.
4) Regular monitoring of the groundwater movement.
5) Train farmers in the new conditions.

10.4 CORROSION AND INCRUSTATION POTENTIAL

Corrosion may occur when water comes into contact with metal materials used in the irrigation scheme. The course of this corrosion is associated with the following water properties, (Twort, et al,1974; Scully,1975; Mason,1988).

1. Low pH or acidity.
2. A high free CO_2.
3. An absence of temporary hardness (or alkalinity).

From the chemical analysis which was carried out (Table

10.1), it seems that generally pH ranges between 7-8.4 indicating neutral to alkalinity and therefore no trend for corrosion. The sample of the well W.443 indicates pH 6.6 (i.e. acid water), which is localised phenomenon and may not influence the quality of the groundwater to a considerable extent. Thus, the analysis of the water from well W.441 sited almost 500m from the previous well indicated pH 8.1.

The aquifer is mainly calcareous, therefore carbon dioxide (CO_2) may be present in the groundwater but the calcium content as well helps to absorb it so that the resulting water is not as corrosive as one which has little or no calcium bicarbonate ($Ca(HCO_3)_2$) content.

The most used index for predicting corrosion potential is the Langelier Index. The Langelier Index was proposed in 1977 by Morton who derived this expression (Mason ,1988):

$$LI=pH+\log C+\log A+0.025T-0.011S^{\frac{1}{2}}-12.30$$

where:

LI= Langelier Index

pH= pH value

C= Calcium hardness or calcium ion content expressed as $CaCO_3$ (mg/l)

A= Alkalinity expressed as e.$CaCO_3$ (mg/l)

T= Temperature in °C where T lies between 0 and 25°C

S= Total dissolved solids (mg/l) where S is less than 1000mg/l

The Langelier Index values are mainly positive indicating that the waters are slightly encrusting. The negative values are not significant. This as expected from limestone derived waters (see Table 10.9).

The chloride content is also high, according to the

Table 10.9 The Groundwater corrosion potential according to the Langelier Index

Well No.	Langelier Index
W.508	-0.2
W.490	0.44
W.502	0.65
W.250	0.46
W.443	-0.15
W.2450	1.56
W.64	0.35
W.2007	1.24
W.323	0.07
W.456	0.27
W.104	0.54
W.139	0.18
W.744	1.16
W.739	0.61
W.758	0.59
W.1392	1.00
W.1569	0.77
W.2951	0.14

Guidelines Table 10.2. As reported by E.M.U.,(1982), manufacturers of pumping systems, concentration of chlorides > 150mg/l it is possible there will be an occurrence of corrosion in the metal (hole corrosion). Furthermore, L.G. Hutton,(1983), notes that high chlorides accelerate corrosion of concrete structures.

If fertilizers, however, are injected into the irrigation water, possible precipitation due to water chemistry must be considered. For example, if calcium (Ca) concentration is greater than 120mg/l, most phosphorus fertilizers will cause clogging of emitters. Clogging is more severe if bicarbonate (HCO_3) is high (>300mg/l). Anhydrous or liquid ammonia should not be applied through these systems as the ammonia can increase pH of the water to values 11 and cause rapid precipitation of calcium carbonate ($CaC0_3$) which clogs the entire system (F.A.O.,1989).

Throughout the coastal plain there are numerous wells with metallic installations as far as is known significant corrosion problems were not reported.

Incrustation of screen slots and pipeline systems is more likely with waters of high pH. Such effects, particularly of those of the harder form due to high concentrations of sulphates (sulphates > 100mg/l) scarcely reported. Slight incrustation might be due to precipitation of bicarbonates, of calcium or magnesium may take place.

10.5 CONTAMINATION

Percolation of sewage through the ground may contaminate an aquifer due to the transference of nitrogen compounds from the sewage forming nitrate ion in the water. The concentration of this conservative ion in a water, if it exceeds the 30 mg/l may render unfit for irrigation purposes. The F.A.O. guidelines (Table 10.1) states the restrictions of practising certain quality of water. In addition, there exists the possibility of bacterial and virus infestation of underground aquifers, (Barnes and Wilson, 1978; Sinton,1986).

However, several sample analysis demonstrated high concentration of nitrates as from the well W. 2007 - 170 mg/l, W. 139 - 95 mg/l, W. 739 - 58 mg/l, W. 758 - 59 mg/l, W. 1392 - 55 mg/l, W. 1569 - 105 mg/l and W. 2951 - 60 mg/l; it may indicate contamination resulting from the septic field leachate from nearby houses.

CHAPTER 11

THE GROUNDWATER LEVEL FLUCTUATIONS

11.1 GENERAL CONSIDERATION

Groundwater level fluctuations result from changes in pressure head or fluid potential on the groundwater system. It is heavily caused by differences between the groundwater storage caused either from supply (inflow) or withdrawal (outflow) (Leopold,1974). Other diverse influences on groundwater levels include meteorological phenomena (atmospheric, tidals etc.), seismic shocks, external loads, all of which are related to a greater or lesser extent to geographical location (Brassington,1988). Despite the intrinsic interest of these factors, such fluctuations are not very important in groundwater investigation unless there is a certain reason to deal with. On the other hand the influence of these is broadly considered as difficult to predict.

Groundwater levels can show secular variations which may be attributed to consecutive wet and dry years in which rainfall exceeds or is below the mean average. Many groundwater levels yet show seasonal pattern fluctuations. This results from influences such as rainfall and irrigation pumpings that follow well-defined seasonal cycles. Characteristic short-term fluctuations have always been experienced elsewhere. Short-term fluctuations scarcely reflect momentary changes in hydrostatic pressure but generally is a response to pumping in a locality.

11.2 THE PREPARATION OF HYDROGRAPHS AND THE WATER TABLE CONTOUR MAPS

Much information is available about groundwater fluctuation because records exist from tens of wells in the study area, and measurements here go back over 20 years. These measurements have been used in this study to produce a number of hydrographs and water table contour maps.

The reported well measurements have been chosen in such a way in order to portray the actual hydrological conditions found within the various aquifer zones which the coastal plain has been sub-divided for the purpose of the current investigation, (see section 7.2). The hydrographs are shown in Figures 11.1a and 11.1b.

The water table contour maps illustrate the seasonal fluctuations for the hydrologic years 1980/81 and 1987/88. The rainy season in Cyprus extends from November to March. Thus, it defines the hydrologic year to start in November and end in October of the following year. The produced maps show the water table levels at the beginning and at the end of the hydrologic years of 1980/81 and 1987/88 and the water table at the end of March when the rainy season ends and the irrigation begins over the coastal plain. The water table contour maps are illustrated in Appendix I.

The precipitation over the study area was approximately the same in both hydrologic years (section 12.1) and therefore the influence of the continuous irrigation from the P.I.Project may be determined. As mentioned before the P.I.Project has been fully implemented since 1985.

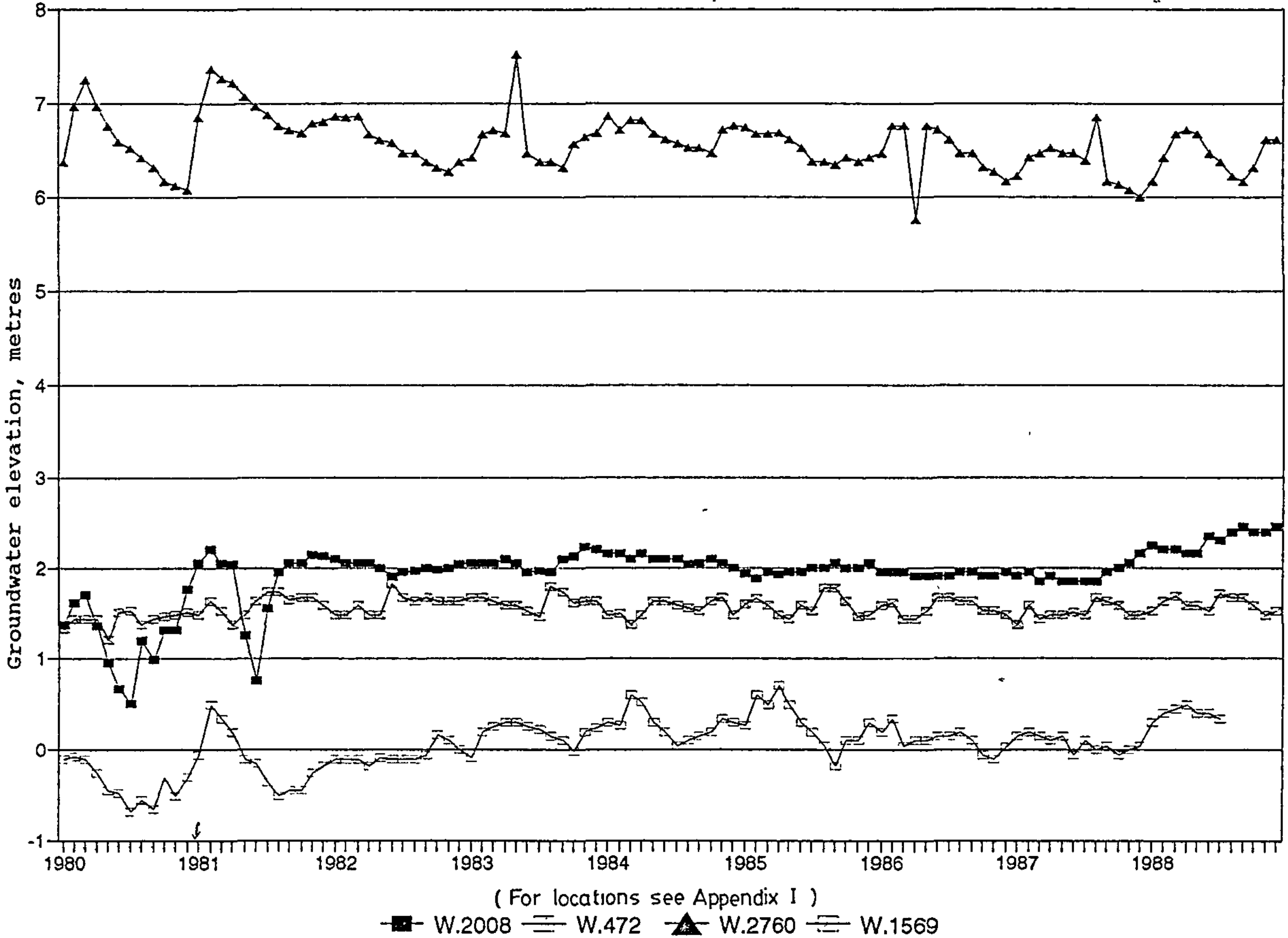
The water table contour maps have been produced by using the computer programme, Quick-Serf (Q.S.) - Version 2, which has also been used to produce the map of the basement of the coastal plain aquifer as is described in section 7.3.2. The resulted capacities with respect to a fixed area datum allowed to estimate the seasonal variations and to calculate storage capacities. This approach to storage computation is considered separately in section 12.2.

11.3 AN ASSESSMENT BASED ON THE HYDROGRAPHS AND WATER TABLE CONTOUR MAPS

In order to recognise the secular variations of the groundwater levels in the coastal plain calcarenite aquifer,

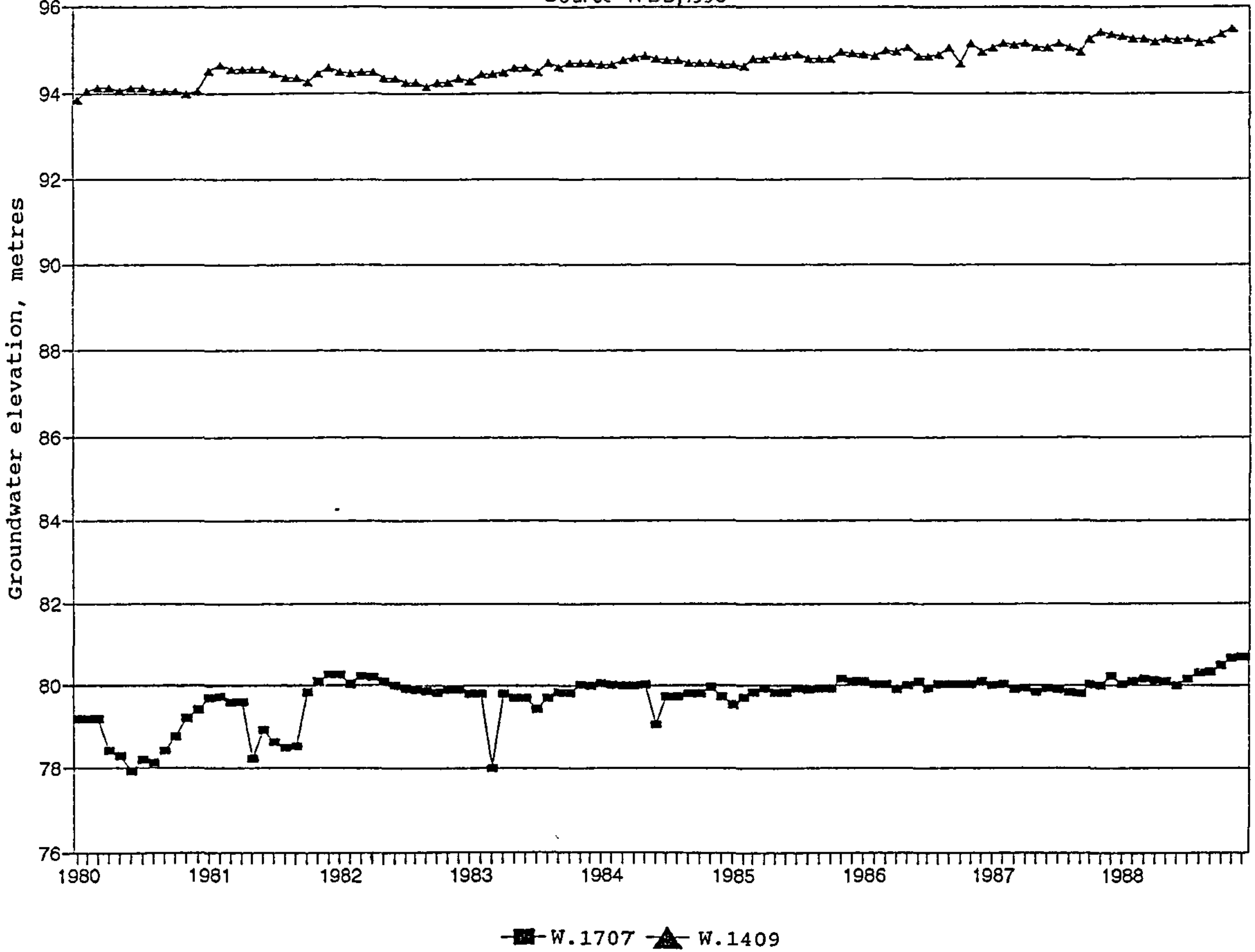
Fig. XVIa Seasonal fluctuations of the water table in the Coastal Plain calcarenite aquifer 1980-1988

Source:WDD,1990



calcarenite aquifer 1980-1988

Source WDD,1990



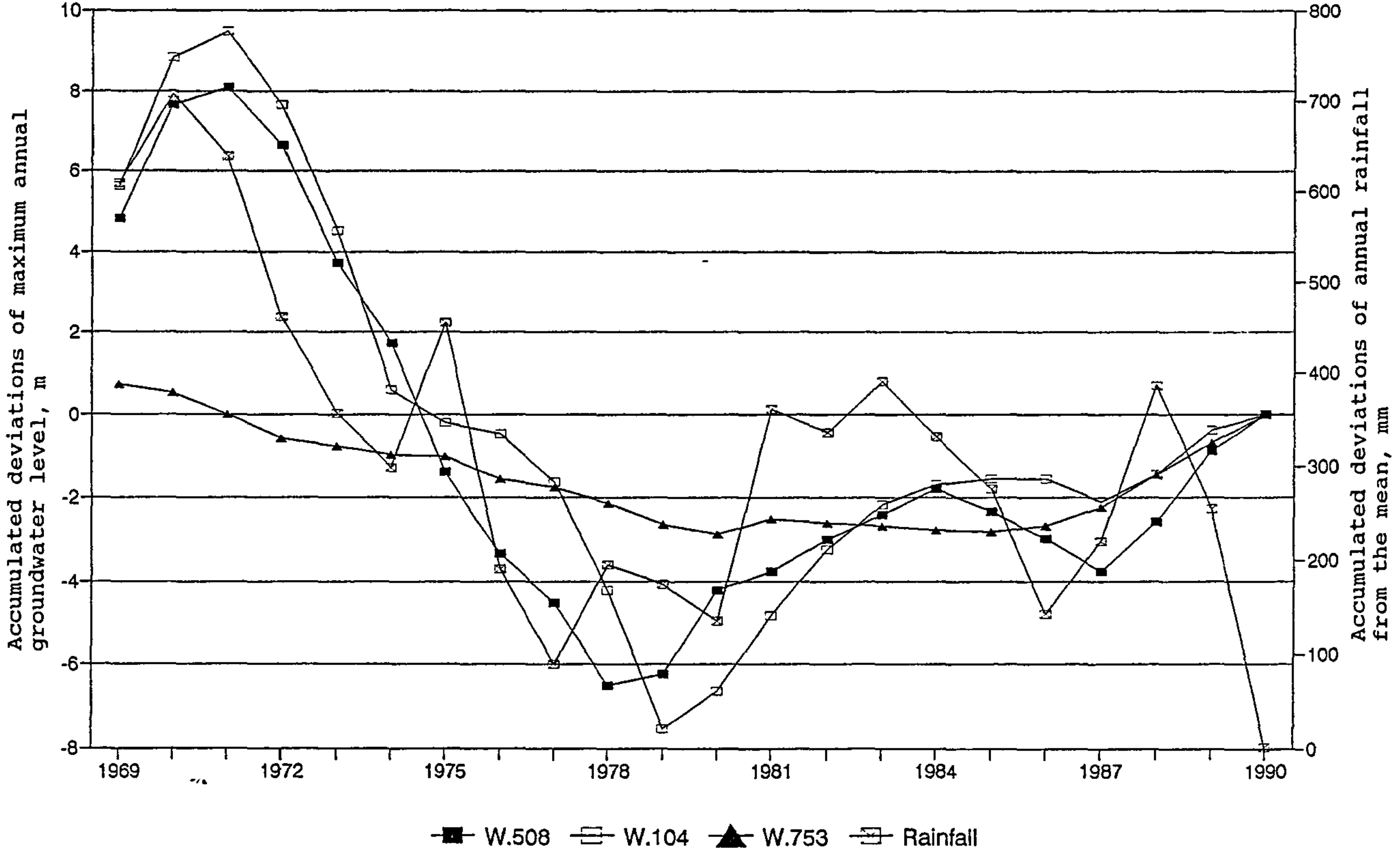
the synthesis of the accumulated deviation of both the maximum annual groundwater levels from particular selected wells and the annual rainfall from the mean, has been produced. Alternating series of wet and dry years in which rainfall is above or below the mean, may produce long periods of groundwater level fluctuations. In general terms this is compatible within the data plotted in Fig.11.2. The groundwater level fluctuations greatly follow the same pattern to that of the rainfall fluctuations with some peaks indicating the influence of the pumpages in the contributing area. However, the hydrograph of the W.753 is diverged and seems to indicate an erratic pattern.

In this figure it is apparent that there is a constant lack of time of approximately three to four months between accumulated rainfall and the response of the water table. This is better demonstrated within the early plotted data up to the year 1974 from the wells W.508 and W.104.

It is understood that the influence exerted by the rainfall through the mechanism of infiltration-percolation into the aquifer is a long process which is dependent on many parameters. Of these, the most important parameters are the intensity and duration of the areal precipitation and the landform drainage and geology in the area concerned.

As in an arid region, much of the precipitation of Cyprus comes in a few fairly heavy falls. This encourages immediate run-off and causes flash flows of rivers and rivulets which last for a few hours. The concentration of the rainfall mainly in the three winter months leads to saturation of the soil and higher proportion of run-off in relation to percolation. The little rainfall during the summer months falls on the parched ground and much evaporates quickly and much soaks down a few centimetres; there is very little run-off unless the falls are very heavy which is rather uncommon.

Fig. 11.2 Secular variations of maximum annual groundwater level and annual rainfall in the Paphos Coastal Plain



Precipitation however, is the primary source of recharge to the groundwater. This was deduced by computing the saturated thickness before and after the rainy season. The results are provided in Table 12.2. These computations were based on the water table contour maps and showed an increase in groundwater level after the winter as in March 1981 and 1988 ranging an average between 43% and 28% respectively.

An indication of the magnitude of the seasonal and the short-term fluctuations is better illustrated with the hydrographs presented in Fig.11.1a. Within this figure it can be seen that almost all the peaks respond at the late winter or after lasting the rainy season, which is in agreement with the records of maximum groundwater levels per year as provided in Table 11.1. This can be explained by the variations showing the rainfalls in the region and also the considerable time the infiltrated water requires to percolate into the groundwater because of the heavy texture of the overlying soil. Also, within these hydrographs a sharp decline of the water-table of even a few meters appears. These adverse effects are certainly associated with pumpage occuring in the same well or nearby.

Another group of hydrographs (Fig. 11.1b) which were made-up from measurements from wells located over higher plane and at a considerable distance from pumpages showing a steady increase of the water table level after 1985. Even though the increase of the water table level is small it can be inferred that the irrigated water from the P.I.Project, partly percolates to the groundwater almost at a constant rate per year.

The hydraulic basement of the aquifers lies almost everywhere, well above sea level and only some locations along the shore line are below it. As has been observed in the hydrographs of the wells No. 472 and No. 2008 (Fig.11.1a), sometimes groundwater level falls near to or below sea level.

Table 11.1 Maximum absolute static water level for selected wells of the Coastal Plain aquifer for the period 1969-90

Well No. 508		Well No. 104		Well No. 753	
Month/Year	W.Level(m)	Month/Year	W.Level(m)	Month/Year	W.Level(m)
4/69	19.09	5/69	24.27	2/69	24.27
5/70	17.07	4/70	21.80	12/70	23.31
2/71	14.71	5/71	19.27	3/71	22.98
9/72	12.78	4/72	16.78	1/72	22.98
3/73	11.32	3/73	15.48	1/73	23.31
1/74	12.28	5/74	14.69	3/74	23.31
4/75	11.13	7/75	17.83	2/75	23.50
4/76	12.30	5/76	18.32	10/76	23.01
5/77	13.07	3/77	17.50	1/77	23.31
6/78	12.26	3/78	16.00	7/78	23.16
5/79	14.53	1/79	15.30	12/79	23.01
6/80	16.28	1/80	19.53	3/80	23.31
5/81	14.68	6/81	20.42	2/81	23.90
3/82	15.01	4/82	20.20	3/82	23.41
5/83	14.88	4/83	19.70	5/83	23.46
1/84	14.83	5/84	19.10	3/84	23.41
6/85	13.73	5/85	18.75	3/85	23.51
3/86	13.61	4/86	18.60	6/86	23.66
6/87	13.44	6/87	18.10	4/87	23.96
5/88	15.48	6/88	19.25	4/88	24.29
4/89	15.93	5/89	19.68	3/89	24.31
2/90	15.13	1/90	19.00	6/90	24.21

Source: W.D.D., 1992; Author's Research, 1992

Therefore, pumpage should accordingly be limited in these areas in order to reduce the risk of sea water intrusion.

In general, the water table contour maps showed consistent gradients towards the sea at any time. However, the groundwater table gradient varies from place to place. In the eastern area, for instance, it was 0.6 - 1.5%, as in March 1988 and in the western area it was 1.8 - 3% over the same period.

CHAPTER 12

ESTIMATE OF THE POTENTIAL CAPACITY OF THE CALCARENITE AQUIFER

12.1 CONCEPT METHODOLOGY

To further study the potential of the aquifer, the estimate of the recharge and the discharge (input and output) and the storage capacity of the calcarenite aquifer are needed. In order to define these parameters a particular design program was carried out. This is outlined herebelow.

To determine the extent of the influence of the precipitation and the extent of the effects of the irrigation use of the P.I.Project into the hydrological regime of the aquifer the analysis of the seasonal groundwater fluctuations of two different hydrologic years, of the 1980/81 and the 1987/88, are considered along with for comparison purposes. The several hydrographs and the water table contour maps have been produced to depict the seasonal water table fluctuations in the aquifer. By the drawing of the water table maps the programming (see section 7.3.2) was possible also to produce the water bearing capacities which is to be analysed in the following section to derive the changes in groundwater head for water balanced computations.

The hydrological year has been defined (section 7.3.2) as lasting from November to October of the following year. Although rainfalls may start in October pumping still occurred. Most usually the essential rainy season starts in November and ends in March. From March provision of water to the farms is done through irrigation until the start of the rainy season in November.

However, the chosen hydrological year 1980/81 responded to the conditions before the implementation of the P.I.Project (this Project is distributed all over the area which overlays the calcarenite aquifer; it has fully been implemented since

1985) and the year 1987/88 responded to the conditions after. Also, the chosen hydrological years above were considered in respect to the precipitation occurred over the area. Thus, the years considered have been chosen to have approximately the same precipitation; hence the average annual precipitation in 1980/81 was 549mm and in 1987/88 it was 547mm. Groundwater tables show to respond to precipitation fluctuations. This has been set out within the several hydrographs and determined by the water table contour maps (Appendix I). The chosen means would provide the maximum potential extent of the aquifer during periods of normal to high precipitation. It is worth mentioning that, because the coastal plain aquifer is not an over year storage reservoir (see section 9.7) the preceding years of the two chosen hydrological years were not taken into account.

12.2 THE COMPUTATIONS OF RECHARGE OUTFLOW AND STORAGE CAPACITY OF THE AQUIFER

The computations of the water balance and storage capacity of the aquifer was based on the following classical equation (Walton,1970; Leopold,1974; Bowen,1980; Brassington,1988).

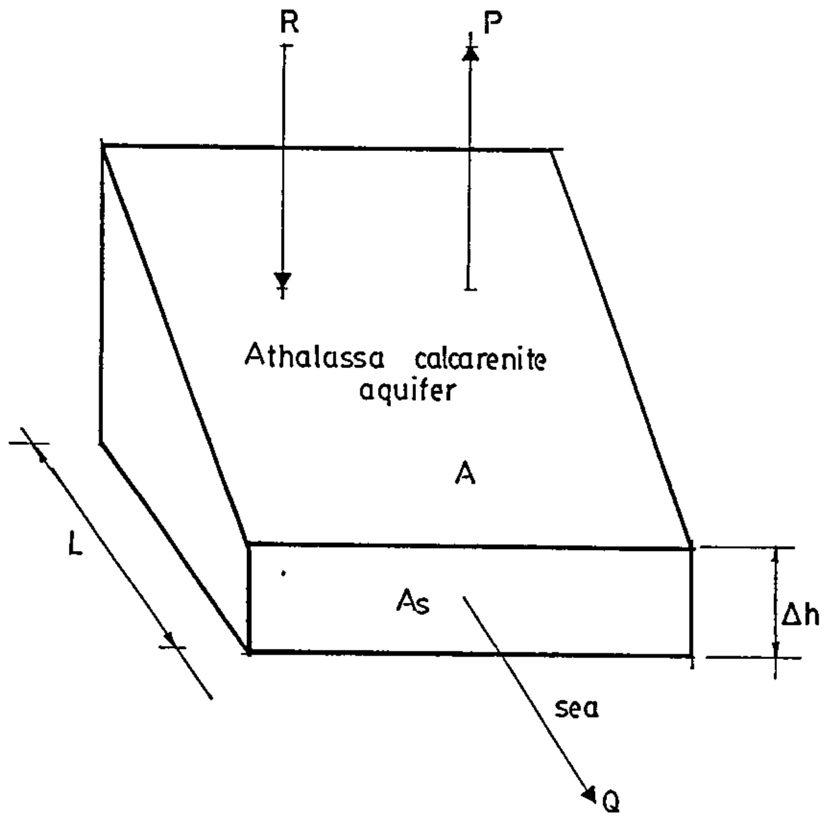
$$R=Q+P+ h.A.S \tag{12.1}$$

where R= recharge into the aquifer
Q= subsurface outflow
P= pumpage
h=rise in water table level
A= surface area of the particular zone
S= specific yield.

The components of the water balance of the aquifer system can be best analysed as shown schematically in Fig.12.1.

Computations of recharge by the above equation assumed that other outflows such as evaporation are negligible because of the nature of the aquifer (the water table lies almost everywhere over a depth of 3 to 15m as shown on the water table

Fig. 12.1 Water balance model



maps, Appendix I) and that the subsurface outflow to the sea and none to the other aquifers of calcarenite nearby. It is also important to note that there is no other possible source of recharge besides the rainfall and the irrigation return inflows because the coastal plain bounds the impermeable rocks (chalky marls, marls etc.) of the Pakhma formation which is well exposed within the Kissonerga-Kouklia escarpment (see sections 8.3 and 8.4).

Further using Darcy's equation

$$Q = K.A_s.i \qquad (12.2)$$

where K= aquifer permeability

A_s= cross-section area through which the outflow takes place.

i= water-table gradient at the outflow

Using equations 12.1 and 12.2 above, the following equations were derived to calculate the changes in storage and outflows of the aquifer for the hydrological years 1980/81 and 1987/88 including the irrigation season.

For November 1980	: Storage= $h_{N80}.A.S$	(12.3)
For March 1981	: Storage= $h_{M81}.A.S$	(12.4)
Outflow (Nov'80-Mar'81)	: $Q_1=K.A_1.i_1$	(12.5)
Recharge (Nov'80-Mar'81)	: R_1=Stor(Mar'81-Nov'80)+Q_1	(12.6)
For October 1981	: Storage= $h_{Oct'81}.A.S$	(12.7)
Outflow (Mar'81-Oct'81)	: $Q_2=K.A_2.i_2$	(12.8)
Recharge (Mar'81-Oct'81)	: R_2=Stor(Oct'81-Mar'81)+P+Q_2	(12.9)
Total Outflow	: Q_1+Q_2	(12.10)
Total Recharge	: R_1+R_2	(12.11)
For November 1987	: Storage= $h_{N87}.A.S$	(12.12)
For March 1988	: Storage= $h_{M88}.A.S$	(12.13)
Outflow (Nov'87-Mar'88)	: $Q_1=K.A_1.i_1$	(12.14)
Recharge (Nov'87-Mar'88)	: R_1=Stor(Mar'88-Nov'87)+Q_1	(12.15)

For October 1988	: Storage= $h_{Oct'88}.A.S$	(12.16)
Outflow (Mar'88-Oct'88)	: $Q_2=K.A_2.i_2$	(12.17)
Recharge (Mar'88-Oct'88)	: R_2=Stor(Oct'88-Mar'87)+P+Q_2	(12.18)
Total Outflow	: Q_1+Q_2	(12.19)
Total Recharge	: R_1+R_2	(12.20)

The calculation of outflow is set out in Tables 12.1a and 12.1b.

12.3 ESTIMATION OF THE AQUIFERS POTENTIAL

Based on the information from the hydrogeological sections (section 8.3) and the results from the pumping test analysis (section 9.7) and the chemical analysis too (section 10.3), this study can conclude that the coastal plain calcarenite aquifer consists of a thin and low storativity aquifer with poor quality of water content.

The actual potential capacity of the aquifer was pointed out after the analysis of the seasonal behaviour of the groundwater table for particular selected years, as in the preceeding section (12.2). The produced groundwater storage capacities of the aquifer and the estimated recharge and outflow quantities at different seasons are provided in Tables 12.2a and 12.2b.

The extracted figures within these tables (12.2a and 12.2b) showed similar fluctuations for the two years in question (i.e. 1980-81 and 1987-88), despite the continuous irrigation supplies from the P.I.Project in the irrigation season (i.e. March - October) of 1988. It is however, difficult to explain this outcome. This may reflect the basic uncertainty and inaccuracy in the available data used for the calculations and even the physical and hydrogeological characteristics of the calcarenite aquifer. It may partly be due to the fact that groundwater table responds to precipitation after a considerable period has passed (section

Table 12.1a Seasonal variations in outflow 1980-81

Zone	1	2	3	4
k (m/d)	20	20	20	16
Nov'80-Mar'81	8100	7000	5040	5060
As(m^2) (mean)				
Mar'81-Oct'81	7425	6300	5040	5060
Nov'80-Mar'81	0.016	0.028	0.013	0.050
h/ L (mean)				
Mar'81-Oct'81	0.01525	0.0250	0.0140	0.040
Nov'80-Mar'81	2592	3920	1310	4048
Outflow(m^3/d)				
Mar'81-Oct'81	2264	3150	1411	3238
Nov'80-Mar'81	388800	588000	196500	607200
Outflow(m^3)				
Mar'81-Oct'81	475440	661500	296310	679980
Total Outflow(m^3) Nov'80-Oct'81	864240	1249500	492810	1287180

Table 12.1b Seasonal variations in outflow 1987-88

Zone	1	2	3	4
k (m/d)	20	20	20	16
Nov'87-Mar'88	8100	6300	4680	5060
As(m^2) (mean)				
Mar'88-Oct'88	7425	5600	3960	5060
Nov'87-Mar'88	0.0175	0.0150	0.020	0.050
h/ L (mean)				
Mar'88-Oct'88	0.0165	0.020	0.013	0.055
Nov'87-Mar'88	2835	1890	1872	4048
Outflow(m^3/d)				
Mar'88-Oct'88	2450	2240	1030	4453
Nov'87-Mar'88	425250	283500	280800	607200
Outflow(m^3)				
Mar'88-Oct'88	514500	470400	216300	935130
Total Outflow(m^3) Nov'87-Oct'88	939750	753900	497100	1542330

Table 12.2a Estimates of the storage capacity of the Coastal Plain calcarenite aquifer (1980-81)

Zone		1	2	3	4
Area km^2		12.04	14.40	6.76	12.25
k (m/d)		20	20	20	16
S(%)		6.0	6.0	7.5	5.0
h (m) mean water table	Nov'80	3.25	6.30	6.21	1.65
	Mar'81	4.76	7.79	7.83	2.95
	Oct'81	4.24	7.08	6.88	2.46
Storage(m^3)	Nov'80	2347800	5443200	3148470	1010625
	Mar'81	3438624	6730560	3969810	1806875
	Oct'81	3062976	6117120	3488160	1506750
Pumpage(m^3)		721400	438400	463100	692600
Outflow(m^3)	Nov'80-Mar'81	388800	588000	196500	607200
	Mar'81-Oct'81	475440	661500	296310	679980
Recharge(m^3)	Nov'80-Mar'81	1479624	1875360	1017840	1403450
	Mar'81-Oct'81	821192	486460	277760	1072455
Outflow(m^3)	Nov'80-Oct'81	864240	1249500	492810	1287180
Recharge(m^3)	Nov'80-Oct'81	2300816	2361820	1295600	2475905
(Q/R)100		37.5	52.9	38.0	52.0

Table 12.2b Estimates of the storage capacity of the Coastal Plain calcarenite aquifer (1987-88)

Zone		1	2	3	4
Area (km^2)		12.04	14.40	6.76	12.25
k (m/d)		20	20	20	16
S(%)		6.0	6.0	7.5	5.0
h(m) mean water table	Nov'87	3.88	4.36	5.81	2.35
	Mar'88	4.69	6.54	6.75	2.92
	Oct'88	4.45	6.16	6.40	2.57
Storage(m^3)	Nov'87	2802912	3767040	2945670	1439375
	Mar'88	3388056	5650560	3422250	1788500
	Oct'88	3214680	5322240	3244800	1574125
Pumpage(m^3)		332900	263500	209000	302600
Outflow(m^3)	Nov'87-Mar'88	425250	283500	280800	607200
	Mar'88-Oct'88	514500	470400	216300	935130
Recharge(m^3)	Nov'87-Mar'88	1010394	2167020	757380	956325
	Mar'88-Oct'88	674024	405580	247850	1023355
Outflow(m^3)	Nov'87-Oct'88	939750	753900	497100	1542330
Recharge(m^3)	Nov'87-Oct'88	1684418	2572600	1005230	1979680
(Q/R)100		55.8	29.3	49.4	79.9

11.3). Thus, groundwater table continues to be influenced from the winter rainfalls till May and even early June as indicated with the maximum water levels in Table 11.1. On the other hand, the existence of the P.I.Project since 1985 has not influenced the potential of the calcarenite aquifer as far as it was believed. Meanwhile, modern irrigation practices such as the sprinklers and the trickle drips have been employed all over the project area. These irrigation techniques have been developed for this purpose, among others, to eliminate losses with the proper management. Thus, the minor influence into the groundwater has to be considered.

The groundwater outflow to the sea (Table 12.1) from the zones 1, 2 and 3 are relatively small because it is distributed thinly in a wide area along the shoreline. It may not be technically and economically feasible to exploit all these water underdrained in the sea. In zone 1, conditions are quite encouraging for some developments. This is discussed in Chapter 13. Zone 4, however, has a higher outflow of between $1.28 \times 10^6 m^3$ in 1980-81 to $1.54 \times 10^6 m^3$ in 1987-88, which could be exploited by developing underground collection systems, but this unfortunately cannot be considered because of the construction of hotels and other tourist establishments over there.

The storage capacity of the coastal plain calcarenite aquifer varies from season to season responding to any changes produced by precipitation and pumpages (section 11.3). Therefore, the maximum capacity should occur after higher precipitation over the area. In 1968-69 as was referred to in section 9.4, rainfalls over the study area exceded 170%. Concerning this hydrological year S. Afrodisis (1969) had conducted a hydrogeological survey for the coastal plain in question which was consolidated by carrying out water balance estimates. The basic data and the results of this study are presented in the Table 12.3.

Table 12.3 Storage computation for 1967-68

Zone	Area	S(%)	h- Nov'67	h- Mar'68	Storage- Nov'67	Storage- Mar'68
1	11.0 km^2	8	3.0 m	6.5 m	$2.6*10^6 m^3$	$5.7*10^6 m^3$
2	16.0 km^2	8	3.5 m	7.6 m	$4.5*10^6 m^3$	$9.7*10^6 m^3$
3	8.7 km^2	8	4.5 ?m	9.0 m	$3.1*10^6 m^3$	$6.2*10^6 m^3$
4	8.0 km^2	8	2.4 m	4.6 m	$1.5*10^6 m^3$	$2.9*10^6 m^3$

Source: Afrodisis, 1969

It is apparent that the figures in Table 12.3 for S and Area values are quite different from that determined by this study, but the estimates may indicate the maximum potential capacity of the aquifer during periods of very high rainfall.

Data and findings presented in this thesis may, however, be more representative to the average weather conditions over the region.

It is obvious throughout this investigation that the coastal plain aquifer is poor groundwater resource. Nevertheless, bearing in mind the limited natural resources on the island, groundwater resources of any volume even those within poor aquifers, must be considered for an optimum exploitation programme.

Therefore, the Paphos coastal plain calcarenite aquifer can be considered accordingly for a certain development.

CHAPTER 13
GROUNDWATER MANAGEMENT AND POSSIBLE DEVELOPMENT

13.1 GENERAL

As far as calcarenite is concerned, it may be observed that the calcarenite aquifer hydraulic characteristics vary considerably from place to place and yet experience showed that conditions may be different throughout the entire depth of the saturated strata (i.e. no-homogeneity exist).

However, the investigation carried out and the studies performed enable some specific remarks and conclusions to be drawn over the conditions prevailed at the greatest part of the coastal calcarenite aquifer which may affect alternative development options and preliminary designs.

Before this study proceeded, it was assumed that the coastal plain aquifer had abundant and good quality water for irrigation. It was also argued (see section 7.1) that the infiltration losses through continuous irrigation over the plain, from the P.I.Project should have markedly been contributing to the augmentation of the potential recharge into the calcarenite aquifer, other than that of the areal rainfall. As this investigation programme has been coming to an end, it becomes more apparent that the former studies as well as the preliminary estimates which were conducted occasionally by governmental agents during recent droughts, were only partly true.

Following the analysis given in Table 12.2, it can now be inferred that the calcarenite aquifer is of limited potential capacity. Recharge into the aquifer is mainly vertical by direct infiltration of the rainfall and lesser from return flow through irrigation. The discharge rate is low and is subject to seasonal variability. Because of its geometry, low specific yields, high transmissibilities developed locally, and its proximity to the sea, it depletes rapidly during the summer. Thus, there has been a small rise in the water table since 1985 in locations with reduced pumping and increased recharge following irrigation from the P.I.Project. Water quality is variable but is usually inferior to that supplied by the P.I.Project. In fact the bulk of the calcarenite water is probably unsuitable for continuous irrigation of crops lightly sensitive to salinity.

The main problems that must be tackled by conducting groundwater developments along the coastal plain are:

(a) recovery of groundwater in an aquifer of small saturated thickness,

(b) prevention of the sea water encroachment where the basement is below the sea level (see hydraulic basement contour map, Fig.8.2a and 8.2b),

and (c) irrigation use of water of inferior quality.

The possible ways of developing the aquifer can be based on the existing private pumping facilities or otherwise government new schemes must be constructed for optimum exploitation.

The abundant dug-wells and wells may constitute a good background for a certain developing programme. As has been mentioned earlier, there are yet many wells equipped with mechanical or electromechanical pumping devices which are often used for supplementary provision but there is a large number of wells which have been abandoned so far and now need to be rehabilitated.

A more attractive idea is to encourage farmers for higher utilization of the groundwater. This can be succeeded by providing the farmers with incentives such as subsidising energy, spare parts, low interest loans etc. The areas where further development is possible should be specified and extraction rates in all areas should be established. Advice on water quality control and integration options with water from other resources, like the P.I.Project supply, should be made available to the farmers as well.

Intensive pumping can be avoided where there is a risk of sea water intrusion but it is possible to extract some groundwater quantities when the water table in the area allows it. However, continuous monitoring by a competent body is essential everywhere in all seasons.

This proposal may not give future guarantee, because of the readily available irrigation water supplied by the P.I.Project at reasonable prices. On the contrary, there are such difficulties experienced by the farmers themselves in maintaining the pumping units, especially on small holdings that it may eventually lead to disregarding them.

Groundwater development schemes executed and operated by the government, in this particular case, avoid much of the difficulties mentioned above. Indeed, the yield can be maximised as a government policy result without the objections of the high cost involved which does make it not attractive for individuals.

The physical and hydraulic characteristics of the calcarenite aquifer suggests that the limited potential of this groundwater resource may only be exploited by developing small schemes which will be flexible and less costly in maintenance and operation.

Two kind of government groundwater developments have been envisaged as to be the best that conform to the aquifer conditions. These are: (a) the construction of an underground drainage collector running parallel to the coastline which is to turn-off much of the underflows into the sea and from where the water will be diverted into the existing irrigation system and/or (b) the construction of a pattern of multiple boreholes within specified localised areas containing sufficient groundwater which has to be operated in conjunction with the existing irrigation network. These two possible developments have been considered in more detail during ths investigation and the findings are presented in the following sections.

13.2 THE SUBSURFACE DRAINAGE COLLECTOR

The basic idea was provided from the chain-of-wells which have successfully been experienced in the area until the recent past (Chapter 6). However, chain-of-wells have been used to exploit superficial deposits in large plains, here with the recommended development it is intended to tap also shallow underflows but even more to reduce the wastages into the sea.

It has already been pointed out in Chapter 9 that important quantities of groundwater flow continuously to the sea. It was estimated in section 12.3 that some two million cubic metres of groundwater underflowed into the sea from the middle-eastern zones and about one and a half million cubic metres of groundwater underflowed from the western zone of the coastal plain into the sea also, as in 1988 (Table 12.2). The constructed contour maps which indicate the water table at different seasons, in conjunction with the map of the hydraulic basement and the hydrogeological sections all of them provided evidence of the average head at the proximity of the sea, the locations endangered with sea water intrusion and the sort of the aquifer medium in place (Chapter 8). These allowed to make some preliminary assessments in order to define the most promising locations in the area for the construction of groundwater developments.

Initially three sites had been selected; one within the middle-eastern shoreline extending from zone 1 over zone 2 and one within the western shoreline (zone 4). The latter was at the end, abandoned because of the site constraints; the most coastal strip has been shifted from the irrigation area to a tourist zone and there have already been large buildings set up.

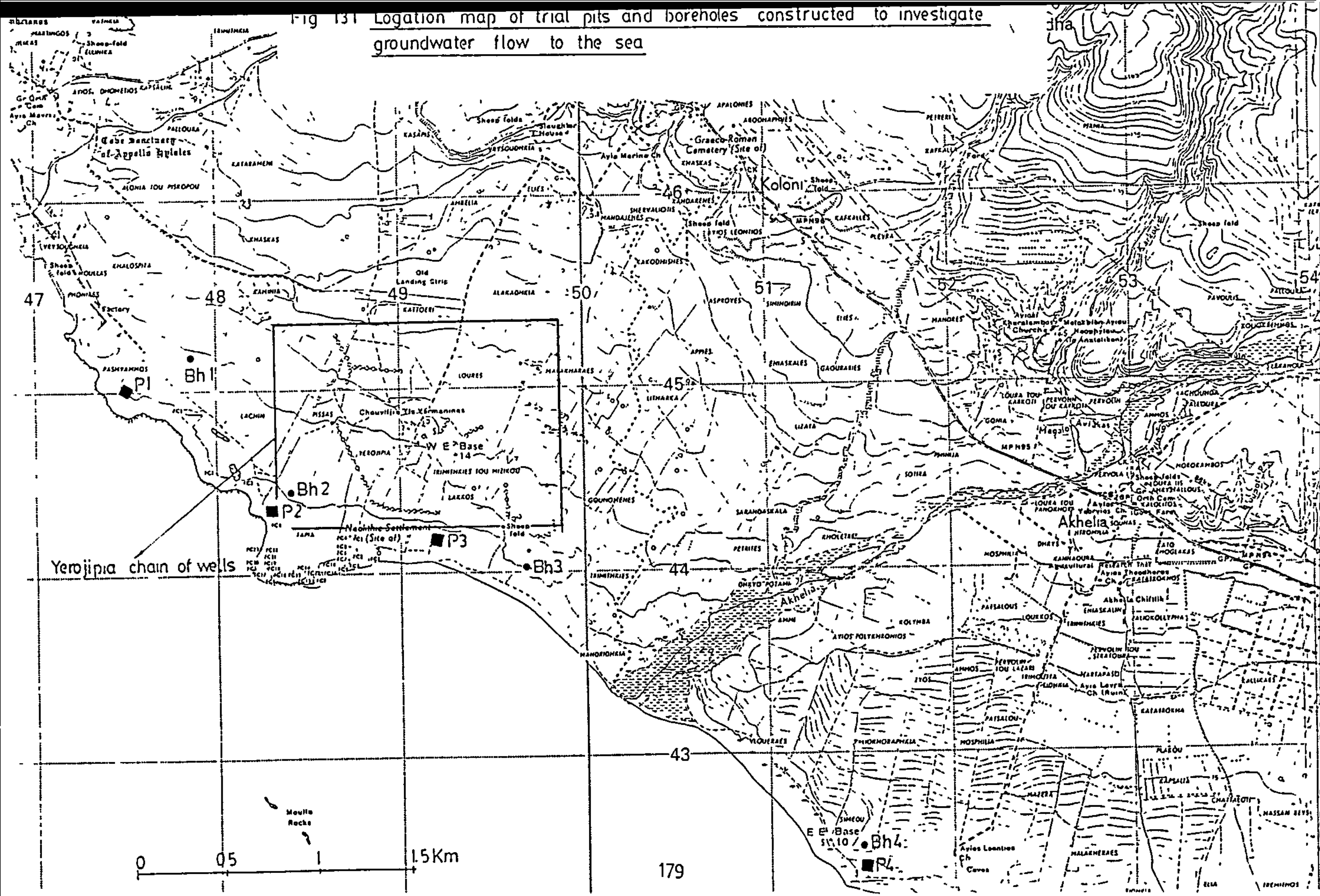
A comprehensive site investigation programme was planned and executed in the area in March 1991 in order to gain exact information of the aquifer physical and hydraulic characteristics required as an input for the design of an exploitation programme with optimum results. The investigation included excavation of boreholes and trial pits at key locations, short pumping tests, survey levelling etc. of the site in question.

The position of the pits and the boreholes were determined after the reconnaissance of the site. There are tell-tale signs to look for when locating shallow groundwater. The occurrence of spots of intensive green, reeds and hedges, for instance often reveal superficial groundwater movement. Also pronounced gradients combined with erosional happenings can help to recognise promising locations. In addition, old records of water levels from the wells existed in the area were considered together with the evidence above in order to define underflow occurrence.

The pits were excavated by using a digger and had an average depth of 2.3m. Where water table has been deeper or hard rock predominated machine-driven helical auger of 6" in diameter was employed. The drillings were of 9m depths on an average. Pipe-casing of 4" PVC was applied everywhere (at the end also within the pits were installed the same pipe-casings for observation purposes). This network of the four pits and the four drillings is shown in Fig.13.1.

A pumping test was attempted, but because of the small diameter of the well and due to the clay lining produced during the drilling, the infiltration in the well was insignificant so that testing had failed. Therefore, the pits were provided as an alternative solution.

Fig 131 Location map of trial pits and boreholes constructed to investigate groundwater flow to the sea



However, because of the shape of the pits (there was little excavation) and the technical problems associated to it, a formal pumping test has been difficult to be proceeded. Therefore, the informal test which was finally carried out provided only some impression of the potential of the proposed developments. The results of the tests are shown in Table 13.1 and discussed afterwards.

The test was carried out by performing one hour pumping and after almost steady conditions were achieved. The discharge rate shown in Table 13.1 is at the near constant recharge head occurred. The estimated mean average of $71m^3$/day for a 100m trench may help to assess the potential of the proposed drainage trench over 1.8km and 1.2km long, along the shoreline of zones 1 and 2 respectively. A suitable design system can contribute water for the period between late winter and summer, however, before depletion of the groundwater occurred. An amount of 200 - $250x10^3m^3$ under normal rainfall conditions may be anticipated from a certain development.

In spite of the inferior quality and the low discharge rate anticipated, such accumulated quantities of water may challenge a new approach for alternative resources management. The envisaged development is briefly considered according to the following lines.

A long trench would be excavated parallel to the shoreline between 30 and 50m inland in order to ensure the least depth of the excavation. For design purpose the likely adverse inflow effects on the excavation by sea intrusion after fresh water lowering to sea level should be taken into account. The length of the excavation must break over some distance in order to maintain consistent gradients towards a terminal manhole. Indeed, the length and the depth may depend upon the actual conditions, on site i.e. hydrogeology, water level, physical constraints etc. But each section between

Table 13.1 Estimates of discharge from trial pit excavations

Pit No.	Pit-Excavation (Length x Width x Depth)	Change from the initial water level	Discharge rate	Estimated m^3/day or 100m trench
1	6.0 x 0.6 x 2.6m^3	0.23m	2.51/min	60
2	6.0 x 0.6 x 2.8m^3	0.29m	3.71/min	88
3	6.0 x 0.6 x 2.7m^3	0.24m	3.01/min	72
4	6.0 x 0.6 x 3.0m^3	0.31	2.71/min	65
		mean average:		71

manholes can be of 100 - 150m length and 2.5 - 3.0m depth. The breadth of the excavation is a function of the drainage capacity only and it has nothing to do with the infiltration rate into the system. Thus, a breadth of 1.20m can be enough for the proposed drainage collection system to perform satisfactorily with a PVC pipe of 0.60m diameter. The space of the excavation, on both sides of the PVC collector must be filled with graded gravel. The manholes must be of a concrete structure where the electric-submersible pump can be facilitated.

A typical drawing of the proposed development and some essential information is illustrated in Fig.13.2.

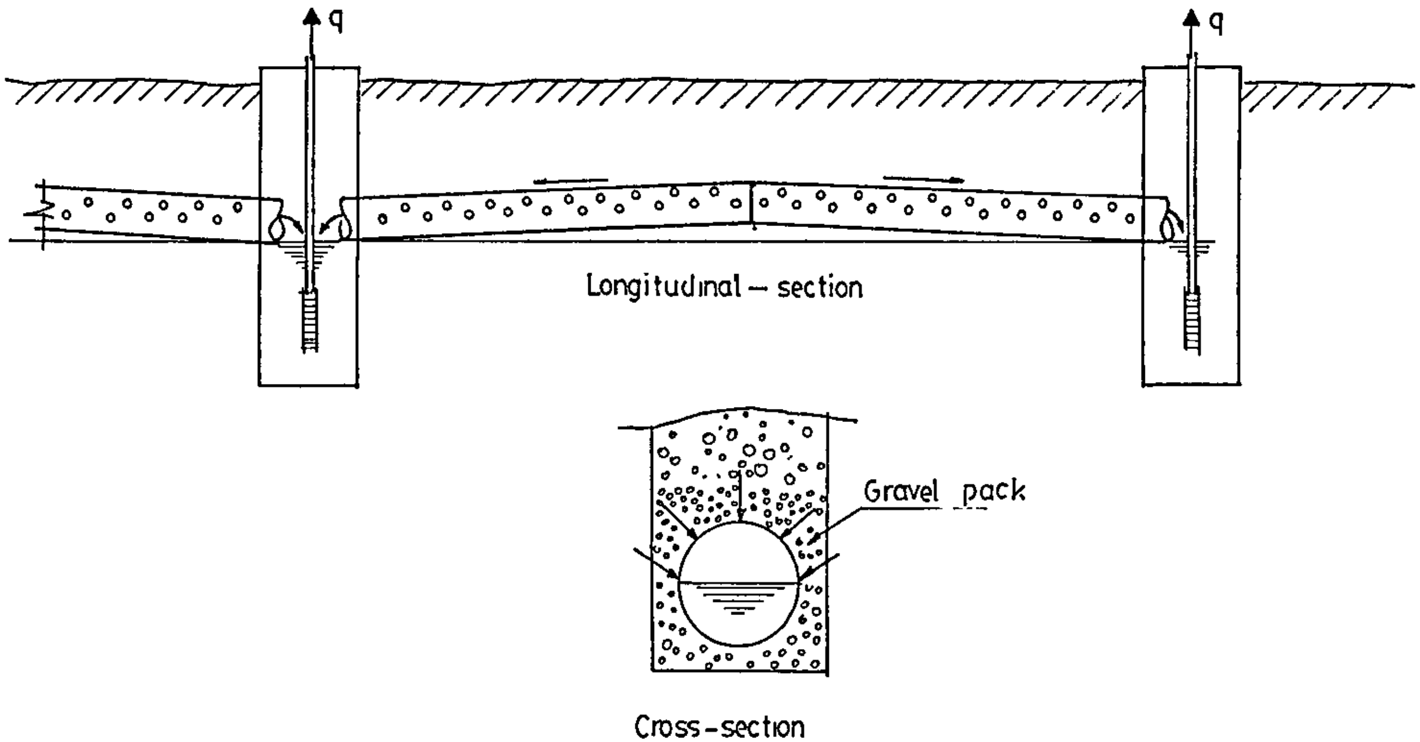
13.3 BOREHOLE PATTERN EXTRACTION

In addition to the proposed development along the shoreline other developments can be designed to utilize the annual cycles of aquifer recharge and groundwater recessions so that aquifer losses to the sea between winter up to summer are reduced as far as possible.

It is now certain that throughout the coastal aquifer some groundwater underdrains into the sea. It is found within this investigation that the trench system can be exploited near $0.2x10^6m^3$ out of $2.5x10^6m^3$ because of the difficulty to develop a greater exploitation programme by considering the entire coastal strip. The main problems encountered have been geomorphological obstruction, hydrogeological and hydrological constrictions, build-up areas etc.

Nevertheless, it is possible to secure more resources from the losses to the sea by groundwater developments inland. This can be achieved by intensifying pumping through a particular designed scheme. Such a scheme can be a combination of boreholes constructed in special arrangement within locations of most promising yields. This scheme can be operated in conjunction with the existing farmers pumping

Fig. 132 Schematic diagram of a subsurface drainage collector



facilities and may not be affecting the previous discussed developments.

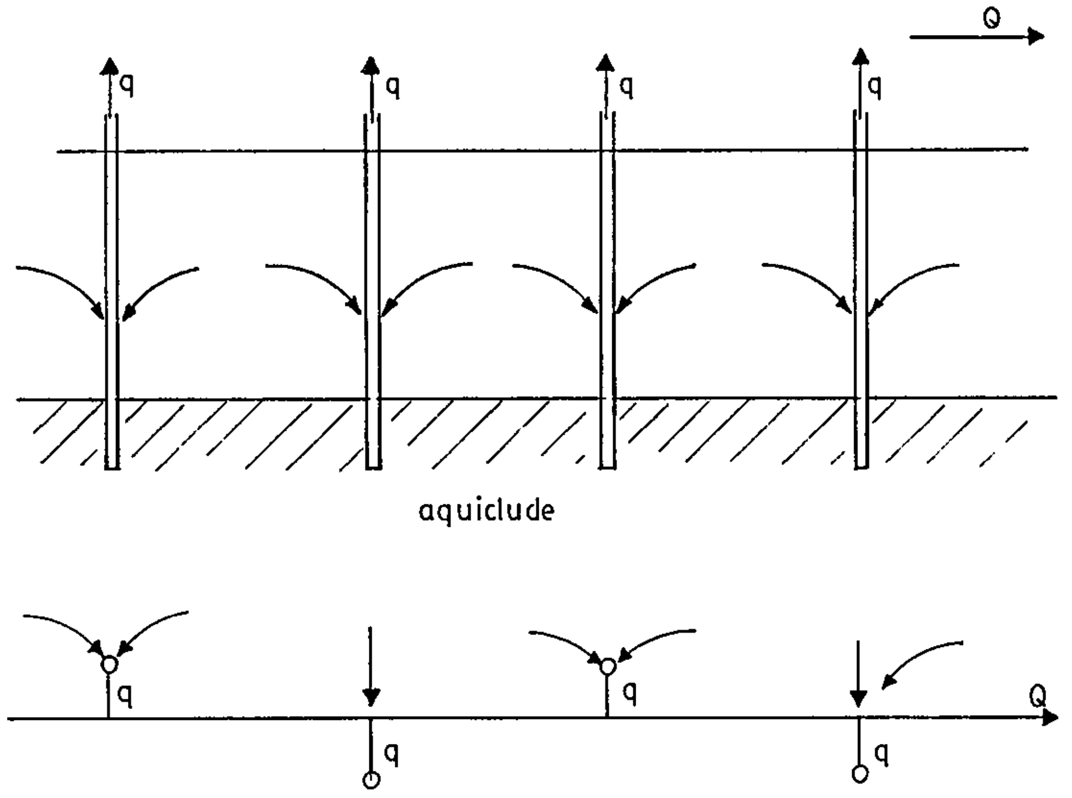
13.3.1 An overview of the proposed scheme

Each section of the proposed scheme will consist of a series of boreholes, the total numbers of which must be defined after a detail hydrogeological investigation of the site concerned. Of course, the number of boreholes is a function of the potential of the particular location. The boreholes must have the largest possible diameter to increase seepage into the well and to allow maximum storage below the water level. For storage purposes, the depth of the drillings must come across the layers of the marly sequences which consist of the basement of the aquifer. For the construction of such a well, are available by licensed contractors special augerings with disc up to 0.90m diameter.

The boreholes can be equipped with electrosubmersible pumps of 2.5 - 3.0 kw and 4" diameter with a total head approximately 30m and an average output of $15m^3/h$. An automatic level switch must by installed in such a manner so that any reasonable amount of groundwater has to be tapped. Each pumping device will be functioning individually according to the drop and rise of the water level in the particular well. A collector conveyor must be connected with all the pumps and the discharge water can be introduced directly for irrigation use or can be stored nearby for later use. Because quality is an essential parameter for groundwater utilization, a properly designed system must be considered to allow mixing of the groundwater with the water from some other resources if there is a need.

A typical layout providing an impression of the proposed scheme is given in Fig. 13.3. The construction pattern can follow a triangle arrangement in order to allow larger area of seepage.

Fig. 13.3 Triangle arrangement for the drillings



The location of the wells pattern needs to be determined by investigation and confirmation by a pumping test.

The proposal scheme can be developed wherever reasonable resources occur, but also the remainder of the coastal plain aquifer needs to be considered for optimum exploitation. The latter can be managed as has been outlined earlier in this chapter; i.e. private groundwater utilization must be encouraged by the State with the provision of financial support. This proposal ought to be considered to help the farmers to overcome the cost of rehabilitation, the maintenance or the fuel expenses and also to tackle the other difficulties related to this matter.

PART C

RESEARCH ON WASTEWATER AS A RESOURCE

CHAPTER 14

THE PAPHOS MUNICIPALITY WASTEWATER AS A POTENTIAL WATER SOURCE FOR GROUNDWATER RECHARGE

14.1 BACKGROUND INFORMATION

Addressing the need for improved sewerage infrastructure, the Municipality of Paphos commissioned a Master Plan and Feasibility Study to examine present and future sewerage requirements of the urban area through the year 2010.

The Master Plan was organised by the Town Planning Bureau of Cyprus, 1990. The established guidelines for the pattern of development of the Greater Paphos area is over a period ending in the year 2000. The document provides basic data regarding the following aspects of the Paphos urban area:

- Land use zoning (i.e. residential, tourist, agricultural)
- Building regulation
- Future urbanization and undeveloped areas
- Specific land regulations

The information published in the urban Master Plan served as a basis for the sanitary scheme of the Paphos town and its environs. For the feasibility study of this scheme Louis Berger International were hired as consultants. The same firm also designed the Limassol and Larnaca town sanitary schemes. In their study emphasis was given to the technology applied for effluent treatment. The author proposes that the effluent be considered for irrigation, this would reduce the need for fresh water.

In order to comply with the Cyprus Provisional Quality Standards for effluent reuse (Table 14.1) the final effluent must be tertiary treated. The consultants, however, believe that even the secondary treatment process may produce acceptable quality effluent for irrigation use under controlled conditions.

Table 14.1 Provisional Quality Standards for Treated Domestic Sewage Effluent Used for Irrigation

Irrigation of:	BOD (mg/l)	TSS (mg/l)	Fecal Coliform (/100ml)	Intestinal Worms (No./1)	Treatment Required
Amenity areas of unlimited access	10[a] 15[b]	10[a] 15[b]	50[a] 100[b]	Nil	Secondary and tertiary and disinfection
Crops for human consumption and amenity areas of limited access	20[a] 30[b]	30[a] 45[b]	200[b] 1,000[b]	Nil	Secondary and storage >1 week + disinfection; tertiary + disinfection
	--	--	200[a] 1,000[b]	Nil	Stabilization/maturation pond w/retention>30 days; Secondary + storage>30 days
Fodder crops	20[a] 30[b]	30[a] 45[b]	1,000[a] 5,000[b]	Nil	Secondary and storage >1 week or tertiary + disinfection
	--	--	1,000[a] 5,000[b]	Nil	Stabilization/maturation pond w/retention>30 days; Secondary + storage>30 days
Industrial crops	50[a] 70[b]	--	3,000[a] 10,000[b]	--	Secondary and disinfection
	--	--	3,000[a] 10,000[b]	--	Stabilization/maturation pond w/retention>30 days; Secondary + storage>30 days

[a]Values not to be exceeded in 80 percent of samples in a month.
[b]Maximum value allowed.

Notes:
1. Irrigation of vegetables is not allowed.
2. Irrigation of ornamentals for trade purposes is not allowed.
3. No substances accumulating in the edible parts of crops and proved to be toxic to humans or animals are allowed in effluent.

Source: CH2M Hill Intern., 1993

They also carried out an estimate of the operating cost for both a secondary and tertiary treatment process.
The estimation is as follows:

Cost per m^3, C£	Year 2002	Year 2012
Secondary treatment	0.13	0.09
Tertiary treatment	0.05	0.03

The reuse of the effluent in particular, was not included in the contract terms of reference and therefore this issue was not further studied by Luis Berger International.

Water resources however, available to Cyprus are scarce and their rational management and development are critical to efficient economic management. The Cyprus government has made every effort to increase the availability of water for all uses and most of the available conventional water resources have been developed. As a step forward it is now under consideration, by the water resources planners, a more ambitious strategic plan to exploit the unconventional water supply sources being available in the island (Christodoulou,1993). These are the domestic effluent of the largest towns in the island, (i.e. Limassol,1992; Larnaca,1993; Nicosia,1995). Sewerage and treatment plant are under construction for the above towns, but for the Paphos urban area, this is still being scheduled.

This programme of sewerage projects has been carried out in response to the concern of the Government that the effluent resulting from the projects above, should be optimally utilized. This is especially important for the agriculture. By using alternative supplies for irrigation, freshwater supplies can be transferred to domestic uses that require water of a higher quality.

Within the G.P.W.S.S. (section 3.1) it is envisaged (H. Humphreys,1993) that by the years 2000 and 2020 an amount of $2.4x10^6m^3$ and $3.6x10^6m^3$ respectively of reclaimed water, after treatment of the Paphos urban area effluent, should be available for irrigation use. The distribution pattern of the reclaimed water per month for the same year, according to the consultants estimates should be expected to be as on Table 14.2.

14.2 THE QUALITY OF THE RECLAIMED WATER REQUIRED FOR IRRIGATION PURPOSES IN CYPRUS

The type of crops that can be irrigated with reclaimed wastewater depends upon the quality of the effluent, the amount of the effluent used and the health regulations concerning the use of sewage or sewage effluent on crops.

The quality of effluent appropriate for various irrigation uses was considered by a meeting of environmental specialists and epidemiologists at Engelberg, Switzerland (June, 1985) sponsored by World Bank, U.N. W.H.O. and International Reference Centre for Waste Disposal. Their conclusions are given in Table 14.3.

In Cyprus, a Technical Working Committee agree quality standards, acceptable for different uses, derived from those of the Engleberg Report. The agreed standards are, more stringent. These are as in Table 14.1.

Also the State Institute of Agricultural Research in Nicosia carried out similar work in order to be persuaded by Cyprus standards. This work is provided as Provisional Quality Standards and are in line with the above, (i.e. Table 14.1).

These agricultural limitations may be overcome by adopting an appropriate cropping pattern and methods of irrigation, but concerning this particular case of Paphos coastal plain, there is no room for such a shift. The Paphos Irrigation Project is networked throughout the coastal plain providing continuous unrestricted water and the agriculture

Table 14.2 Proposed reclaimed effluent supply for 2000 and 2020

Months	Year 2000	Year 2020
Jan	$130x10^3m^3$	$179x10^3m^3$
Feb	$123x10^3m^3$	$172x10^3m^3$
Mar	$178x10^3m^3$	$254x10^3m^3$
Apr	$183x10^3m^3$	$279x10^3m^3$
May	$230x10^3m^3$	$339x10^3m^3$
Jun	$265x10^3m^3$	$384x10^3m^3$
Jul	$267x10^3m^3$	$395x10^3m^3$
Aug	$309x10^3m^3$	$456x10^3m^3$
Sep	$262x10^3m^3$	$388x10^3m^3$
Oct	$216x10^3m^3$	$330x10^3m^3$
Nov	$150x10^3m^3$	$225x10^3m^3$
Dec	$140x10^3m^3$	$191x10^3m^3$
Total	$2.453x10^6m^3$	$3.592x10^6m^3$

Source: H. Humphreys, 1993

Table 14.3 Tentative Microbiological Quality Guidelines for Treated Wastewater Reuse in Agricultural Irrigation (1)

Reuse Process	Intestinal nematodes(2) (geometric mean no. of viable eggs per litre)	Faecal coliforms (geometric mean no. per 100ml)
Restricted irrigation (3) Irrigation of trees, industrial crops fodder crops, fruit trees (4) and pasture (5)	< or = 1	not applicable (3)
Unrestricted irrigation of edible crops, irrigation of sports fields, and public packs (6)	< or = 1	< or = 1000 (7)

(1) In specific cases, local epidemiological, sosiocultural, and hydrogeological factors should be taken into account and these guidelines modified accordingly.

(2) Ascaris, tricharis and hookworms.

(3) A minimum degree of treatment equivalent to at least a 1-day anaerobic pond followed by a 5-day facultive pond or its equivalent is required in all cases.

(4) Irrigation should cease two weeks before fruit is picked and no fruit should be picked off the ground.

(5) Irrigation should cease two weeks before animals are allowed to graze.

(6) Local epidemiological factors may require a more stringent standard for public lawns, especially hotel lawns in tourist areas.

(7) When edible crops are always consumed well-cooked, this recommendation may be less stringent.

Source: The Engelberg Report, 1985

established so far within the study area is unlikely to shift. Therefore, it does not appear feasible to introduce restrictions on the crops to be planted, to allow wastewater effluent to be used for irrigation.

Further to the above, it is extremely difficult to persuade farmers to accept inferior water quality to be distributed through or apart from the existing facilities of the P.I.Project which covers the most arable area in the region; even though this water is supplied on different days to those of the fresh water.

Reclaimed water is one of the unconventional resources that may be used for irrigation. Since reclaimed water reuse has not been generally practised in Cyprus and since it is essential to maintain good public health standards existing in the island, a high degree of control of such reuse is considered necessary.

It is assumed that effluent from the Paphos Municipality and its environs will proceed further treatment to remove the maximum possible suspended solids and pathogens and supply an end product complying with the Provisional Standards for unrestricted irrigation as in Table 14.1. Treatment for removal of other substances, such as metals and toxic compounds, may not be necessary since the concentrations of these in the influent wastewater are expected to be insignificant because no industrial wastewater will be permitted to be discharged to sewers.

In addition to the physico-biochemical treatment provided through the conventional and advanced treatment process it is proposed to further treat the effluent by Soil Aquifer Treatment (S.A.T.). This will produce a high quality effluent. Since the Ezousa river gravel aquifer may not be further sustained as an essential water resource due to the proposed developments within the river basin for upstream (section 14.7), the S.A.T. may provide the alternative development of the groundwater resource in this course.

14.3 GROUNDWATER RECHARGE WITH RECLAIMED MUNICIPAL WASTEWATER

14.3.1 General consideration

The reuse of wastewater, after treatment for irrigation needs and the replacement of equal freshwater quantities which can be used for domestic water consumption is a very important water resource management option. Groundwater recharge is one of the methods for combining water reuse and effluent disposal as well. This is practised in many parts of the world like the U.S. (particularly in Arizona and California), Israel, U.K., Germany, Netherlands and many others for decades (Todd et al.,1976; Tahal,1986; Peavy et al.,1986; Crook et al.,1990).

However, recharging groundwater with reclaimed effluent has several purposes. The underlying reasons for this procedure are quite varied, as most important of which may be mentioned (a) purification and equalization of water quality, (b) to store the reclaimed water for future use, (c) maintenance of groundwater levels, either to create hydrostatic barriers to prevent seawater intrusion into freshwater aquifer or to control and prevent ground subsidence etc. and (d) to augment non-potable or potable groundwater aquifers, (Huisman et al.,1990; Viessman et al.,1985; Crook et al.,1990).

The method of artificial recharge can be accomplished by surface spreading or direct injection. With surface spreading, reclaimed water percolates from spreading basins through an unsaturated zone to the groundwater. Direct injection entails pumping reclaimed water directly into the groundwater usually into a confined aquifer. In coastal areas, direct injection effectively creates barriers that prevent seawater intrusion. In other areas direct injection may be preferred where groundwater is deep or where the topography or existing land use makes surface spreading impractical or too expensive. Spreading or injection can be performed with various configuration systems. This is a function dependent upon the purpose of the recharging, the economics and the physical conditions. Such configurations are illustrated in Fig.14.1.

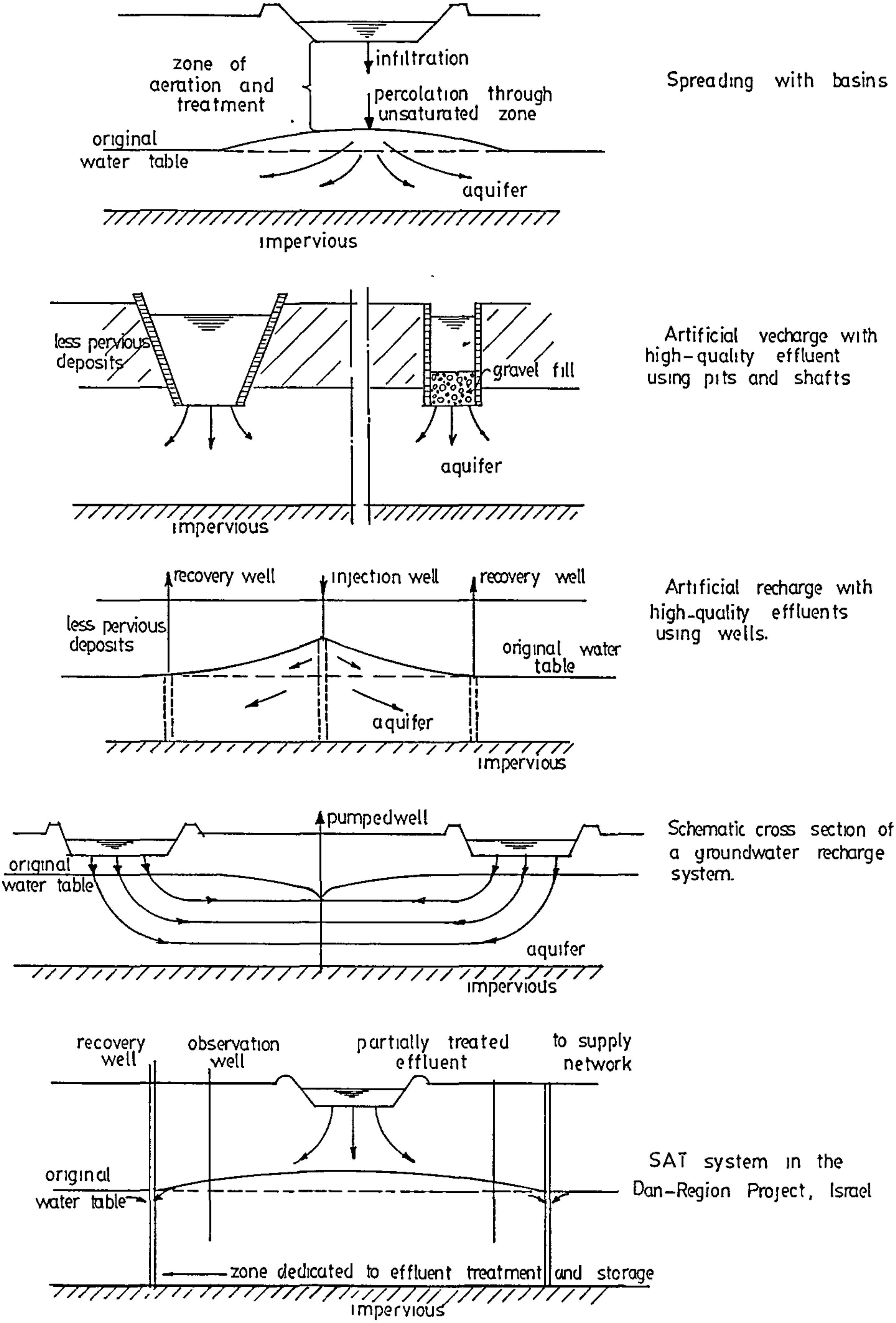
Groundwater recharge with reclaimed water is not a straight-forward action but there are many constraints involved in its application. The basic constraints are water quality, the potential of health hazards, economic feasibility, physical limitations, legal restrictions and the availability of reclaimed water. Of these constraints, the health concerns are by far the most important as they pervade all potential recharge projects.

Meanwhile, cost/benefit and environmental concerns associated with this development have expanded interest in reclaiming municipal wastewater to supplement existing water supplies, worldwide, (Huisman et al.,1990; Viessman et al.,1985; CH2M Hill,1993).

As a matter of course the effluent discharged from a sewage treatment plant, as that proposed for Paphos Municipality and its environs, must be dealt with in such a manner so as not to cause a public health hazard, sanitary or aesthetic nuisance, damage or interfere with the use of property. These difficulties can be eliminated by employing such a method of advanced treatment plus the soil-aquifer treatment process, (S.A.T.). Quantitively this leaves little work to do for the aquifer, but qualitatively the purification accompanying underground flow is still of the utmost importance. In this set-up the purification possibilities of artificial recharge are reserved for polishing purposes and as a second line defence against chemical, bacteriological, virological contamination.

Fig. 14.1 S.A.T. system configurations

Source: Todd, 1980; Peavy et al, 1986; Huisman, 1990



Beyond the technical problems, however, that will have to be resolved and the know-how to be gained, the important subject of developing public acceptance and reassuring psychological objections to the use of treated wastewater must be achieved.

14.3.2 <u>The soil-aquifer treatment process (S.A.T.)</u>.

Where sewage effluent is to be used for unrestricted irrigation a fairly intensive treatment technology is required to comply with the relevant quality standards. Most usually such a stage process consists of primary treatment (i.e. screening, grinding, settling) and secondary (biological) treatment, coagulation, sedimentation, sand filtration and chlorination. Whenever higher quality is required (irrigation of vegetable eaten raw etc.) it may be possible to incorporate both a natural system and/or a physical/chemical system into an overall tertiary strategy. Instead of the primary and secondary stage, where conditions allowing it carousel systems (i.e. lagooning or oxidation ditch treatment) are employed as well. This later method, where hydrogeological conditions are favourable, it can incorporate the innovative soil-aquifer treatment (S.A.T.), a concept which represents a latest approach to the wastewater treatment; that is experience in Israel, (Tahal,1986). Although, the California State's draft regulations, developed by the Department of Health Service (DOHS) in 1976, specified the level of treatment prerequisited for surface spreading of reclaimed water to be up to the conventional secondary stage followed by carbon absorption and percolation through at least 3m of unsaturated soil (Hultquist et al.,1991).

The effect of S.A.T. occurs during infiltration of the effluent through the soil and percolation through the vadose zone (the zone between the soil surface and the water table) and then passage in the aquifer. The soil-aquifer system acts as a natural filter improving water quality in different ways as most important of which may be mentioned (a) mechanical straining, (b) sedimentation, (c) absorption, (d) bio-chemical and (e) bacteriological activities (Viessman et al.,1985; Crook et al.,1990). It should be realised that in nature no such partition is present, while the interaction of this process together with others still partly understood or even fully unknown is of paramount importance (Huisman et al.,1990).

The system converts the treated effluent into "renovated water" which possesses superior quality by removing essentially all the suspended organic solids, micro-organisms and phosphorus and reduce at some extent the concentrations of nitrogen and heavy metals.

There are yet still continuing health concerns of its long-term utilization and therefore strong objections for its use for domestic supplies. These are, principally, associated with the organic consistents (stable matters are detected even within the advanced treated effluent like mutagenic compounds etc.) which are not well enough understood to permit settling limits and creating treatment control systems (Nellor,1985; Asano,1992).

Groundwater recharge with reclaimed municipal wastewater, however, raises many complex and difficult problems at its application. Some of the major problems are mentioned below.

The problem of clogging the soil pores with suspended material in treated effluent would make it very difficult to recharge the effluent from conventional secondary sewage treatment plant by direct injection through a well. It is essential that injection water be free of suspended matter. Water injected should be disinfected to prevent biological cultures from blinding the soil pores.

The mixing of two different waters such as highly treated effluent and existing groundwater in an aquifer may produce an unstable water. If unstable conditions exist, the mixture of waters will either form a precipitate or dissolve some of the surrounding material. The formation of a precipitate can clog the formation and reduce its capacity either to accept or to transmit additional recharge water. Dissolution of the surrounding soil particles will obviously add to the local concentration of dissolved solids in the recharged water, (Luis Berger Int.,1992).

Biological problems may arise from introducing disease carrying organisms into groundwater supplies and from possibilities of biological growths clogging the surface of the recharge medium. Pathogenic microorganisms may survive for long periods in the soil, (World Bank,1980; Shuval,1977). The incidence of viral contamination is a real possibility. However, this depends, a great deal upon the hydrogeological properties of the medium strata percolated. For instance, calcarenite aquifers as presenting fissures and fractures set a considerable risk for groundwater contamination. Due to these uncertainties, such schemes should only be implemented in those sections of the aquifers where no potable supply is extracted.

The local experience with artificial groundwater recharge using reclaimed municipal wastewater is very limited. Experience is quite extensive in many other parts of the world. Such schemes have given reliable results and an economic way of boosting this water resource. Until properly operated, demonstrational schemes are implemented and local research and know-how is achieved, the experience attained over similar conditions as to Cyprus, should be looked for and studied too.

14.3.3 The potential and purifying capacity of the S.A.T. System

It has well been demonstrated through experimental as well as operational projects in the U.S.A. and Israel that soil-aquifer treatment process produced high quality effluent. Also, from an economic standpoint the low investment required, it is an advantage that may stimulate interest particularly within the less technologically advanced countries.

Concerning the history art of the S.A.T. system, it can be mentioned that the following developments conducted in California and Arizona in the U.S.A. and at Tel-Aviv in Israel, which is a country quite close to the Cyprus environment. These are described below:

Two significant projects for groundwater recharge have been implemented in California, one in Montebello Forebay area and another in Orange Country (Crook et al,1990). The former has been used as a source of replenishment since 1962 when approximately $15x10^6m^3$/an. of disinfected activated sludge secondary effluent was spread in the Montebello Forebay that has an estimated usable storage capacity of $960x10^6m^3$. In 1978 the reclamation plants were upgraded to provide tertiary treatment with dual-media filtration or filtration with activated carbon and chlorination/dechlorination. Under normal operating conditions the batteries are rotated through a 21 day cycle. The cycle consists of three 7-day periods during which the basins are filled to maintain a constant depth, the flow to the basins is terminated and the basins are allowed to drain and dry out thoroughly. This wetting and drying operation serves several purposes, including maintenance of aerobic conditions in the upper strata of the soil and vector control in the basins.

The reclaimed water produced complies with primary drinking-water standards and meets total coliforms and turbidity requirements of less than 2.2MPN/100ml and 2NTU, respectively. Analysis of samples taken at three Water Reclamation Plants (WRPs) from October 1988 through September 1989 provides examples of reclaimed water quality (Table 14.4). The WRPs tested for some constituents in samples taken

Table 14.4 Analysis of reclaimed water-Montebello Forebay, 1988-89

Parameter	Units	San Jose Creek	Whittier Narrows	Pomona	Discharge Limits
Suspended solid	mg/l	<3	<2	<1	15
BOD	"	7	4	4	20
Turbidity	TU	1.6	1.6	1.0	2
Total Coliform	No/100ml	<1	<1	<1	2.2
Total dissolved solids	mg/l	598	523	552	700
Nitrate and nitate	"	1.55	2.19	0.69	10
Chloride	"	123	83	121	250
Sulfate	"	108	105	82	250
Fluoride	"	0.57	0.74	0.50	1.6
Arsenic	"	0.005	0.004	<0.004	0.05
Aluminium	"	<0.06	<0.10	<0.08	1.0
Barium	"	0.06	0.04	0.04	1.0
Cadmium	"	ND	ND	ND	0.01
Chromium	"	<0.02	<0.03	<0.03	0.05
Lead	"	ND	ND	<0.05	0.05
Manganese	"	<0.02	<0.01	<0.01	0.05
Mercury	"	<0.0003	ND	<0.0001	0.002
Selenium	"	<0.001	0.007	<0.004	0.01
Silver	"	<0.005	ND	<0.005	0.05
Lindane	"	0.05	0.07	<0.03	4
Endrin	"	ND	ND	ND	0.2
Toxaphene	"	ND	ND	ND	5
Methaxychlor	"	ND	ND	ND	100

ND means not detected.

Source: Crook et al, 1992

daily and other in samples taken bi-monthly to provide these yearly averages.

A project involving groundwater recharge by the injection of the reclaimed water is operated in the Orange Country. The project has a design capacity of $0.7m^3/s$ and can treat secondary effluent activated sludge followed by unit operating: lime classification for removal of suspended solids, heavy metals and dissolved minerals; carbonation for pH control, mixed-media filtration for removal of suspended solids, absorption with activated carbon for removal of dissolved organics; reverse osmosis for the demineralisation; and chlorination for biological control and disinfection.

The produced reclaimed water is injected in such a manner so that water flows toward the ocean forming a seawater barrier and flows inland to augment the potable groundwater supply. Before injection the product water is blended 2:1 with water not subject to contamination.

The system reliably produces high-quality water. No coliform organisms were detected in effluent tested during 1988. The effluent were essentially free of measurable levels of viruses. The average turbidity of filter effluent was 0.22 F.T.U. and did not exceed 1.0 F.T.U. in 1988. The average C.O.D. and T.O.C. concentrations for the year were 8mg/l and 2.m/l respectively.

The city of Phoenix in Arizona has been interested in renovating part of its sewage effluent by S.A.T. and in exchanging it with high quality groundwater from a nearby irrigation district for augmenting its municipal water supply. Phoenix have been experimenting with the S.A.T. system since 1967 with the Flushing Meadows project (Todd et al.,1976; Bouwer, et al.,1980) and continued with a large demonstration plan, since 1975, that is the 23rd Avenue project (Bouwer, et al.,1984). Both projects infiltration basins were constructed in the dry Salt River bed were very suitable for high rate wastewater reclamation by groundwater recharge. The Flushing Meadows project contained six recharge basins with infiltration rates decreasing from grass to gravel to bare soil basins. The soil consisted of about 1m of loamy sand underlain by sand and gravel layers. The 23rd Avenue project consists of a 16ha lagoon split lengthwise into four infiltration basins of 4ha each. The soil profile consists of sand and gravel layers.

The results of the Phoenix studies showed that the renovated water from the S.A.T. projects meets the public health and agronomic requirements for unrestricted irrigation including vegetable crops that are consumed raw. In this project secondary effluent was used. The secondary treatment step (biological), however, was not considered necessary because the S.A.T. system could handle relatively large amounts of organic carbon. Such treatment, will be more effective and economical for renovated water from S.A.T. system than for effluent from conventional treatment plant.

An analysis posed quality parameters of the reclaimed water in Phoenix is shown in Table 14.5.

In Israel (the Dan Region Project), the S.A.T. system has been used since 1970 for reclaiming and reusing wastewater. In the period of 1974 to 1986 some $285 \times 10^6 m^3$ was pumped out and put to use. The wastewater undergoes biological treatment in facultive oxidation ponds with recirculation and chemical treatment by the high lime-magnesium process followed by detention of the high pH effluent in polishing ponds. The partially-treated effluent is recharged to the regional groundwater aquifer by means of spreading basins. The S.A.T. system involves intermittent flooding of the spreading basins, controlled passage of the effluent through the unsaturated zone and aquifer and subsequent pumping by means of recovery wells which surround the recharge area. The S.A.T. system has

Table 14.5 Analysis of reclaimed water - Phoenix, Arizona

	Flushing Meadows	23rd Avenue
Suspended solids	<1 mg/l	1mg/l
Total dissolved solids		790mg/l
Total organic carbon	5 mg/l	3.2 mg/l
Nitrate as nitrogen	6.25 mg/l	5.3 mg/l
Phosphate	0.51 mg/l	0.37 mg/l
Fluoride	1.66 mg/l	0.7 mg/l
Boron	0.5-0.7 mg/l	0.5-0.7 mg/l
Viruses	ND	ND

ND means not detected

Source: Bouwer et al 1980; Bouwer et al 1984 shown good to very good removal (70% efficiency) for suspended solids, BOD, COD, TOC, UV absorbency, $KMnO_4$ consumption, detergents, phenols, ammonia and phosphorous. Moderate removal (40 to 70%) for total and filtered nitrogen mineral oil, Cv, Cu, Hg, Ni and Se was monitored. No enteroviruses were detected in the reclaimed water. The Table 14.6 and 14.7 show the S.A.T. performance for various parameters.

During the period 1977-1986, $169x10^6m^3$ of effluent were treated in the lime-clarifiers, and $135x10^6m^3$ of these were recharged to the groundwater aquifer. A total water amount of $138x10^6m^3$ was pumped from the aquifer in the period 1974-86 and supplied to the south of the country.

The S.A.T. process on the basis of the above has been termed as a reliable, low cost and easily operated system for water storage and reuse, (Tahal,1986).

14.4 EXPERIENCE IN ARTIFICIAL RECHARGE IN CYPRUS

With the high dams built not far from the coast the groundwater replenishing regime in most areas has been affected and downstream aquifers depend at great deal on artificial groundwater recharge either through controlled releases from the impounding reserves directly onto the downstream river beds or through purposely built spreading grounds at strategic points on the aquifers. This trend will continue as long as existing domestic supply schemes continue to operate on the basis of groundwater extraction and until the planned water supply treatment plants are completed. This also holds true for irrigation as long as the existing dependence on the aquifers for it is maintained and until direct supplies are provided from the dams to substitute an equal amount of groundwater.

Furthermore, artificial groundwater recharge is practised by W.D.D. for the purpose of building up reserves in aquifers on the occasion of wet years (when spills from the dams occur

Table 14.6 Dan Region Project - 1986
Basic wastewater parameters

Parameter	Units	a) Before SAT RE	a) After SAT (Well 54) RW	Percentage Removal %
Suspended solids	mg/1	66	0	100
BOD	mg/1	28.5	<0.5	>98
BOD £	mg/1	6.4	<0.5	>98
COD	mg/1	126	10.7	92
COD £	mg/1	57	10.7	81
TOC	mg/1	59	2.4	96
DOC	mg/1	25.7	2.4	91
UV 254 Absorbance	CE X 10	277	46	83
$KMnO_4$ Cons., as O_2	mg/1	19.2	1.7	91
$KMnO_4$ f Cons., as O_2	mg/1	10.5	1.7	84
Detergents	mg/1	1.87	0.23	88
Mineral Oils	mg/1	0.5	<0.1	>80
Phenols	mg/1	6	0.9	85
Ammonia, as N	mg/1	7.2	<0.02	100
Total	mg/1	17.8	7.1	60
Filtered N	mg/1	12.0	7.1	41
Phosphorus	mg/1	3.22	0.034	99
Alkalinity, as $CaCO_3$	mg/1	176	210	
pH	--	9.5	7.8	

a) Yearly average

Source: Tahal, 1986

Table 14.7 Dan Region Project - S.A.T. performance bacteriological and virological quality

Parameter	Before SAT a) RE	After SAT (Well 54) RW
Bacteria, Concentration b)		
Total bacteria	190,000	-
Coliforms	89	-
E. Coli	<28	-
Streptococcus Faecalis	286	-
Viruses, Concentration		d)
Enterviruses c)	0	0

a) Yearly average
b) Confirmed results retained by the multiple tube technique in MPN/100 ml (except total bacteria in No./1 ml)
c) Tests were carried out on 400 1 samples

Source: Tahal, 1986

or when the contents in the surface reservoirs are high) upon which we can partly rely on dry years.

Three recharge methods are feasible in Cyprus, well injection, surface recharge using infiltration basins and surface recharge through release of water on dry river bed channels (Jacovides,1993). Since well injection requires water sources which are free of suspended solids the only potential water at this time would be the impounding reservoirs which also might need the lesser treatment. All of the potential water sources could be used for recharge through surface recharge using infiltration basins or through release on active river bed channels when dry.

Emphasis will be placed on the latter two techniques since these seem to be more apt for the possibility of using the same approach for wastewater reuse through recharge.

However, artificial recharge has been practised occasionally in many parts of the island but the most systematic have yet afforded are; the recharge over the Yermasoyia and Kouris Delta wellfield since 1982 and 1987 respectively and over the Phasouri aquifer in Limassol since 1984.

14.4.1 Yermasoyia delta. In the case of Yermasoyia (Georghiou,1990), water is released from the same named impounding reservoir of $13.6x10^6m^3$ capacity sited near 5.5km from the river's reach. The wellfield is actually the lower course of the river gravel aquifer which has a thickness varying from 35m to 50m between the dam and the coast. Computations based on the evaluation of the interstitial velocities or the velocity at which the tracer moves (Tririum, Oxygen-18, and Deuterium had been used) and pumping test analysis showed the former 16±3m/day tracer average velocity and the later approximately 160m/day permeability. On the basis of these computations, released water takes 1 year to reach the coast and about 140 days to reach the wellfield.

The project performed well and no reduction in the infiltration rate had been noted. Chemically the groundwater is similar to that of the water in the surface reservoir. Bacteriological analysis from all the boreholes show that the 10 to 20 metres of unsaturated thickness of alluvial sediments provides an efficient protection to bacteriological pollution.

On this wellfield has been recharged since 1982 about $37.25x10^6m^3$. In effect the Yermasoyia river bed aquifer has been turned into a natural treatment plant for domestic water supply without the need of complicated and expensive surface water treatment requiring chemicals, qualified technical and managerial personnel and the necessary civil engineering structures.

14.4.2 Kouris delta

Since the completion of the Kouris dam ($115x10^6m^3$ max storage) in 1987 the natural recharge of the river bed and the river delta aquifer has been completely cut-off. Both aquifers consists of an essential resource for the domestic supplies to Limassol and the local irrigation demands.

The artificial recharge here is performed through flooding of the active dry river channel and on ponding the water in two recharge ponds within the river bed. In addition four other ponds were constructed at different locations for the same purposes. The total recharged water in 1987-91 came up to $25.4x10^6m^3$.

14.4.3 Akrotiri aquifer

Artificial recharge by spreading into ponds has been exercised in Akrotiri aquifer. A pond of $54x10^3m^2$ storage capacity and $17,500m^3$ surface area was constructed in 1984. Later on, in 1990, two others of $6,000m^3$ and $9,000m^3$ storage capacity and $3,400m^3$ and $4,400m^3$ surface area respectively was added to the scheme. This aquifer consists of alluvial sediments, mainly sandy gravel and the water table lies about 7 to 8m below ground surface. Water level fluctuates between 1 and 2m, below mean sea level at the beginning and end of the irrigation season (i.e. March/April and October/November).

Infiltration rates have been observed to change throughout the operation; due to accumulated from sediments and the consequently phenomena. This, however, ranges between 0.8m/day and 0.4m/day but sometimes drops near to 0.2m/day because of the problems referred to above, in addition to the blooming of the vegetation happens. Cleaning operations improve the infiltration up to 0.7m/day, (W.D.D.,1992).

The recharged water is provided from the Kouris dam and Yermasoyia dam and since 1991 with reclaimed groundwater pumped from the Limassol town aquifer.

The artificial recharge operations mentioned above have become a routine practice in the W.D.D.. Monitoring facilities and computer models have currently been introduced in order to upgrade groundwater management studies.

However, in two to three years time the municipal wastewater treatment schemes of the Limassol and Larnaca area are to be completed and in the near future the Paphos scheme is anticipated to start. Whereas, the local experience on the matter is very limited, the problem has already emerged for deciding as how and where the effluent is to be disposed of or utilised for; this has become a very pressing and imminent concern.

In the case of Limassol-Amathus sewage treatment plant, CH2M Hill and Forum Architects have been contracted recently (1993) to investigate the potential reuse of the effluent. These consultants used a workshop approach to identify and analyse the effluent reuse alternatives. The first alternative option has been considered, the recharge of the reclaimed water into the Kouris Delta (see section 1.2.5) in basins and then extracted from wells located downgradient of the spreading ponds and delivered to the irrigation distribution system. The recharge basins under this projection would be used throughout the year for reclaimed water.

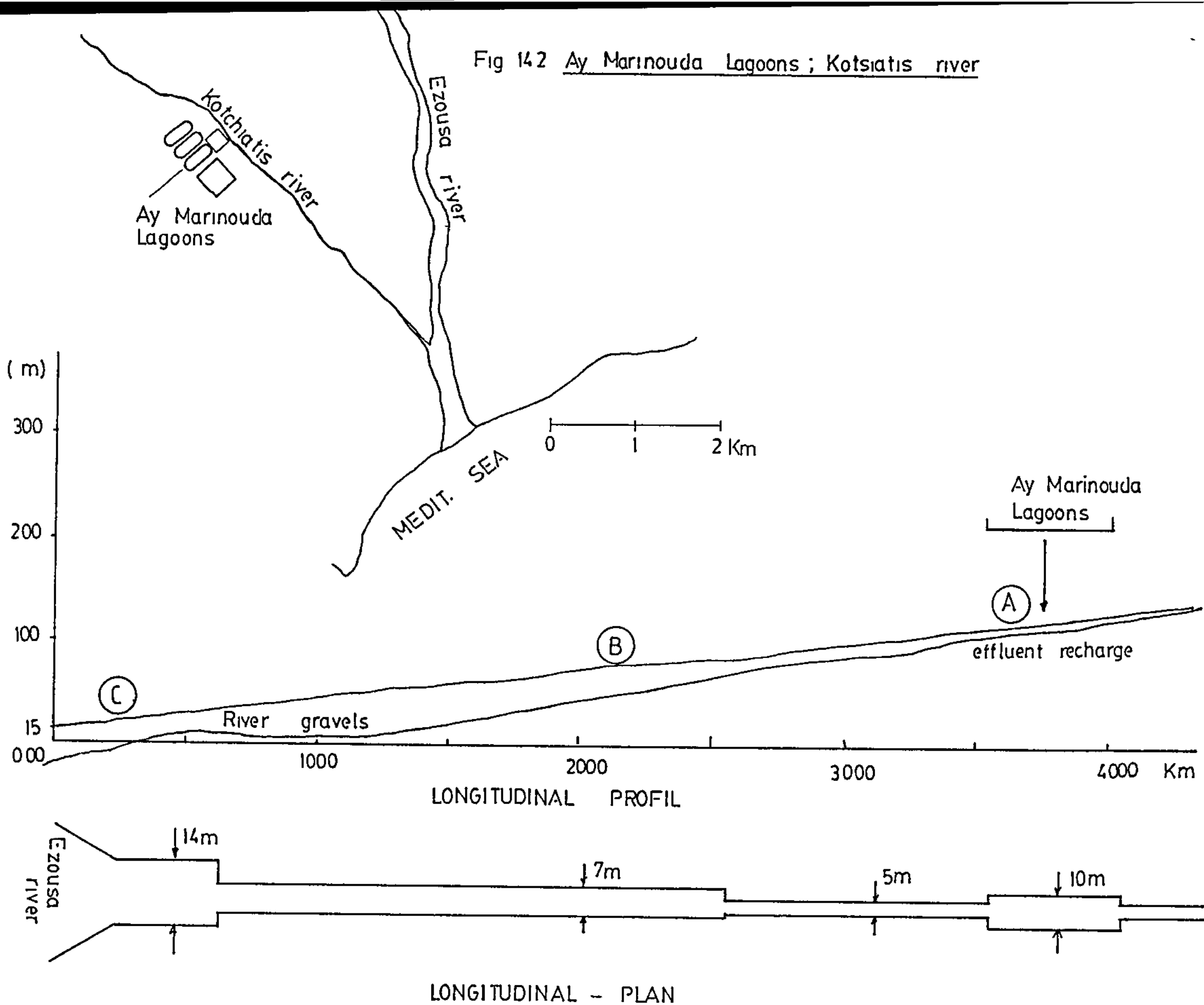
It is considered necessary that any agricultural reclaimed water reuse program would involve a development period in which demonstrations of reuse are conducted for the purpose of familiarising the farmers with reclaimed water. This consideration is based principally on two findings; preliminary contacts with the Ministry of Agriculture people and farmers in the local proposed reuse areas and the apparent desire of the W.D.D. to ensure the safe long-term use of the reclaimed water. These reuse demonstrations will give the farmers confidence in the safety of using reclaimed water and safe use.

14.5 THE AYIA MARINOUDA LAGOONS - A LITTLE EXERCISE WITH TREATED EFFLUENT RECHARGING MINOR GRAVEL BED

Septic tanks in the Paphos area are periodically emptied by trucks who transport the sewage to municipal lagoons located in the vicinity of Ayia Marinouda (Fig.14.2). The system was put into operation in 1984 and initially consisted of two settlement lagoons each with a capacity of $200m^3$. The system was later expanded by the addition of two aeration lagoons each with capacity of $1350m^3$.

In 1985, a new lagoon was constructed off the Kotchiatis channel (a tributary of the Ezousa river), with underdrain system consisting of aggregate materials in order to let the final treatment of the effluent prior to discharge into the channel. In 1986, a new settlement lagoon of $500m^3$ capacity was constructed to treat sewage from the slaughter house nearby. This settlement lagoon operates in connection with

Fig 142 Ay Marinouda Lagoons ; Kotsiatis river



one of the two aeration tanks. In 1990, five new lagoons were constructed to handle the large increase in sewage quantities. These lagoons each have a capacity of 300m^3 and operate in connection with the second aeration tank. The designed depth of all the lagoons is about 1.30m.

The system receives 180-250m^3 daily from the Paphos urban and tourist resorts. In addition 10-12m^3 per day is transported from the slaughter house nearby. All this information was available from the sanitary division of the Paphos Municipality responsible for the operation of the system.

The treated effluent first flows over a distance of 2.0km through the channel chalk bed and eventually infiltrates into the gravels downstream until it joins the Ezousa river. This gravel bed section has approximately 1.7km length and it is of major importance from this standpoint to the furthest treatment of the effluent recharge. A longitudinal section of the Kotchiatis river may be as in Fig.14.2. The hydrogeological characteristics of the gravel course should be similar to that of the other rivers of the area but because of the more silty matrix often accumulated within the lower section of the channel transmissibility is assumes to be between 130 and 250m^2/day. There are no facilities for any pumping test at the immediately vicinity and no other method was possible.

The matter in question is the degree at which the effluent may be treated by passing through this gravel bed. Unluckily, there has not been a bio-chemical analyses available to prove the quality of the effluent after infiltration. Although some analysis was available providing evidence only of the effluent quality before recharge into the gravel resources. Therefore, for the purpose of this study a pit was excavated in the mid-river bed and before the channel come across the Ezousa river and some samples were received for certain analyses. Due to economic constraints the analysis was limited to two chemical and two biological analysis. These should be considered only as an indication of the treatment efficiency of the stream fluvial deposits because otherwise a more extensive program is needed for a comprehensive assessment and this is out of the scope of this study.

The determined parameters of the effluent quality are shown in Table 14.8.

It is apparent that the infiltrated effluent underwent further treatment by underdraining through the fluvial deposits of the Kotchiatis. It is worth mentioned that the domestic effluent of the above lagoons system has been flowing through this channel since its establishment, (1984). Therefore, if pollution should have occurred downstream, this might have been detected within the water samples determined quality parameters.

The reclaimed water seems very good in relation to the irrigation quality standards as in Table 14.1, even for unrestricted applications.

14.6 ALTERNATIVE BASINS FOR RECHARGING THE TREATED EFFLUENT

14.6.1 General

Two basins may be considered within the study area as provided for possible recharging of the produced effluent from the proposed sewage system of the Paphos urban area. These are the coastal plain which contains the Athalassa calcarenite aquifer and the Ezousa river gravel bed. According to Luis Berger International (1992), the treatment plant will be set-up near to the Ezousa river-lower section, near the sea (Fig.14.4). Due to the construction costs it is favourable to employ the Ezousa river rather than either the Xeros or the Dhiarizos river which both pass further east, that is 8km and 11km respectively. In the case of the Xeros river, the

Table 14.8 Ayia Marinouda Lagoons effluent quality parameters

	BOD_5(mg/l)			COD(mg/l)			Nitrates (mg/l)			Faecal coliforms (No/100ml)			Suspended solids (mg/l)		
Date	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
1/6/92	65	40	0.15	51.9	50.2	0.57	35	2.2	11	--	--	--	--	--	--
17/8/92	32	86	0.12	64.6	20.7	0.35	25	6.6	Nil	8800	1950	Nil	82.8	76.0	8.1

Note: The A, B and C indicates the sapling points (Fig.14.2); i.e. A is after treatment (exit of the aerated lagooning); B is at mid-channel point (surface flow) and C is at the end-channel (groundwater flow).

available gravel course lies downstream of the Asprocremmos dam within near 3km from the sea. The Xeros gravel is proposed to be used for recharge of the raw water from the dam for increased Paphos water supply (W.D.D.,1992).

14.6.2 <u>The calcarenite aquifer through the S.A.T. And its limitations</u>

The Athalassa calcarenite formation, which underlain to coastal plain could have been available for effluent recharge in many locations; at least where state properties are available (zone 2) and where land is considered of less value in terms of agricultural purposes that lie over the Terrace.

However, the hydrogeological characteristics of the calcarenite aquifers do not encourage S.A.T. application. The hydrogeological characteristics of the Athalassa calcarenite aquifer varies considerably from location to location, due to the variable stratification and consolidation of the overburden rock (see Chapter 8 and 9). In places there is a very low transmissibility rate, while nearby fissure and solution channels (karstic phenomena) set-up different properties. Low transmissibility however decreases the rate of discharge in the well. Because transmissibility is associated with the pore size of the aquifer, where transmissibility is low, clogging of the porous formation material may be expected from suspended material.

On the other hand, where fissured rock and openings occur, these are favourable conditions for dispersing material. This could spread pathogenic organisms. Groundwater seepage to the sea occurs (Chapter 12). The recharged effluent will contain considerable amounts of nutrients and eutrophication problems along the coast may appear.

As far as it is known, in many parts of the world where S.A.T. is practised successfully (section 14.3.3) the recharge basins are underlain by very permeable material. In California the Montebello Forebay wastewater reclamation plant involves groundwater recharge into spreading basins adjacent to the Rio Hondo and San Gabriel rivers where it percolates through permeable alluvium into the groundwater (Todd,1980; Crook et al.,1990). In Arizona, city of Phoenix, a sewerage treatment plant provides secondary effluent which are spread in particular design basins of sandy loam, (Todd,1980; Bouwer et al.,1980; Bouwer et al.,1984). In Israel the Dan Region Project is performed within very permeable material as sand and tuffs (Tahal,1986).

In a lecture with the subject "Water Re-use" held 1st of July 1992 in Nicosia Dr. Takachi Asano stressed over the performance of the S.A.T. system in respect to the formation application. It was emphasised that strata of restricted permeability is not recommended for the purpose of S.A.T. because of clogging; sand and gravel aquifers are the most effective. In the view of the Consultants (CH2M Hill,1993) to the Limassol Sewerage Board, they suggested that this problem could be overcome by treating the municipality wastewater up to an advanced stage and later to divert the reclaimed effluent to the gravel aquifer of the Kouris Delta.
They consider this solution a smaller risk for health and environmental aspects.

14.6.3 The Ezousa basin

Similarly to the situation in Limassol it seems most appropriate to discharge Paphos treated effluent into the gravel aquifer.

14.7 THE EZOUSA RIVER GRAVEL AQUIFER

14.7.1 Physiographic briefing

The Ezousa river runs parallel to the other two major rivers of Dhiarizos and Xeros for distance up to 46km from its headwaters areas in the Troodos Massif to the coast. The hydrological regime of the three rivers and the catchment characteristics were discussed in section 5.1.

The Ezousa river is often deeply entrenched between steep valley sides but may expand in areas of bedrock less resistant to fluvial erosion. The upstream parts of the valley are often 100 and 300m wide with flat alluviated bottoms. Downstream the river channel breaches the Kissonerga-Kouklia escarpment and expands on the coastal plain to weakly incised, partly broadened channels with widths between 100 and 400m.

Throughout the river catchment area different rocks outcrop, these consist mainly of lavas and ultrabasic of the Upper Pillow Lavas series of the Troodhos Ophiolites and the Mamomia Group, together with chalky limestones and marls of the Lefkara and Pakhma formation. The lithology of the river bed has resulted from the fractured and erosional process of these geological units.

The channel contains considerable accumulations of coarse alluvium up to 11km from the coast. Further upstream the river runs directly on bedrock.

The gradients of the river bed are irregular. In the far upper portion it slopes approximately 11% to 9%, along the middle of the gradient gently to 2% and it ends at the coastal plain with a gradient of 1%.

14.7.2 The gravel aquifer geometry

The alluvium of the Ezousa valley is water bearing, the aquifer being supplied by infiltration through the river bed. The gravel aquifer occupies the valley bottom only and therefore is very long but narrow, although it tends to widen considerably in the coastal plain.

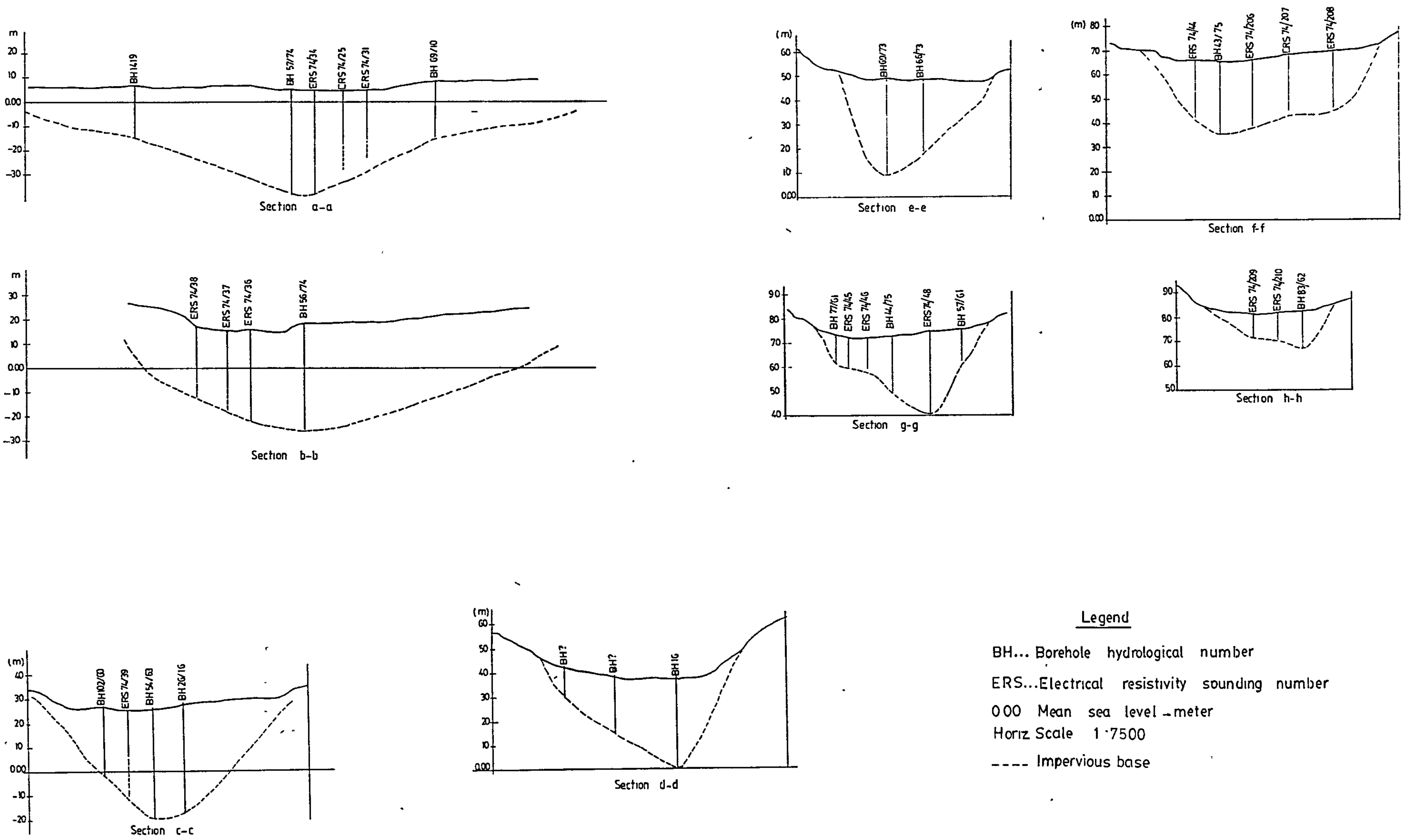
Investigation was conducted for the purpose of this study in order to draw the lateral and longitudinal extent of the gravel aquifer. The cross-sectional areas of the gravel aquifer has been known in various locations. This has been achieved through the lithological logs of boreholes drilled in the aquifer by the G.S.D. and the information provided through the interpretation of several electrical resistivity soundings carried out by the same department in 1976. Although knowledge of the gravel aquifer extent was limited up to 7.5 km from the river reach. Personal field experience and background information (SOGREAH,1976), however, have clearly proved that only the lower rivers portion merits consideration, since it contains the largest accumulation of alluvial materials. This course of the river can further be divided into two distinct parts. These are a) the relatively deeply-trenched upstream reach in which the river has its bed deep into the chalky limestone and; b) the less markedly trenched downstream reach at the calcarenite of the coastal plain.

It has been observed that during the summer there are local reductions in the groundwater flow section within the upstream reach. This may be resulted from a narrowing of the valley and/or the presence beneath the gravel of sills which act as underground flow regulation. These sills which often occur at places where the bed sections is at its narrowed, can be determined by the presence of volcanic rocks (Mamonia formation) or limestone.

Assessments carried out for this study based on simplified geometric delineation of the river gravel aquifer and the several cross sections indicated that the lower reach towards the sea consists the larger aquifer. This segment is to be considered for S.A.T. application. The extent of the river gravel aquifer is outlined in 8 cross-sections (Fig.14.3) and a longitudinal section (Fig.14.4).

The geometrical characteristics of the river gravel aquifer up to 7.5km from the sea, as were estimated from the drawn sections at various locations as given in Table 14.9.

Fig. 14.3 Ezousa river gravel – cross sections



Legend

BH... Borehole hydrological number

ERS...Electrical resistivity sounding number

0 00 Mean sea level – meter

Horiz. Scale 1 : 7500

---- Impervious base

Fig.144 Ezousa river gravel longitudinal section

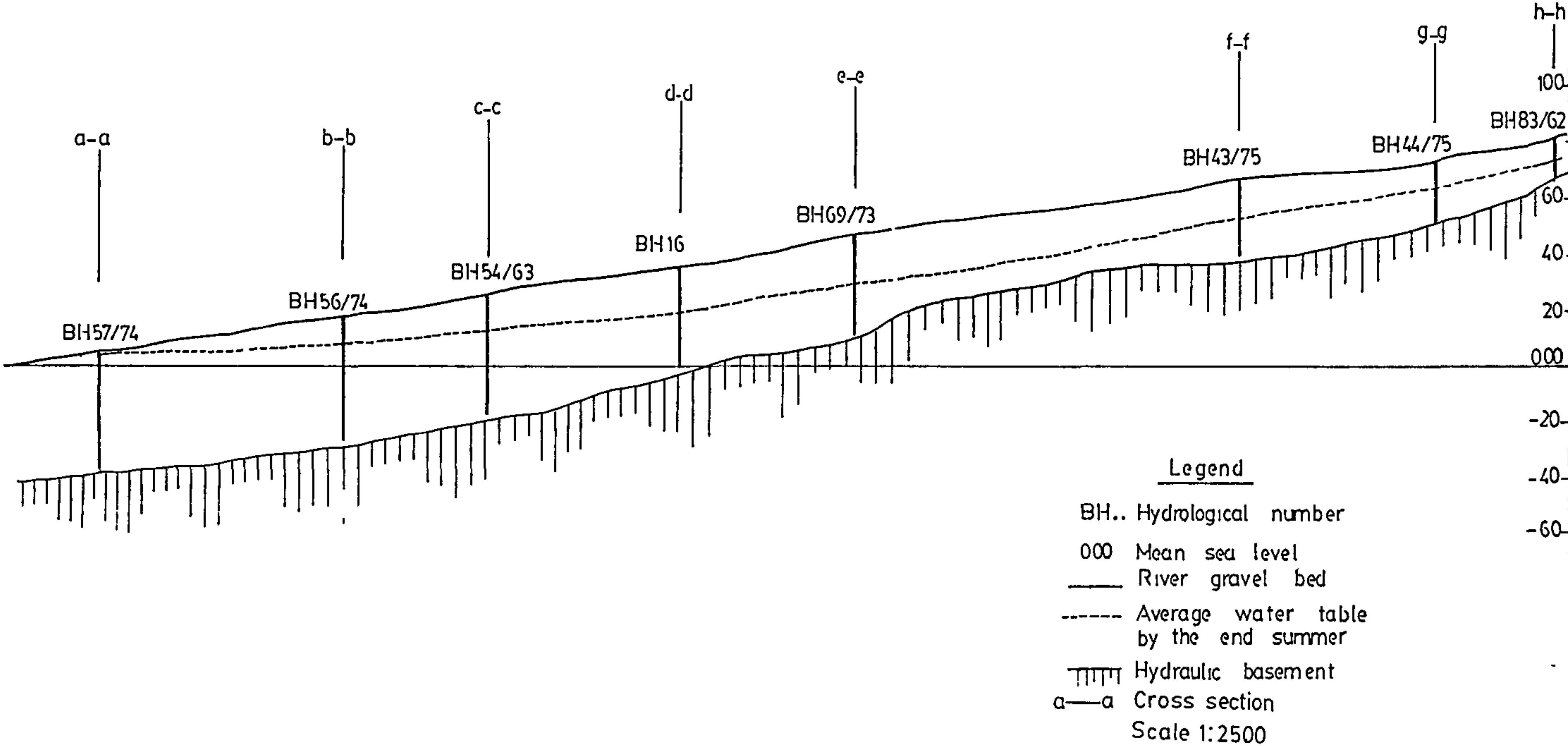


Table 14.9 <u>Ezousa river bed gravels</u>

section	length	depth	Plan area between sections	Cross-sectional area	volume of gravel-alluvium
a-b	1120	44m	$532000m^2$	$25800m^2$	$23408000m^3$
b-c	650m	44m	$201278m^2$	$16000m^2$	$8856250m^3$
c-d	880m	42m	$189514m^2$	$11250m^2$	$7959600m^3$
d-e	800m	36m	$282889m^2$	$6840m^2$	$10184000m^3$
e-f	1760m	31m	$448232m^2$	$5890m^2$	$13895200m^3$
f-g	900m	24m	$278437m^2$	$9900m^2$	$6682500m^3$
g-h	540m	18m	$102375m^2$	$4950m^2$	$1842750m^3$

14.7.3 The hydrogeological characteristics of the Ezousa gravel aquifer

The transmissibility properties of the river fluvial deposits is of primary importance for S.A.T. applications. This may control its use an an integrated system for further treatment of the Paphos urban domestic effluent within the Ezousa basin.

In order to find out transmissibility values, pumping test data which was available from former workers (G.S.D.,1975 and W.D.D.,1978) were analysed. Due to the lack of interference test and incomplete data regarding drawdown test, methods that including "type-curves" have not been afforded. Therefore, the recovery method of analysis has been applied as the most reliable under these circumstances.

Interpretation of the recovery test data showed that permeability values generally reduces with depth. This due to the fact that the aquifer is not homogeneous; it consists of materials varying from large igneous boulders through cobbles, gravels and sands, sand and silts, etc. Lenses of silts and marls horizons are frequent too. The lithological logs of the drilled boreholes in the river bed also reveal the same situation. Transmissibility was found to vary considerably from upstream reach to downstream reach of the river gravel aquifer as it is shown in Table 14.11 below. Since accumulation of coarser material have always depended on velocity head and since gradient over this lower portion is near 1% this phenomenon can be explained (i.e. higher transmissibility values upstream and lower downstream).

Because of the use of the recovery method of the pumping test data analysis, the estimate of the specific yield co-efficient was not possible (section 9.3.1.2). Therefore, an assessment of the following information was carried out to define specific yield.

As it is referred to in section 9.3.2.1 the three rivers in Paphos have a similar regime and drain through valleys with outcrops of the same geological formation. The Xeros river which is only a short distance from the Ezousa may have quite similar hydrogeological characteristics (Kramvis,1992). Extensive pumping tests which were carried out by the G.S.D. in 1976 for the hydrological investigation of the Xeros river prior to the construction of the Asprocremmos dam showed that an average of 13% of specific yield could be considered reasonable. These findings generally comply with most of the river aquifer properties in Cyprus. Thus, the specific yield of 13% has been adopted for the purpose of this study.

The Ezousa river gravel aquifer transmissibility constants are given in Table 14.10. The location of the borehole which was used for pumping test can be found in Fig.14.3.

The maximum storage capacity of the gravel aquifer as a recharge basin can be estimated by considering the gravel volume (Table 14.9) and the specific yield coefficient of 13%. An amount approximately $9x10^6m^3$ of reclaimed water can be recharge-storage on an annual basis. Regarding the recharge-discharge flow pattern, this is a function contingent upon many parameters and will need pilot studies before being applied to the river basin aquifer treatment and storage system.

14.8 RECHARGE AND DISCHARGE OF TREATED EFFLUENT WITHIN THE EZOUSA GRAVEL AQUIFER

14.8.1 General approach

Significant quantities of reclaimed water (section 14.1) complying to the Provisional Standards for unrestricted irrigation use (section 14.2) would provide an excellent source for reliable supply to the area served by the P.I.Project. With this way equal quantities of fresh water

Table 14.10 Hydraulic characteristics of the Ezousa gravel aquifer

B/H No.	Location	$T(m^2/d)$	Aquifer thickness	Mean average of "T"
57/74	downstream	882	43.5	
56/74	"	998	46.0	1179
51/74	"	1658	30.5	
10/73	upstream	1124	24.0	
19/84	"	1784	27.5	
51/75	"	2527	24.0	2385
43/75	"	4105	30.5	

can be saved in the Asprocremmos dam, which is the principle source of this project, to be used either for domestic purposes through the proposed water supply treatment plant or to increase water reserves for the dry years. This availability of water resource can be ensured qualitatively as well as quantitively by recharging the treated effluent in the Ezousa basin at a distance over the full length of the gravel bed (7km is considered) in order to increase detention time for polishing purposes.

This is an alternative way for water renovation, to obtain the best water quality feasible by smoothing out variations in chemical and physical composition and by retaining the least traces of impurities after an intensive pre-treatment has removed the major part of the pollutional load, (Huisman et al.,1990; Tahal,1986).

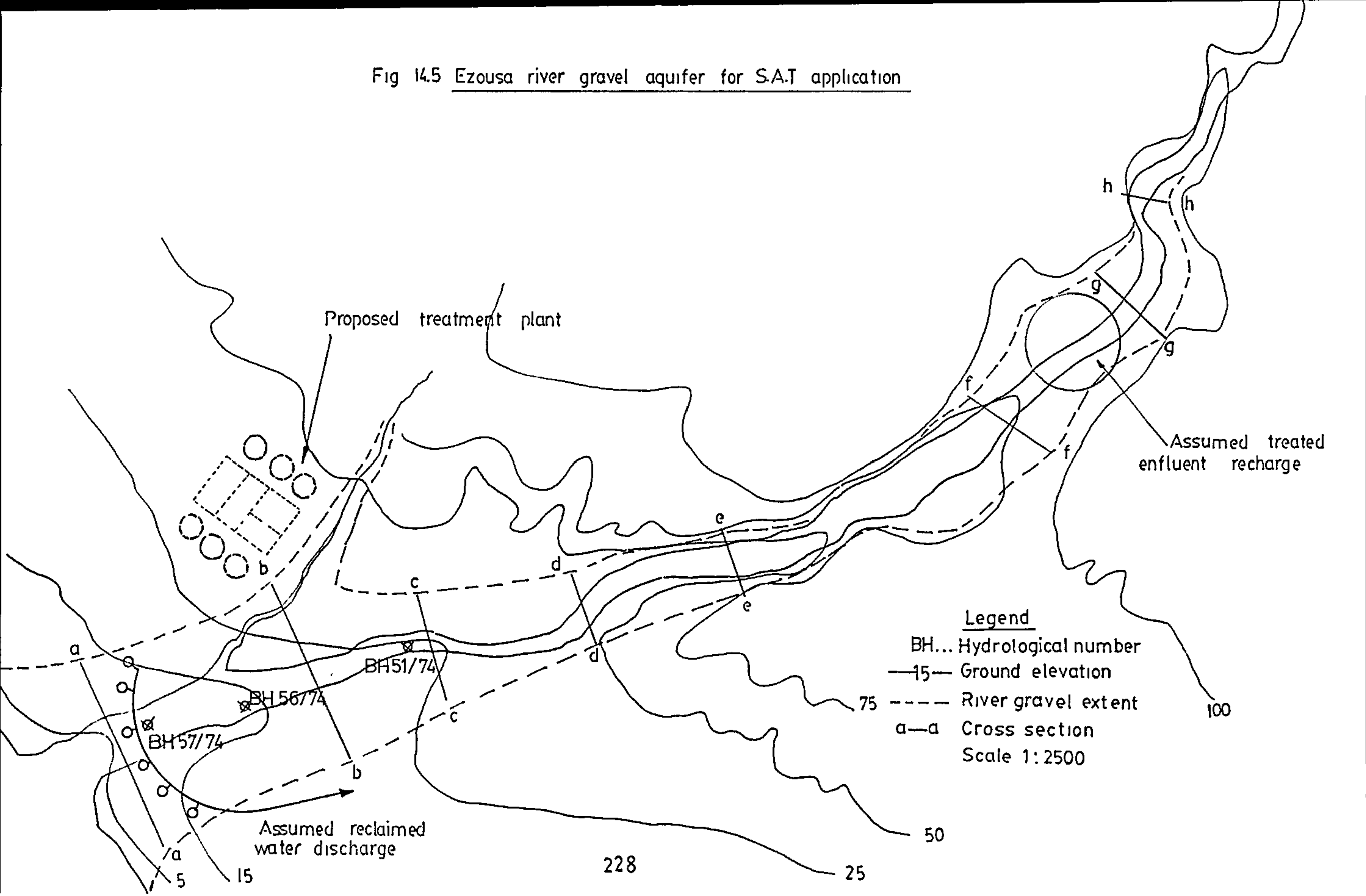
Psychologically, such a recharge has the added advantage that the reclaimed water is collected as groundwater and thus loses its identity of sewage water.

The renovated water can be pumped out further downstream before seepage into the sea. Both sites which may be considered suitable for recharge and discharge are shown in Fig.14.5.

14.8.2 <u>The recharge</u>

In general terms, two methods can be distinguished over recharge techniques as referred to in section 14.2. These are the surface spreading and recharge through wells (direct injection). The employing of this later technique, without any doubt brings about the most important drawback which is the danger of clogging. Regular cleaning is expensive and is difficult operationally. On the other hand by considering the construction cost of the drill holes, plus the casing required (this is always necessary in rivers fluvial deposits) and the distribution pipeline, this alternative option may be removed.

Fig 14.5 Ezousa river gravel aquifer for S.A.T application



Having in mind, however, the local experience of recharging into similar fashion geohydrological basins of the Ezousa gravel aquifer, like the Yermasoyia and Kourris Delta with raw waters from the impounding reservoirs nearby (section 14.4), the proposed effluent recharge scheme is likely to work out in the same manner as well.

Although, recharging basins with raw water from the impounding reservoirs have so far performed satisfactorily (Jacovides,1993), but it is questionable whether the spreading ponds used to be employed there by W.D.D. can be intensively used for recharging reclaimed wastewaters. The main concern is the danger of increasing eutrophication process caused with the concentration of nutrients (nitrates and phosphorus) and the favourable climatic conditions in the region, (long sunlight seasons). Eutrophication even can occur in open infiltration ditches followed also by silting-up of the system. The silting is not only due to the production of organic matter within the water body, but is also caused by an indirect effect of algae growth; the enhanced pH promotes precipitation of finely grained carbonates in the infiltration water-soil column, resulting in severe clogging of the porous material (Oskam and Lijklema,1989).

Since tertiary treatment process is assumed for the Paphos treatment works, the resulted effluent still contains a high concentration of nutrients. Therefore, a further stage of treatment is required for denitrification and phosphorus removal.

The growth of algae can be prevented, in addition to the reduction of nutrients, by light limitations. This can be achieved by distributing the reclaimed effluent through a subsurface spreading system. Clogging of the recharged system is still possible and effective maintenance of the recharge process needs to be studied.

Subsurface spreadings have well been developed worldwide for recharging fresh and raw waters into aquifers and the technology applied is described in many textbooks (Fair et al.,1966; Huisman et al.,1990;). The construction of draining system for spreading purposes greatly depends on the local geohydrological conditions and the natural extent of the basin concerned. A typical subsurface spreading may be as shown in Fig.14.6).

After a preliminary study over the consideration of the proposed site, it has been found that the most suitable location to establish the recharge site is 7km upstream (Fig.14.5). The further the distance for the effluent to travel, the better the discharge quality. For storage purposes with this arrangement, it is possible to use the full capacity of the river gravel aquifer.

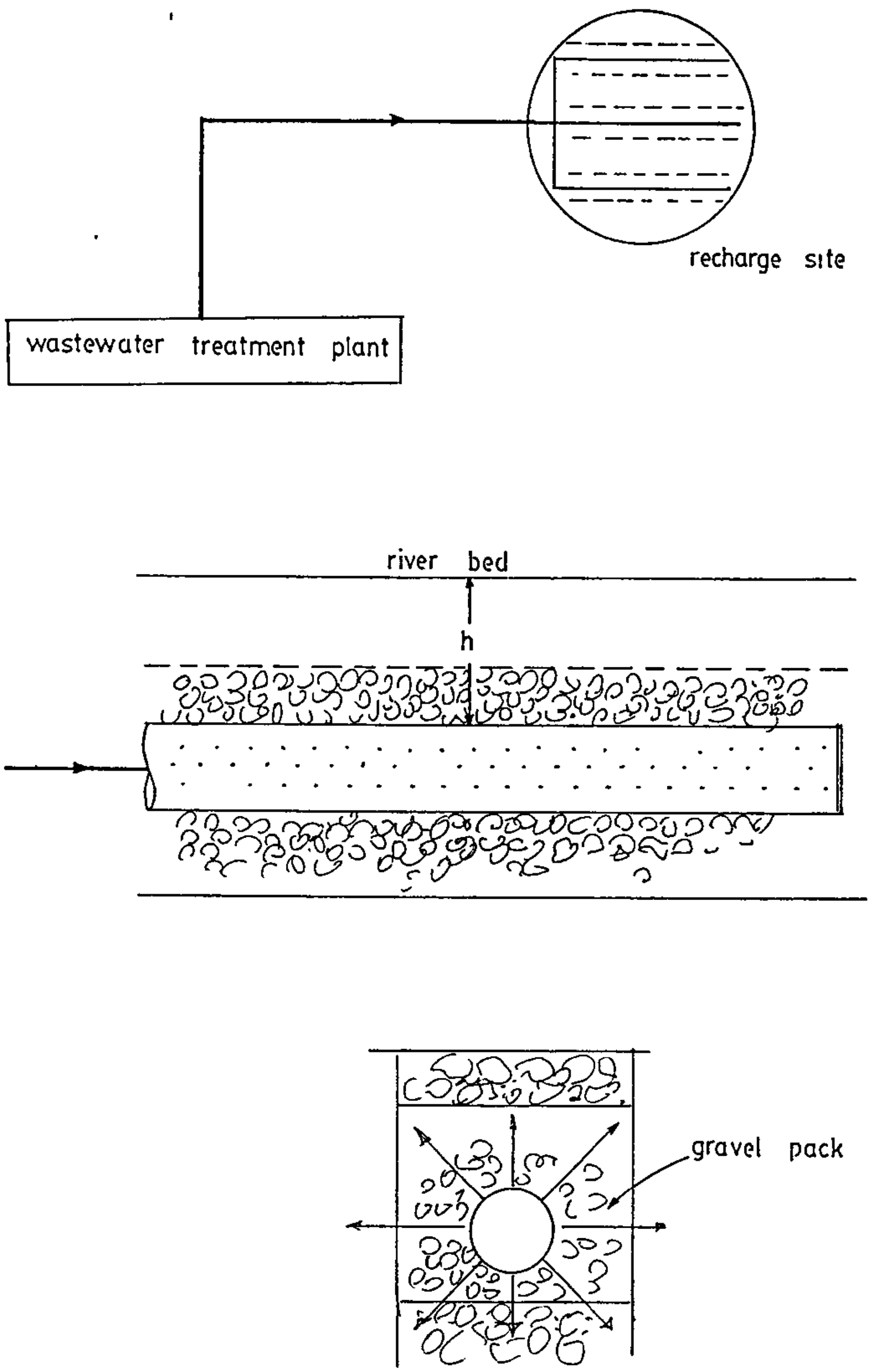
The pumping cost to push the effluent from the treament plant up to the proposed site which is 4km away and has an elevation difference of 50m, it is estimated to be approximately C£0.009 per m^3. This is in line with the average cost paid by the P.I.Project which maintaims pumpings at similar hydraulic parameters (W.D.D.,1993).

14.8.3 The discharge

Discharging can be performed along the utmost lower reach of the gravel aquifer. The intention is that to control quite effectively the sensitive balance between the reclaimed-stored water and the sea water on the other hand. The hydraulic basement of the Ezousa river gravel aquifer lies beneath the mean sea level over a distance of 2.8km, inland. At its reach, the bedrock lies down at the maximum near 40m (see Fig.14.3 and 14.4).

Along this zone a linear pattern of boreholes can be constructed to ensure control so that available quantities of reclaimed water be pumped out before, being lost to the sea

Fig 14.6 Sub-surface spreading of treated effluents



(see Fig.14.5). The boreholes equipped with electric-submersible pumps could be connected together to a delivery pipeline to convey the renovated water into the main canal of the P.I.Project for further distribution.

Along the lower river aquifer there are 3 boreholes well equipped with electric-submersible pumps which supply the P.I.Project (Fig.14.5) these boreholes are:

b/h 51/74 powered with 36KW motor and output $110m^3/h$

b/h 56/74 powered with 88KW motor and output $290m^3/h$

b/h 57/74 powered with 58KW motor and output $150m^3/h$

These boreholes can be used as well to pump out the renovated water. Because the proposal discharge scheme is to be operated within the same hydraulic limits, the costs should be comparable. This has currently risen to C£0.007 per m^3 (W.D.D.,1993).

Because quality aspects are of primary importance an advance monitoring program needs to be established for providing continuous information over the improvement or deterioration of the supplied water. This program should also have the capability to consider likely impacts in the marine environment nearby. It is worth mentioning that the nearby beach is important for tourism.

PART D

SUMMATION

CHAPTER 15

CONCLUSION AND RECOMMENDATIONS

The first stage of any water resources-scheme development programme should be to maximise the use of the existing resources. Particularly, this is necessary where resources are of limited extent as in the case of Cyprus. Since groundwater development is usually an order of magnitude less expensive than surface developments or far less than artificially water producing as desalting of sea water, for example, there are sound economic reasons among others to promote certain developments wherever is possible. Furthermore, groundwater resources planning and development, after the recent progress in artificial recharge, challenge a new approach to the problem of water optimum utilization. Therefore, there is every reason to be reconsidering it as a combined package with the effluent re-use.

Within this concept approach to the water resources management the investigation of the Paphos Coastal Plain Aquifer was proceeded.

The assessment of the potential of the possibilities for the operative utilization of the groundwater resources within the calcarenite aquifer is based upon existing data and early findings from the field work.

By drawing the current investigation programme, however, the following pronounced objectives may have been covered.

Objective 1.1 Extent of the Aquifer. Throughout the current study it is apparent that the calcarenite aquifer of the coastal plain is of limited lateral extent due to the Pakhna impermeable rocks exposed within the Kissonerga-Kouklia escarpment which binds the plain from the north. The depth of the aquiferous horizon varies considerable from place to place while often this interrupted or interbedded by layers of calcareous marls.

This depth was found to range between 3 and 15m. The base of the aquifer is undulating but with consistent slope towards the sea. In the eastern sector this is about 1.4-2% and in the western sector is about 3-5%. The map has been produced to show the hydraulic basement of the aquifer (Fig.8.2a,8.2b and 8.2c).

Objective 1.2, Aquifer Characteristics. It is certain now, through the several pumping test analysis and the water balance computations that the calcarenite aquifer is of limited storage capacity (the specific yield is about 6%) and its replenishment depends a great deal upon areal precipitation.

It is also discouraging that the aquifer, because of its physical geometrical and lithological characteristics cannot serve as a long time reservoir. It drains quickly into the sea with or without extraction of pumpings and no appreciable over-year storage is possible.

Objective 1.3, Water Quality. From a hydrological point of view, it is however, an aquifer with limited potential capacity and the groundwater is of poor quality. It generally contains high concentration of $CaCO_3$ and the water may be classified as hard to very hard. The relation between the salinity and alkali hazards, have been processed/analysed using to the F.A.O. Guidelines (Table 10.2). Most of the samples confined within slight to moderate effects and therefore irrigation may be used cautiously, if the conditions are favourable. Some of the waters are suitable only for salt tolerant crops.

Objective 1.4, To Estimate Existing Uses of the Aquifer. Because of the readily and good quality water supplied by the P.I.Project, private extractions have been limited near to 8-15% of the total water provided for irrigation per year.

An amount of $3.8x10^6m^3$ is estimated to lose into the sea within a coastline over 22km long as in the year 1988.

Objective 1.5, To Identify Possible Methods of Increasing Utilisation. The favourable conditions for intensive extractions may be considered the period up to June/July (i.e. before such a depletion occurred due to the gravity losses).

Three possible way for exploitation would be considered, these are : (a) to develop an infiltration gallery system along to fringe line in order to secure underflow to the sea; (b) to intensity extractions by a properly design pattern of boreholes in the more promising locations further inland and (c) to encourage farmers to advance their pumping facilities and increase groundwater utilization. The former two developments can be proceeded by the government because of institutional and financial reasons but the later one can be proceeded by the farmers themselves but even better with the governments support.

It has been apparent from the beginning of this study that it was intending to consider the potential use of the reclaimed effluent within a comprehensive planning utilization of the available resources in the region. This is thought to be achieved by developing a particular program towards the recharging of the tertiary treated domestic effluent of the Paphos urban area into the Ezousa river gravel aquifer. The overall concept is to proceed further quality treatment through the S.A.T. system in order to comply the renovated water to the Provisional Standards of Cyprus for unrestricted use and to ensure the bulk of this water within the gravel storage capacity as well.

The specific objectives of the current study for this issue are as follows:

Objective 2.1 To review the worldwide available experience over the employment of the S.A.T. system and to identify possibilities for its application in Cyprus conditions. The materials provided from various sources but especially the references to applications in California (Montebello Forebay and Orange Country), in Arizona (Phoenix) and in Israel Dan Region Project have provided information which determined the efficiency of the S.A.T. system. This encourages for wider applications elsewhere impermeable horizons allow it as in the case of the Ezousa gravel basin within the study area.

The art of the recharging is well known in Cyprus but with the use of raw waters diverted within river gravel aquifer for water supply purposes. However, this may pave the way for functioning renovated effluent as well.

Objective 2.2 To investigate the physical extent and the hydrogeological characteristics of the Ezousa gravel aquifer as a proposed site for S.A.T. application. The field survey showed that the fluvial material accumulated over 7km long within the river basin may consist a natural system for higher treatment of the reclaimed effluent and on the other hand the storage capacity of the sorted material (maximum capacity $9x10^6m^3$) may allow to augment groundwater resources to that extent as the bulk of the effluent in question over the year. The renovated water should be extracted and supplied via the P.I.Project network for unrestricted use within the Projects area if the discharge water persists to the higher quality required by the Cyprus Provisional Standards (section 14.2).

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APPENDIX I

WATER TABLE MAPS

Fig. 1.1 <u>Water Table contour map of zone-1 for November 1980</u>

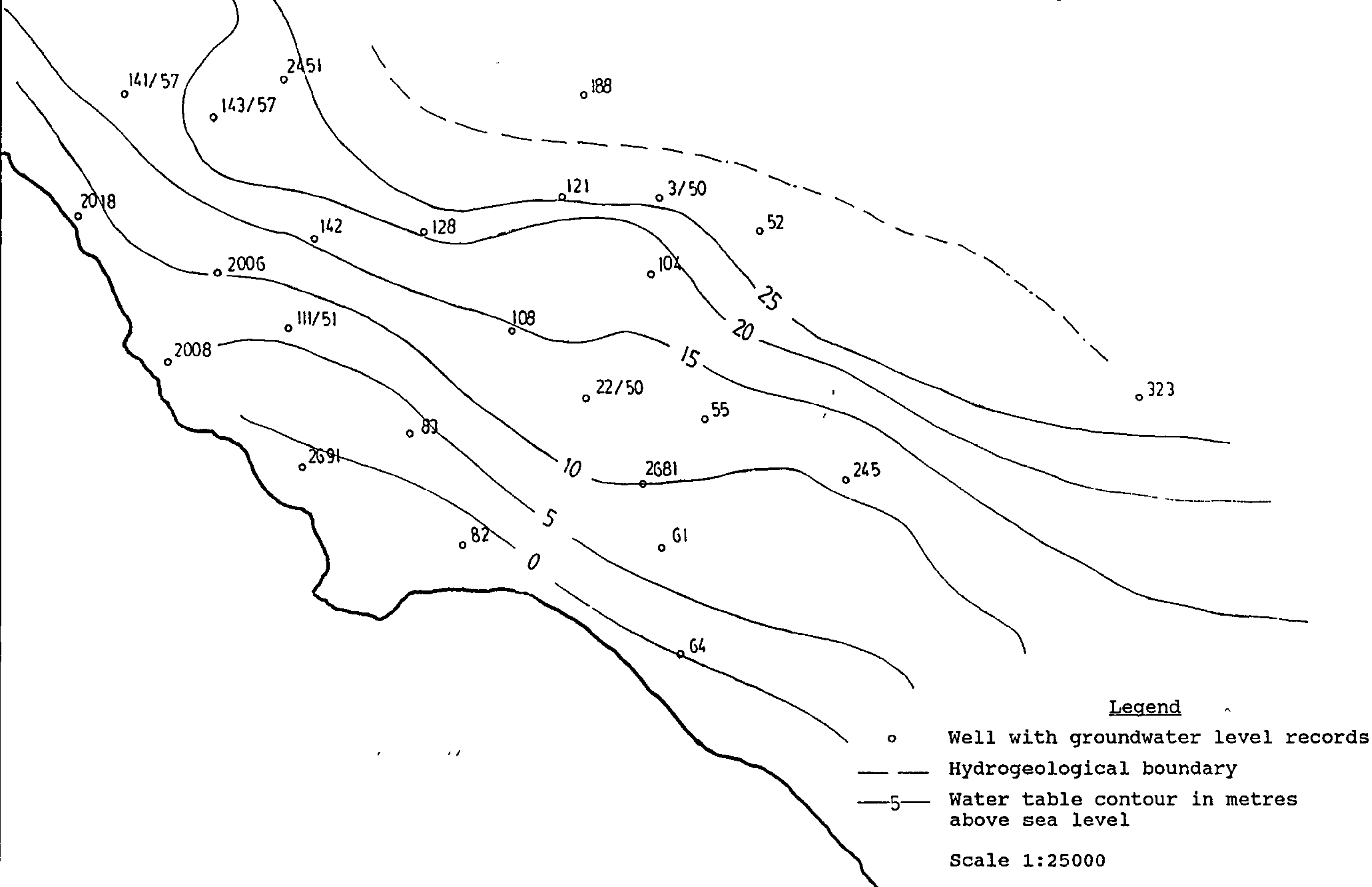


Fig. I.2 Water Table contour map of zone-1 for March 1981

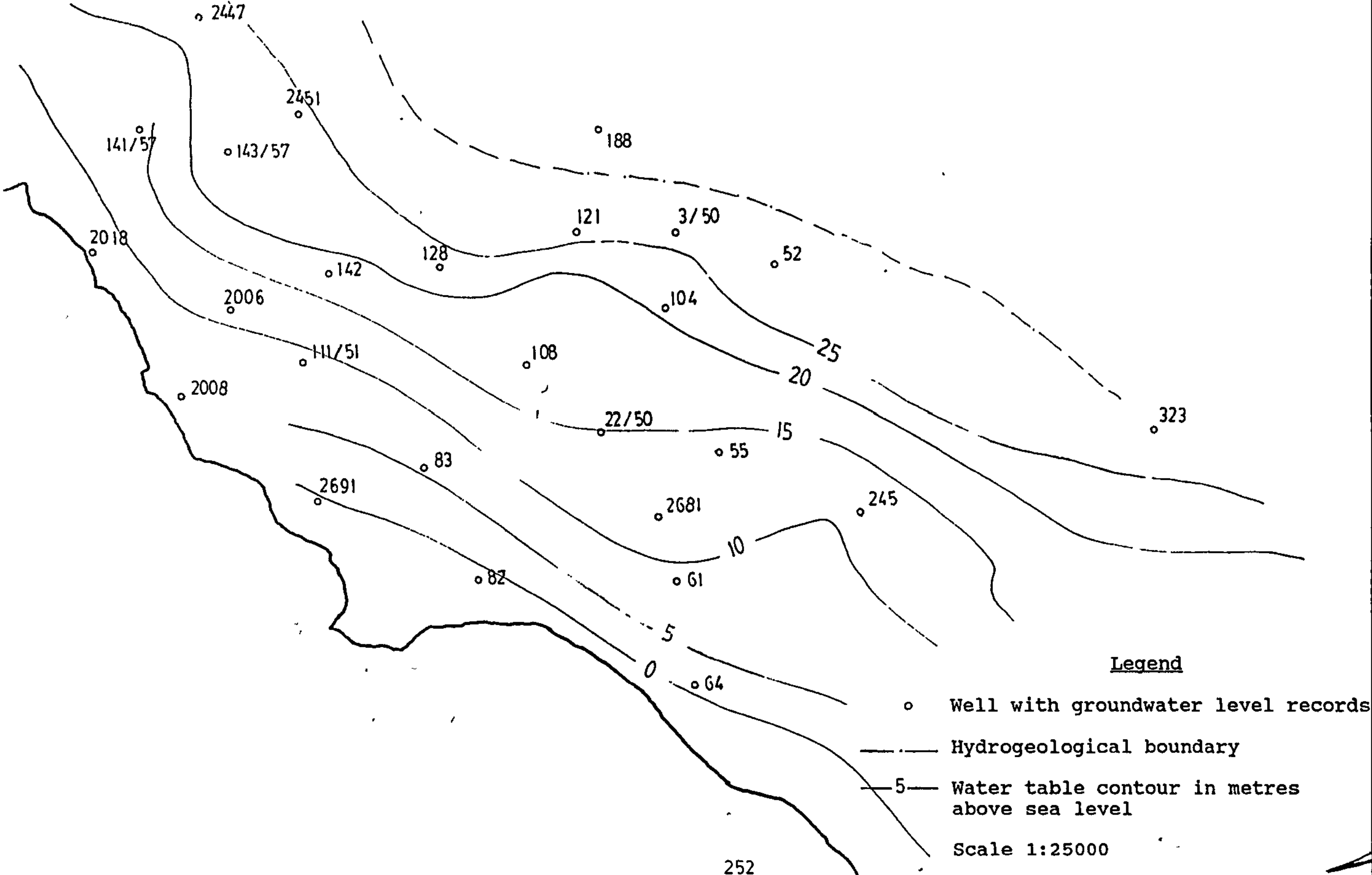


Fig. I.3 Water Table contour map of zone-1 for November 1981

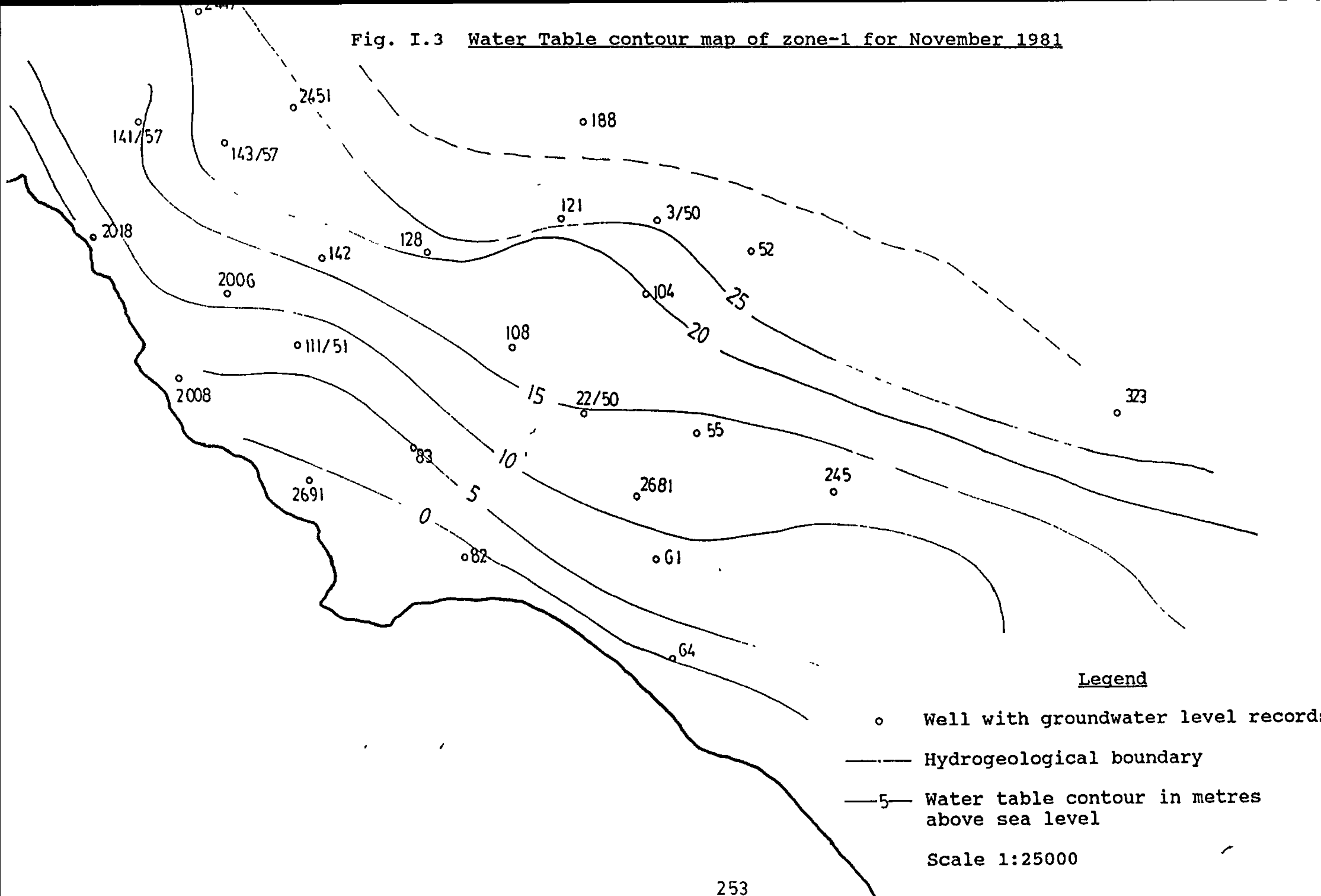


Fig. I.4 Water Table contour map of zone-1 for November 1987

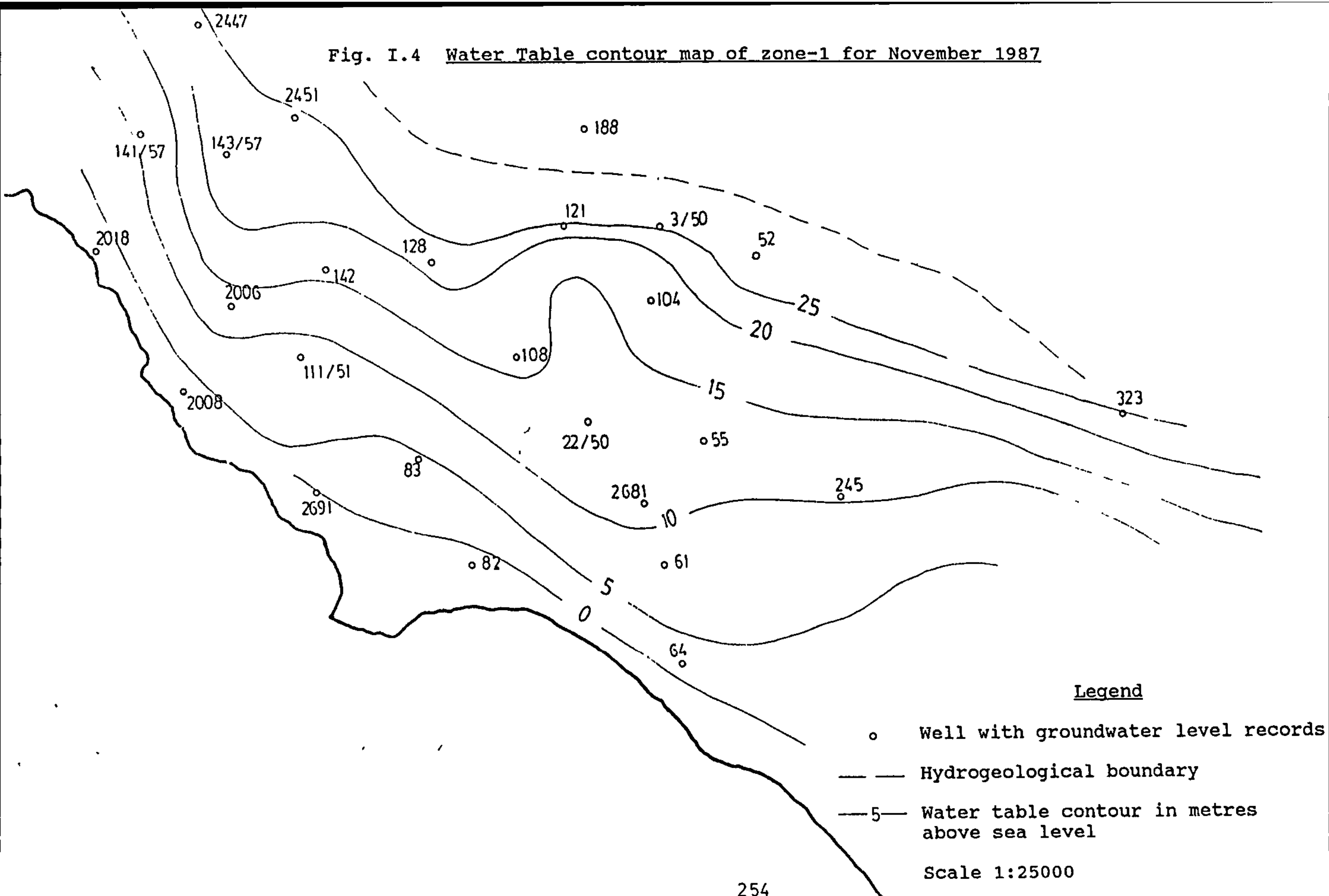


Fig. I.5 Water Table contour map of zone-1 for March 1988

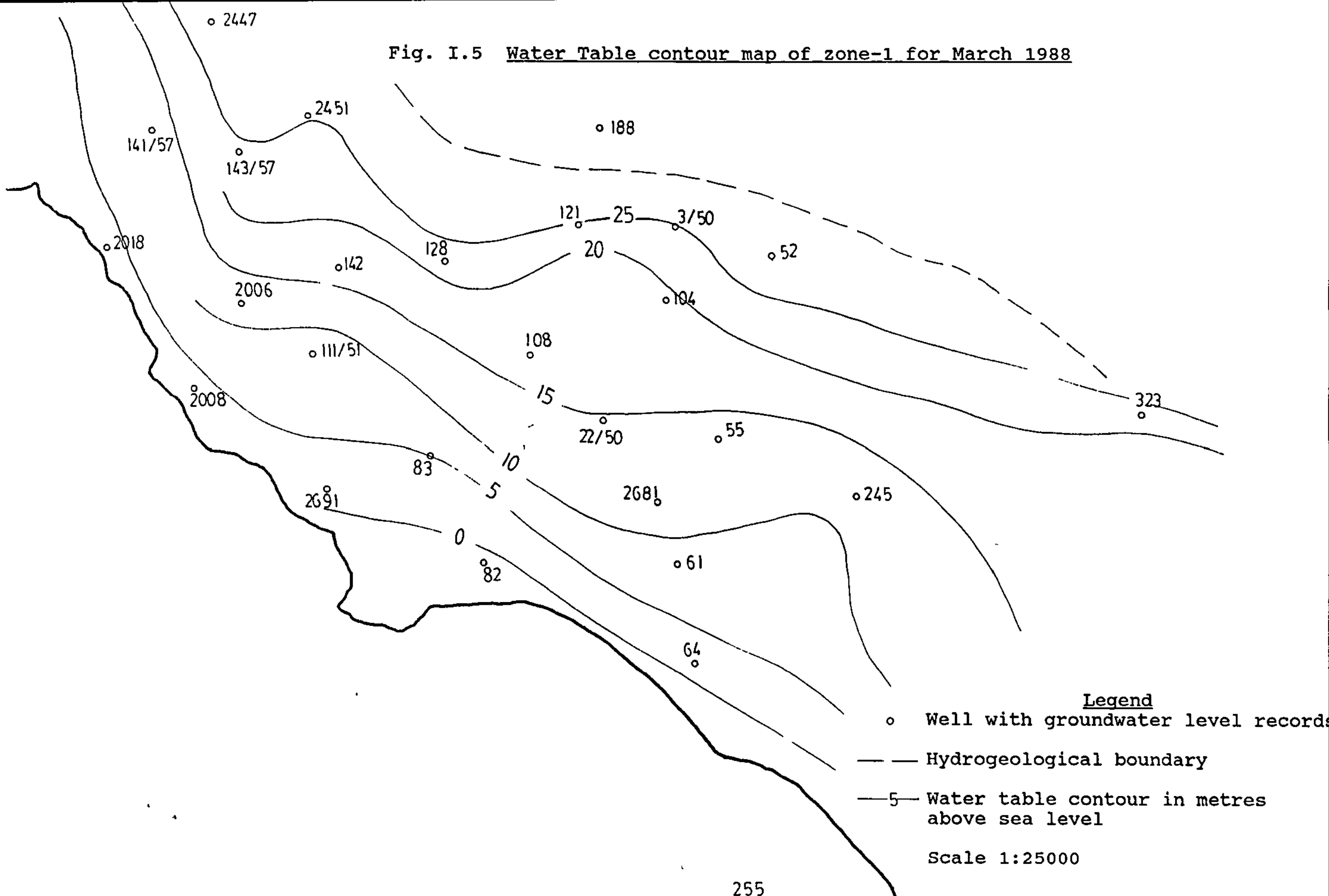
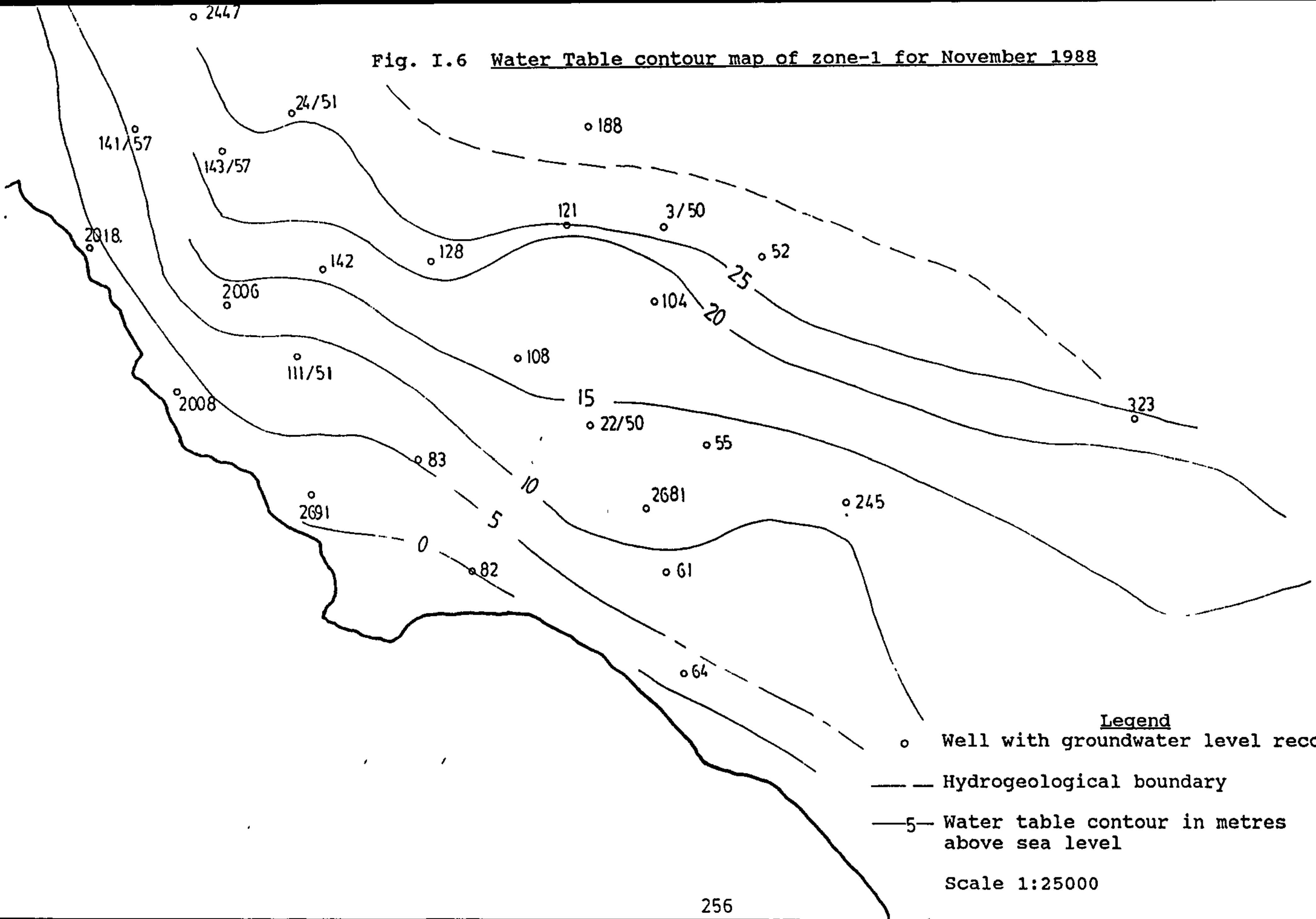


Fig. I.6 Water Table contour map of zone-1 for November 1988



Legend

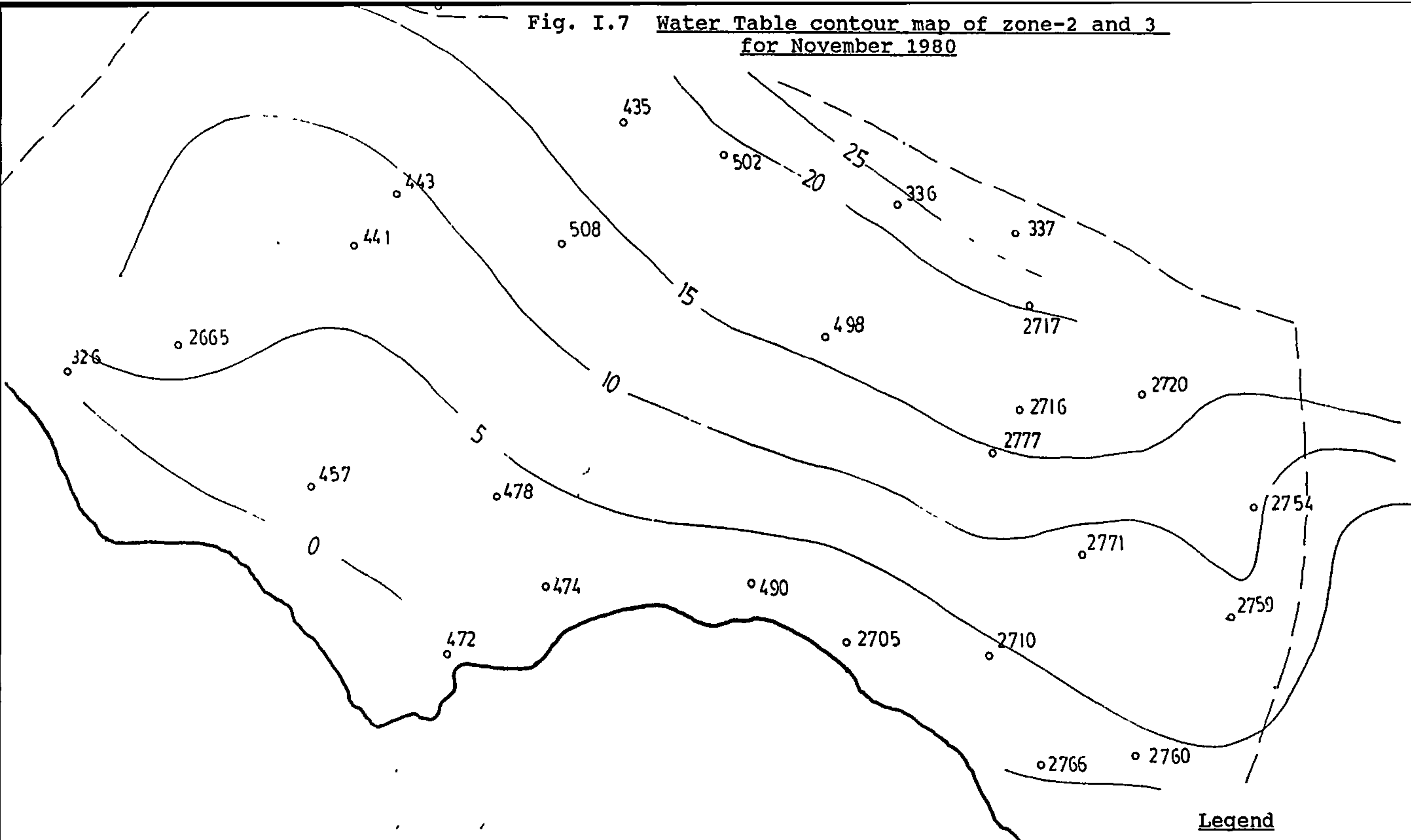
o Well with groundwater level records

— — Hydrogeological boundary

—5— Water table contour in metres above sea level

Scale 1:25000

Fig. I.7 Water Table contour map of zone-2 and 3 for November 1980



Legend

o Well with groundwater level records

—·— Hydrogeological boundary

—5— Water table contour in metres above sea level

Scale 1:25000

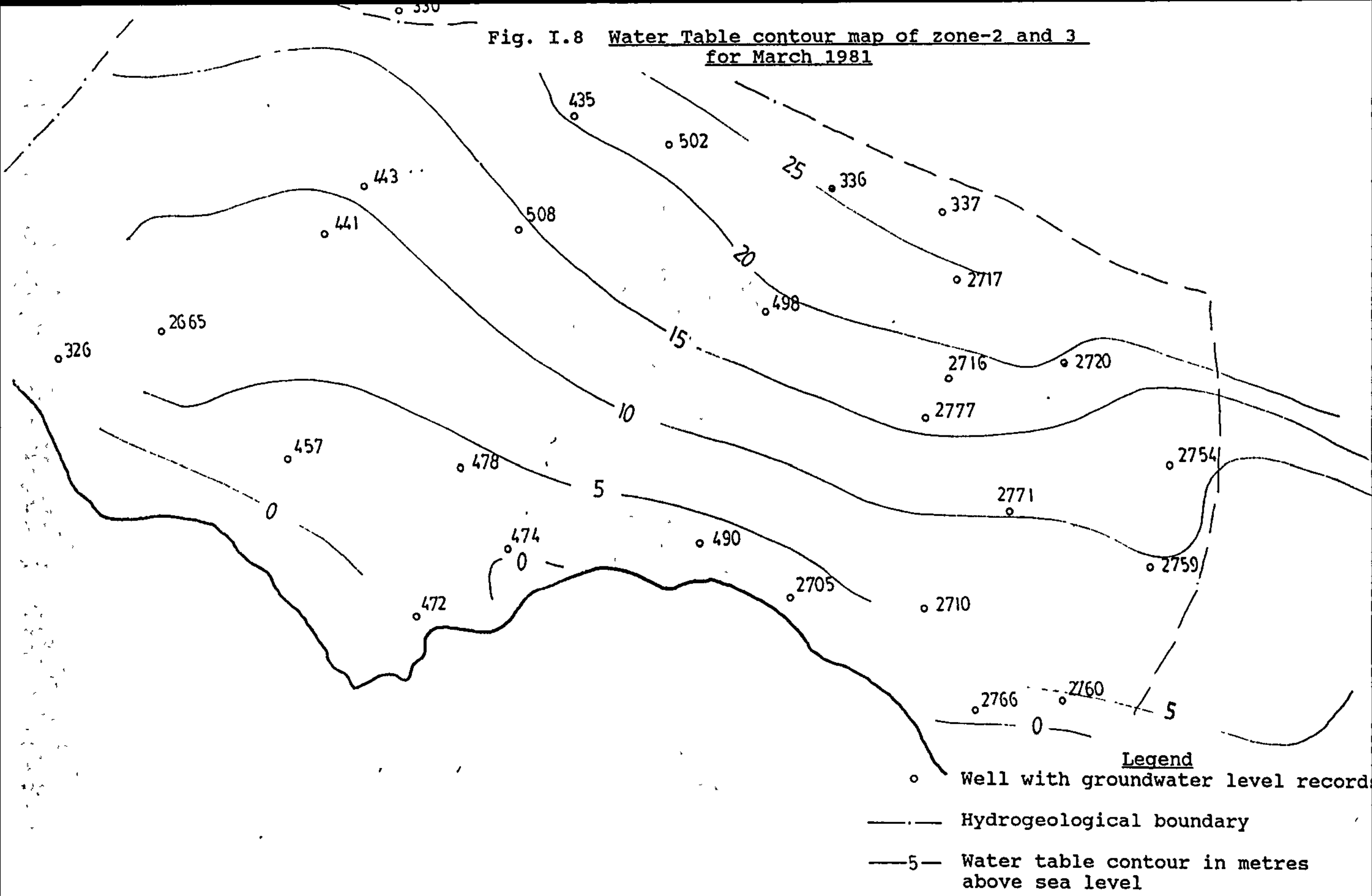
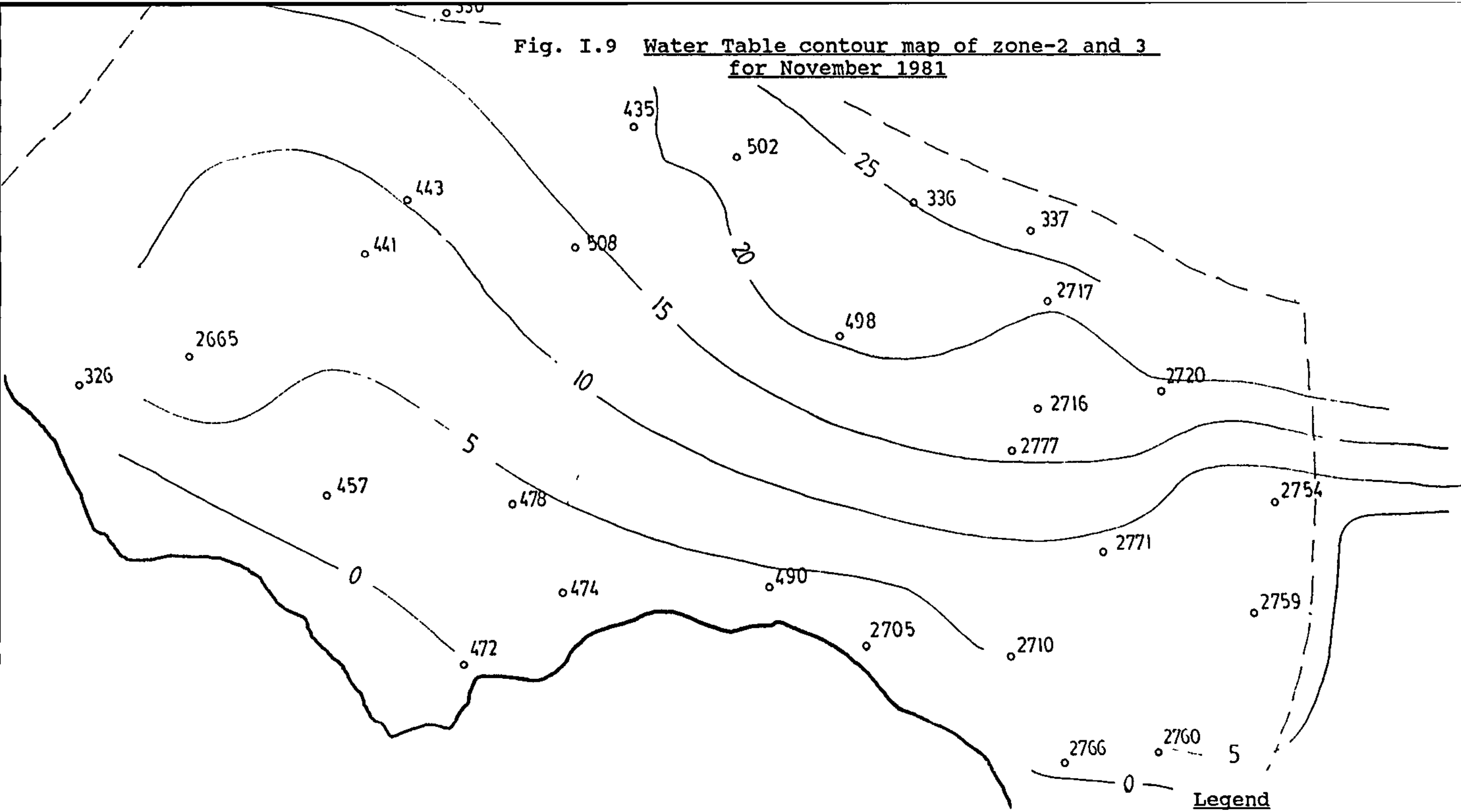


Fig. I.8 Water Table contour map of zone-2 and 3 for March 1981

Scale 1:25000

Fig. I.9 Water Table contour map of zone-2 and 3 for November 1981



Legend

o Well with groundwater level records

—·— Hydrogeological boundary

—5— Water table contour in metres above sea level

Scale 1:25000

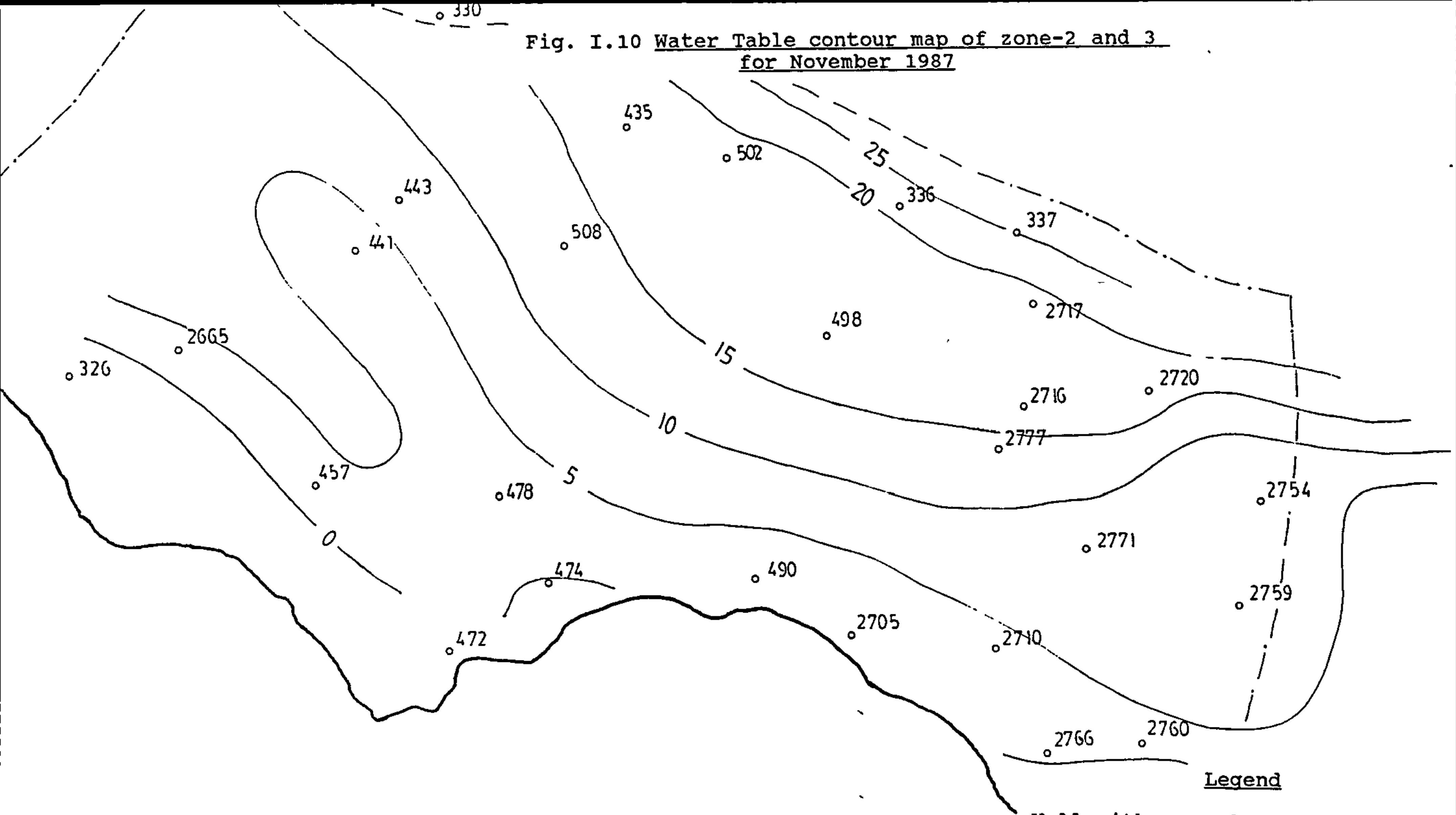
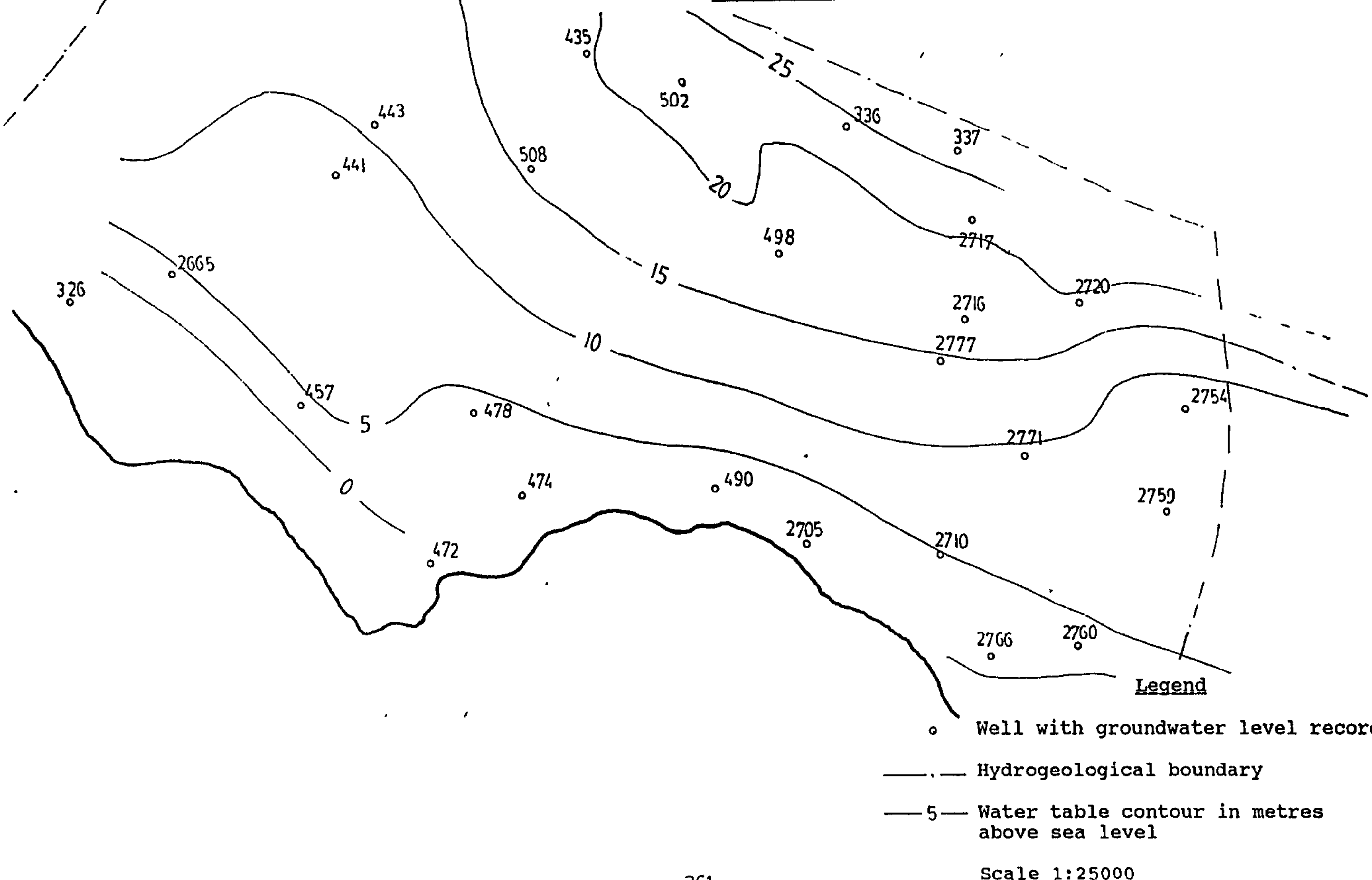
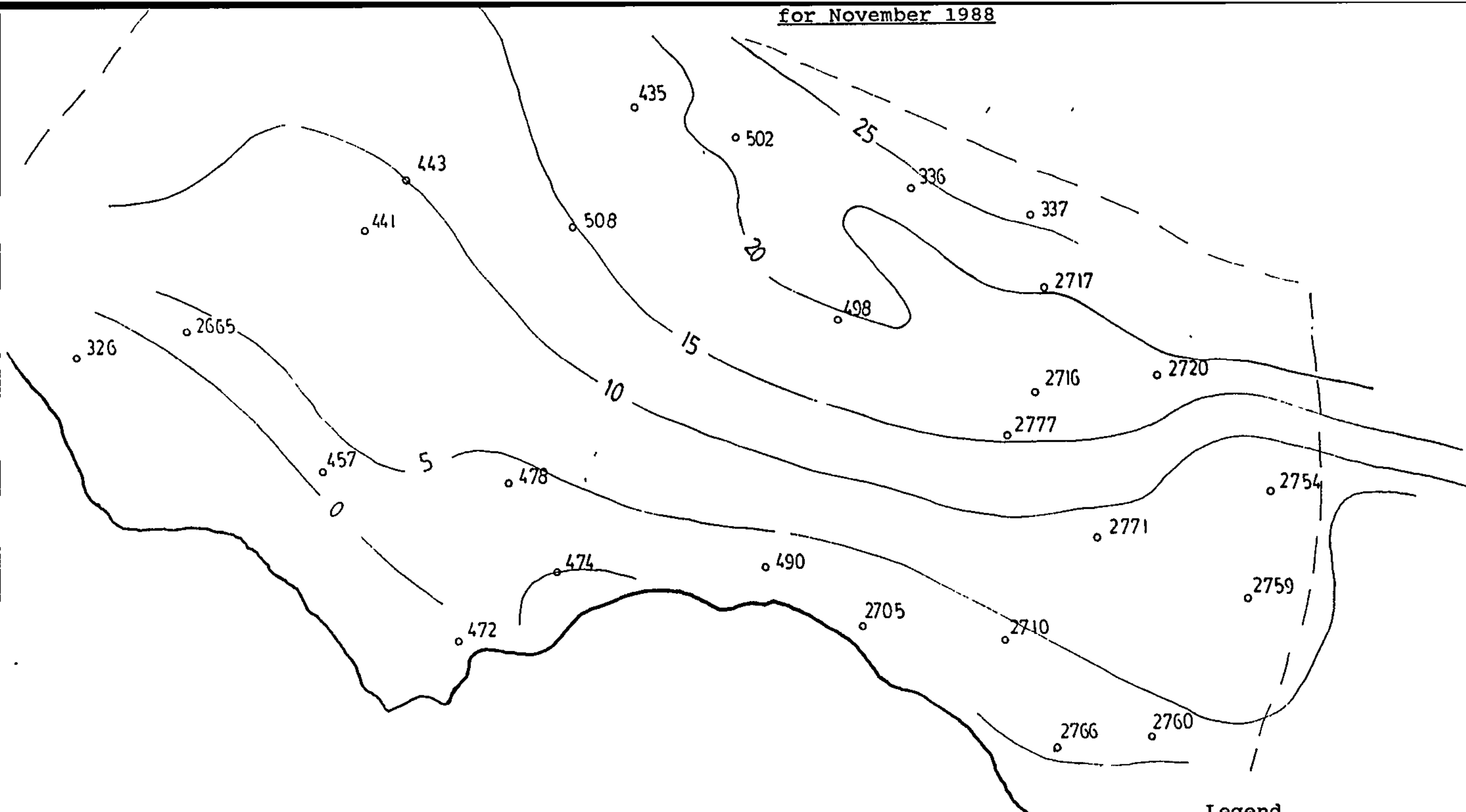


Fig. I.10 Water Table contour map of zone-2 and 3 for November 1987

Fig. I.11 Water Table contour map of zone-2 and 3 for March 1988



for November 1988



Legend

o Well with groundwater level record

— — Hydrogeological boundary

—5— Water table contour in metres above sea level

Scale 1:25000

Fig. I.13 Water Table contour map of zone-4 for November 1980

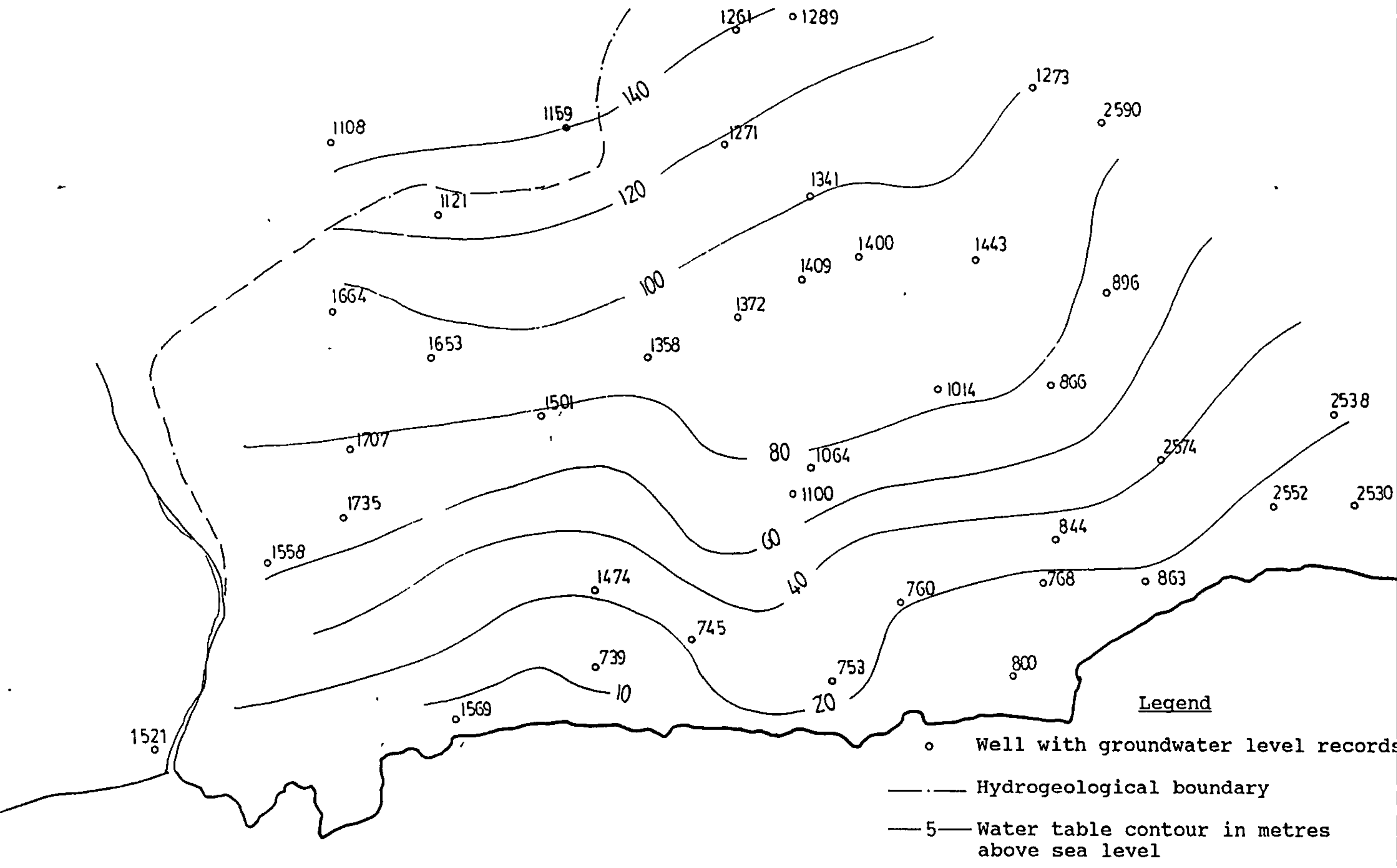
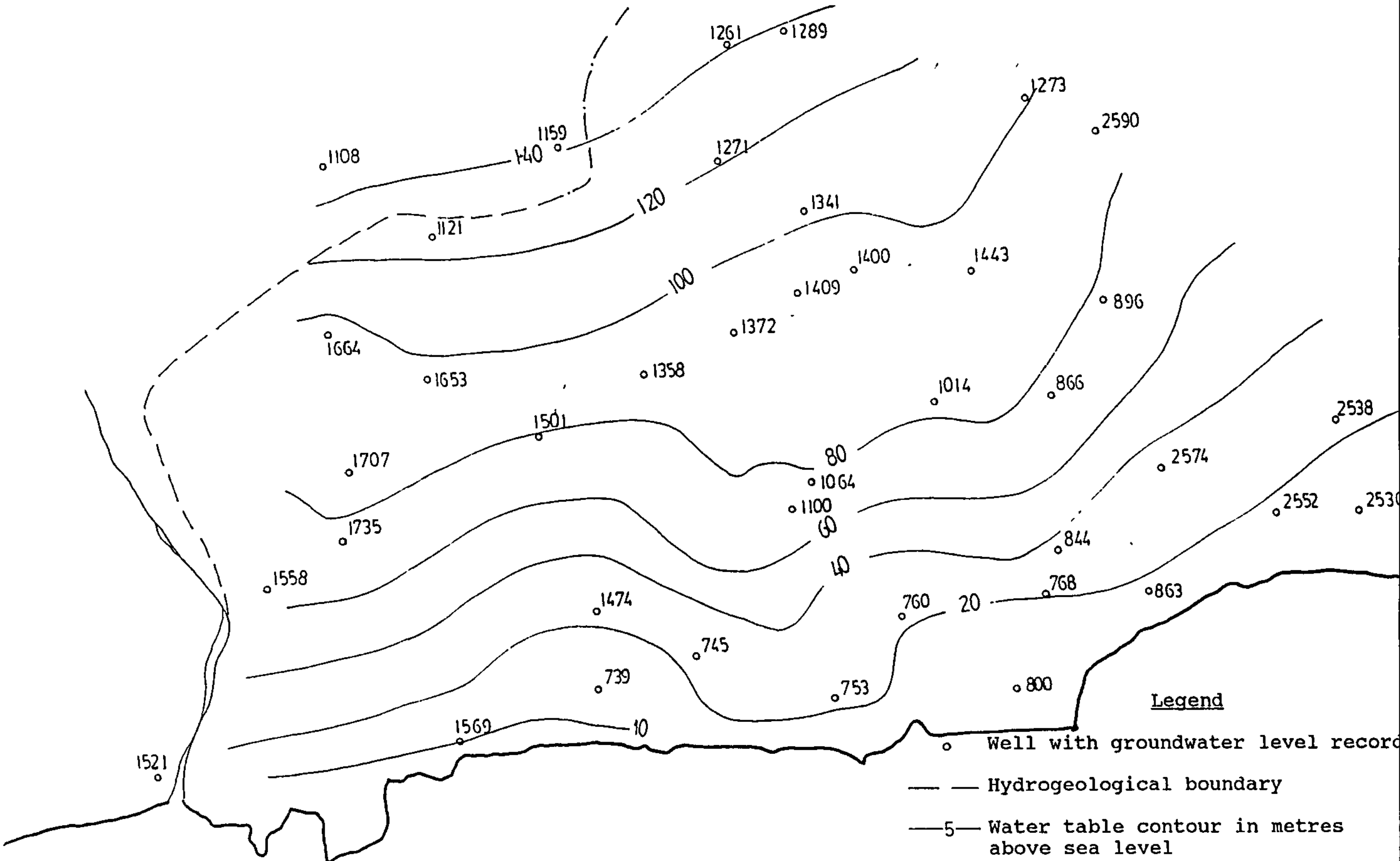


Fig. I.14 Water Table contour map of zone-4 for March 1981



Legend

o Well with groundwater level record

— — Hydrogeological boundary

—5— Water table contour in metres above sea level

Scale 1:25000

Fig. I.15 Water Table contour map of zone-4 for November 1981

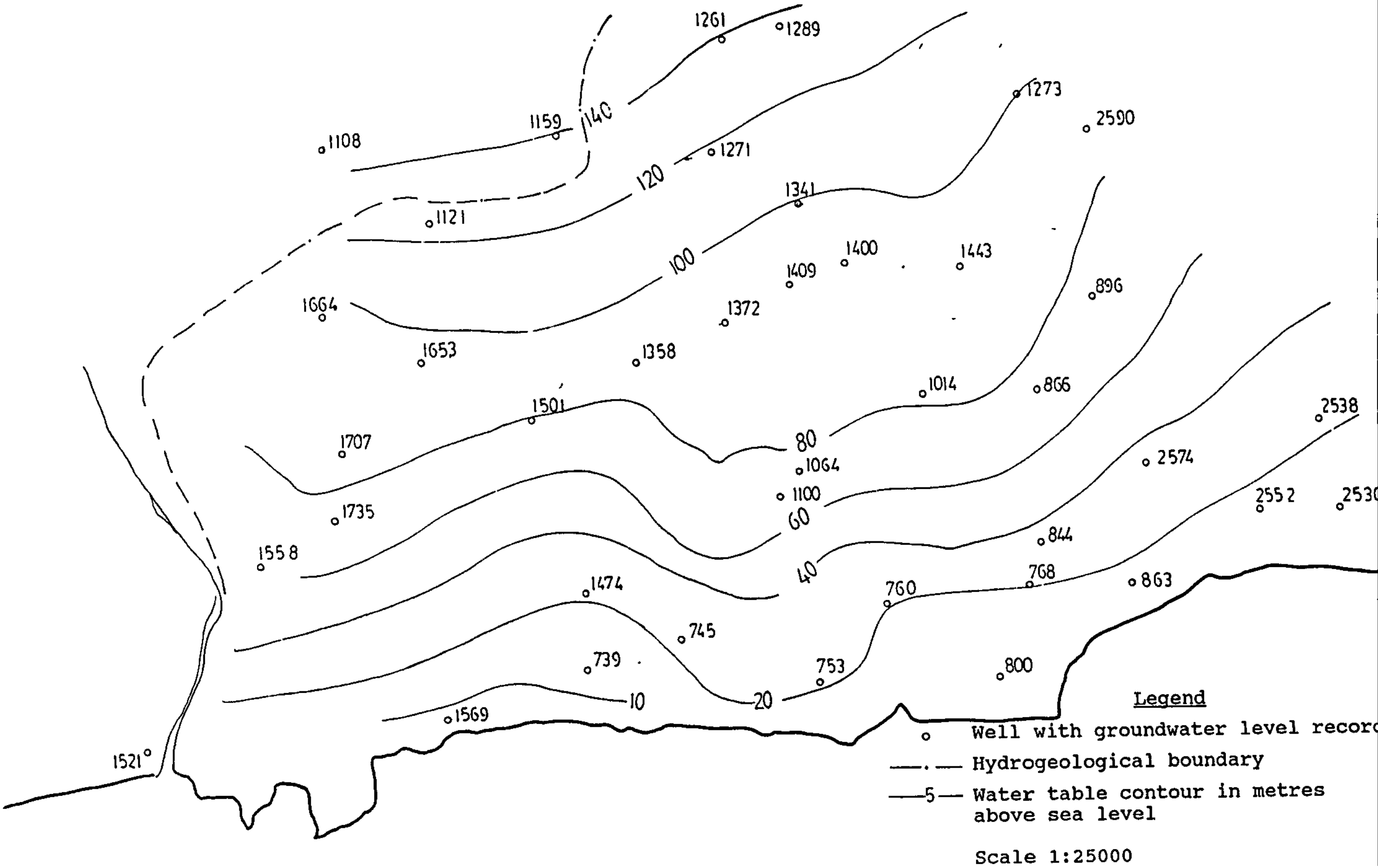
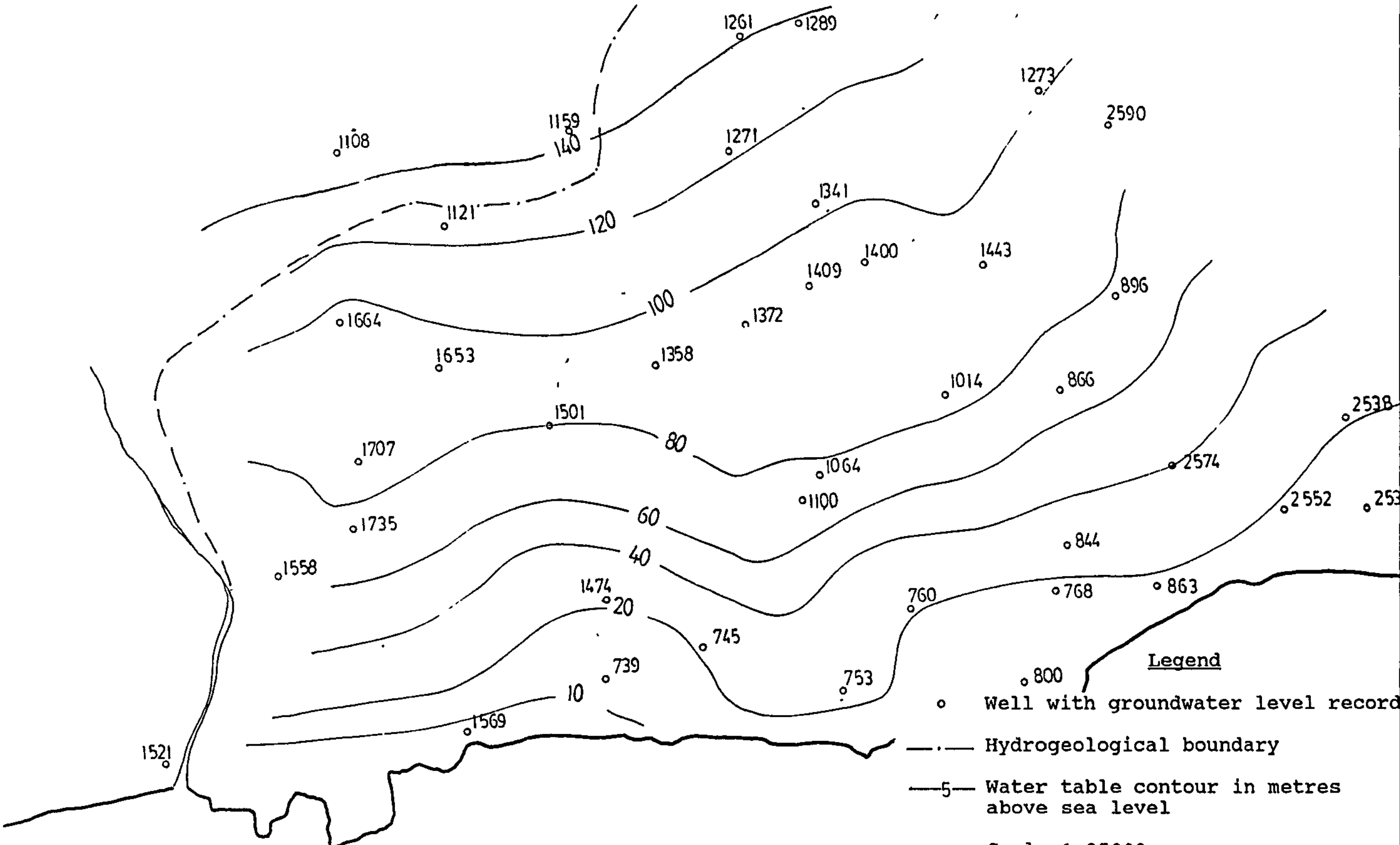


Fig. I.16 Water Table contour map of zone-4 for November 1987



Legend

o Well with groundwater level record

—·— Hydrogeological boundary

—5— Water table contour in metres above sea level

Scale 1:25000

Fig. I.17 Water Table contour map of zone-4 for March 1988

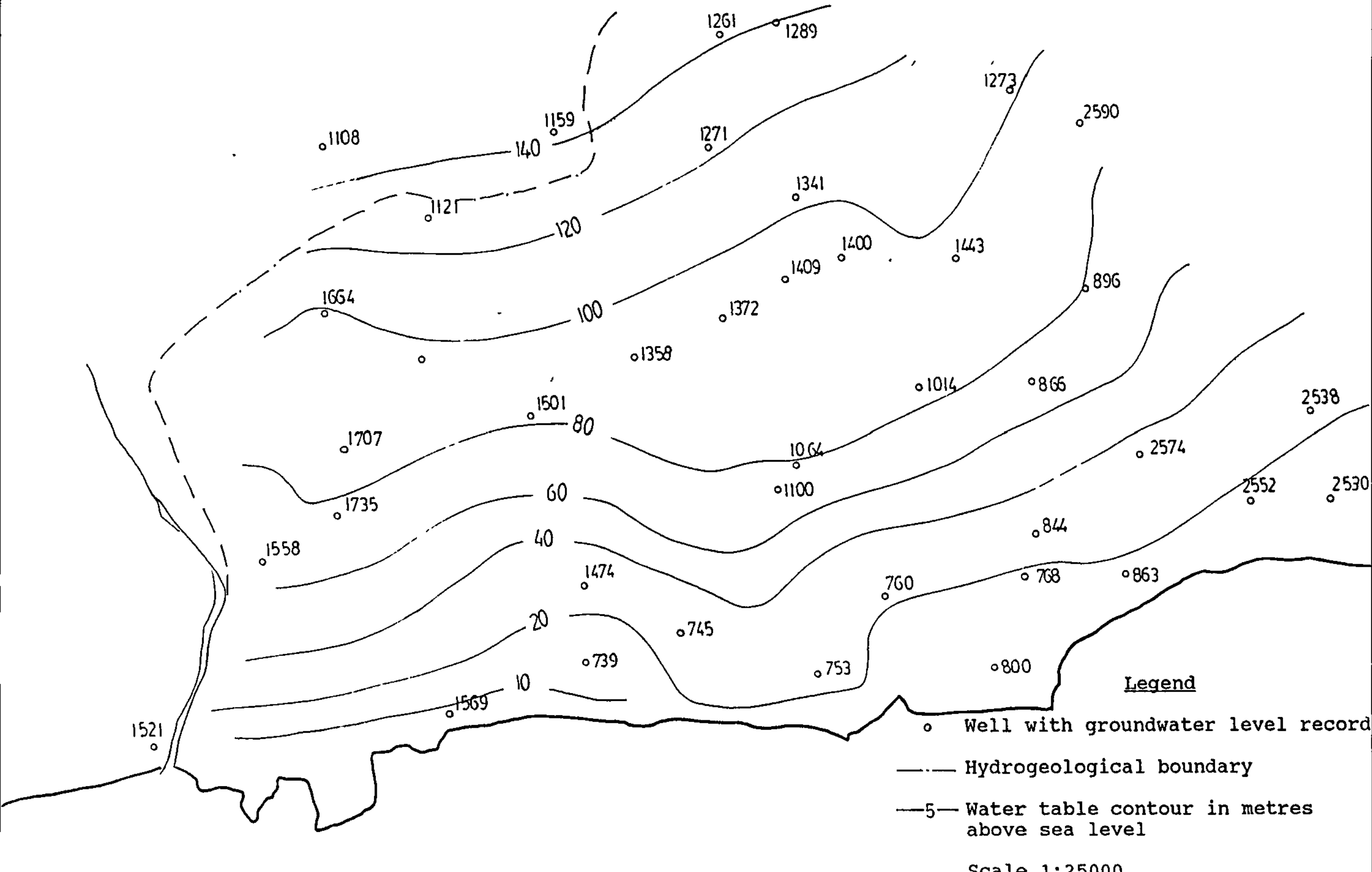
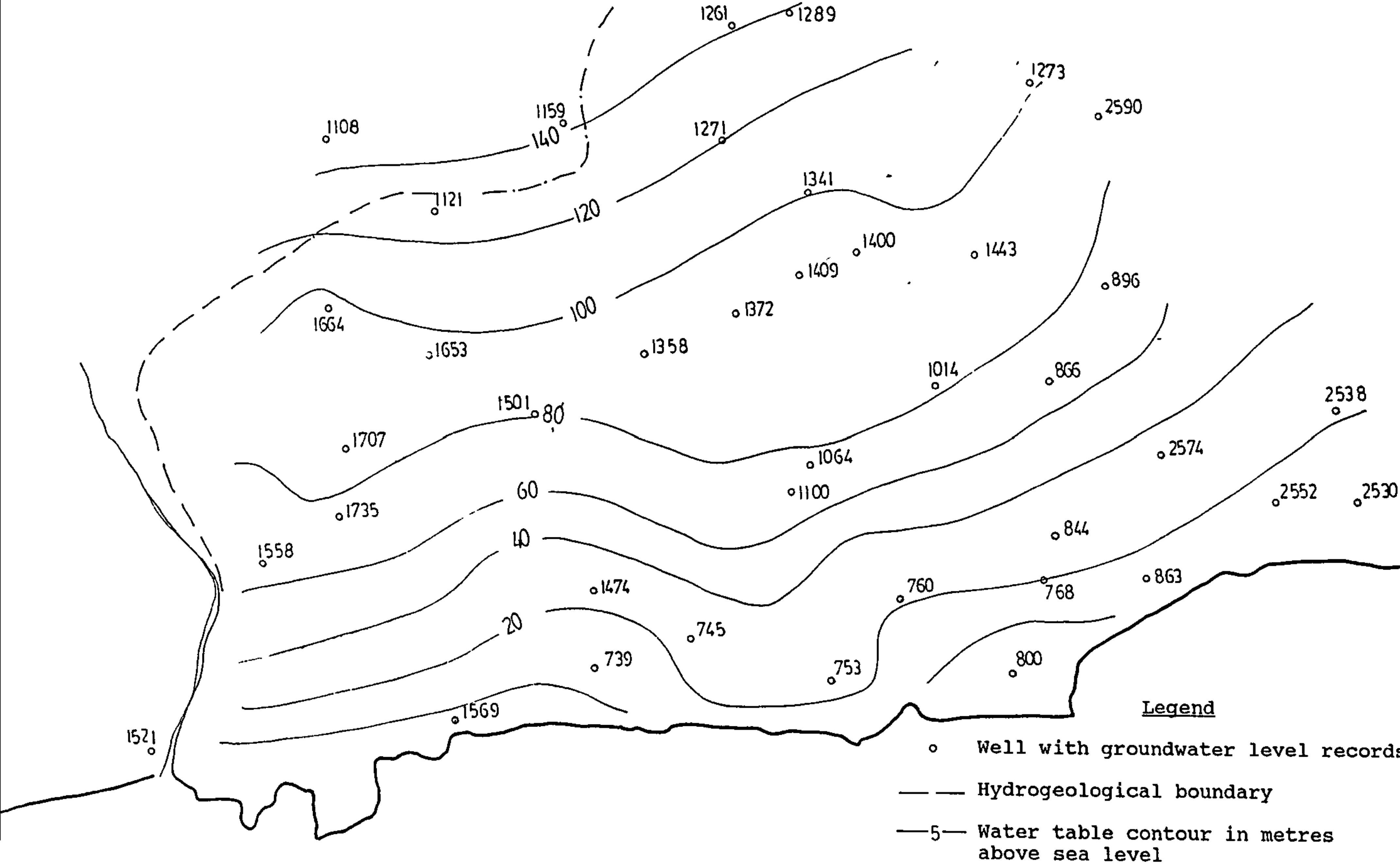


Fig. I.18 Water Table contour map of zone-4 for November 1988



APPENDIX I I

BOREHOLE LOGS

Hydrological No 20

Location - zone 1

Summary Logs:	0 - 0.9 m Silt
	0.9 - 7.3 m Silt, clayey gravel
	7.3 - 9.7 m Silt with sandy gravel
	9.7 - 12.2 m Marl
	12.2 - 17.7 m Calcarenite
	17.7 - 26.6 m Chalk marl

Observation borehole was 42.67m from the pumped borehole

Ground elevation 26.63m

Static water level 7.02m

Discharge rate 25.5m^3/h

Drawndown 3.40m

Aquifer saturated thickness 10.68m

Suction 17m

Hours pumped:40

Hydrological No 23

Location - zone 1

Summary Logs: 0 - 0.6m Soil

0.6 - 4.6m Silt, sand with gravel

4.6 - 6.7 m ~Silt, calcareous materials

6.7 - 10.6 m Shelly-calcarmite

10.6 - 15.9 m Grey marl

for the observation borehole: 0 - 0.6 m Soil

0.6 - 1.5 m Silt and clay

1.5 - 7.6 m Silt, clay, calcare

7.6 - 10.7 Shelly calcarenite

10.7 - 18.3 m Grey marl

Observation borehole was 23.33 m from the pumped borehole

Ground elevation 17.18 m

Static water level 4.00m

Discharge rate 15.7m^3/h

Drawndown 3.75m

Aquifer saturated thickness 6.6m

Suction: 11m

Hours pumped:23

Hydrological No 24

Location - zone 1

Summary Logs:	0 - 3.6m Silt
	3.6 - 7.3 Silt with gravel
	7.3 - 9.0 Marl, sandy
	9.0 - 11.3 Calcarenite
	11.3 - 67.0 Marl grey

for the observation borehole:	0 - 5.2 m Silt, clayey with gra
	5.2 - 8.5 Marl, sandy
	8.5 - 11.0 Calcarenite
	11.0 - 12.2 Marl, grey

Observation borehole was 24.08 m from the pumped borehole

Ground elevation 17.90 m

Static water level 7.71m

Discharge rate 6.7m^3/h

Drawndown 3.29m

Aquifer saturated thickness 6.6m

Suction 4m

Hours pumped:11

Hydrological No 5

Location - zone 2

Summary Logs:	0 - 1.00m Soil
	1.0 - 3.00 m Gravel, fine with coarse sand
	3.0 - 4.90 m Silt, clayey
	4.9 - 5.80 m Yello marl
	5.8 - 8.50 m Calcarenite
	8.5 - 33.00 m Grey marl

for the observation borehole:	0 - 4.9 m Soil
	4.9 - 6.1 m Calcarenite
	6.1 - 7.6 m Yellow marl
	7.6 - 8.2 m Calcarenite
	8.2 - 9.1 m Yellow marl
	9.1 - 30.5 m Grey marl

Observation borehole was 24.38 m from the pumped borehole

Ground elevation 13.10 m

Static water level 3.32m

Discharge rate $4.5m^3/h$

Drawndown 7.68m

Aquifer saturated thickness 5.18m

Suction 11m

Hours pumped:14

Hydrological No 7

Location - zone 2

Summary Logs: 0 - 1.0 m Silt
1.0 - 2.1 m Clay
2.1 - 4.3 m Gravel
4.3 - 5.5 m Calcarenite, cemented with gravel
5.5 - 12.2 m Sandy marl
18.2 - 17.7 m Calcarenite
17.7 - 24.4 m Grey marl
27.4 - 33.0m Grey marl

for the observation borehole: 0 - 1.2 m Silt
1.2 - 4.0 m Gravel
4.0 - 5.5 m Calcarenite
5.5 - 12.2 m Yello marl
12.2 - 18.3 m Calcarenite
18.3 - 24.4 m Grey marl

Observation borehole was 24.38 m from the pumped borehole

Ground elevation 9.40 m

Static water level 2.18 m

Discharge rate $29m^3/h$

Drawndown 4.93m

Aquifer saturated thickness 15.52m

Suction 17m

Hours pumped:24

Hydrological No 14

Location - zone 2

Summary Logs:	0 - 1.5 m Silt
	1.5 - 3.0 m Silt, sandy
	3.0 - 7.6 m Silt, gravel
	7.6 - 12.2 m Gravel
	12.2 - 13.1 m Calcarenite
	13.1 - 15.0 m Marl, yellowish
	15.0 - 30.5 m Marl, grey

for the observation borehole:	0 - 1.5 m Silt
	1.5 - 3.0 m Silt, sandy
	3.0 - 6.1 m Silt, gravel
	6.1 - 9.1 m Silt, sandy
	9.1 - 12.8 m Calcarenite, shell
	12.8 - 15.2 m Marl, yellowish
	15.2 - 30.5 m Marl, grey

Observation borehole was 24.62 m from the pumped borehole

Ground elevation 15.16 m

Static water level 8.42m

Discharge rate 6.3m^3/h

Drawdown 2.58m

Aquifer saturated thickness 4.68m

Suction 11m

Hours pumped:14

Hydrological No 22

Location - zone 2

Summary Logs:	0 - 3m Silt
	3 - 8.5 m Calcarenite, shelly
	8.5 - 21.3 m Grey marl
	21.3 - " "

for the observation borehole:	0 - 2.7 m silt
	2.7 - 8.5 m calcarenite, shelly
	8.3 - 18.3 m Grey marl
	18.3 - " "

Observation borehole was 24.08 m from the pumped borehole

Ground elevation 3.22 m

Static water level 1.67m

Discharge rate 14.8m^3/h

Drawndown 5.00m

Aquifer saturated thickness 5.80m

Suction 11m

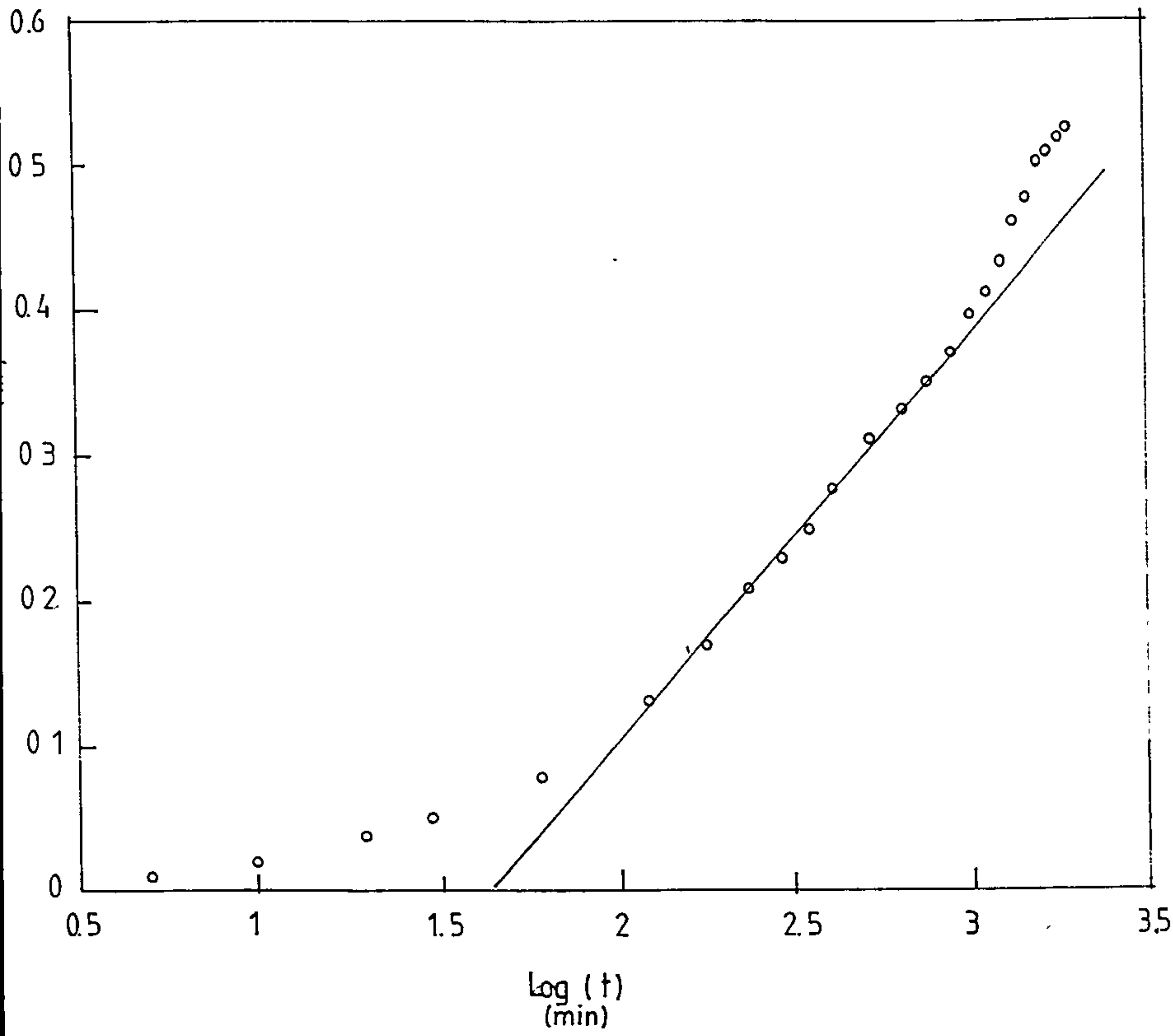
Hours pumped:50

APPENDIX III

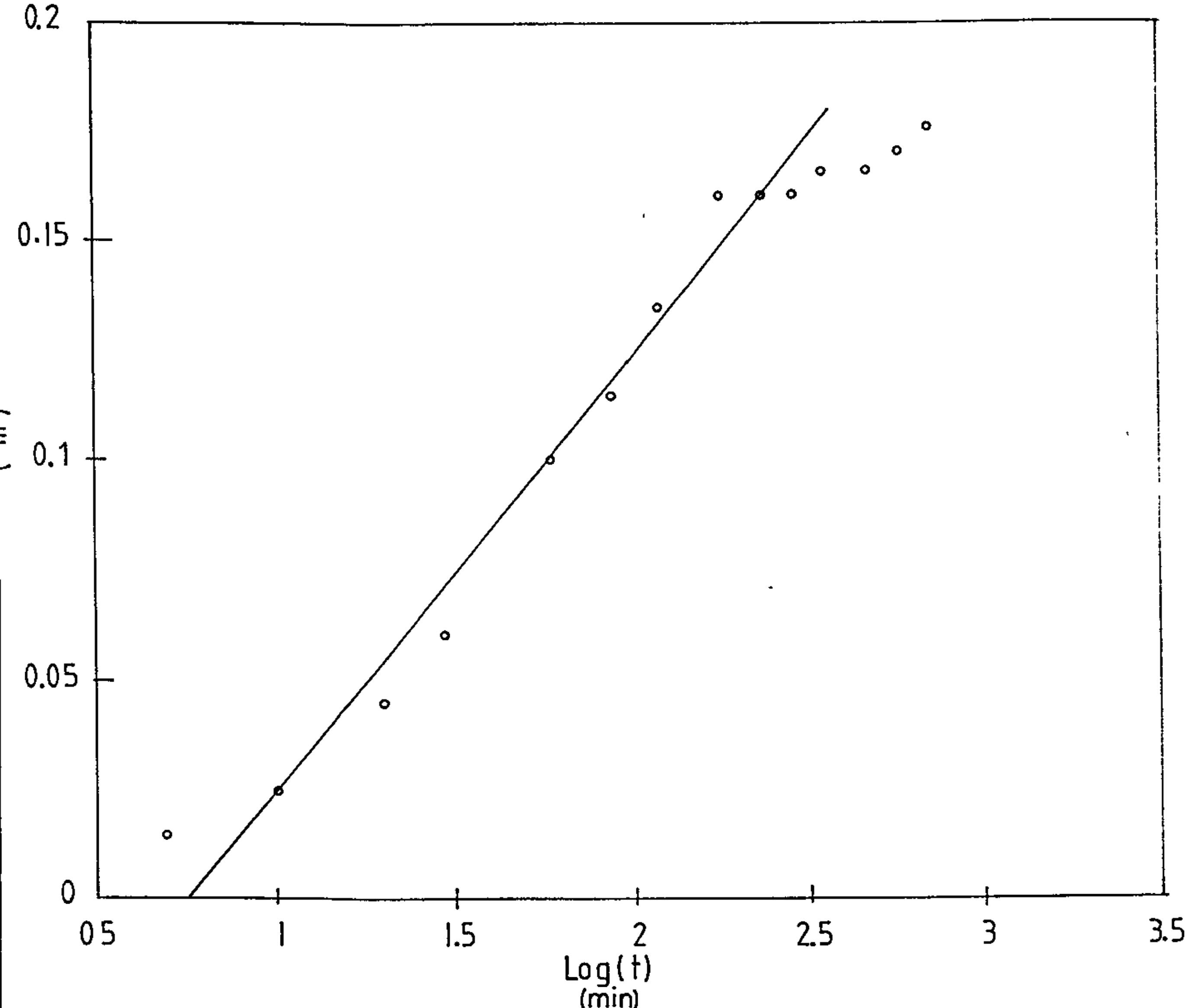
PUMPING TEST ANALYSIS - GRAPHS

(For borehole locations see Fig. 7.1, 14.4)

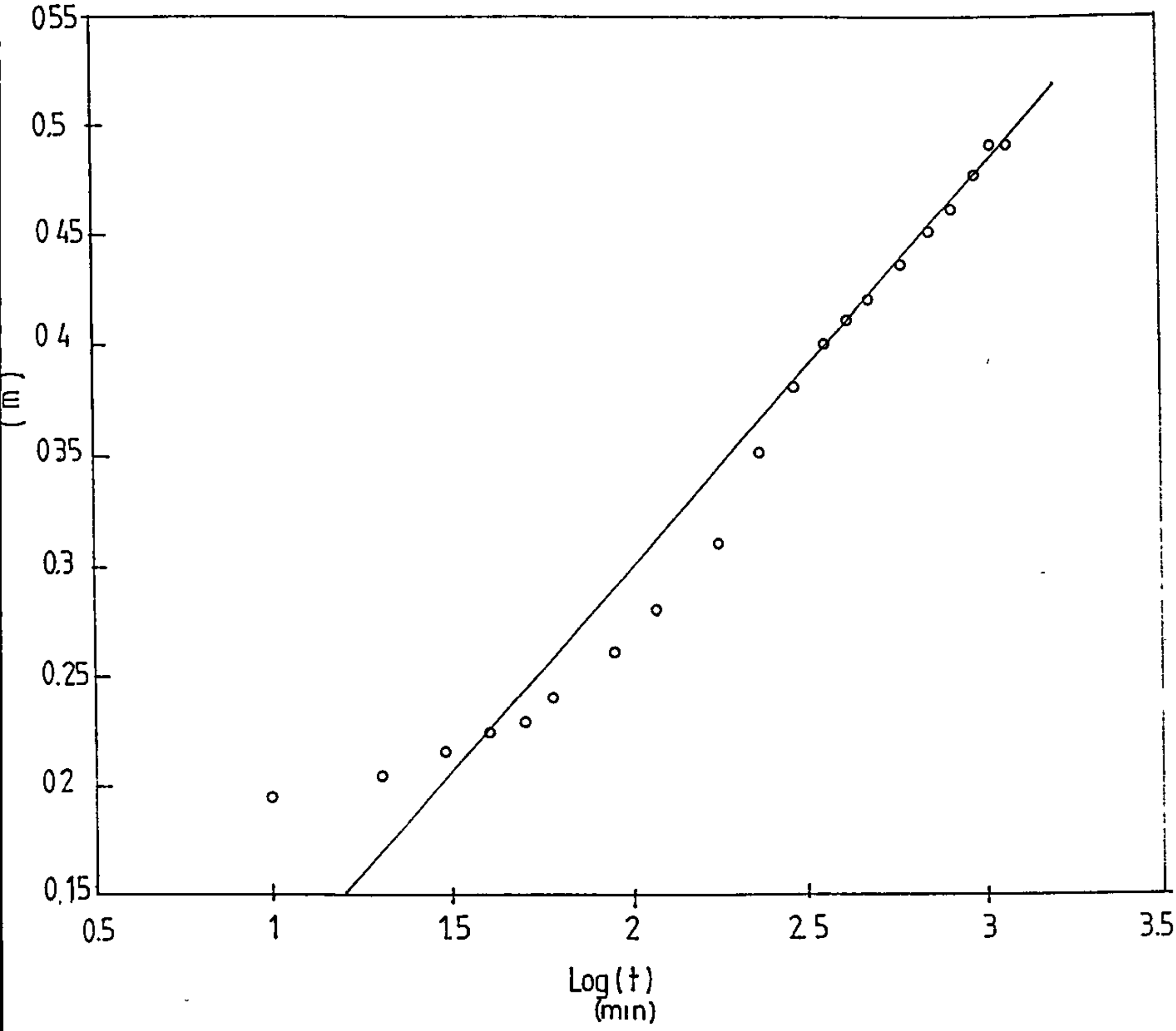
BH 20 (JACOB METHOD OF ANALYSIS)



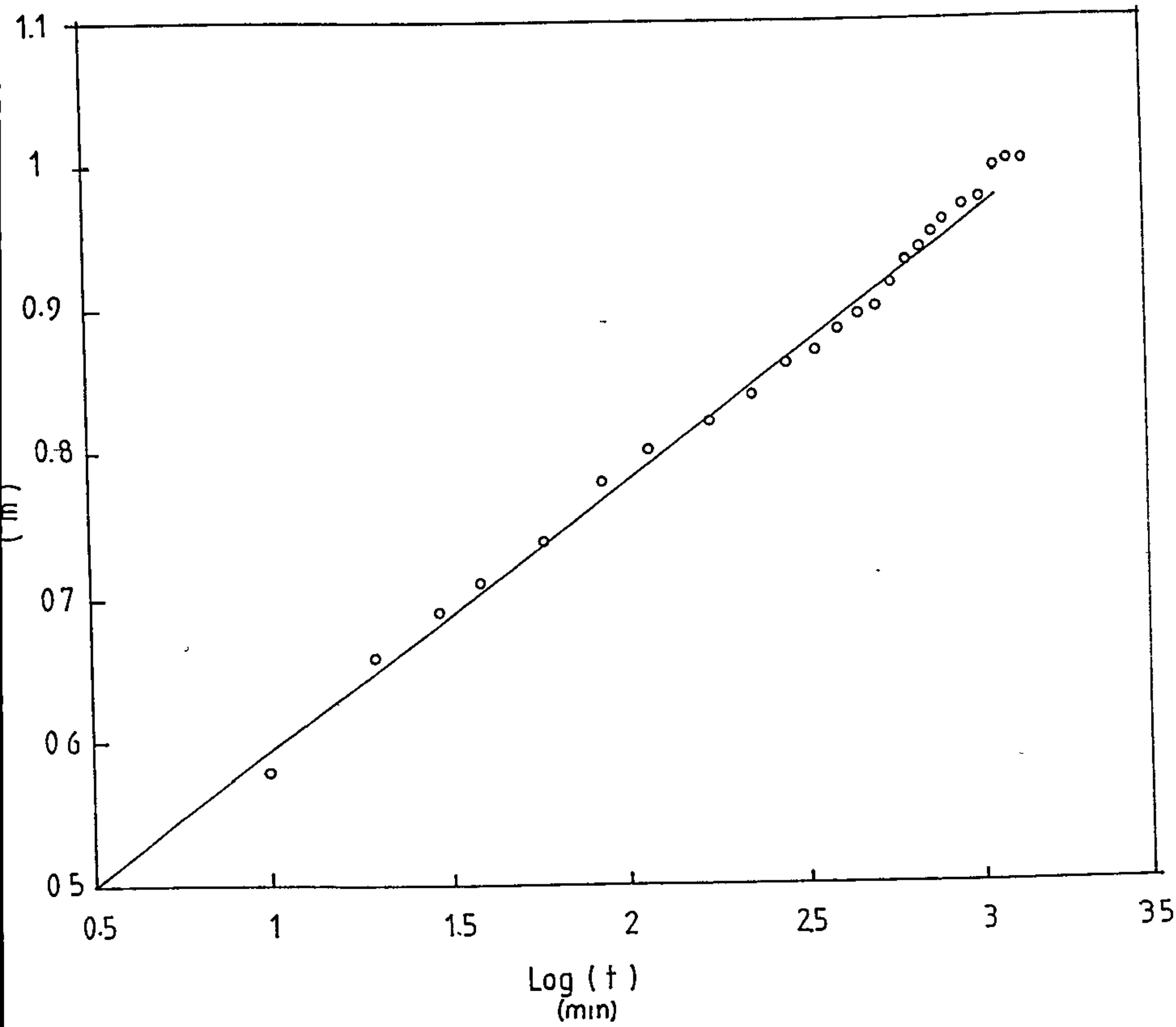
BH 24 (JACOB METHOD OF ANALYSIS)



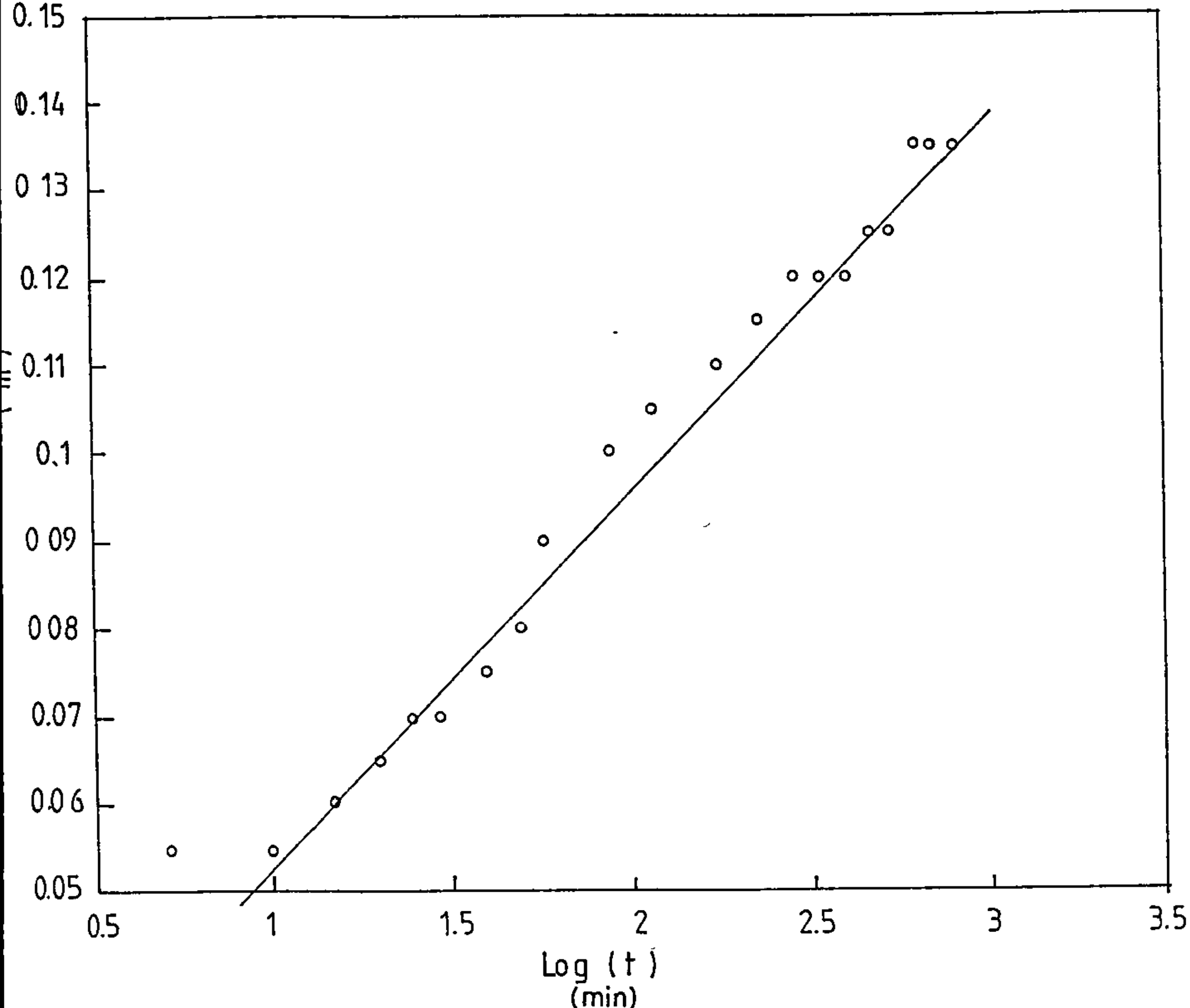
BH5 (JACOB METHOD OF ANALYSIS)

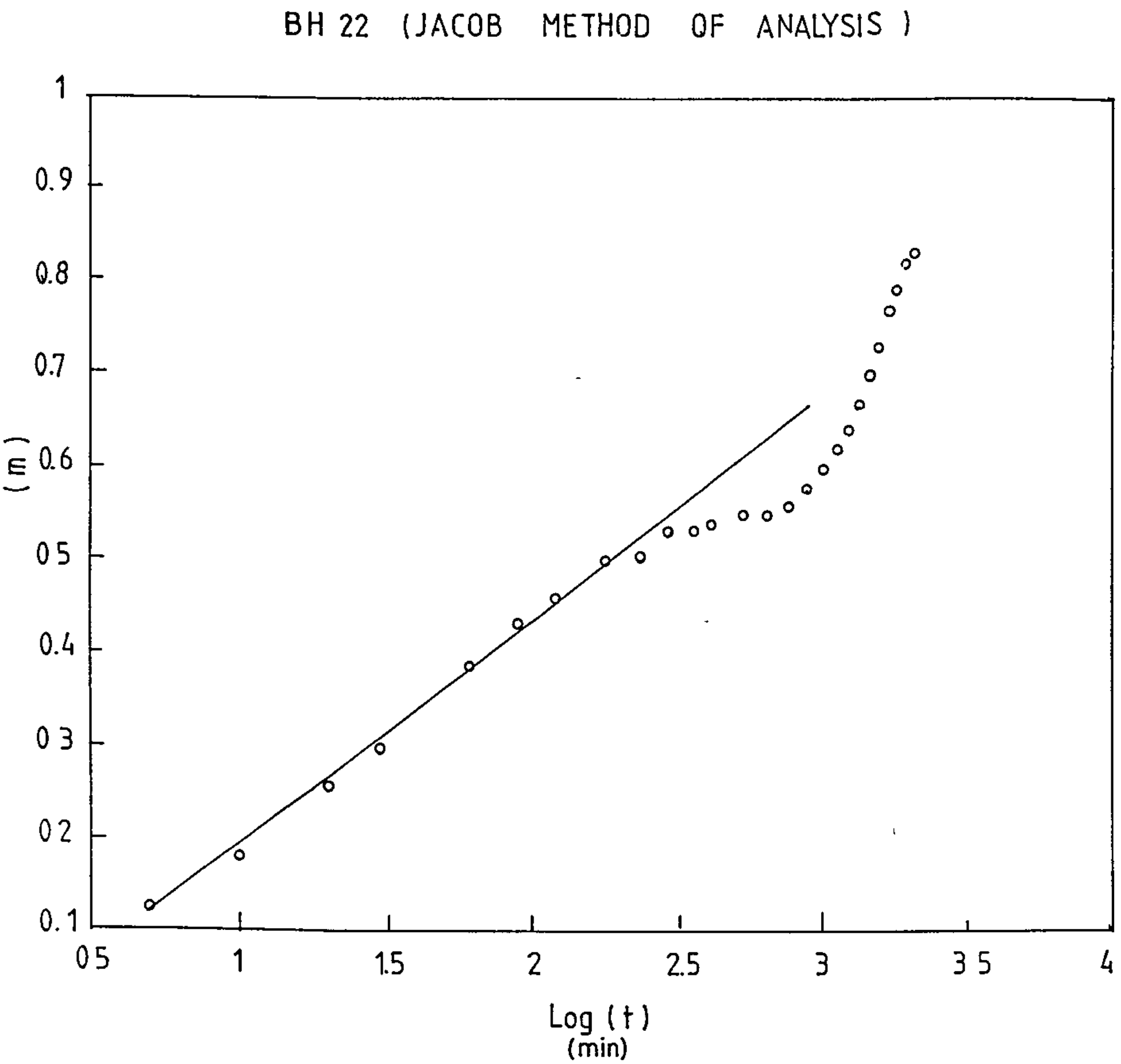


BH 7 (JACOB METHOD OF ANALYSIS)

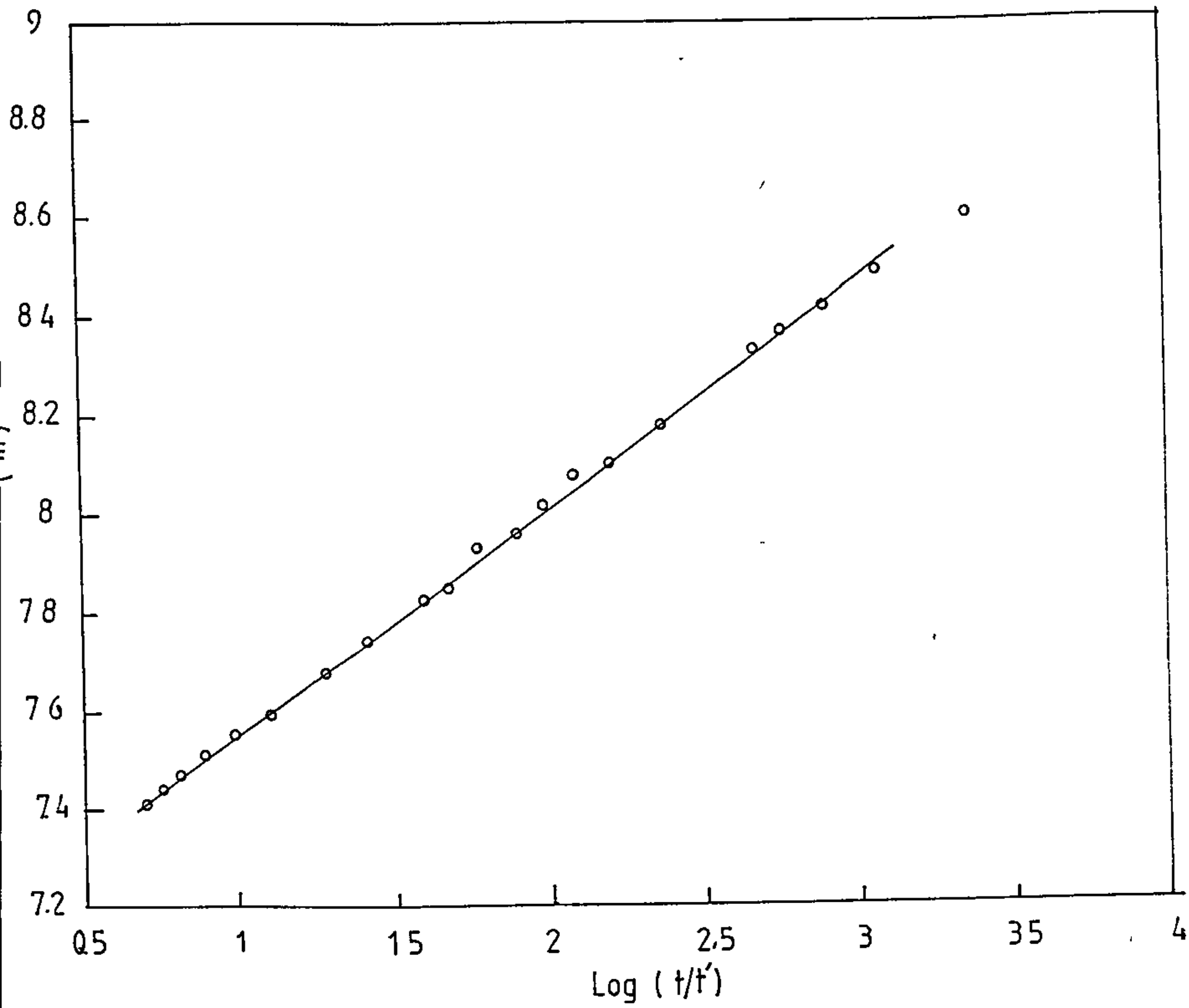


BH 14 (JACOB METHOD OF ANALYSIS)

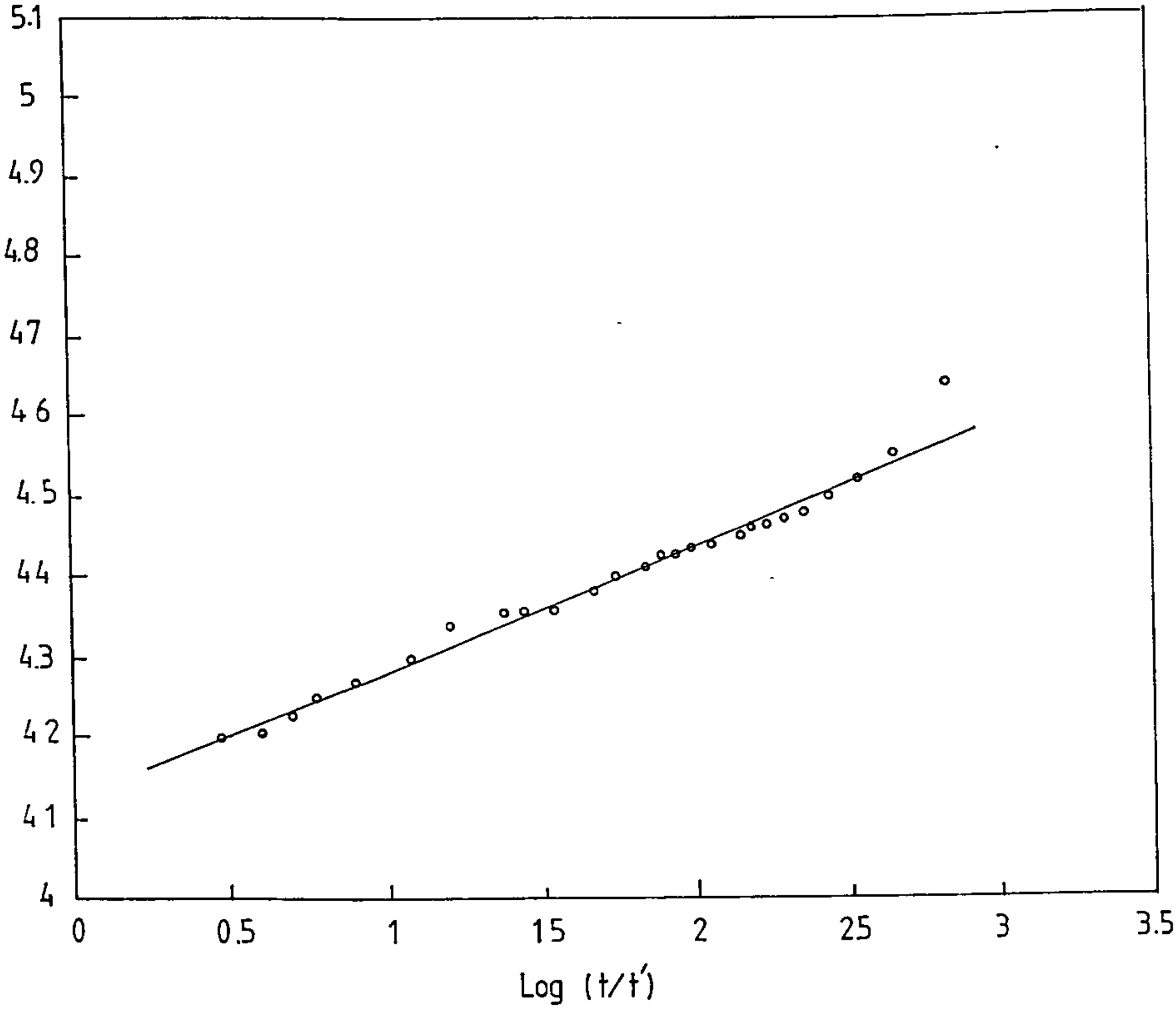



BH 22 (JACOB METHOD OF ANALYSIS)
1
0.9
0.8
0.7
0.6
0 5
0.4
0 3
0 2
0. 1
(m)
0 5
1
1.5
2
2.5
3
3 5
4
Log (t)
(min)

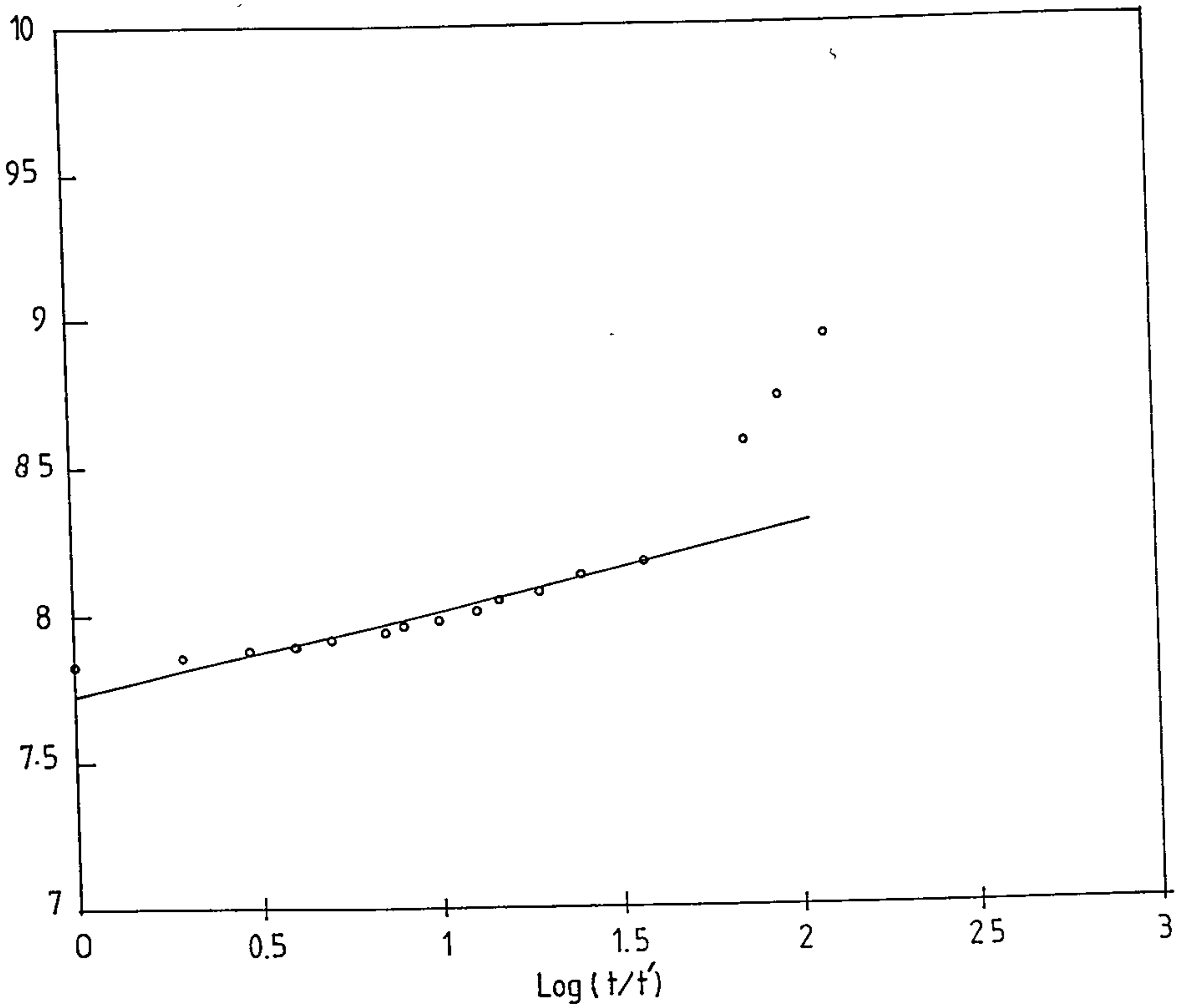
BH 20 (RECOVERY METHOD OF ANALYSIS)



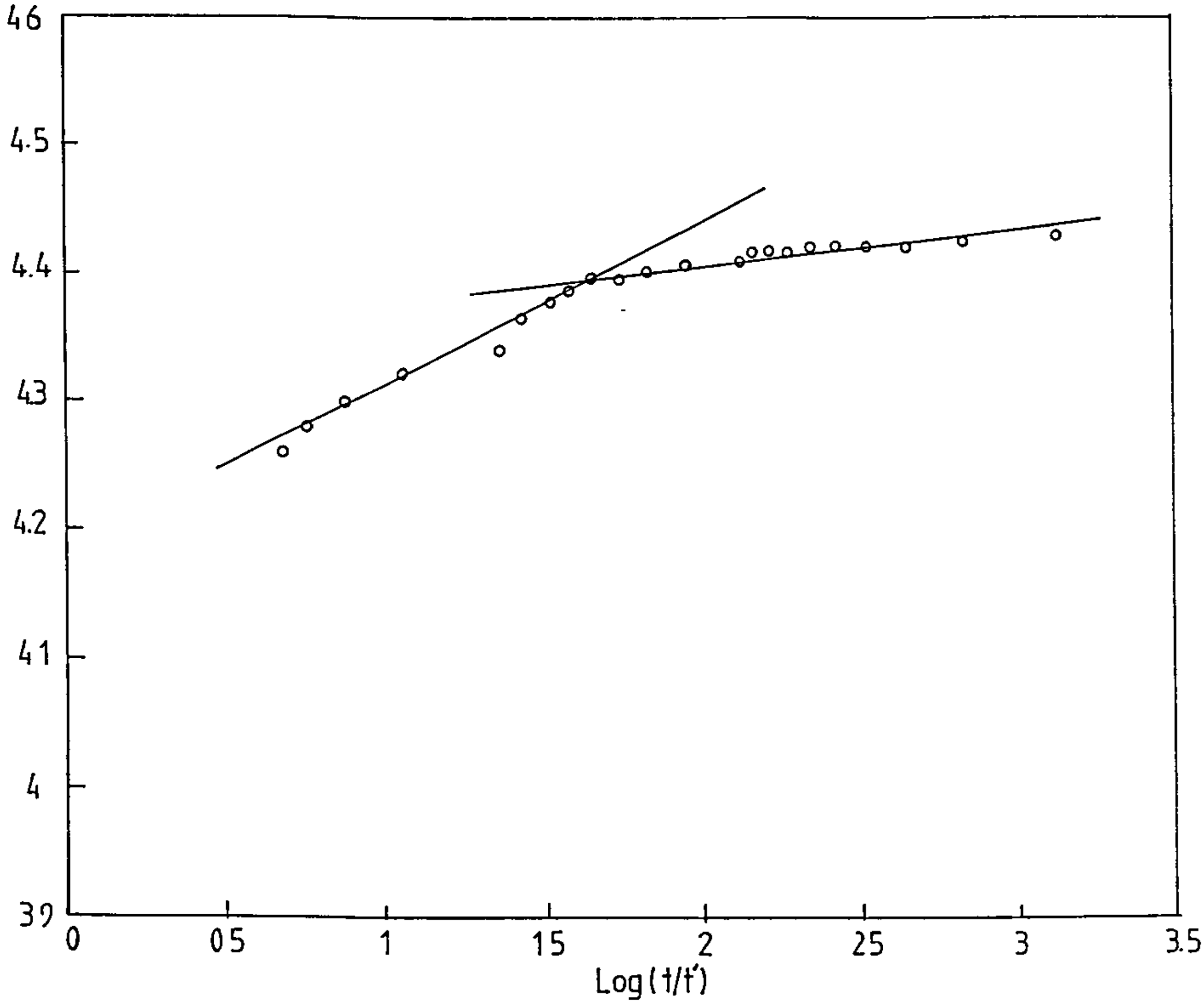
BH 23 (RECOVERY METHOD OF ANALYSIS)



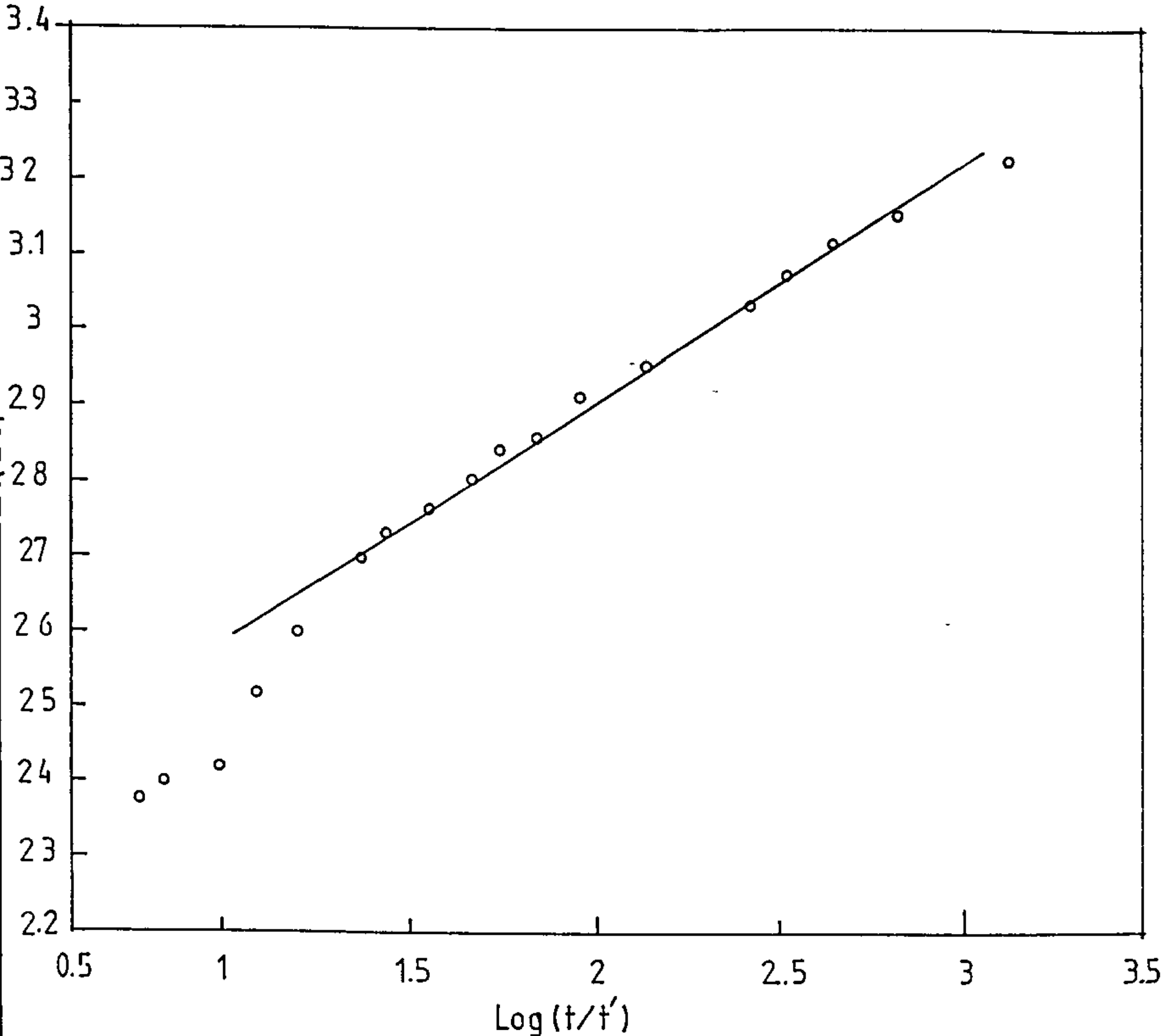
BH24 (RECOVERY METHOD OF ANALYSIS)



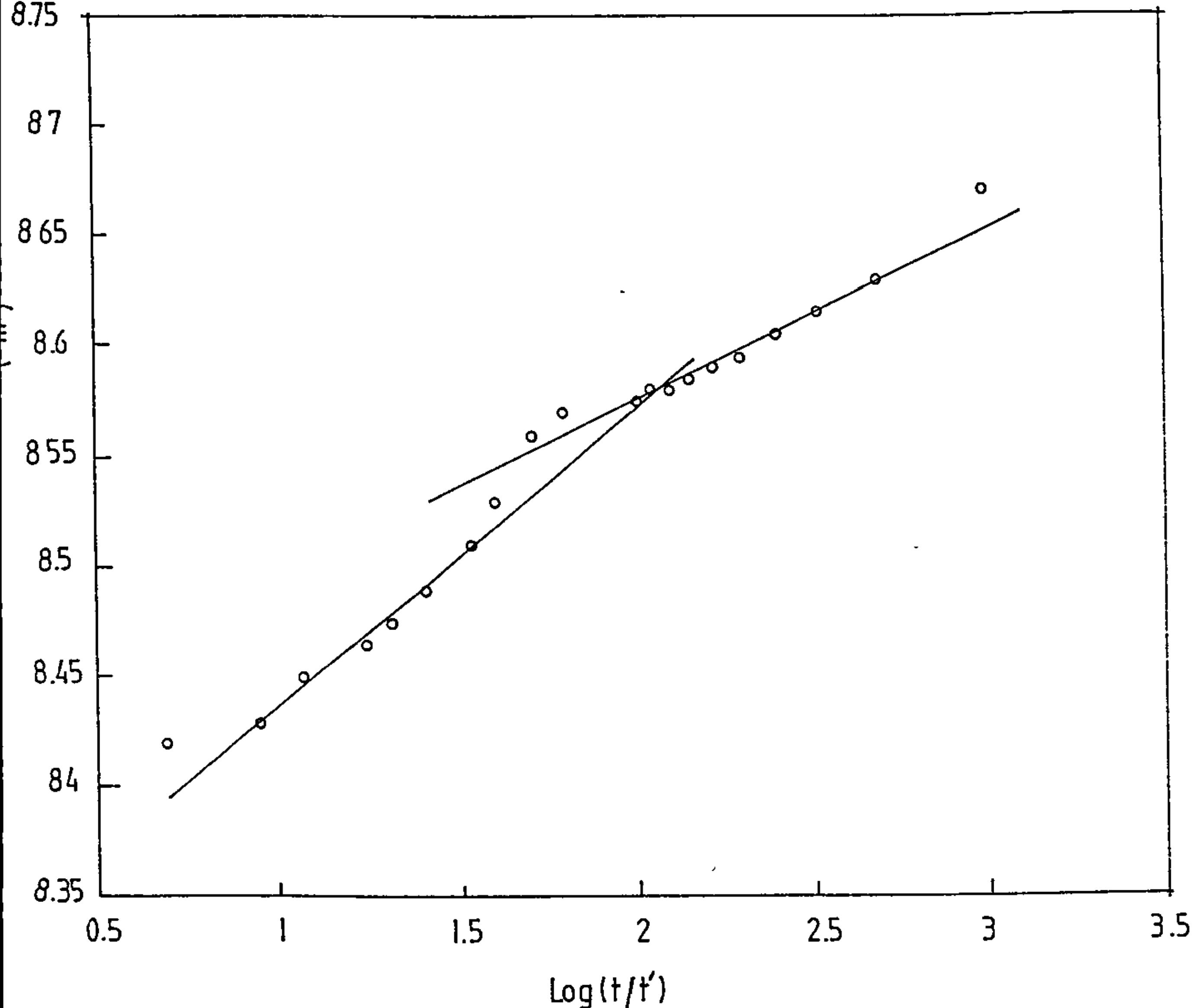
BH 5 (RECOVERY METHOD OF ANALYSIS)



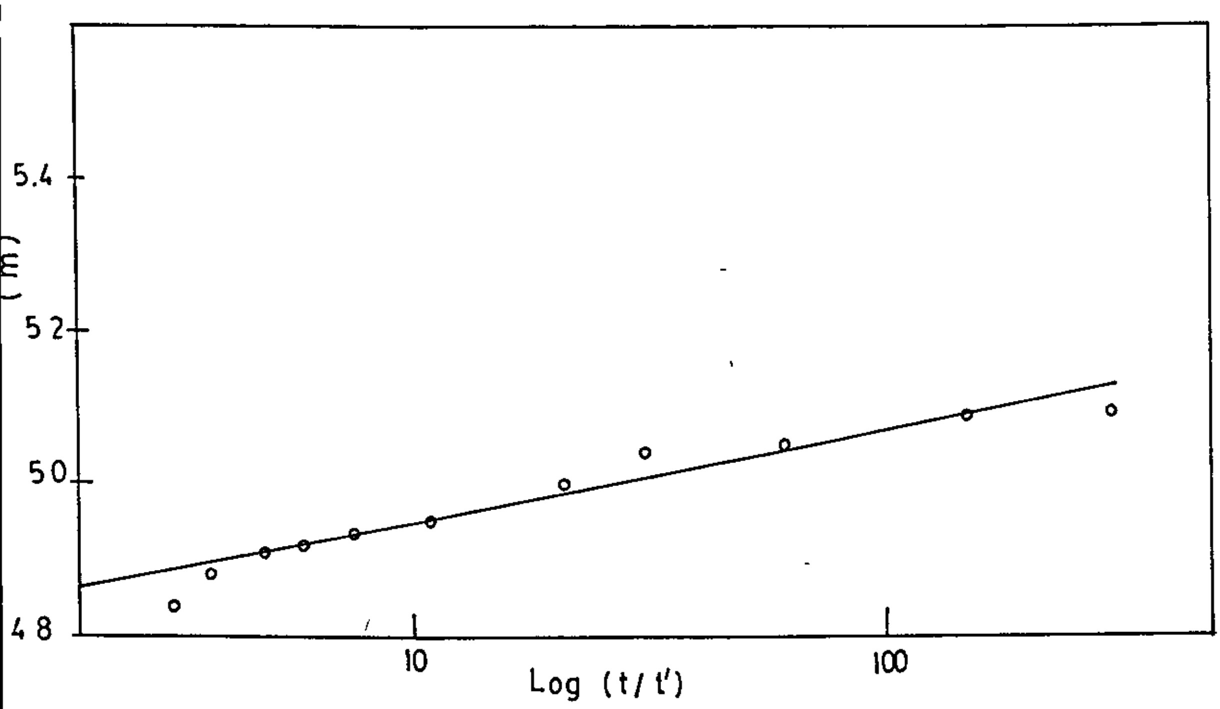
BH 7 (RECOVERY METHOD OF ANALYSIS)



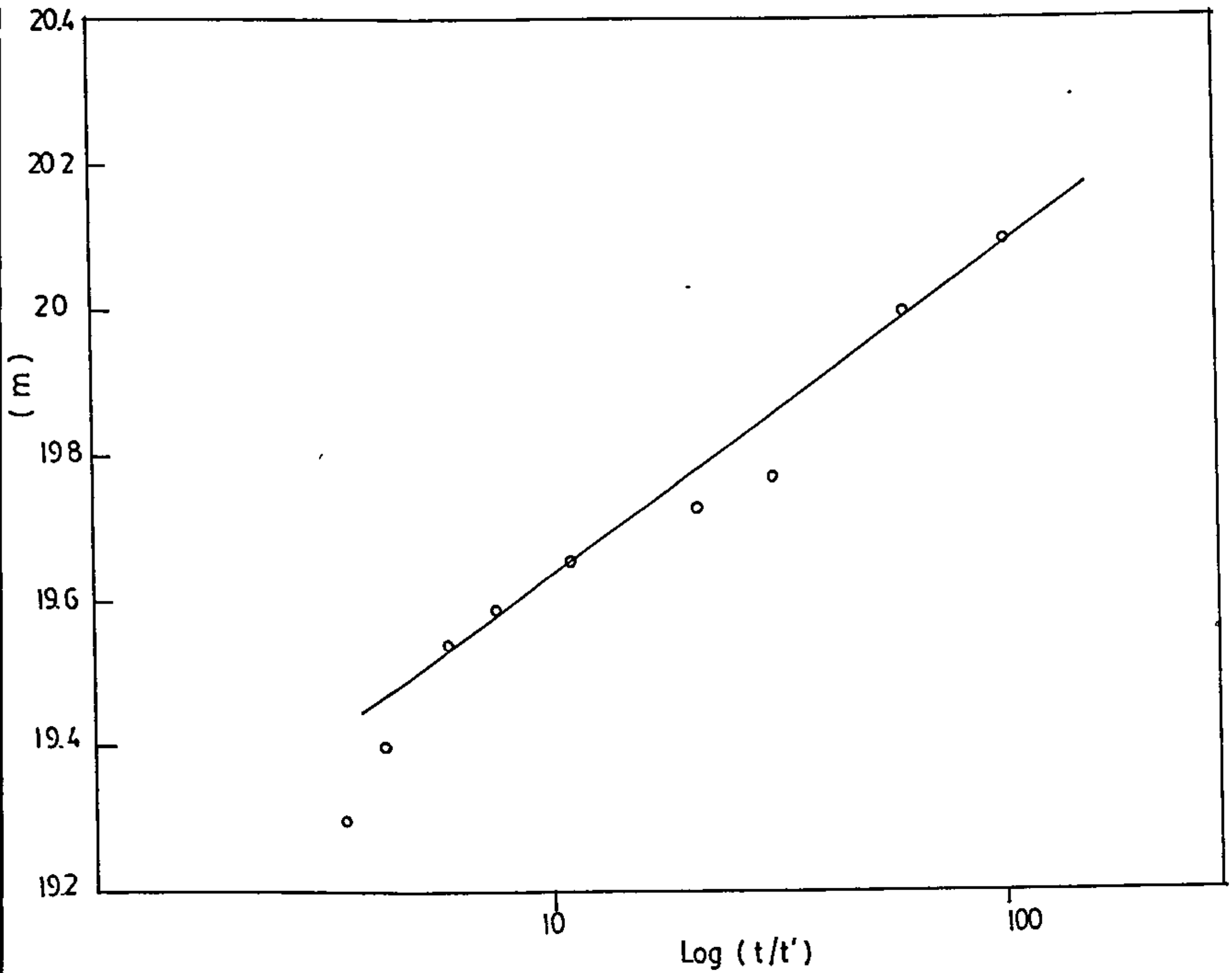
BH 14 (RECOVERY METHOD OF ANALYSIS)



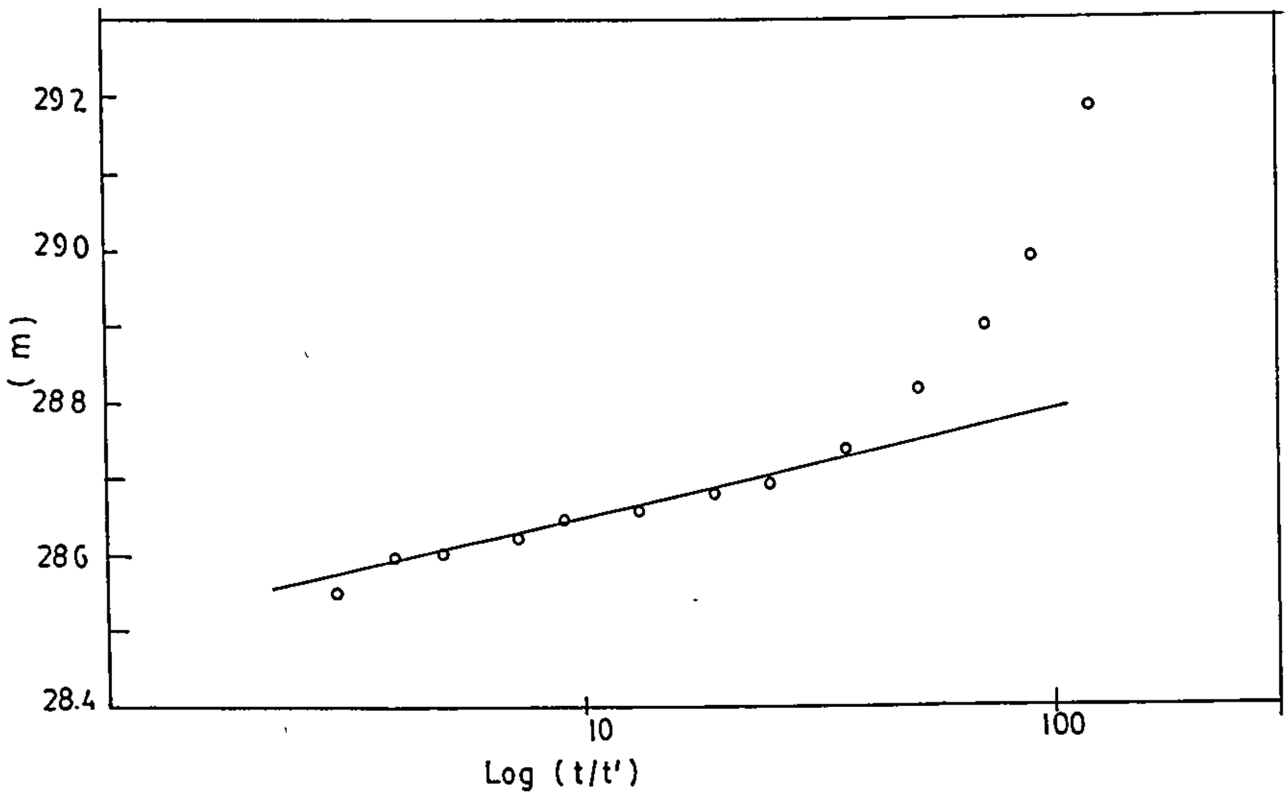
W. 108 (RECOVERY METHOD OF ANALYSIS)



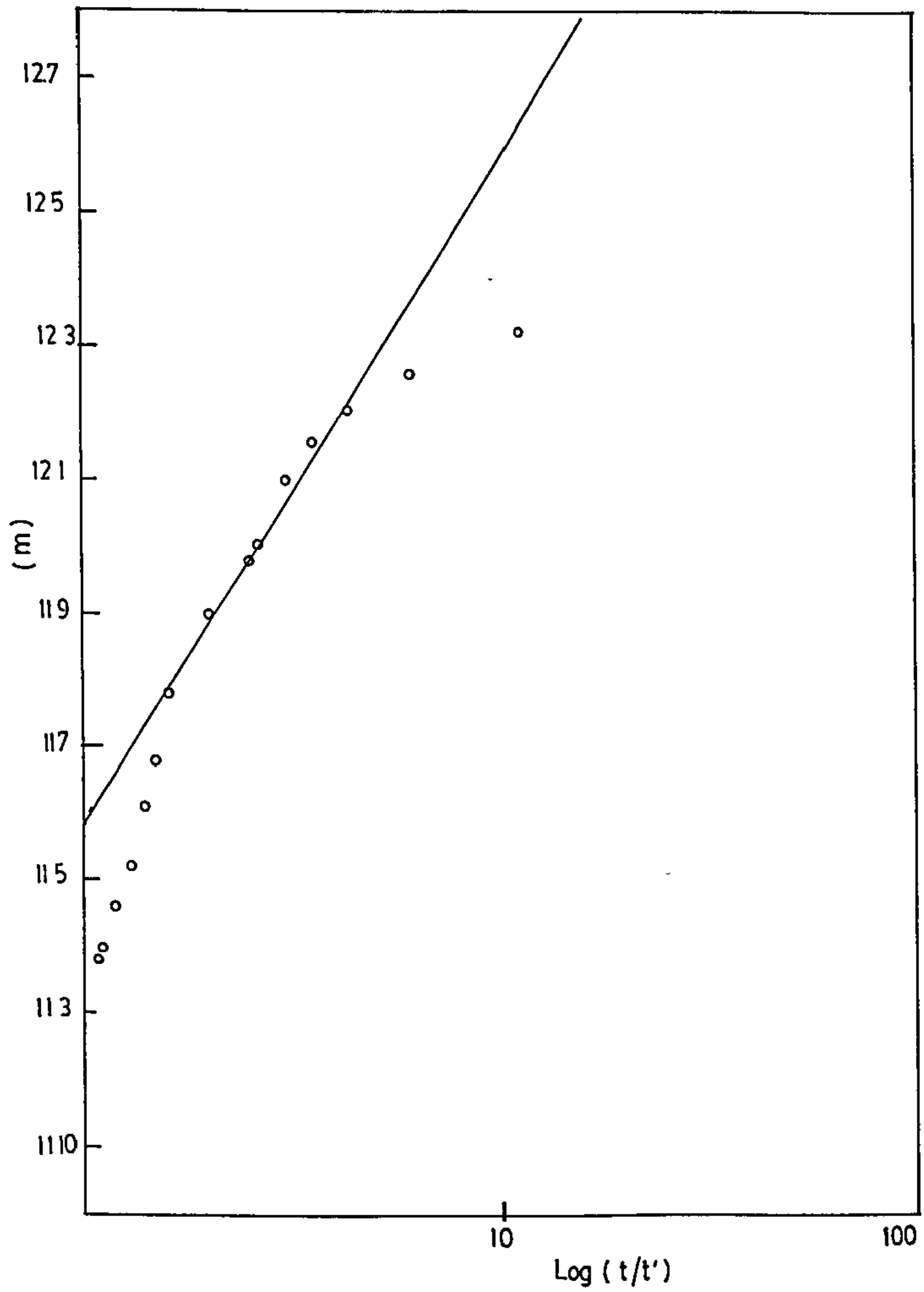
W. 140 (RECOVERY METHOD OF ANALYSIS)



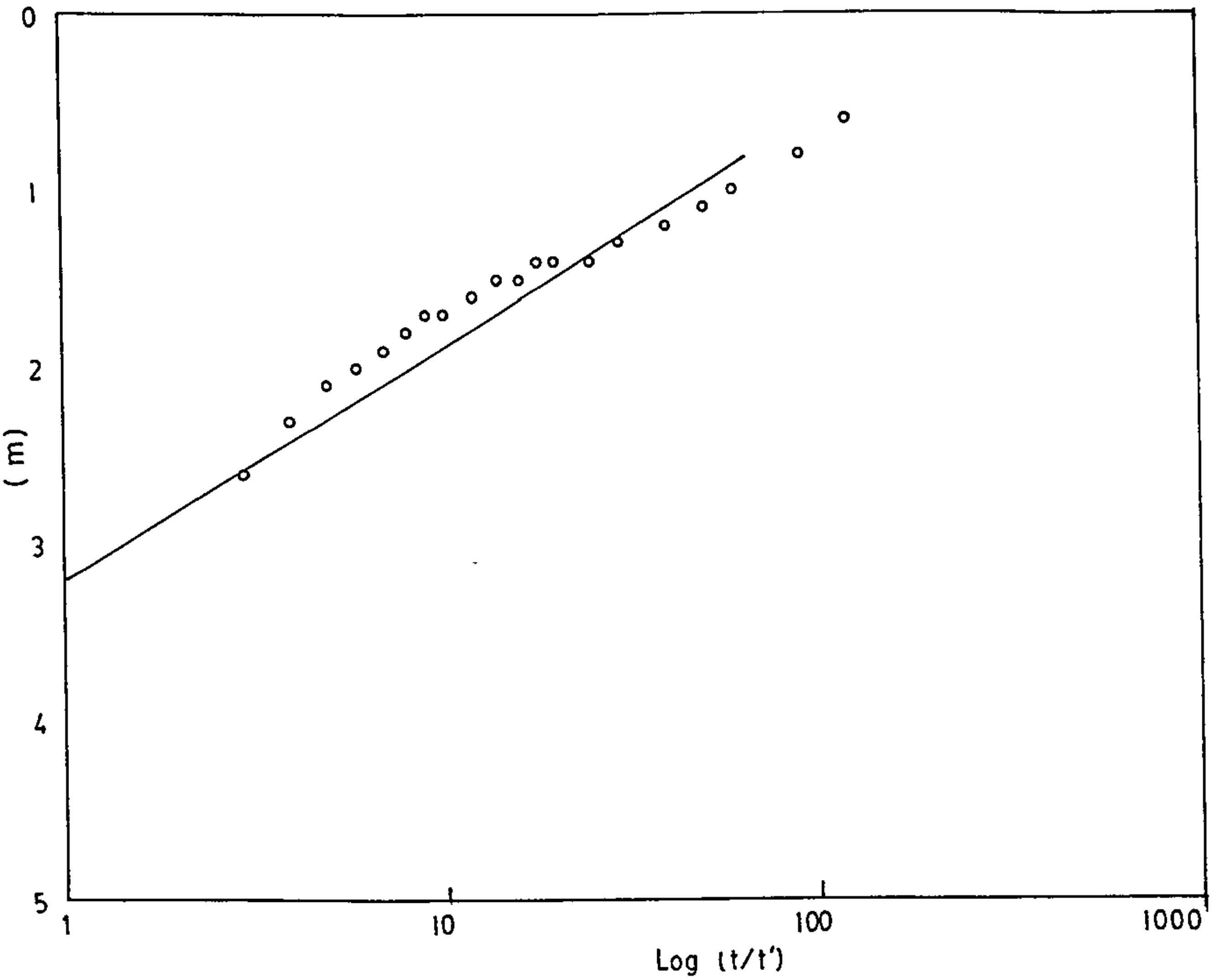
BH 233 (RECOVERY METHOD OF ANALYSIS)



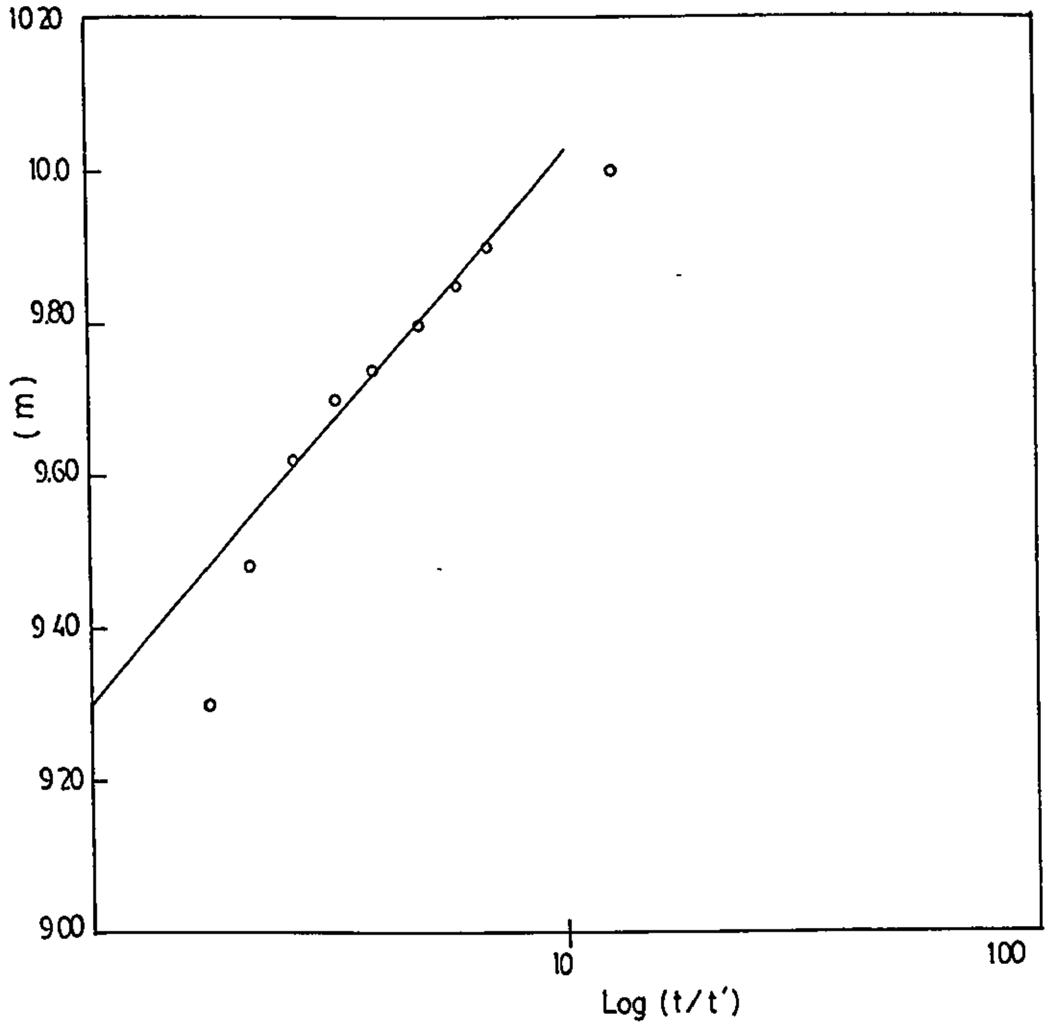
W. 2785 (RECOVERY METHOD OF ANALYSIS)



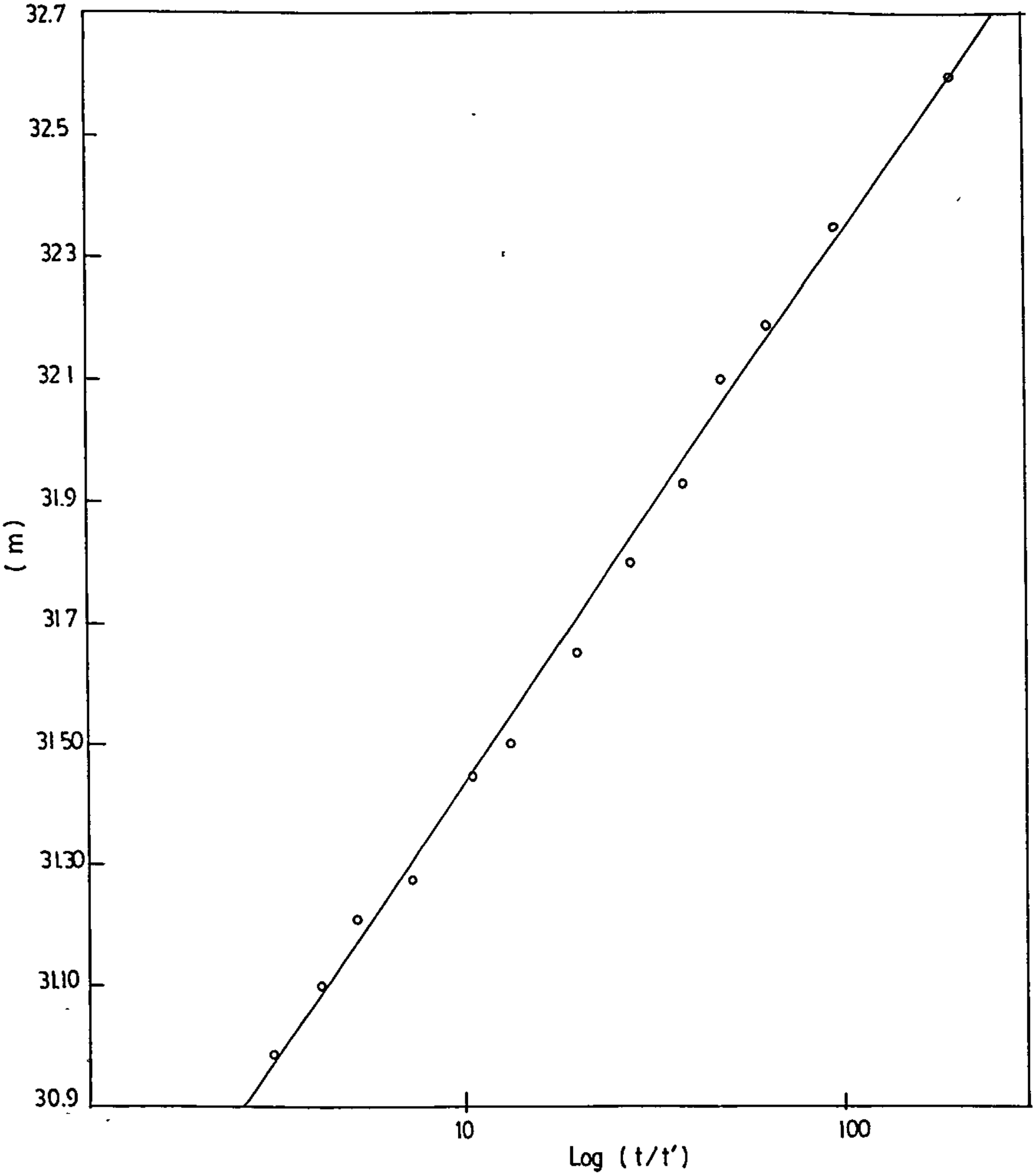
BH 151 (RECOVERY METHOD OF ANALYSIS)



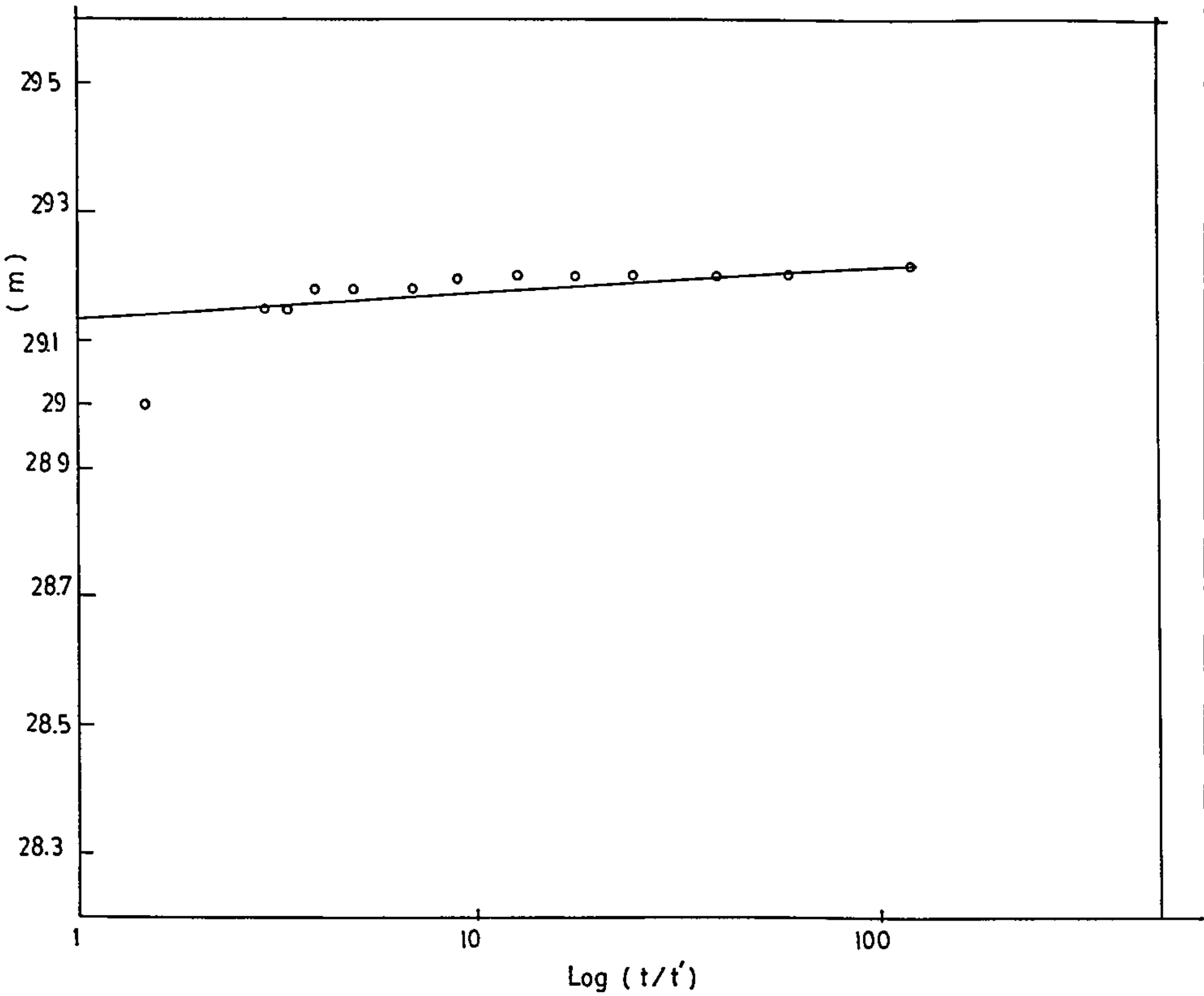
W 1171 (RECOVERY METHOD OF ANALYSIS)



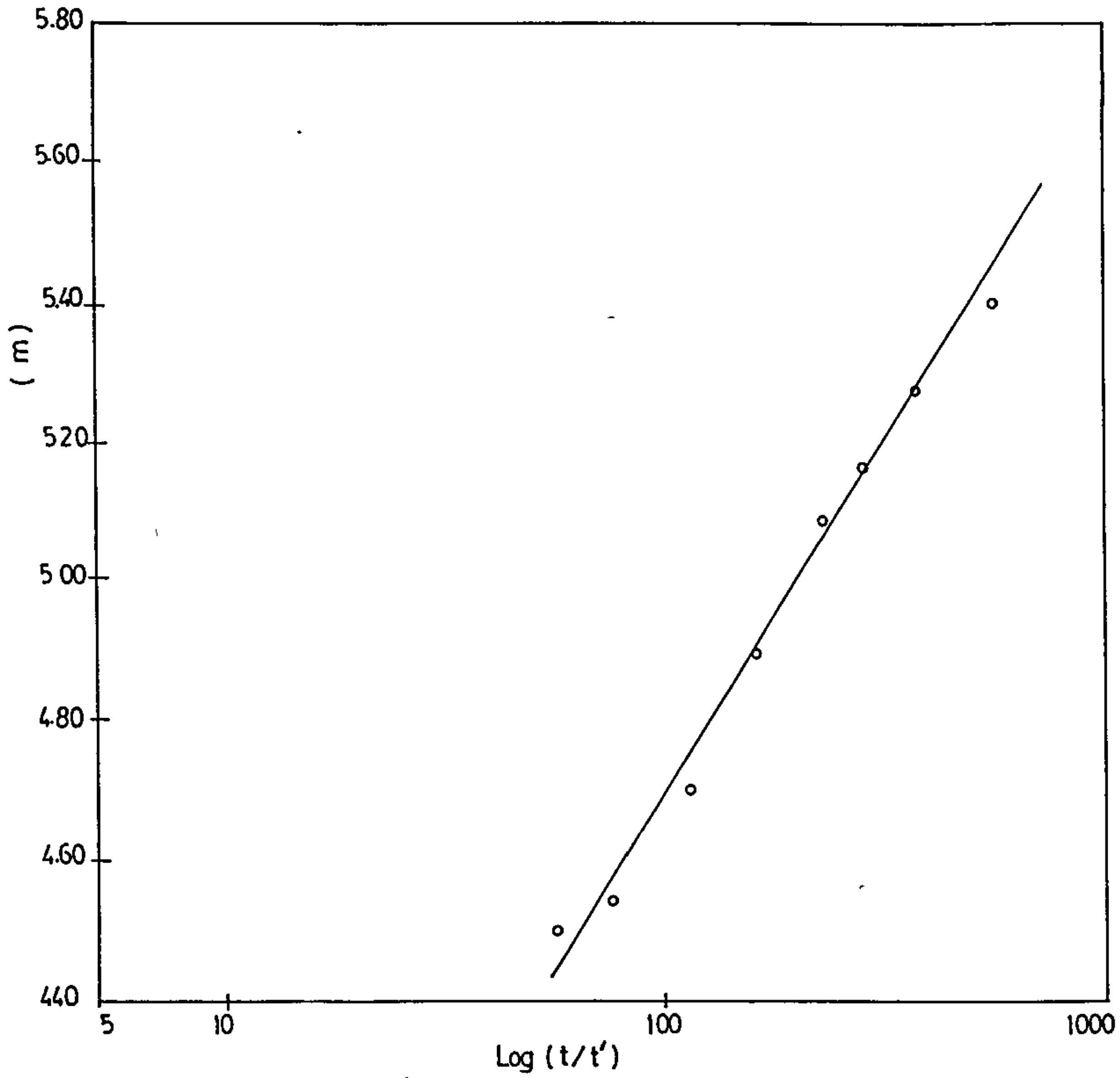
W. 1196 (RECOVERY METHOD OF ANALYSIS)



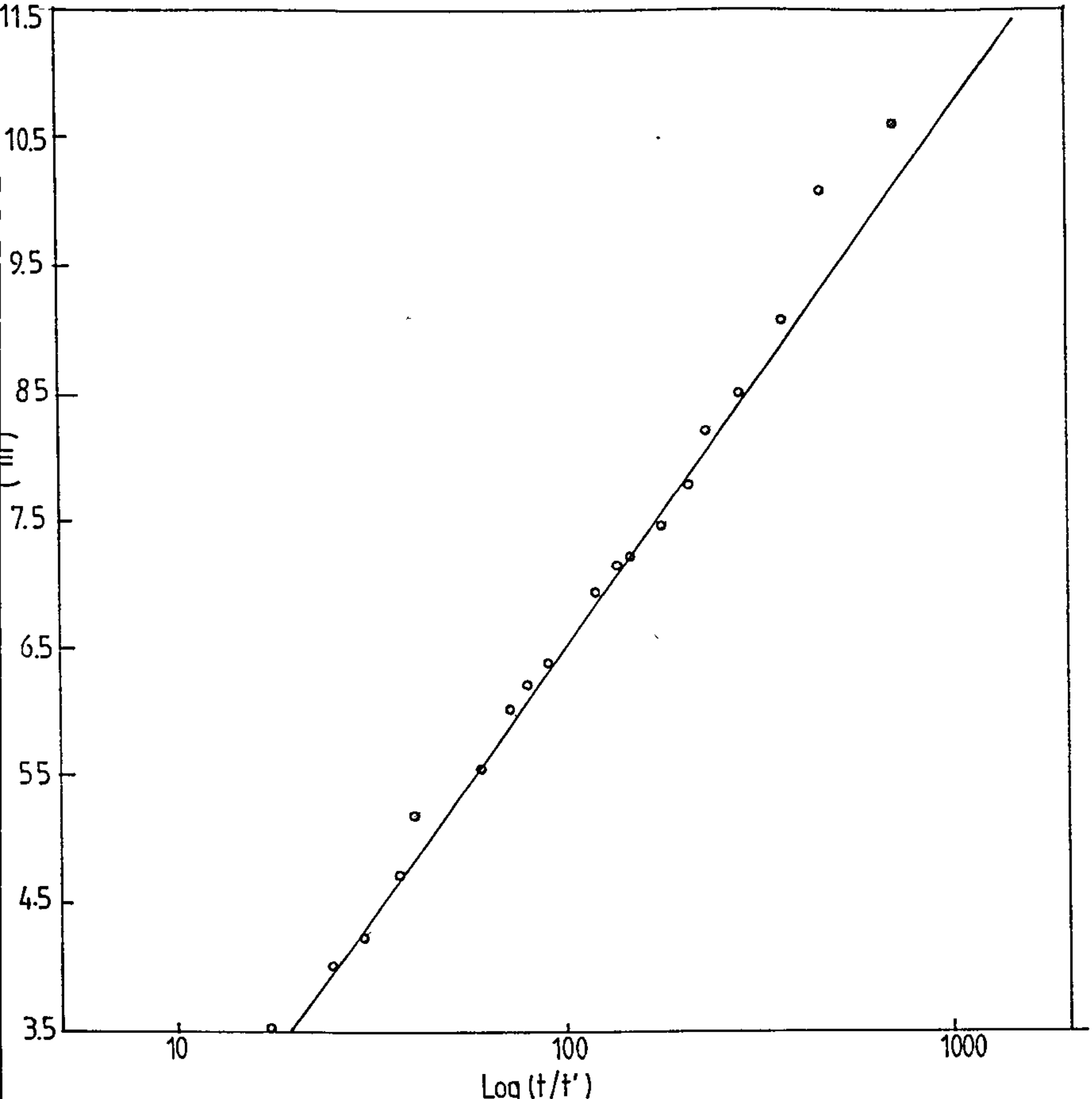
W.1662 (RECOVERY METHOD OF ANALYSIS)



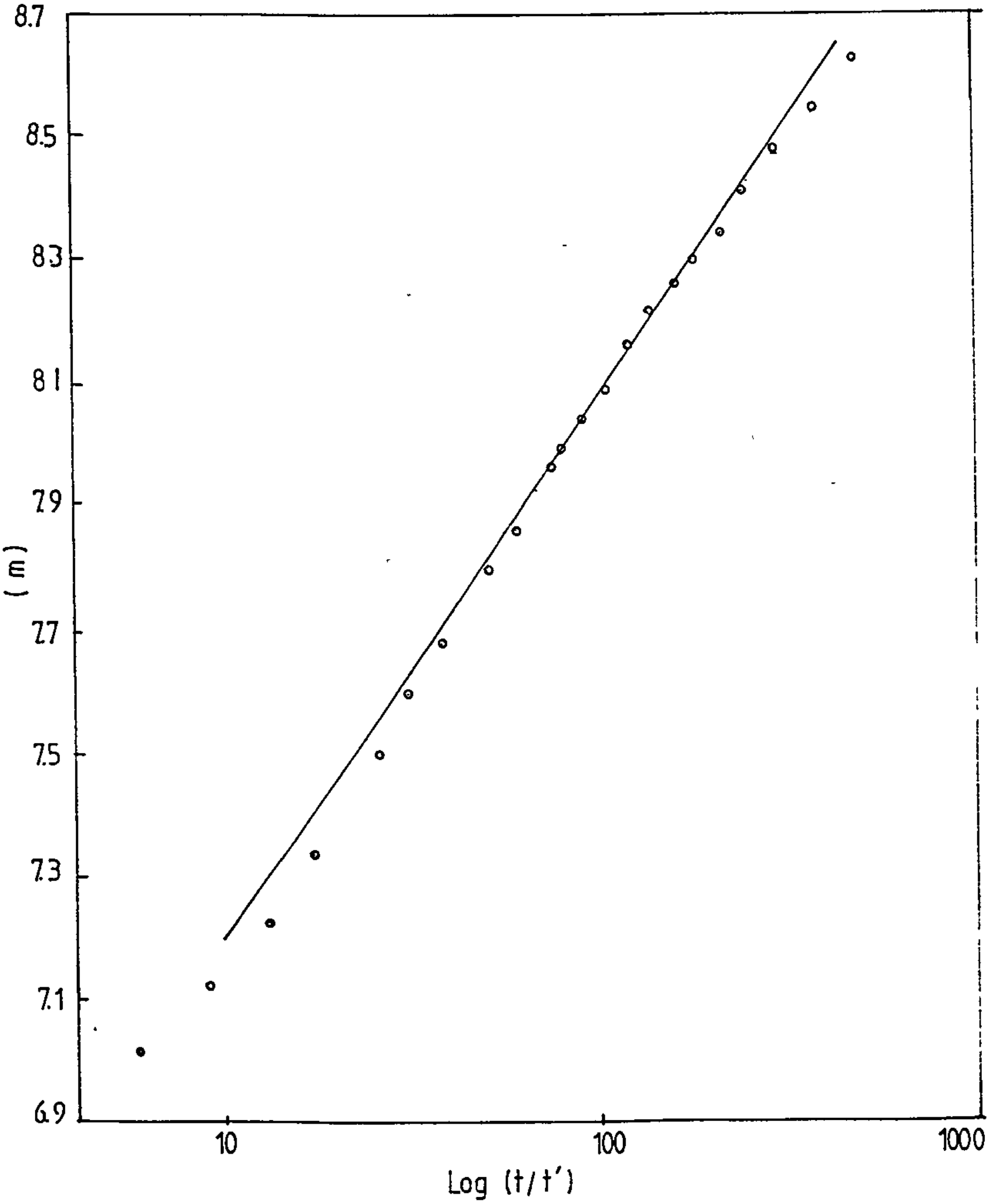
W. 3491 (RECOVERY METHOD OF ANALYSIS)



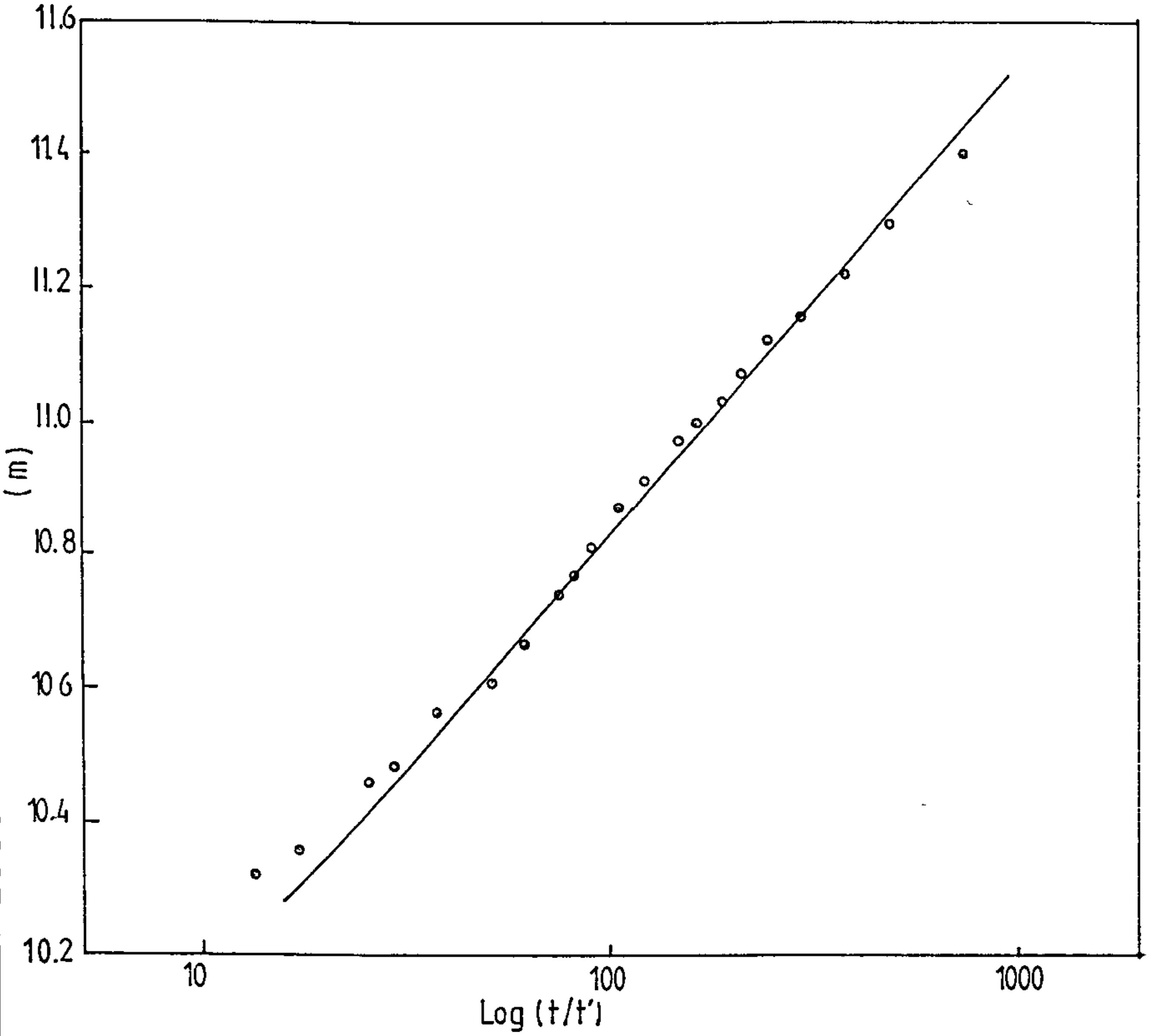
BH 57/74 (RECOVERY METHOD OF ANALYSIS)



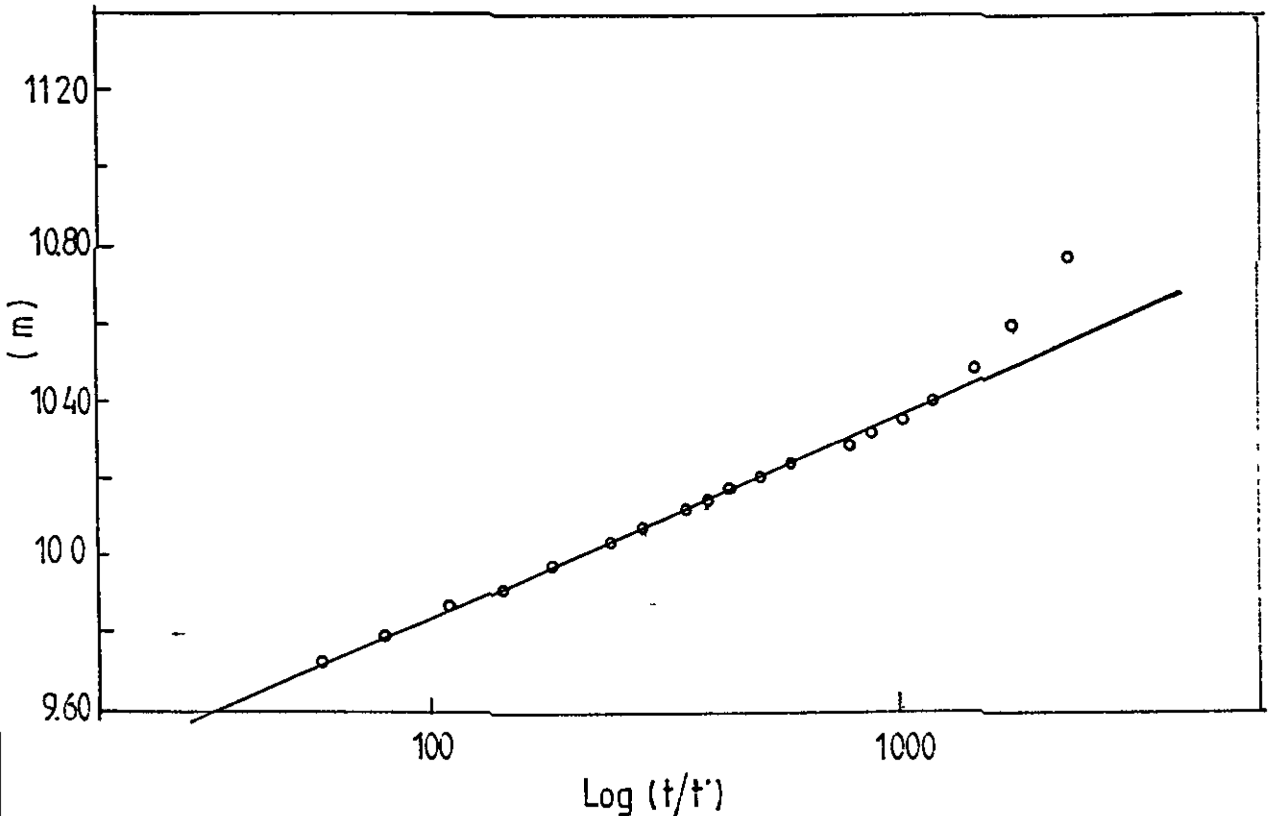
BH 56/74 (RECOVERY METHOD OF ANALYSIS)



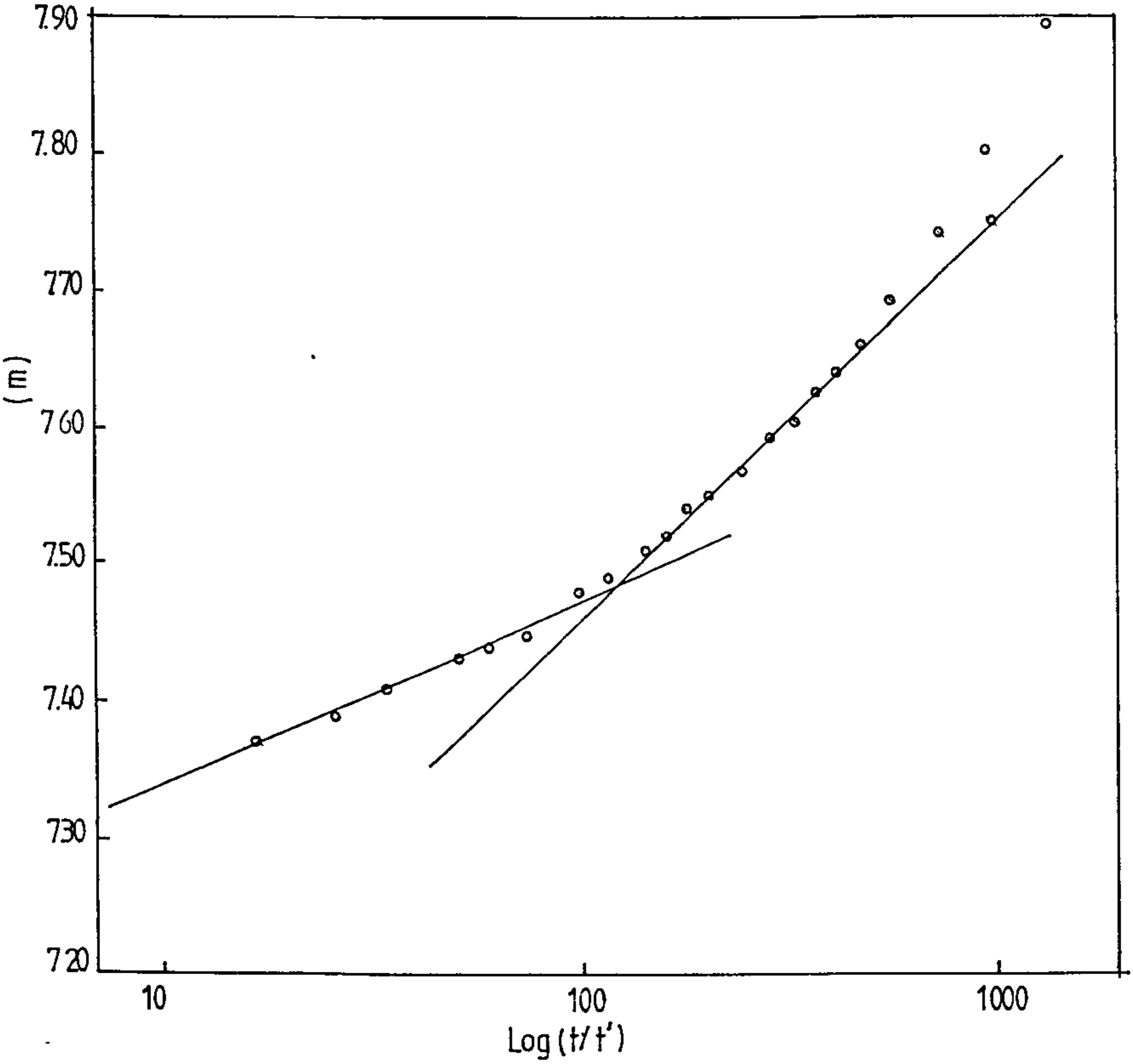
BH 51/74 (RECOVERY METHOD OF ANALYSIS)



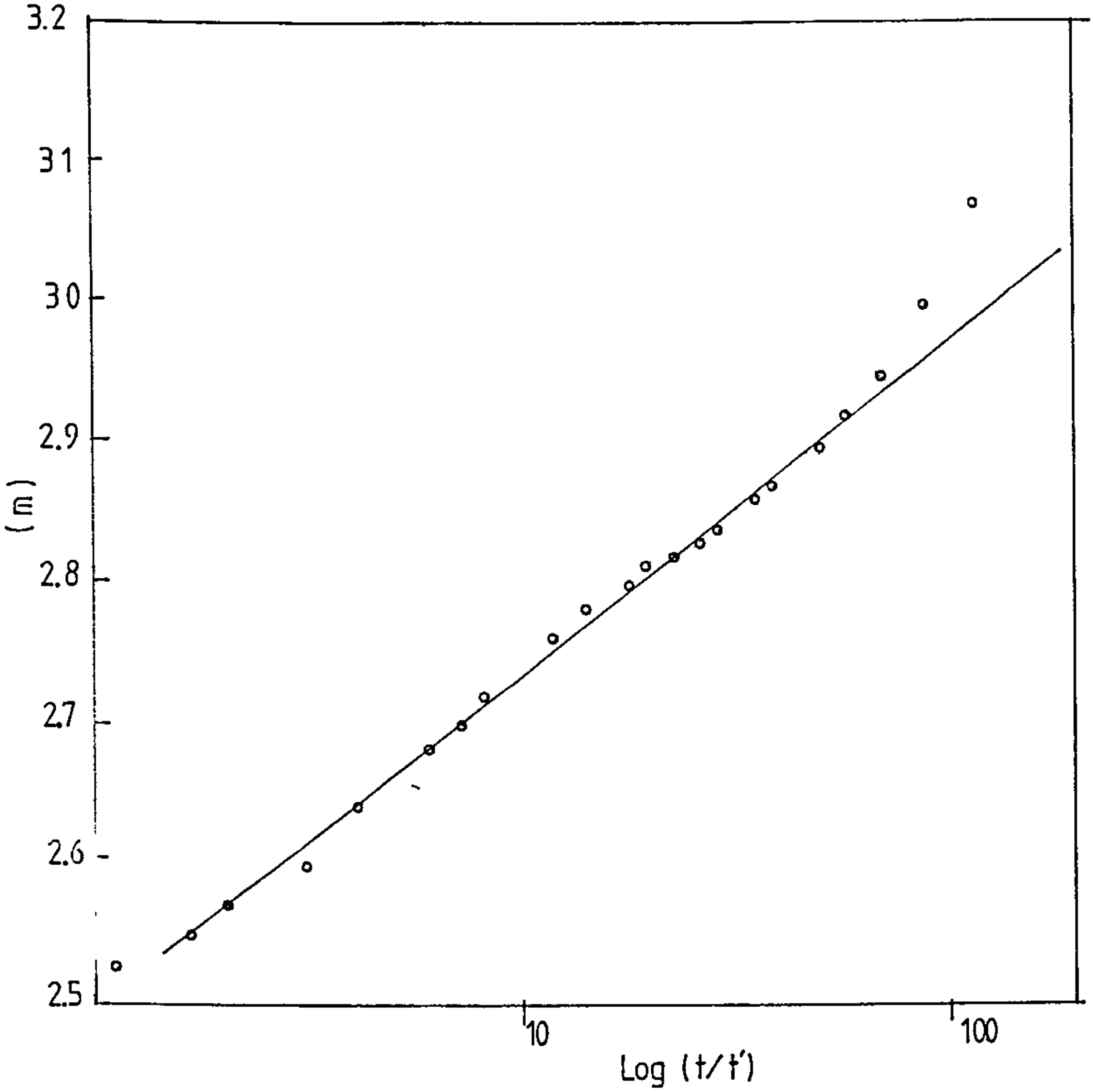
BH 10/73 (RECOVERY METHOD OF ANALYSIS)



BH 79/84 (RECOVERY METHOD OF ANALYSIS)



BH 51/75 (RECOVERY METHOD OF ANALYSIS)



BH 43/75 (RECOVERY METHOD OF ANALYSIS)