AN INVESTIGATION OF THE GROUNDWATER SEEPAGE AND IRRIGATION RETURN FLOW OF THE MIDDLETON AREA OF THE GREAT FISH RIVER

by

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CHAPTER 1

1. INTRODUCTION

This study is concerned with the factors responsible for mineralisation of water in the Great Fish River, in particular the irrigation return flow and groundwater seepage components. A small irrigated area in the lower Fish River Basin was chosen for a detailed study of irrigation water input, groundwater and seepage water fluctuations, and the affect of soils and rocks on river water mineralisation. The sections that follow provide a regional and physiographic background for the Middleton study area.

1.1 Irrigation in the Great Fish River Basin

The Great Fish River Basin, comprising 30 500 km^2, is situated in the Cape Province of the Republic of South Africa between latitudes 31^o to 33^{o}S and 25^o to 27^{o}E (Figure 1.1). With its source in the Nardousberg east of Graaff Reinet, the river flows 630km before entering the sea north-east of Port Alfred.

Irrigation in the valley began just after the turn of the century, when flood waters were diverted onto lands by means of small weirs along the river. The use of highly mineralised "fountain" or seepage water (le Roux, 1979) during periods of low flow resulted in the application of substantial volumes of soluble salts to the cultivated lands. The sporadic flow of the river necessitated the construction of large storage reservoirs, namely Grassridge Dam, Lake Arthur and Kommandodrift Dam. However, due to rapid sedimentation and a consequent loss in storage capacity of the reserivours, a voluntary delisting programme, where irrigable land was taken out of production, was implemented in 1961 (Hall, 1978). From 1961 to 1971, 5800 ha of land were delisted in the Fish River irrigation schemes (Tordiffe, 1978).

With the completion of the Oviston Tunnel in 1975, which linked

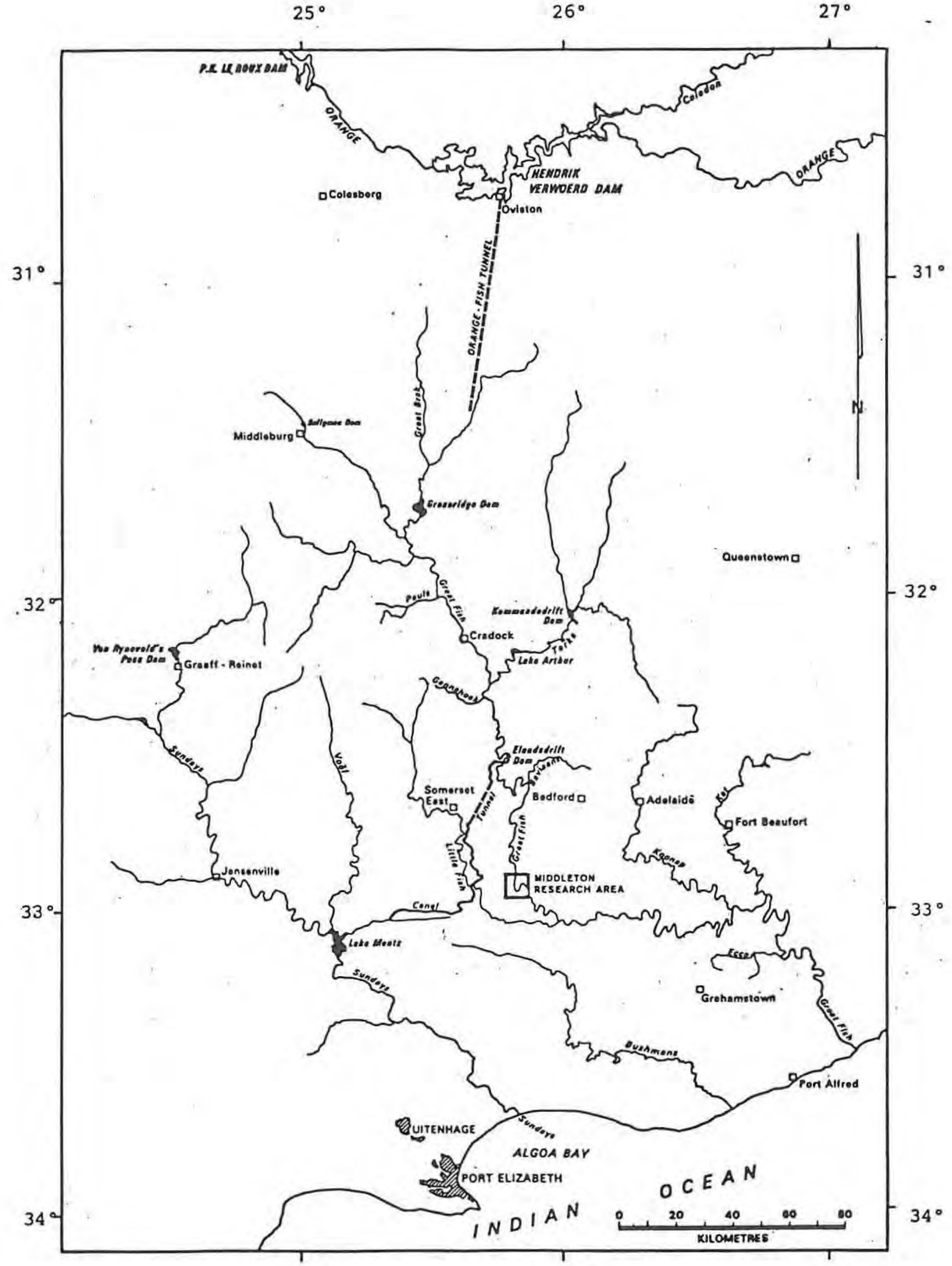


FIGURE 1.1 LOCATION MAP OF THE GREAT FISH RIVER BASIN

the Orange River with the Great Fish River Basin, a new assured supply of water became available for irrigation (Hall, 1978). This resulted in 3000 ha of land being rescheduled for irrigation in 1975, with a further 12000 ha being planned for the future. The emphasis has shifted from quantity to quality of irrigation water.

The irrigation area can be divided into two main zones :

1. The Grassridge Dam region which supplies the Great Brak and Great Fish River up to the Middleton irrigation area with water. This region can itself be divided into two areas, namely, the area upstream, and the area downstream, from Elandsdrift Barrage.

2. The Kommandodrift Dam/Lake Arthur region which supplies irrigation areas along the Tarka River with water (Hall, 1978).

The old system of water distribution has been retained in the valley with weirs diverting water into unlined irrigation canals. Small furrows, fitted with sluices, in turn lead water to private unlined storage ponds. Flood irrigation is the accepted system due to a number of factors :

(i) the high capital cost of overhead irrigation in relation to the crops that can be cultivated;

(ii) the existing distribution system of furrows which lends itself to flood irrigation;

(iii) the slow intake-rate and high salinity of the soils (van der Ryst, 1981).

Ground water, because of its high salt content and low yields, is unsuitable for irrigation purposes.

1.2 The Mineralisation Problem

Water applied to croplands is enriched in soluble salts by a number of processes. Firstly, high evapotranspiration rates concentrate salts already present in the irrigation water, as almost salt-free water is removed leaving behind a mineralised residue (Hem, 1959).

Evapotranspiration, as well as the initial salt content of the water passing into and through the root zone, exert a strong influence on soil water quality (Rhoades and Merrill, 1975). As the percolate passes through the soil it may mobilize soluble salts present in the soil as well as react chemically with adsorbed cations and anions present (Miller et al., 1981). Salts may also be precipitated from the soil water during these processes. The enriched leachate may then be discharged through either seepage from the soil or, if the leachate has percolated into the solid rock aquifers, by groundwater discharge to the river or drainage canal.

One of the major problems associated with irrigation farming worldwide is that the river serves both as the main conveyor of irrigation water as well as the drainage canal for seepage flow returning to the river. Rivers, such as the Syrdarya, Chirchik and Zeravshan in Central Asia (Stepanov and Chembarisov, 1978), the Price River in Utah (Ponce and Hawkins, 1978), the Rio Grande in southern Texas (Hipp, 1977), the Salt and Gila Rivers in Arizona (Hem, 1959) and the Great Fish, Sundays and Berg Rivers in South Africa show a progressive mineralisation downstream due to leaching of salts from irrigated land (Hall and Görgens, 1978). In the case of the Great Fish River, mineralised irrigation return flows of the upper schemes ~~is~~ are discharged into the river and again used lower down stream with the irrigation water. Coupled with "natural" groundwater seepage, the result is a progressive mineralisation of the Fish River water as it flows downstream (Tordiffe, 1978).

Detailed hydrochemical surveys of the Fish River during October 1982 and April 1983 (Lindley, 1983) were conducted in an attempt to place the high degree of mineralisation at Middleton (Table 1.1.) in the broader context of mineralisation in the Fish River System. These surveys confirmed the trend of progressive mineralisation downstream (Figure 1.2).

TABLE 1.1 Salinity Values of Fish River Water showing progressive mineralisation downstream

SAMPLED AT	RANGE mg/l	AVERAGE mg/l
Grassridge Dam	415 - 530	470
Katkop Weir	420 - 800	600
Elandsdrift Weir	830 - 1 130	980
Mortimer Weir	1 400 - 1 825	1 610
Inkeer	1 055 - 1 715	1 400
Middleton Weir	1 000 - 1 800	1 400

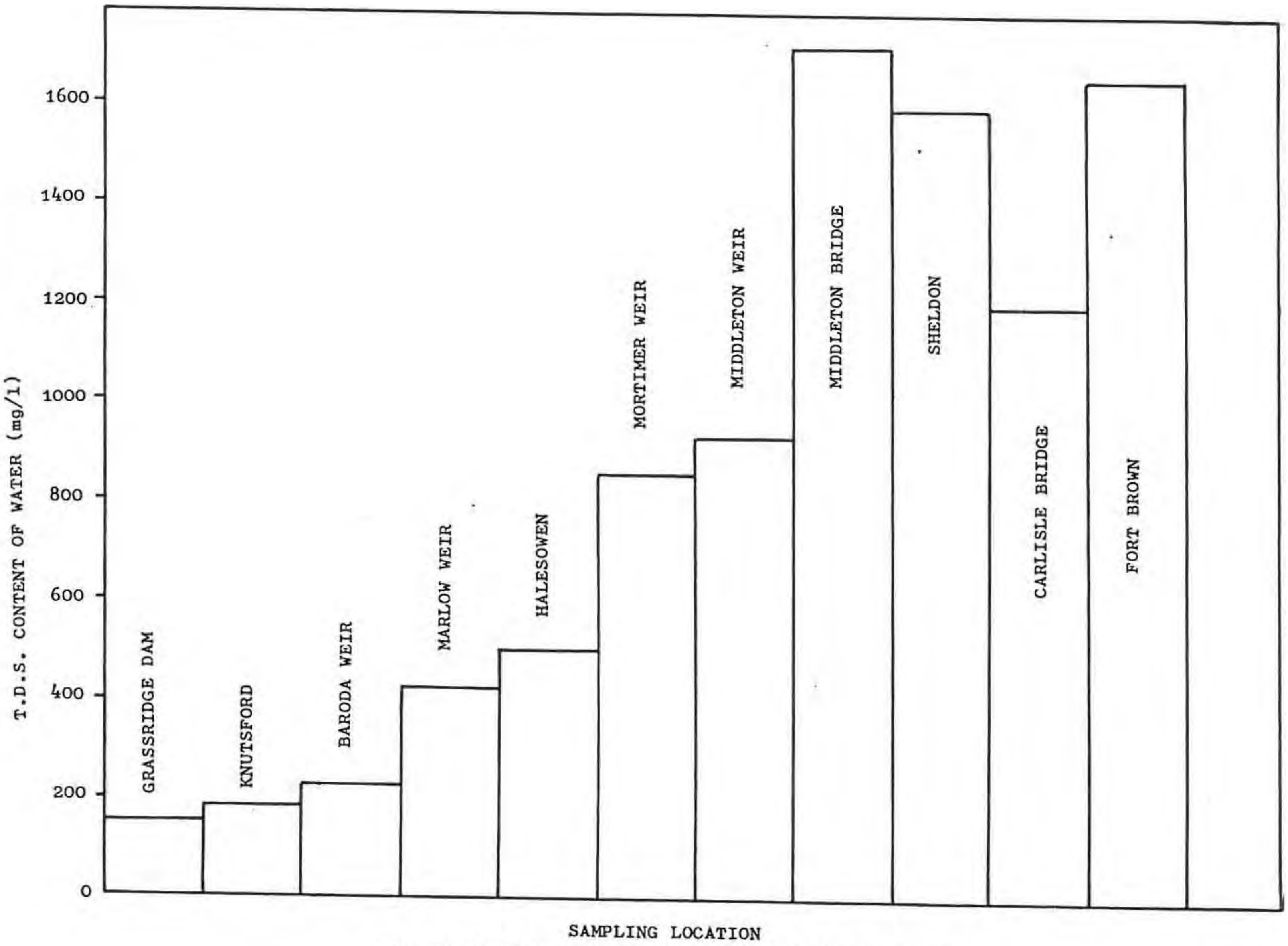
(van der Ryst, 1980)

Although serious mineralisation of soils and adjacent rivers may result during dryland farming (Miller et al., 1981; Hillman, 1981; Jenkin, 1981), the application of large volumes of irrigation water leads to an acceleration in the mineralisation of both surface and groundwater bodies and the annual loss of thousands of hectares of arable land (Hipp, 1977). However, poor quality irrigation water (in excess of 2000mg/l dissolved solids) is being used successfully in Texas (Hipp, 1977), Isreal, India and Algeria (Kovda et al., 1971) but under careful management and where the occurrence of well drained soils permit its use. Where soil drainage is limited, such as in the Great Fish River Basin, waterlogging and the build up of soluble salts in the soil profile is inevitable (le Roux, 1979).

The agricultural sector is currently the largest water consumer in South Africa and expectations are that this will remain the case for several decades to come. Legislation concerning the drainage of mineralised waters may be needed if the mineralisation problem is to be solved.

1.3 Mineralisation Research in the Great Fish River Basin

Many studies and research programmes have been conducted in an attempt to determine the nature, extent and origin of



SURVEY UNDERTAKEN OCTOBER, 1982 (LINDLEY, 1983)

FIGURE 1.2 Bargraph of TDS Content of Great Fish River water, showing progressive downstream mineralisation

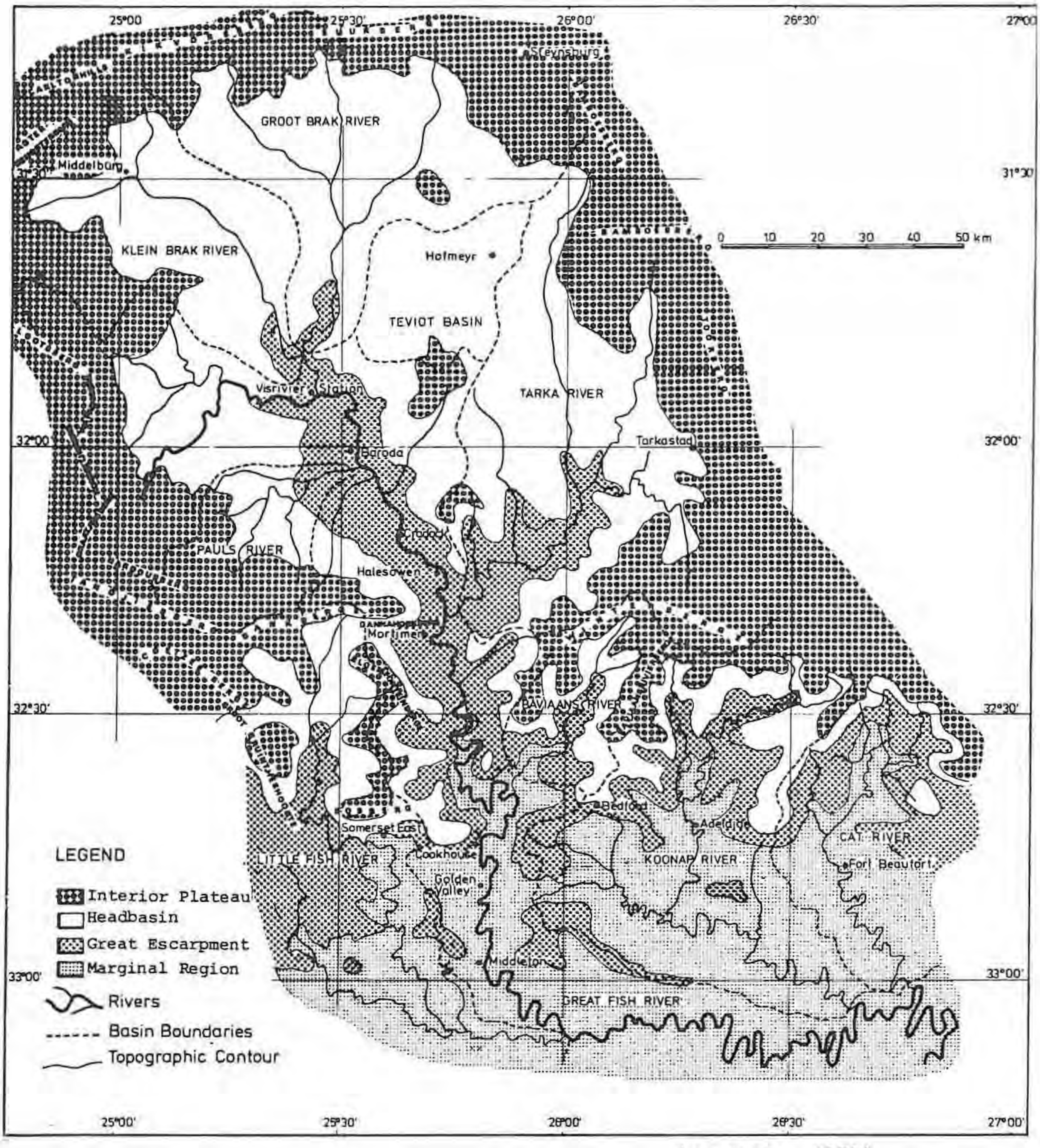
mineralisation in the Great Fish River Valley. A summary of the more salient research programmes is listed in Table 1.2. Most of the research has been co-ordinated by a standing Working Group for Mineralisation comprising representatives from government departments, research organizations and universities. Since 1974 these various efforts have been progressively reigned together to form an intergrated work programme with the primary objective being the development of a conceptual mathematical model of the whole system (Viljoen and Görgens, 1976; Van Rooyen, Hall and Görgens, 1977; Van Veelen et al., 1978; Viljoen and Hall, 1978; Hall and du Plessis, 1979; Görgens and Stone, 1981). Much of the research has been related to the spatial and temporal variations in river water quality, particularly during irrigation releases from the main storage reservoirs.

1.3.1 Hydrogeo-chemical Research

The relationship between groundwater chemistry, and geology and topography was studied by Tordiffe (1978) and Tordiffe and Botha (1981) respectively.

Tordiffe (1978) considers rock weathering and the adsorption and ion exchange during the interaction of surface and groundwater with the surrounding rocks to be the main geochemical factors responsible for changes in the chemical composition of groundwater. Mudstone, in particular, is able, upon weathering, to release substantial quantities of ions into solution. Groundwater in the Great Fish River Basin is restricted mainly to joints and fractures in the sedimentary rocks. Consequently, fracture zones, as well as the formation of groundwater compartments, resulting from the intrusion of dolerite dykes and sills, exert a strong influence on both the flow and quality of groundwater.

Macrotopography appears to exert a strong influence on groundwater chemistry (Tordiffe and Botha, 1981). High percentages of Ca^{++} and HCO_3^- are observed in the higher lying Interior Plateau (Figure 1.3), whilst high Na^+ and Cl^- percentages are encountered in the groundwater of the Headbasin and Marginal Region. These chemical compositions are



(Tordiffe, 1978)

FIGURE 1.3 Topography of the Great Fish River Basin.

characteristic of areas of recharge and discharge respectively. It is proposed that the higher lying areas, that is, those areas 1060m above mean sea level, are characterised by a dynamic groundwater system while the lower lying areas (760m a.m.s.l) are characterised by stagnant conditions. There is also a close correlation between groundwater chemistry and river water chemistry which, according to Tordiffe (1978), is conclusive proof of the influence of groundwater on the baseflow of the river.

Viljoen and Liebenberg (1974) conducted an intensive sampling programme at various weirs down the river in order to determine the change in chemical quality of the seepage water. They found a positive correlation between the amount of seepage at a weir and the size of the irrigated area within that particular reach of the river.

An environmental isotope survey was undertaken by Verhagen (1979) where it was found that extreme groundwater salinities are due to leaching of the soils on infiltration. Tritium measurements of saline seepages from the river bank suggest that they are associated with shallow cycling waters, and may be substantially separate from deeper groundwater movement.

1.3.2 Pedological Research

The National Institute for Water Research conducted a preliminary deep strata pedological survey in 1974 on irrigated lands along the Fish River. Thirty profile holes were drilled between Fish River Station in the north and Middleton in the south. The salt contents of the different strata in each profile were determined. The results (Viljoen, 1975) indicated such a large variation in soil chemical properties that it was decided that an intensive survey of the deep strata soils in a limited river reach would be necessary to understand their role in the mineralisation of the river reach (Hall and Görgens, 1978).

An intensive study of the deep soils was undertaken by le Roux (1979) between Katkop and Baroda Weirs. The most significant findings of Le Roux's survey are :

(i) there is great variation in soil texture with depth in alluvial soils resulting in complex movements and storages of water and salts;

(ii) the soil water is rich in sodium and chloride ions indicating stagnant flow conditions;

(iii) salt accumulation appears to be related to the presence of clay-rich layers;

(iv) deep soils from irrigated lands appear less saline than those from non-irrigated areas due to the leaching effect of irrigation water.

In order to obtain a greater understanding of the processes contributing to the geohydrological problem, study aims and objectives have been formulated (page 13).

TABLE 1.2 Research Undertaken in the Great Fish River Basin

YEAR	STUDY BY	NATURE OF INVESTIGATION
1915	du Toit	A study of the porosity of rocks in the Karoo System
1937	Frommurze	Investigation of the water-bearing properties of the major formations
1946	Bond	Geochemical survey of the groundwater supplies
1949	Kent	A study of the thermal waters, particularly the "sulphuretted spring" north of Cradock
1966 and 1976	Johnson	Investigation of the stratigraphy and sedimentology of the Cape and Karoo Systems in the Eastern Cape Province
1971	Hydrochemical Working Group for the Orange River Project	Assessment of the extent of mineralisation in the Fish and Sundays Rivers. Recommends the canalization of irrigation water from the H F Verwoerd Dam
1972	Scott, Allanson and Chutter	Investigation of the possible effects of the implementation of the Orange River Project on the hydrobiology of the Fish River and Sundays River
1974	Viljoen and Liebernberg	Qualitative and quantitative investigation of seepage water from Grassridge Dam to Sheldon
1975	Viljoen	A study of the salt content and distribution in alluvial soils along the Fish River
1976	Viljoen and Görgens	Correlation studies of the hydrochemistry of groundwaters in irrigated and non-irrigated areas in the upper Fish River catchment
1977	Kingsley	A study of the stratigraphy and sedimentology of the Ecca Group in the Eastern Cape Province
1978	Viljoen and Hall	Hydrochemical investigation of the Fish and Sundays Rivers

TABLE 1.2 (continued)

1978	Van Veelen, Triebel, Bang and van Robbroeck	Study of mineralisation in the Fish River by making use of the results of a test release from Grassridge Dam. Confirmed the influence of groundwater seepage on river mineralisation
1978	Tordiffe	Qualitative assessment of the major aspects responsible for the chemical quality of the groundwater in the Fish River Basin, and its effect on irrigation water quality
1979	Hall and du Plessis	Simulation of flows and salinity in the upper catchment of the Fish River using daily flow data and total dissolved solids levels for the period 1-5-77 to 30-4-79
1979	le Roux	Investigation of salt accumulation and distribution in deep alluvial soils in the upper catchment of the Fish River
1979	Verhagen	Environmental isotope and chemical study of groundwater and river water in the Great Fish River Basin
1980	Hall, du Plessis and Hudson	Modelling river flow salinity. It was concluded that chloride concentrations are associated with surface or near surface mineralisation processes
1980	van Robbroeck, Triebel, Schultz and van Veelen	Feasibility study of a water supply scheme in the Committeesdrift area of the lower Fish River
1981	Tordiffe and Botha	As investigation was conducted to determine the relationship between macrotopography and the groundwater quality in the Fish River Valley
1982	du Plessis, Hahne, Hayman, Hall and Viljoen	Description of data used in the development of the systems model, FLOSAL, which was developed for use in simulation of the natural hydrological and mineralisation processes in a river system with particular reference to the Fish and Sundays River catchments.
1983	Lindley	An investigation of factors influencing mineralisation in the Great Fish River with particular reference to water quality surveys conducted in October 1982 and April 1983.

1.4 Study Objectives

The main objective of the study is to obtain detailed and accurate data on, as well as determine the major factors contributing to, the water quality of base flow, in the form of groundwater seepage and irrigation return flows, entering the Fish River.

The specific aims are as follows :

(i) to obtain data on the thickness and extent of the saturated lithologies, both consolidated and unconsolidated;

(ii) to define and identify the major aquifers and investigate the relationship between lithology and geochemistry in both irrigated and non-irrigated areas;

(iii) to identify the locations and directions of flow for groundwater and irrigation seepage contributions to streamflow;

(iv) to identify recharge areas and mechanisms of groundwater flow;

(v) to determine the effect of soils on the hydrochemistry of groundwater and return flows;

(vi) to investigate the relationship between irrigation and increased mineralisation.

CHAPTER 2

THE STUDY AREA

2.1 Location

Based on the research aims, it was necessary to select a study area in the Fish River Valley, representative of the Valley as a whole, where detailed research could be undertaken.

An area of approximately 25 km^2 just south of Middleton (latitude 25^0 49'15"; longitude 32^0 57'10") (Figure 2.1) was chosen on the basis of map, aerial photography, and field visit data as it fulfilled a number of important requirements:

(i) Substantial area of gently sloping irrigated lands of both colluvial and alluvial origin (Plate 1);

(ii) Irrigation by a single source, Middleton Canal (Plate 2), which terminates within the study area;

(iii) Presence of non-irrigated 'control' area on the adjacent right bank of the Fish River;

(iv) The presence of water courses likely to carry water at times of heavy or prolonged rain (Plate 3);

(v) The irrigated lands are under the control of one irrigation board;

(vi) The general accessibility of the area by vehicle to nearly all places where drilling and other equipment may be required.

(vii) Situated some five kilometres south of the southern limit of the Karoo dolerites, the effect of dolerite intrusion on the occurrence and flow of groundwater in the

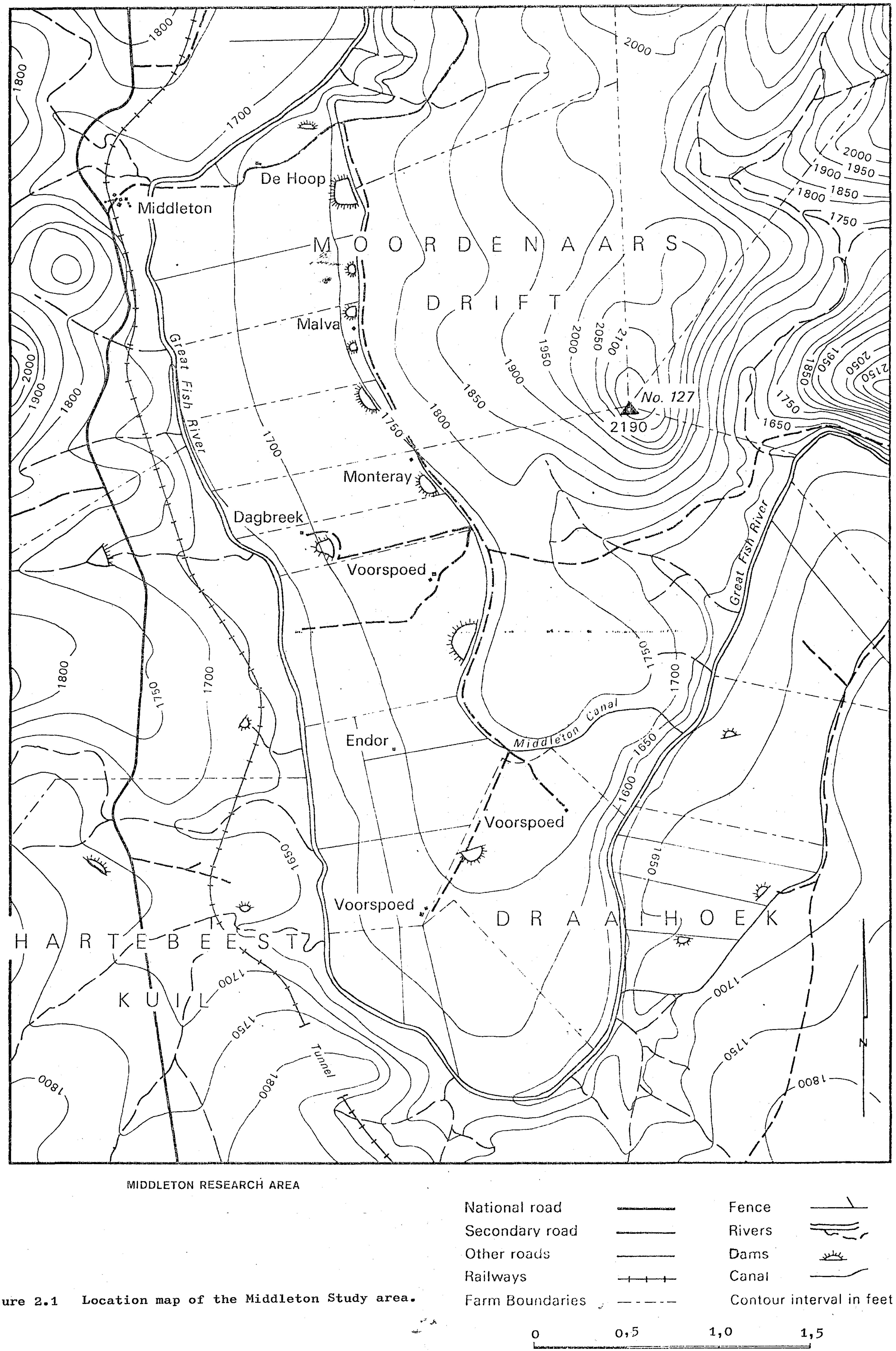


Figure 2.1 Location map of the Middleton Study area.

PLATE 1. Gently sloping irrigation lands in the study area. (a) canal (b) river

PLATE 2. The Middleton Canal - An example of an unlined earth canal.

PLATE 3. Ephemeral tributary of Great Fish River. Jointed bedrock exposed in the stream bed (a)

Middleton area is considered insignificant.

The study area can be divided into three main zones (Figure 2.2) namely :

1. The gently sloping irrigated lands adjacent to the river;
2. The non-irrigated veld north-east of the Middleton canal;
3. The non-irrigated "control area" on the right hand bank of the river.

2.2 Physiography

2.2.1 Relief

To place the study area into the broader context of the Great Fish River Basin, there follows a brief description of the topography of the Basin.

Tordiffe (1978) describes the topography of the Great Fish River Basin in terms of four provinces, namely, the Marginal Region, the Great Escarpment, the Headbasin, and the Interior Plateau (Figure 1.3).

The Marginal Region:

Below the Great Escarpment (760 metres a.m.s.l.) lies the rather undulating landscape of medium to low relief termed the Marginal Region (of which the study area forms part).

The Great Escarpment:

This forms the area of high relief lying between the 760m and 1370m topographic contours. Parts of the province, which have only a sparse vegetation cover, are easily eroded, the result being the development of colluvial pediments at the base (Tordiffe, 1978).

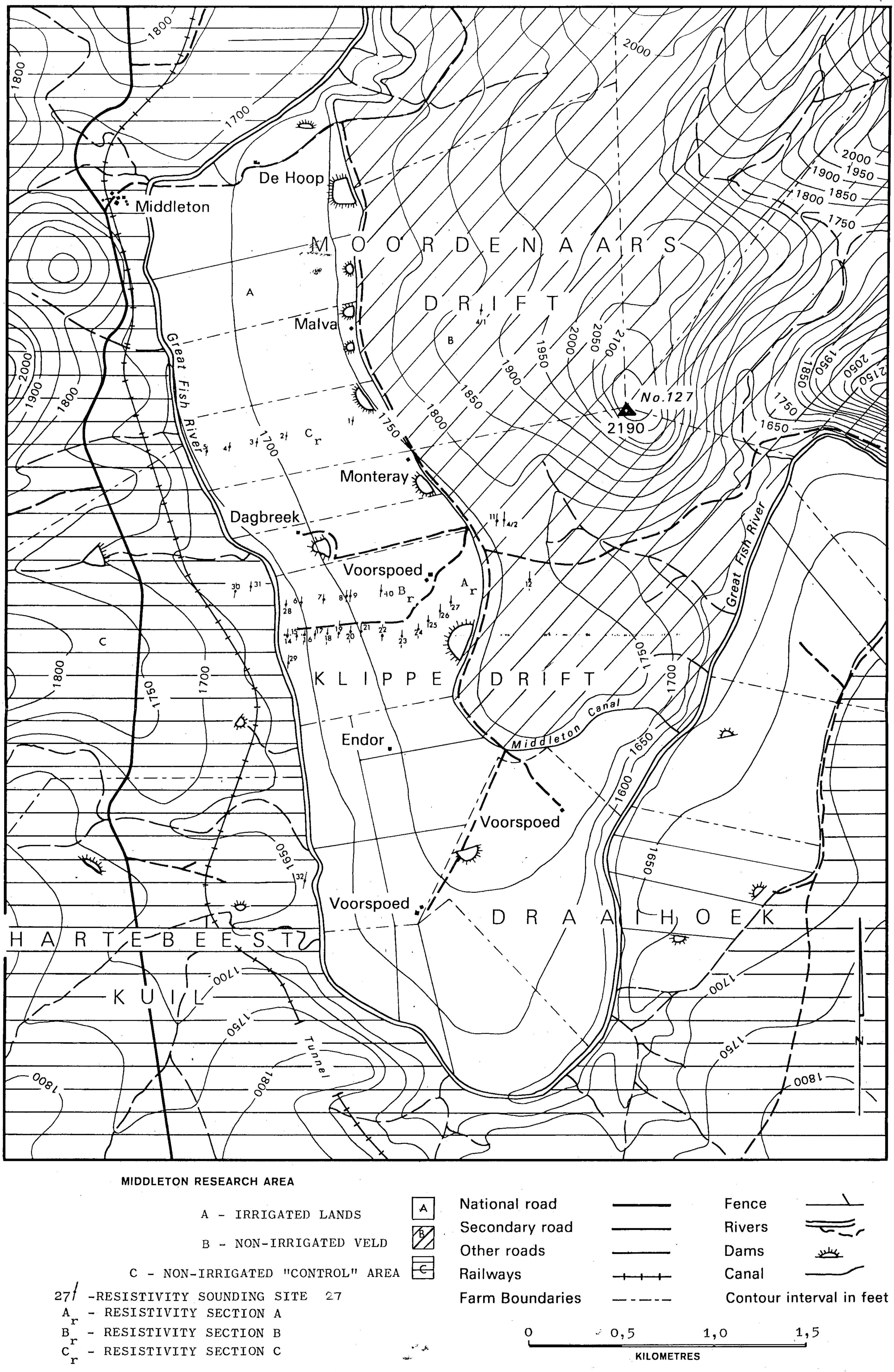


Figure 2.2 The three main zones of the study area and V.E.S. sites.

The Headbasin:

The largest part of the Headbasin lies between the 1060m and 1370m topographic contours and consists of an almost circular basin, 100 km in diameter, which has been eroded into the Interior Plateau.

The Interior Plateau:

This geomorphologic province constitutes the water divide between the Great Fish River Basin and the Orange, Kei and Sundays Rivers. Relative to the Marginal Region and the Headbasin, this province exhibits high relief (Tordiffe, 1978).

2.2.2 Climate and Vegetation

The climate of the Great Fish River Basin can be described as arid to semi-arid (Acocks, 1975) with hot summers and cold winters. The rainfall, which occurs mainly in the form of summer thunderstorms, varies between 350 and 450mm per annum (le Roux, 1979). Although most of the rain falls during January, February and March, when evapotranspiration is at its highest, great variations do occur. Monthly evapotranspiration always exceeds monthly precipitation, resulting in less than 5 percent of rainfall reaching the groundwater table (Tordiffe, 1978).

The natural vegetation is sparse and can be described as False Karroid Broken Veld (Acocks, 1975), although Grassveld appears along the Great Escarpment and Valley Bushveld (Fish River Scrub) in the lower part of the Marginal Region (Tordiffe, 1978).

2.2.3 Farming

Mixed farming is practised, with sheep being largely sustained by feed grown under irrigation. With the assured supply of water after the advent of the Orange-Fish River Scheme, farming has been geared more towards cash crops (le Roux, 1979).

In the Middleton study area the main crops are maize (sweetcorn), lucern and wheat, while sheep are grazed on the non-irrigated land above the canal.

2.3 Geology

Geology exerts the most important influence on the occurrence, magnitude and quality of subsurface waters. As it is the soils and rocks that are the major sources of soluble salts in seepage and groundwaters, an examination of the geology is of paramount importance in any mineralisation study. Table 2.1 lists the lithologies found in the Middleton study area as well as their percentage outcrop area.

TABLE 2.1 LITHOLOGIES FOUND IN THE STUDY AREA

		Formation	Percentage Outcrop area
Increasing age	Recent	calcrete	1
		colluvium	38
		alluvium	37
	Koonap Formation	olive green "pencil" weathered mudstone	5
		greenish-grey silty mudstone	8
		mottled grey sandstone	11

2.3.1 Consolidated Formations

The study area is underlain by sedimentary rocks of the Koonap Formation of the Beaufort Group (Figure 2.3). The Koonap Formation lithologies represent a transitional environment of deposition between the marine or lacustrine deposits of the Ecca Group and the fluvial sediments of the Beaufort Group (Johnson, 1976). (Figure 2.4).

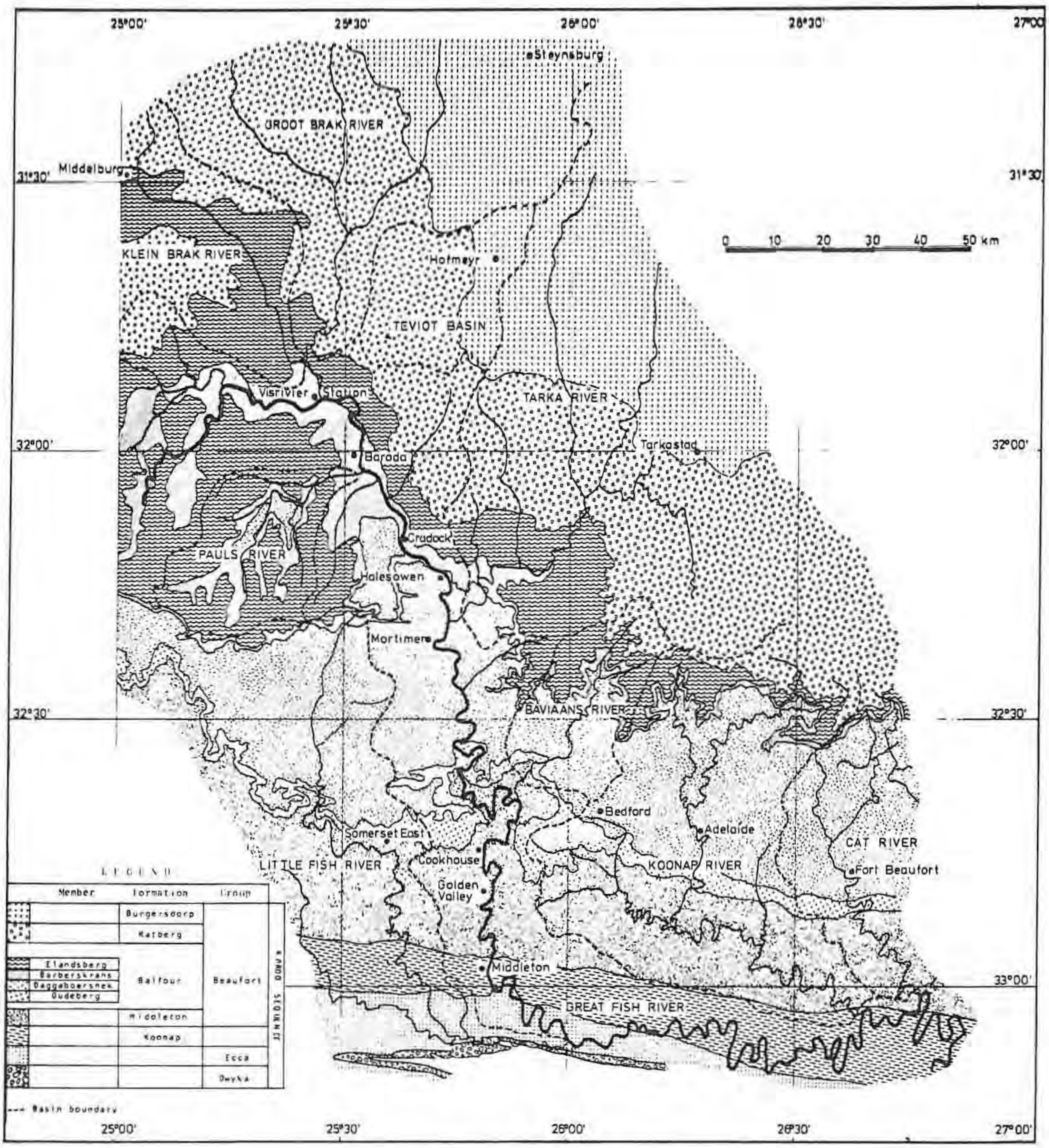
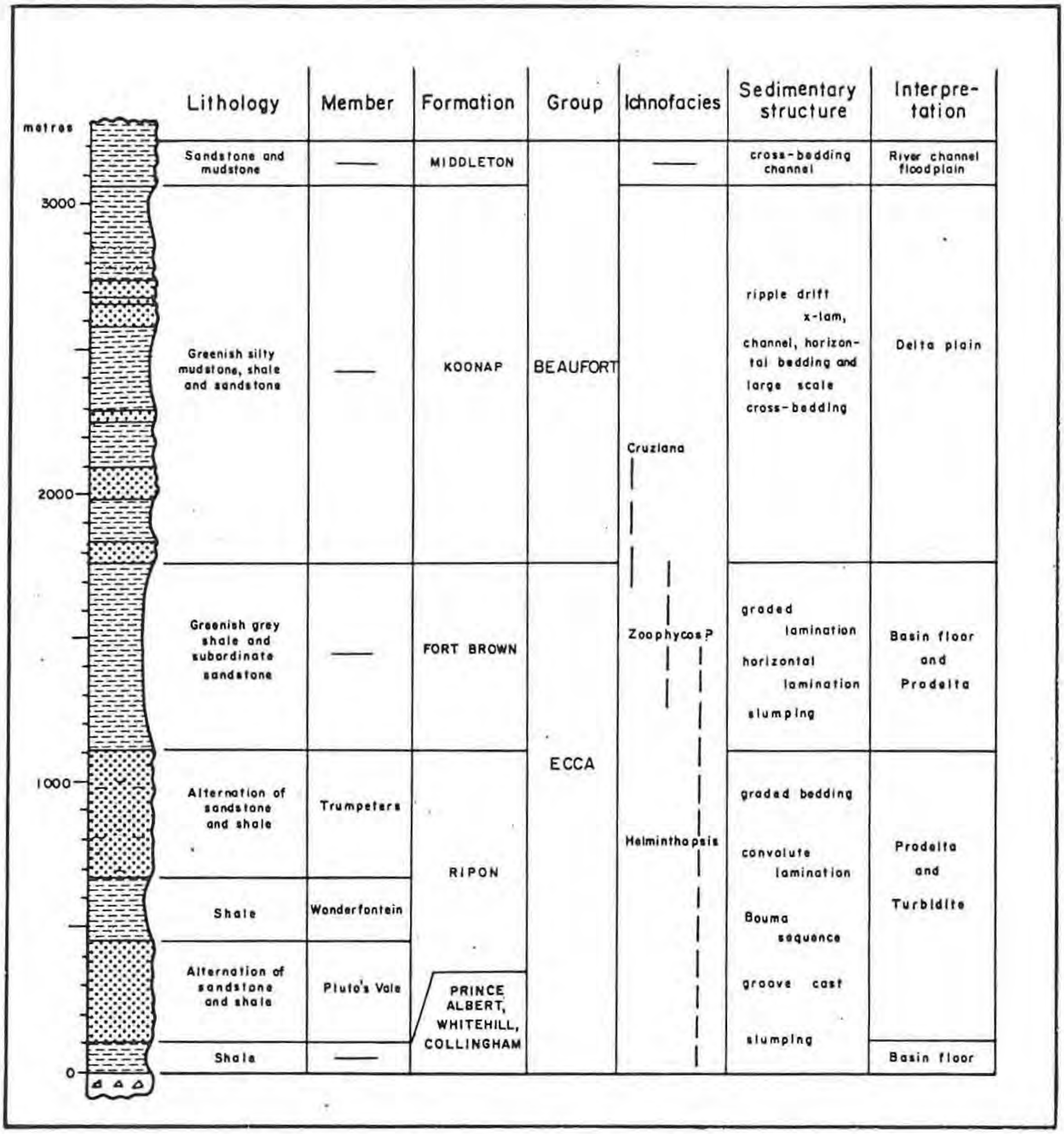


FIGURE 2.3 GEOLOGICAL MAP OF THE GREAT FISH RIVER BASIN (TORDIFFE, 1978)



Lithology	Member	Formation	Group	Ichnofacies	Sedimentary structure	Interpretation
Sandstone and mudstone	—	MIDDLETON	BEAUFORT	—	cross-bedding channel	River channel floodplain
Greenish silty mudstone, shale and sandstone	—	KOONAP		Cruziana	ripple drift x-lam, channel, horizontal bedding and large scale cross-bedding	Delta plain
Greenish grey shale and subordinate sandstone	—	FORT BROWN	ECCA	Zoophycos?	graded lamination horizontal lamination slumping	Basin floor and Prodelta
Alternation of sandstone and shale	Trumpeters	RIPON		Helminthopsis	graded bedding convolute lamination Bouma sequence groove cast slumping	Prodelta and Turbidite
Shale	Wonderfontein					
Alternation of sandstone and shale	Pluto's Vale	PRINCE ALBERT, WHITEHILL, COLLINGHAM				
Shale	—					Basin floor

FIGURE 2.4 GENERALISED COLUMN OF THE ECCA AND LOWER BEAUFORT GROUPS

(KINGSLEY, 1981)

The cyclic, upward fining beds of the Koonap Formation are characteristic of a delta plain depositional environment (Plate 4). Lenticular bodies of mottled grey, medium to fine grained sandstone grade upward into greenish-grey, silty mudstones and massive mudstones (Kingsley, 1977, 1981).

Although the regional dip of the strata is between 4^o and 10^o towards the north (Soekor, 1966), the formations are characterised by gentle folds with east - west trending axes, the folding having occurred during the Cape Orogeny. Intense jointing and fracturing, also with an east - west trend, is present.

2.3.2 Recent Deposits

Overlying consolidated sedimentary rocks in some areas are fairly substantial thicknesses of recent deposits of alluvium and colluvium. The alluvial soils are concentrated close to the river while the colluvial soils, derived mainly from weathering of the surrounding rocks, are found on the slopes and plains (van der Ryst, 1981). A lack of leaching, related to the high clay content of the soils, has resulted in the precipitation of calcium carbonate and the development of a calcrete layer at or near the surface of most of the soils (Tordiffe, 1978).

CHAPTER 3

HYPOTHESES

Based on past research and theoretical concepts, a number of hypotheses have been formulated.

Aquifer Geometry and Lithology

(i) A laterally extensive water table situation is present in the alluvial aquifer, while the consolidated formations are represented by discrete aquifers.

(ii) Although the fractured rock aquifers are themselves discrete there is hydraulic continuity between the fractured sandstone/mudstone aquifers and the overlying alluviul aquifer.

(iii) The main aquifer is found in the fractured sandstone, while minor amounts of water are associated with the mudstone and alluvium.

(iv) The fractured sandstone aquifer is anisotropic resulting in a strongly directional component to flow (in joints, fractures) while the alluvial aquifer is isotropic (flow takes place in various directions).

Hydrochemistry

(v) The weathered mudstone is the principal lithological contributor of mineral salts to the groundwater.

(vi) Because salts are leached from the soils to the groundwater and irrigation results in a rising of the groundwater table, the groundwater below irrigated lands will have a higher salinity than groundwater from non-irrigated veld.

(vii) Recharge takes place through irrigation, precipitation, and leakage from unlined canals and farm reserviors.

Soils

(viii) Particle size distribution influences both soil moisture content and salt accumulation in soils.

(ix) Concentration of salts in the soils by processes of evapotransporation and the application of irrigation water results in a progressive mineralisation of water moving vertically and laterally through the soils.

In order to test the hypotheses, data are required. The data collection phase of the project encompassed three main fields, namely, geology, hydrology and pedology, all of which included the appraisal of work already undertaken in the Great Fish River Catchment.

1. Geology

This involved the scrutiny of geological maps and aerial photographs, the mapping of rock outcrops, which included the measurement of dip and strike of the beds and the collection of rock samples, the measurement of electrical properties of the rock formations using surface geophysical methods, and the drilling of exploration boreholes to determine lithology and provide access to the acquifers.

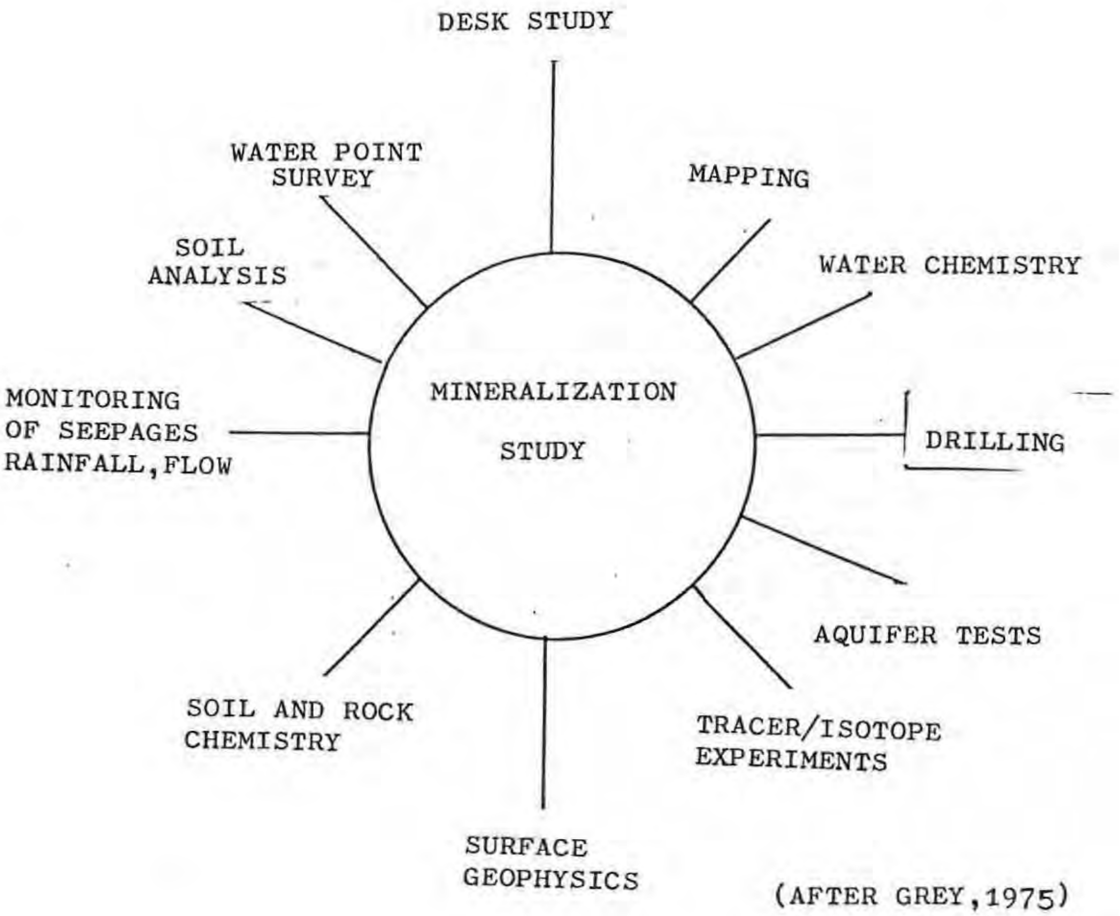
2. Hydrology

Based on an initial borehole survey and conductivity measurements of all water points, selected water samples were collected for detailed hydrochemical analysis. River, canal and seepage water chemistry was monitored, water samples obtained during drilling were analysed and aquifer and tracer tests were undertaken to determine aquifer parameters such as transmissivity and storage. The collection of water samples for tritium determination provided valuable information on recharge and water residence time, while the monitoring of groundwater levels provided data on the effect of irrigation on groundwater movement.

3. Pedology

The role of soils in terms of water retention, salt accumulation and salt mobilization were studied using various field and laboratory techniques.

The components of a mineralisation study may be summaried as follows :



(AFTER GREY, 1975)

CHAPTER 4

GEOLOGY

4.1 Geological Mapping

Geological mapping was subdivided into the mapping of:

1. Recent deposits;
2. Consolidated formations

1. Recent Deposits:

Recent deposits consist of alluvium, adjacent to and deposited by the river, and colluvium, derived from hill-slope weathering and transported by various processes to the base of slopes. For hydrological purposes the alluvium + colluvium will be grouped together. The alluvial soils vary in thickness from 10m at the river bank to less than a metre in the non- irrigated veld above the canal (Figure 4.1). Near river areas are covered by approximately 0,5m of river sand deposited during the 1974 flood. Depositional features such as cross bedding and pebble lenses are present throughout the alluvium profile, while a pebble/boulder layer is laterally extensive at the base of the alluvium. Prominent seepages are evident in certain areas above river level but seepage probably occurs below river level along the entire length of the river.

2. Consolidated Formations:

Exposures are restricted to road cuttings and to various places along the river. Poor exposures are found on hill slopes. Immediately evident is the cyclic nature of the sandstones and mudstones (Plate 4), characteristic of a deltaic environment of deposition. In outcrop, the beds are generally 1 to 2m in thickness although beds in excess of

10m are encountered. Lenses of mudstone and channel sandstone which pinch out over 10's of metres are common. The dip of the beds is predominantly towards the north but gentle folding does occur. Sandstone beds have a strike between 115^{0} to 150^{0} and a dip between 5^{0} and 19^{0}, north and south. Mudstone beds strike between 114^{0} and 156^{0} and dip between 2^{0} and 15^{0}, north and south (Figure 4.1). The sandstones are medium to fine grained (Plate 5), are grey in colour, and are characterised by micro-cross-lamination, flat bedding, and in thicker strata by large-scale trough-cross-bedding. The sandstones are overlain by dark grey silty mudstones, with minor crosslamination, and grey to green massive mudstones which exhibit "pencil" weathering (Plates 6 & 7). The mudstones are often characterised by a red or purple staining.

Intensive jointing and fracturing, exerting an important influence on groundwater occurrence and flow, is present in both sandstones (Plate 8) and mudstones. Joints in sandstone strike between 120^{0} and 145^{0} and dip between 80^{0} and 90^{0}, north and south. These joints, which are often filled with quartz, were formed by stress relief and by various forces during the folding of the strata. The mudstones are characterised by two prominent jointing patterns, 80^{0} and 138^{0}, with a dip of between 75^{0} and 90^{0}, north and south (Figure 4.2). The absence of good exposures resulted in a need to examine the geology in greater detail by geophysical methods and exploration drilling.

4.2 Electrical Resistivity Soundings

4.2.1 Introduction

Surface geophysical methods are used to obtain information about subsurface conditions, such as type and depth of materials, depth of groundwater, depth of bedrock, and salt content of groundwater (Bouwer, 1978; Fretwell and Stewart, 1981). The success of the various techniques employed depends on variations in physical

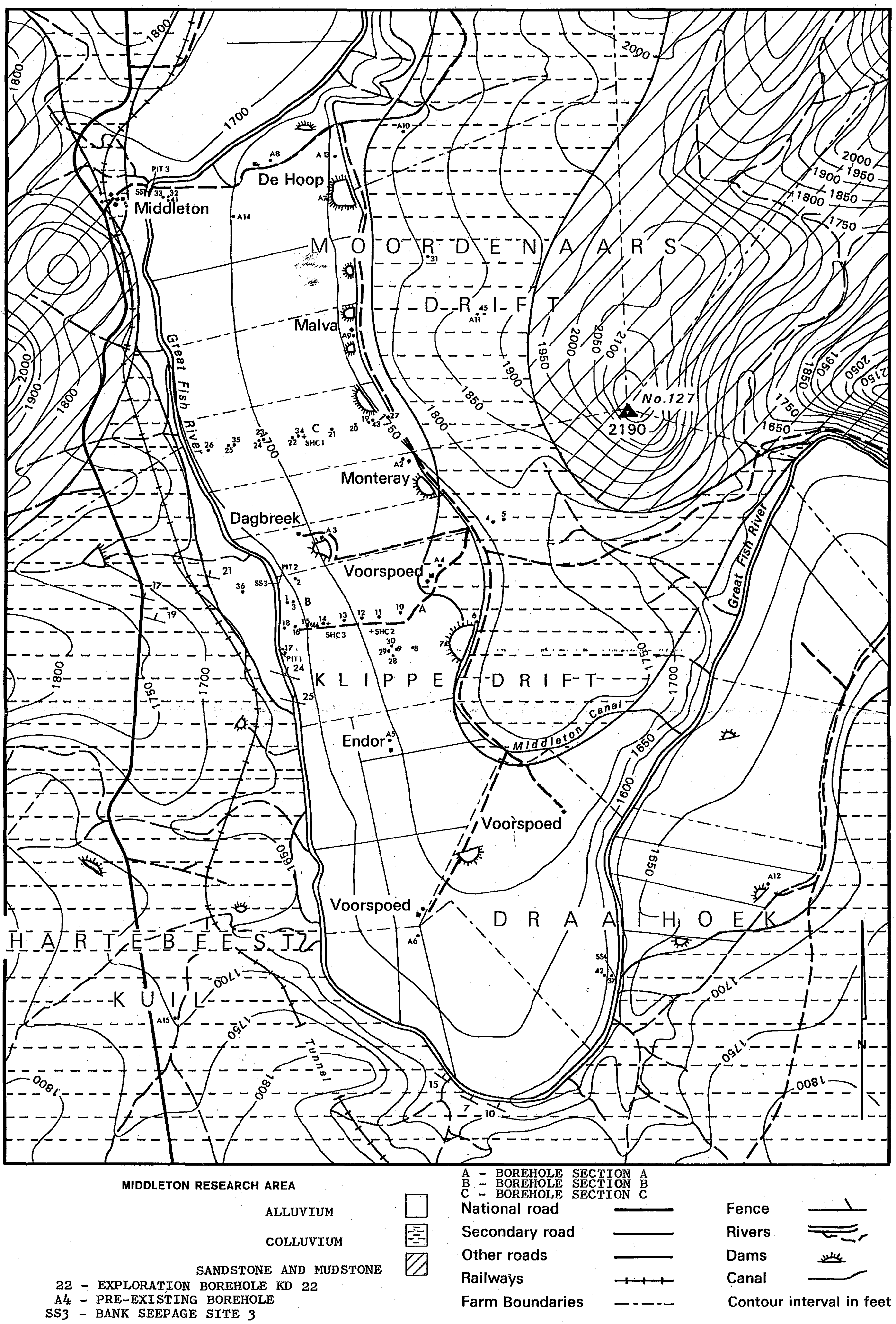
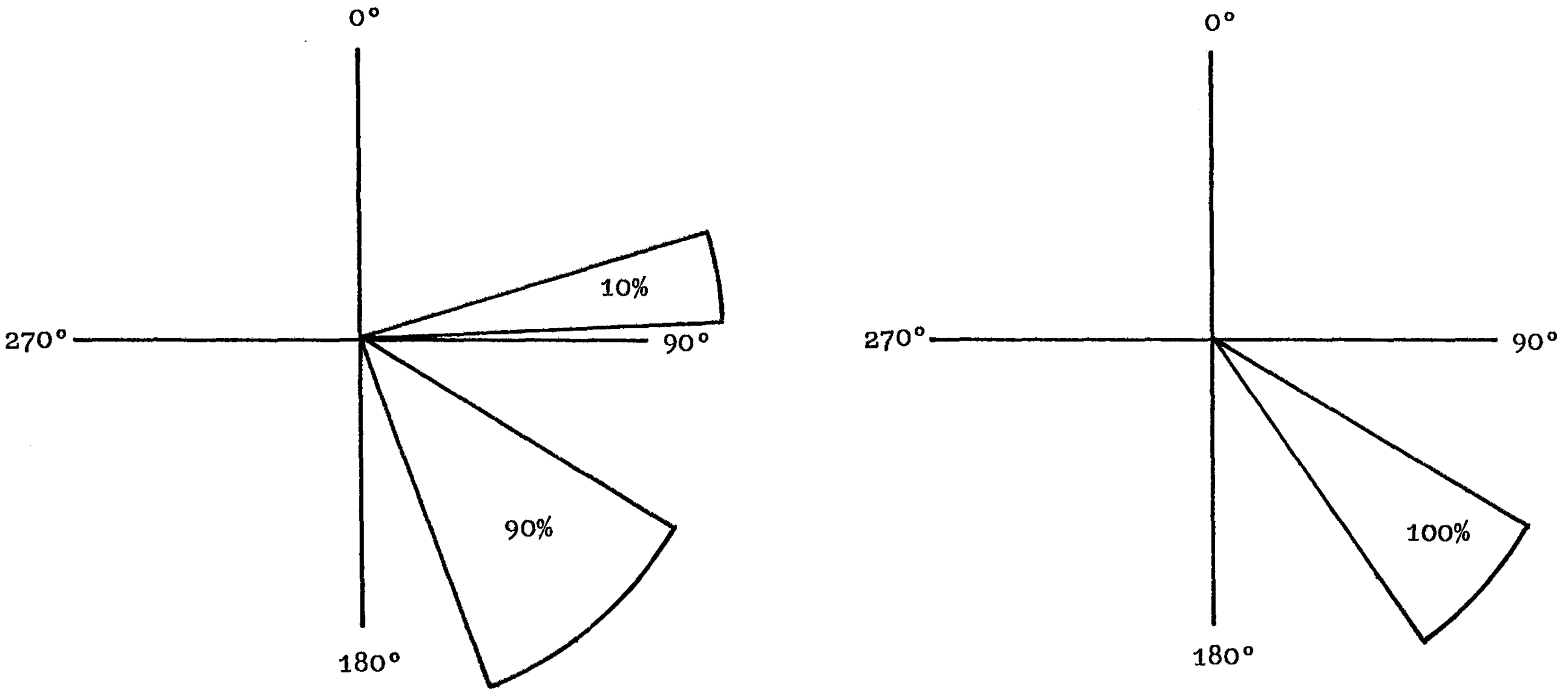


Figure 4.1 Geological outcrop map of the Middleton Study area, and borehole and seepage sites.



ORIENTATION OF JOINTS AND FRACTURES IN MUDSTONE

ORIENTATION OF JOINTS AND FRACTURES IN SANDSTONE

Figure 4.2 Rose diagram of joint and fracture patterns.

PLATE 4. The cyclic, upward fining beds of the Koonap Formation.
(a) Sandstone (b) Mudstone

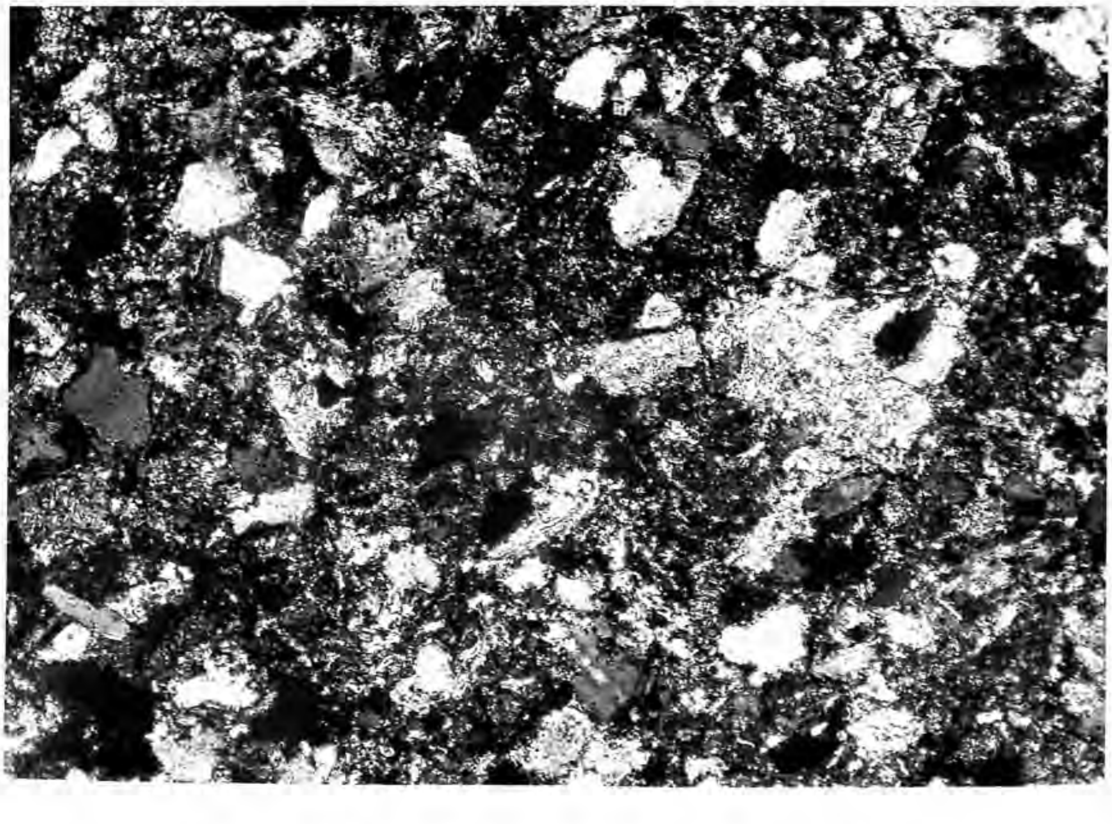


PLATE 5. A thin section of the fine to medium grained mottled sandstone (magnified 2,5 x)

PLATE 6. A thin section of the massive "pencil" weathered mudstone (magnified 2,5 x)

PLATE 7. The massive "pencil" weathered mustone in outcrop

PLATE 8. The jointed and fractured mottled sandstone in outcrop.

properties of the earth, such as density, electrical conductivity, and magnetic susceptibility, as well as the complexity of the geological units (Davis and de Wiest, 1966).

Electrical resistivity and seismic refraction are the two most widely applied techniques (Barker and Griffiths, 1981), these being most successful in the mapping of horizontal or gently dipping strata at relatively shallow depths (Davis and de Wiest, 1966; Van Zijl, 1977). The electrical resistivity method has been used successfully in monitoring groundwater quality (Fretwell and Stewart, 1981), in predicting aquifer properties such as permeability and transmissivity (Kosinski and Kelly, 1981; Heigold and Gilkeson, 1979), and in determining extent and thicknesses of geological layers (Van Zijl et al., 1981; de Beer et al., 1981). The wide use of the electrical resistivity method is related to its relatively low cost when compared with test drilling. Resistivity surveys are not practical in all groundwater investigations, and usually a combination of drilling and geophysical measurements will provide the optimum solution (Zohdy et al., 1974).

4.2.2 The Electrical Resistivity Method

Although all earth materials are able to conduct electricity to some degree, the presence of high resistivity quartz, calcite and feldspar in sedimentary rocks results in most of the electricity being conducted by mineralised water contained within pores and fissures within the formation itself - this is known as electrolytic conduction (Fretwell and Stewart, 1981; Davis and de Wiest, 1966; U.S. Department of the Interior, 1977). Consequently, resistivities in a porous rock system are predominantly the result of :

(1) electrical properties of the ionic solutions,

(2) porosity of the rock matrix,

(3) the degree of saturation of the formation,

(4) the volume of water present,

(5) the presence of clay minerals (Barker and Griffiths, 1981).

The resistivity of earth materials is a very widely varying parameter because of the variability in resistivity of naturally occurring water. One of the inherent weaknesses of the electrical resistivity method is that measured variations in apparent resistivity may be related to interstitial fluids and may have nothing to do with changes in formation (Van Zijl, 1977).

The resistivity method is based on evaluating the apparent resistivity (ρa) of subsurface material, by passing a known current through the ground between 2 current electrodes (A and B) and measuring the resulting potential difference between 2 potential electrodes (M and N) (Worthington, 1978). Unless the volume of earth being measured is isotropic and homogeneous, the resistivity measured is not the true resistivity of the layer but rather the apparent resistivity, which can be written as the ratio of the measured potential to the theoretical potential created in a homogeneous isotropic earth by the same current (Van Zijl, 1977). The apparent resistivity is neither a measure of the true resistivities of the subsurface formations nor the average resistivity of the formation, but is a measure of the effect of all the layers between the maximum depth of penetration and the surface (Davis and de Wiest, 1966).

Based on Ohm's Law for direct current,

$$R = \frac{\Delta V}{I}; \quad ..... (1)$$

where V is the potential difference between the ends of a conductor and I the intensity of the current which flows in the conductor (in the direction of decreasing current); the apparent resistivity (ρa) of the volume of earth between the electrodes can be written as

$$\rho a = K \frac{\Delta V}{I} \quad ..... (2)$$

K is the geometric factor, and is calculated from any specific array of 4 electrodes by

$$K = \frac{2\pi}{\left(\frac{1}{AM} - \frac{1}{AN} - \frac{1}{BM} - \frac{1}{BN}\right)} \quad .....(3)$$

(Van Zijl, 1977).

The basis for making an electrical sounding, irrespective of the array used is that the further away from a current source the measurement of potential difference is made, the deeper the probing will be (U.S. Department of the Interior, 1977). The two most common arrays used in vertical sounding are the Schlumberger array and Wenner array. In both, all four electrodes are placed symmetrically in a straight line. However, in the Schlumberger array, the voltage (MN) electrodes do not have to be moved each time the distance between the current electrodes is increased to measure ρa at increased depth (Bouwer, 1978). In practice MN 1/ AB in the Schlumberger configuration ($K = \pi \frac{AM.AN}{MN}$), while AM = MN = NB = a in the Wenner configuration ($K = 2\pi a$) (Van Zijl, 1977).

The Schlumberger sounding method was used in this study. A sounding is performed by progressively increasing the current electrode spacing AB and measuring the potential difference between M and N. The Schlumberger technique is consequently the least prone to electrode effects as only AB is moved while MN remains fixed, or vice versa (Van Zijl, 1977). At each current electrode spacing an apparent resistivity (ρa) is calculated according to formula (2) and the values are plotted against $^{AB}/_{2}$ on bilogarithmic graph paper (Van Zijl, 1977). The graphs of ρa against $^{AB}/_{2}$ form the basis for interpreting the geo-electric properties of the subsurface.

4.2.3 Data Collection

As the main aim of vertical electrical sounding was to delineate the contact between the unconsolidated alluvium and the underlying consolidated bedrock, i.e. to produce geo-electric profiles, soundings were undertaken in three profiles perpendicular to the left bank of the river, using the Schlumberger (1929) sounding technique. Consequently, little information concerning the geo-electric nature of the underlying bedrock could be expected as the soundings were carried out perpendicular, and not parallel, to the strike of the bedrock. As the drilling of calibration holes forms an integral part in the interpretation of geo-electric sounding curves, the soundings were undertaken, where possible, in areas accessible to a drilling rig.

Lands contoured parrallel to the river made siting of the soundings relatively easy and high contact resistance was limited to those areas where dry sand (deposited during the 1974 flood) overlays the more conductive clayey top soil. In addition, four single soundings were undertaken in the non-irrigated veld to determine geo-electric properties of those areas overlain by less than a metre of soil (Figure 2.2).

Maximum $^{AB}/_{2}$ distances varied between 100m and 500m, the soundings being carried out until the final rising portion of the curve was defined by at least 5 points. The presence of metal fences and electrical pylons also restricted the AB electrode separation. The distance between successive soundings on a profile at first varied between 100m and 300m (profiles B and C). As this distance proved too great for variations in the pre-alluvium erosion surface to be detected, a spacing of 50m was chosen for profile A.

Data were obtained for each sounding in accordance with standard CSIR procedures (Van Zijl, 1977) and were plotted on bilogarithmic graph paper. Thereafter, the curves were interpreted according to the method followed by Smith (1982), the final curves being modified, using geological data, by a computer technique (Ghosh, 1971).

4.2.4 Curve Matching and Data Interpretation

The goal of the interpretation of an electrical resistivity survey is the extraction of the geological and geohydrological information contained in the measured sounding curves (de Beer et al., 1981). Initial interpretations of the Schlumberger VES (vertical electrical sounding) field curves were made by a partial curve matching technique, based on the determination of the relevant Dar Zarrouk parameter for each layer (Joubert, 1977; Smith, 1982). The Dar Zarrouk parameters described by Maillet (1947), are transverse resistance T and longitudinal conductance S. In a resistive bed between two more conductive beds, electrical current will tend to flow perpendicular to the bedding so that such a bed will be characterized by its transverse resistance (T = thickness x resistivity). However, in a conductive bed between two more resistive beds, electrical current will tend to flow along the conductive bed, parrallel to the bedding so that such a bed is characterized by its longitudinal conductance

$$\left(S = \frac{\text{thickness}}{\text{resistivity}}\right)$$

(de Beer et al., 1981; Van Zijl, 1977).

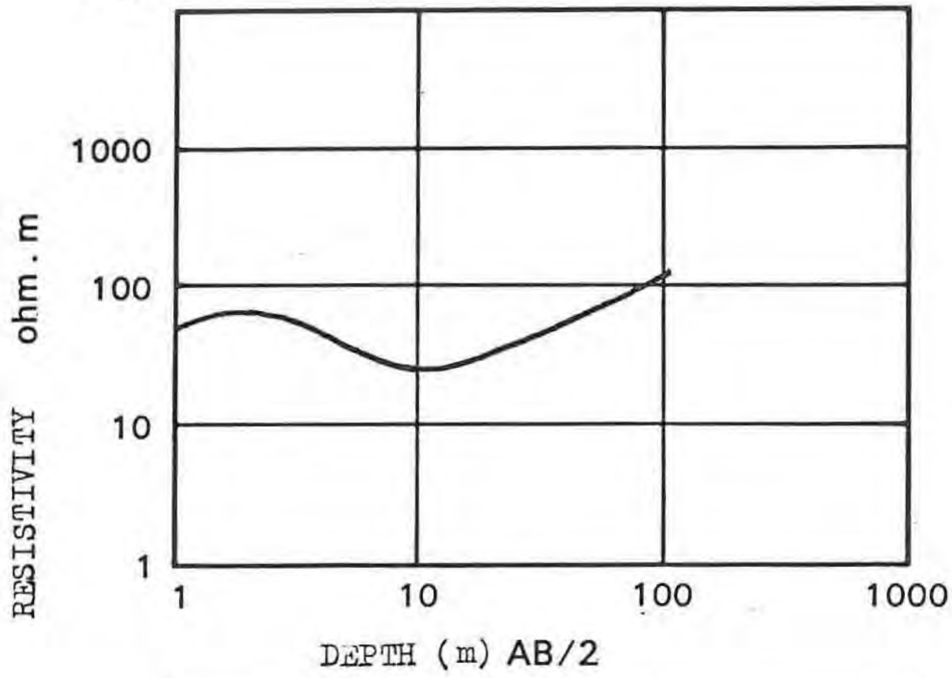
As a first step in this interpretation procedure the multi-layer sounding curve was decomposed into simpler three-layer sections. This decomposition was achieved by matching the different parts of the sounding curve to theoretical curves contained in Joubert (1977). The method followed is well described by Smith (1978). In this way the number of layers was determined. The sounding curves measured in this survey are of various types. The most numerous are 4-layer HA and KH curves and 3-layer H and A curves. However, some 5-layers curves, e.g. KHA and QHA are also found. Given these calculated values of T and S, combined with estimated resistivity values obtained from curve matching, it was possible to calculate resistivities and thicknesses for all geo-electric layers present. Examples of sounding curves from the study area are shown in Figure 4.3, while the remaining curves are contained in Appendix A.

SOUNDING No. 1/1
EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
1,8	75,6
10	20
7	46,66
R	500

TOTAL S = 0,6738 Siemens

TYPE HA

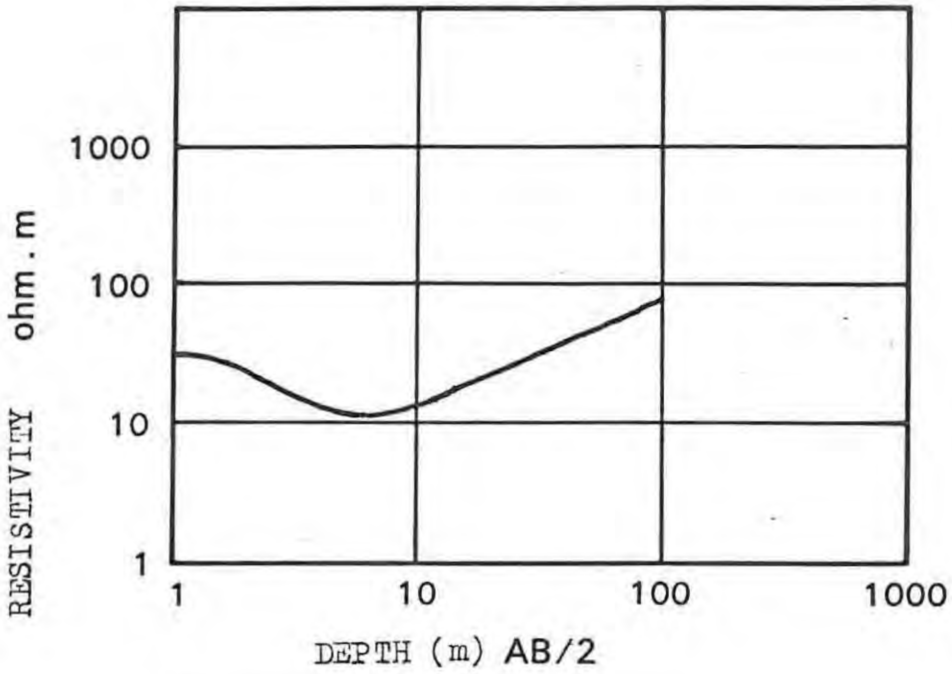


SOUNDING No. 1/3
EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
1	35,8
6	8,46
9	29,7
R	600

TOTAL S = 1,0402 Siemens

TYPE HA



SOUNDING No. 2/7
EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
1,7	10,6
14,56	23
R	800

TOTAL S = 0,7934 Siemens

TYPE A

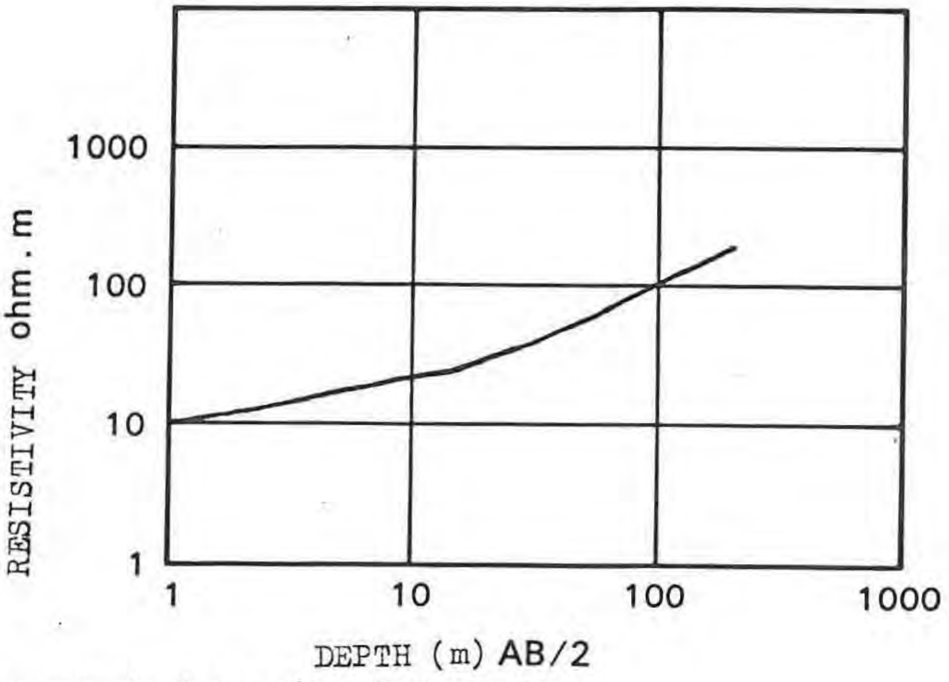


FIGURE 4.3 Selected VES curves showing various type curves measured in the study area

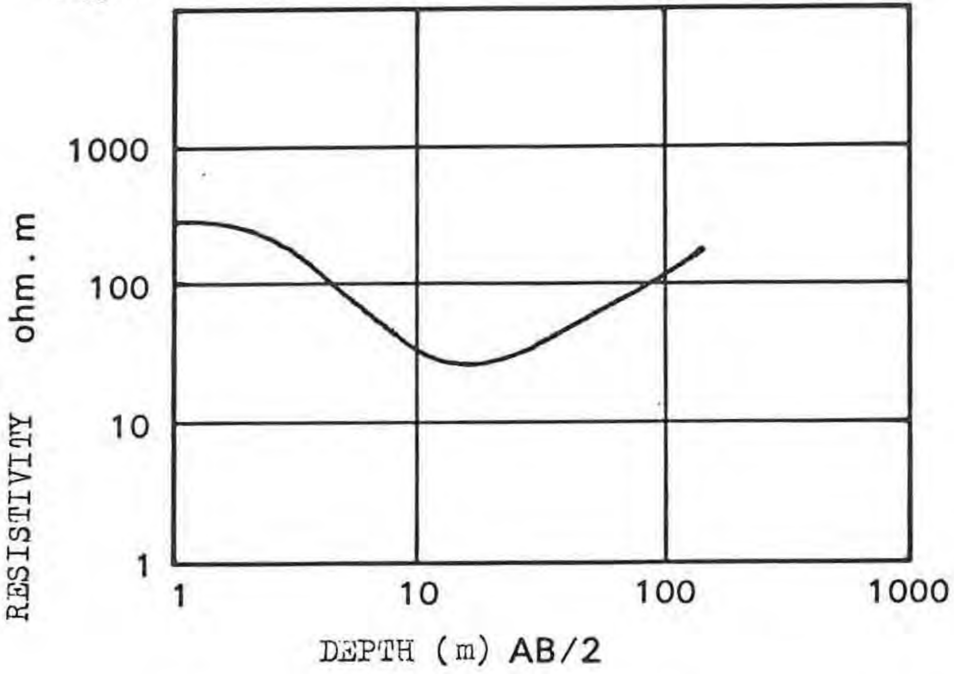
SOUNDING No.3/14

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
2	267
15	18,4
R	2000

TOTAL S = 0,8227 Siemens

TYPE H



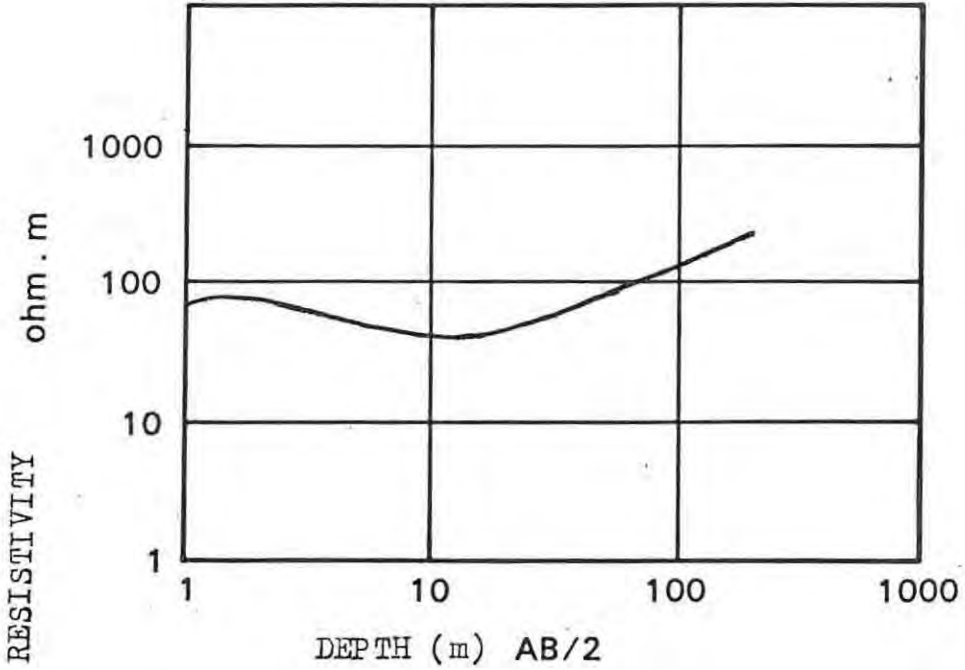
SOUNDING No. 3/15

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
1,35	85
3	50
10,6	30
30	250
R	750

TOTAL S = 0,5492 Siemens

TYPE QHA



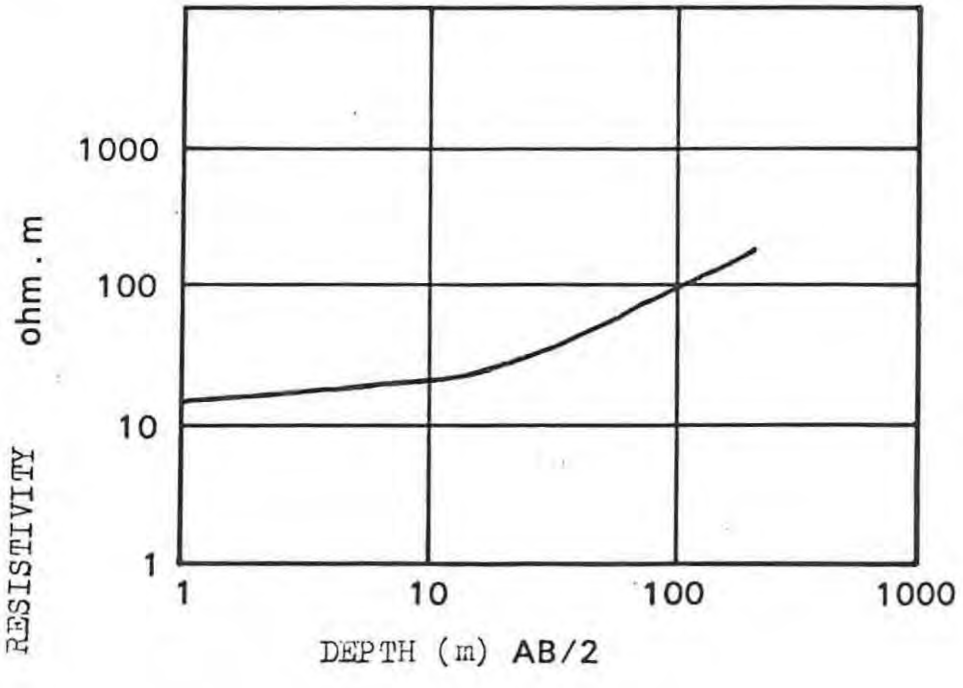
SOUNDING No. 3/17

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
1,9	15
2,4	30
8,7	14
6	80
R	850

TOTAL S = 0,9031 Siemens

TYPE KHA



The geo-electric section obtained in this way is not a unique interpretation and did not in all instances correlate with the geologic section because of these problems of equivalence and suppression, which cannot be resolved without the drilling of calibration boreholes. The principle of equivalence relates to a formation which is either resistive or conductive in relation to the overlying or underlying formation, while the principle of suppression relates to a formation which possesses intermediate resistivity in relation to the overlying or underlying formation (Worthington, 1978). Consequently the boreholes were drilled along two section lines perpendicular to the river and using this data the geo-electric sections were checked and modified using a liner filter technique described by Ghosh (1971) and Johansen (1975). The resistivity parameters obtained in this way were used to interpret curves measured away from boreholes.

The aim of delineating the contact between the alluvium and solid bedrock was, in most instances, achieved. However, as was anticipated, little geo-electric data of the consolidated formations was obtained, except for an apparent resistivity value for all units below the alluvium. This lack of differentiation of the geology into separate geo-electrical units was due not only to the soundings being undertaken perpendicular to strike of the bedrock but also to the cyclic nature and limited thickness of the sandstone and mudstone layers.

Based on sections A, B and C (Figures A.2 to A.4, Appendix A) the alluvium could be divided into 5 geo-electric categories. These correspond more to moisture content within the alluvium than to geo-electrical differences between clay, sand and pebbles, although moisture content may be related to the presence of these units. The following categories are based on apparent resistivity values :

CATEGORY (GEO-ELECTRIC)	APPARENT RESISTIVITY (Ω.m)	THICKNESS (m)
Dry clay-rich top soil	36 - 75	0,6 - 1,8
Moist clay-rich top soil	8 - 15	1,4 - 1,7
Dry river sand	85 - 267	0,6 - 2,0
Moist sand and clay	8 - 23	6 - 18
Sand and pebbles	33 - 46	7 - 11
Bedrock	Average 762	

Accurate logging of the alluvium was made difficult by the use of an air-lift percussion drilling rig during the drilling programme. In some instances, no sample was blown to the surface during drilling of the alluvium and therefore inaccuracies could be present in the borehole logs. Also the presence of fractured weathered bedrock below the alluvium may have resulted in an overestimate in the thickness of the alluvium. When soil sampling holes were drilled near boreholes (using a sampling tube) a discrepancy of up to 2m in the depth of alluvium was found.

Because of irrigation practices, the alluvium was in various moisture holding states. For example, in sounding 3/14 (Figure 4.3), the very dry river sand, (deposited during a flood event) showed up as a resistive geo-electric layer having a resistivity of 267Ωm. This was followed by a single conductive layer of 18 Ωm which geologically included moist sand, clay and pebbles. In the case of sounding 3/19 (Figure A.1, Appendix A), the partially moist top soil had a resitivity of 18Ωm, followed by saturated sand (9Ωm) and unsaturated sand and pebbles (71Ωm).

In section C, sounding 1/3, 1/4 and 1/5 overestimated the thickness of the alluvium by between 1 and 4m. This is probably due to the effect of suppression where the weathered/fractured bedrock is too thin to be recognised as a separate unit and is included with the alluvial layer above it. However, sounding 1/2 showed no correlation between geo-electric layers and the contact between the alluvium and underlying bedrock - in fact the base of the third geo-electrical layer corresponded to the base of the second mudstone layer. Sounding 5/1 showed the presence of two geo-electrical layers before the final layer. These correspond to dry river sand and clay (45Ωm - 2,3m thick) and moist clay, sand and pebbles (110Ωm - 14,2m thick). In the case of sounding 3/24, the weathered sandstone located below the clay was picked up as part of the unconsolidated material.

It must be stressed that it was only after careful borehole correlation and modification of the initial curve-matching results by a computer technique that the contact between the alluvium and bedrock was defined. Although the VES method is ideally suited to two layer problems, (e.g. alluvium overlying bedrock), the presence of clay, calcrete, sand and pebbles, all in various moisture holding states, resulted in difficulties in matching geo-electric to geologic layers. The VES method, although confirming the heterogeneity of the alluvium, was of little value in defining the thickness of the alluvium and in locating groundwater reservoirs.

4.3 Drilling

4.3.1 Purpose and Site Selection

The drilling of test holes provides the most accurate information about the geologic profile and the depth and quality of groundwater at a given site (Bouwer, 1978). During this investigation 38 boreholes and 7 soil sampling holes were drilled. The purpose of drilling was :

- to obtain data on the thickness and extent of the saturated lithologies (both consolidated and unconsolidated),
- to collect soil and rock samples for laboratory analysis (soil and rock chemistry, soil moisture content, and particle size analysis),
- to identify the major aquifers,
- to provide access to the aquifers in order to undertake aquifer tests,
- to provide observation holes for aquifer tests,
- to collect water samples and measure piezometric levels,
- to calibrate the results obtained from vertical electrical soundings.

4.3.2 Test Boreholes

Initial site selection was based mainly on the location of resistivity soundings, ten boreholes being drilled on such sounding sites. In order to provide detailed hydrogeologic data, drilling was concentrated in the central portion of the study area on the farms Klippedrift (Voorspoed) and Moordenaarsdrift (Monterey) (Figure 4.1). The boreholes were drilled in two sections perpendicular to the river, the purpose being twofold :

- to determine variation in the thickness of alluvium from the canal to the river,
- to obtain data on variations in water quality, water occurrence and water levels from the canal to the river.

Three holes, KD 2, KD 32 and KD 37 were drilled near prominent saline seepage sites (in an attempt to understand the origin of the seepage water); holes KD 5 and KD 45 were drilled in non-irrigated veld; hole KD 36 was drilled in the "control area" on the right hand bank of the river (no observation hole was drilled because of the low yield encountered); and holes KD 3, KD 4, KD 33, KD 34 and KD 35 were drilled as observation holes for aquifer tests (for holes KD 1, KD 5, KD 32, KD 25 and KD 26 respectively). Hole KD 6 was drilled to monitor seepage from the Middleton Canal and KD 7 to monitor seepage from an irrigation pond. With the exception of KD 45 and the seven soil sampling holes, all boreholes were drilled using a Rock Giant air-rotary drilling rig. Casing was installed in all boreholes, the length of the casing varying according to the thickness of the unconsolidated or weathered/fractured zone. Casing, perforated on site using an oxy-acetelene cutting torch, was installed in those holes where monitoring of the irrigation seepage was deemed necessary.

4.3.3 Soil Sampling Holes

A cable-tool percussion drilling rig was employed to obtain soil samples, using the drive core sampling tube method as described by Johnson, (1972), for chemical, particle size and soil moisture analysis. A drilling-tool was used to penetrate layers of calcrete and clay, when encountered, and sampling was restricted to areas of unconsolidated alluvium. Samples were collected at one metre intervals. Three holes were cased with perforated casing to facilitate the use of tracers. In addition, hand-dug pits and auger holes were excavated along the river bank to provide data on irrigation return flow water.

4.3.4 Sampling Techniques

Both the availability of an air-rotary drilling rig and the need for a large number (37) of fairly shallow holes (between 20m and 60m in depth) in as short a time as possible, made the air-rotary method the most feasible in this investigation. This method, where air is used as the circulating fluid to bring samples to the surface, yields limited geologic data (non-representative samples) because of grinding of the samples and mixing from various depths (U.S Department of the Interior, 1977). Consequently, accuracy in sampling was sacrificed for drilling speed. The rapid drilling action is achieved by a pneumatic hammer fitted to the lower end of the drill pipe, which combines the percussion effect of cable-tool drilling and the rotary action of rotary drilling (Johnson, 1972). The air-rotary method, best suited to the drilling of hard rock formations, resulted in poor samples being obtained from the alluvium and weathered bedrock, due to the blowing of material into cavities within the borehole. Water samples were taken every time water was encountered and a blow test to determine the final yield was undertaken after the completion of the drilling.

In order to obtain accurate data on the unconsolidated alluvium, a drive-core sampling method was employed. A sampling tube, attached to the drilling jars of a cable-tool percussion rig, was driven into the alluvium and a sample obtained at one metre intervals. According to the U.S. Department of the Interior (1977), a sample so obtained may be defined as a representative sample because, although density and structure were not preserved, soil moisture and grain size are retained.

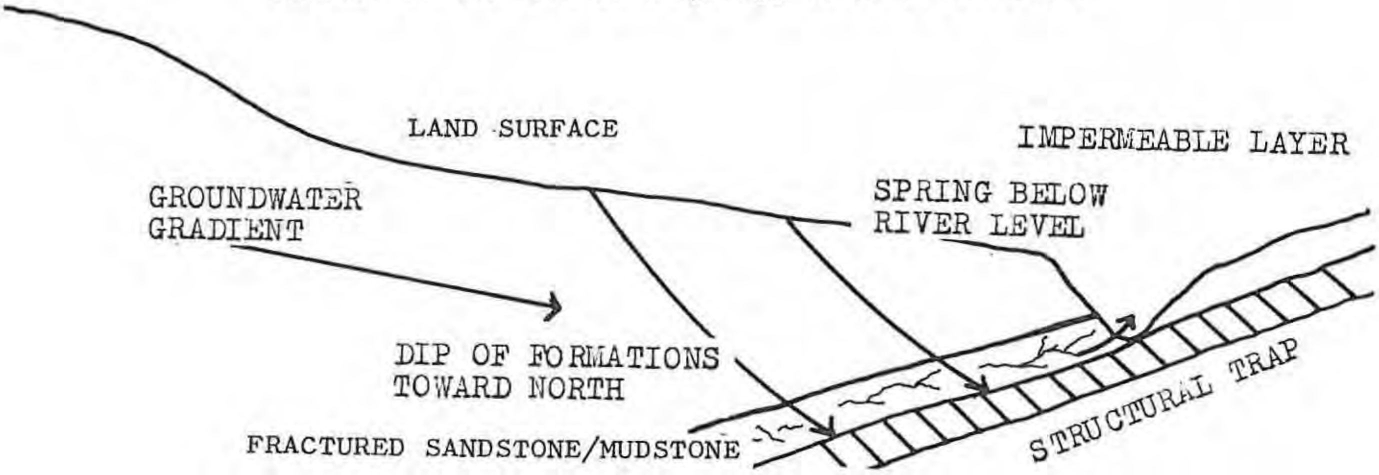
4.3.5 Results of Drilling Programme

(a) Unconsolidated Formations:

Table 4.1 contains the data obtained during the drilling programme, Figures 4.4 to 4.7 contain examples of the borehole logs, (the remaining logs being contained in Appendix B) while the geological sections (A, B and C) are drawn in Figures B.1 to B.3 (Appendix B). From section A it is evident that the thickness of the alluvium varies from about 12m in the vacinity of the river (borehole KD 1) to less than 1m near the canal (borehole KD 6) (Plate 9). River migration, during earlier geological times, has resulted in variations in the elevation of the pre-alluvium bedrock surface, as can be seen in section C (borehole KD 19), where 23m of alluvium overlie the bedrock. Calcrete was encountered at varying depths in the majority of holes (Plate 10), and a fairly continuous pebble layer was found at the alluvium/bedrock contact in most holes in section C, while only in these holes nearer the river in section A. The typically fluvial depositional environment was evident in the heterogeneity of the alluvial soils. Although most consisted of a mixture of sand, silt and clay, some profiles consisted predominantly of sand (KD 26) while others predominantly of clay (KD 25). Water was encountered at the Alluvium/bedrock contact in those holes near the river, while partially saturated horizons were encountered at various depths during the drilling of some holes (e.g. KD 34 and KD 40). Details of particle size analysis and soil moisture content are discussed in Chapter 7.

(b) Consolidated Formations

The nature of the consolidated formations, as discussed in section 4.1, was confirmed during the drilling programme. The lenticular form of the mudstones and channel sandstone results in vertical and horizontal variations in lithology over fairly short distances. The apparent randomness in the depth at which water was encountered is related to the discontinuous and discrete nature of the sandstones and mudstones (section A, Figure B.1). The dip and gentle folding of the rocks further complicates the discontinuous nature of the layers. Water was encountered in fractures and joints in the sandstones and mudstones. These fracture and joint zones, which are of limited width (0,20m to 0,40m, although fracture zones of 2m were encountered) are related to stress relief, differential compaction and/or folding of the strata. Not only does the depth at which water was encountered vary, but the quantity and quality of the groundwater varied over short lateral and vertical distances (expanded in Chapter 6). The occurrence of dipping permeable strata over less permeable strata may result in a structural trap situation where water is forced to the surface in the form of a spring, below river level.



STRUCTURAL TRAP SITUATION WHERE WATER IS FORCED TO THE SURFACE

From the drilling results, a discontinuous, discrete aquifer system is postulated where localized areas of high transmissivity are found within areas of low transmissivity. The presence and flow of water is directly related to the presence of permeable secondary fractures. Only limited amounts of seepage water are found within the alluvium, which, due to its high clay content and poorly sorted nature, exhibits a low transmissivity.

TABLE 4.1. DATA OBTAINED DURING DRILLING PROGRAMME.

BOREHOLE	DEPTH (M)	DEPTH AT WHICH WATER WAS ENCOUNTERED (M)	FORMATION IN WHICH WATER WAS ENCOUNTERED	QUALITY OF WATER (mg/ℓ)	FINAL YIELD (BLOW TEST) (M^3/DAY)	CASING LENGTH (M) X DIAMETER (MM)
KD 1	37	14 25 30,5	PEBBLES/MUDSTONE MUDSTONE FINE SANDSTONE	1580 1625 1937	87,3	18,3 X 165
KD 2	18	SEEPAGE	ALLUVIUM	2496		18,3 X 165
KD 3	37	14 30	PEBBLES/MUDSTONE SANDSTONE	1593 1801	87,3	18,3 X 165
KD 4	49	33,4 48	SANDSTONE/MUDSTONE SANDSTONE	1164 1144	27,3	6,1 X 165
KD 5	52	37 50	MUDSTONE SANDSTONE	1287 2099	54,6	6,1 X 165
KD 6	18	SEEPAGE	MUDSTONE	975		6,1 X 165
KD 7	25	SEEPAGE	MUDSTONE	1014		6,1 X 165
KD 8	48	21	FINE SANDSTONE/ MUDSTONE	1131	27,3	6,1 X 165
KD 9	37	27	SANDSTONE	1742	5,4	6,1 X 165
KD 10	37	SEEPAGE		1612		6,1 X 165
KD 11	37	31	SANDSTONE	1372	5,4	12,2 X 165
KD 12	55	53	SANDSTONE	2061	32,4	12,2 X 165
KD 13	37	25	MUDSTONE/ SANDSTONE	2106	54,6	18,3 X 165
KD 14	37	23 32	SANDSTONE SANDSTONE	2139 2548	43,6	18,3 X 165
KD 15	37	29 35	SANDSTONE FINE SANDSTONE	3786 1118	65,5	18,3 X 165
KD 16	37	29,5 35	FINE SANDSTONE/ MUDSTONE MUDSTONE	NO SAMPLE 2002	109,1	18,3 X 165
KD 17	37	25	SANDSTONE	1917	21,8	14 X 165
KD 18	37	25	SANDSTONE/ MUDSTONE	1833	109,1	12,2 X 165
KD 19	55	52	SANDSTONE	1059	5,4	24,4 X 165
KD 20	55	25	SANDSTONE	1164	7,6	25,4 X 127
KD 21	43	37	SANDSTONE	1339	54,6	18,3 X 127

TABLE 4.1. DATA OBTAINED DURING DRILLING PROGRAMME.

BOREHOLE	DEPTH (M)	DEPTH AT WHICH WATER WAS ENCOUNTERED (M)	FORMATION IN WHICH WATER WAS ENCOUNTERED	QUALITY OF WATER (mg/ℓ)	FINAL YIELD (BLOW TEST) (M^3/DAY)	CASING LENGTH (M) X DIAMETER (MM)
KD 22	37	26,5	SANDSTONE	1570	87,7	18,3 X 127
KD 23	18	16	PEBBLES/SANDSTONE	3140		18,3 X 127
KD 24	37	32	SANDSTONE/MUDSTONE	3471	5,4	18,3 X 127
KD 25	35	14 32,5	PEBBLES/SANDSTONE MUDSTONE	3393 3250	43,6	18,3 X 127
KD 26	37	20 30,5	SANDSTONE FINE/SANDSTONE	3281 3231	5,4	18,3 X 127
KD 27		NO WATER ENCOUNTERED				22,5 X 127
KD 28	43	31	SANDSTONE/MUDSTONE	1810	2,2	6,1 X 165
KD 29	37	29	FINE SANDSTONE/MUDSTONE	2165	5,4	6,1 X 165
KD 30	42	33	FINE SANDSTONE	1827	2,2	6,1 X 165
KD 31	55	NO WATER ENCOUNTERED				6,1 X 165
KD 32	31	17 26	MUDSTONE MUDSTONE	5772 5200	1309	18,3 X 152
KD 33	31	17 26	MUDSTONE MUDSTONE	5585 4810	1091	18,3 X 165
KD 34	37	26	SANDSTONE	1768	87,3	14,5 X 165
KD 35	35	14 32,5	PEBBLES/SANDSTONE MUDSTONE	3211 3276	109,1	15 X 165
KD 36	37	16 26	PEBBLES/MUDSTONE MUDSTONE	1724 2171	5,4	18,3 X 165
KD 37	67	10 22,5 57	ALLUVIUM/MUDSTONE MUDSTONE MUDSTONE	3621 2600 2275	43,6	18,3 X 165
KD 38 *	9,5					
KD 39 *	10					
KD 40 *	13					
KD 41 *	15,3	SEEPAGE	ALLUVIUM			16 X 165
KD 42 *	12,6	SEEPAGE	ALLUVIUM	3198		12,2 X 165
KD 43 *	23	SEEPAGE	ALLUVIUM	1424		23 X 152
KD 44 *	15,5	SEEPAGE	ALLUVIUM			16 X 165
KD 45 *	67	65	SANDSTONE	3556	54,6	3 X 152

* SOIL SAMPLING HOLE

BOREHOLE NO: KD 1

CADASTRAL FARM: KLIPPE DRIFT

BLOW TEST YIELD: 1,01 ℓ/s

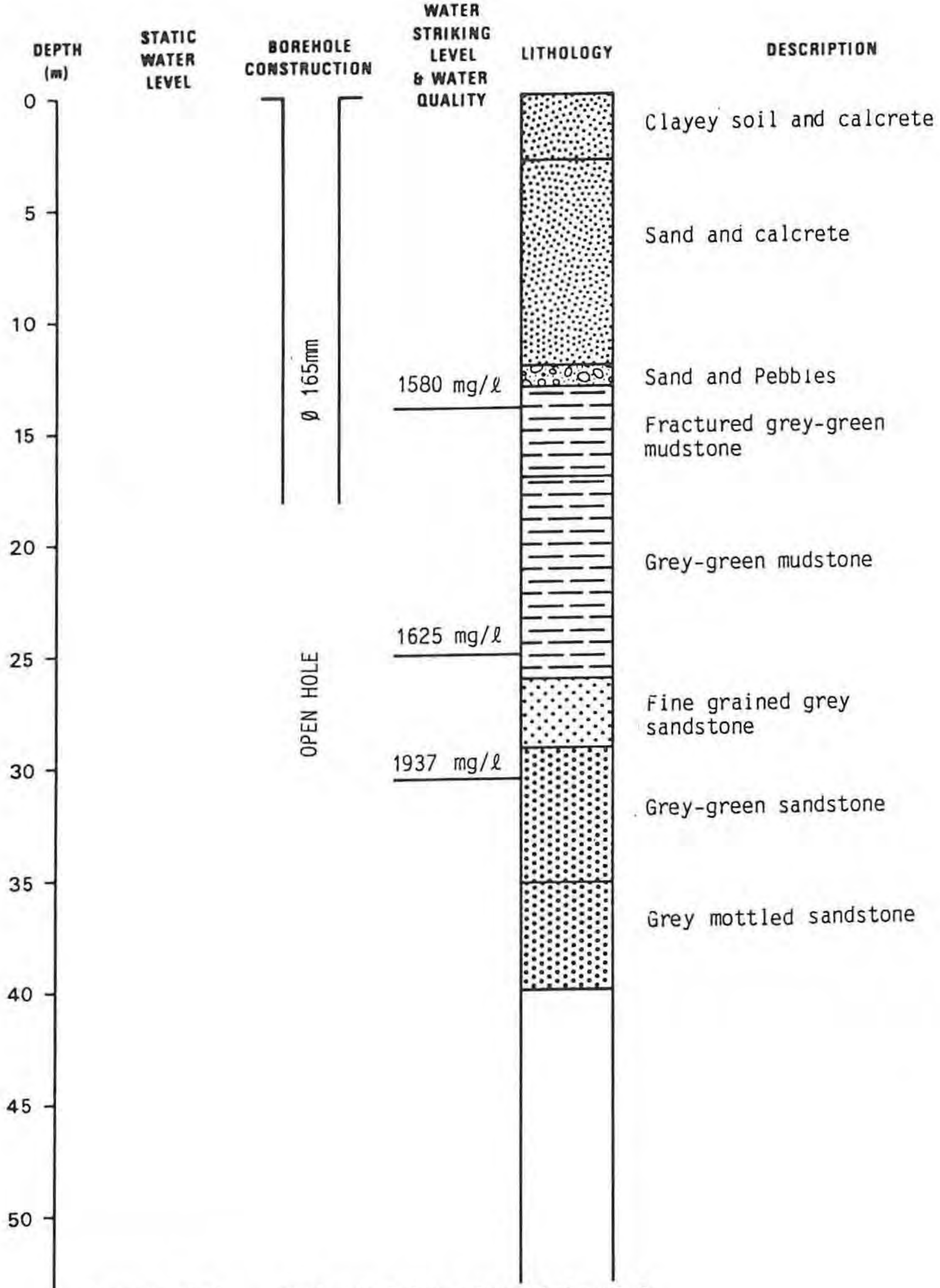


FIGURE 4.4 Geological log of borehole KD 1

BOREHOLE NO: KD 5
CADASTRAL FARM: KLIPPE DRIFT
BLOW TEST YIELD: 0,63 ℓ/s

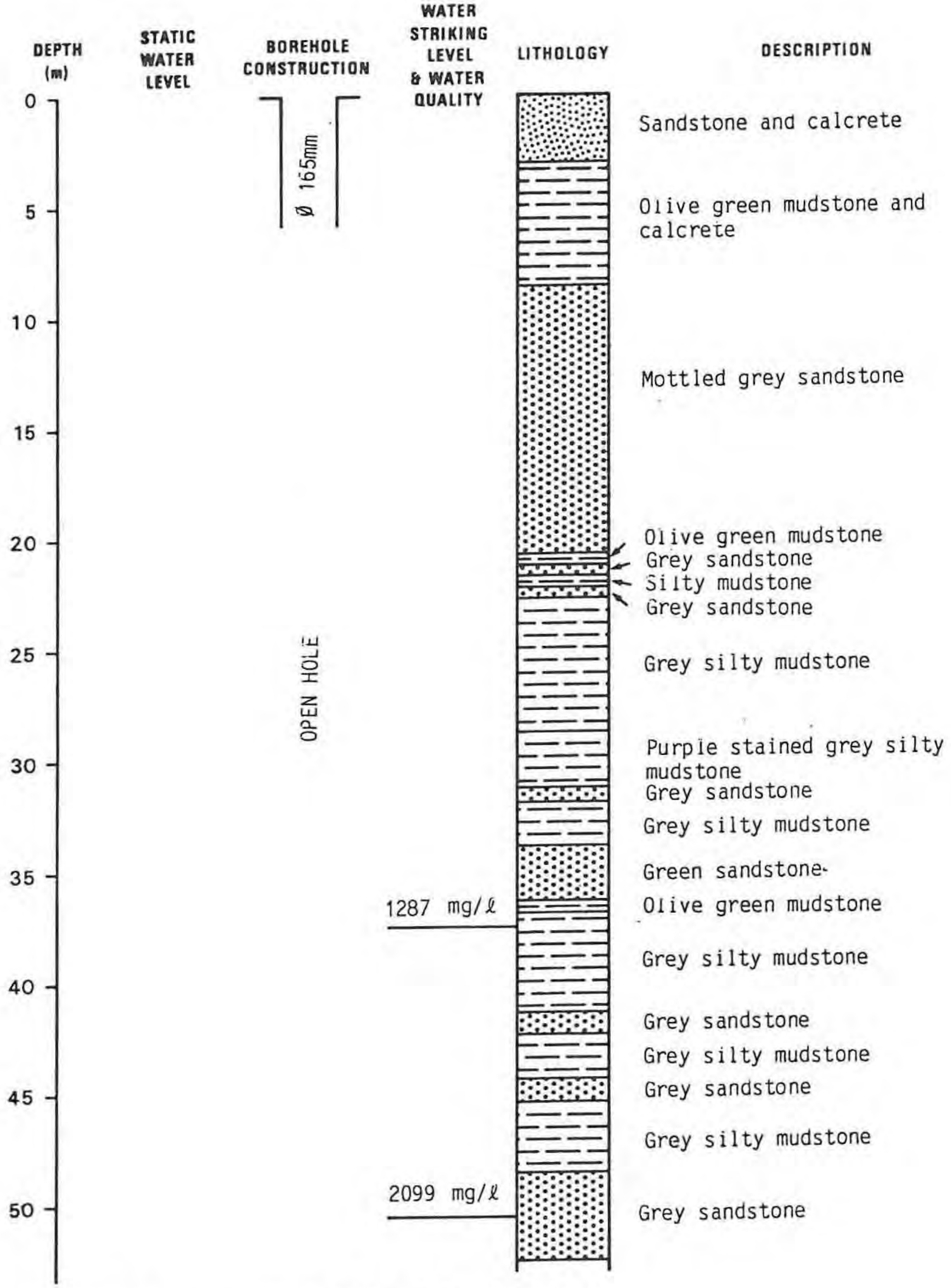


FIGURE 4.5 Geological log of borehole KD 5

BOREHOLE NO: KD 25

CADASTRAL FARM: MOORDENAARS DRIFT

BLOW TEST YIELD: 1,26 ℓ/s

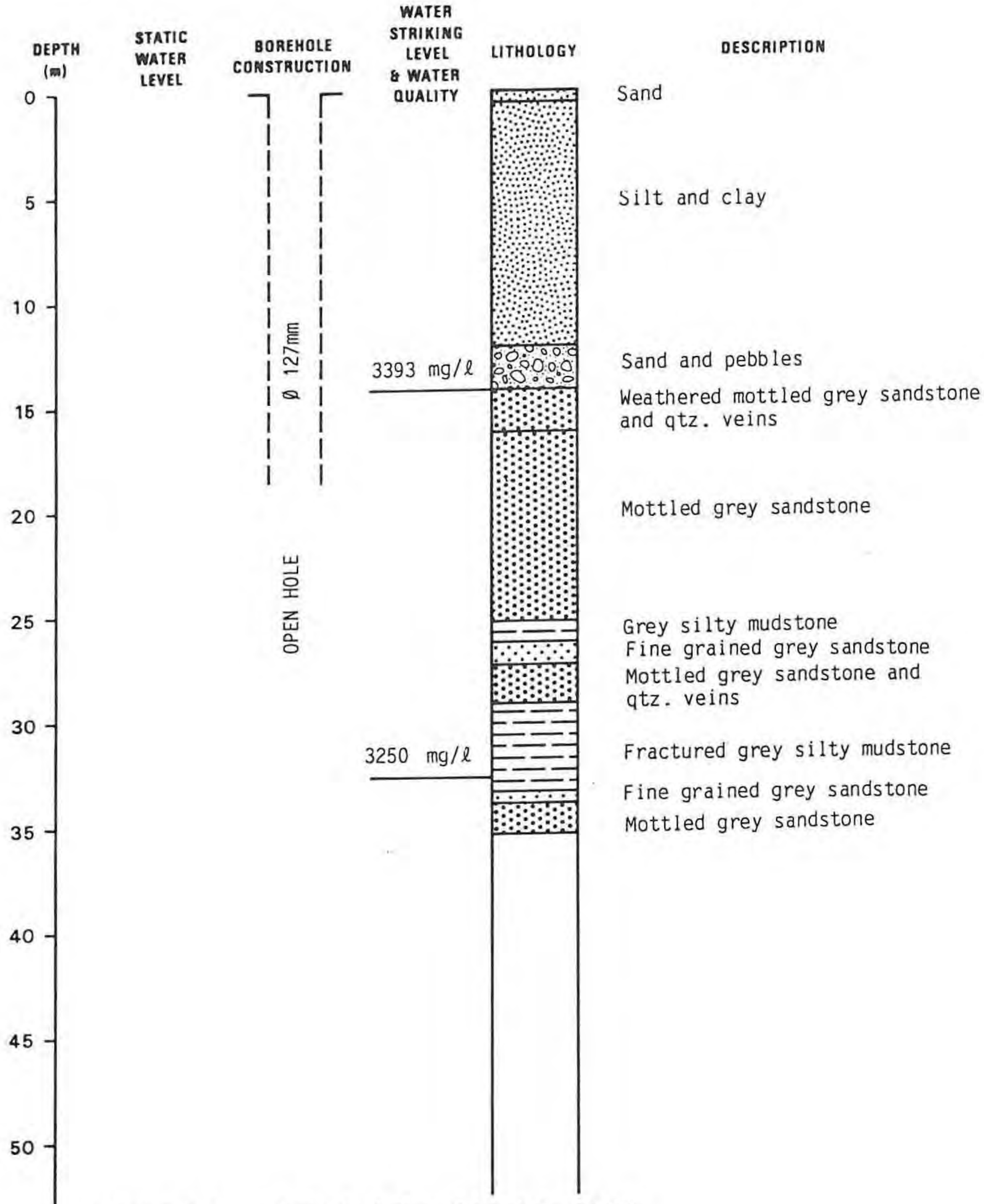


FIGURE 4.6 Geological log of borehole KD 25

BOREHOLE NO: KD 32

CADASTRAL FARM: MOORDENAARS DRIFT

BLOW TEST YIELD: 15.20 ℓ/s

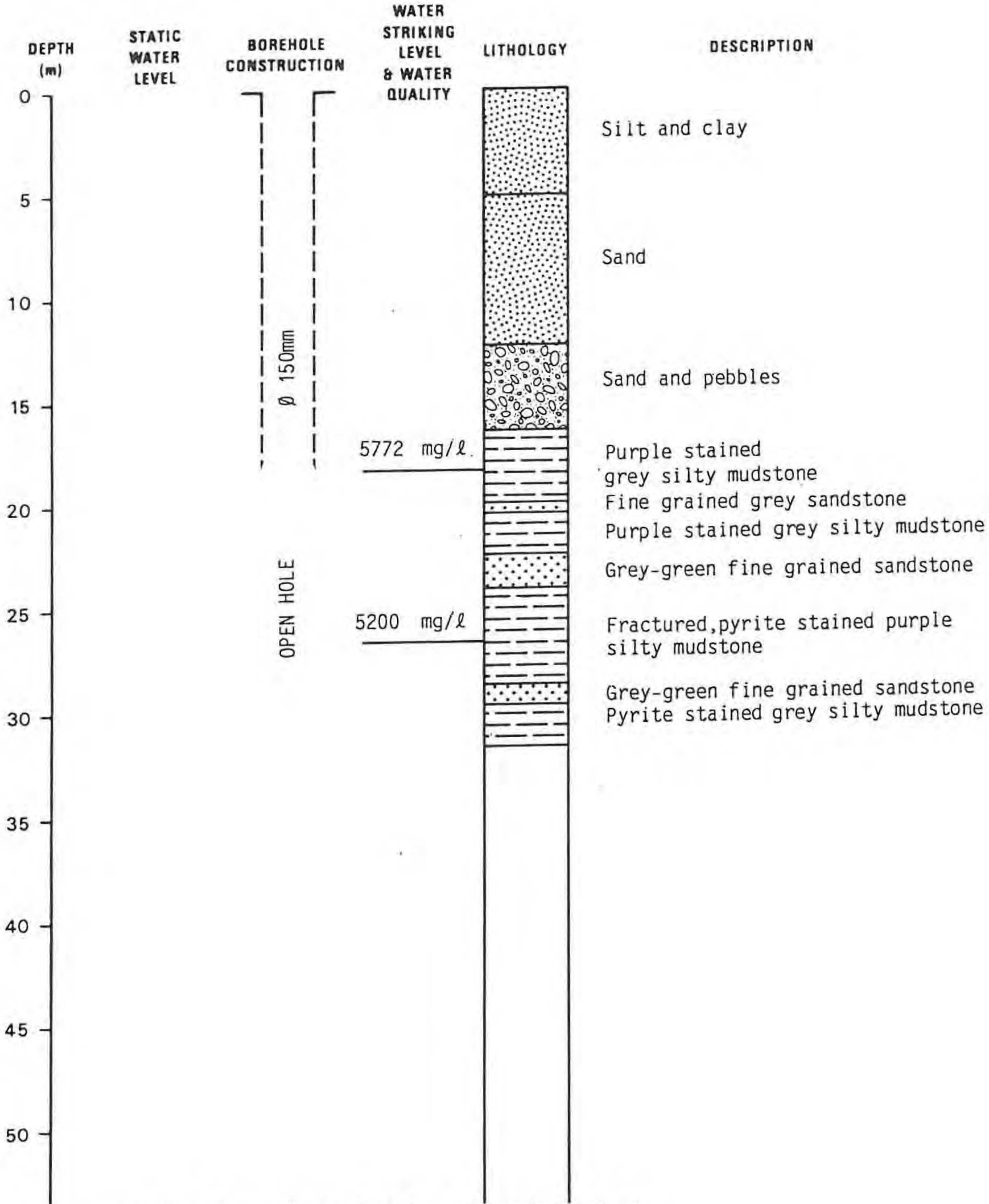


FIGURE 4.7 Geological log of borehole KD 32

PLATE 9. A view of the Great Fish River in the study area showing (a) alluvium thickness and (b) laterally extensive pebble layer

PLATE 10. Fractured calcrete (a) enclosing a fractured fine grained sandstone.

CHAPTER 5

GEOHYDROLOGY

5. PRINCIPLES OF AQUIFER TESTS

5.1 Aquifer Test Objectives

The controlled abstraction of water from boreholes or wells is one of the fundamental aspects of groundwater resources investigations. It leads to the determination of the aquifer characteristics of transmissivity (T) and storage coefficient (S), which are in turn important in providing a quantitative understanding of the natural flow of water through an aquifer and its response to abstraction (Jones and Rushton, 1981; Narasinham, 1969).

Transmissivity is "the product of the average hydraulic conductivity and the thickness of the aquifer" (Kruseman and de Ridder, 1970, pg 20) and can be thought of as the ease with which an aquifer is able to yield water. T is expressed in terms of m^2 per day. Storage coefficient is defined as "the volume of water released or stored per unit surface area of the aquifer per unit change in the component of head normal to that surface". (Kruseman and de Ridder, 1970, pg 21). It is a dimensionless term, has an order of magnitude of 10^{-4} to 10^{-6} for the confined parts of the aquifer, and depends on the elasticity of the aquifer material and the fluid (Kruseman and de Ridder, 1970).

Pumping tests provide data on which long-term yield potential, in the supply of groundwater for domestic and industrial use, can be estimated. When investigating yield of an aquifer, tests may range from a few short steps to long-term tests lasting a number of months (Del Mar Gonzales and Rushton, 1981) and may vary from a single pumping well with a battery of multilevel observation wells (Briz-Kishore and Bhimasankaram, 1982) to a single pumping well with no observation wells (Johnson, 1972). In addition to providing values of S and T, pumping tests were undertaken to provide data on pumping induced changes in water quality as well as data on the presence and influence of hydrological and geological boundaries, following the method outlined by Brereton (1979).

5.2 Well Hydraulics

The total drawdown induced in a pumping well consists of two components, namely aquifer loss and well loss (Brereton, 1979). Aquifer loss is the inevitable loss of head due to laminar flow of water through the aquifer, while well loss is a function of turbulent flow within the well and immediately adjacent part of the aquifer (Jones and Rushton, 1981).

Consequent to the well discharge a pressure gradient is created in the vicinity of the pumped well, resulting in the "cone of depression", which includes the necessary flow of water to sustain the well discharge (Narasinhan, 1969). The behaviour of the cone of depression is a function of several factors, such as the aquifer parameters, the aquifer configuration and the rate of well discharge. At the beginning of the test, the cone develops fast as the pumped water is initially derived from the aquifer storage immediately surrounding the well. But as the pumping continues and the area of influence increases, the cone expands and deepens at a decreasing rate due to a larger volume of water becoming available (Kruseman and de Ridder, 1970). The decline in water-levels is proportional to the pumping rate, and decreases logarithmically away from the observation well.

Various types of controlled pumping tests have been devised in order to study the characteristics of the cone of depression.

5.3 Types of Pumping Tests

Pumping tests may be divided into two main categories, namely well tests and aquifer tests.

5.3.1 Well Performance or Step-drawdown Tests

The step-drawdown test is a test in which the drawndown in a well is observed while the discharge rate from the well is increased in steps (Clark, 1977). Drawdown measurements are made within the abstraction well and the discharge is kept constant during each step. Step-drawdown tests are usually undertaken to enable the determination of the yield-drawndown characteristics of the abstraction well for the selection of pump type and for estimation of the maximum potential of the well (Brereton, 1979; Kruseman and de Ridder, 1970). However, the step-drawdown test also provides valuable information on well efficiency which is important for modifying drawdown values when undertaking constant rate tests, especially when no observation wells are present. Failure to take account of well loss results in an underestimation of the transmissivity of the aquifer (Clark, 1977). The determination of aquifer and well losses, and the selection of a suitable yield for the constant rate aquifer tests were the main reasons for undertaking step-drawdown tests in the present study. Prior to undertaking these tests, the wells were developed by bailing and surging following the techniques described by Jones and Rushton (1981).

5.3.2 Aquifer Tests

Whereas the step-drawdown test provides information on the hydraulic conditions in the immediate vicinity of the well, the aquifer test provides information on the hydraulic properties of the aquifer within the area of pumping influence of the abstraction well (Brereton, 1979). An aquifer test consists of pumping one well at a constant rate and recording both the drawdown in that well and the drawdown caused by this pumping in other nearby observation wells (Johnson, 1972). The yield is determined from the preceding step-drawdown test with a view to producing measurable drawndowns in all observation wells (Jones and Rushton, 1981).

During this study, measurements of drawdown were made at predetermined intervals using an electric sounder, and yield kept constant by using a valve in the pump outlet pipe. The yield was calculated by measuring the time required to fill a container of known volume. The duration of an aquifer test depends on the type of aquifer to be tested and the degree of accuracy required in determining the hydraulic properties. A period of 24 hours is generally accepted for confined aquifers, as are encountered at Middleton (Kruseman and de Ridder, 1970). The advantage of a longer period of pumping is that the presence of boundary conditions, previously unknown, may be revealed.

The hydraulic characteristics of an aquifer are found by substituting the values of drawdown measured in the observation wells, their distance from the abstraction well, and the well discharge in an appropriate formula (Jones and Rushton, 1981; Kruseman and de Ridder, 1970).

5.3.3 Recovery Test Data

By measuring the recovery of water levels after the cessation of pumping, a mirror image of the pattern of drawdown measured during the abstraction phase should be obtained (Jones and Rushton, 1981; Johnson, 1972).

Recovery test data may be more reliable than drawdown data especially when the yield of the abstraction well was not constant during the pumping period (Kruseman and de Ridder, 1970). The phenomena of surcharge, where water levels recover rapidly during the early phase of recovery due to the return of water from the pump column, was particularly noticable when pumping low yielding formations during the Middleton study.

In low yielding formations it is often difficult to undertake a conventional constant rate aquifer test, because of the well's low specific capacity, which may cause the pump to break suction during the test. Also, most of the drawdown data obtained will probably reflect casing storage effects rather than true aquifer parameters. The best method for analysing these formations is to pump the borehole to pump suction and then monitor recovery levels (Schafer, 1980). During the Middleton study, the aquifer parameters of the low yielding alluvial aquifer were determined by performing recovery tests on large-diameter, partially penetrating dug wells (Plate 11). The method employed required monitoring of the recovery to 50% of the maximum drawdown level. The advantage of using a recovery method is twofold :

- there is no head loss due to turbulent flow caused by pumping;
- all the water that flows into the wells must come from the aquifer and consequently aquifer properties play a significant part in the recovery (Herbert and Kitching, 1981).

A transmissivity value of 1,1 m^2/day was determined for the aluvial aquifer in this way (test curves contained in Appendix C, Figures C.1 and C.2).

5.4 Methods of Analysis

A number of techniques exist for determining aquifer parameters from data obtained during pumping tests. These are based largely on the work of Theim (1870), Theis (1935) and Jacob (1946). The various methods of analysis are well documented in Kruseman and de Ridder (1970).

Analysis of pumping test data from the Middleton study followed mainly the assumptions of the non-equilibrium well formula devised by Theis (1935) where the parameters T and S can be determined from the early stages of a pumping test rather than having to wait until water levels in observation wells have reached equilibrium (Johnson, 1972). Step-drawdown tests were analysed using a computer programme (Seward, 1982) based on the work of Bierschenk and Wilson (1961). Constant rate aquifer tests were analysed using the Jacob method (Jacob, 1946), the Theis recovery method (Theis, 1935), the Hantush image method for one recharging boundary (Hantush, 1956) and a calculator method devised by Paschette and Mc Elwee (1982), while aquifer parameters from large diameter dug wells were determined by the recovery method of Herbert and Kitching (1981).

A number of assumptions underly these methods of analysis :

- the aquifer has a seemingly infinite areal extent;
- the aquifer is homogeneous isotropic and of uniform thickness over the area influenced by the pumping test;
- prior to pumping, the piezometric surface is horizontal over the area influenced by the pumping test;
- the aquifer is pumped at a constant discharge rate;
- the pumped well penetrates the entire aquifer and thus receives water from the entire thickness of the aquifer by horizontal flow (Kruseman and de Ridder, 1970, pg 46).

Step-drawdown Test Analysis

The step-drawdown test provides data for the calculation of well loss (C) and aquifer loss (B) (Brereton, 1979). The well loss calculation is vital in the analysis of tests on abstraction wells with no observation wells. The knowledge of the well loss component of drawdown allows correction of drawdown data to yield the true drawdown, thereby making possible the analysis of constant discharge tests in such wells. (Clark, 1977).

A computer programme by Seward (1982) was used to derive values of well loss and aquifer loss. From those values a factor called "well efficiency" defined as "the ratio of aquifer loss to total drawdown" (Clark, 1977, pg 137) was calculated. Theorectically, in a 100% efficient well, there will be no well losses so that well drawdown is equal to drawdown caused by aquifer losses (Jones and Rushton, 1981).

The Jacob Method of Analysis

The Jacob method (Cooper and Jacob, 1946), based on the Theis formula (Kruseman and de Ridder, 1970), is a straight line method of analysis, in which the time-drawdown relation is plotted on semilog paper and the best fitting straight line is drawn through the plots, disregarding a few early points. The slope of the straight line determines the transmissivity while its intercept with the zero drawdown axis aids the determination of S (Narasinhan, 1969).

The Theis Recovery Method of Analysis

Transmissivity is calculated using the Theis recovery method by plotting residual drawdown, i.e., the difference between the original water level prior to pumping and actual water level measured at a certain moment t" since pumping stopped, against $^{t}/_{t"}$ on semilog paper ($^{t}/_{t"}$ is the time since pumping commenced divided by the time since pumping stopped) (Kruseman and de Ridder, 1970). A straight line is fitted to the data plots and T is determined from the slope of this line.

Hantush's Image Method (for one recharge boundary)

The concept of a homogeneous isotropic aquifer of seemingly infinite areal extent is seldom encountered in nature. Geohydrological boundaries occur which manifest themselves as departures (in observed time-drawdown data) from the classical Theis curves. They may take the form of either positive recharge boundaries (e.g. a stream or another aquifer in hydraulic continuity with the pumped aquifer) or negative barrier boundaries (e.g. fault planes, impervious layers or merely a decrease in permeability of a particular layer) (Del Mar Gonzalez and Rushton, 1981).

The problem of an inhomogeneous finite aquifer is solved by using image wells and the principal of superposition (Kruseman and de Ridder, 1970). During this study Hantush's image method was used for those wells, situated near the Great Fish River, which showed recharge boundary effects.

Calculator Method of Paschetto and Mc Elwee

This method is based on the Theis equation and the "best" T and S values in the least squares sense were obtained (Paschetto and Mc Elwee, 1982). A feature of the programme is the calculation of the absolute error at an "average" data point in the drawdowns. An error of several tenths of a metre or more would indicate either poor data or a hydraulic situation that cannot be represented by the Theis equation.

5.5 Aquifer Test Results

During the Middleton study 8 constant rate aquifer tests (duration varying between 420 and 2880 minutes), 4 step-drawdown tests (step duration varying between 60 and 90 minutes) and two 50% recovery tests (on partially penetrating wells) were undertaken. In six of the 8 constant rate tests observation holes were sufficiently close to provide storativity values for the aquifer.

Well selection for the pumping tests were based on "blow yields", obtained by jetting compressed air into the well during drilling and after completion of the well.

5.5.1 Step Drawdown Tests

The step drawdown test data are plotted in Figures 5.1 to 5.4. "Well efficiency" values were calculated using aquifer and well losses (Clark, 1977). It is noted that well efficiency decreases with increasing yield, this being due to an increase in the turbulent flow and consequently leading to greater well loss (Brereton, 1979). The reasons for the high "well efficiency" values are twofold :

- most of the water is derived from shallow aquifers, hence low frictional losses in the casing string;
- most of the water is derived from secondary joints and fractures doing away with the need for screens, hence low turbulent losses in the vicinity of the well (Brereton, 1979; Clark, 1977).

The negative B value is usually attributed to recharge boundary conditions. However, in the case of well KD 35 it is probably due to pump inefficiency at high pumping rates. Pumping rates for the constant rate aquifer tests were selected on the basis of providing suitable drawdowns in both abstraction and observation wells (i.e. measurable, but not too closely approaching pump suction).

5.5.2 Constant Rate Aquifer Tests

Figures 5.5 and 5.6 contain examples of the data for both the abstraction and recovery phases of these tests, while the aquifer parameters are tabulated in table C.1, Appendix C (the remaining aquifer test curves are contained in Appendix C).

5.5.3 Aquifer Test Curves

Four main types of aquifer can be identified from the tests. These reflect the heterogeneity of both the sandstone and mudstone aquifers present in the Koonap Formation.

Type 1

The first, most abundant type is defined by rapid drawdown during the early stages (within first ten minutes) followed by a constant, gentle increase in drawdown. Wells which show this type of drawdown relationship include KD 1, KD 15, KD 22, KD 25, KD 35, KD 34 and KD 37. The initial rapid drawdown reflects water derived from casing storage, while the latter constant increase shows the response of the entire aquifer system to pumping. Also during the early stages of pumping, the permeability of the aquifer immediately surrounding the well is low; consequently the rate at which the aquifer is dewatered from the zone of influence is not equal to the rate of pumping resulting in rapid drawdowns (Britz-Kitshore and Bhimasankaram, 1982), i.e. further development occurred during the early stages of the test. In most cases the entire plot is a smooth line indicating that the groundwater flow during pumping is laminar.

Type 2

The second type is similar to Type 1 but shows negative boundary conditions during the final stages of the test. As this type was only encountered in well KD 5, where the test was run for 2880 minutes, it is a reasonable assumption that either recharge or barrier boundary conditions may have been encountered, should pumping have been continued, in the latter stages of Type 1 curves (which were pumped on an average for 1440 minutes).

Type 3

The third type, of which wells KD 32, KD 33 and KD 4 are examples, is typical of aquifer tests undertaken in "patchy" aquifers (Barker and Herbert, 1982). Here it is postulated that the aquifer is generally of low transmissivity but has within it pockets of relatively high transmissivity. Wells KD 32, KD 33 and KD 4 are drilled within pockets of fairly high transmissivity, this being reflected in the gentle slope of the aquifer test curve during the early stages of the test. However, as pumping progresses, the zone of influence extends into the area of low transmissivity resulting in a rapid increase in drawdown, this being reflected in a continuous increase in the slope of the test curve. The rate of drawdown then becomes dominated by the transmissivity of this outer region. However, the final stage of the curve shows once more a flattening of the curve refecting the influence of a postive recharge boundary.

Type 4

This type is defined by a curve which shows a constant increase in drawdown with time. Well KD 3 is representative of this type. The very limited drawdown (0,27m) measured in this observation well after 1440 minutes of pumping, compared to 6,8m measured in the abstraction well (KD 1), 18m away, indicates a very low connectivity between the wells (probably a lower degree of fracturing in the vicinity of KD 3). This again illustrates the "patchy" nature of the aquifer, where the transmissivity varies greatly over fairly short distances.

Aquifer Type

Based on the aquifer test curve, the fractured rock aquifers of the Middleton study area can be defined as being "confined" in nature, i.e. "a confined aquifer is a completely saturated aquifer whose upper and lower boundaries are impervious layers" (Kruseman and de Ridder, 1970, pg 19).

Aquifer Yield

Aquifer yield varies considerably over the study area and did not appear to be related to rock type. For example, yields from mudstone aquifers varied between 38 and 588m^3/day, and the sandstone aquifers between 57 and 72m^3/day. The yield appears rather to be related to the degree of fracturing present. Such a variability in yield was observed by Barker and Herbert (1982) in the Deccan Trapps of India.

PLATE 11. Seepage water collection Pit 2. Water level in Pit (a) is approximately 0,40m above river level (b).

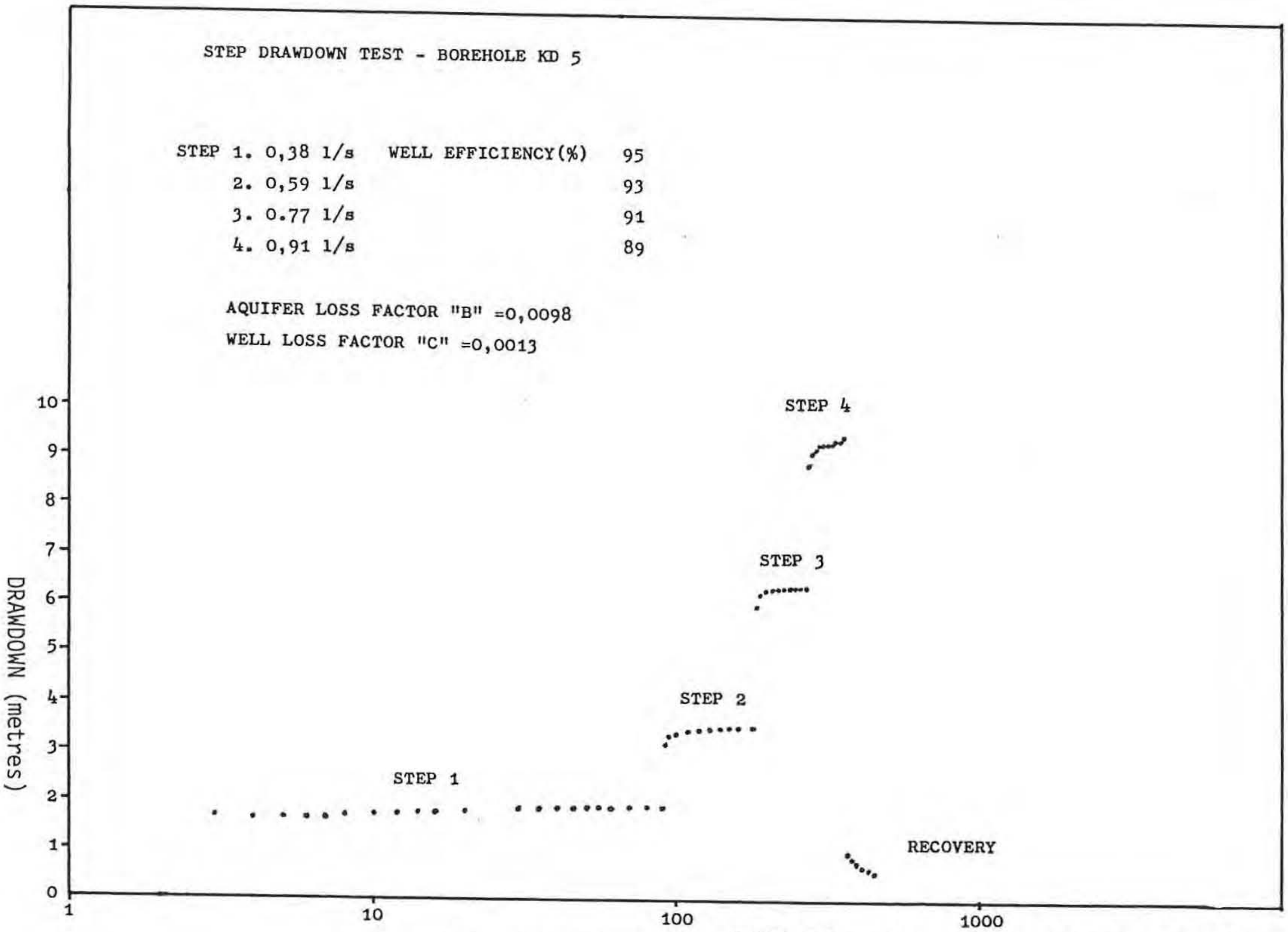


FIGURE 5.1 Step drawdown test - Borehole KD 5

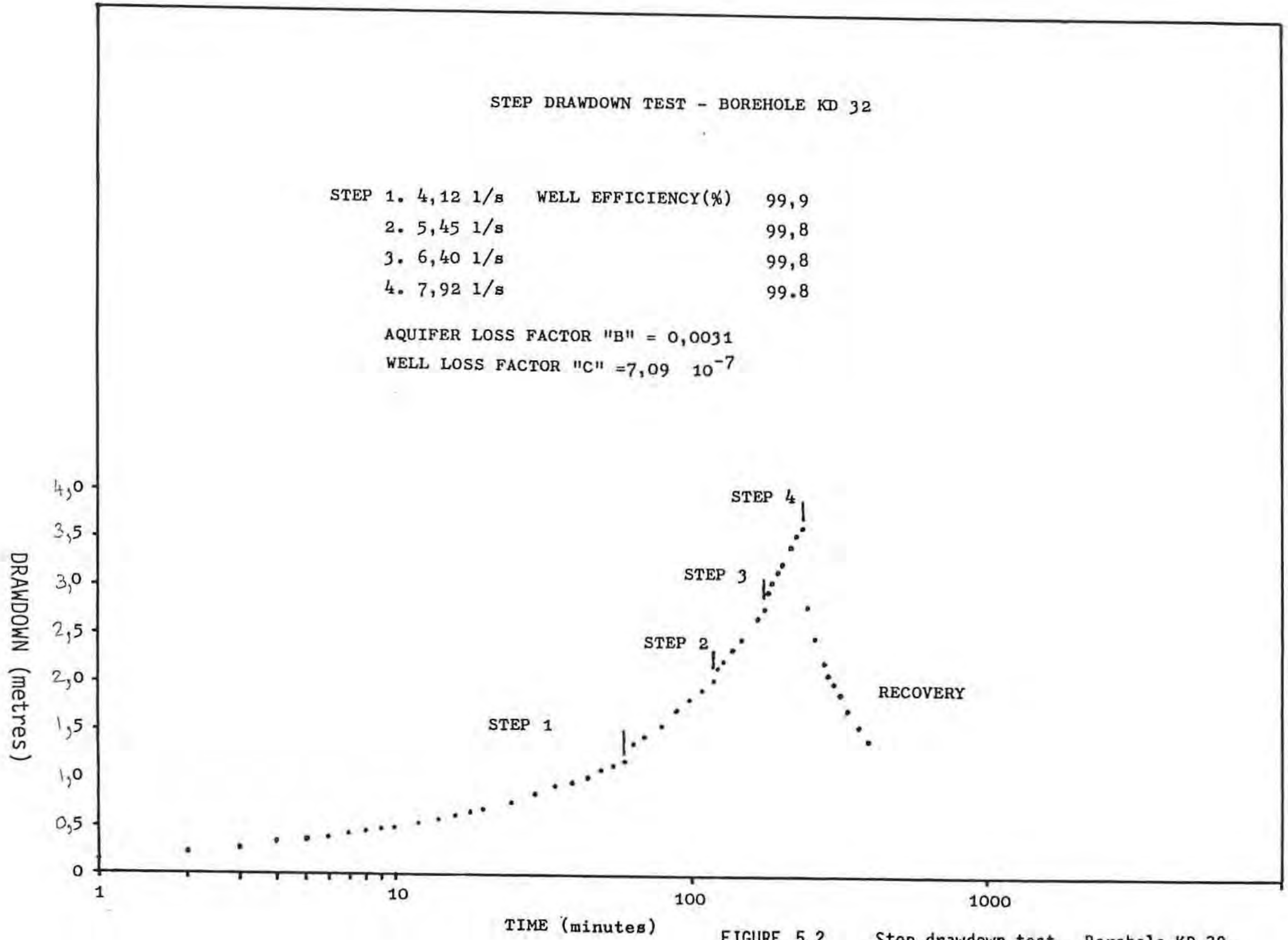


FIGURE 5.2 Step drawdown test - Borehole KD 32

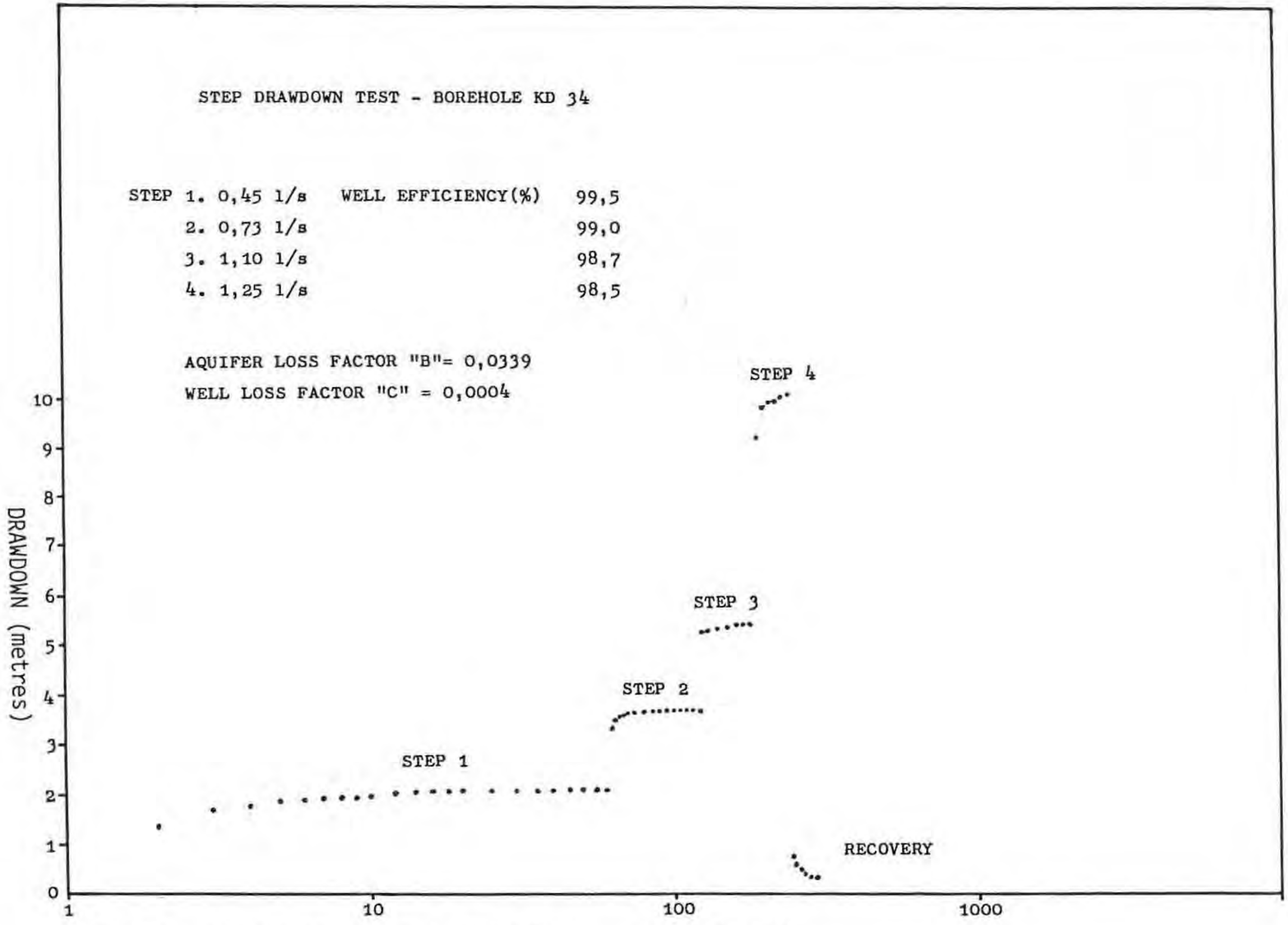


FIGURE 5.3 Step drawdown test - Borehole KD 34

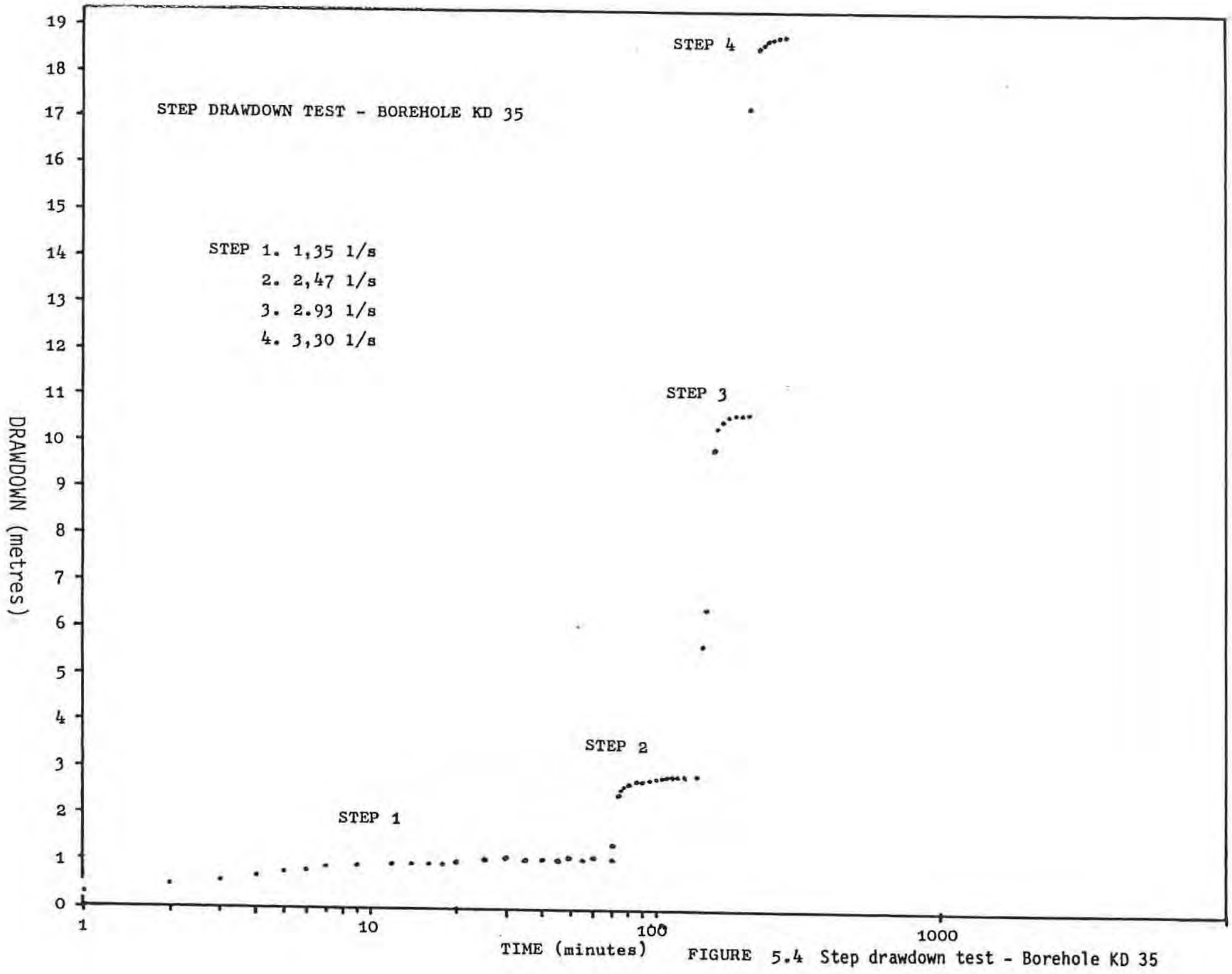


FIGURE 5.4 Step drawdown test - Borehole KD 35

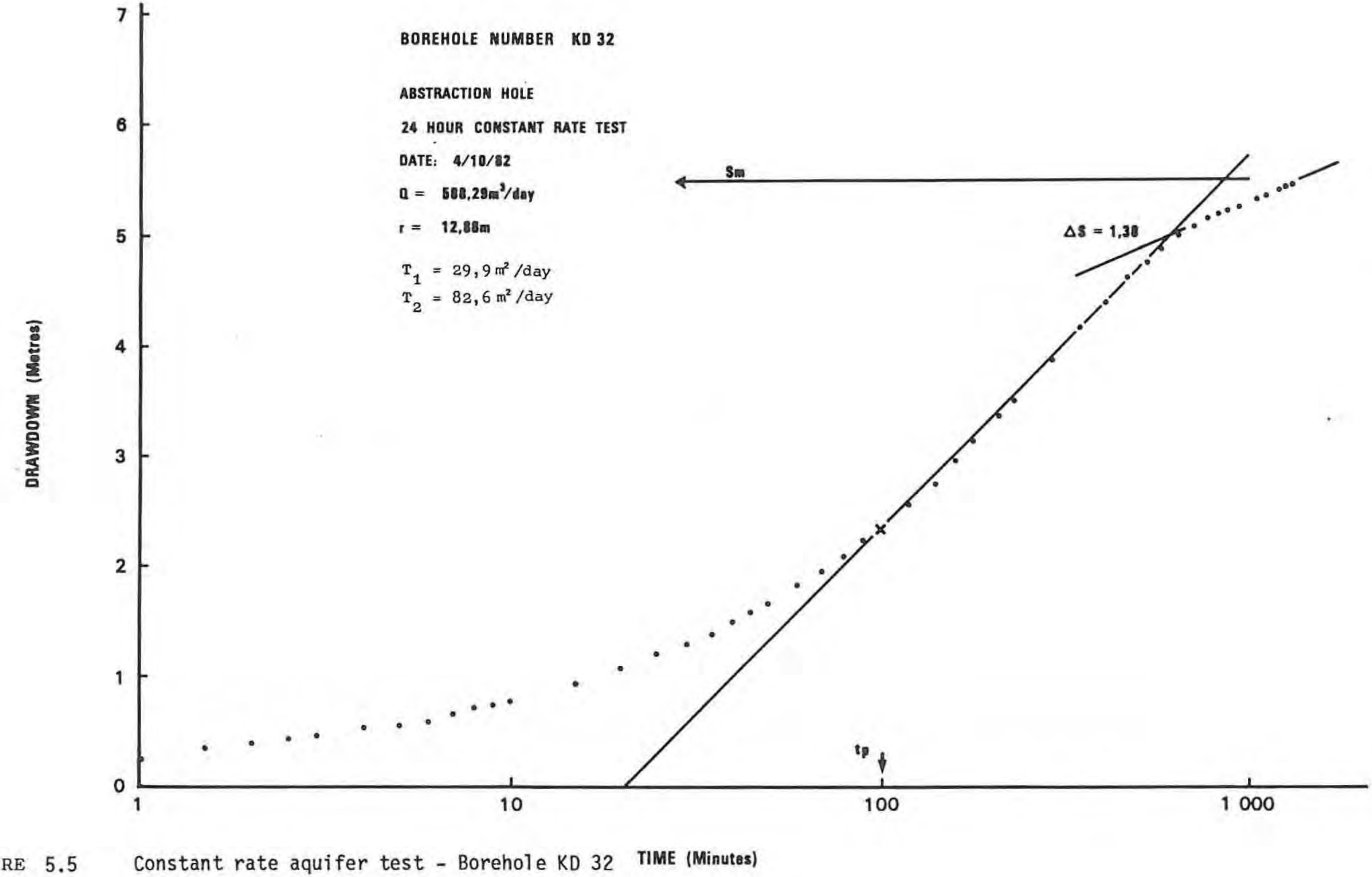


FIGURE 5.5 Constant rate aquifer test - Borehole KD 32

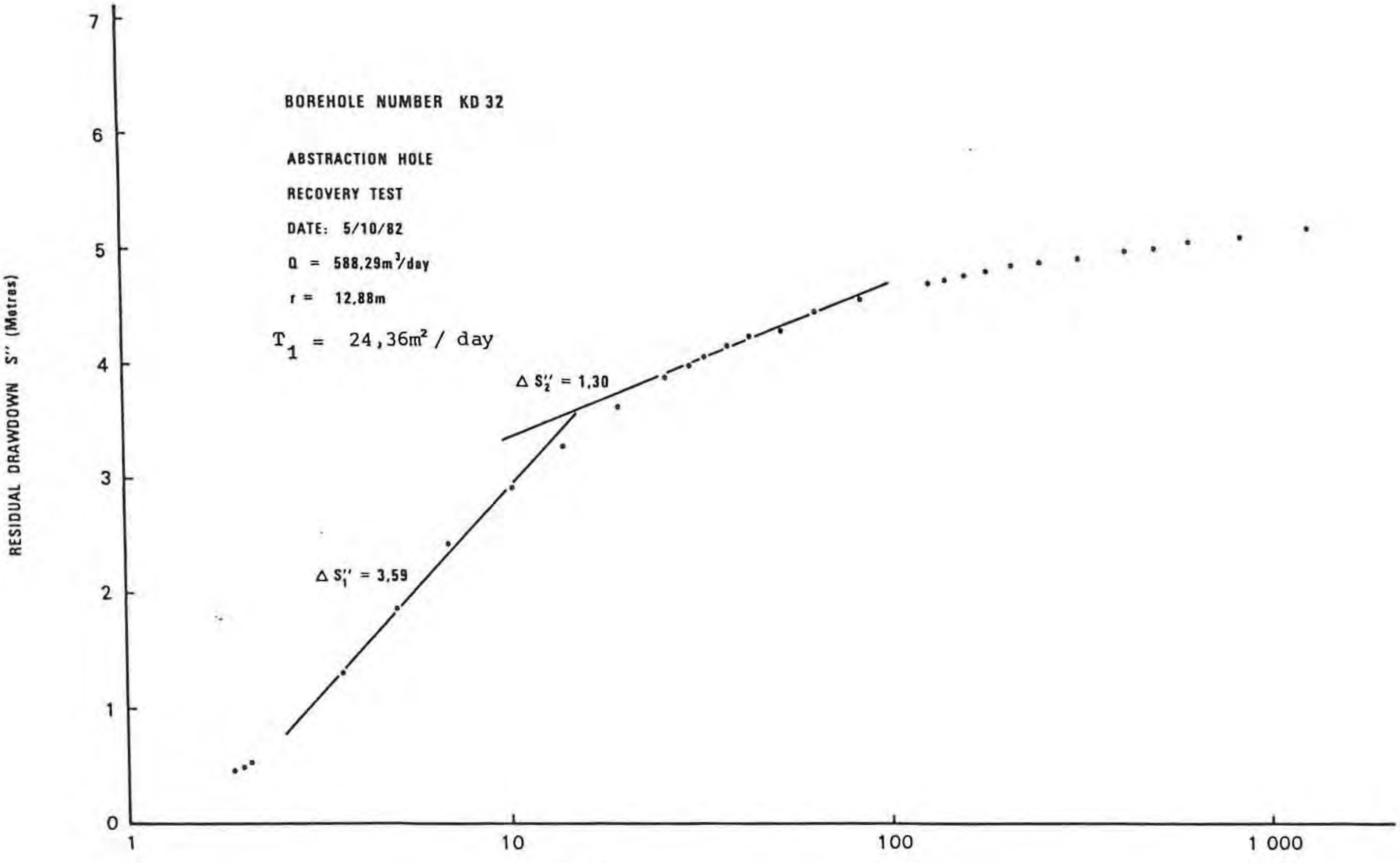


FIGURE 5.6 Recovery test - Borehole KD 32

CHAPTER 6

HYDROCHEMISTRY

6.1 Sources of Soluble Salts in Water

Soluble salts, which eventually find their way to rivers, may be derived from a number of sources, namely, groundwater seepage (Tordiffe, 1978), air-borne salts or aerosols (Wipplinger, 1980), decaying natural vegetation (Malekuti and Gifford, 1978), nitrogen and potassium chloride fertilizers (Hill, 1982) and salt pickup by overland flow (Ponce and Hawkins, 1978). In the Middleton area, however, the contribution of soluble salts by irrigation return flow, and the chemical weathering of soils and rocks, far outweighs any contribution by rainfall and overland flow, which have an average total dissolved solid (TDS) content of 20mg/l and 190mg/l respectively (from 4 rainfall events measured during 1982).

As depicted in Figure 6.1, irrigation water forms the major input into the hydrochemical system (70% of applied water). During its residence in and its passage through the soil, as well as its storage in and transmission through the fractured sandstones and mudstones, the irrigation water undergoes chemical changes which result in an increase in the TDS content of seepage water. Irrigation water possesses two major characteristics which may be detrimental to both seepage water quality and soil properties, namely salinity and sodicity (Cass, 1979).

6.1.1 Salinity

Salinity refers to the total quanity of salts present in irrigation or soil water. These salts usually consist of chlorides, sulphides, carbonates and bicarbonates (anions) and sodium, calcium and magnesium (cations). The presence of dissociated ions in solution renders a water electrically conductive, the conductivity being dependent on the number and

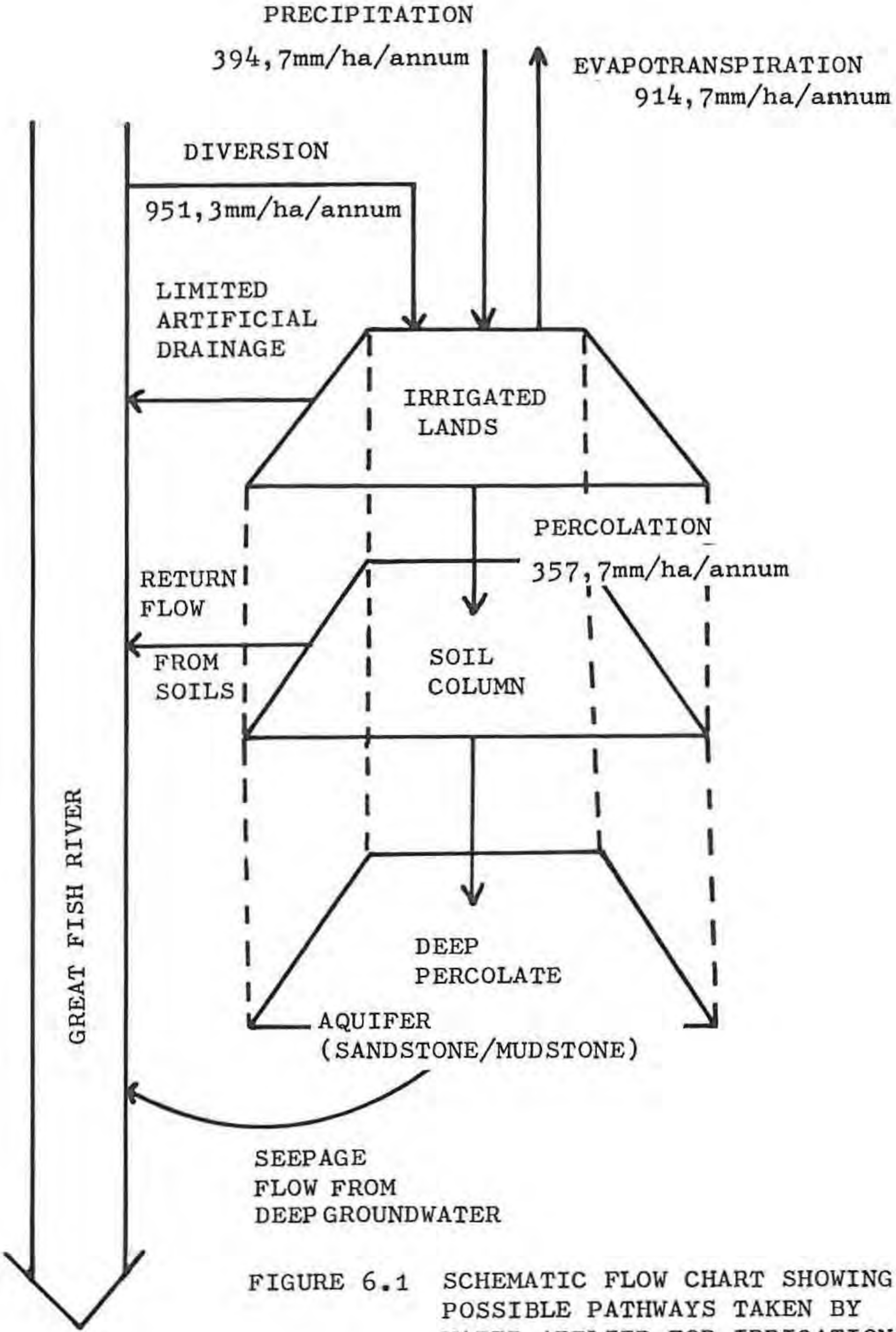


FIGURE 6.1 SCHEMATIC FLOW CHART SHOWING POSSIBLE PATHWAYS TAKEN BY WATER APPLIED FOR IRRIGATION

kinds of ions present, their relative charge and their "mobility" (Hem, 1959) as well as the temperature of the solution (Johnson, 1972). Salinity is usually measured in terms of electrical conductance of water, expressed in millisiemens per metre (mS/m) at 25°C, or as a TDS value, expressed in mg/l (Cass, 1979).

6.1.2 Sodicity

Sodicity, which refers to the quantity of sodium in relation to calcium and magnesium in soil or water, is discussed more fully in Chapter 7. Calcium and magnesium, provided they are not in excess, have a favourable effect on soil properties, whereas sodium has an adverse effect on swelling and aggregate stability (Hem, 1970; Rhodes and Merrill, 1975).

6.1.3 Salt Accumulation in the Soil

The portion of irrigation water actually consumed by plants or evaporated is essentially free from dissolved salts. Consequently, most of the soluble matter originally in the irrigation water remains behind after evaporation and increases the salinity of the soil solution (Hem, 1959). Unless the soil drainage is adequate, salt and water will tend to accumulate in the soil (Cass, 1979). Drainage is important because even poor quality water (TDS content of 2000 to 4000 mg/l) has been applied successfully on well drained soils in Israel and Texas. In contrast fresh river water in Northern India, Iran and Central Asia has induced strong secondary salinization after a relatively short period of time due to adverse soil properties (Kovda et al., 1971; Edmonds, 1981).

Since irrigation causes the intensification of soil moisture movement, natural salts are mobilized from high-lying areas to low-lying areas and from well drained soils to poorly drained soils, where they accumulate or are discharged as saline seepages (Cass, 1979). Studies in the North American Great Plains (Miller et al., 1981) revealed that TDS values ranged from 3200 mg/l in recharge areas to 40900 mg/l in discharge (seepage) areas.

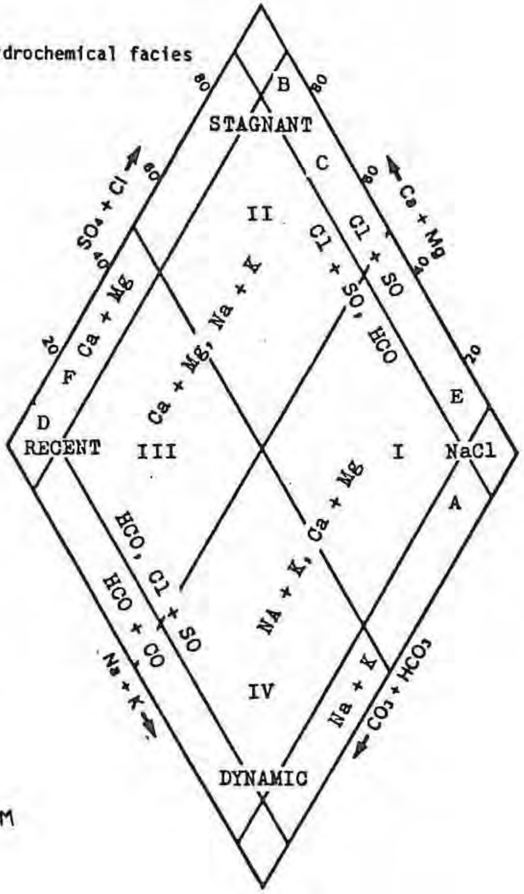
Because of the processes of adsorption and dissolution in the soil, the salt content of seepage water not only increases but also changes in composition.

6.1.4 Relationship between Water and the Minerals with which it comes into Contact

A general relationship exists between the mineral composition of a natural water and that of the solid materials with which the water has been in contact (Hem, 1950). This is a consequence of the relatively slow movement of groundwater in both soils and consolidated formations which results in chemical reactions between the water and solid materials (Johnson, 1972). A simple relationship exists between the chemistry of recharge and discharge water when an aquifer receives direct recharge from rainfall or irrigation without encountering any other aquifers. More complex relationships occur when the aquifer is overlain by soils in which dissolution, base exchange and precipitation occurs, as well as mixing with other waters (Hem, 1959).

The degree to which chemical equilibrium is reached between the groundwater and the environment in which it occurs depends largely on the residence time of the water. The residence time is inturn dependent on the permeability of the geological strata through which ~~it~~ the groundwater flows and on the hydraulic head which is developed. Tordiffe and Botha (1981) found that the macro-toprography of the Great Fish River Basin appears to exercise some influence on the rate of groundwater movement which can be observed in the regional distribution of dissolved salts. High percentage of Ca^{++} and HCO_3 ions are found in the high-lying recharge areas of the catchment while high Na^+ and Cl^- percentages are found in the low-lying, "stagnant" reaches of the river valley. The role of soils as a reservoir for salts is discussed in Chapter 7. The irrigation water, which percolates through the soils, enters the consolidated formations through pores, joints and cleavages, and reacts with the mineral surfaces with which it comes into contact (Tordiffe, 1980). Water acts as a solvent on practically all minerals, its chemical action being increased by the presence of dissolved CO_2 (Hem,

FIGURE 6.2 Piper diagram showing hydrochemical facies



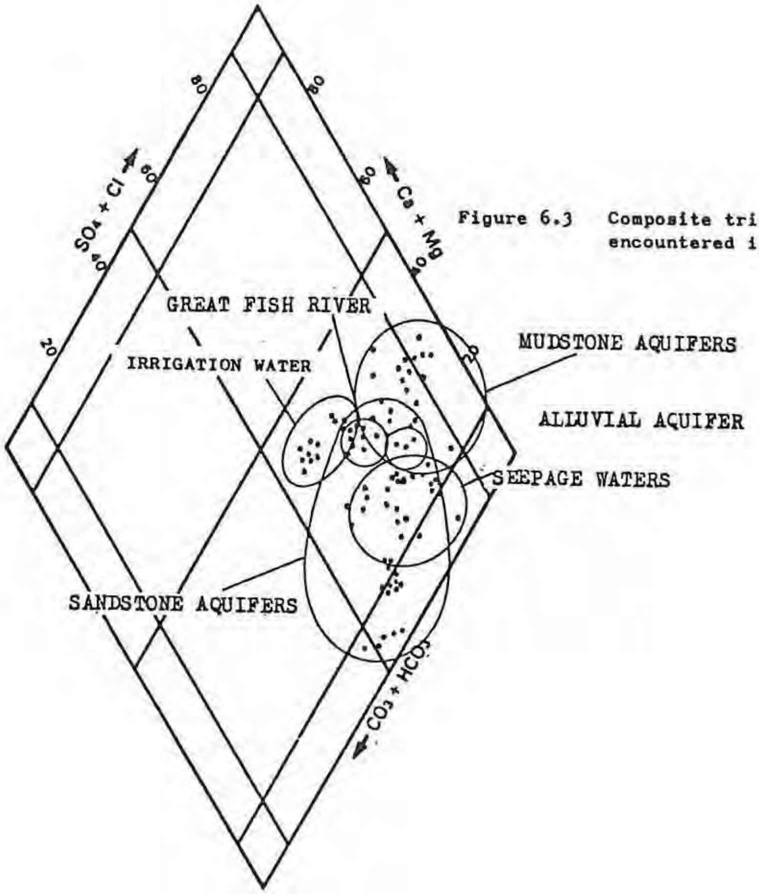


Figure 6.3 Composite trilinear plot of waters encountered in the study area.

SOURCE TYPE		SAMPLE NUMBER	$^{Mg}/_{Ca}$	$^{K}/_{Na}$	$\frac{Cl-(Na+K)}{Cl}$	$\frac{Cl}{Anions}$	$\frac{SO_4}{Anions}$	$\frac{Na}{Cations}$	T.D.S. CONTENT
SANDSTONE	KD 1	030081	4,4	0,025	-0,62	0,55	0,18	0,85	1937
	KD 17	019159	1,2	0,0005	-0,19	0,57	0,19	0,65	1911
	KD 22	031547	1,74	0,025	-1,19	0,41	0,19	0,89	1573
	KD 5	034800	0,98	0,018	-2,88	0,41	0,19	0,74	1125
	KD 14	031483	1,8	0,034	-0,42	0,56	0,19	0,78	2321
	KD 45	030406	2,16	0,020	0,0025	0,66	0,20	0,70	3718
MUDSTONE	KD 32	032677	2,5	0,006	0,007	0,76	0,20	0,73	4602
	KD 37	017041	0,56	0,03	-0,047	0,77	0,11	0,74	2275
	KD 16	029936	2,59	0,038	-0,22	0,62	0,19	0,76	2002
	KD 25	031568	1,76	0,003	-0,63	0,53	0,16	0,86	3250
	KD 5	015040	0,96	0,08	-1,03	0,42	0,19	0,76	1437
SANDSTONE MUDSTONE	KD 24	023982	2,4	0,039	-0,45	0,59	0,23	0,83	3471
	KD 13	022193	2,06	0,027	-0,31	0,59	0,22	0,76	2216
IRRIGATION WATER		030545	1,31	0,008	-0,69	0,38	0,19	0,60	620
		029997	1,87	0,005	-0,30	0,48	0,20	0,61	1352
		034659	1,40	0,007	-0,58	0,38	0,19	0,58	620
		017829	1,70	0,007	-0,36	0,48	0,21	0,64	1144
SEEPAGE	SS 1	015128	12,8	0,006	-0,51	0,62	0,19	0,89	6643
	PIT 2	025874	27,9	0,004	-0,69	0,48	0,20	0,87	2243
	SS 1	029226	4,3	0,006	-0,48	0,61	0,21	0,88	6500
	PIT 1	016077	2,6	0,009	-0,66	0,47	0,17	0,75	1807
	SS 1	033166	8,4	0,019	-0,42	0,62	0,20	0,86	6500
	PIT 1	032485	2,4	0,006	-0,61	0,48	0,17	0,74	1820
	PIT 2	030046	2,4	0,006	-0,81	0,49	0,20	0,84	2307
	KD 2	024847	0,206	0,008	-0,57	0,55	0,23	0,76	2496
	KD 37	019549	1,92	0,008	0,098	0,68	0,17	0,62	2600
10/8/82	KD 6	020942	1,07	0,05	-0,91	0,39	0,21	0,69	975
9/9/82	KD 6	023889	1,15	0,058	-0,93	0,39	0,20	0,69	975
LEAKAGE WATER FROM CANAL, POND									
9/9/82	KD 7	018743	2,94	0,057	-0,89	0,34	0,14	0,57	1014
15/12/82	KD 7	023622	2,47	0,041	-0,28	0,40	0,18	0,50	1138
ALLUVIAL WATER	KD 42	025350	1,6	0,0007	-0,60	0,54	0,18	0,81	3198
	KD 43	021796	3,08	0,011	-1,51	0,37	0,15	0,90	1424

TABLE 6.1. A COMPARISON OF VARIOUS WATERS USING ION RATIOS.

1959), leaving behind a residue enriched in less soluble components. The predominant sedimentary rock types in the Fish River catchment are mudstone and a fine grained sandstone or greywacke (Tordiffe, 1980). The mudstone, because of its fractured nature (great surface area exposed to weathering) and ability to release large amounts of dissolved ions upon weathering, is very important in terms of mineralisation of groundwater.

6.2 Water Sample Collection and Analysis

Although a single sample from a surface water source may have little value, a single sample from a groundwater body may represent closely the quality of water from that source for many years (Hem, 1959).

Conductivity measurements of all water points in the Middleton study area were made and on this basis over 200 samples were analysed by the Hydrological Research Institute for pH and major element (i.e. Total alkalinity, NH_4, Ca, Cl, NO_3, Na, Mg, F, Si, K, SO_4 and P) determinations. Th~~is~~ese data were then stored and analysed using a computer programme which converted parts per million, to equivalents per million and percentage equivalents per million. It also provided a means of comparing various ions graphically by the use of a plotting routine.

In an attempt to understand the great variations in water quality over the study area, the samples were grouped according to various categories, e.g. irrigation and seepage water, water from sandstones and mudstones, and plotted on Piper trilinear diagrams (Figures 6.2 and 6.3, and Figures D.1 to D.6, Appendix D). The ions were also compared by calculating various ratios (Table 6.1) and, following the procedure of Hem (1959), by plotting selected ratios against total dissolved solid content (Figures 6.4 and 6.5).

TABLE 6.2 A COMPARISON OF TYPICAL IRRIGATION, ALLUVIUM AND SEEPAGE WATERS

WATER TYPE	PERCENTAGE EQUIVALENTS PER MILLION						
	CATIONS				ANIONS		
	Mg	Ca	Na	K	SO_4	Cl	TAL
Irrigation	22,5	17,0	60,0	0,5	18,8	38,4	42,8
Alluvium	12,0	10,8	76,6	0,4	22,5	55,5	22,0
Seepage	9,7	0,8	89,0	0,6	18,5	61,9	19,6

6.3 Irrigation, Alluvium and Seepage Water Chemistry

Typical irrigation, alluvium and seepage water samples are tabulated in Table 6.2.

6.3.1 Irrigation Water

All irrigation water samples, which form the input into the system, plot within the "NaCl" field of the Piper diagram, but towards "recent recharge". The TDS content of the samples range from 599 mg/l to 1291 mg/l (average is 821 mg/l). The equivalent percentage Na is approximately 60% while that of Cl varies between 40% and 50%.

6.3.2 Seepage Water

Seepage water samples, on the other hand, have higher equivalent percentages Na and Cl and plot in the vacinity of "NaCl brines" (equivalent percentage Na 80% and Cl 50% to 60%). The higher percentage Na, as well as the higher $^{Mg}/Ca$ ratio could be as a result of base exchange between the irrigation percolate and the adsorbed salts in the soils (see Chapter 7).

In both irrigation and seepage water, the $^{SO_4}/\text{Total}$ anions ratio remains constant at 0,20. The most striking feature, however, is the great increase in TDS content of the irrigation percolate as it drains to the river. This is particularly evident in samples taken from seepage SS1 and pit 2 (Table 6.3). The TDS value of pit 1 is not representative of seepage water as

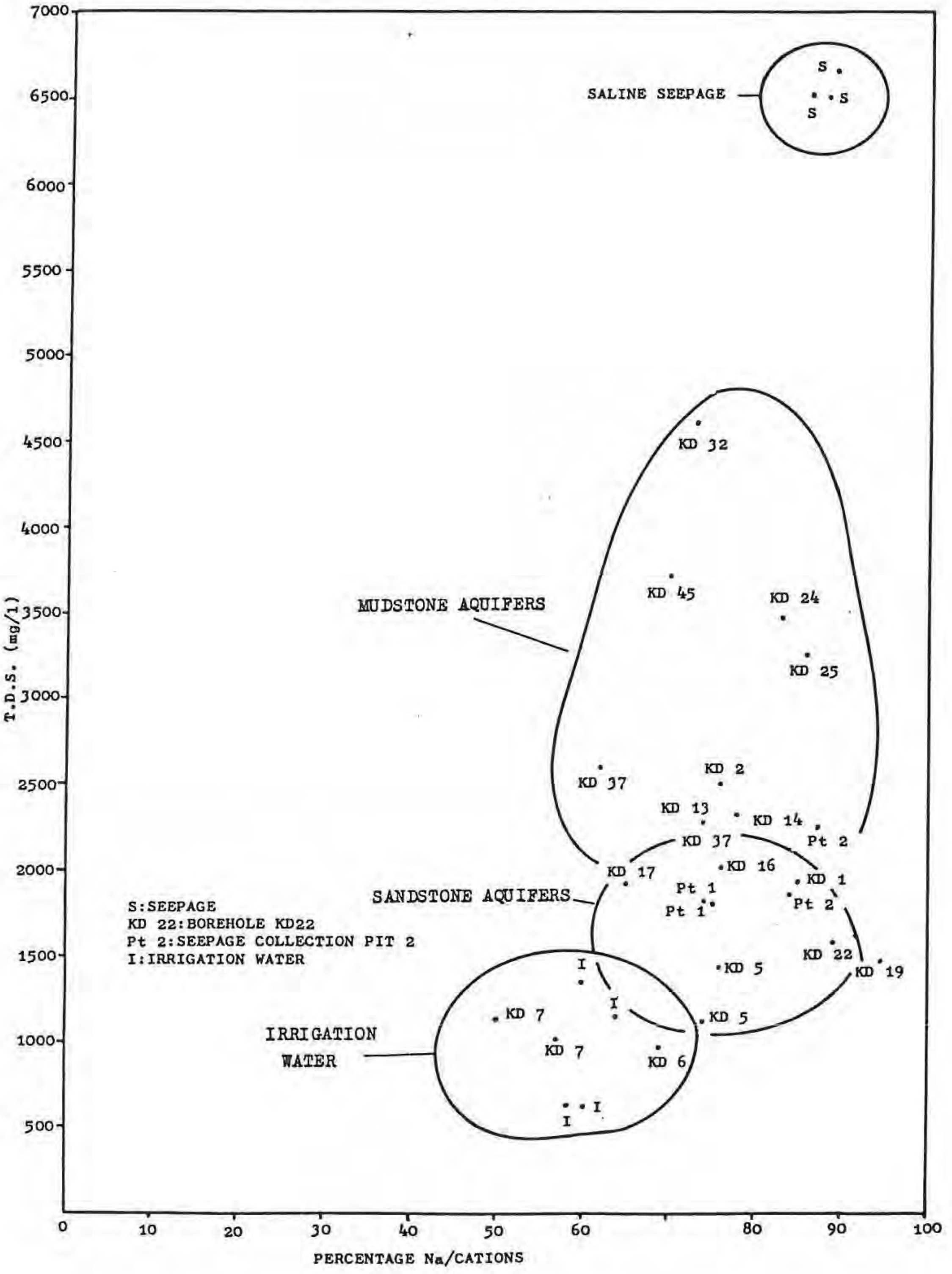


FIGURE 6.4 Graph of percent Na/cations aginst TDS content of various waters

COLLECTION SITE	DATE	T.D.S. CONTENT
SEEPAGE SITE SS 1.	19/2/82	5352 *
	4/3/82	5842*
	29/4/82	6765
	23/6/82	6741
	22/7/82	6643
	6/8/82	6578
	9/9/82	6565
	13/10/82	5993 *
	27/10/82	6500
	15/2/83	5707
PIT 2	3/6/82	2242
	13/6/82	2309
	9/9/82	3120
	28/3/83	2347 *
PIT 3	16/11/82	6500
	28/3/83	5317 *
Φ PIT 1	6/5/82	1859
	13/5/82	1820
	20/5/82	1807
KD 2	3/8/82	2496
SS 4	5/10/82	3237
KD 37	24/8/82	2603

* OWN CONDUCTIVITY MEASUREMENTS

Φ MIXTURE OF SEEPAGE WATER AND RIVER WATER.

TABLE 6.3. T.D.S. CONTENT OF SEEPAGE WATER FROM VARIOUS SAMPLING POINTS.

it consists of a mixture of seepage and river water. The higher Cl^- content of seepage and groundwater can be attributed to a change from a bicarbonate character to a chloride character as the water gradually passes from the environment of recharge (irrigation) to the environment of discharge (seepage).

There are large spatial variations in seepage water quality along the length of the river (i.e. from 2242 mg/l to 6643 mg/l). Although this may be related to changes in soil salinity, this does not appear to be the case with seepage site SS1. There is no evidence of abnormally high salinities in soil samples obtained from borehole KD 41, situated north-east of SS1. A possible explanation is the seepage of "deeper", mineralised groundwater into the alluvium at this point. In fact hydrochemical analyses from borehole KD 32 and SS1 reveal similar chemical characteristics.

A comparision of irrigation water samples which have been enriched, hypothetically, by evaporation with no salt mobilisation in the soil (Rhoades and Merrill, 1975), and seepage water samples collected in the field, on a trilinear graph, reveals similar equivalent percentages of the various ions (Figure D.6, Appendix D). This is further evidence that bank seepage represents an enrichment of irrigation water.

6.3.3 Alluvial Water

Alluvial water from soil sampling holes shows similar equivalent percentages and TDS content to the river bank seepage samples (especially KD 2 and pit 2) (Table 6.3). Water from boreholes near the canal and farm reserviors, e.g. KD 6, A 6 and KD 7 show low TDS values and low equivalent percentage Cl due to direct seepage of irrigation water. Le Roux (1979) suggests significant losses of irrigation water from both canals and earth storage ponds, which may lead to water logging and subsequent mineralisation problems.

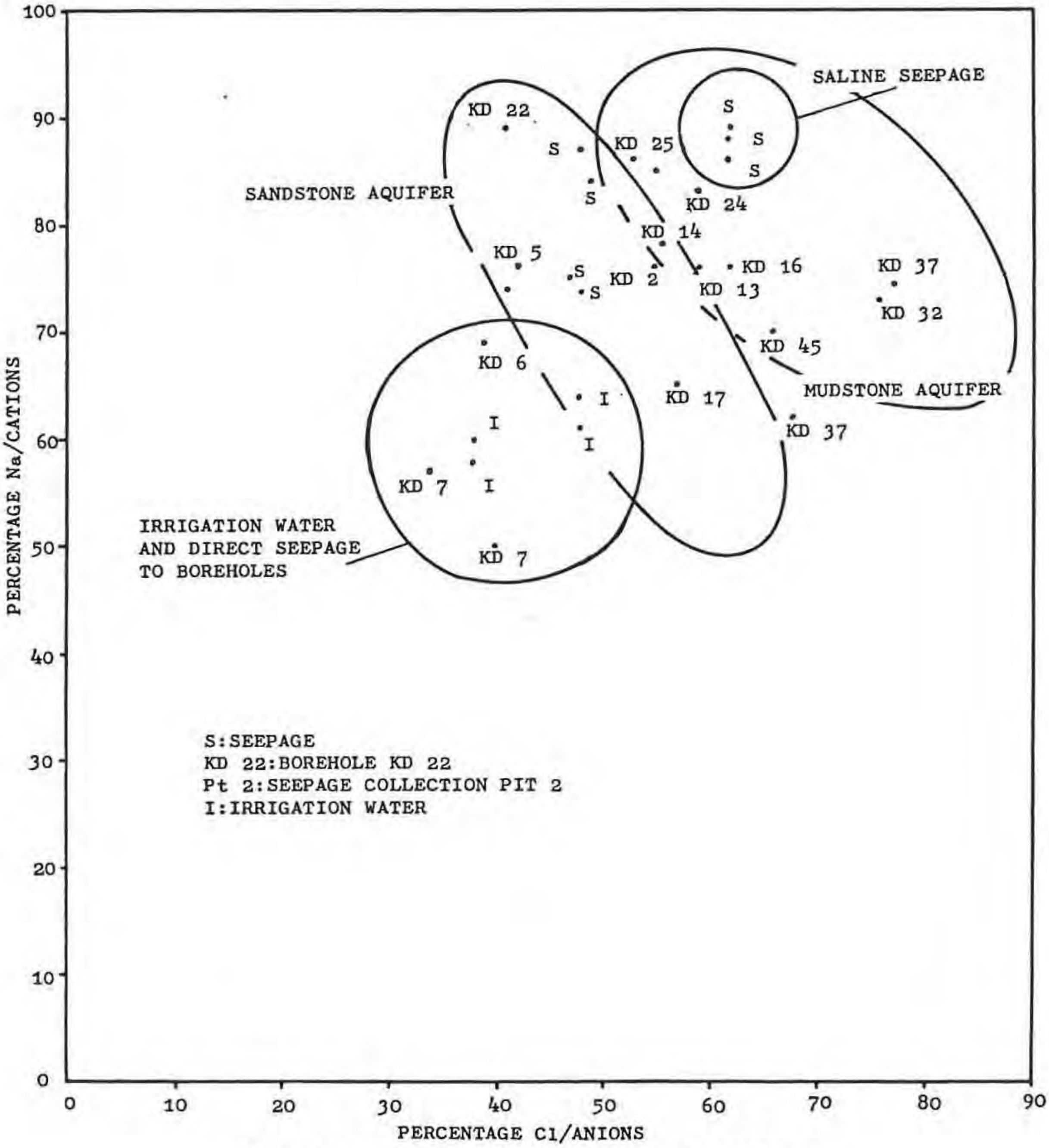


FIGURE 6.5 GRAPH OF PERCENT Cl/ANIONS AGAINST PERCENT Na/CATIONS

6.4 Hydrochemistry of the Sandstone and Mudstone Aquifers

Both the sandstone and mudstone aquifers show considerable variation in percentage equivalents. The majority of samples plot in the "NaCl" field of the Piper diagram, both within the areas representing stagnant and dynamic environments.

Although the Piper diagram illuminates the varying percentage equivalents of the ions, it does not distinguish between waters having a high or low TDS content. Table 6.1 shows that, generally, the water associated with the mudstones has a higher TDS content than that with the sandstones. Although equivalent percentage Na is approximately the same for both sandstone and mudstone waters (± 70%), the mudstones have on average a higher equivalent percentage Cl (62%, as opposed to 52% for the sandstones).

This is to be expected as the mudstones contain a high percentage adsorbed cations and anions which can be mobilized upon weathering and during base exchange. The percentage Cl is a good indicator of the residence time of the water. That is, waters with a high Cl content are indicative of a stagnant environment while a low Cl content indicates a more dynamic environment (Hem, 1970).

The alternating, cyclic nature of the sandstones and mudstones, however, result in water found within some sandstones (e.g. borehole KD 45) having a similar composition to that found in the mudstones. This is as a result of the percolation of water through the various layers, and consequently changing chemically, as it returns to the river.

Although waters found within a thick sequence of mudstones, for example KD 32, KD 33 and KD 37, have a high TDS content, some waters encountered in mudstones have low dissolved solid values, e.g. KD 1 and KD 5. Other factors such as residence time, the salinity of the overlying soils and the quality of irrigation water play an important role in determining the TDS content of the groundwater. Both boreholes KD 6 and KD 10, whose water levels fluctuate greatly during flow in the canal and application of irrigation water respectively, show that in some areas rapid, preferential flow of groundwater within the soils is possible. The TDS content and equivalent percentage Cl is also low in these two boreholes, indicating good circulation of groundwater.

6.5 Tracer Tests for the Determination of Groundwater Flow Paths and Residence Times

Tracers, both natural and artificial, were used in this study to determine the direction of movement of groundwater, its residence time in an aquifer, and consequently the transmissivity of the aquifer.

Tracers may be chemical, radioactive or biological in nature (Llamas, et al., 1981; Neretnieks, et al., 1982).

(a) Natural Isotope Tracers

Environmental tracers present a distinct advantage over artificial tracers in that the system can be sampled at a particular instant and location, whereas artificial tracers often require long periods of sampling before the tracer is detected (Verhagen, 1980). Environmental isotopes include tritium (^3H), deuterium (^2H) and radio carbon (^{14}C). Tritium, being part of the water molecule, moves essentially as water does and is therefore an almost perfect tracer (Allison, 1980). The tritium content of the atmosphere and water increased significantly after 1952 because of thermonuclear weapon testing (Toran, 1982). As its natural occurence in the atmosphere is negligible, its appearence in groundwater is an almost certain indication of recharge (F.A.O., 1982). Tritium analysis was performed on seven water samples. This revealed that all waters sampled are younger than 20 years, with some of the higher tritium values indicating complete turnover within the last 10 years. The tritium analyses are listed in Table 6.4

TABLE 6.4 TRITIUM ANALYSIS OF SELECTED GROUNDWATERS IN THE STUDY AREA

BOREHOLE	TRITIUM UNITS	DESCRIPTION OF WATER
KD 34	11,0 ± 0,8	Indicates recent recharge from irrigation water
KD 5	8,7 ± 0,7	
seepage site SS1	7,6 ± 0,6	
KD 32	5,1 ± 0,6	
KD 36	5,4 ± 0,6	water from non-irrigated control area
KD 15	2,7 ± 0,4	fairly stagnant water indicating little interaction with irrigation water
KD 37	0,2 ± 0,3	

Tritium analyses of waters from boreholes KD 34, KD 5, KD 32 and seepage site SS1 point to recharge taking place partially through direct infiltration by rainfall in areas of sparse soil cover and mainly by percolation of irrigation water through the soils to the fractured rock aquifers. Very little water (0,06 l/s) was encountered in borehole KD 36, in the non-irrigated control area on the right hand bank of the river. The fairly "young" water encountered in this aquifer reflects recent, direct recharge from rainfall.

The low tritium values of waters encountered in holes KD 15 and KD 37 are indicative of stagnant conditions with little recharge from irrigation percolation taking place.

(b) Artificial Tracers

Two fluorescent dyes, fluorescein and Rhodamine B, were used at Middleton in an attempt to determine :

(i) rates and direction of flow of seepage water within the unconsolidated alluvium;

(ii) the interaction between shallow water within the alluvium and the "deeper" groundwater.

Artificial tracers include various chemical, radioactive or biological compounds which are introduced at a point source, and whose appearence at natural or artificial points of outflow are then monitored. Flourescent dyes radiating various colours are available which are very effective for direct observation in clear water. In quantitative measurements a fluorimeter is used (White, 1976; McLaughlin, 1982).

During the Middleton study, tracer tests were undertaken both under natural flow conditions (boreholes KD 43 and KD 15) as well as under induced flow during an aquifer test (boreholes KD 23 and KD 24 - Figure 6.6). No tracer was detected in observation holes KD 15 and KD 24 even after lengthly periods of sampling (720 hours and 149 hours respectively). Tests undertaken at seepage pit 3 and seepage site 1, where the tracer was injected into auger holes 1,5m up gradient from the monitoring points, revealed that preferential seepage zones exist adjacent to the river. Whereas fluorescein was detected after only 15 hours in seepage site 1 (Plate 12), no dye was detected in seepage pit 3 even after 720 hours.

The rather inconclusive results from the tracer tests could be attributed to a number of factors :

(i) dye was adsorded onto clay particles;

(ii) the horizontal flow rates at the base of the alluvium are very low;

(iii) interaction between alluvial water and "deeper" groundwater only takes place in the vacinity of fractures;

(iv) tracer tests were undertaken during the early part of the irrigation season (low hydraulic gradient and limited flow within the alluvium);

(v) In some areas there is no percolation of alluvial water into the fractured rock aquifers (KD 23 and 24).

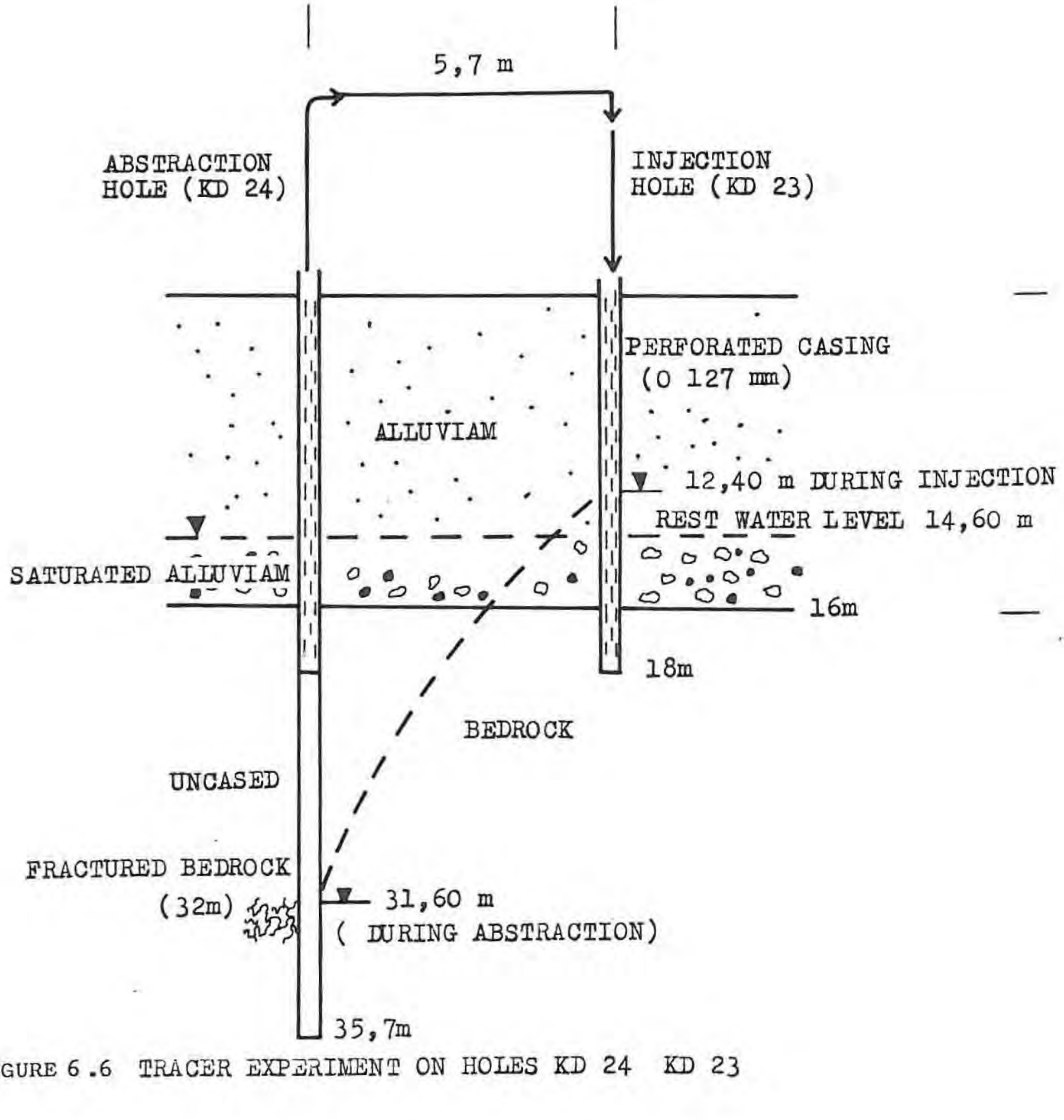


FIGURE 6.6 TRACER EXPERIMENT ON HOLES KD 24 KD 23

6.6 Spatial and Temporal Variations in Hydrochemistry

Changes in hydrochemistry during drilling and aquifer tests provide a framework for examining spatial and temporal variations in water quality.

6.6.1 Changes in Hydrochemistry During Drilling

Some noteworthy changes in TDS content and equivalent percentage ions of waters encountered during drilling were observed. These changes are important in the explantion of the spatial variation in water quality and in determining the nature of the aquifers (Table 6.5, and Sections A and C, Appendix B).

(a) Variations in Hydrochemistry with Depth

Borehole KD 5, for example, shows a progressive increase in TDS content with depth. The good quality water associated with the mudstone at 37m (1287 mg/l) is probably related to a dynamic circulation of water (see low Cl value) while the poorer quality water associated with the sandstone at 53m is as a result of stagnant conditions (high percentage Cl). This is again observed in boreholes KD 1, KD 14 and KD 37.

In borehole KD 15, however, the opposite occurs. Poor quality water (3783 mg/l), high in percent Cl, is found in the sandstone at 29m while good quality water with a low percentage Cl is associated with the fine grained sandstone at 35m. Boreholes KD 37, KD 32 and KD 25 show a similar trend although not as pronounced as KD 15.

In two out of six boreholes drilled where water was encountered at the contact between alluvium and bedrock, the alluvial water had a higher TDS content than water encountered lower in the fractured rock aquifers (indicating low flow conditions). Not only does this support Tordiffe's (1978) theory that due to the low hydraulic conductivity of the alluvium, most of the seepage takes place in fractures and joints in the consolidated bedrock, but it also reinforces the assertion that a preferential flowpath - discrete aquifer system exists.

(b) Lateral Variations in Hydrochemistry

Not only does water quality change with depth but changes are also observed over fairly short lateral distances. Boreholes KD 4 and KD 5 are examples where a change of over 900 mg/l is observed over a distance of 35m. Together with variations in the depth at which water was encountered and the limited hydraulic continuity between some boreholes, these three trends reinforce the assertion that the aquifers are discontinuous or "patchy" in nature and that groundwater flow is governed by the size and number of fractures and joints present. Groundwater flow may therefore become restricted resulting in fairly stagnant conditions. Preferential flowpaths through the soil, by means of cracks and solution channels in the calcrete, and through the fractured sandstones and mudstones, is consequently an important mechanism in explaining large variations in water quality over short distances.

Preferential seepage sites along the river bank, e.g. SS1, pit 2, and SS4, indicate that through the mechanisms of sorting and compaction, irrigation return flow is concentrated in certain areas.

From sections A and C (Appendix B), there appears to be a trend of increasing TDS content of groundwater from the canal to the river, found also by le Roux (1979). This confirms the assertion that seepage water becomes progressively mineralised as it returns to the river. Those waters far from the river which have a high TDS content (e.g. KD 5 at 53m and KD 45 at 65m) were encountered at some depth and are probably indicative of stagnant conditions.

6.6.2 Changes in Hydrochemistry During Aquifer Tests

Of the eight constant rate aquifer tests undertaken (Table 6.5), two showed a slight increase in TDS content with time, two a decrease in TDS content, while TDS content of four remained fairly constant throughout the duration of the test.

The constant water quality again supports the idea of limited interconnection between aquifers, i.e. flow of water with a higher or lower TDS content was not induced from other aquifers. Boreholes KD 32 and KD 37 show an improvement in water quality during pumping as compared to during drilling. This was a consequence of direct recharge from the river, both boreholes being situated within 100m of the river. The water quality monitored during the pumping of borehole KD 5 showed that flow was induced from the vacinity of borehole KD 4. Generally, however, the water quality was dominated by the highest yielding formation encounted during drilling.

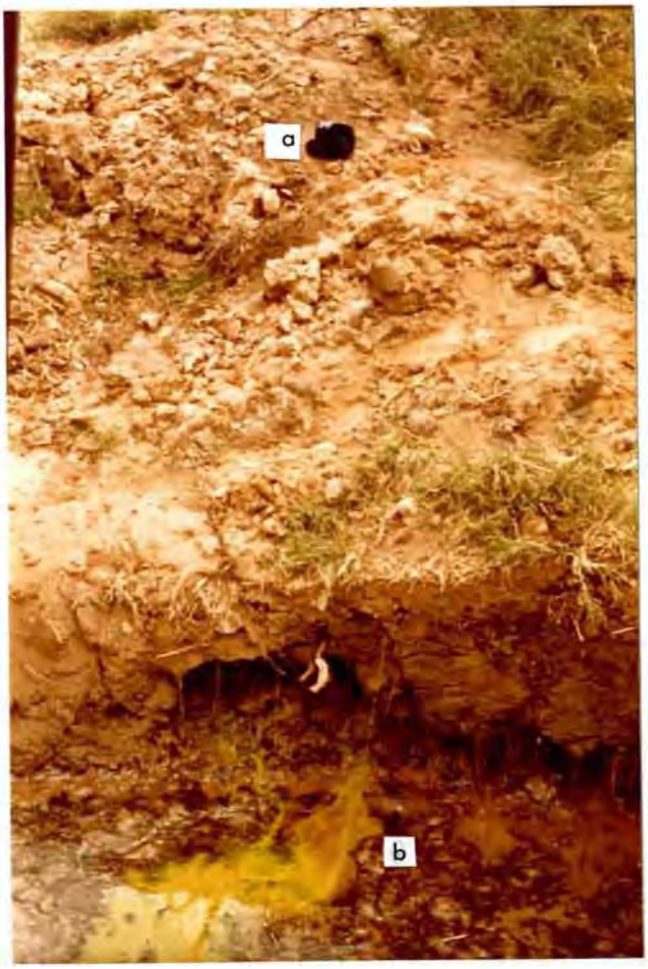


PLATE 12. Tracer test at seepage site SS1. (a) injection site (auger hole) and (b) seepage of fluorescein dye from SS1.

TABLE 6.5 TDS CONTENT OF WATERS OBTAINED DURING DRILLING AND AQUIFER TESTS

	BOTTLE NO.	DATE	TIME	TDS CONTENT	FORMATION AND DEPTH
BOREHOLE KD 5	015040			1287 mg/ℓ	mudstone 37m
DRILLING	028531			2099	sandstone 50m
	028227			3516	sandstone 53m
AQUIFER TEST					
	132522	21/7/82	10.30	1092	
	034800	21/7/82	12.21	1125	
	021112	21/7/82	19.40	1086	
	029780	22/7/82	00.15	1099	
	032329	22/7/82	07.03	1112	
	024134	22/7/82	09.10	1105	
	017216	18/8/82		1268	
	031764	19/8/82	10.04	1437	
BOREHOLE KD 1					**Alluvium**
DRILLING	016956			1580	mudstone 14m
	030081			1937	F.sandstone 30,5m
	028011			2028	sandstone 37m
AQUIFER TEST					
	016549	9/8/82	14.22	2191	
	021212	9/8/82	18.25	2204	
	025684	9/8/82	22.20	2165	
	027700	10/8/82	12.50	2020	
BOREHOLE KD 32					
DRILLING	020545	6/8/82		5772	mudstone 18m
	033072	9/8/82		5200	mudstone 26m
	032677	9/8/82		4602	mudstone 31m
AQUIFER TEST					
	017759	4/10/82	17.46	4212	
	017967	4/19/82	24.00	4154	
	030420	5/10/82	11.40	4108	
BOREHOLE KD 35					**Alluvium**
DRILLING	029943	19/8/82		3211	mudstone 14m
	017982	19/8/82		3276	mudstone 32,5m
AQUIFER TEST					
	024030	24/8/82	10.41	3393	
	019343	24/8/82	16.00	3406	
	019987	26/8/82	09.20	3380	
BOREHOLE KD 34	026027	16/7/82		1768	sandstone 26m
DRILLING	034956	16/7/82		1671	sandstone 37m
AQUIFER TEST	034640	21/8/82	12.20	1742	
	032948	31/8/82	13.20	1742	
	031999	31/8/82	14.25	1736	
	024569	31/8/82	15.55	1755	
	024488	1/9/82	09.37	1749	
	031984	1/9/82	09.57	1749	
	023091	1/9/82	15.15	1775	
	032615	2/9/82	09.10	1781	
BOREHOLE KD 15					
DRILLING		28/6/82		3783	sandstone 29m
		28/6/82		1118	f.sandstone 35m
AQUIFER TEST					
	021265	22/9/82	09.28	3536	
	016305	22/9/82	14.23	3536	
	019920	22/9/82	15.23	3536	
BOREHOLE KD 37					**Alluvium**
DRILLING	024864	24/8/82		3621	mudstone 10m
	019549	24/8/82		2600	mudstone 21m
	017041	24/8/82		2275	mudstone 57m
AQUIFER TEST					
	020776	24/9/82		1996	
	024504	27/9/82		2113	

6.7 Hydrochemistry of Water from Non-irrigated Areas

Fifteen water samples were collected from boreholes in the non-irrigated farming areas near Middleton. TDS content of these waters varied between 1100 and 4160 mg/l, although the average salt content was 1959 mg/l. Most of the samples plotted in the "NaCl" field of the Piper diagram (Figure D.6, Appendix D), close to samples from boreholes KD 5, KD 36 and KD 45 (stagnant water areas). In comparison to samples obtained from irrigated areas (average TDS content 3385 mg/l), these waters contain less Na (due to the lesser importance of base exchange) and a greater percentage Cl (because of static water conditions).

6.8 Hydrochemistry of Great Fish River Water

Although the TDS content of river water varied between 1008 mg/l and 2490 mg/l during 1982, the equivalent percentage cations and anions remained fairly constant - Na ± 70% and Cl ± 50%. When compared to irrigation water, the river water contained a higher percentage Na and Cl. All points plotted within the "NaCl" field of the Piper diagram. "Normal" (non-release) Fish River water always had a higher TDS content than irrigation water because the percentage "baseflow" of the river water is greater than that of irrigation water (the irrigation water being diluted with Orange River water).

CHAPTER 7

THE AFFECT OF SOILS ON MINERALISATION

7.1 Sources of Soluble Salts

Salts originate from the physical and chemical weathering of rocks and minerals (le Roux, 1979; Fitzpatrick, 1980) and consist mainly of various proportions of the cations sodium, calcium and magnesium and the anions chloride and sulphate as well as carbonate and bicarbonate (Richards, 1954). Chemical weathering involves the processes of hydrolysis, hydration, solution, oxidation and carbonation. It is particularly the feldspars that play an important role in the release of soluble salts, e.g. K^+ ions from K-feldspar and Na^+ and Ca^{++} ions from plagioclase (Mackenzie, 1975). The concentration of salts in soils, which leads to the formation of saline soils, is frequently brought about by irrigation, which not only introduces salts from other areas into the soil but also stimulates a capillary rise of groundwater (Richards, 1954; Fitzpatrick, 1980).

The processes of evaporation and transpiration tend to concentrate the salt in the soil solution resulting in an accumulation of salts released by weathering (Bresler, 1977). This is particularly prevalent in arid and semi-arid regions where evapotranspiration exceeds precipitation and where natural leaching is limited (Tordiffe, 1978).

7.2 The Affect of Excess Soluble Salts on Soils

In arid and semi-arid regions leaching is usually local in nature and soluble salts may not be transported far. Restricted drainage is a factor that usually contributes to the salinization of soils. This low permeability, which impedes the downward movement of water, is brought about by unfavourable soil texture or the presence of indurated layers (Richards, 1954).

Soluble salts effect the physical properties of soils in numerous ways, e.g. swelling, water adsorption and drainage. They also effect the chemical properties in terms of cation and anion adsorption, and precipitation of salts (le Roux, 1979). A permeability problem related to water quality occurs when the rate of infiltration into and through the soil is reduced by the effect of specific salts such as sodium (Ayers and Westcot, 1976). Soil particles adsorb and retain cations as a consequence of electrical charges at the surface of the soil particle. Cation adsorption, being a surface phenomenon, is identified mainly with the fine silt, clay and organic matter fractions of soils. The reaction whereby a cation in solution replaces an adsorbed cation is termed cation exchange (Richards, 1954). The presence of sodium influences the physical properties of the soil, particularly permeability, by effecting the swelling and dispersion of clay. If the ratio of soldium to total cations is high in the irrigation water and initially low in the soil, the increase of the equivalent sodium percentage causes a reduction in the permeability (Kovda et al., 1971). The rate of infiltration is also greatly dependent upon the nature of the soil. A fine grained soil exerts an initial positive influence on the infiltration ratio which later becomes negative due to swelling. Soils rich in clay minerals such as montmorillonite, for example, expand greatly when wet and consequently have a deleterious effect on the infiltration rate (Tordiffe, 1978). Texture exerts a strong influence on drainage (Dan, 1973). Soil layers rich in silt and clay may result in lateral rather than vertical movement of soil water. Because of their low hydraulic conductivity, clay rich layers are usually rich in salts (le Roux, 1979). The great variation in texture of alluvial soils results in a complex movement of salts and moisture in the soils and therefore also in salt accumulation.

7.3 Distribution of Salts in Soils

Although under present conditions of over irrigation at Middleton water is able to drain through to the water table, in semi-arid regions precipitation is insufficient to leach the soils. The combined effect of lack of water and lack of organic acids, due to sparse natural vegetation, results in less leaching and the precipitation of a calcium carbonate or "calcrete" layer in the soils (Tordiffe, 1978; Fitzpatrick, 1980). Irrigation water can play the role of a very strong solvent but many soluble components present in applied water can precipitation after irrigation (Kovda et al., 1971). Le Roux (1979) found that in the Fish River Valley, soluble salts tend to accumulate at 2m and 4,75m while calcrete accumulates at 2,5 and 7m. Not only does the salt content vary between layers but also between sampling profiles.

7.4 Changes in Soils Brought About by Irrigation Water

Irrespective of its source, all irrigation water contains dissolved salts, the type and amount of which depends on its origin and on its course before use (Ayers and Westcot, 1976). Water-soluble salts entering the soil profile through the process of irrigation may accumulate in the root zone or may be leached out of this zone, depending on the transport processes and solute interactions within the soil (Bresler, 1976). The long-term action of irrigation water on different types of soil depends on the properties of the soil itself, and especially on draingage conditions and on the balance of subsoil water and salts (Hanks et al., 1976). Irrigation water can either suppress the elevation of the salt layer or, through the formation of a water table and capillary action, salts may be precipitated higher up in the soil profile. Coupled with the total dissolved solid content of the irrigation water, drainage and leaching will determine whether irrigation will have a positive or negative effect on the mineralisation of soils. There is evidence (le Roux, 1979) that the use of the water since the inception of the Orange River Project has had a positive effect on Fish River Valley soils and that salts are being leached from the soil profile. The T.D.S. content of this leachate, however, determines the amount of salts being returned to the river in the form of irrigation return flows. The wrongs caused by irrigation with highly mineralised water during the years before the Orange River

Project (le Roux, 1979) are now being righted but at the "cost" of highly mineralised return flows.

7.5 Analysis of Soils from the Middleton Study Area

Various analyses were undertaken on soil samples from the alluvial profile in an attempt to determine the effect of physical soil parameters on moisture movement and to elucidate the role of soils as both a reservoir for, and source of, soluble salts. These included particle size and soil moisture analysis, determination of saturated hydraulic conductivity, and macro-element and adsorbed cation determinations.

7.5.1 Particle Size and Soil Moisture Analysis

Thirty-nine samples from four boreholes, obtained using the drive core sampling tube method, were analysed for variations in particle size. On average, 67 percent of particles fell in the range 0,05 - 0,147mm (fine sand). The size range "less than 0,005mm", i.e. fine silt and clay, was singled out for special attention as it was assumed that this category would be most significant in terms of moisture retention (Tables 7.1 and 7.2).

Duplicate samples, which had been stored in airtight containers after sampling, were then analysed gravimetrically and the percentage moisture in each sample noted (Tables 7.1 and 7.2) and Tables E.1 to E.7, Appendix E).

Figures 7.1 to 7.4 are plots of "percent silt and clay" and "percent moisture" against "depth" in the soil profile. In all cases there is a direct relationship between "percent silt and clay" and "percent soil moisture". This is not surprising as the finer particles, through various chemical and physical bonds (Richards, 1954), are better able to retain moisture than the coarser particles. An interesting feature of all four soil sample profiles is a decrease in soil moisture in the area between 5 and 6m. There may be a number of reasons for this, these being :

			TOTAL DISSOLVED SOLIDS (mg/ℓ).																	ADSORBED CATIONS.				
DEPTH (M)	PERCENT MOISTURE	P.S.A. PERCENT SILT + CLAY	TAL	NH_4	Ca	Cl	NO_3	Na	Mg	F	Si	K	SO_4	P	TDS	Na	Mg	K	Ca	CATION CONTENT (mg/ℓ)	Na	Mg	K	Ca (me/100g)
1	5,2	17,6	2600	5	400	1000	144	1733	133	60	180	47	800	1,4	8133	733	800	473	4267	6273	0,96	2	0,4	6,4
2	5,2	8,2																						
3	5,2	14,4	2867	6	200	1800	31	2667	67	60	353	133	1133	1	10067	933	733	667	5867	8200	1,2	1,8	0,5	8,8
6	3,4	1,6	1000	3	67	200	3	533	0	27	93	47	667	4	2867	1667	733	633	1267	4300	2,1	1,8	9,5	1,9
7	7,6	0,6	2733	3	0	333	4	1400	0	40	200	27	733	1,3	6267	600	4799	427	1333	7150	0,8	11,8	0,3	2
8	27,6	4,6	867	1	0	133	1	400	0	27	93	27	533	6	2400	1466	67	480	1267	3280	1,9	0,2	0,4	2
9	7,5	1,6	2267	4	0	133	3	1133	67	20	160	27	667	2	5000	1120	1667	613	1267	4667	1,6	4,1	0,5	2
10	7,4	0,6	1867	2	0	267	3	1067	0	20	140	47	600	1	4467	1333	1067	580	1933	5913	0,7	2,6	0,5	3

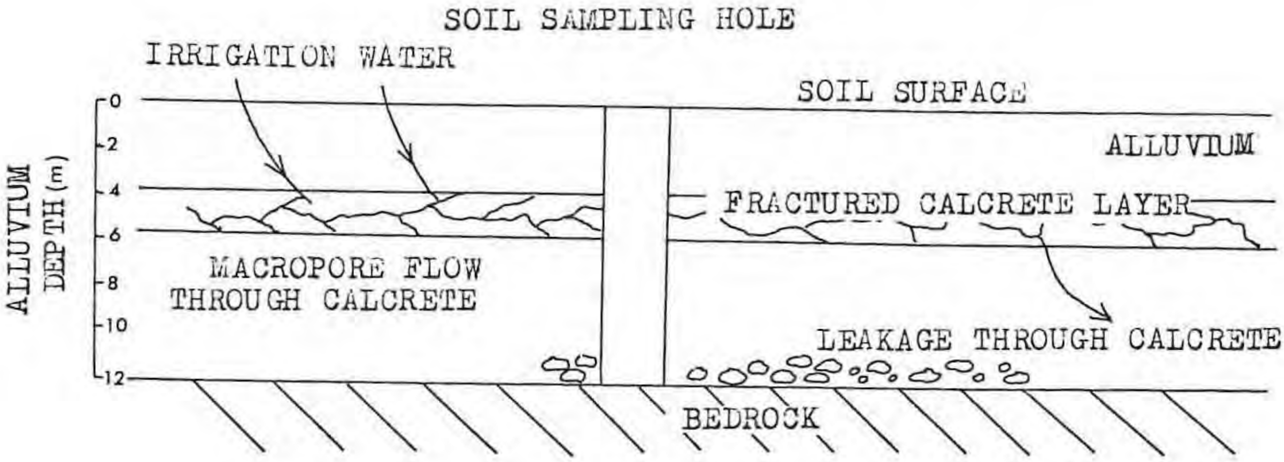
TABLE 7.1. VÀRIATION IN SOIL TEXTURE AND CHEMISTRY WITH DEPTH - BOREHOLE KD 34.

			TOTAL DISSOLVED SOLIDS (mg/ℓ).																	ADSORBED CATIONS.				
DEPTH (M)	PERCENT MOISTURE	P.S.A. PERCENT SILT + CLAY	TAL	NH_4	Ca	Cl	NO_3	Na	Mg	F	Si	K	SO_4	P	TDS	Na	Mg	K	Ca	CATION CONTENT (mg/ℓ)	Na	Mg	K	Ca (me/ 100g)
$^{1}/2$	5,9	12,6	933	3	67	67	1	400	67	40	220	67	467	17	2600	267	1533	507	5333	7640	0,4	3,8	0,4	8
$1^{1}/2$	6	14,6	2067	7	0	333	4	1200	0	20	80	47	600	2	4867	533	1200	267	6067	8067	0,7	3	0,2	9,1
$2^{1}/2$	7,2	12,3	1400	2	0	1133	9	1400	0	47	153	60	733	16	5400	600	1733	413	0	2746	0,8	4,3	0,3	0
$3^{1}/2$	8,8	16,6	2733	4	67	133	1	1267	67	20	253	47	467	11	5667	533	2000	367	22133	25033	0,1	4,9	0,3	33,2
$4^{1}/2$	9,5	18,4	2533	6	133	200	2	1267	67	33	220	73	600	4	5667	533	2599	407	23000	26539	0,7	6,4	0,3	34,5
$5^{1}/2$	8,5	20,5	2067	5	133	933	1	1400	67	33	207	73	600	5	6067	467	3067	347	23267	27148	0,6	7,6	0,3	35
$6^{1}/2$	7,5	22,4	1800	4	133	467	3	1200	67	27	147	60	800	5	5133	467	3000	300	21533	25300	0,6	7,4	0,2	32,3
$7^{1}/2$	6,5	8,4	1733	5	200	667	1	1067	133	20	180	67	667	1	5200	400	2933	260	19467	23060	0,5	7,2	0,2	29,2
$8^{1}/2$	6,5	8,5	2200	3	67	1133	5	2000	133	100	213	273	733	20	7400	1467	3667	973	0	6107	1,9	9	0,8	0
$9^{1}/2$	8,4	25,6	2133	3	0	667	1	1667	67	27	200	207	667	6	6133	1600	3067	0	0	4667	2	7,6	0	0

TABLE 7.2. VARIATION IN SOIL TEXTURE AND CHEMISTRY WITH DEPTH - BOREHOLE KD 38.

(i) the water infiltrating below the root zone does not reach the lower alluvial layers;

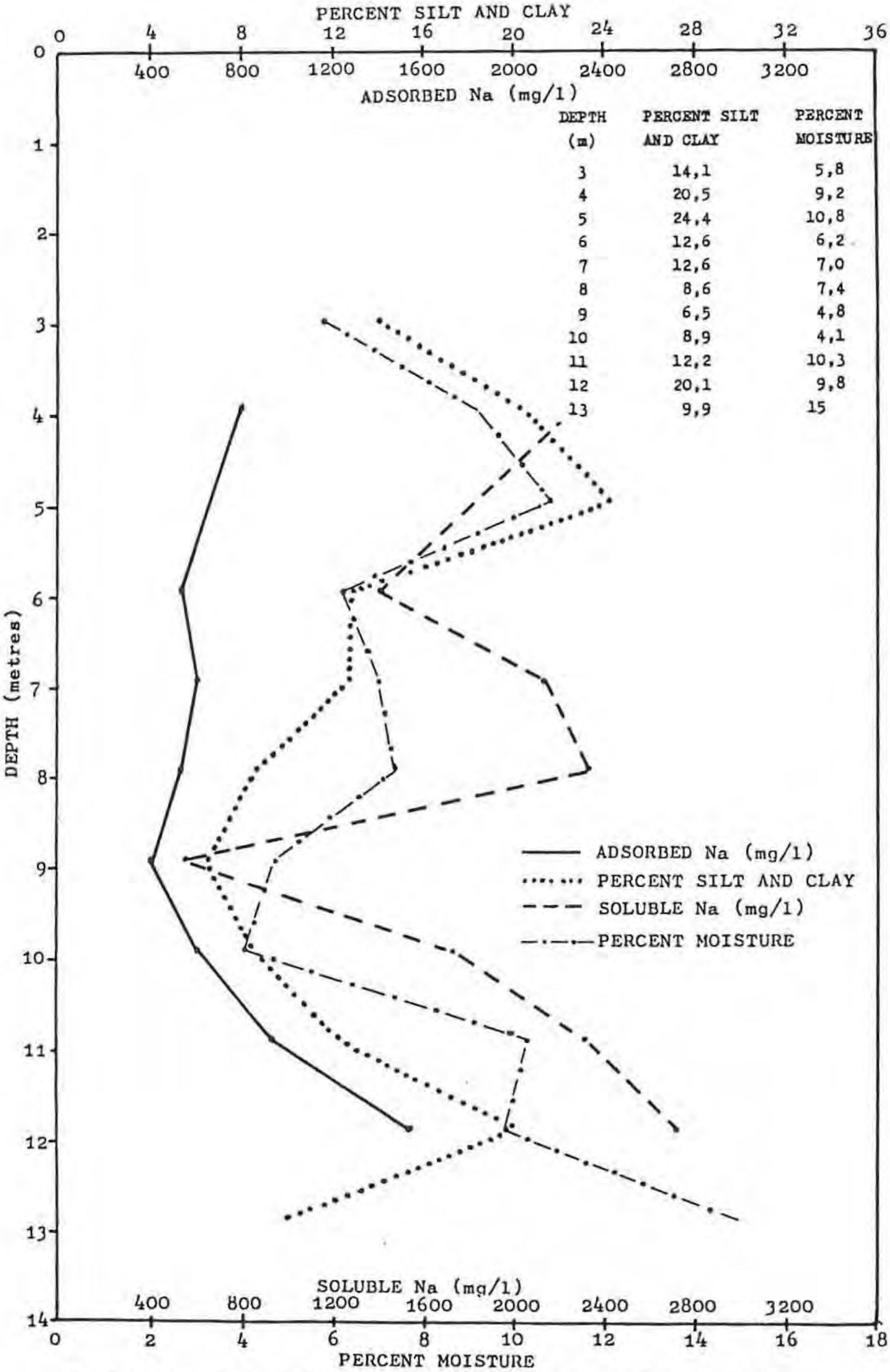
(ii) there is pronounced macropore flow within the alluvium through cracks and solution channels within the calcrete layers; i.e.



(iii) the soil sampling was undertaken towards the beginning of the irrigation season; consequently the soil/alluvium profile was only partially moist;

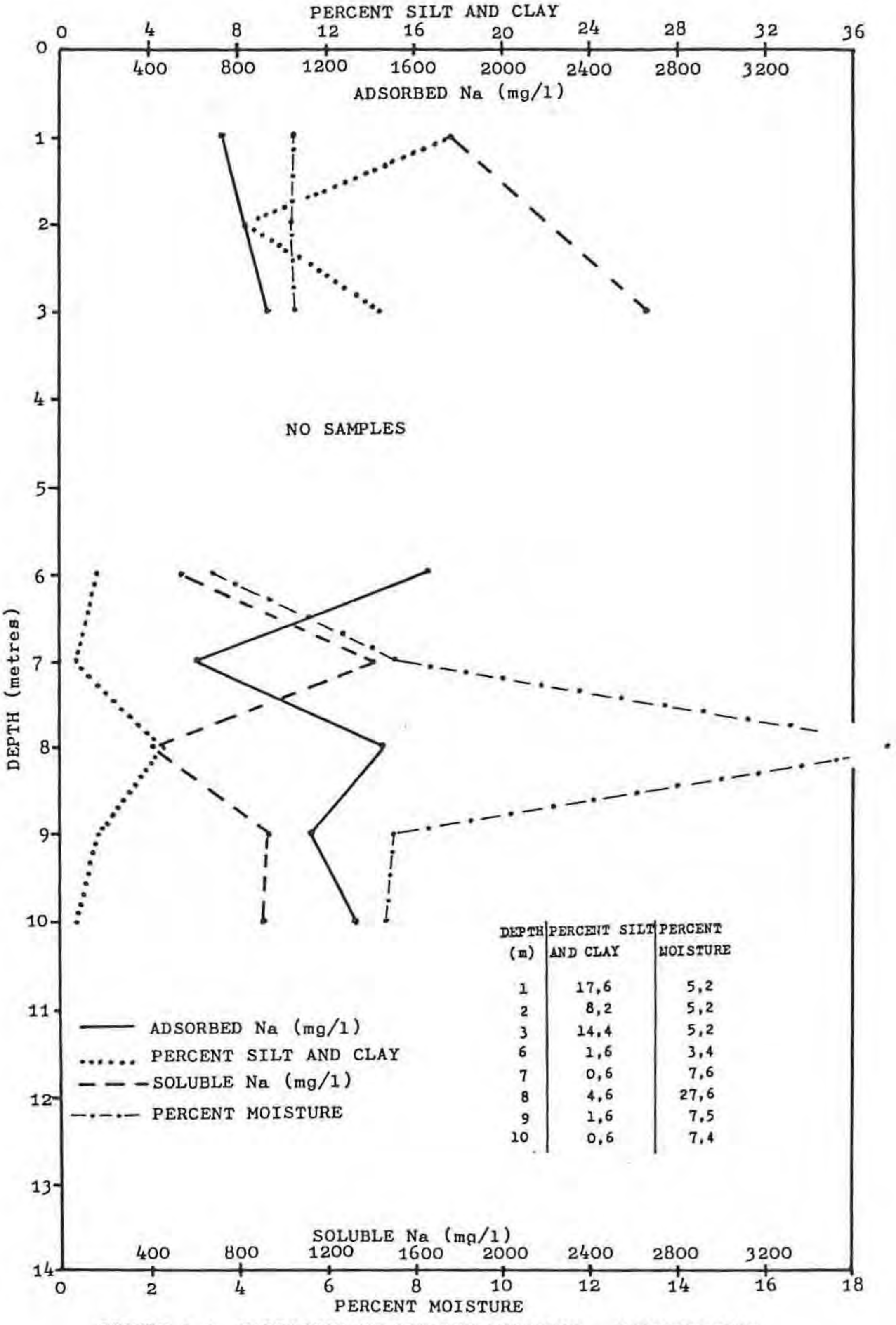
(iv) As mentioned above, the moisture appears to be associated with the layers possessing a higher percentage silt and clay. The sandy layers, i.e. those which have a high percentage of particles greater than 0,05mm, are conspicuous in their lack of soil moisture. Good examaples of this are the samples obtained at 9 and 10m in borehole 40, i.e. 90% and 92% particles greater than 0,05mm respectively.

The first possibility is discounted because of the moisture located lower in the profile, as well as evidence from bank seepage. The other three probably all affect the soil moisture content to a certain extent.



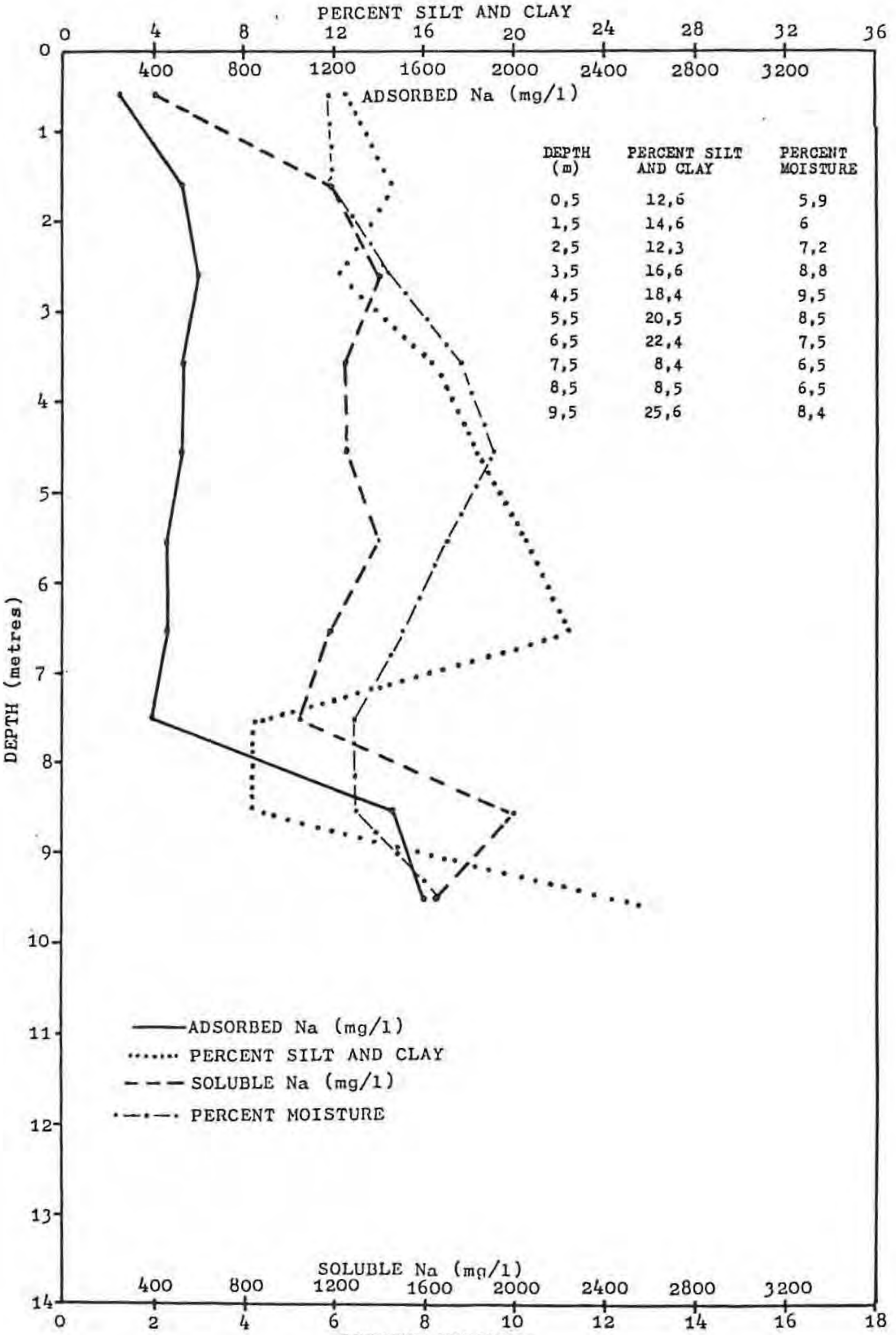
DEPTH (m)	PERCENT SILT AND CLAY	PERCENT MOISTURE
3	14,1	5,8
4	20,5	9,2
5	24,4	10,8
6	12,6	6,2
7	12,6	7,0
8	8,6	7,4
9	6,5	4,8
10	8,9	4,1
11	12,2	10,3
12	20,1	9,8
13	9,9	15

FIGURE 7.1 VARIATION IN PERCENT MOISTURE , PERCENT SILT AND CLAY , AND SOIL CHEMISTRY WITH DEPTH BOREHOLE KD 40



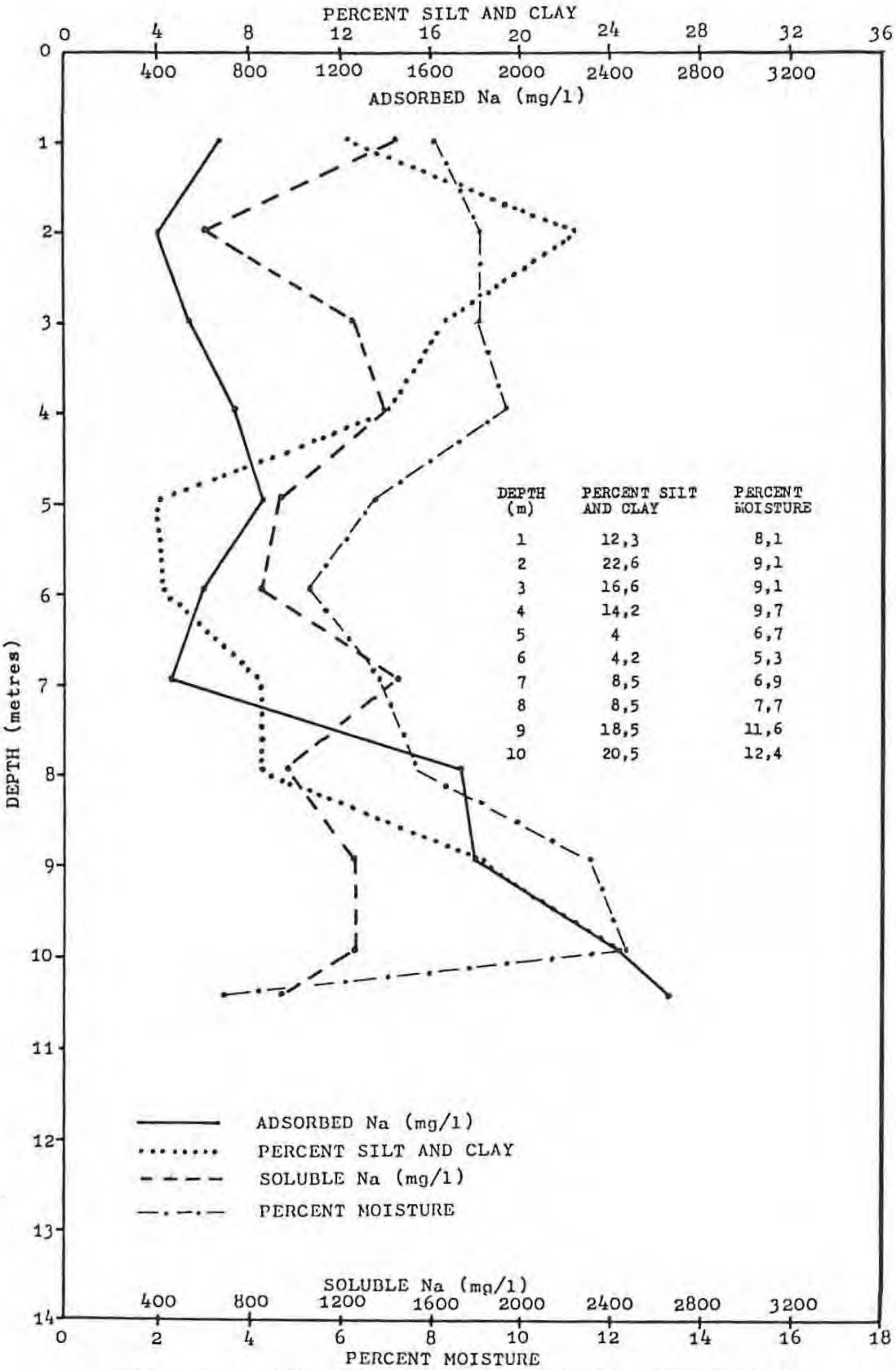
DEPTH (m)	PERCENT SILT AND CLAY	PERCENT MOISTURE
1	17,6	5,2
2	8,2	5,2
3	14,4	5,2
6	1,6	3,4
7	0,6	7,6
8	4,6	27,6
9	1,6	7,5
10	0,6	7,4

FIGURE 7.2 VARIATION IN PERCENT MOISTURE , PERCENT SILT AND CLAY , AND SOIL CHEMISTRY WITH DEPTH BOREHOLE KD 34



DEPTH (m)	PERCENT SILT AND CLAY	PERCENT MOISTURE
0,5	12,6	5,9
1,5	14,6	6
2,5	12,3	7,2
3,5	16,6	8,8
4,5	18,4	9,5
5,5	20,5	8,5
6,5	22,4	7,5
7,5	8,4	6,5
8,5	8,5	6,5
9,5	25,6	8,4

FIGURE 7.3 VARIATION IN PERCENT MOISTURE , PERCENT SILT AND CLAY , SOIL CHEMISTRY WITH DEPTH BOREHOLE KD38



DEPTH (m)	PERCENT SILT AND CLAY	PERCENT MOISTURE
1	12,3	8,1
2	22,6	9,1
3	16,6	9,1
4	14,2	9,7
5	4	6,7
6	4,2	5,3
7	8,5	6,9
8	8,5	7,7
9	18,5	11,6
10	20,5	12,4

FIGURE 7.4 VARIATION IN PERCENT MOISTURE , PERCENT SILT AND CLAY , AND SOIL CHEMISTRY WITH DEPTH BOREHOLE KD 41

7.5.2 Saturated Hydraulic Conductivity

Six undisturbed soil cores were collected from various locations and depths (Figure 4.1) and, after being saturated in the laboratory, were tested in a constant head permeameter, following the technique described by the Klute (1965). From the Darcy equation, v = ki, k, the hydraulic conductivity, is the effective flow velocity of water in soil at unit hydraulic gradient, i.e. when the driving force is equal to one gravity (Richards, 1954). The results from the tests are tabulated below :

Profile	Depth (m)	Saturated hydraulic conductivity (m/day)	Specific permeability (Darys)
1	0,45	$7{,}224 \times 10^{-3}$	$8{,}69 \times 10_{-3}$
2	0,55	$5{,}397 \times 10^{-3}$	$6{,}49 \times 10^{-3}$
2	1,0	$69{,}530 \times 10^{-3}$	$83{,}70 \times 10^{-3}$
3	0,30	$6{,}599 \times 10^{-3}$	$7{,}94 \times 10^{-3}$
3	0,65	$20{,}60 \times 10^{-3}$	$24{,}80 \times 10^{-3}$
4	0,35	$3{,}610 \times 10^{-3}$	$4{,}34 \times 10^{-3}$

TABLE 7.3 Saturated hydraulic conductivity determinations of selected Middleton soils

The values compare well with the category "fine sand, silt and clay" as given by Todd (1960). Although cores were only collected from the first metre of the soil profile, (due to difficulties in extracting an undisturbed soil core), they none the less reveal the low saturated hydraulic conductivities present. Even if the saturated hydraulic conductivity increases with depth, soil water percolation (drainage) will be limited by the low values found in this upper layer. Particle size analysis was undertaken on three of the core samples (Table 7.4). This revealed that the low saturated hydraulic conductivities are associated with high percentages silt and clay.

Profile	Depth (m)	% Clay	% Silt	% Fine sand	% medium sand	% Coarse sand	Saturated hydraulic cond m/day
3	0,30	32,45	16,39	48,74	2,39	0,03	$6{,}6\times10^{-3}$
1	0,45	18,22	8,69	68,63	4,31	0,15	$7{,}2\times10^{-3}$
2	0,55	22,89	8,70	42,56	23,78	2,07	$5{,}3\times10^{-3}$

TABLE 7.4 **Particle size analysis data of soils used in saturated hydraulic conductivity tests.**

Implications

The fact that the soil moisture appears to be related to the presence of silt and clay, and that there are layers of low saturated hydraulic conductivity present which limit percolation, all point to poor drainage and consequently low leaching of the soil profile. It is to be expected that if the saturated hydraulic conductivity of surface soil is as low as 24×10^{-3} m/day, leaching and irrigation may present serious difficulties

(Richards, 1954). However, the presence of fairly substantial amounts of bank seepage (1,0 litre per minute per metre of bank) indicate that deep percolation is occurring which means that the mechanism of preferential macropore flow through the calcrete is probably important.

7.5.3 Soil Chemistry

Sixty-eight soil samples from eight boreholes and three surface samples were analysed for macro-element determination as well as adsorbed cations, using various standard extraction procedures employed by the Hydrological Research Institute (H.R.I.). The results are presented in Tables 7.1 and 7.2 and E.1 to E.7, Appendix E. From the macro-element analysis, the T.D.S. values of the saturated extract are in the order of 6000 to 7000ppm and are fairly constant throughout the soil profile (in the same order of magnitude). Na, Cl, TAL and SO_4 make up 82 percent of the total dissolved solids.

In an attempt to correlate variations in chemistry with soil moisture and particle size, Na was plotted against depth in Figures 7.1 to 7.4. Although discrepencies do occur, there does appear to be a positive relationship between the amount of Na and the variables "percentage silt and clay", and "percentage moisture". This can be accounted for by the fact that ions would tend to accumulate in areas of high moisture content, i.e. areas of poor drainage. The major anomaly is in borehole KD 34 where the lowest proportion of Na is associated with a fairly high percentage silt and clay, and percentage moisture.

A better correlation exists between exchangeable Na and percentage silt and clay. This can be explained in terms of chemical (electrical) bonding where the Na ions are adsorbed onto the surface of clay particles. Na, Ca and Mg cations are always readily exchangeable. During the cation exchange process, the reaction between calcium saturated soil and NaCl solution may be written :

$$CaX_2 + 2NaCl \rightleftharpoons 2NaX + CaCl_2,$$

where X designates the soil exchange complex. Where the percentage exchangeable Mg exceeds Ca (as in the case of Middleton soils) and where the percentage Na is high, the soils have adverse physical properties, i.e. low hydraulic conductivity and high swelling of clays. Sodicity is defined as the effect of an excess amount of exchangeable sodium in the soil on soil permeability and structure deterioration, and a direct toxic effect of exchangeable sodium on plants specifically sensitive to sodium (Richards, 1954).

Examination of data reveal that there is a great reservior of exchangeable cations available for mobilization by deep irrigation percolate (Tables 7.1 and 7.2, and E.1 to E.7, Appendix E). The high percentage calcium is somewhat unrealistic as this is mainly as a result of calcrete present in the soil profile. Calcrete itself is evidence of calcium carbonate and calcium sulphate precipitation due to poor drainage and high evapotranspiration in the geological past.

Soils in the Middleton area can be classified as saline as the saturation extract exceeds 2600mg/l (4000μS/cm) and as base saturated (exchangeable sodium percentage > 15) i.e. saline-alkali soils (Richards, 1954). There are consequently sufficient salts due to the process of leaching alone to give rise to substantial mineralisation.

Characteristics of Saline - Alkali Soils

Soils of this class are characterised by their appreciable content of soluble salts and exchangeable sodium. As can be seen from Table 7.5, the Middleton soils have both a total dissolved solid content greater than 2600mg/l as well as an exchangeable sodium percentage greater than 15. Both replacement of exchangeable sodium and leaching are required for reclamation of these soils.

7.5.4 The Affect of Irrigation Water on Soils in the Study Area

So far, only the salts, both in the soil solution and adsorbed to silt and clay particles, have been considered. Now the focus shifts to the role of irrigation water, as this ultimately determines the dynamism of the system. The actual suitability of a given water for irrigation depends on the specific conditions of use - crop grown, various soil properties, irrigation management practices, especially leaching fraction, frequency of irrigation and climatic conditions (Kovda, 1971). In the hypothetical case where no salts are mobilized in the soil during downward percolation of irrigation water, enrichment of the percolate occurs only be means of evapotranspiration. In order to study the effect of enrichment due to evapotranspiration alone, irrigation water samples were analysed using a computer programme modified by Oster and Rhodes (1975). Briefly, the model calculates the resultant equilibrium chemical compositions of waters assumed to be concentrated from the initial compositions by the factor $(^1/LF_a)$, LF_a being the particular leaching fraction, appropriate for a given fractional interval of the rootzone (Rhoades and Merrill, 1975). Tables E.8 to E.20, Appendix E contain the calculated ion concentrations of irrigation water passing below the rootzone for five leaching fractions, namely 5%, 10%, 20%, 30% and 40% (the leaching fraction is the fraction of infiltrated water that passes beyond the rootzone). Figure E.1, Appendix E is a Piper plot of the leachate for the various leaching fractions. It is clear that the greater the leaching fraction, the lower is the T.D.S. content of the leachate. This is well illustrated in Figure 7.5

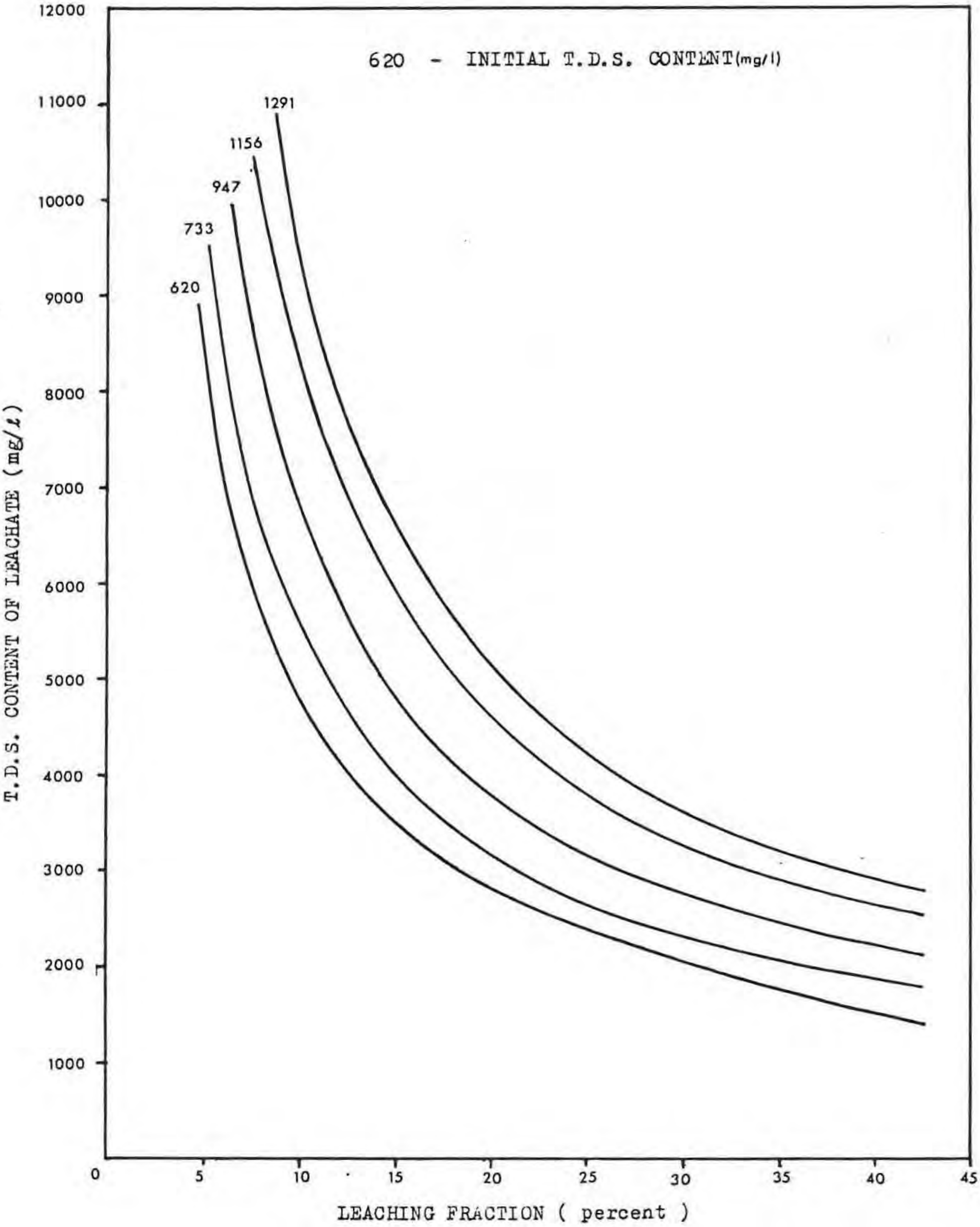


FIGURE 7.5 PLOT OF T.D.S. CONTENT OF LEACHATE AGAINST LEACHING FRACTION (data from study area)

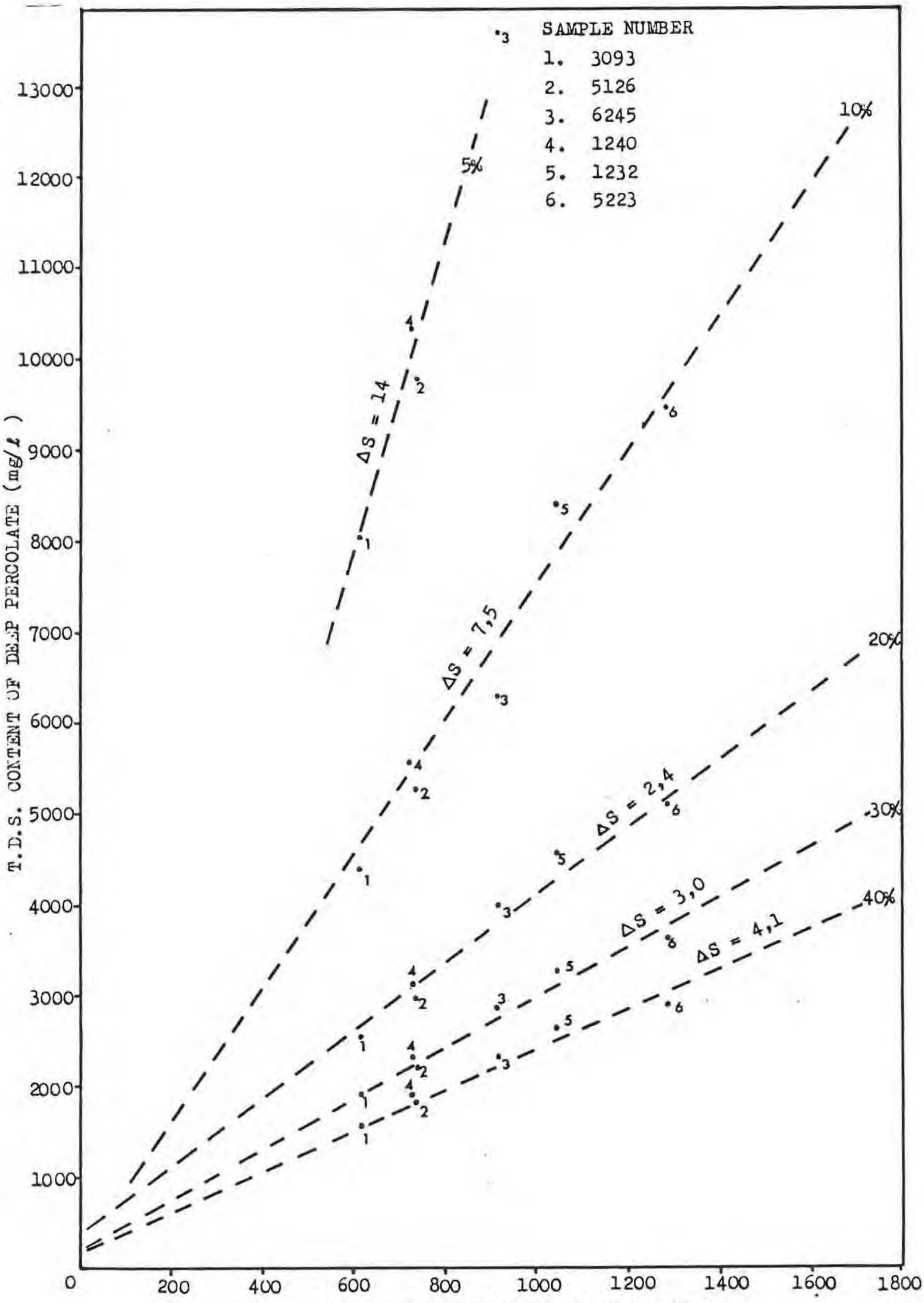


FIGURE 7.6 PLOT OF T.D.S. CONTENT OF DEEP PERCOLATE AGAINST T.D.S. CONTENT OF IRRIGATION WATER (data from study area)

SELECTED SATURATION EXTRACT DETERMINATIONS												
Soil Type & Sample No.	TDS content	Cations me/l					Anions me/l				SAR	Exchange-able Na %
		Ca	Mg	Na	K	Total	TAL	SO	Cl	Total		
	mg/l											
Normal Soils R-2867	546	2,76	1,69	5,22	0,18	9,85	6,63	2,67	0,44	9,74	3,5	3
Saline Soils 574	9035	31,5	37,2	102,0	0,21	170,95	4,5	90,0	78,0	172,5	17,4	13
Nonsaline Alkali Soils 535	2053	1,10	0,3	29,2	4,1	34,7	27,1	4,6	7,5	39,2	35,0	46
Saline Alkali Soils 2740	10855	32,4	38,2	145,0	0,51	216,2	3,29	105	105	213,3	24,4	26
Middleton KD34-1m	8133	20	11	75,3	1,2	107,5	52	17	28	97	19,1	36
Middleton KD34-3m	10067	10	5,5	116	3,4	135	57,3	23,6	50,7	131,6	41,7	40

Table 7.5 Comparison between saline-alkali soils and Middleton soils.

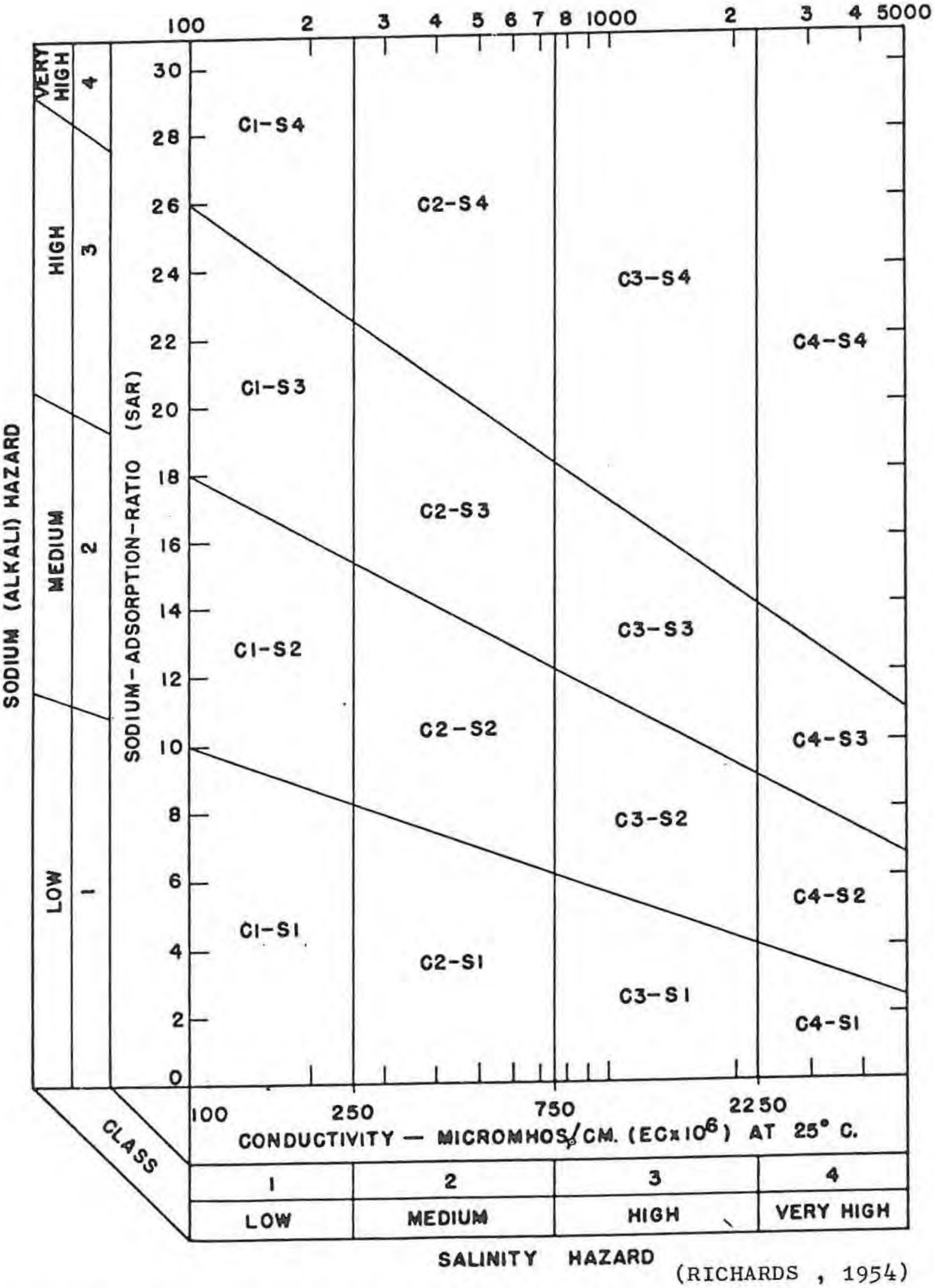
where leaching fraction is plotted against T.D.S. content of leachate. It is also evident that an increase in initial T.D.S. content of irrigation water (for a particular leaching fraction) will result in an exponential increase in the T.D.S. content of the leachate. The deleterious effect of poor soil texture and structure can be seen in Figure 7.5. The lower the drainage, and consequently the smaller the leaching fraction, the greater will be the T.D.S. content of the leachate.

The preceeding discussion, which assumes no salt pick-up in the soil, shows that even with a good quality irrigation water (400ppm) and a leaching fraction of 20%, the expected TDS content of the leachate can be as high as 1900ppm (i.e. almost a 5 fold increase). One must therefore assume that in the field situation where there is salt mobilization in the soil, and where T.D.S. content of irrigation water is high (up to 1147ppm), the salinity problem will be magnified greatly. (Figure 7.6 illustrates the effect of increasing T.D.S. content of irrigation water on T.D.S. content of leachate).

One cannot assume that an improvement in irrigation water quality will result in a lowering of the TDS content of the seepage water in the short term (although from Table 7.6 there may be some evidence to support this). The high TDS content of the soil solution as well as the great reservior of salts available in adsorbed form will result in the high salinity values being maintained for some time (when irrigating with good quality water, H^+ ions replace adsorbed Na^+ ions on a one to one basis). As the soils are base saturated, there are many ions available for future mobilization. Exchange will occur until a new equilibrium is reached between soil and water, after which seepage water quality will again remain constant.

Figure 7.8 shows a diagram for the classification of irrigation waters (Richards, 1954). All irrigation samples from the study area fall into one of three categories :

(i) C2-S1 - medium salinity water with low Na content. Need a moderate amount of leaching in order to avoid salinization of soils.



(RICHARDS , 1954)

FIGURE 7.8 Classification of irrigation waters based on conductivity and Sodium adsorption ratio.

(ii) C3-S1 - high salinity water with low Na content. Cannot be used on soils with restricted drainage.

(iii) C3-S2 - high salinity water with moderate Na content. This type of water presents a serious Na hazard in fine textured soils having high cation - exchange capacity, especially under low leaching conditions.

It is therefore evident that little improvement in soil, and consequently seepage water, salinities can be expected under the present dissolved solid content of irrigation water.

7.6 Affect of Improved Water Quality on Irrigated Soils

Borehole KD36 was drilled in the non-irrigated control area on the right hand bank of the Great Fish River (Figure 4.1). This area has never been irrigated with Orange River water and has in fact been lying fallow since 1974. Table 7.6 is a comparison of T.D.S. and adsorbed Na values for KD36, and two boreholes drilled in irrigated lands. It is interesting to note that the T.D.S. values for KD36 are higher than those for KD38 and KD41, while adsorbed Na values are approximatele the same for all three profiles. This may support the argument that the use of higher quality water since the Orange River Project has resulted in a leaching of salt from the soil profile of the irrigated lands. On the other hand, variations in soil salinity over short distances do occur (compare KD38 and KD44 which are only 50m apart) and the different salinities observed may be a function of factors not directly related to irrigation water quality.

TABLE 7.6 COMPARISON OF TDS AND ADSORBED Na CONTENT FROM IRRIGATED AND NON-IRRIGATED SOILS.

DEPTH	KD 41 T.D.S. mg/ℓ	KD 38 T.D.S. mg/ℓ	KD 36 T.D.S. mg/ℓ	KD 41 ADSORB. Na	KD 38 ADSORB. Na	KD 36 ADSORB. Na
1	6200	2600	3733	667mg/ℓ	267	267
2	3467	4867	6339	399	533	667
3	6067	5400	8400	533	600	667
4	5333	5667	9733	733	533	867
5	4000	5667	8467	867	533	733
6	3733	6067	8200	600	467	800
7	6133	5133	10133	467	467	867
8	3933	5200	4467	1733	400	400
9	4533	7400	12067	1800	1467	2067
10	4133	6133	15333	2467	1600	3600
11	3733		13933	2667		2667
12			10933			1600
13			11467			2267
14			9800			1133
15			2733			600

7.7 Factors which may Lead to a Reduction in the Salinity of the Soils and Leachate

7.7.1 Irrigation Efficiency

This is mainly related to the quantity of water applied and the frequency of application. The higher the salt content of the water, the greater the amount of water that must be passed through the soil to keep the soluble salt content at or below a critical level (Rhoades and Merrill, 1975; Cass, 1979). However, overuse and waste of irrigation water contribute to drainage difficulties and salinity problems. The quantity of irrigation water applied should therefore be carefully controlled and should be based upon consumptive demand of the crops and leaching requirements of the soils (i.e. overirrigate only to ensure a certain predetermined leaching fraction, e.g. 30%) (Frenkel et al., 1978). Increasing irrigation frequency can markedly effect the quality of soil solution, particularly in the root zone. When irrigating with saline water it is important to irrigate frequently. Infrequent application and the use of saline water result in crops being exposed to critical total soil water potentials for long periods (Rhoades and Merrill, 1975).

7.7.2 Leaching

The leaching of soluble salts from the root zone is essential in irrigated soils. This can be accomplished by ponding an appreciable depth of water on the soil surface by means of ridges and thus establishing downward water movement through the soil (Richards, 1954). Preleaching of the soil at the beginning of the crop season (van Rooyen and Moolman, 1980) and controlled overirrigation are the most feasible methods for soil leaching in the Middleton area.

7.7.3 Drainage

Drainage in agriculture is the process of removal of excess water from soil (Richards, 1954). Salts in the irrigation water and in the soil increase the drainage requirements. The high adsorbed

Na percentage of Middleton soils results in unfavourable soil structure and consequently poor drainage. By adding gypsum to the soil or irrigation water, the exchangeable Na percentage is decreased as Na ions are replaced and go into solution (Cass, 1979). The soil structure is thus improved and the leaching fraction increases (particularly soils of the C3-S2 type). However the addition of gypsum may enrich the deep percolate with salts (especially Na and sulphate). The construction and improvement of drainage canals must be encouraged as a means of diverting the saline seepage water away from the river.

7.7.4 Irrigation Water Quality

In the light of the present mineralisation problem, the improvement of irrigation water quality is probably the most feasible solution. Both an improvement in leaching and in drainage results in highly mineralised return flows reaching the river and consequently causing problems in irrigation water quality lower down stream. An improvement in irrigation water quality will result in the need for less water to be applied in order to reduce root zone salinity and therefore less water reaching the groundwater table. Although this may not reduce the salt content of the deeper soil layers, plant growth will not be effected as the root zone will be low in soluble salts. Although not a problem at Middleton, a near surface water table causes many problems in certain parts of the Fish River Valley, e.g. Golden Valley. The use of smaller quantities of low T.D.S. content water will also prevent water logging and salinization of these soils.

CHAPTER 8

RECHARGE AND THE WATER AND SALT BALANCE

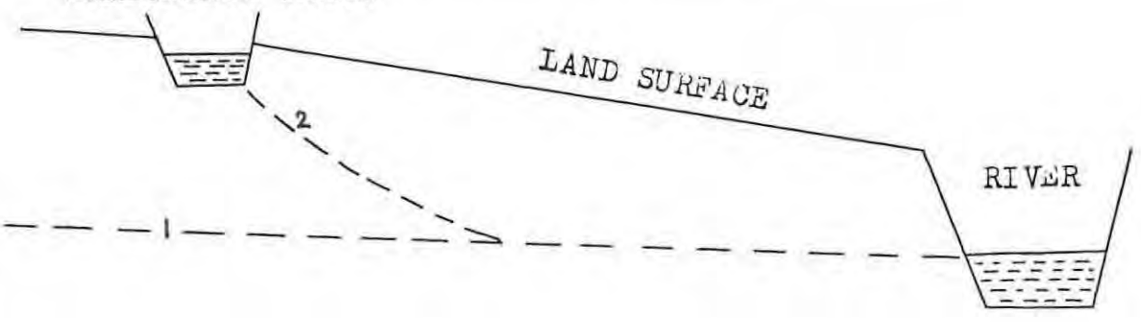
8.1 Recharge To The Alluvial And Fractured Rock Aquifers

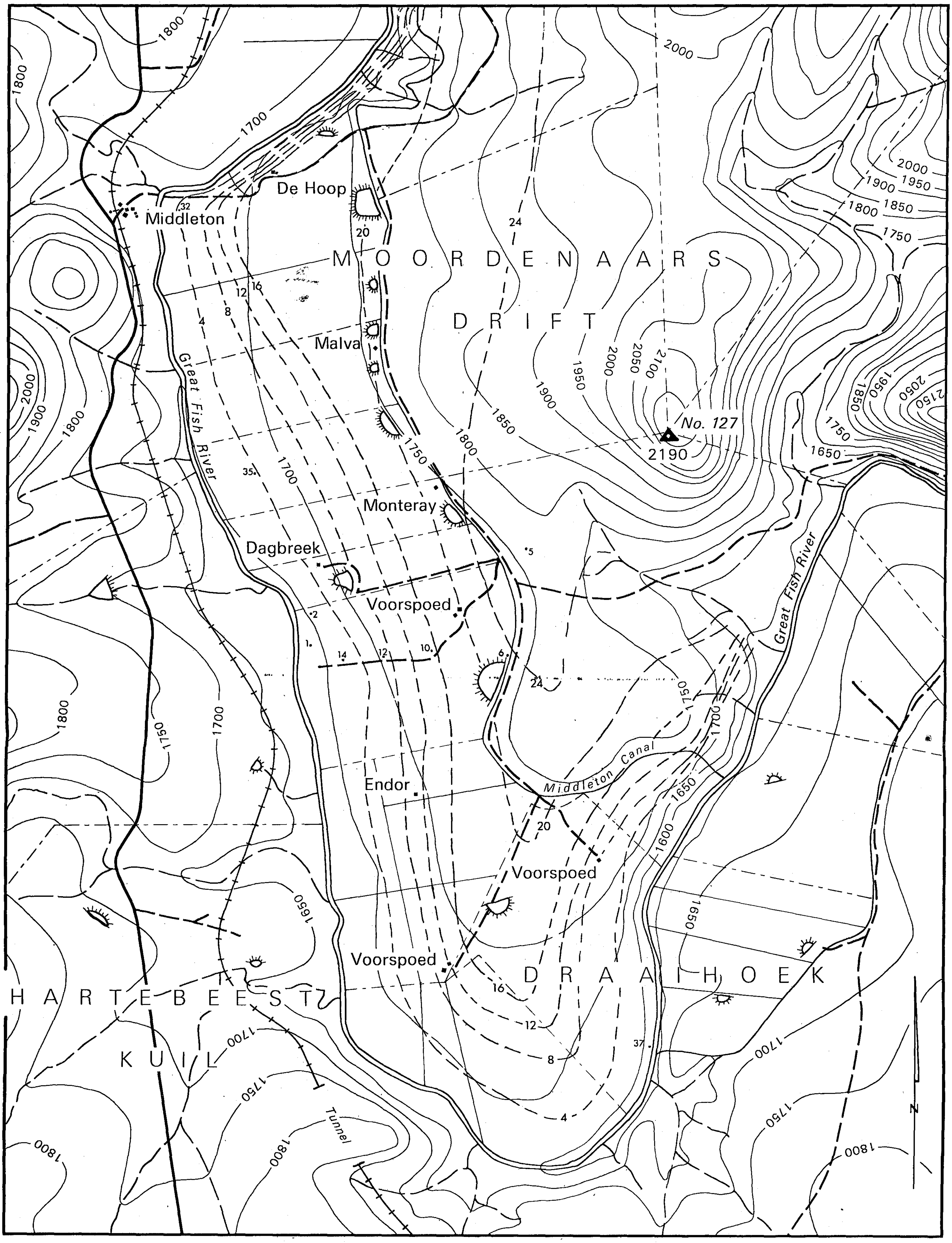
The construction of a groundwater level contour map (Figure 8.1), based on careful levelling of both existing and exploration boreholes, confirmed the effluent nature of seepage along the Great Fish River. The groundwater level contours closely mirror the topographic contours.

Ten water level recorders were installed on various boreholes to monitor fluctuations in water levels during rainfall events and irrigation loads. These levels were monitored between November 1982 and November 1983, the following observations being noted.

1. Recharge to the alluvial and fractured rock aquifers takes place mainly through the infiltration of irrigation water (34% of volume applied), although precipitation (13% of total rainfall) and leakage from canals and irrigation ponds (1%) of recharge contributed to a lesser extent. Substantial leakage from the Middleton Canal, resulting in an elevated groundwater table, takes place where the canal traverses weathered bedrock (Figure 8.2). A recorder on borehole KD 6, adjacent to the Middleton Canal, recorded rapid fluctuations in water level during irrigation leads. A rise of 10m, over a period of 2 months, was recorded in the borehole after the commencement of irrigation in August 1983.

FIGURE 8.2 IRRIGATED LAND - GROUNDWATER TABLE WITHOUT (1) AND WITH (2) CANAL SEEPAGE





MIDDLETON RESEARCH AREA

0 0.5 1.0 1.5
KILOMETRES

FIGURE 8.1 GROUNDWATER LEVEL CONTOUR MAP OF STUDY AREA

WATERLEVEL RECORDER 32

GROUNDWATER LEVEL CONTOUR 4 (metres above river level)

Contour interval in feet 1700

National road

Secondary road

Other roads

Railways

Farm Boundaries

Fence

Rivers

Dams

Canal

Fluctuations were also noted in borehole KD 7, situated immediately below an irrigation pond, reflecting leakage from the pond.

In borehole KD 27, adjacent to where the canal flows through clay-rich alluvial soil, no leakage was observed due to the sealing effect of the clay.

2. There exists a definite correlation between irrigation and groundwater levels, both in the unconfined alluvial aquifer and in the semi-confined/confined fractured rock aquifer. During the irrigation season from late August to April, water levels show a substantial rise, while a corresponding decline is observed during May, June and July when no water is lead onto the lands.

   This correlation is most marked in borehole KD 10, which receives water solely by seepage from fractured bedrock, having penetrated no alluvial soil or fractured rock aquifers during drilling. Eleven days after an irrigation lead on 22 July 1983, the water level in the borehole rose 4,40m in 48 hours. After three months of no irrigation during the winter season, the effect of the irrigation lead during July 1983 was observed in boreholes penetrating both alluvial and fractured rock aquifers, clearly demonstrating the fairly rapid infiltration of irrigation water into both aquifer types. The lag time before the irrigation pulse was recorded varied from five days (KD 2, KD 12 and KD 14) in the alluvial aquifer to fifteen days (KD 4 and KD 5) in the "deeper" fractured rock aquifer (Figure 8.3). Macro-pore flow through fractured calcrete and rock layers is therefore an important mechanism in explaining this fairly rapid recharge rate.

   The water level rise in borehole KD 1, which reflects only fluctuations in the "deeper" sandstone aquifer, is more subdued than those water levels measured in boreholes in hydraulic continuity with the alluvial aquifer. This is a consequence of the dampening effect of the overlying

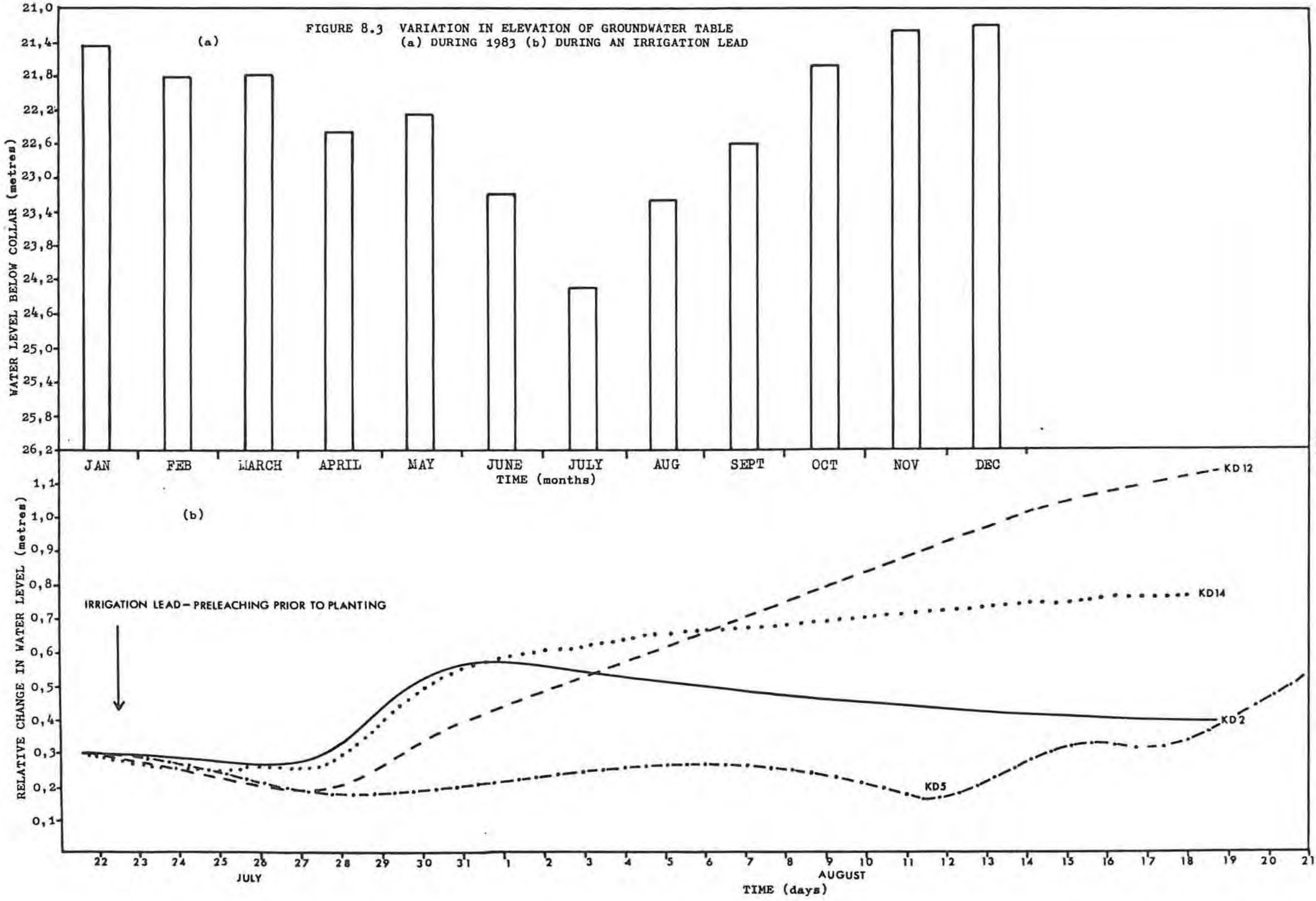


FIGURE 8.3 VARIATION IN ELEVATION OF GROUNDWATER TABLE (a) DURING 1983 (b) DURING AN IRRIGATION LEAD

confining layers.

8.2 The Water Balance

The catchment water cycle is often described by a water balance equation of the form :

$$P + I - S - E - Q_z = 0$$

where P = precipitation
I = irrigation
S = surface runoff
E = evapotranspiration
Q_z = vertical drainage (or capillary rise, respectively positive or negative)

all expressed as a depth of water measured over some convenient time period, such as a year (Cass, 1980).

In the following calculations it has been assumed that the amount of seepage leaving the study area is equivalent to the amount of water passing below the root zone of the irrigated lands. This is probably a valid assumption when the varying water levels over a period of one year are examined, i.e. although fluctuations take place, the pre-winter water levels are restored after irrigation commences once more during the sping.

391,6 hectares of land are irrigated within the study area. Of this, 50% is covered by lucerne, 40% by maize, and 10% by wheat. The amount of water applied during the 1982 season amounted to 3 580 549m^3, i.e. approximately 914mm per hectare, whilst precipitation added a further 394,7mm.

Rainfall and potential evaporation data for the period 1980 to 1983 are shown in Table 8.1, while tha actual evapotranspiration values are contained in Table 8.2 (actual evapotranspiration = crop factor x potential evapotranspiration x percentage area cultivated) (Richards, 1954). Based on these values, the total evapotranspiration for 1982 is 951,3mm per ha. The amount of

		JAN.	FEB.	MARCH	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	TOTAL
POTENTIAL EVAPOTRANSPIRATION		282,9	245,2	157,9	120,4	101,0	87,1	78,0	118,3	145,3	217,9	257,0	316,5	
CROP FACTOR	MAIZE	0,4	0,5	0,55	0,55	0,55	0,1	0,1	0,1	0,1	0,13	0,2	0,23	
	LUCERNE	0,8	0,5	0,5	0,4	0,4	0,3	0,3	0,5	0,5	0,6	0,8	0,8	
	WHEAT	0,1	0,1	0,1	0,1	0,1	0,1	0,15	0,3	0,45	0,6	0,55	0,1	
ACTUAL EVAPOTRANSPIRATION (CROP FACTOR X POT.EVAP. X PERCENTAGE AREA CULTIVATED)	MAIZE	45,3	49,0	34,7	26,5	22,2	3,5	3,1	4,7	5,8	11,3	20,6	29,1	255,8
	LUCERNE	113,2	61,3	39,5	24,1	20,2	13,1	11,7	29,6	36,3	65,4	102,8	126,6	643,8
	WHEAT	2,8	2,5	1,6	1,2	1	0,9	1,2	3,6	6,5	13,1	14,1	3,2	51,7

TABLE 8.1. POTENTIAL EVAPOTRANSPIRATION, CROP FACTOR AND ACTUAL EVAPOTRANSPIRATION FOR STUDY AREA (1982).

		JAN.	FEB.	MARCH	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	TOTAL
1980	RAINFALL	30,5	65,9	38,4	27,6	2,8	10,8	5,0	8,5	26,1	14,5	86,2	24,5	340,8
1980	POT.EVAPOR.	264,0	204,4	182,4	184,6	132,3	106,8	133,0	130,3	142,8	230,0	212,2	256,5	2179,3
1981	RAINFALL	19,8	62,7	94,9	12,1	57,5	7,0	6,6	39,5	5,0	70,6	48,3	66,5	490,5
1981	POT.EVAPOR.	245,3	190,2	166,4	120,6	76,3	63,5	123,1	101,8	173,5	200,1	234,3	254,5	1949,6
1982	RAINFALL	14,9	50,2	31,4	81,9	0,0	46,6	40,5	23,3	29,5	37,4	28,5	10,5	394,7
1982	POT.EVAPOR.	282,9	245,2	157,9	120,4	101,0	87,1	78,0	118,3	145,3	217,9	257,0	316,5	2127,5
1983	RAINFALL	8,2	8,5	21,5	5,0	10,8			0,0					
1983	POT.EVAPOR.	309,7	241,5	199,5	143,5	117,3			146,5					

TABLE 8.2. RAINFALL AND POTENTIAL EVAPORATION DATA FOR THE PERIOD 1980 TO 1983 FOR STUDY AREA. (DEPT. OF AGRICULTURE, MIDDLEBURG)

water reaching the land surface was 1309mm per ha, of which 951,3mm per ha was lost through the process of evapotranspiration. It is assumed that no water was lost by overland flow because of the contoured nature of the lands. 357,7mm per ha is therefore available for percolation to the alluvial and fractured rock aquifers, i.e. 1 400 753m^3 over the study area. In addition, 139 040m^3 can be added for precipitation falling on 704 ha of non-irrigated veld (assuming that 5% of the precipitation reaches the groundwater table in non-cultivated area (Tordiffe, 1978, pg. 38).

The average dissolved solid content of irrigation water is 820,5mg/l, which means that 2,9378 x 10^6 kg of dissolved salts were applied to the land in 1982 (the contribution of salts by rainwater was ignored because of the low TDS content of rainwater, i.e. 20mg/l).

The discharge to the river can be divided into

(a) riverbank seepage and

(b) groundwater flow.

(a) <u>Riverbank Seepage</u>

Discharge (Q) = Aquifer width (W) x Transmissivity (T) x Hydraulic gradient (I)

Aquifer Width (W) = 8737m, i.e. the length of the river in the study area.

Transmissivity (T) = 1,10m^2/day. This is the average transmissivity of the alluvial aquifer as calculated from a "large diameter dug well" aquifer test.

Hydraulic Gradient (I) = 1:33,3. The hydraulic gradient varied between 1:24,6 and 1:50. An average value of 1:33,3 was chosen for the calculation of discharge from the alluvial aquifer.

Q = $288{,}6m^3$/day (105 $343m^3$/year)

Based on this figure, the average discharge per metre of river bank adjacent to irrigated areas is 0,02 litres per minute. Although concentrated seepage sites are found where the seepage flow rate is in the order of 1 litre per minute per metre of riverbank, these sites are more the exception than the rule. The flow from these seepage sites varied according to the irrigation season. The flow rate of 1 litre per minute deminished to 0,2 litre per minute during the winter.

(b) Groundwater Discharge

Similarly, for groundwater discharge, where T is the average transmissivity as calculated from 8 constant rate aquifer tests :

$$\begin{aligned} Q &= WTI \\ &= 8737m \times 38{,}4m^2/\text{day} \times 1/85 \\ &= 3947m^3/\text{day}\ (1\ 440\ 655m^3/\text{year}) \end{aligned}$$

i.e. $3947m^3$ of water is, on average, discharged each day from the "deeper"fractured rock aquifers. Consequently, riverbank seepage accounts for 7% of discharge to the river while baseflow from "deeper" aquifers accounts for 93% of discharge.

8.3 The Salt Load

The average dissolved solid content of riverbank seepage is 4550mg/l. If 105 $343m^3$ of water are discharged from the riverbank each year, the salt load reaching the river is 479 311kg. Similarly, the average dissolved solid content of groundwater is 3385mg/l, which means that 4 876 617kg of salt was discharged via groundwater seepage in 1982. The total mass of salt leaving the study area in one year is therefore 5 355 928kg or 13 677kg per ha (37,5kg/ha/day). On average, 20,6kg/ha/day of salts are applied to the lands which mean that 16,9kg/ha/day of soluble salts are being leached from the alluvial soils and consolidated formations.

Viljoen and Liebenberg (1974) found that the salt load from the Middleton area was in the order of 19,4kg/ha/day. As this value was determined before the increase in irrigation (coupled with the advent of water from the Orange River), it is probable that effluent seepage to the Great Fish River, and consequently salt load, has increased since 1976.

CHAPTER 9

HYPOTHESIS TESTING AND DISCUSSION

Each of the hypotheses stated in Chapter 3 is examined in the light of data obtained during the geophysics, drilling, aquifer testing, soil and hydrochemical phases of the study. Each hypothesis is restated and a summary of the basis of acceptance or rejection is provided.

AQUIFER GEOMETRY AND LITHOLOGY

Hypothesis 1

A laterally extensive water table situation is present in the alluvial aquifer,while the consolidated formations are represented by discrete aquifers.

Two aquifer types can be distinguished in the Middleton study area :

Type 1 : Alluvial Aquifer

This aquifer, which is found at the contact between the alluvium and solid bedrock, is unconfined and laterally extensive, and was encountered in 23 of the 45 boreholes drilled.

It is composed of weathered bedrock material and a poorly sorted conglomerate of sand, silt, clay and pebbles/cobbles. It exhibits marked temporal fluctuations in groundwater level which is related to irrigation leads. The aquifer has a very low transmissivity in the order of $1m^2$/day (Chapter 5, section 5.3.3 for detailed discussion).

Type 2 : Fractured Sandstone/Mudstone Aquifer

A discontinuous confined/semi-confined aquifer system exists in the solid formations where water is confined to secondary fractures and joints in the sandstones and mudstones. The low drawdown measured only 18m away from pumped holes during aquifer tests (e.g. boreholes KD 1 and KD 3) and large variations in salinity over short distances (KD 15 and KD 16) demonstrate the discrete nature of the aquifers (Chapter 6, section 6.1.1). Water in this aquifer type is under piezometric pressure, demonstrated by a rise in water level during drilling. Water was encountered in this aquifer type on 30 occasions.

The hypothesis is accepted.

Hypothesis 2

Although the fractured rock aquifers are themselves discrete, there is hydraulic continuity between the fractured sandstone/mudstone aquifers and the overlying alluvial aquifer.

Tritium analysis of both seepage and groundwater revealed a fairly rapid circulation of water in the system. All water samples analysed had an age of less than 20 years, while some groundwaters (e.g. KD 5 and KD 34) showed complete turnover within the last 10 years (Chapter 6, section 6.5). Corresponding fluctuations of water levels in boreholes penetrating the alluvial aquifer (KD 2) as well as the fractured rock aquifers (KD 10 and KD14), suggest hydraulic continuity between the two aquifer types (Chapter 8, section 8.1). Macropore flow through solution channels and fractures in the calcretes as well as through fractured mudstones and sandstones accounts for the fairly rapid effect of irrigation on the "deeper" groundwater.

The sodium chloride character of both the alluvial and fractured aquifer water is further evidence of this hydraulic continuity (Chapter 6, sections 6.3.3 and 6.4).

The hypothesis is accepted.

Hypothesis 3

The main aquifer is found in the fractured sandstone, while minor amounts of water are associated with the mudstone and alluvium.

Aquifer yield varies considerably over the study area and does not appear to be related to rock type but rather to the degree of fracturing present. Water was encountered on 13 occasions in fractured mudstones, on 20 occasions in fractured sandstone, and on 8 occasions at the contact between the two formations. The largest yield was obtained from borehole KD 32 penetrating a very fractured mudstone layer (15 l/s) while 9 out of 20 sandstone aquifers encountered yielded less than 0,5 l/s (KD 9 and KD 11) (Chapter 5, Table 5.1). Very low yields, in the order of 0,5 to 1,0 l per minute, were measured in the saturated alluvium.

The hypothesis is rejected.

Hypothesis 4

The fractured sandstone aquifer is anisotropic resulting in a strongly directional component to flow (in joints, fractures) while the alluvial aquifer is istropic (flow takes place in various directions.

Both sandstones and mudstones exhibit prominent faulting and jointing patterns related to folding, stress relief and the lenticular nature of channel sandstones and mudstones. The predominent east-west orientation of joints and fractures, as outlined in Chapter 4, facilitates an effluent seepage of groundwater to the river. The fracture zones vary in width from 0,2 to 2m.

The low hydraulic conductivity of clay rich layers in the alluvium inhibits the natural downward percolation of irrigation water. Consequently lateral flow may take place when an impermeable layer is encountered. Macropore flow, in solution channels in the calcretes therefore becomes an important mechanism in transmitting the irrigation percolate to the alluvial aquifer and "deeper" fractured rock aquifers (Chapter 8). The flow in the alluvium may therefore be anisotropic and so the fourth hypothesis is rejected.

Hydrochemistry

Hypothesis 5

The weathered mudstone is the principal lithological contributor of mineral salts to the groundwater.

The lenticular nature of the mudstones and channel sandstones resulted not only in variations in lithology over fairly short distances, but also in the randomness of groundwater occurence and hydrochemistry. Although the dissolved solid content of water in both sandstone and mudstone aquifers varied from moderate (1118mg/l) to fairly high (5772mg/l) because of their interconnectivity and consquent mixing, water from mudstone did, on average, possess a higher dissolved solid content. Water encountered in a thick sequence of mudstones, e.g. KD 32 and KD 37 was found to be rich in dissolved salts, particularly sodium and chloride (TDS content 5200mg/l and 2265mg/l respectively).

Although the equivalent percentage sodium was approximately the same for both sandstone and mudstone aquifers (70%), the equivalent percentage chloride was higher in the case of mudstones (62%, as opposed to 52% for sandstones). Depth to aquifer, which governs recharge, appears to exert an important influence on the quality of groundwater. Sandstone aquifers occuring at depth (e.g. KD 45 at 65m) are often highly mineralised (3556mg/l).

However, pedological studies (Chapter 7) revealed that the soils are able to both store and discharge large quantities of salts and it may well be that the unconsolidated soils are the principal lithological contributor of mineral salts to the groundwater. Until further study on the weathering properties of mudstones is undertaken, the hypothesis is rejected.

Hypothesis 6

Because salts are leached from the soils to the groundwater and irrigation results in a rising of the groundwater table, the groundwater below irrigation lands will have a higher salinity than groundwater from non-irrigated veld.

Although large variations in total dissolved solid content of groundwater occur within both irrigated and non-irrigated area, the average water quality from aquifers underlying irrigated lands is considerably higher than that below non-irrigated veld (average TDS content of aquifers underlying irrigated lands is 3385mg/l as opposed to 1959mg/l for aquifers below non-irrigated veld). Irrigation water both adds salts to and leaches salts from the soil profile, and as such increases the salt load which is discharged to the river. Water chemistry below non-irrigated veld is characteristic of a stagnant environment, high in equivalent percentage chloride, while that found below irrigated lands is representative of a more dynamic environment (higher equivalent percentage CO_3 and HCO_3) (Chapter 6, Table, 6.1). Temporal fluctuations coinciding with the irrigation season were observed in the alluvial and fractured rock aquifers. The increase in hydraulic head resulted in a consequent mobilization of mineralized groundwater from the "deeper" aquifers (Chapter 8, section 8.2).

This hypothesis is accepted.

Recharge

Hypothesis 7

Recharge takes place through irrigation, precipitation, and leakage from unlined canals and farm reservoirs.

The high evapotranspiration rate (951,3mm per annum) and the unfavourable texture of the soil results in approximately 13% of mean annual precipitation reaching the groundwater table. Recharge to the alluvial and fractured rock aquifers therefore takes place mainly through infiltration of irrigation water. Based on calculations in Chapter 8, 34% of the volume of irrigation water applied to the lands reaches the groundwater table.

Limited recharge also takes place through leakage from canals and irrigation ponds, as is evident from water level fluctuations in boreholes KD 6 and KD 7 (recharge assumed to be less than 1% of water reaching groundwater table) (Chapter 8).

The hypothesis is accepted.

Hypothesis 8

Particle size distribution influences both soil moisture content and salt accumulation in soils.

Particle size analysis on samples from the alluvial profile revealed that 67% of particles fell into the size range 0,05 - 0,147mm, i.e. fine sand. However, clay rich layers were encountered throughout the soil profile. Figures 7.1 to 7.4 (Chapter 7) confirm that a positive relationship exists between percent silt and clay, percent moisture, and percent adsorbed Na, with depth.

Low saturated hydraulic conductivities of between 7,2 x $10m^{-3}$ and 69,5 x 10^{-3}m/day were measured, these low values corresponding to the silt and clay rich layers. The resultant poor drainage gives rise to salt and moisture accumulation in the soils.

The hypothesis is accepted.

Hypothesis 9

Concentration of salts in the soils by processes of evapotranspiration and the application of irrigation water results in progressive mineralisation of water moving vertically and laterally through the soils.

The average total dissolved solid content of irrigation water is 820,5mg/l while that of riverbank seepage is 4550mg/l (Chapter 6). This means that through the process of evapotranspiration and salt mobilization, a more than five fold increase in dissolved salts takes place beween the zones of recharge and discharge.

The calculated leaching fraction is in the order of 27 percent (Chapter 8). According to the model of Oster and Rhoades (1975) discussed in Chapter 7, with no salt mobilization in the soil, the leachate should have a total dissolved solid content of 2740mg/l. This means that 1810mg/l salt is mobilized from the soil "reservoir".

Sections A and C (Appendix B) define a progressive increase in mineralization of groundwater from the area of recharge (canal) to the area of discharge (river).

The hypothesis is accepted.

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

With the assured supply of water after the completion of the Oviston Tunnel, linking the Orange and Fish Rivers, the emphasis for irrigation management in the valley shifted from availability of water to water quality. The progressive mineralisation of Fish River water as it flows downstream has a deleterious effect on irrigation farming in the lower reaches of the valley and has necessitated research into the factors responsible for this mineralisation.

A number of studies have been undertaken which have attempted to relate the mineralised baseflow entering the river to factors such as soils, rock type and topography. In this study the mineralisation process at Middleton was viewed as a system (Figure 10.1). In order to elucidate the factors responsible for the mineralisation of irrigation water, the soils and consolidated formations were singled out for special attention. The mineralisation model postulated for the system is shown in Figure 10.2. With reference to the model, the following conclusions have been drawn.

Irrigation water (I), and to a lesser extent precipitation (P) and leakage from canals and ponds (L), forms the input into the system. Evapotranspiration (E) results in 73% of the applied water being lost to the atmostphere. The remaining 27% (LF) passes below the root zone and joins the groundwater reservoir. Besides the concentrating effect of evapotranspiration, mobilisation of salts (S) already present in the soils further increases the TDS content of the percolate. Poor soil texture results in salts being precipitated (Pt) in the soils which may be mobilised during future irrigation leads. Macropore flow (M) through solution channels in the calcretes, and fractures and joints in the consolidated formations, results in vertical percolation (VP) to the "deeper" groundwater predominating over lateral flow (LS) through the soils. Lateral flow within the transmissive fractured rock aquifers returns mineralised seepge water to the river via joints and fractures below river level. In this way 93% of irrigation return flow is

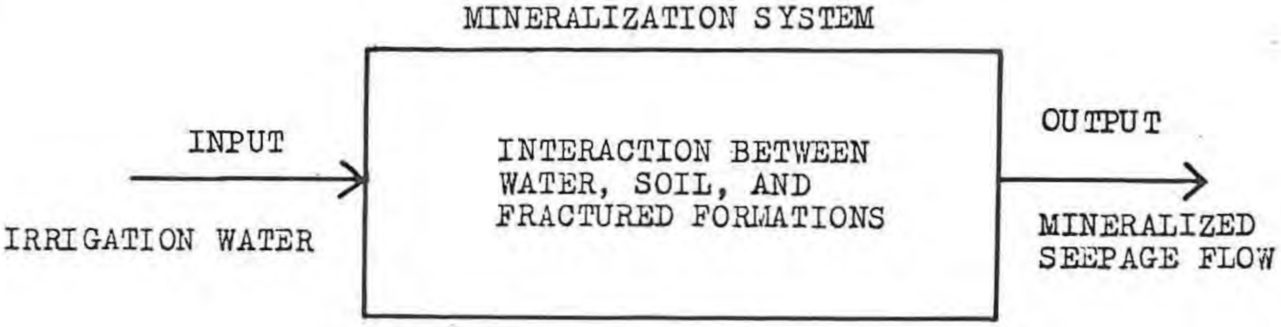


FIGURE 10.1 Mineralization system.

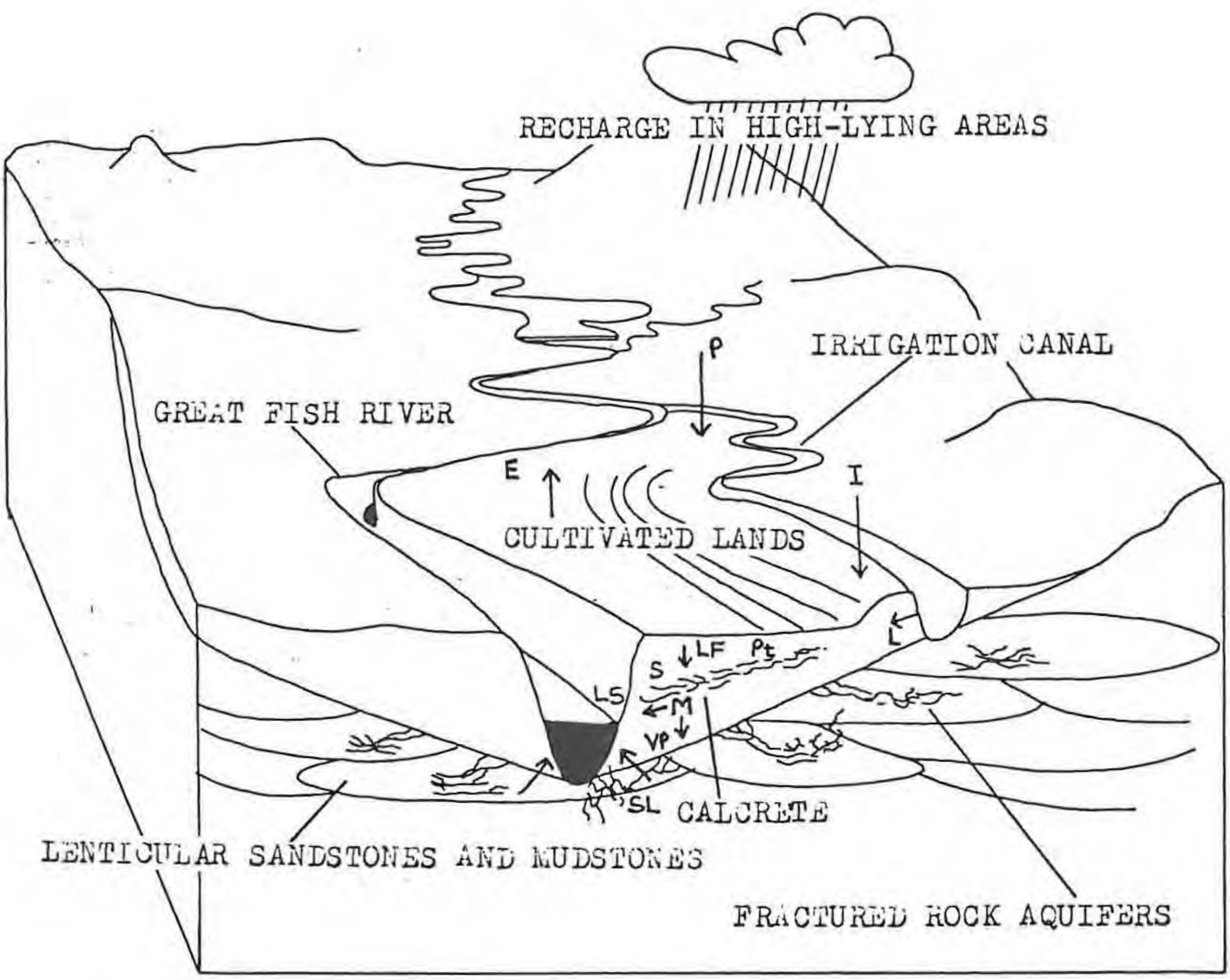


FIGURE 10.2 . SALT TRANSPORT, STORAGE AND MOBILIZATION PROCESSES IN THE STUDY AREA.

accounted for by discharge from fractured rock aquifers while 7% is accounted for by river back discharge. A net loss of salt (SL) from the soils and fractured rock aquifers is taking place at the rate of 2,418 x 10^6 kg per year, resulting in a deterioration of river water quality.

Recommendations

Under the present leaching fraction (0,27) where 27% of the water applied passes below the root zone, the great reservoir of soluble and adsorbed salts present in the soil profile, as well as the high TDS content of groundwater, will result in mineralised water returning to the river even if irrigation water quality is improved. To prevent mineralisation of irrigation supplies, the supply and drainage systems should ideally be separated. The cost of a concrete lined supply canal from Grassridge Dam direct to irrigation schemes would be prohibitive. The alternative is to reduce the volume of drainage water returning to the river.

Three possible solutions to the problem are listed below :

1. an elaborate system of drains installed to intercept the irrigation percolate before it reaches the river;
2. the leaching fraction reduced by applying a smaller volume of water to the soil;
3. a better quality irrigation water applied in order to reduce the input of water borne soluble salts.

Limitations of the devices are discussed below :

1. The high installation and maitenance costs limit artifical drainage as a solution to the mineralisation problem, although it should be considered in areas were new lands are being developed.
2. A reduction in volume of applied water is not feasible unless it is accompanied by an improvement in water quality. At present levels of dissolved solids, a large volume of water is applied to reduce salt concentration within the root zone. The use of smaller volumes of better quality water upstream would result in

a smaller volume of return flow reaching the lower schemes, i.e. less water would percolate to the groundwater table and baseflow would deminish. It is certain that if more lands are developed along the Great Fish River, as is planned for the future, irrigation water in the lower part of the valley will become progressively more mineralised, leading to a deterioration in soils and crops. The future of the valley as an important producer of food crops will be in jeopardy unless careful management of the system is exercised.

Recommendations for further research

A number of questions, related particularly to flow rates within the alluvium and fractured rock aquifers, still remain unanswered. It is recommended that further research be undertaken in the following areas :

1. A similar detailed study be undertaken in the middle reaches of the basin at a site where an elevated water table effects soil minerlisation, and where intrusive dolerite controls groundwater occurrence and flow.

2. Long term artificial tracer studies, using a low level radioactive tracer, be undertaken at Middleton to determine soil moisture flow rates in the alluvium and flow rates in the "deeper" fractured rock aquifers.

3. The cessation of irrigation releases from the large storage reservoirs on the Great Fish River for a period during the winter "non-irrigation" season so that the emergence of river bank and groundwater seepages may be studied more closely.

4. Small scale, plot studies be undertaken to determine :

   (a) the affect of better quality irrigation water on the TDS content of deep percolate;

   (b) the affect of artificial drains and smaller volumes of irrigation water on reducing the leaching fraction;

(c) the affect of alternative irrigation methods, such as sprinkler and drip irrigation, on the volume of irrigation water required.

5. Using the Middleton infrastructure, long term minitoring of water levels, seepage flow, and hydrochemistry of surface and groundwater points in the study area be undertaken so that a more detailed salt and water balance can be determined.

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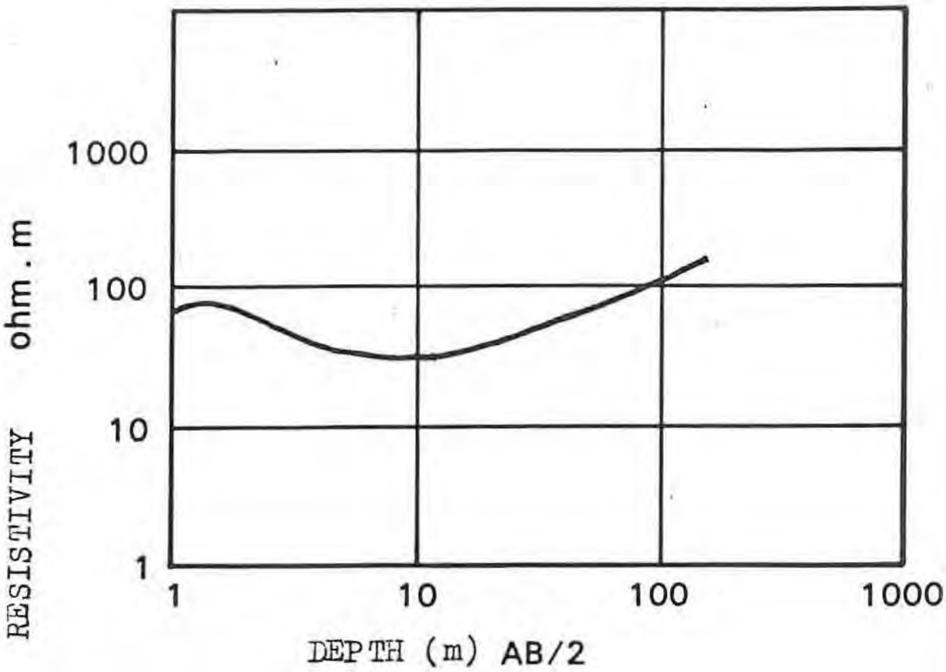
APPENDIX A

SOUNDING No. 2/6

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
0,84	114
11,4	30
22,7	70
R	600

TOTAL S = 0,7117 Siemens

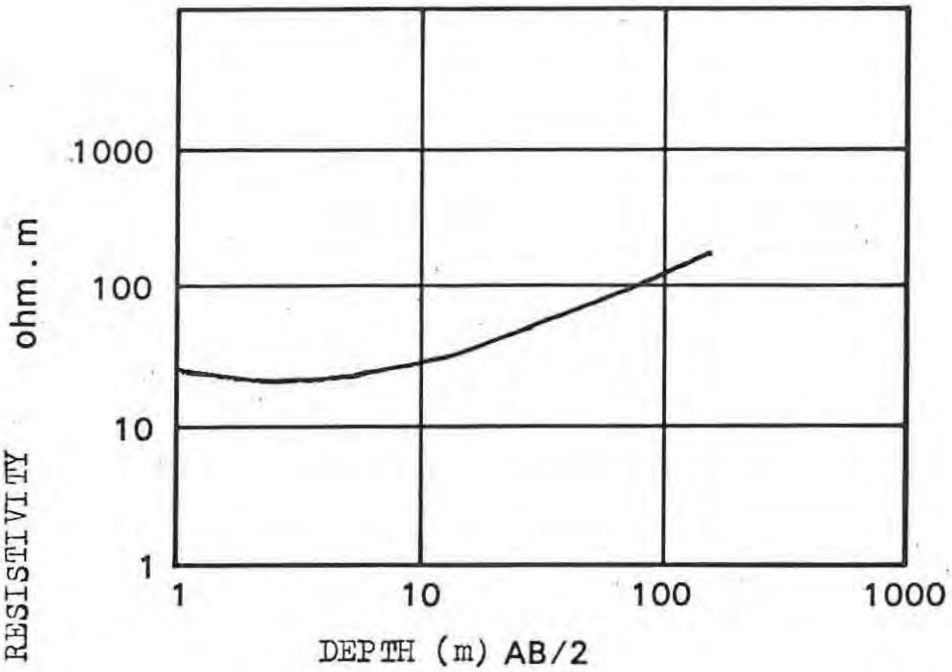


SOUNDING No. 2/8

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
0,38	30
2,9	19
8	28
27	180
R	900

TOTAL S = 0,6010 Siemens



SOUNDING No. 2/9

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
1,44	8
10	28
R	380

TOTAL S = 0,5371 Siemens

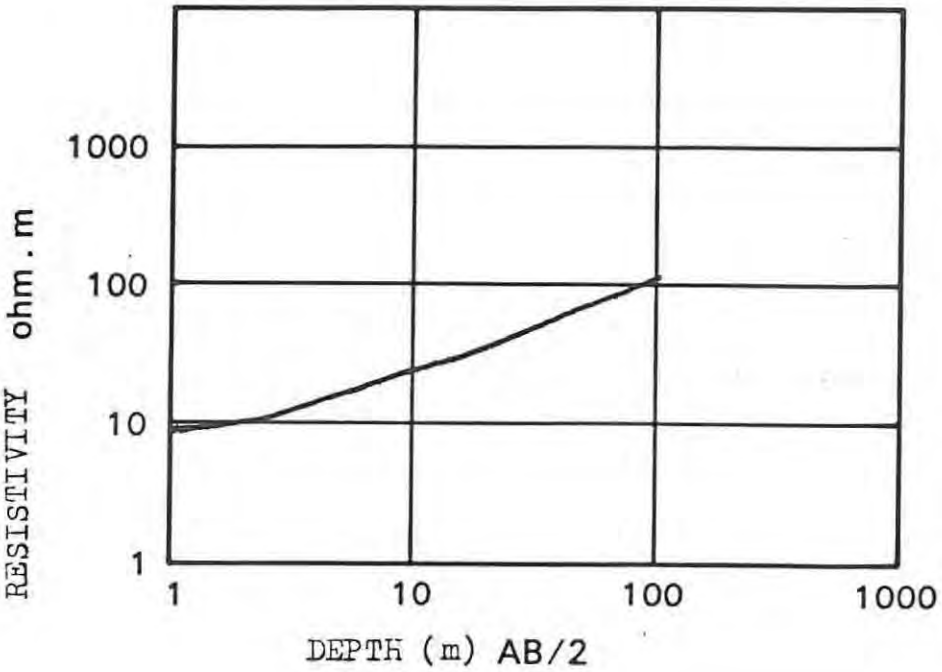


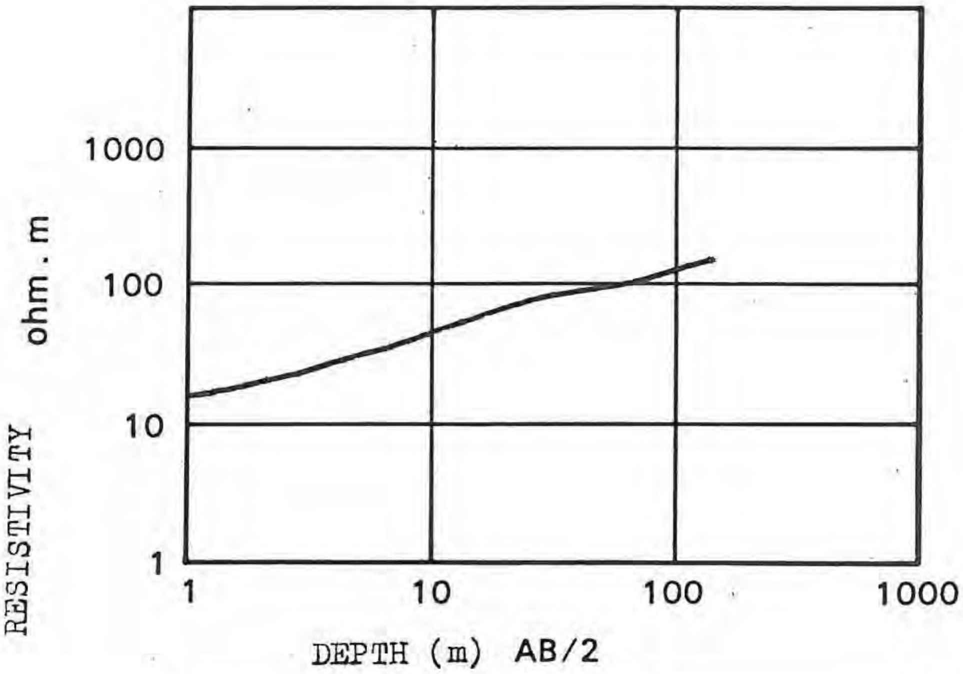
FIGURE A.1

SOUNDING No. 2/10

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
1,4	15,7
2,254	49
40,15	110
R	250

TOTAL S = 0,5002 Siemens

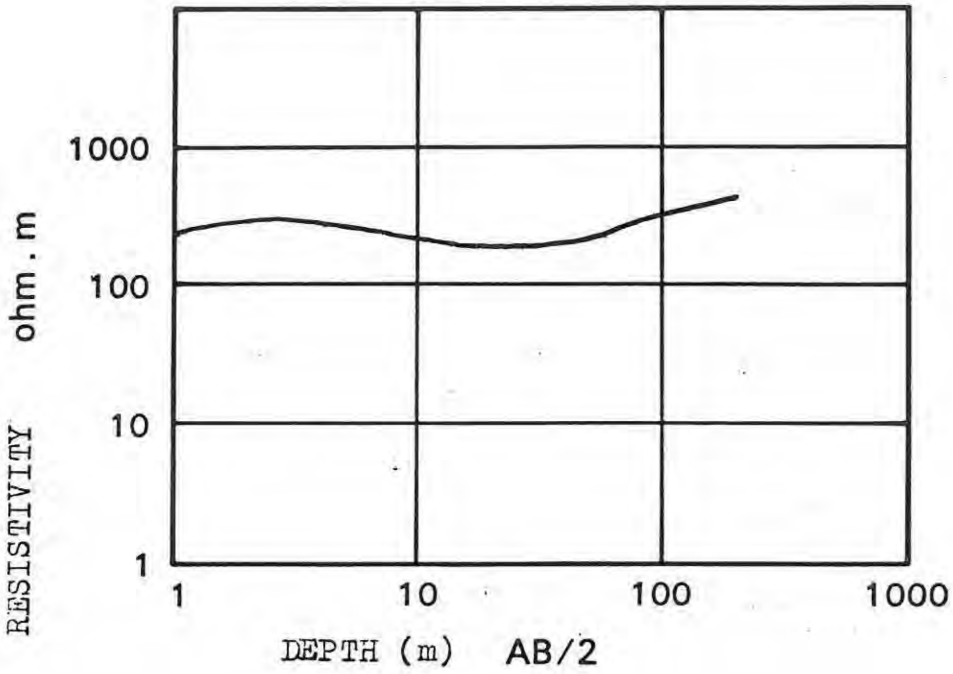


SOUNDING No. 3/11

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
0,47	173
2,5	325
4	160
19	152
R	550

TOTAL S = 0,1604 Siemens



SOUNDING No. 3/12

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
1,13	265
3,74	320
16,43	245
R	1200

TOTAL S = 8,3013 Siemens

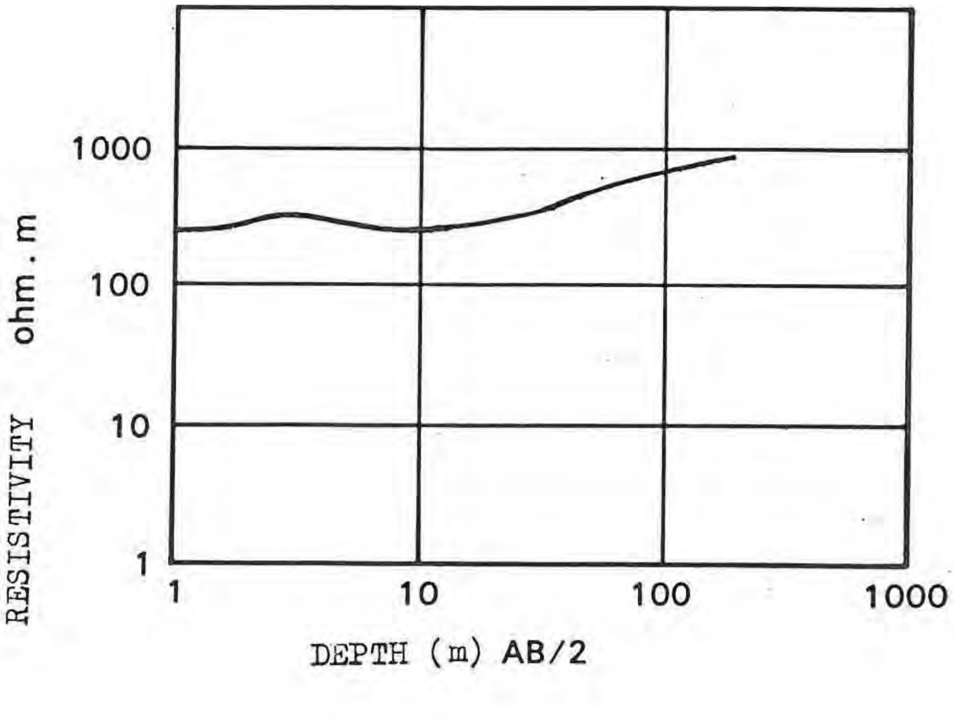


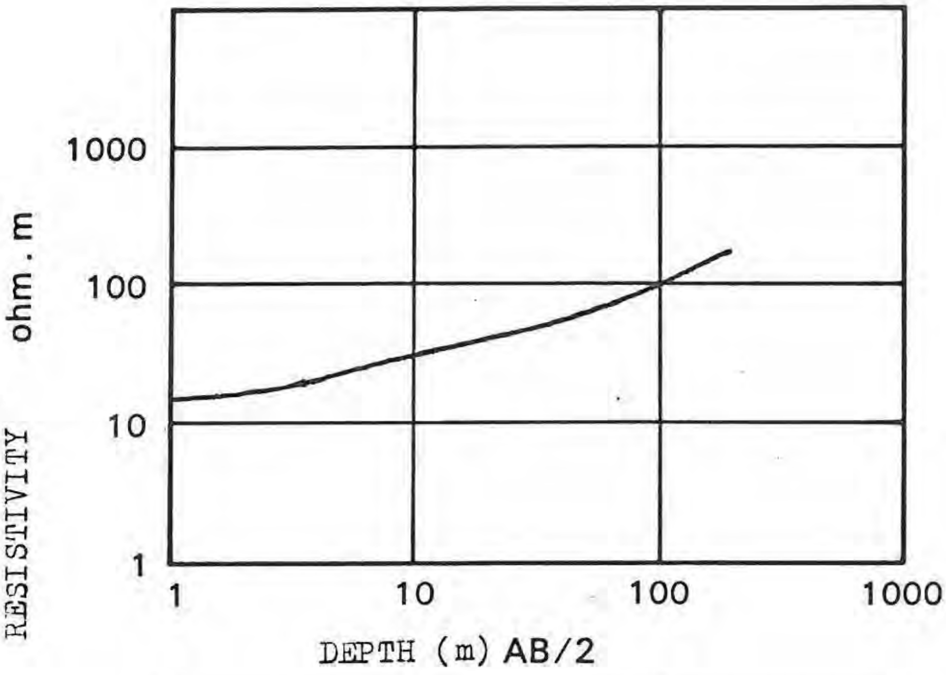
FIGURE A.1

SOUNDING No. 3/16

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
2	15
11,5	42,44
38,5	70
R	900

TOTAL S = 0,9543 Siemens

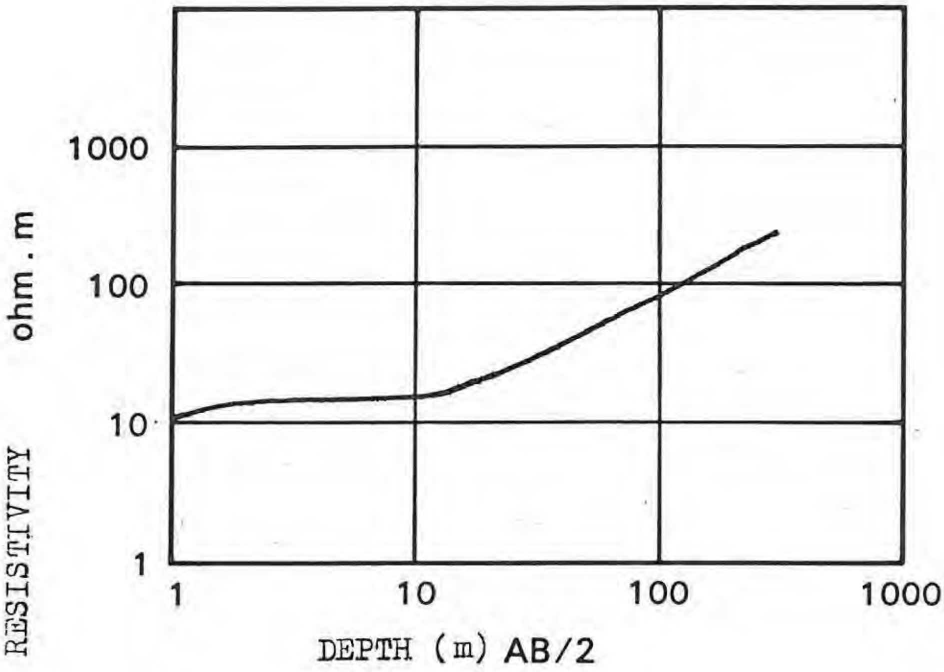


SOUNDING No. 3/18

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
2	14
2,5	18
10,7	16,46
11,2	80
R	1000

TOTAL S = 1,0718 Siemens



SOUNDING No. 3/19

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
2,45	18
7,32	9
5	71
R	900

TOTAL S = 1,0198 Siemens

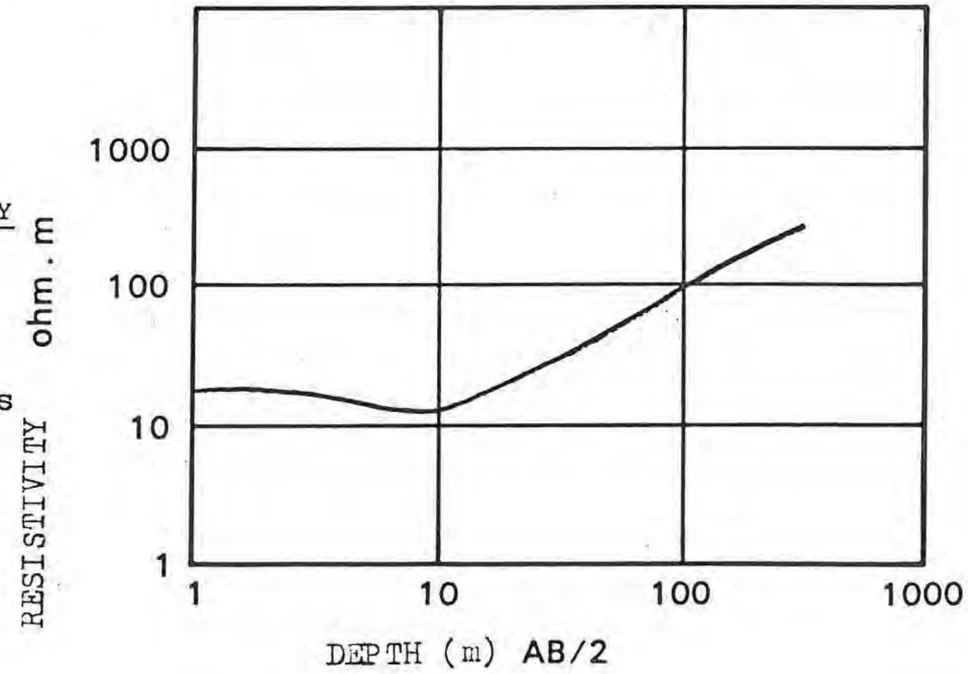


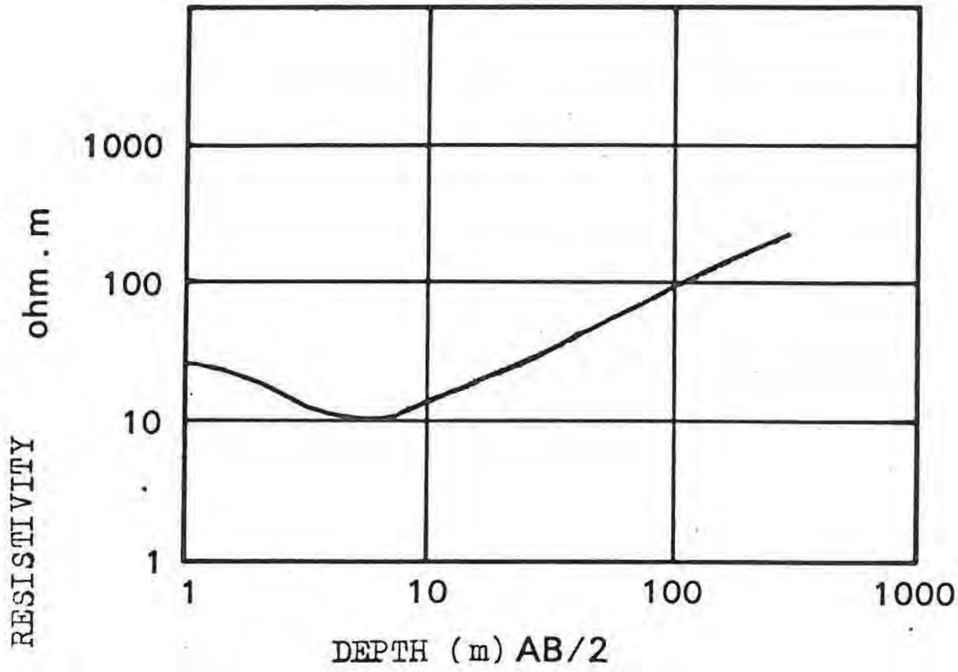
FIGURE A.1

SOUNDING No. 3/20

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
1	28
4,9	8
6	24
R	600

TOTAL S = 0,8982 Siemens

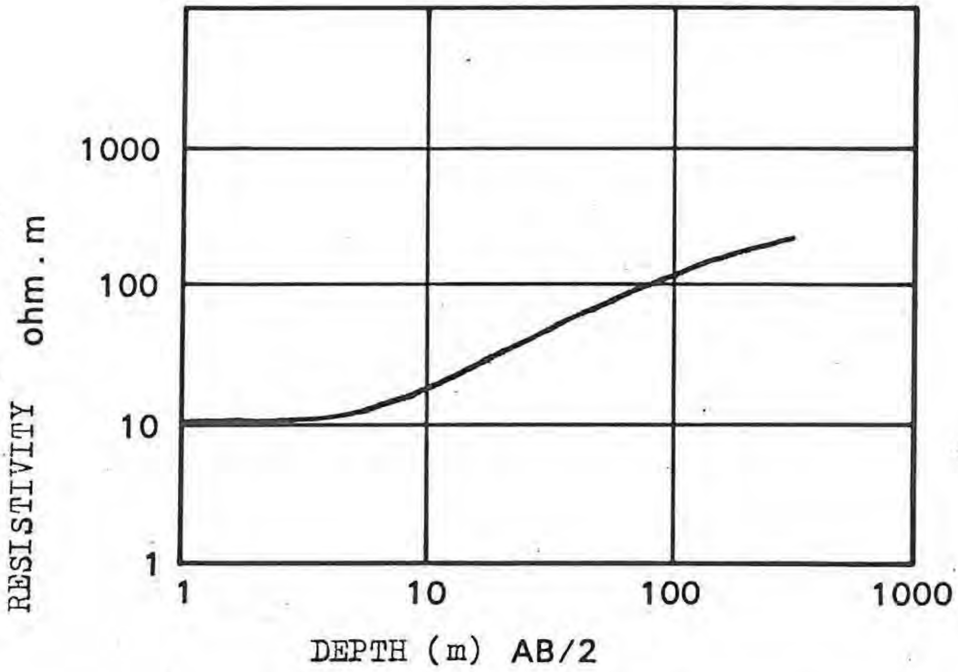


SOUNDING No. 3/21

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
3,375	10
8	37,7
R	320

TOTAL S = 0,5497 Siemens



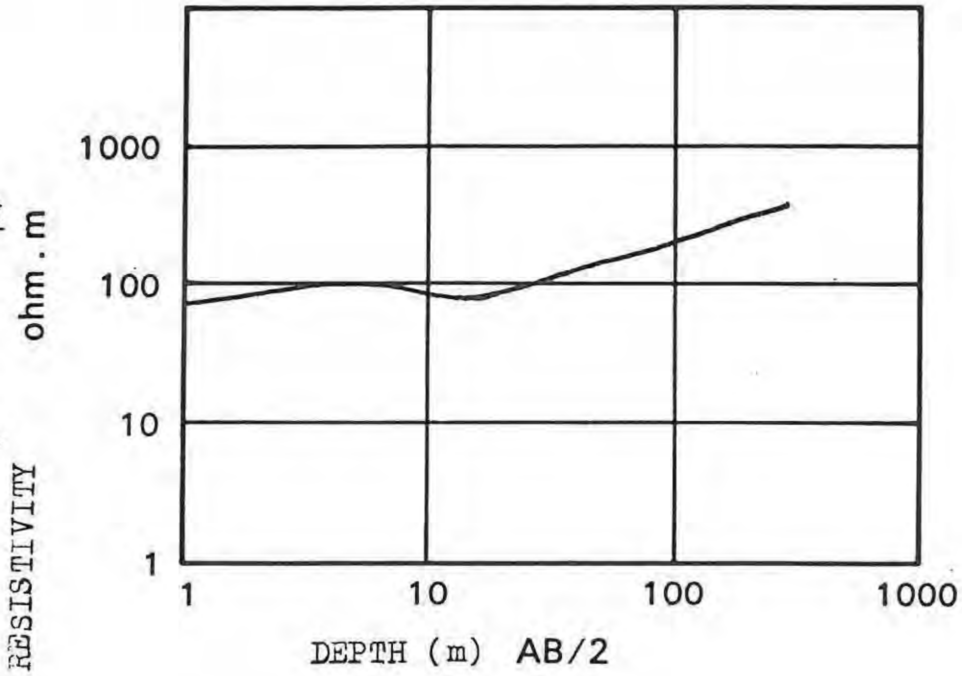
SOUNDING No. 3/22

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
1,45	75
2,9	150
5,5	36,28
50	208
R	700

TOTAL S = 0,4306 Siemens

FIGURE A.1

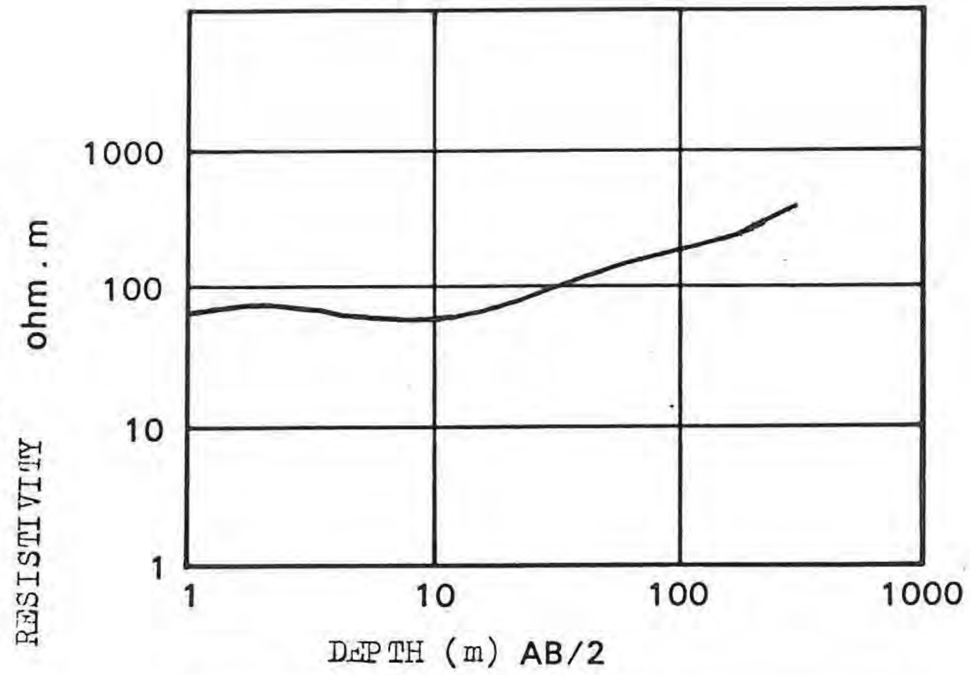


SOUNDING No. 3/23

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
1,5	80
11,1	55
82	200
R	2000

TOTAL S = 0,6306 Siemens

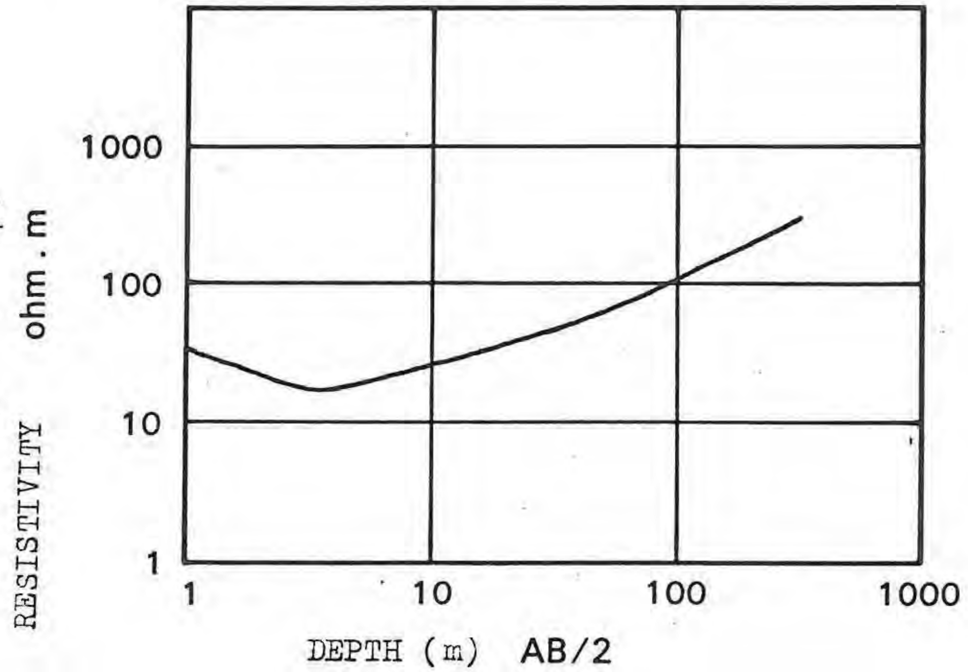


SOUNDING No. 3/24

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
0,95	34
2,56	13
27,6	49,79
R	1100

TOTAL S = 0,7792 Siemens



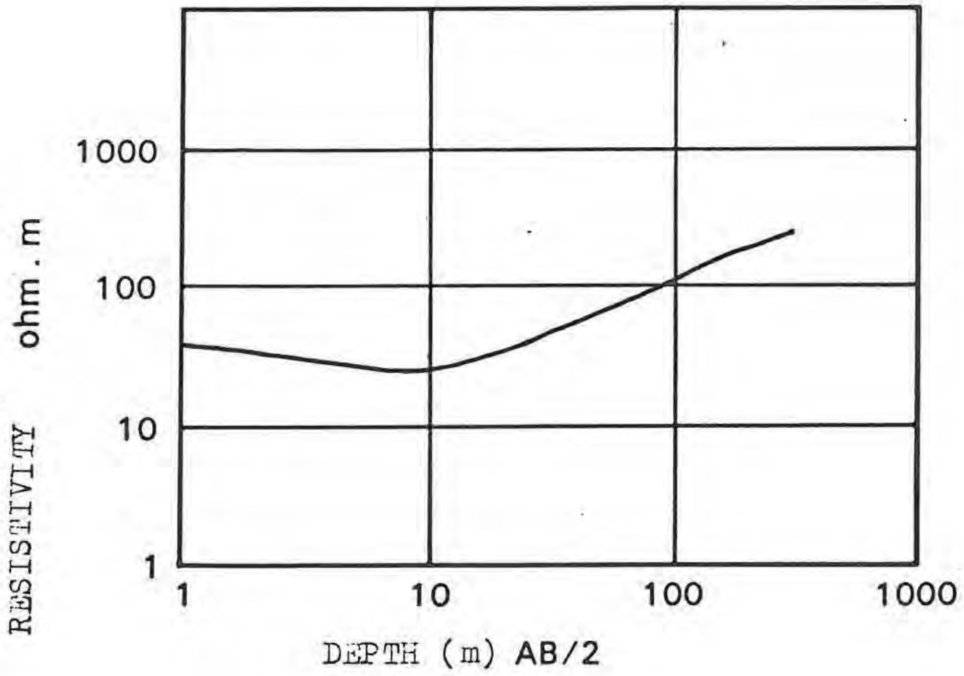
SOUNDING No. 3/25

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
1,3	34
8,4	20
25,2	90
R	550

TOTAL S = 0,7382 Siemens

FIGURE A.1

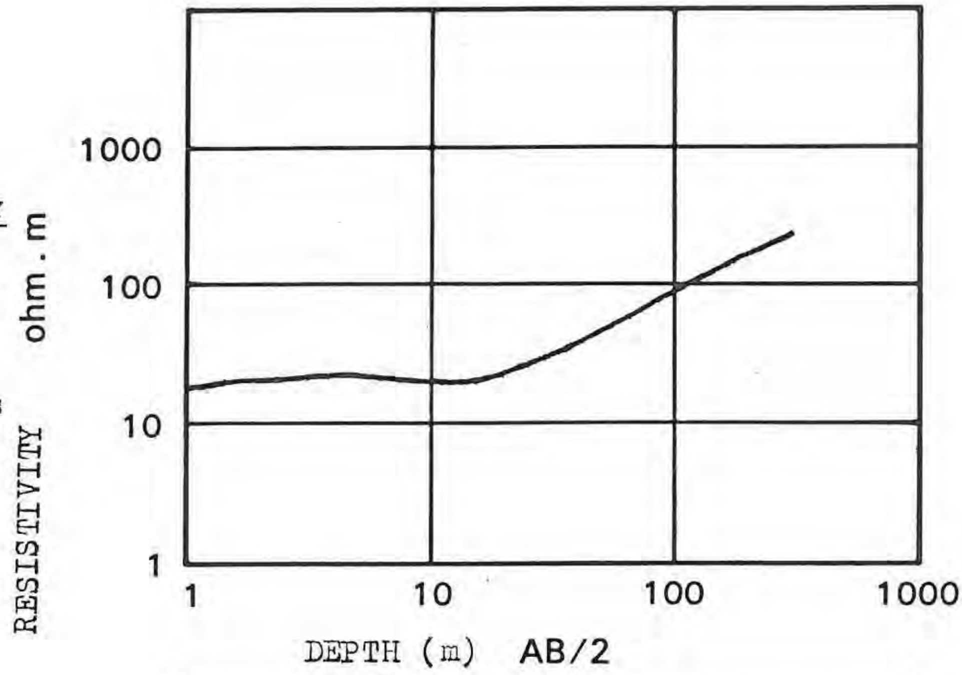


SOUNDING No. 3/26

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
1,19	17,8
1,65	25
14,85	18
R	700

TOTAL S = 0,9579 Siemens

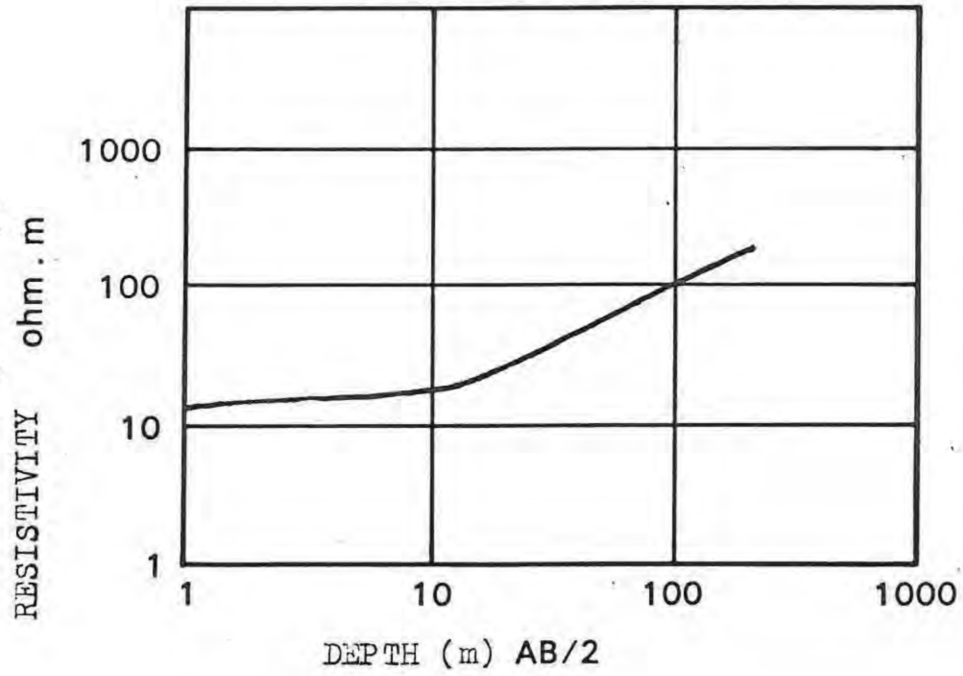


SOUNDING No. 3/27

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
0,48	11
12	17
R	670

TOTAL S = 0,7495 Siemens



SOUNDING No. 3/28

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
1,2	110
15,22	40
57	150
R	2300

TOTAL S = 0,7714 Siemens

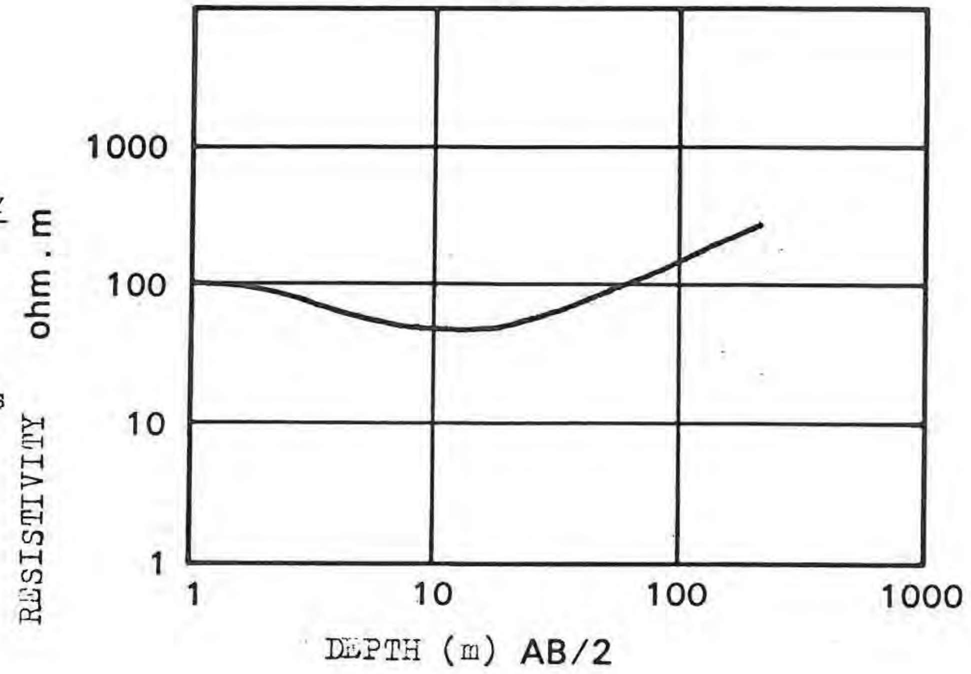


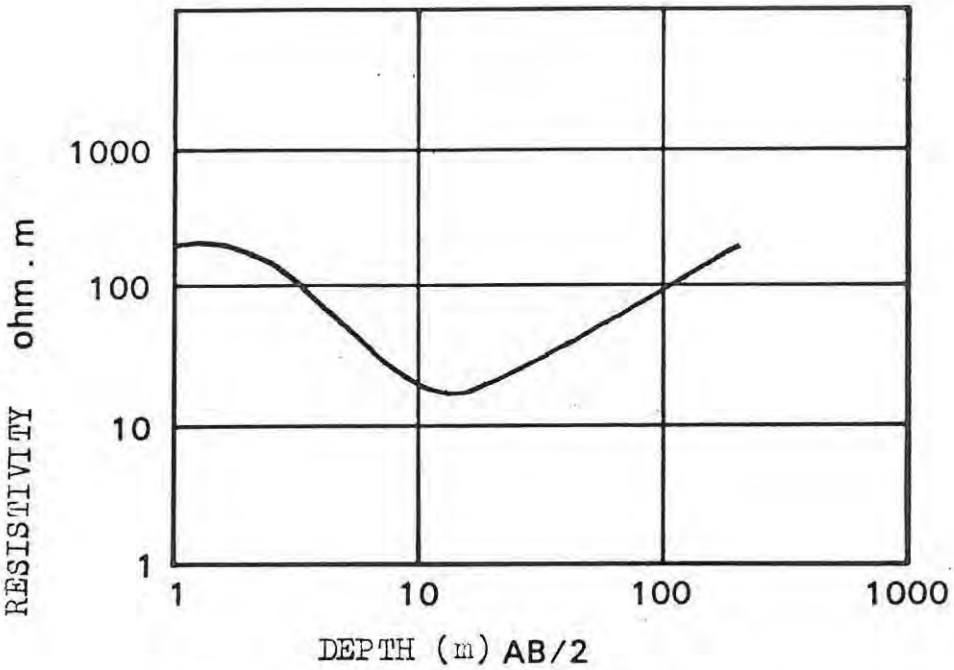
FIGURE A.1

SOUNDING No. 3/29

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
1,75	210
13,4	13,5
R	520

TOTAL S = 1,0009 Siemens

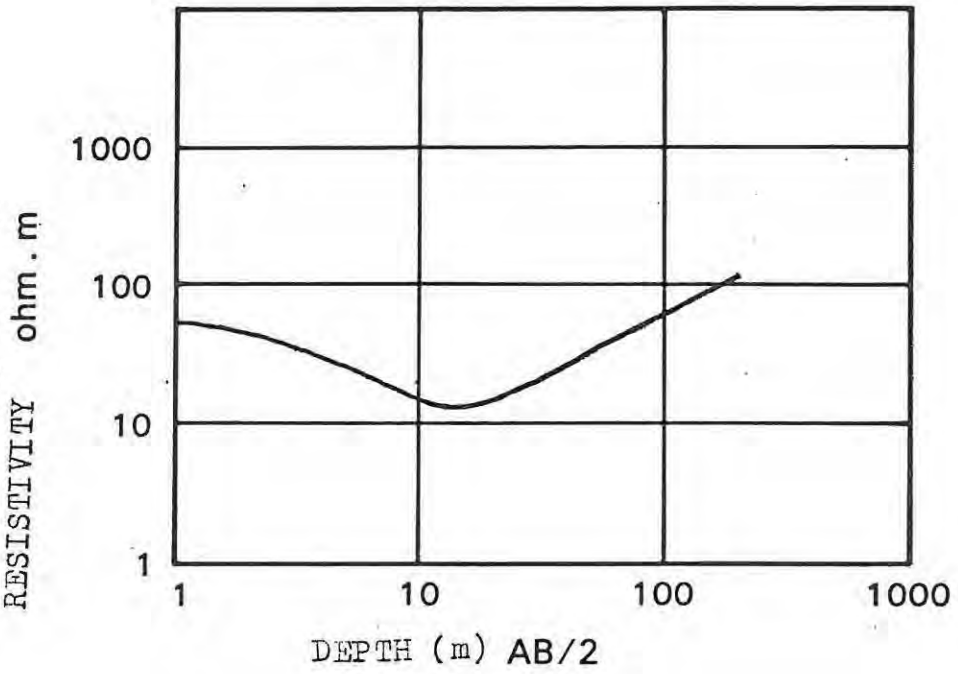


SOUNDING No. 5/1

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
2,32	45
14,16	11
R	440

TOTAL S = 1,3388 Siemens



SOUNDING No. 5/2

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
2,1	155
23,4	11,8
R	395

TOTAL S = 1,9966 Siemens

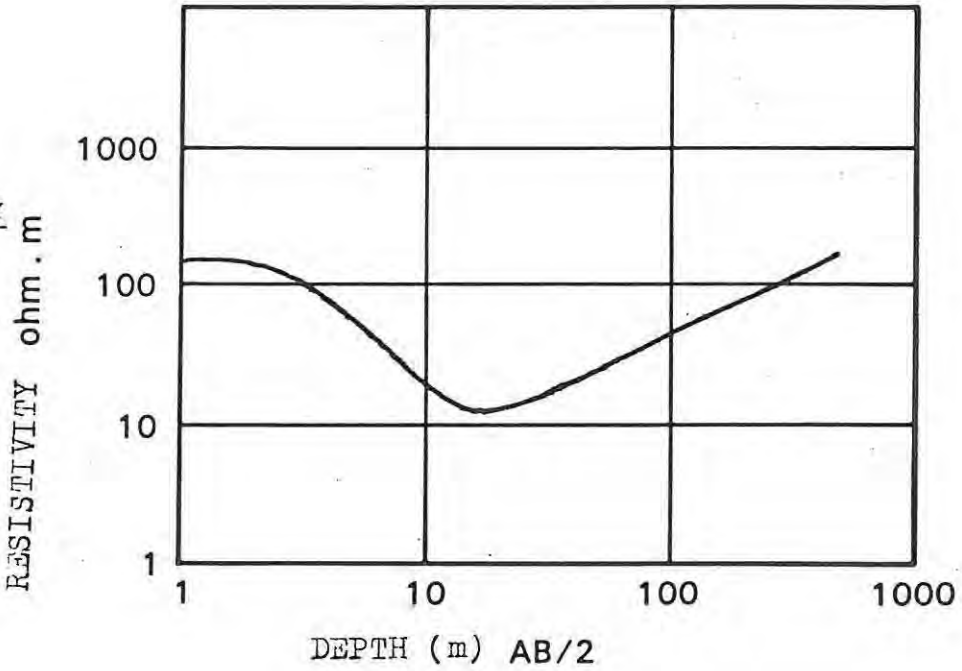


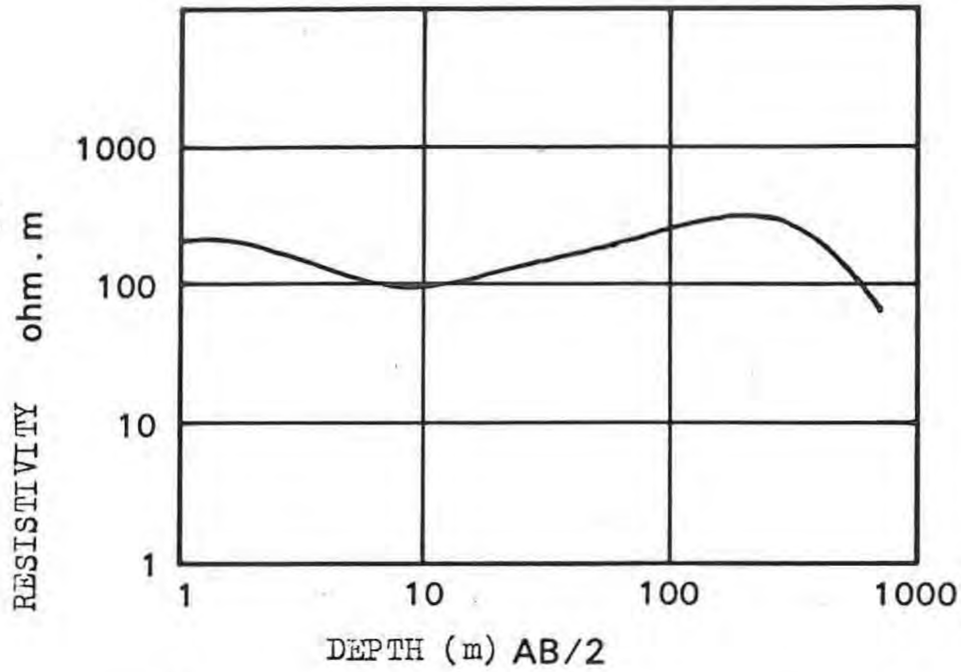
FIGURE A.1

SOUNDING No. 4/1

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
1,6	230
5,6	80
35,7	170
141,9	500
R	10

TOTAL S = 0,5708 Siemens

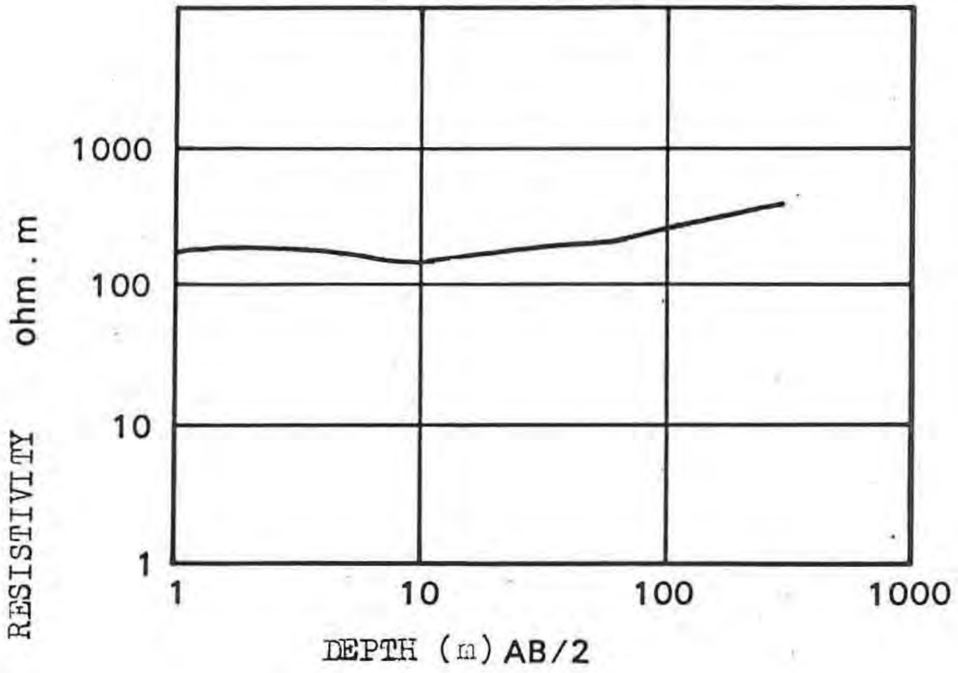


SOUNDING No. 4/2

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
3,6	190
5,4	120
19,0	234
7,5	89,3
R	500

TOTAL S = 0,2291 Siemens



SOUNDING No. 5/32

EARTH MODEL

LAYER THICKNESS (m)	RESISTIVITY (ohm.m)
0,22	420
1,65	30
6,032	130
R	300

TOTAL S = 0,1019 Siemens

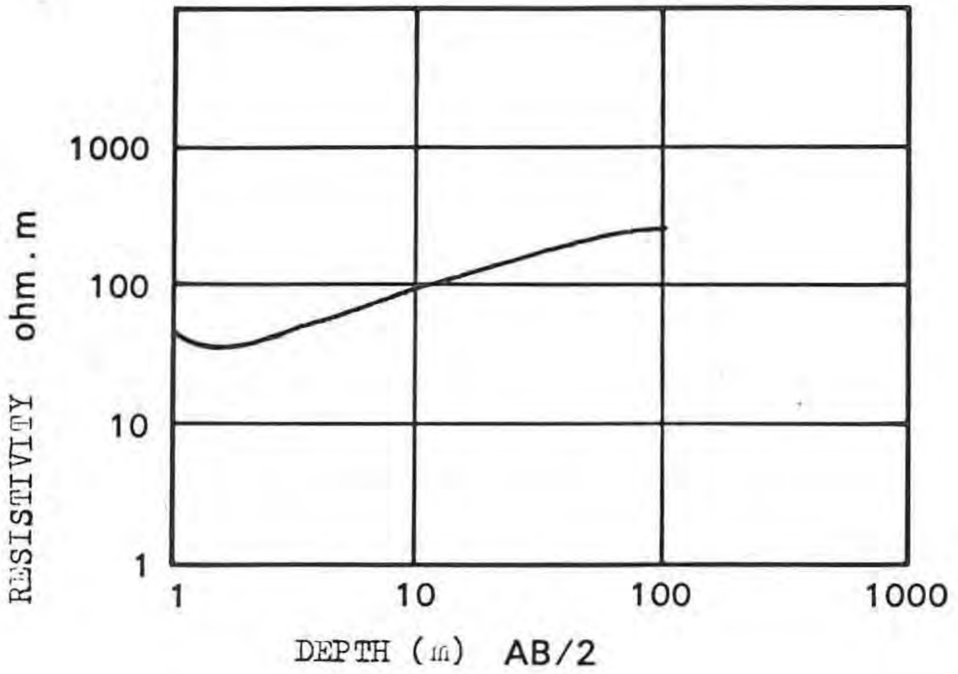


FIGURE A.1

APPENDIX B

BOREHOLE NO: KD 2

CADASTRAL FARM: KLIPPE DRIFT

BLOW TEST YIELD: NO WATER ENCOUNTERED

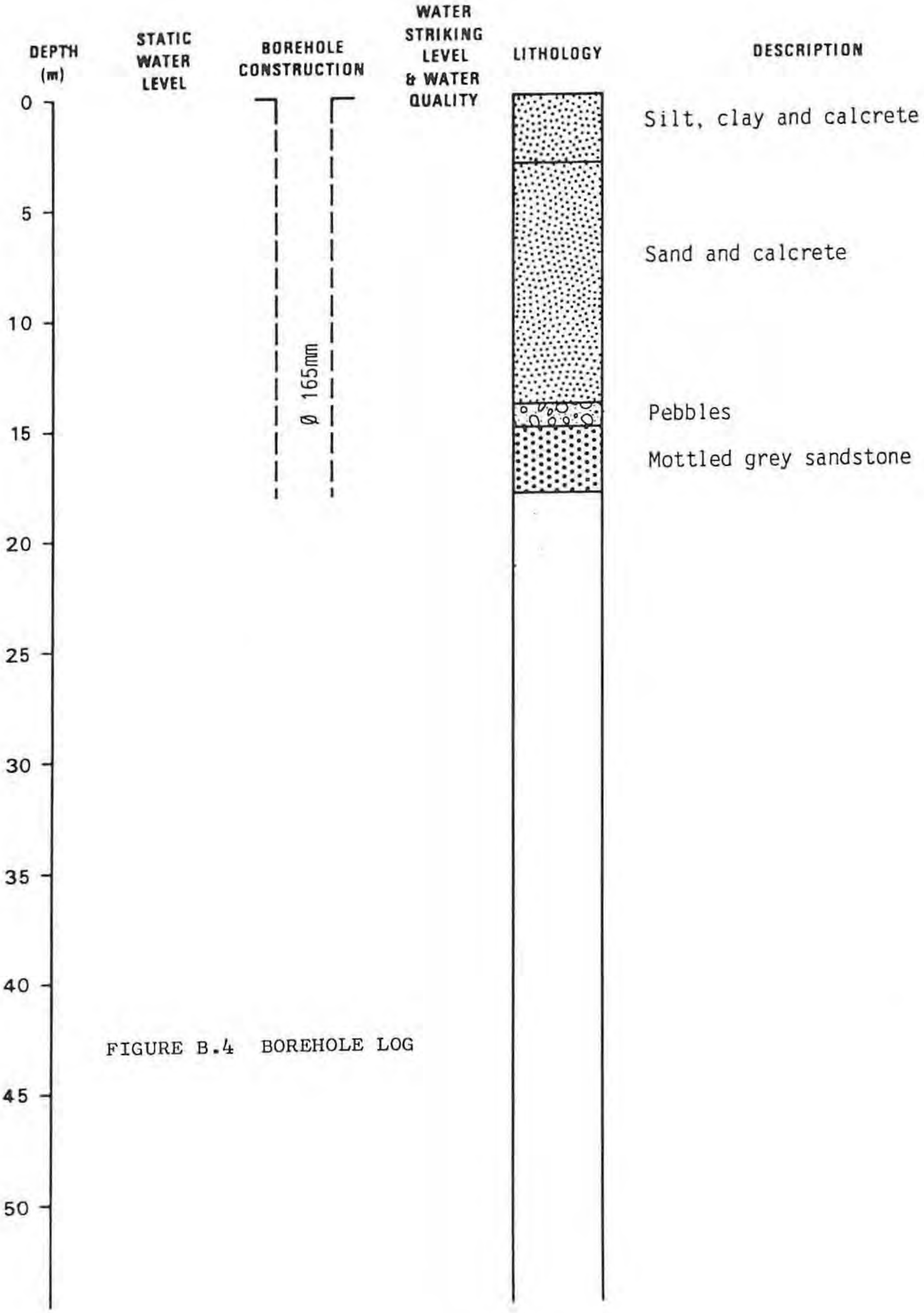


FIGURE B.4 BOREHOLE LOG

BOREHOLE NO: KD 3

CADASTRAL FARM: KLIPPE DRIFT

BLOW TEST YIELD: 1,01 ℓ/s

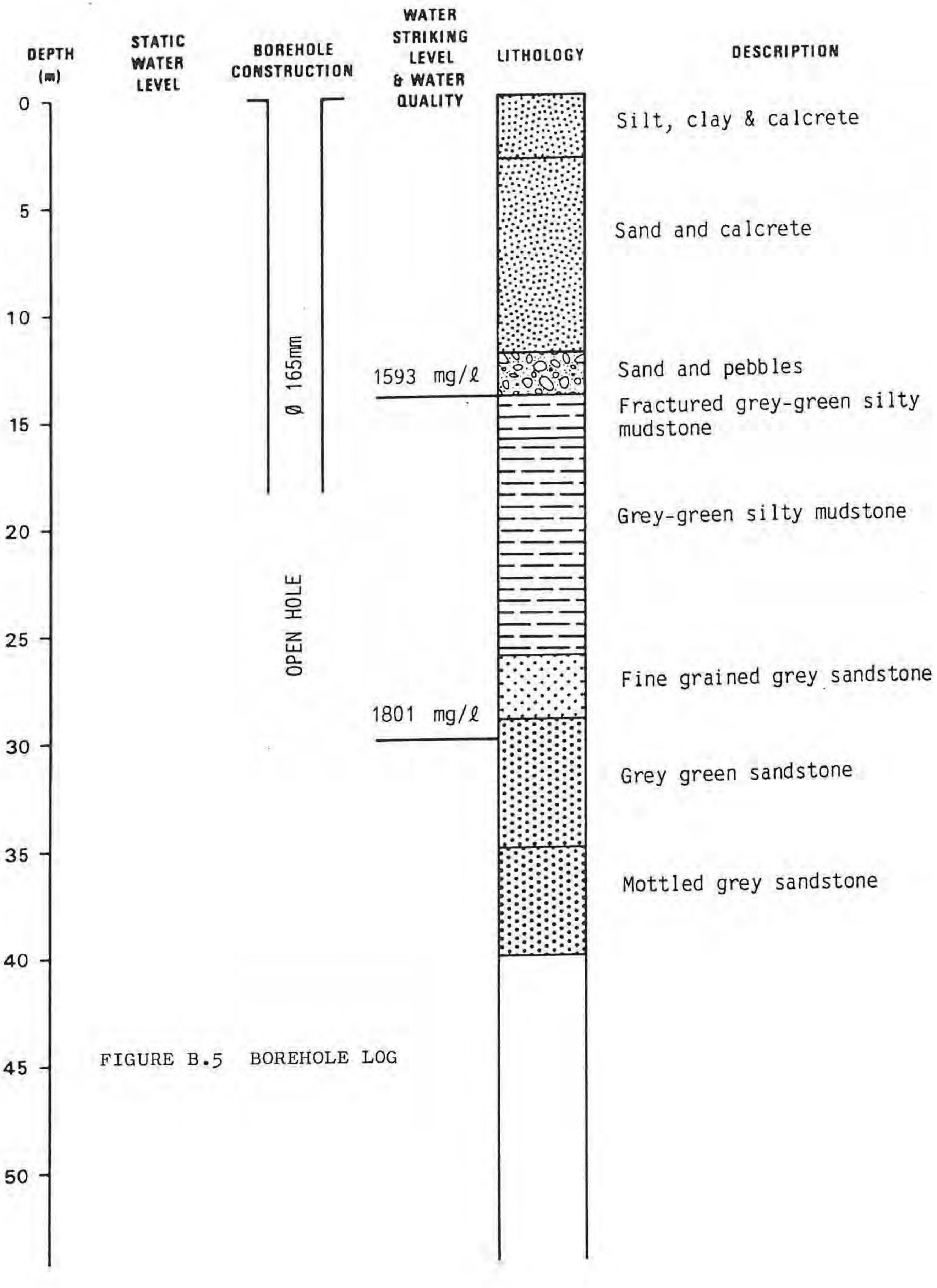


FIGURE B.5 BOREHOLE LOG

BOREHOLE NO: KD 4

CADASTRAL FARM: KLIPPE DRIFT

BLOW TEST YIELD: 0,32 ℓ/s

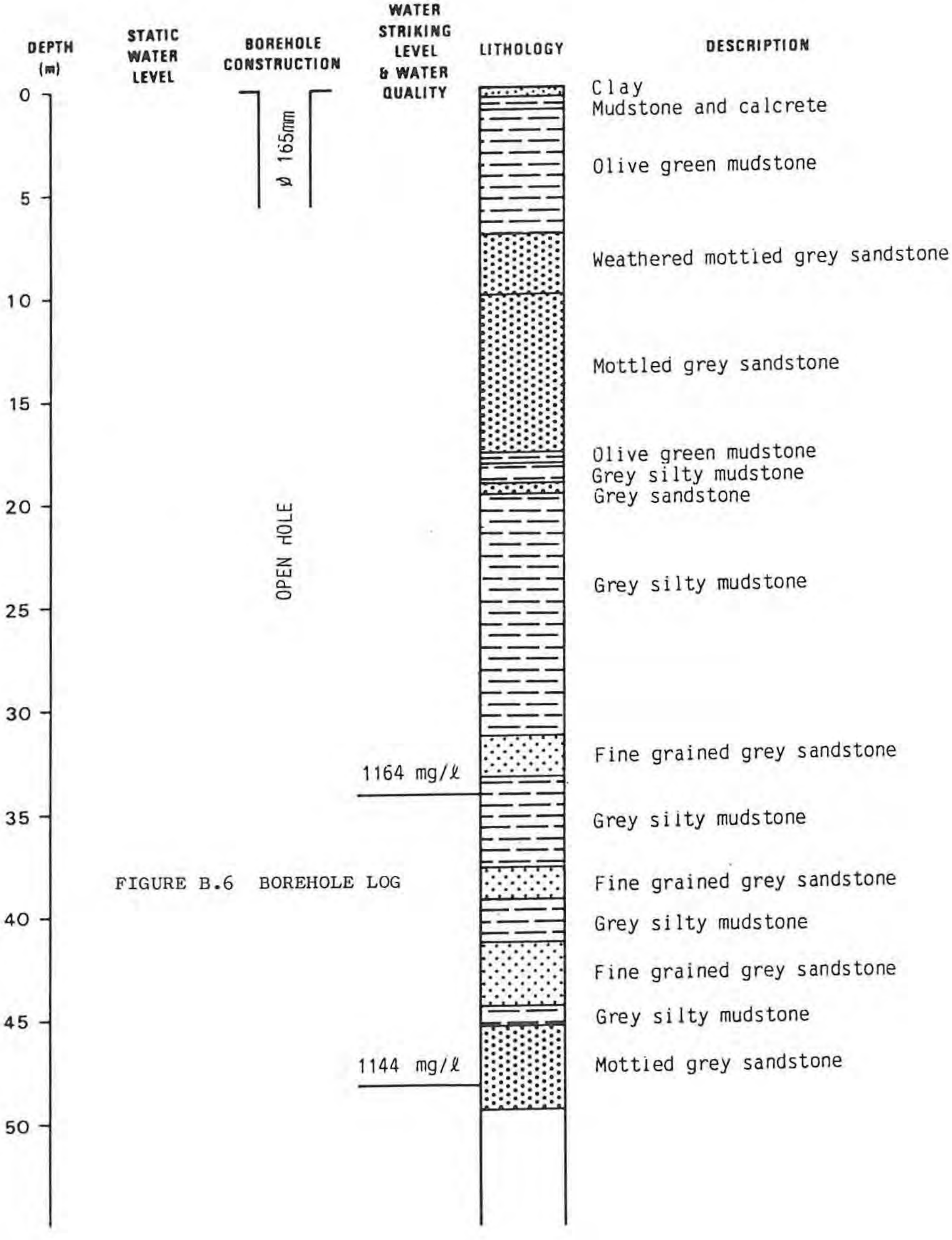


FIGURE B.6 BOREHOLE LOG

BOREHOLE NO: KD 6

CADASTRAL FARM: KLIPPE DRIFT

BLOW TEST YIELD: NO WATER ENCOUNTERED

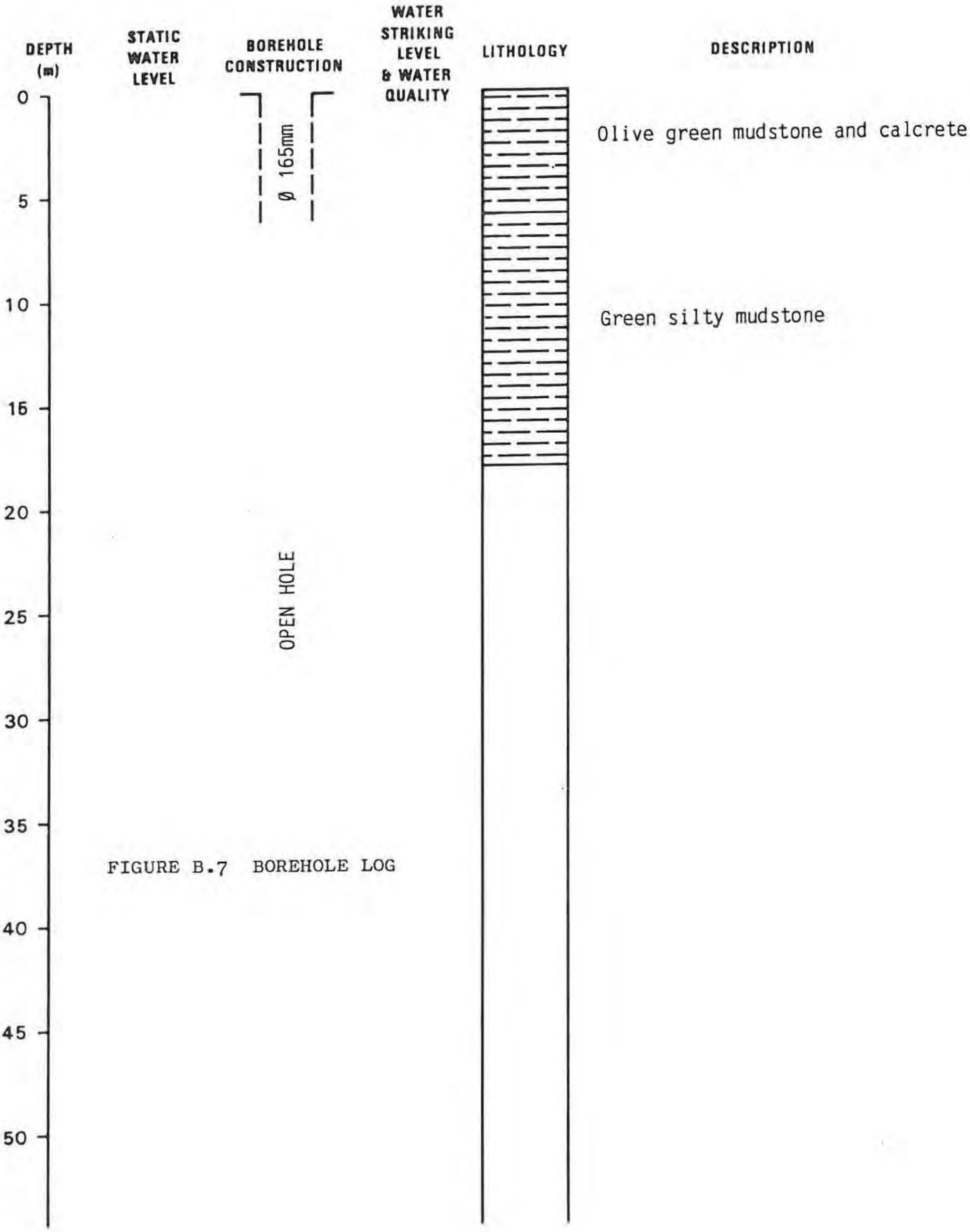


FIGURE B.7 BOREHOLE LOG

BOREHOLE NO: KD 7

CADASTRAL FARM: KLIPPE DRIFT

BLOW TEST YIELD: NO WATER ENCOUNTERED

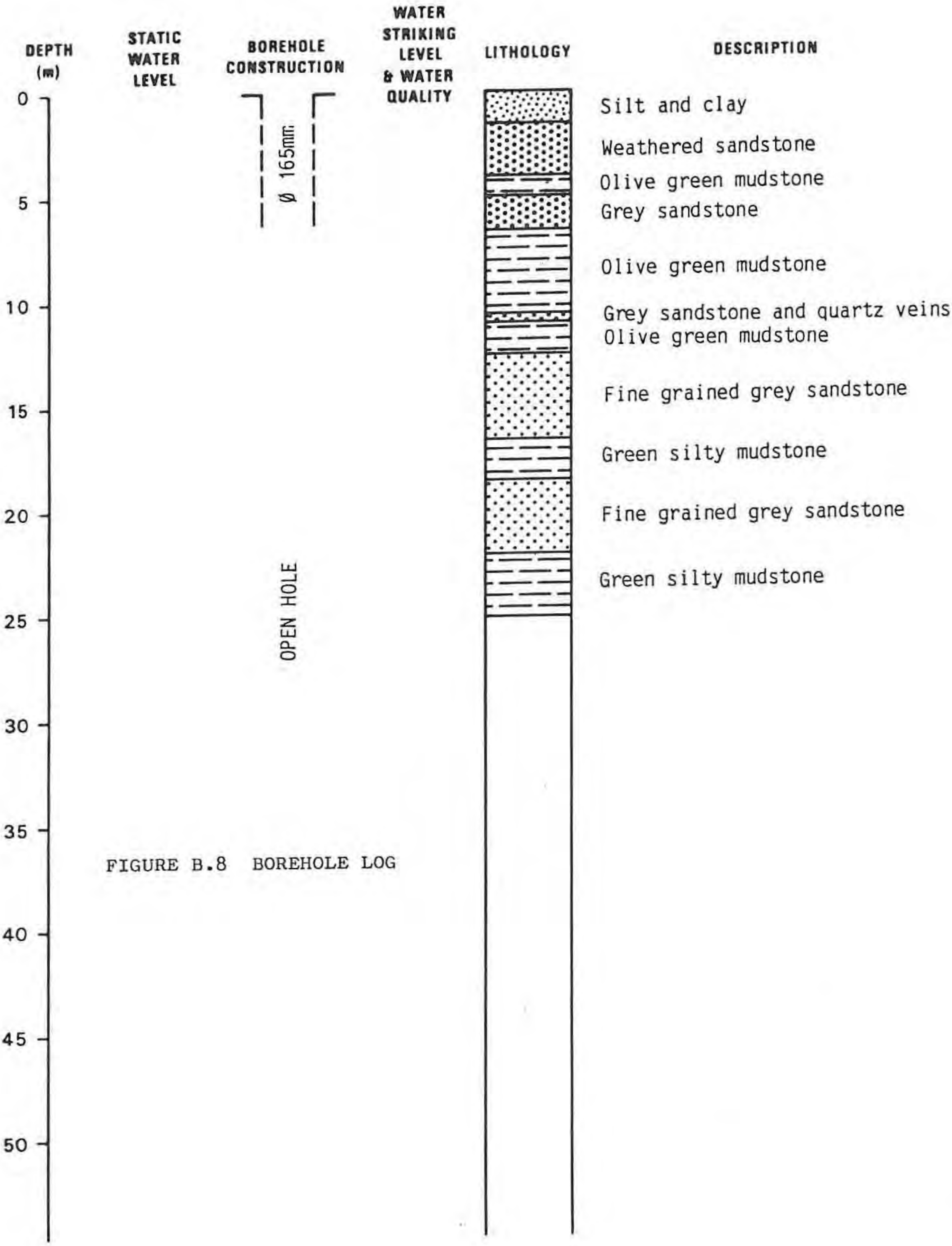


FIGURE B.8 BOREHOLE LOG

BOREHOLE NO: KD 8

CADASTRAL FARM: KLIPPE DRIFT

BLOW TEST YIELD: 0,32 ℓ/s

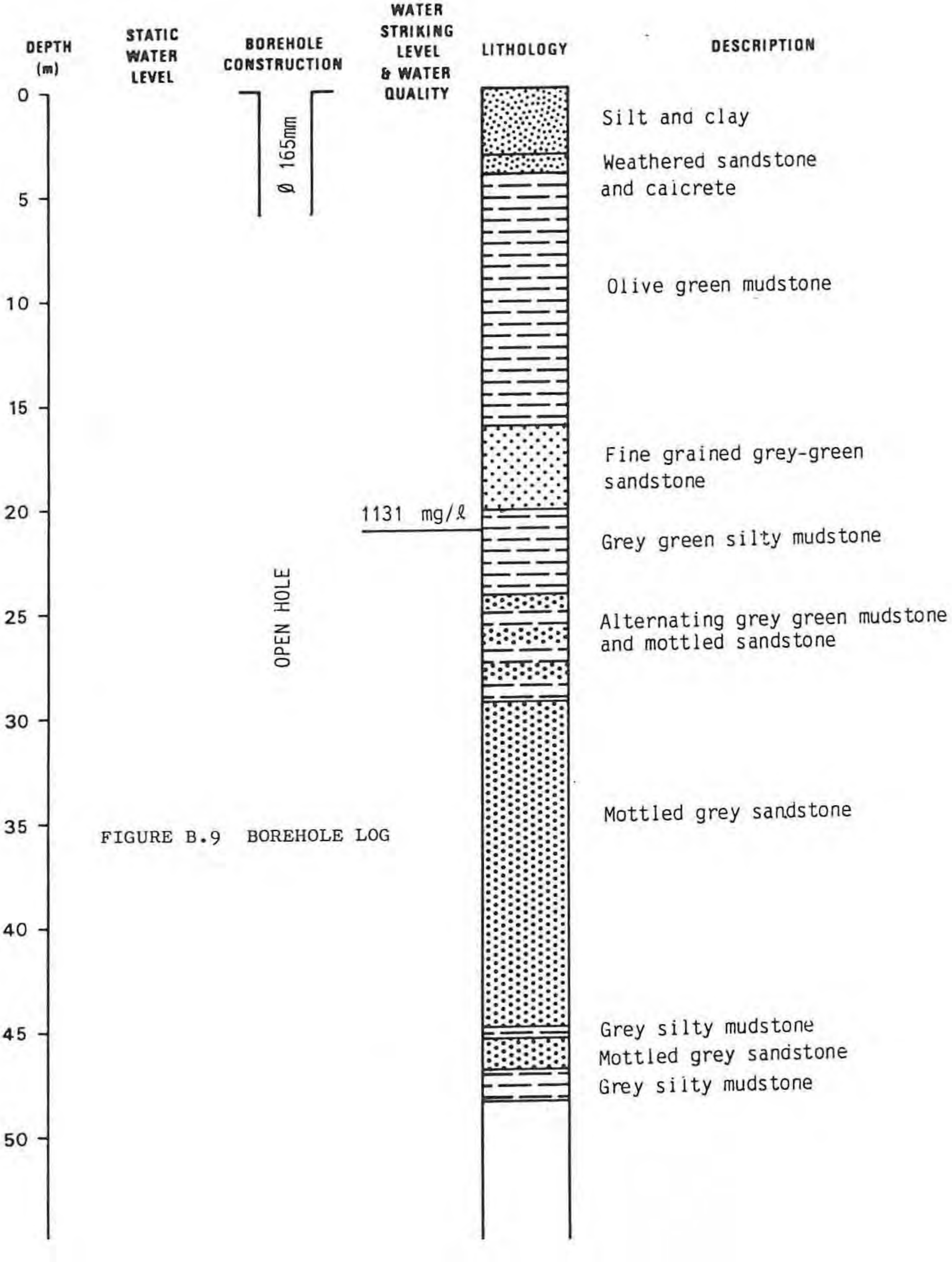


FIGURE B.9 BOREHOLE LOG

BOREHOLE NO: KD 9

CADASTRAL FARM: KLIPPE DRIFT

BLOW TEST YIELD: 0.06 ℓ/s

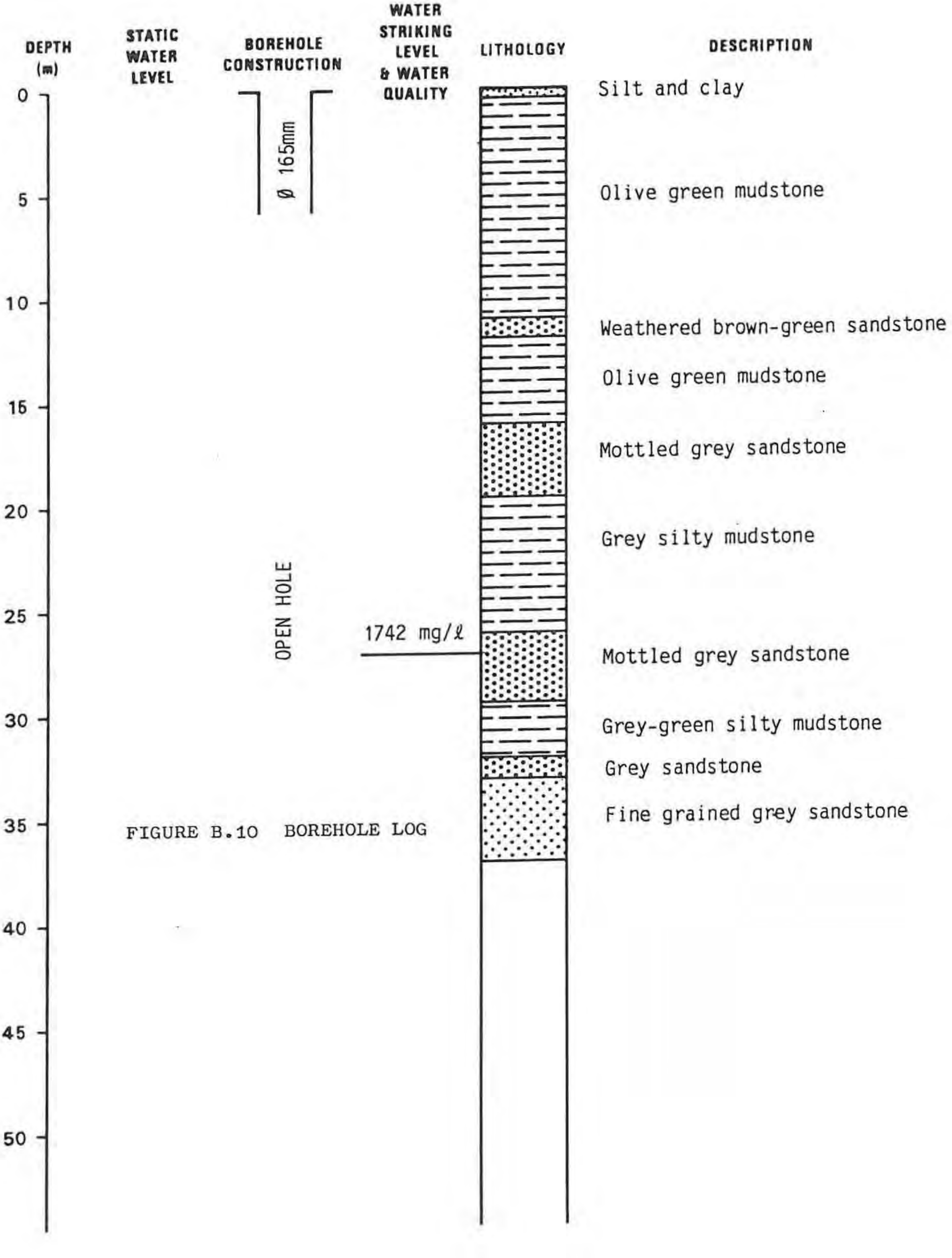


FIGURE B.10 BOREHOLE LOG

BOREHOLE NO: KD 10

CADASTRAL FARM: KLIPPE DRiFT

BLOW TEST YIELD: NO WATER ENCOUNTERED

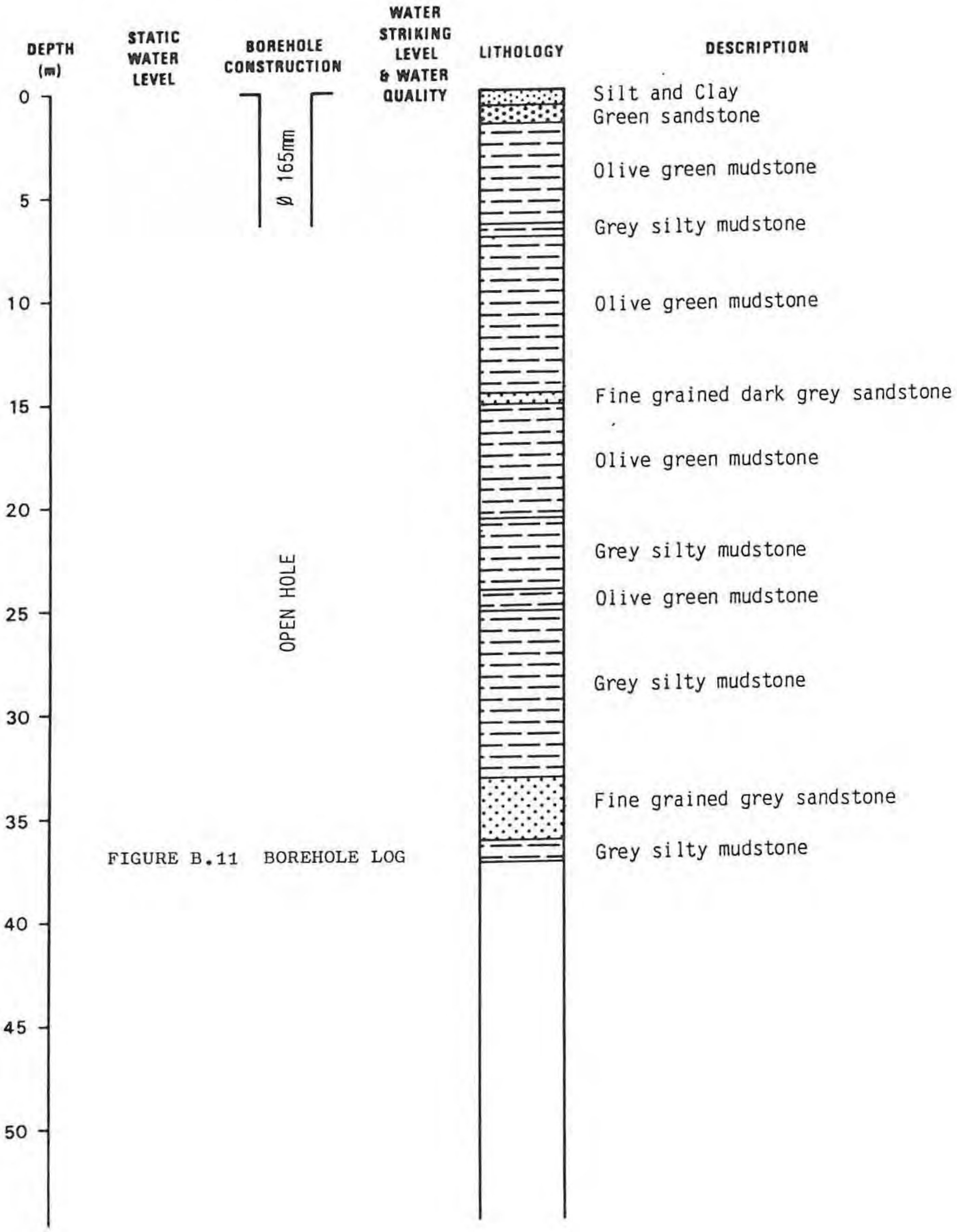


FIGURE B.11 BOREHOLE LOG

BOREHOLE NO: KD 11

CADASTRAL FARM: KLIPPE DRIFT

BLOW TEST YIELD: 0,06 ℓ/s

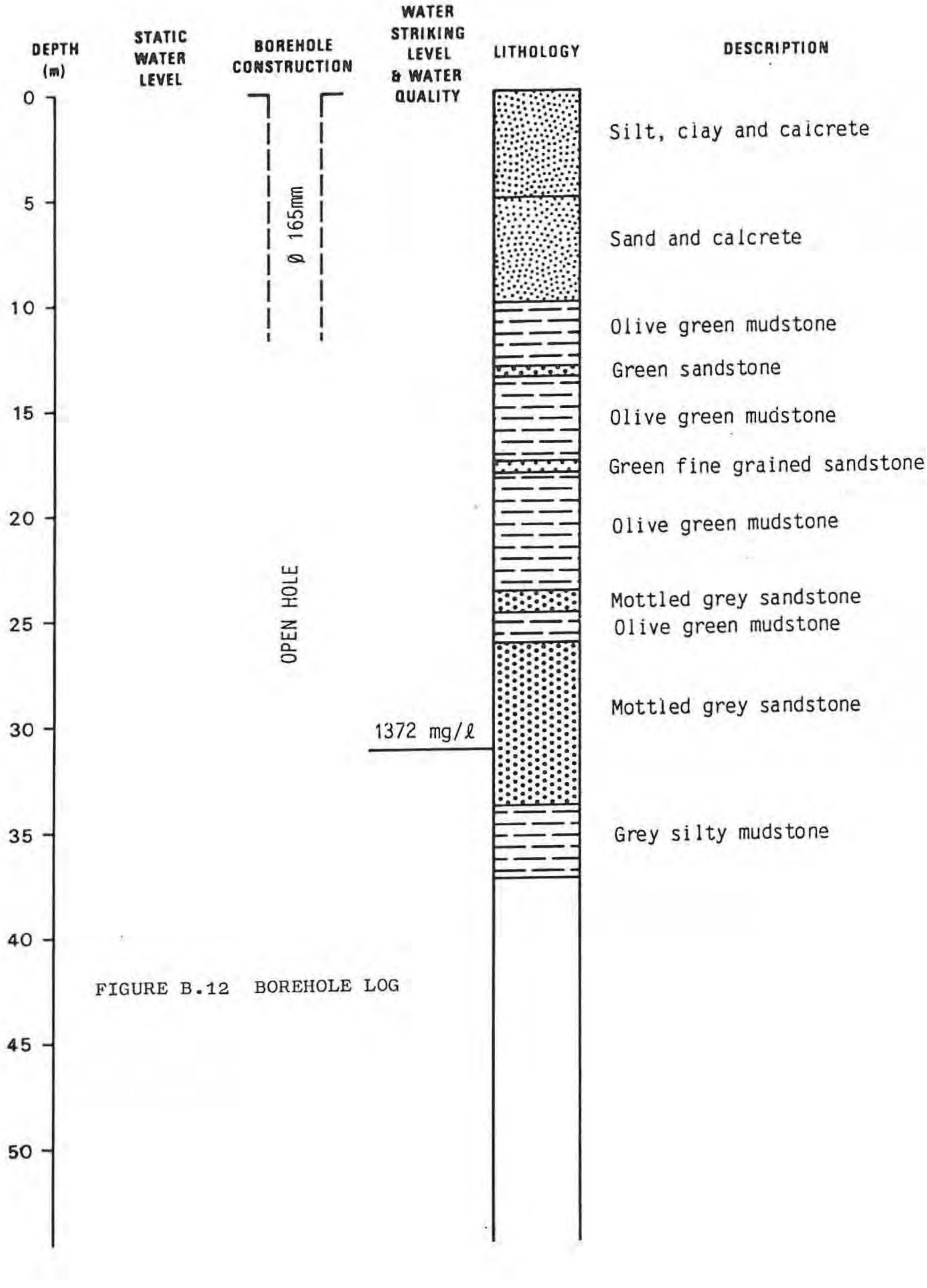


FIGURE B.12 BOREHOLE LOG

BOREHOLE NO: KD 13

CADASTRAL FARM: KLIPPE DRIFT

BLOW TEST YIELD: 0,63 ℓ/s

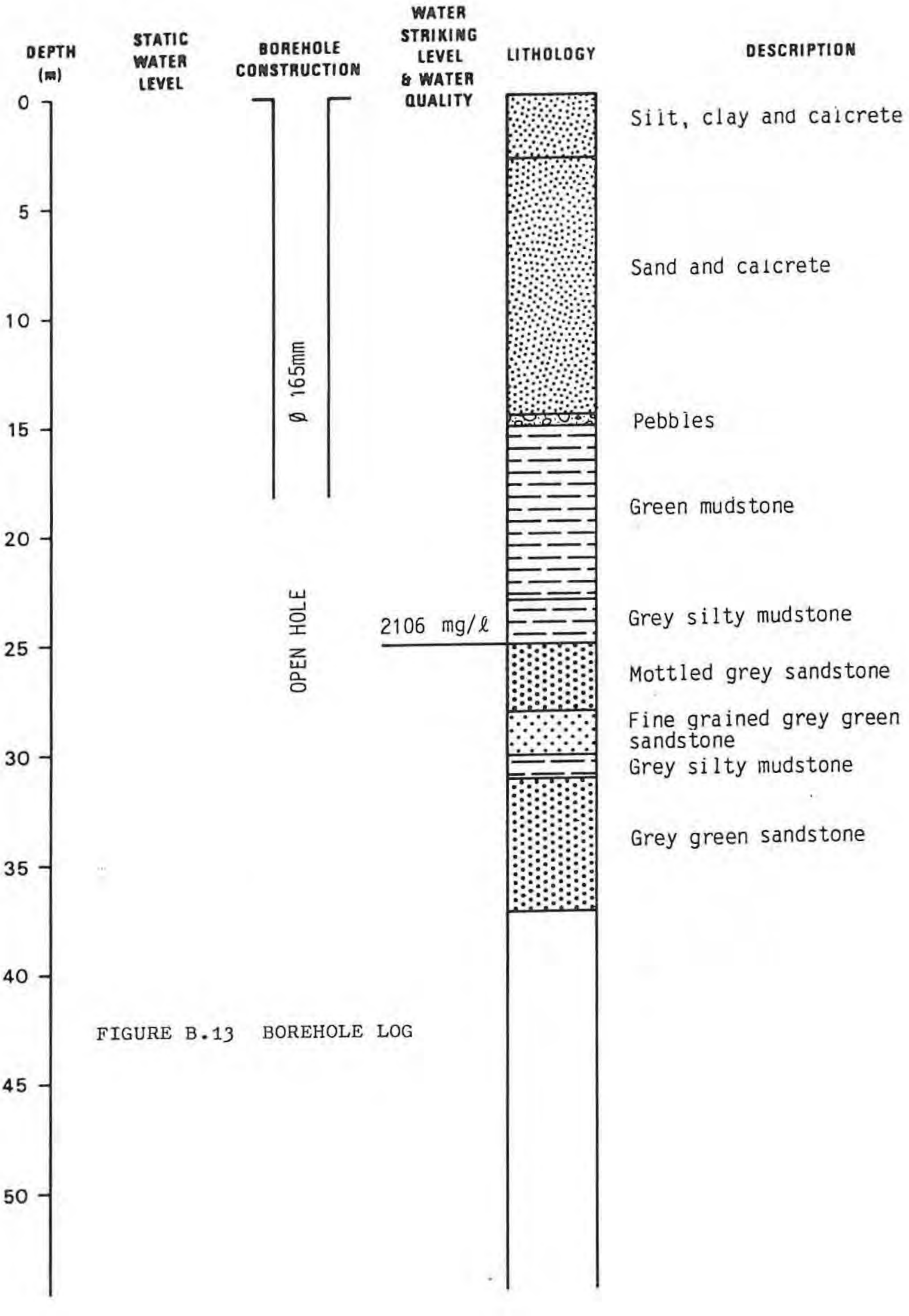


FIGURE B.13 BOREHOLE LOG

BOREHOLE NO: KD 14

CADASTRAL FARM: KLIPPE DRIFT

BLOW TEST YIELD: 0,50 ℓ/s

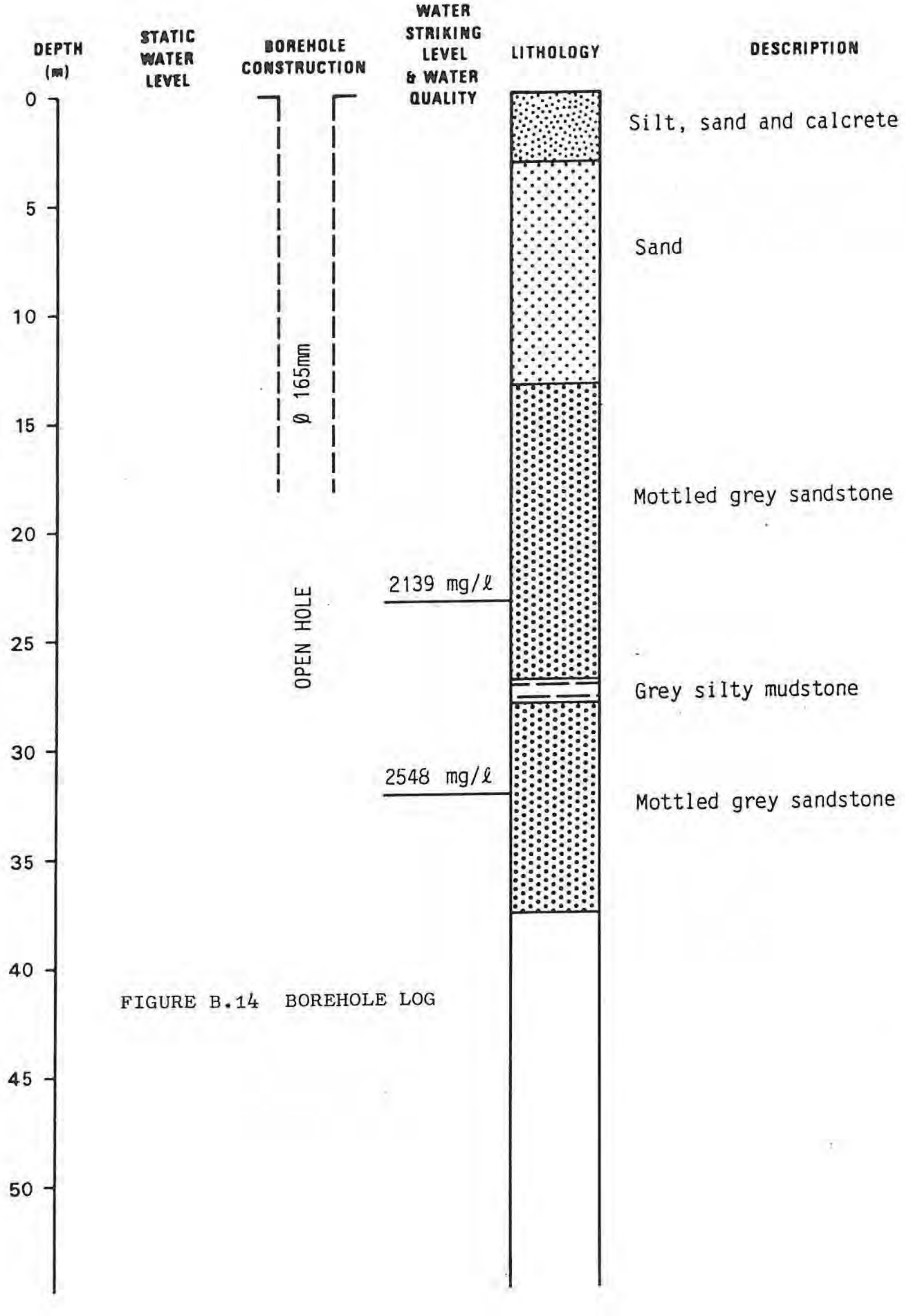


FIGURE B.14 BOREHOLE LOG

BOREHOLE NO: KD 15

CADASTRAL FARM: KLIPPE DRIFT

BLOW TEST YIELD: 0,76 ℓ/s

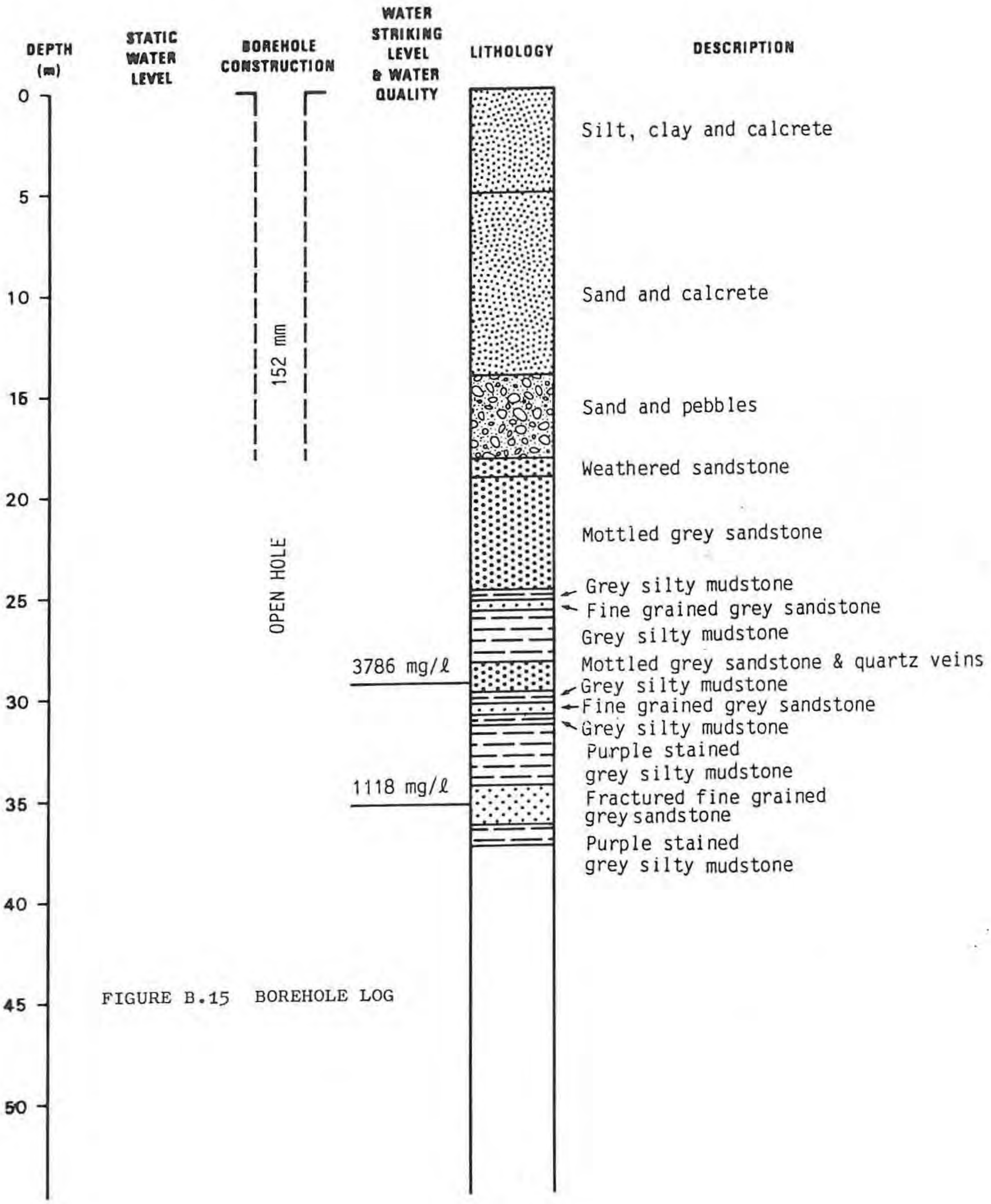


FIGURE B.15 BOREHOLE LOG

BOREHOLE NO: KD 16

CADASTRAL FARM: KLIPPE DRIFT

BLOW TEST YIELD: 1,30 ℓ/s

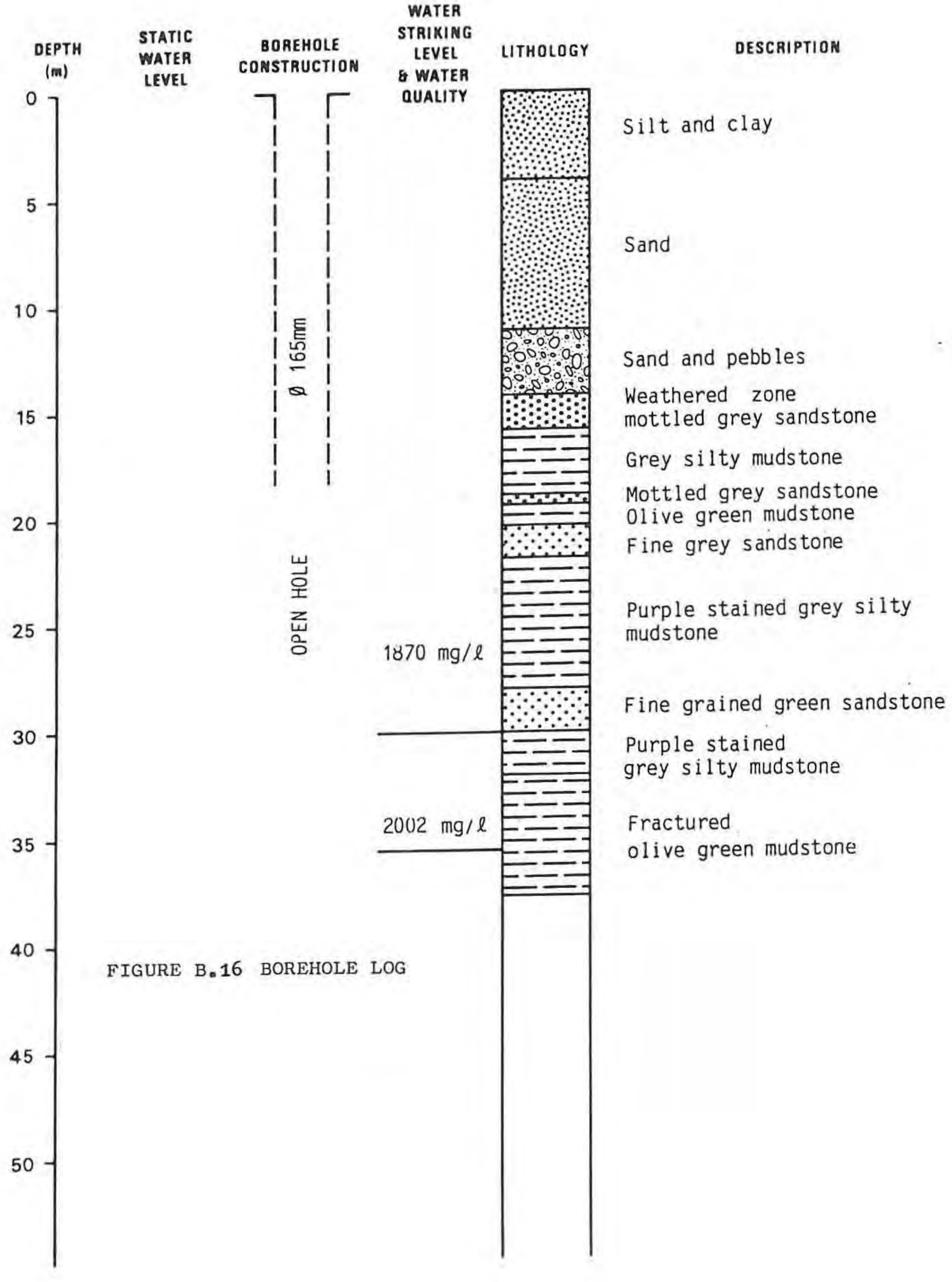


FIGURE B.16 BOREHOLE LOG

BOREHOLE NO: KD 17

CADASTRAL FARM: KLIPPE DRIFT

BLOW TEST YIELD: 0.25 ℓ/s

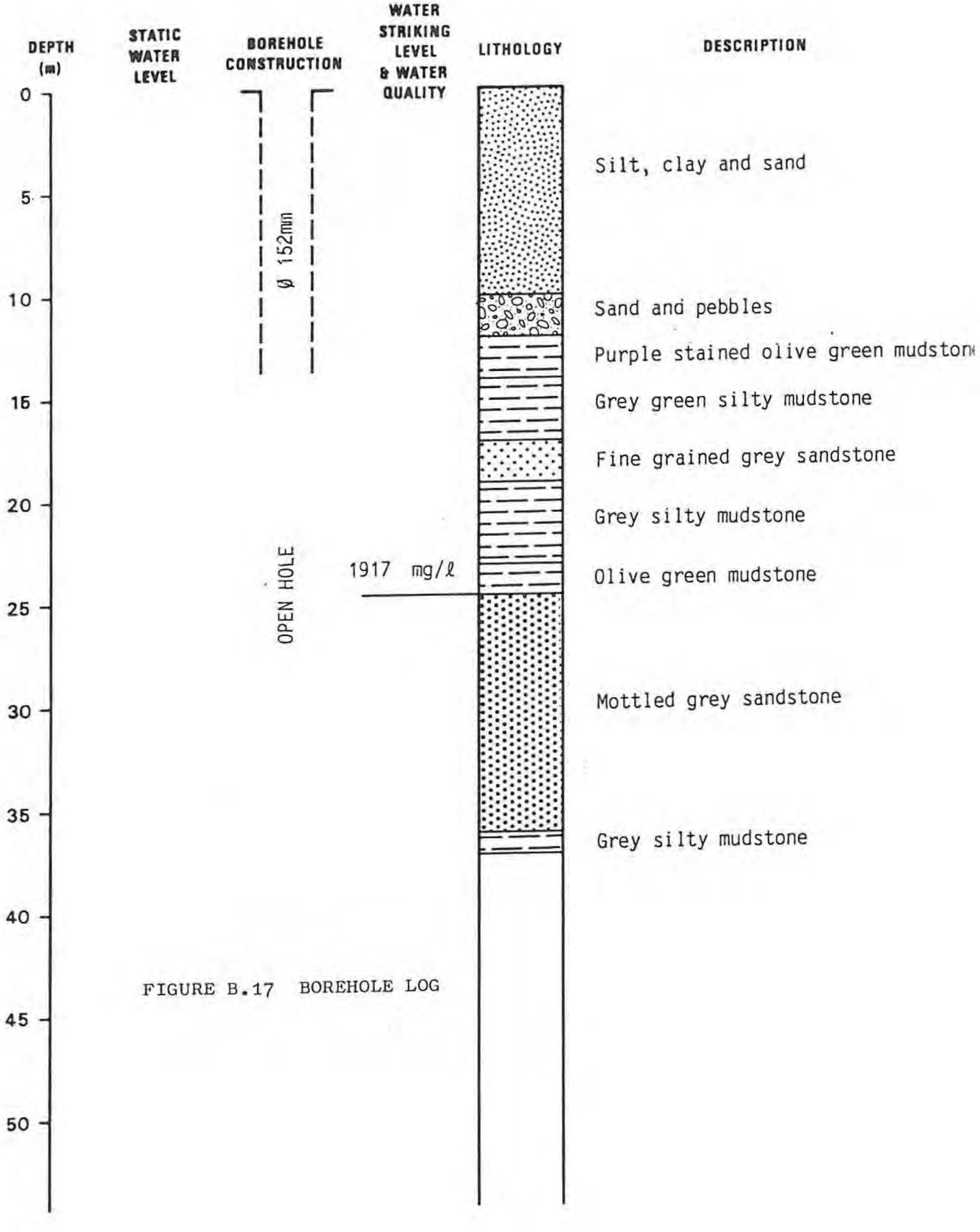


FIGURE B.17 BOREHOLE LOG

BOREHOLE NO: KD 18

CADASTRAL FARM: KLIPPE DRIFT

BLOW TEST YIELD: 1.26 ℓ/s

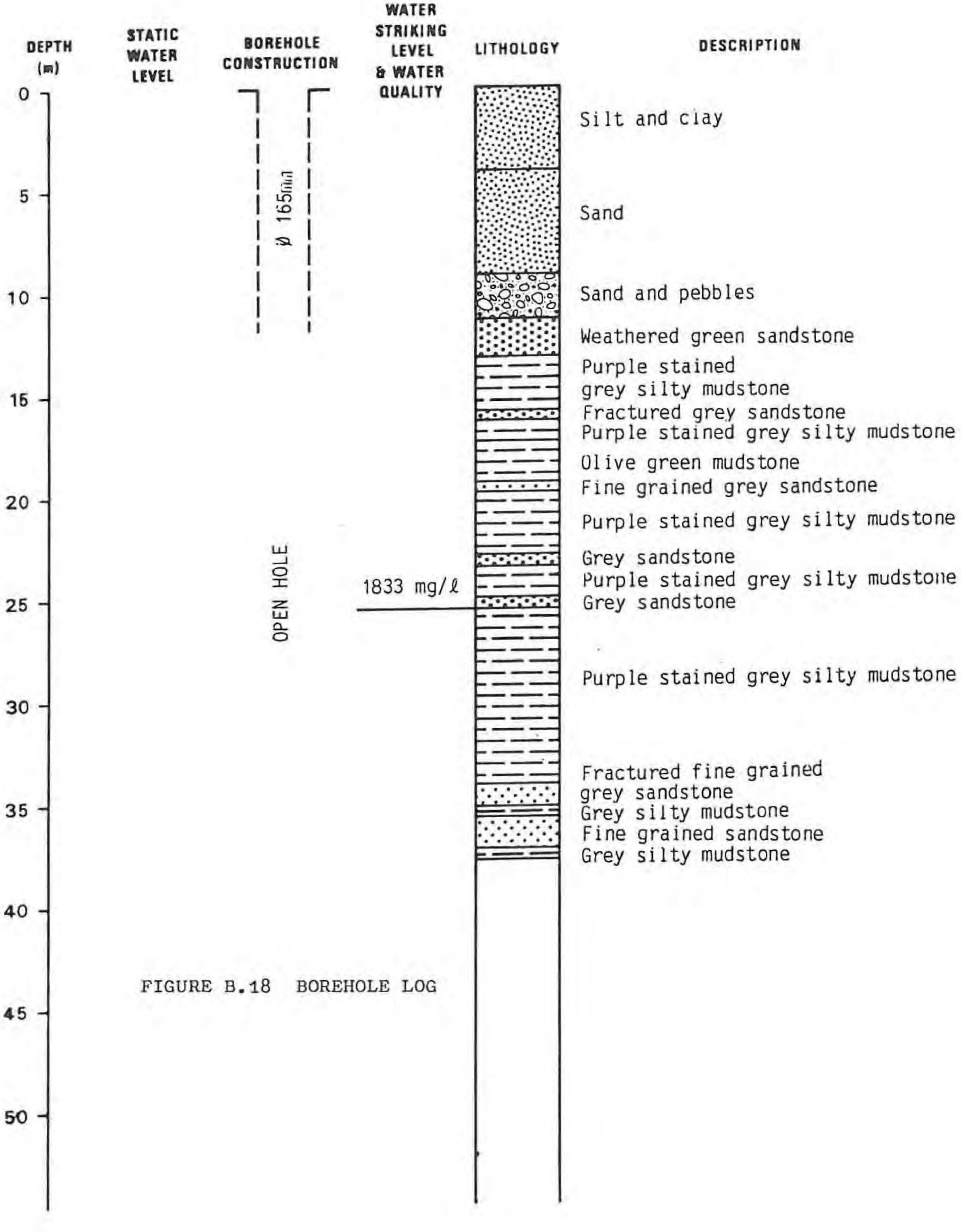


FIGURE B.18 BOREHOLE LOG

BOREHOLE NO: KD 21

CADASTRAL FARM: MOORDENAARS DRIFT

BLOW TEST YIELD: 0,63 ℓ/s

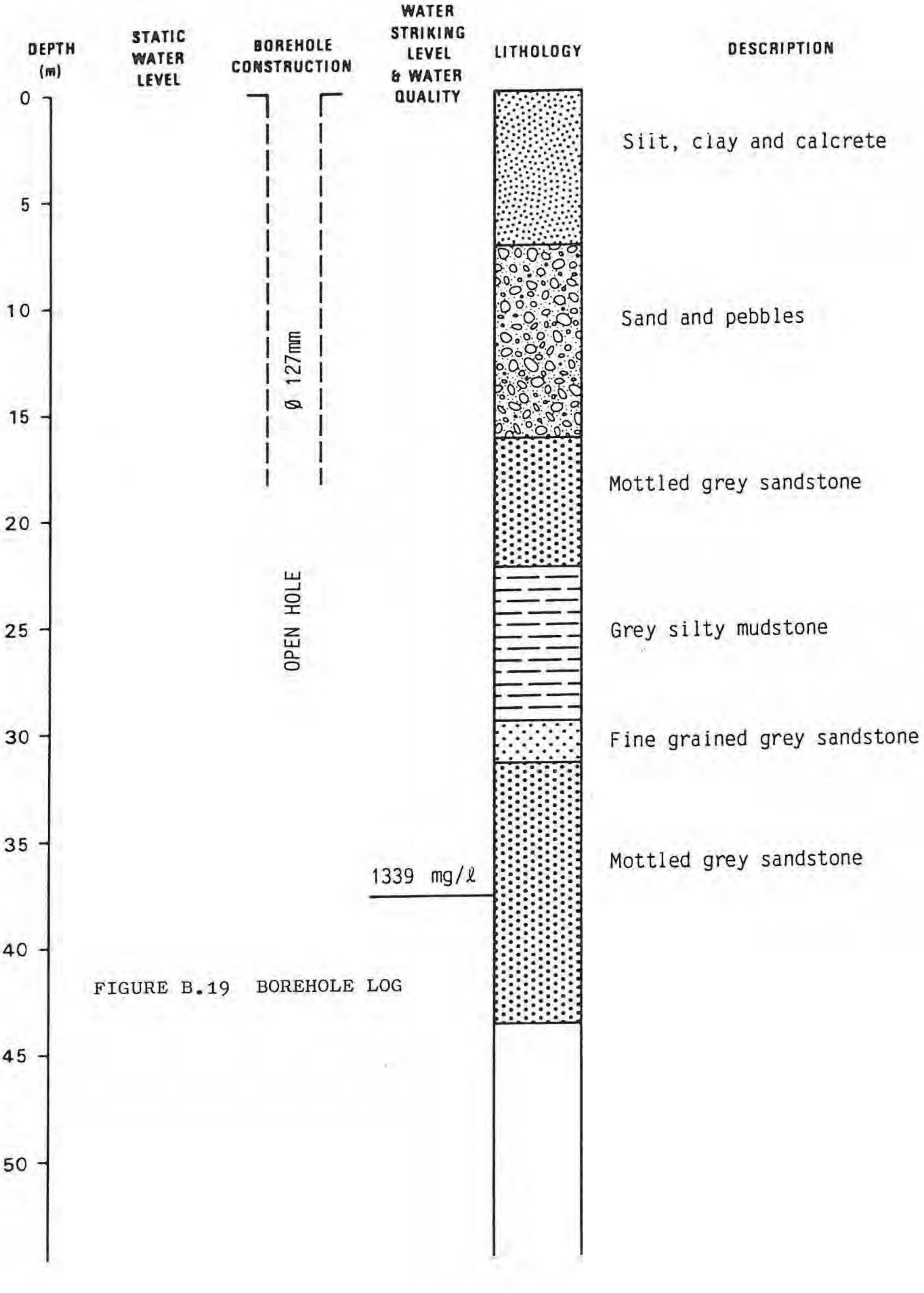


FIGURE B.19 BOREHOLE LOG

BOREHOLE NO: KD 22

CADASTRAL FARM: MOORDENAARS DRIFT

BLOW TEST YIELD: 1,01 ℓ/s

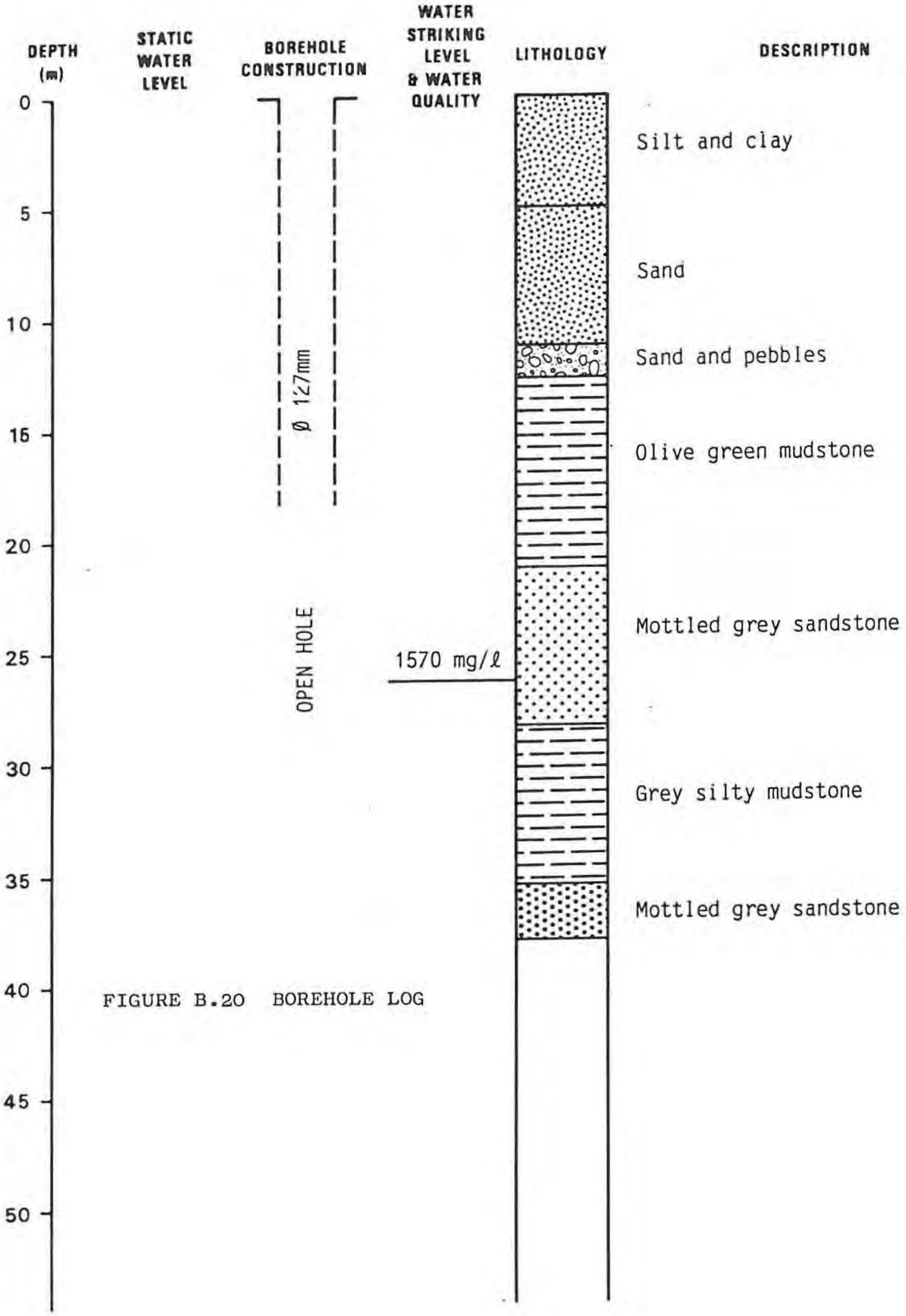


FIGURE B.20 BOREHOLE LOG

BOREHOLE NO: KD 23

CADASTRAL FARM: MOORDENAARS DRIFT

BLOW TEST YIELD: SEEPAGE WATER

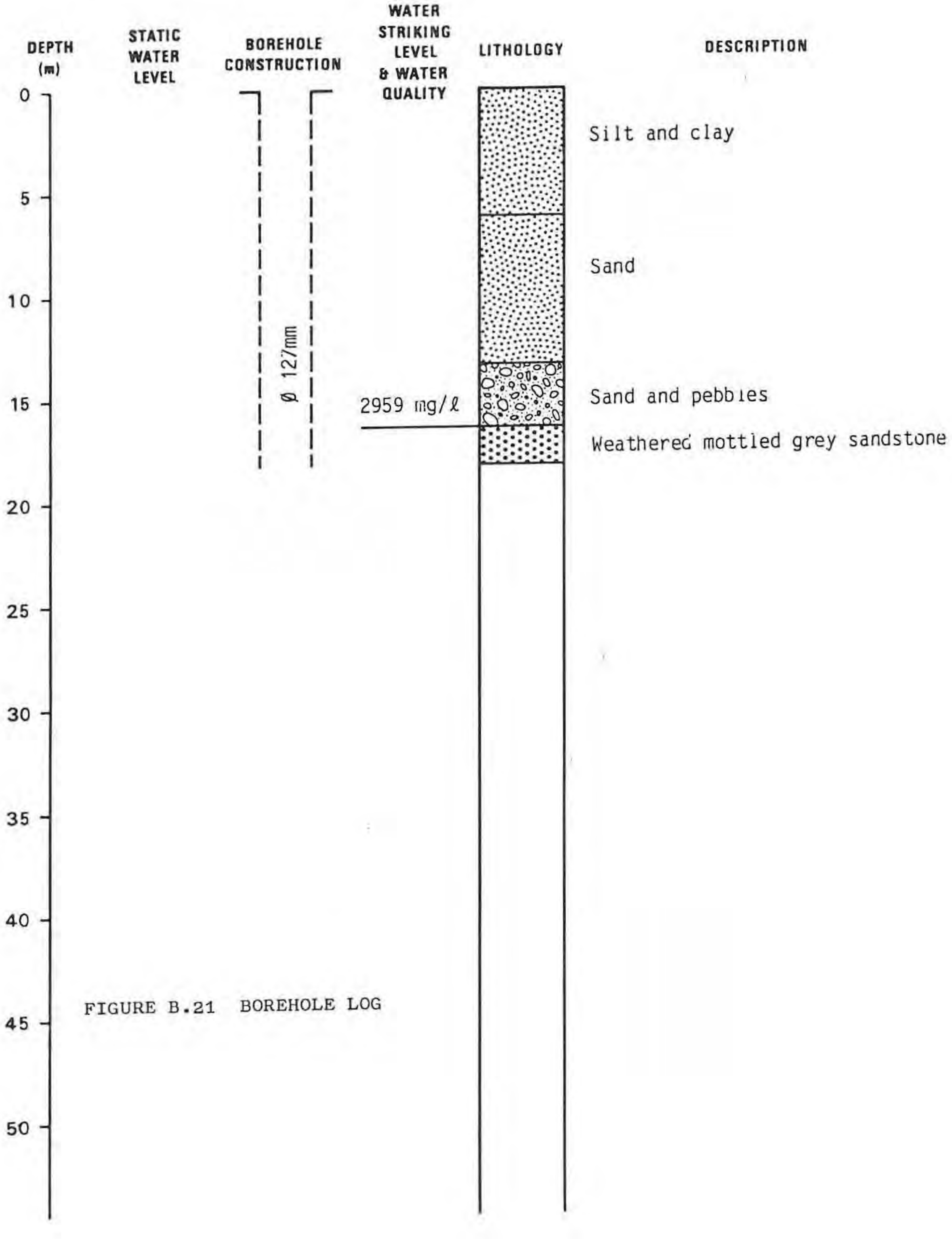


FIGURE B.21 BOREHOLE LOG

BOREHOLE NO: KD 24

CADASTRAL FARM: MOORDENAARS DRIFT

BLOW TEST YIELD: 0,06 ℓ/s

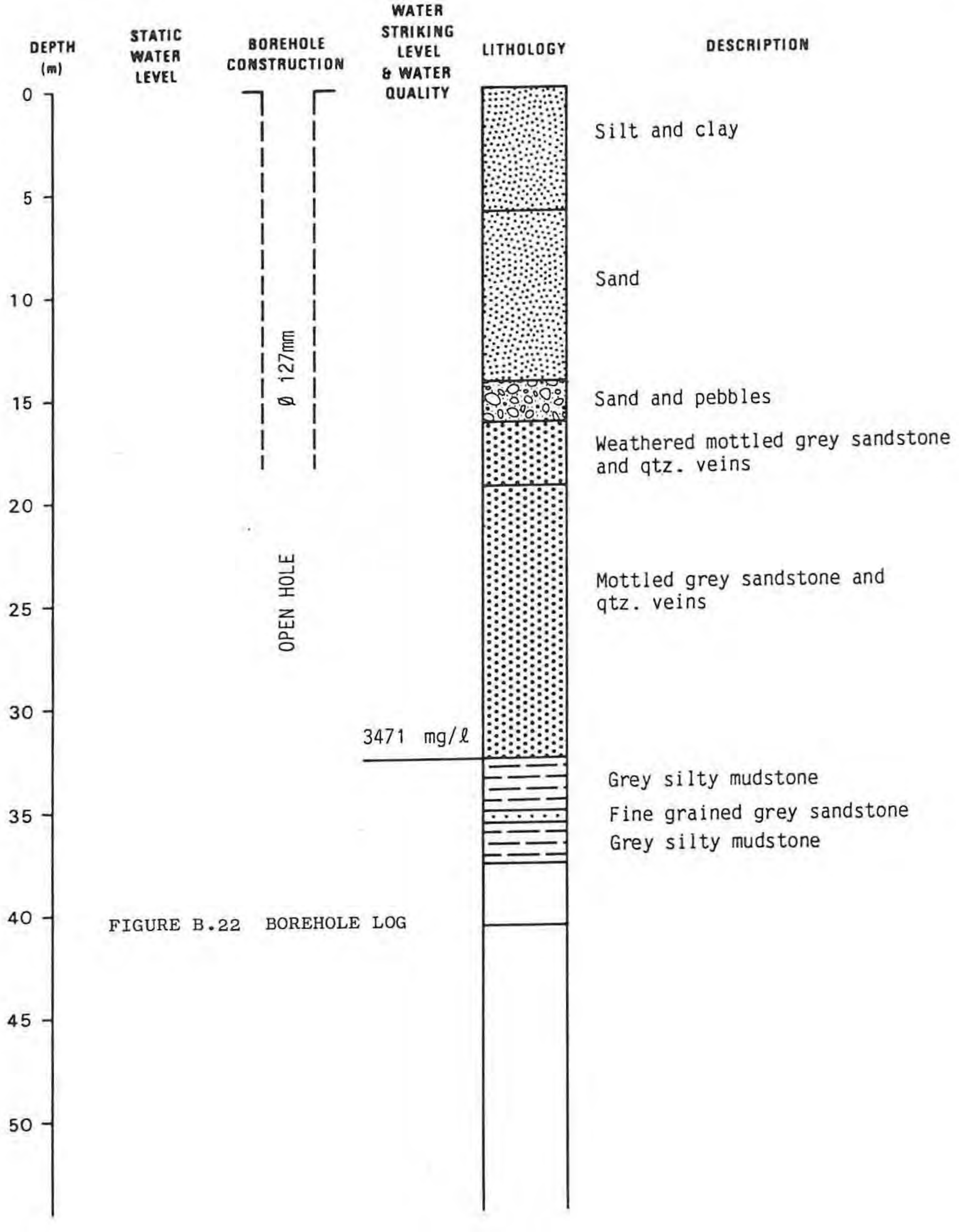


FIGURE B.22 BOREHOLE LOG

BOREHOLE NO: KD 26

CADASTRAL FARM: MOORDENAARS DRIFT

BLOW TEST YIELD: 0,06 ℓ/s

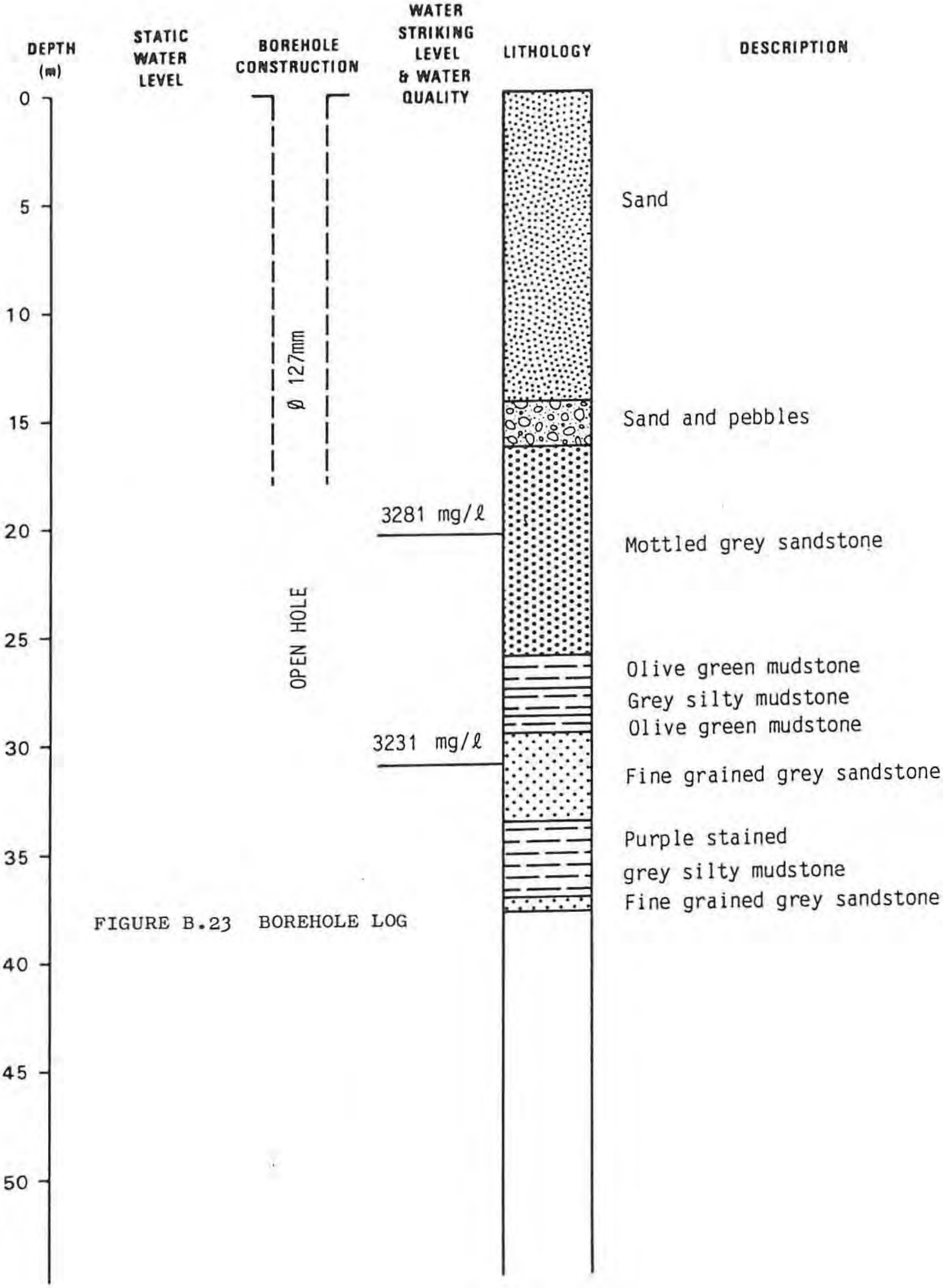


FIGURE B.23 BOREHOLE LOG

BOREHOLE NO: KD 27
CADASTRAL FARM: MOORDENAARS DRIFT
BLOW TEST YIELD: NO WATER ENCOUNTERED

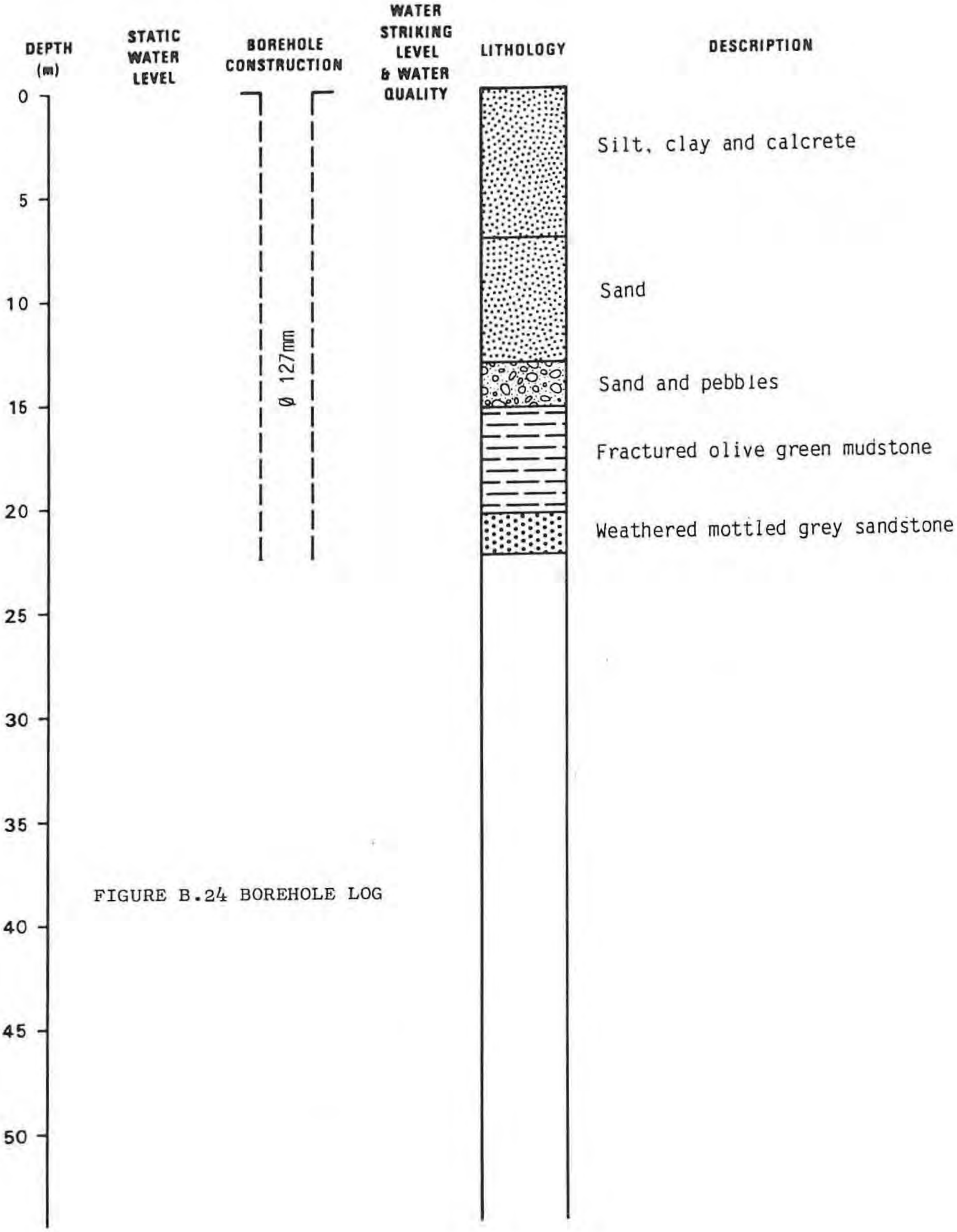


FIGURE B.24 BOREHOLE LOG

BOREHOLE NO: KD 28

CADASTRAL FARM: KLIPPE DRIFT

BLOW TEST YIELD: 0,03 ℓ/s

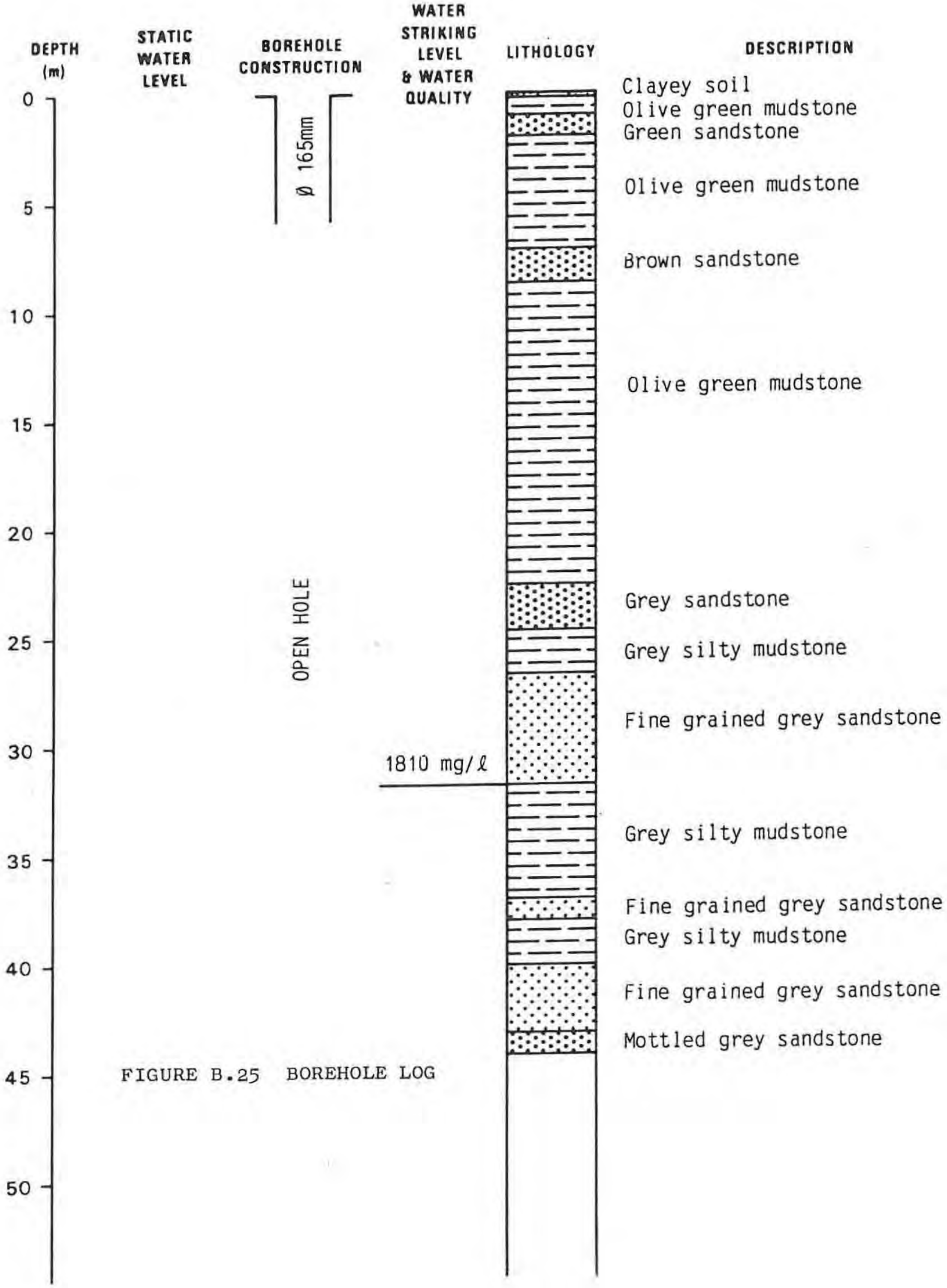


FIGURE B.25 BOREHOLE LOG

BOREHOLE NO: KD 29

CADASTRAL FARM: KLIPPE DRIFT

BLOW TEST YIELD: 0,06 ℓ/s

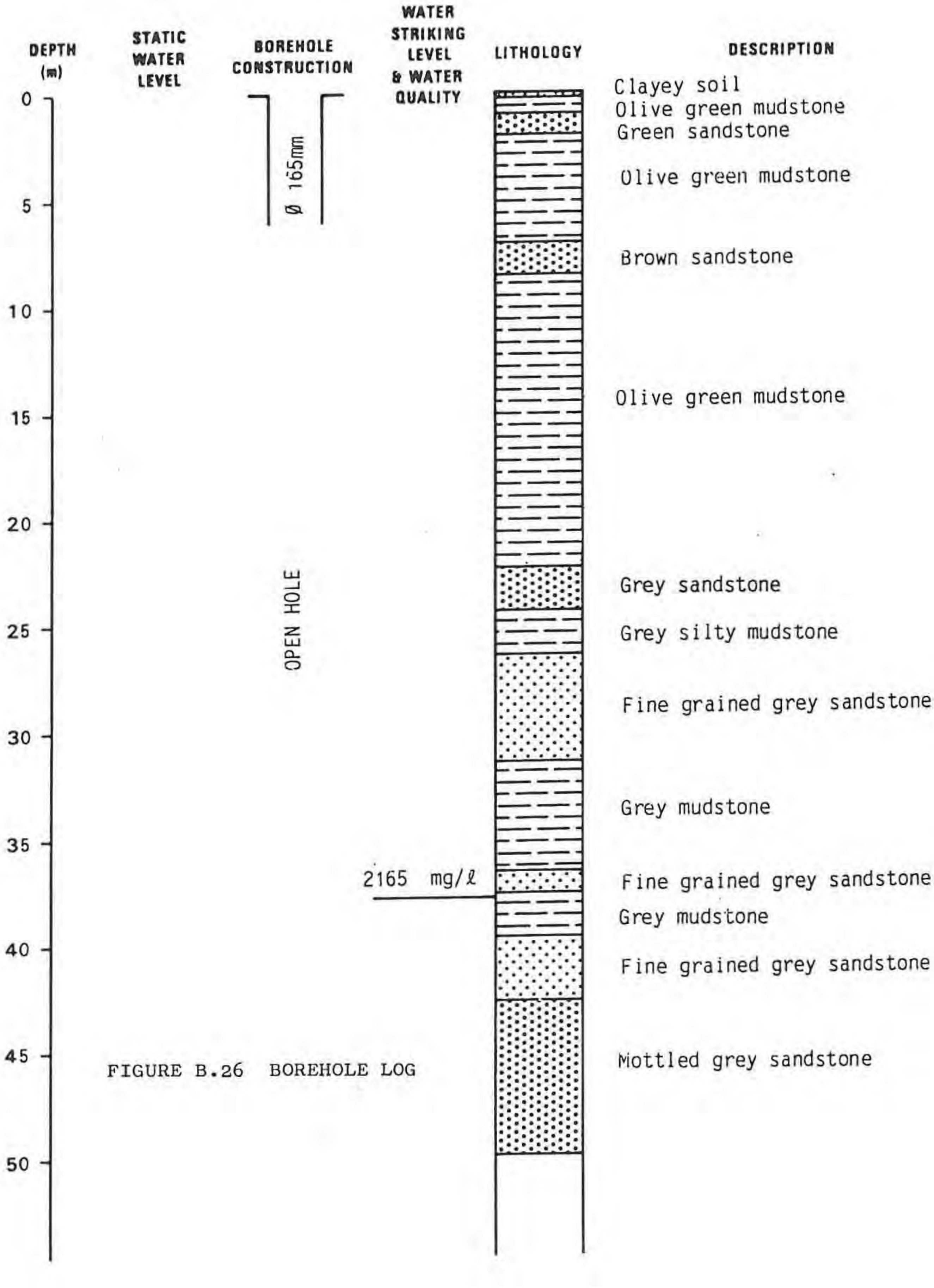


FIGURE B.26 BOREHOLE LOG

BOREHOLE NO: KD 30

CADASTRAL FARM: KLIPPE DRIFT

BLOW TEST YIELD: 0,03 ℓ/s

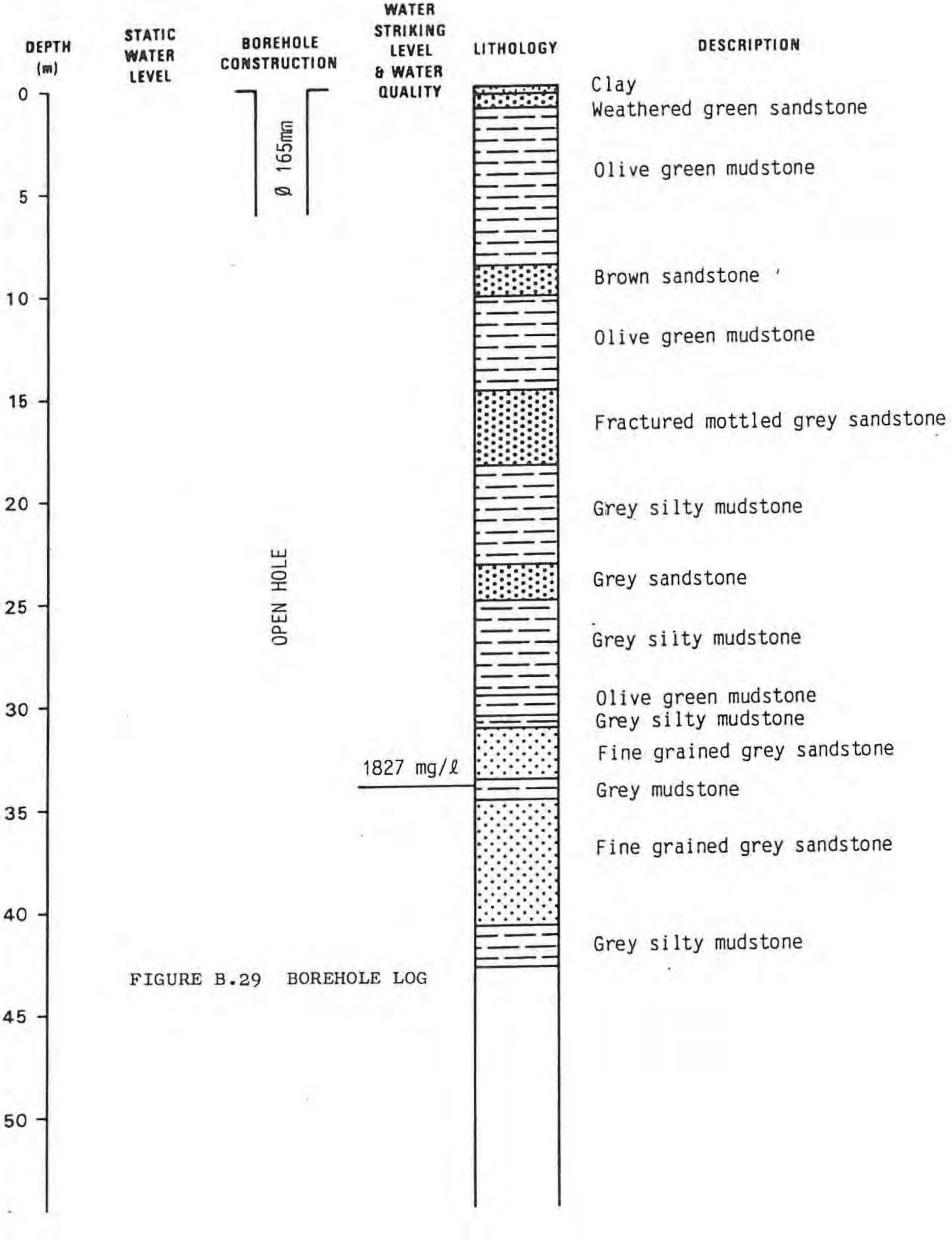


FIGURE B.29 BOREHOLE LOG

BOREHOLE NO: KD 33

CADASTRAL FARM: MOORDENAARS DRIFT

BLOW TEST YIELD: 12,62 ℓ/s

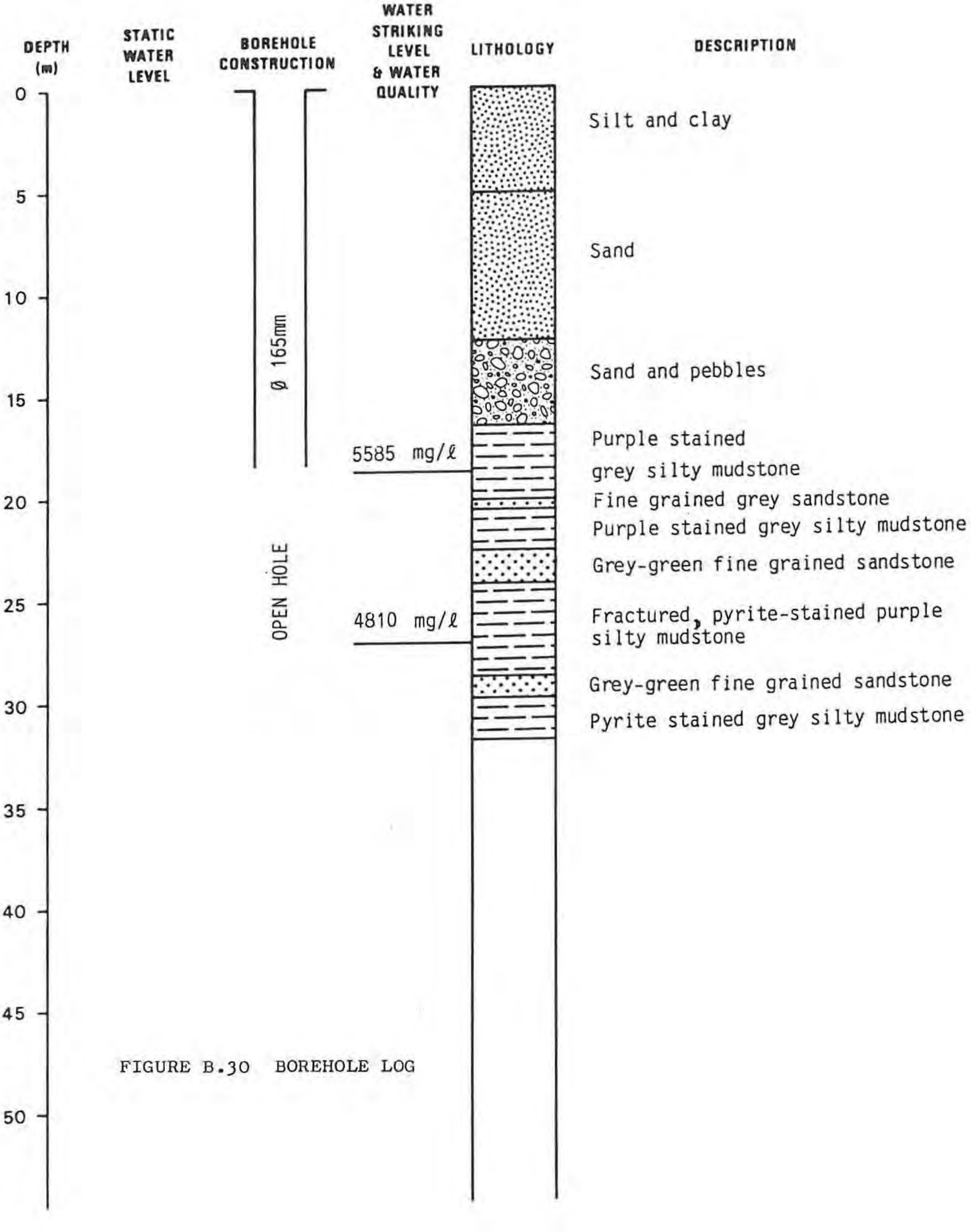


FIGURE B.30 BOREHOLE LOG

BOREHOLE NO: KD 34

CADASTRAL FARM: MOORDENAARS DRIFT

BLOW TEST YIELD: 1,01 ℓ/s

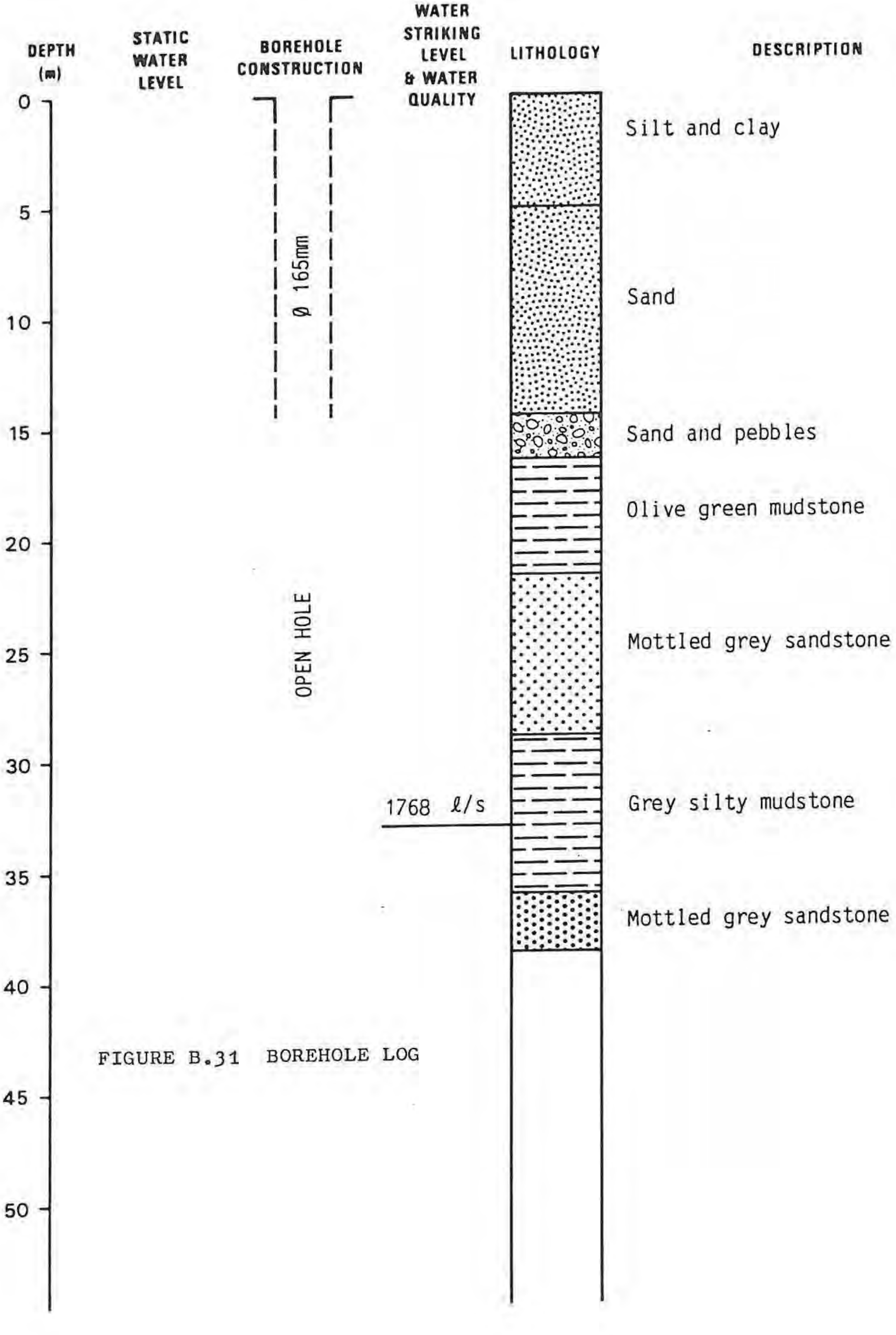


FIGURE B.31 BOREHOLE LOG

BOREHOLE NO: KD 35

CADASTRAL FARM: MOORDENAARS DRIFT

BLOW TEST YIELD: 1,26 ℓ/s

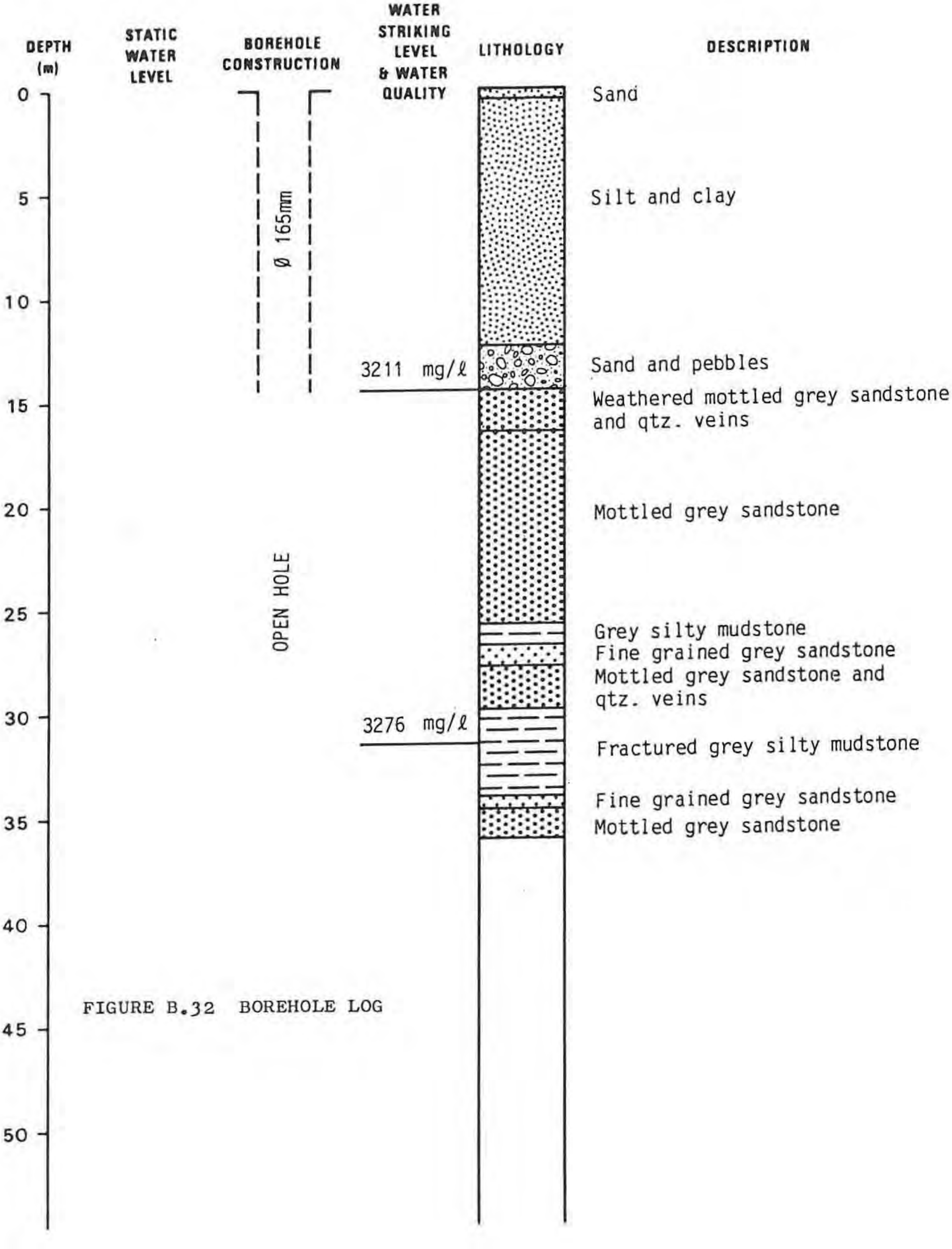


FIGURE B.32 BOREHOLE LOG

BOREHOLE NO: KD 36

CADASTRAL FARM: HARTEBEEST KUIL

BLOW TEST YIELD: 0,06 ℓ/s

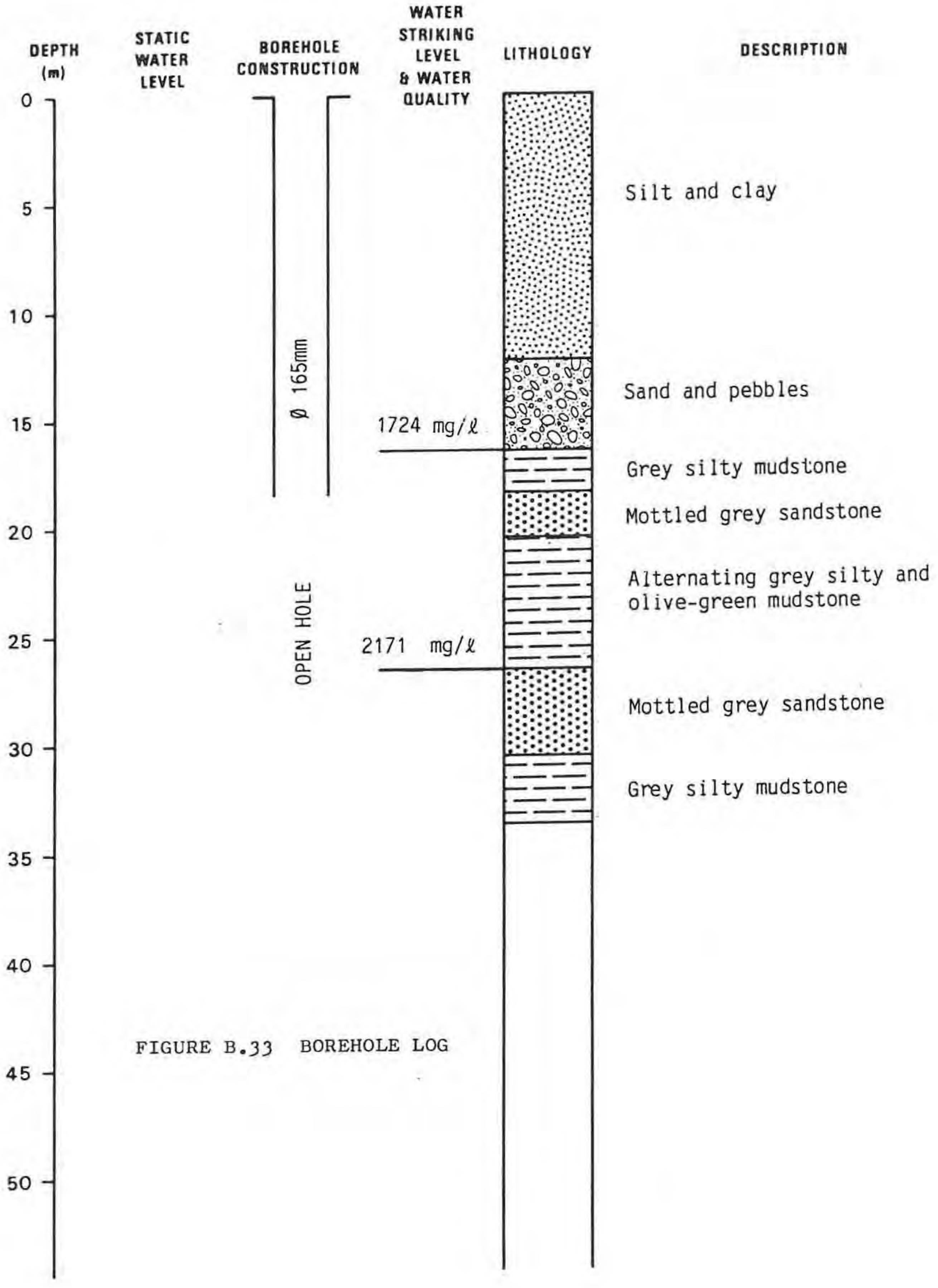


FIGURE B.33 BOREHOLE LOG

BOREHOLE NO: KD 12

CADASTRAL FARM: KLIPPE DRIFT

BLOW TEST YIELD: 0.38 ℓ/s

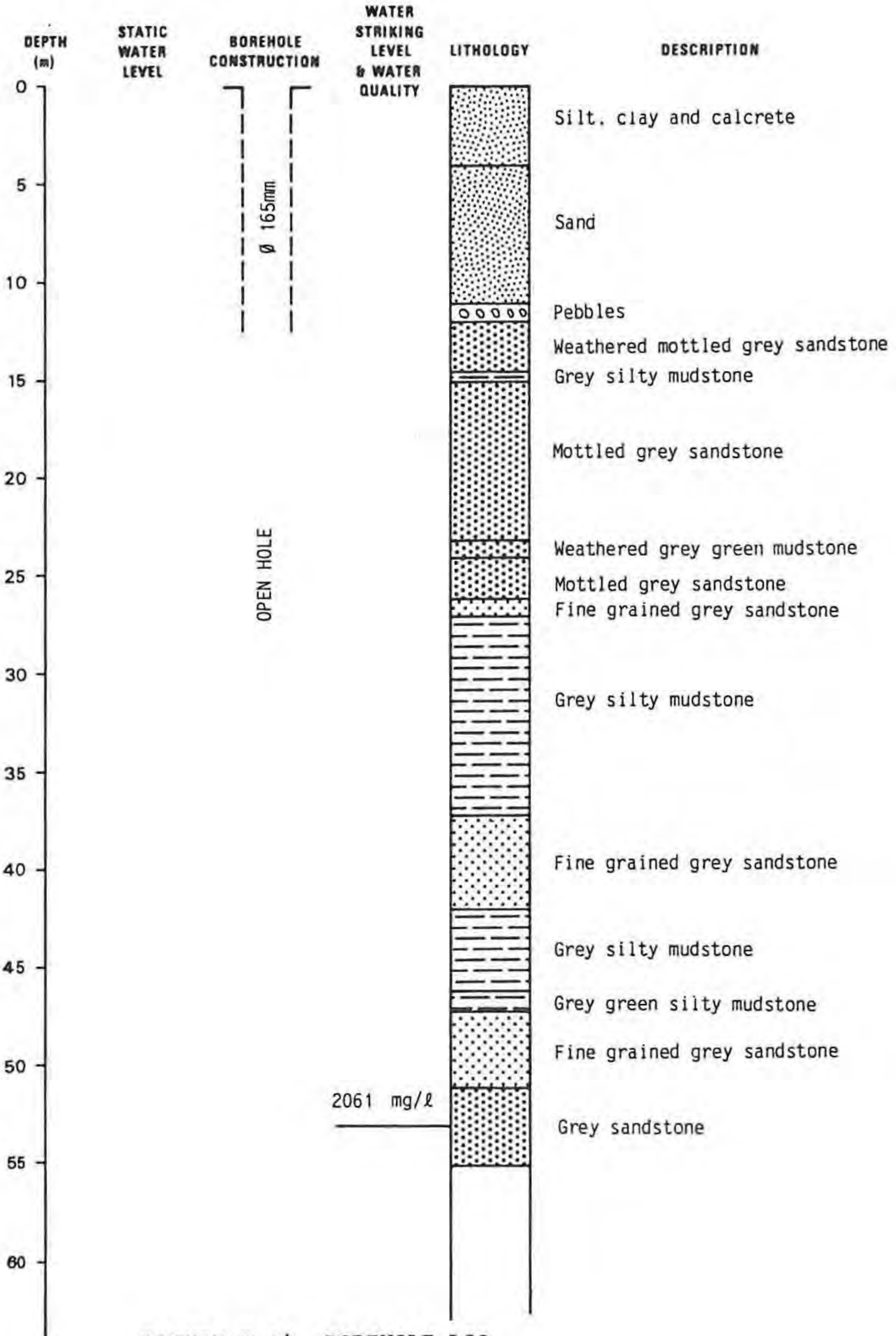


FIGURE B.34 BOREHOLE LOG

BOREHOLE NO: KD 19

CADASTRAL FARM: MOORDENAARS DRIFT

BLOW TEST YIELD: 0,06 ℓ/s

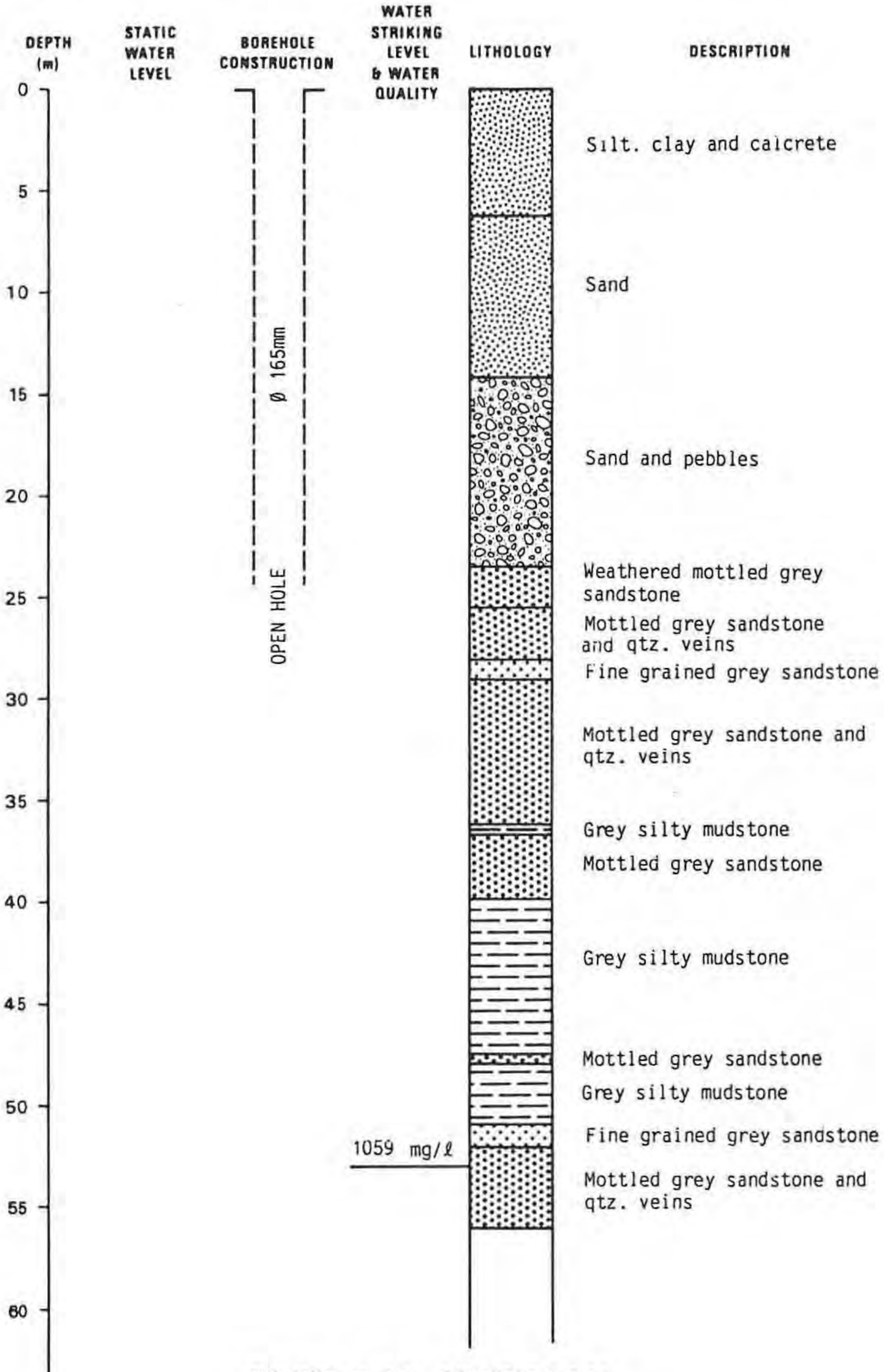


FIGURE B.35 BOREHOLE LOG

BOREHOLE NO: KD 20

CADASTRAL FARM: MOORDENAARS DRIFT

BLOW TEST YIELD: 0,09 ℓ/s

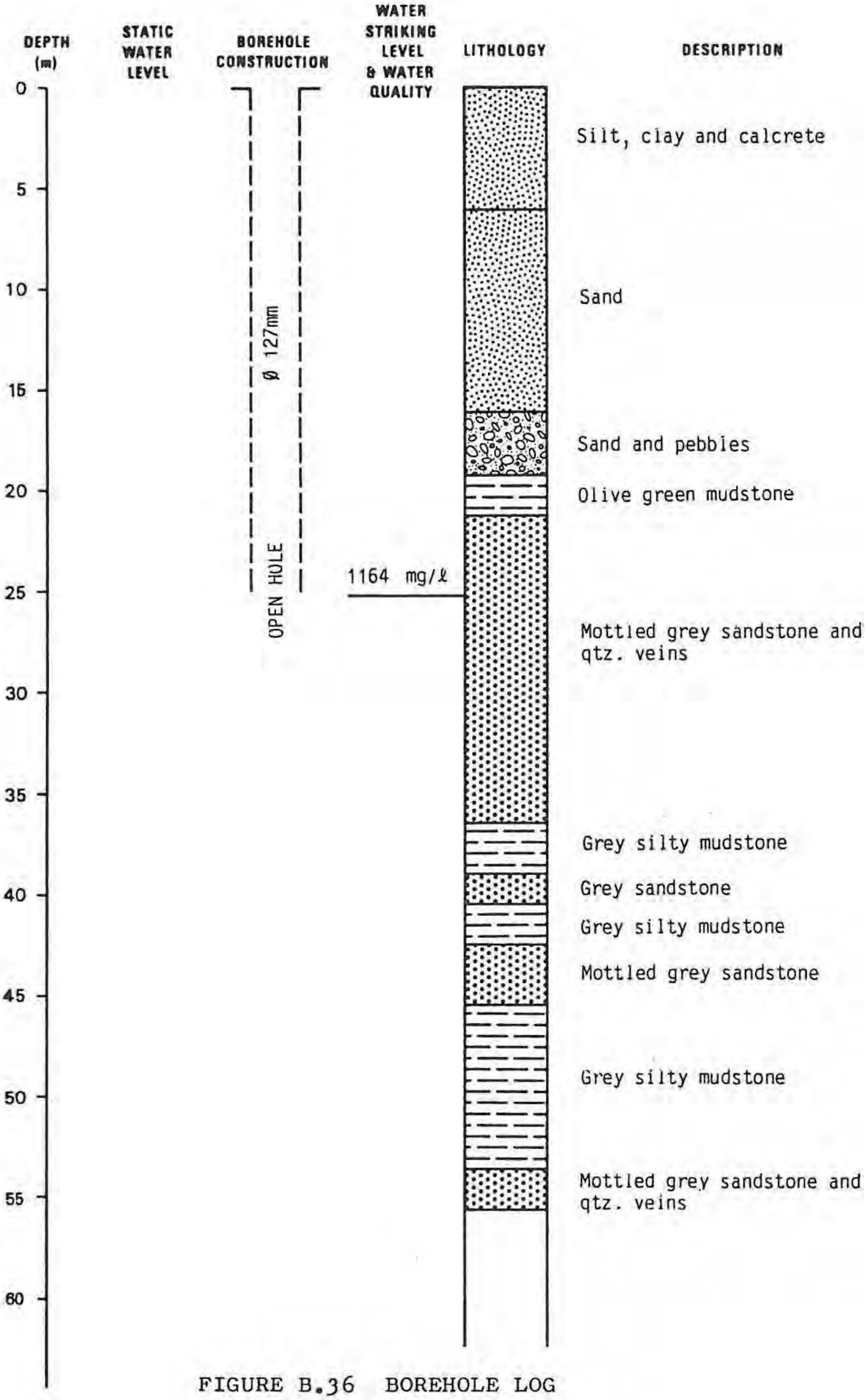


FIGURE B.36 BOREHOLE LOG

BOREHOLE NO: KD 31

CADASTRAL FARM: MOORDENAARS DRIFT

BLOW TEST YIELD: NO WATER ENCOUNTERED

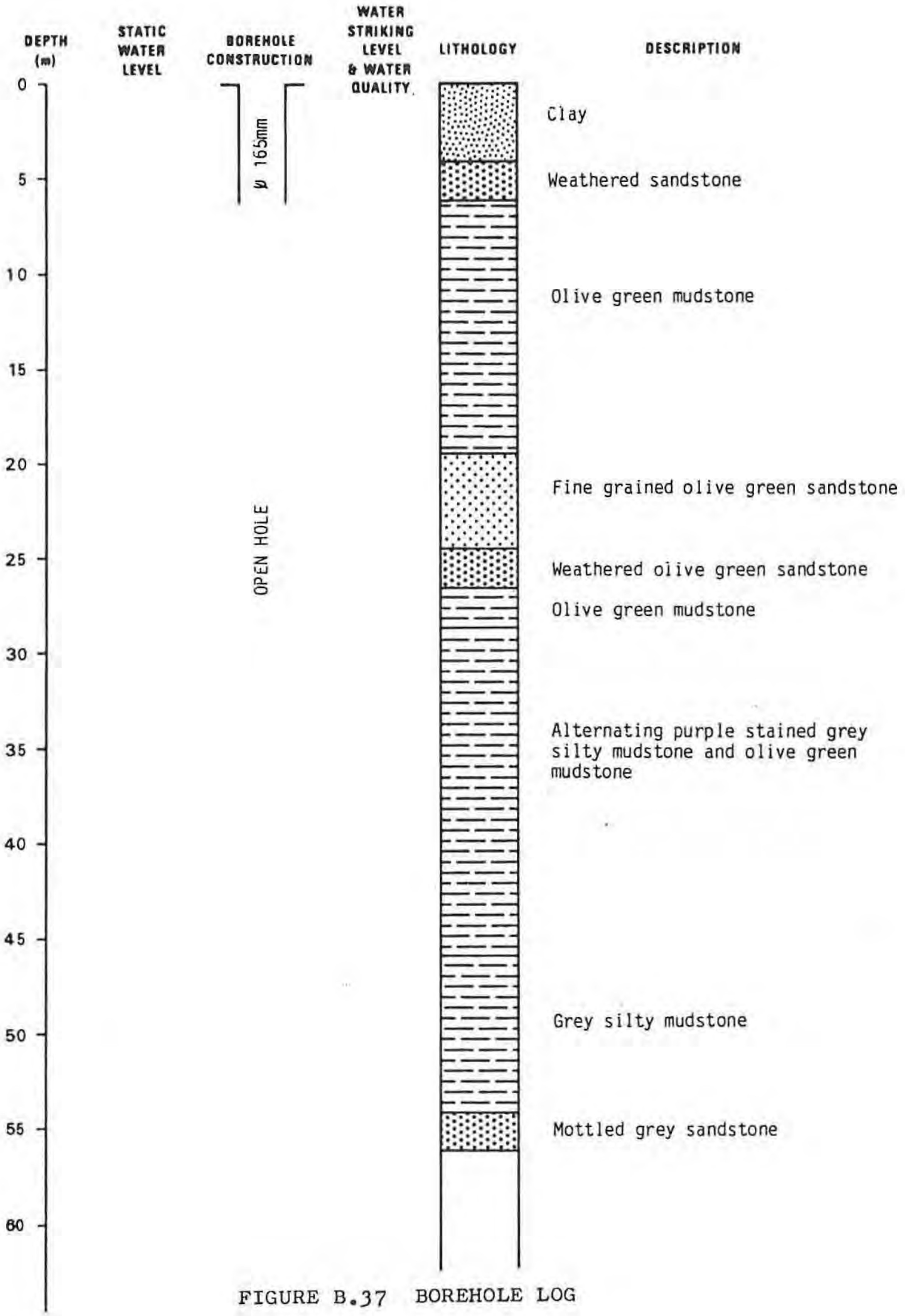


FIGURE B.37 BOREHOLE LOG

BOREHOLE NO: KD 37

CADASTRAL FARM: KLIPPE DRIFT

BLOW TEST YIELD: 0.50 ℓ/s

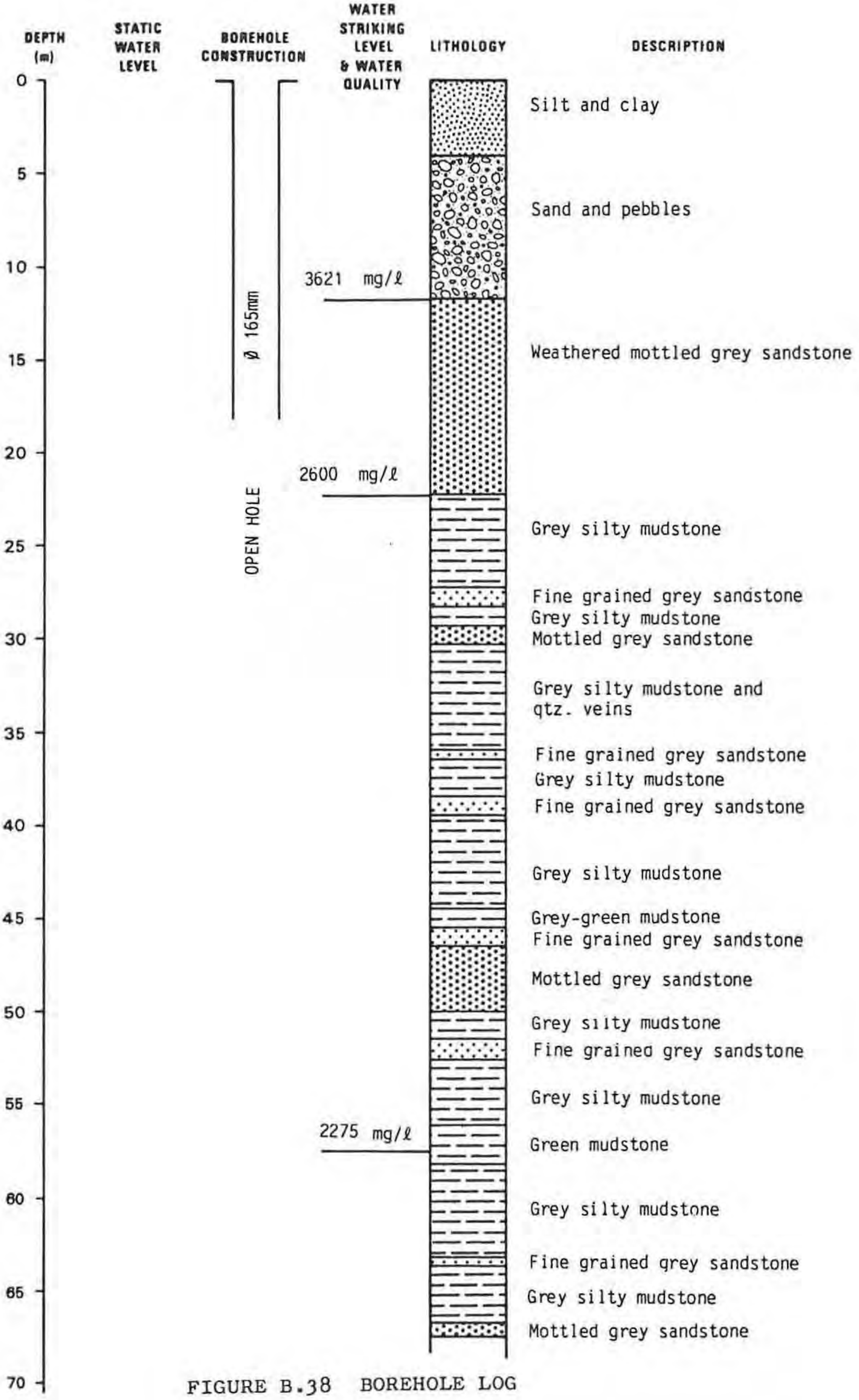


FIGURE B.38 BOREHOLE LOG

BOREHOLE NO: KD 45

CADASTRAL FARM: DRAAIHOEK

BLOW TEST YIELD: 0.63 ℓ/s

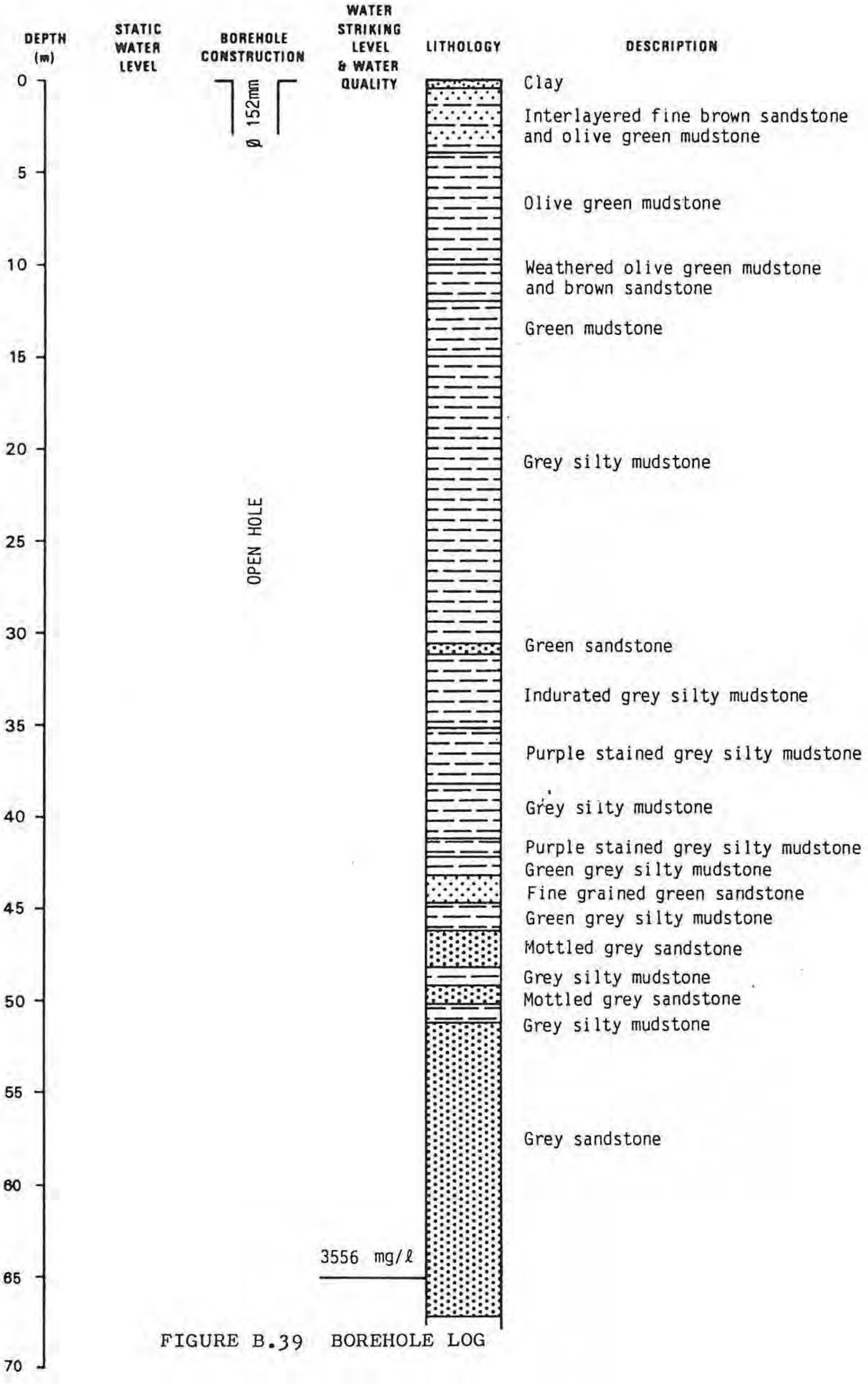


FIGURE B.39 BOREHOLE LOG

APPENDIX C

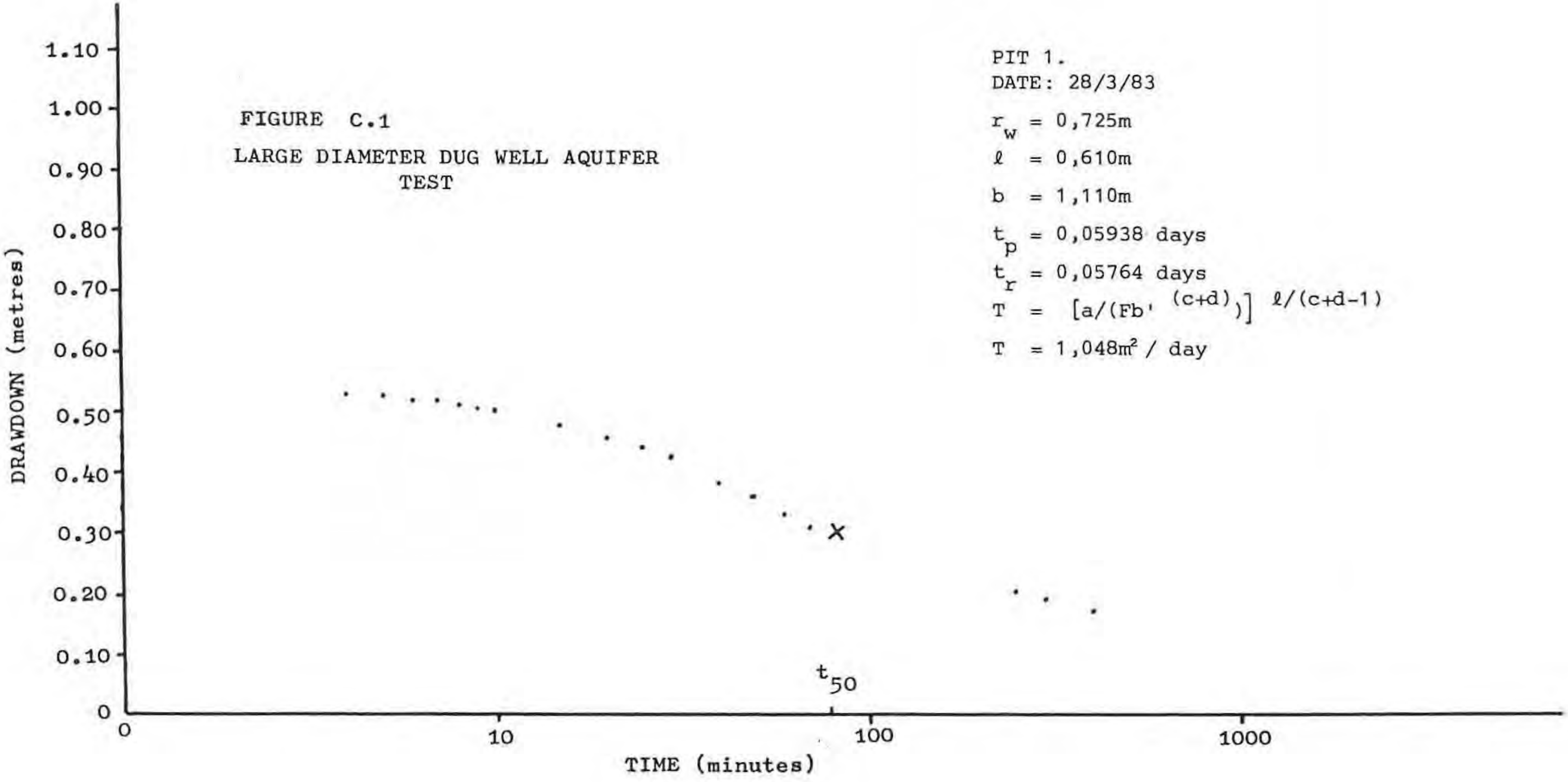
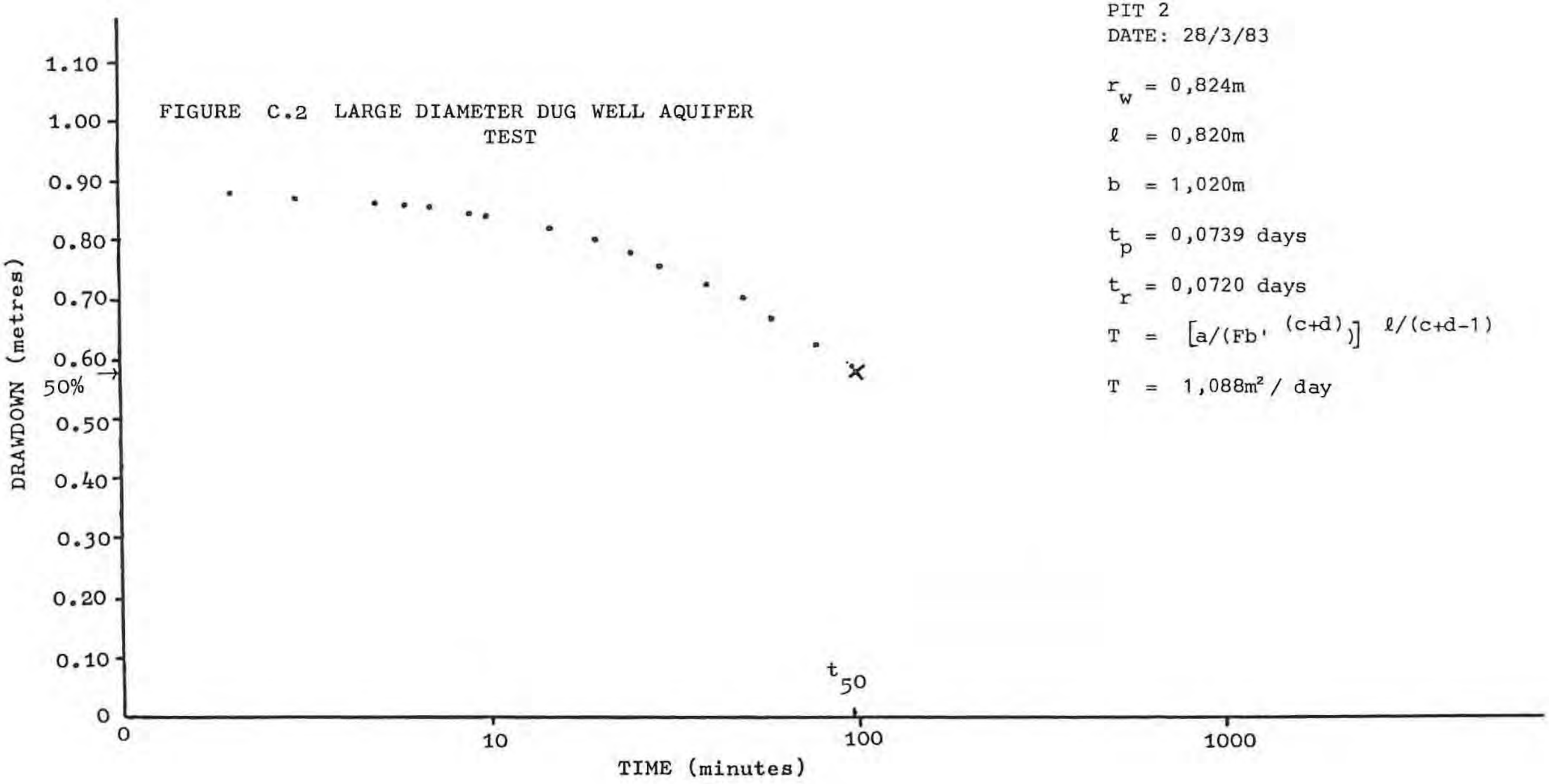


FIGURE C.1

LARGE DIAMETER DUG WELL AQUIFER TEST

PIT 1.
DATE: 28/3/83
r_w = 0,725m
ℓ = 0,610m
b = 1,110m
t_p = 0,05938 days
t_r = 0,05764 days
$T = \left[a/(Fb'^{(c+d)})\right]^{\ell/(c+d-1)}$
T = 1,048m² / day

FIGURE C.2 LARGE DIAMETER DUG WELL AQUIFER TEST



PIT 2
DATE: 28/3/83

r_w = 0,824m

ℓ = 0,820m

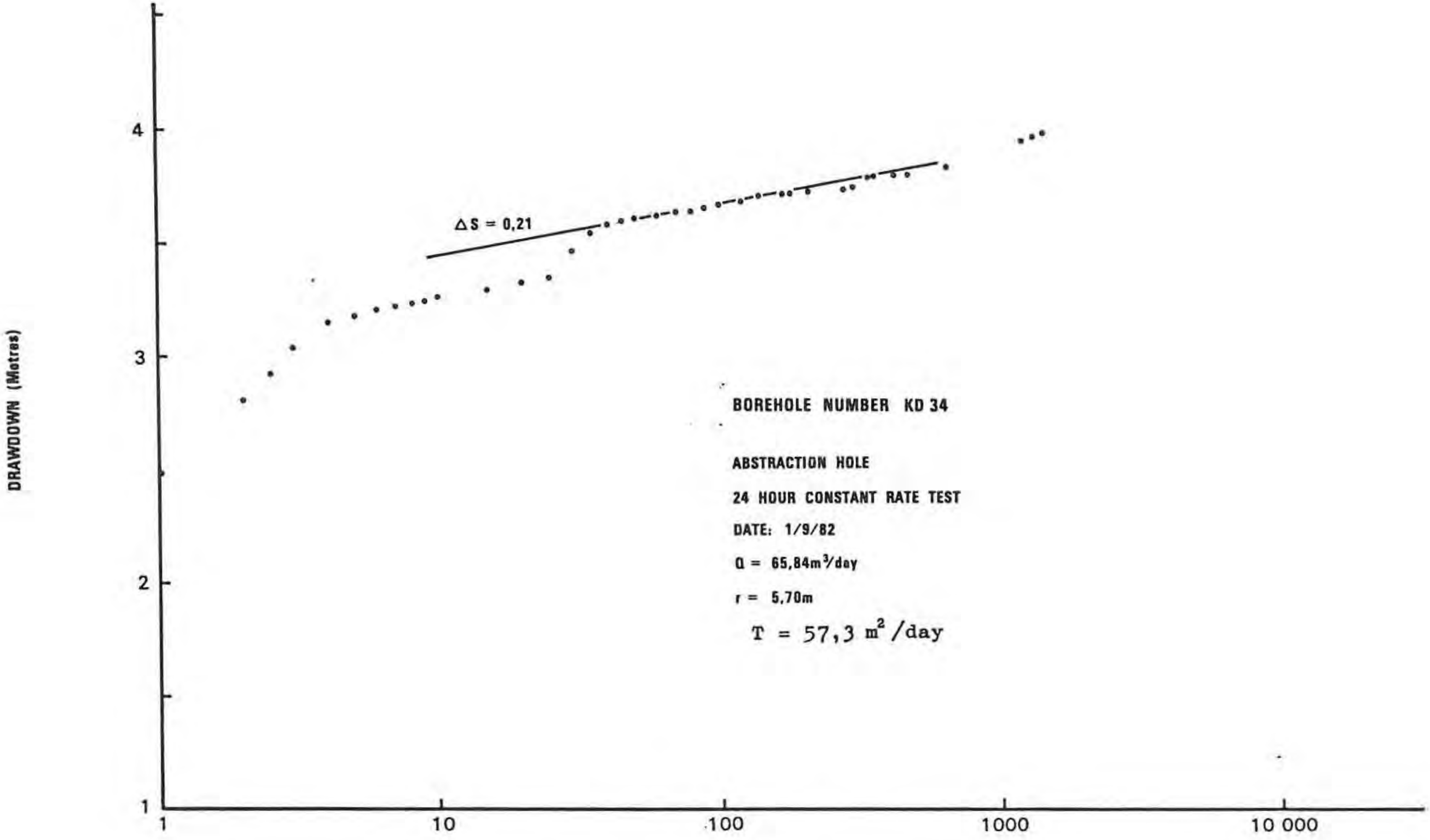
b = 1,020m

t_p = 0,0739 days

t_r = 0,0720 days

$T = \left[a/(Fb'^{(c+d)})\right]^{\ell/(c+d-1)}$

T = 1,088m² / day



BOREHOLE NUMBER KD 34

ABSTRACTION HOLE

24 HOUR CONSTANT RATE TEST

DATE: 1/9/82

$Q = 65{,}84 m^3/day$

$r = 5{,}70 m$

$T = 57{,}3 m^2/day$

FIGURE C.1 AQUIFER TEST

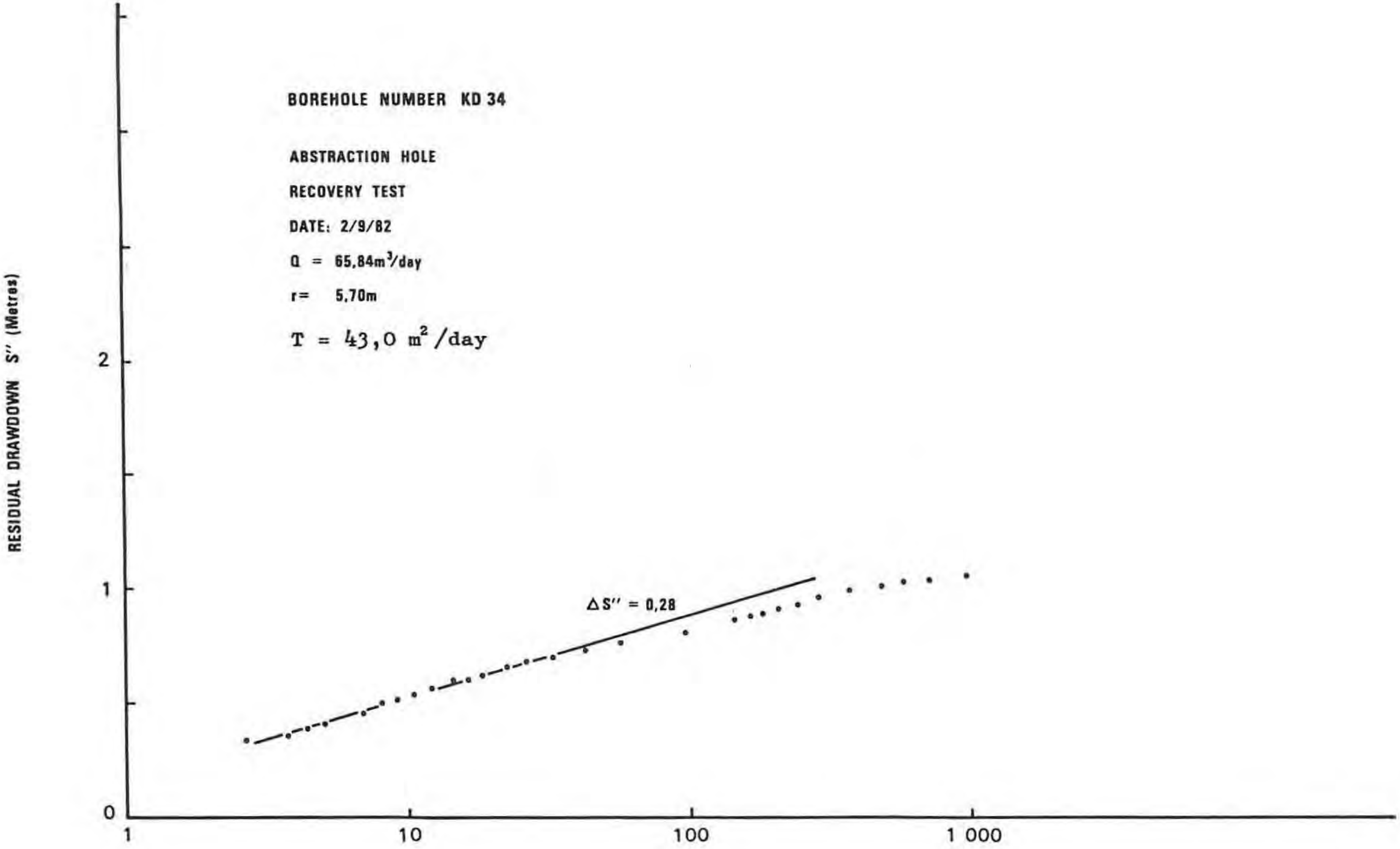
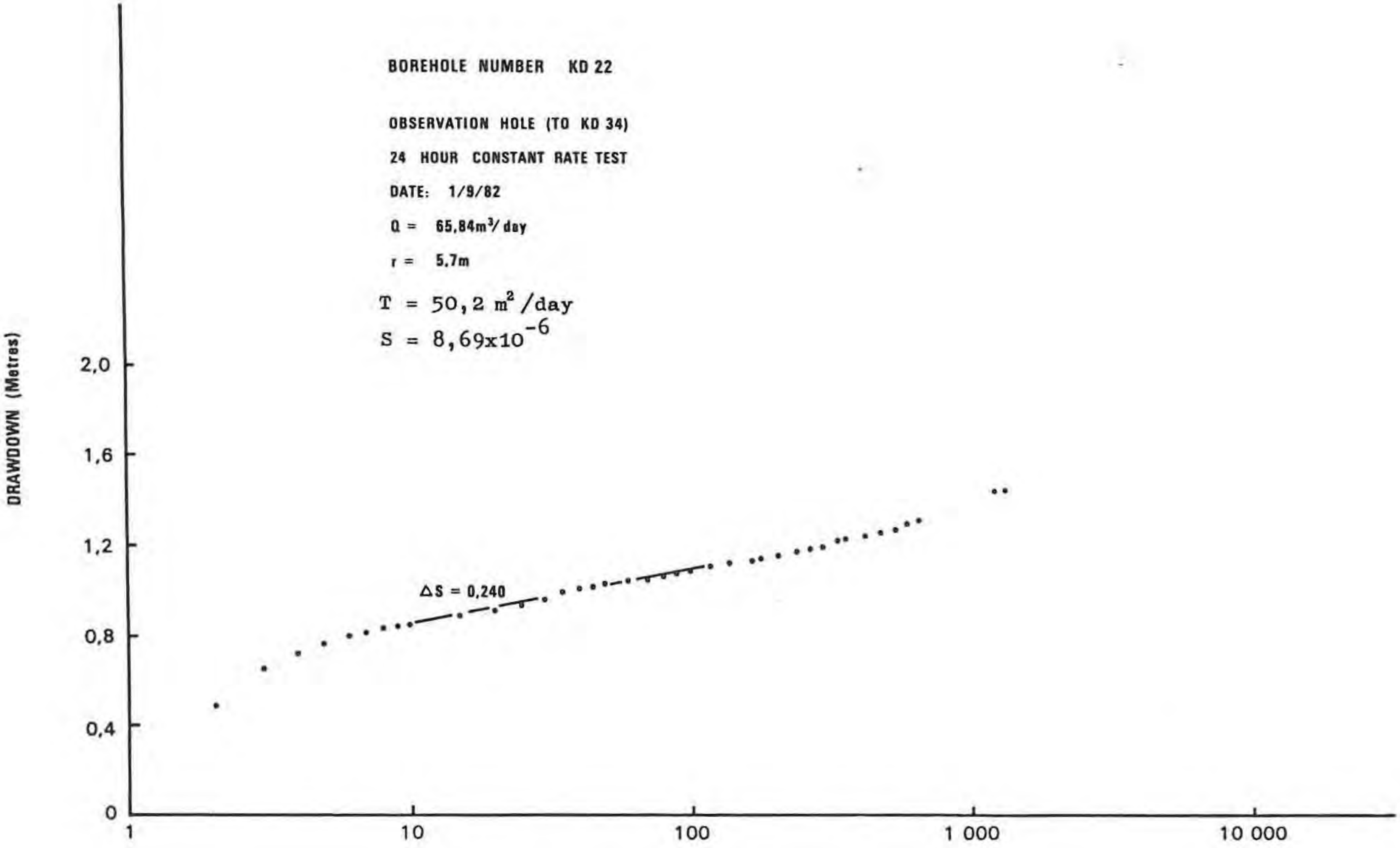


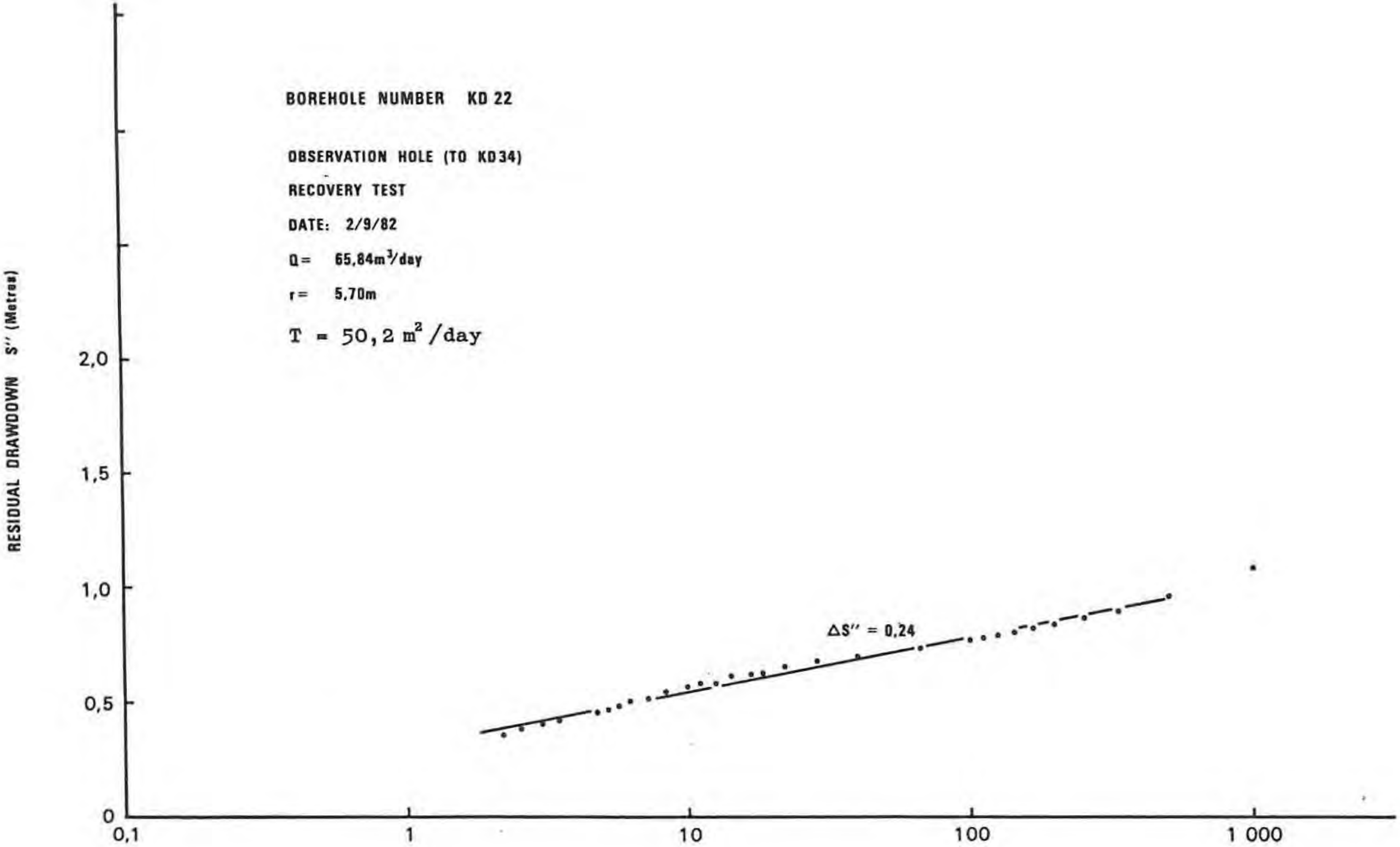
FIGURE C.2 AQUIFER TEST



$T = 50,2\ m^2/day$

$S = 8,69x10^{-6}$

FIGURE C.3 AQUIFER TEST



BOREHOLE NUMBER KD 22

OBSERVATION HOLE (TO KD34)

RECOVERY TEST

DATE: 2/9/82

Q= 65,84m^3/day

r= 5,70m

T = 50,2 m^2/day

FIGURE C.4 AQUIFER TEST

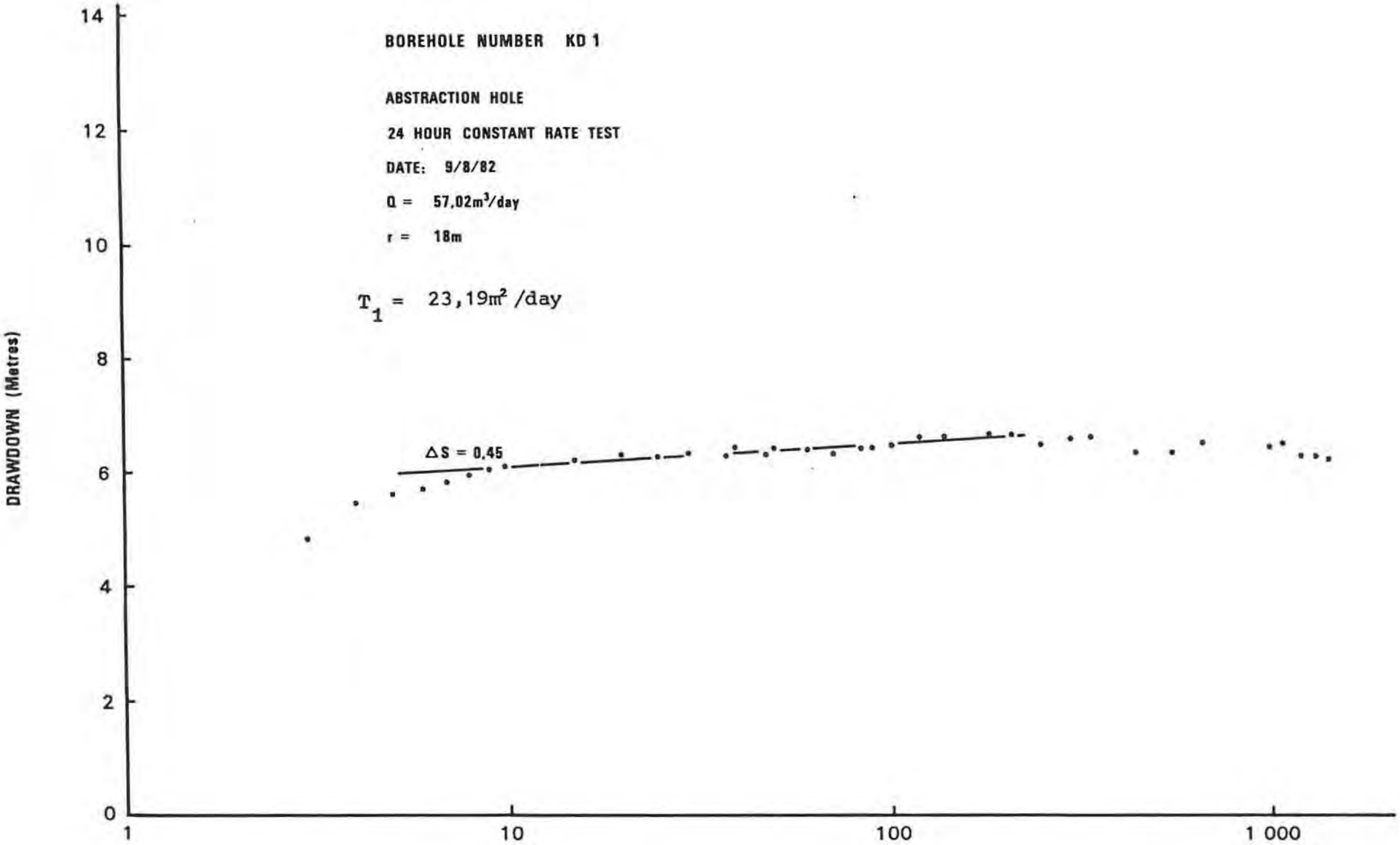


FIGURE C.5 AQUIFER TEST

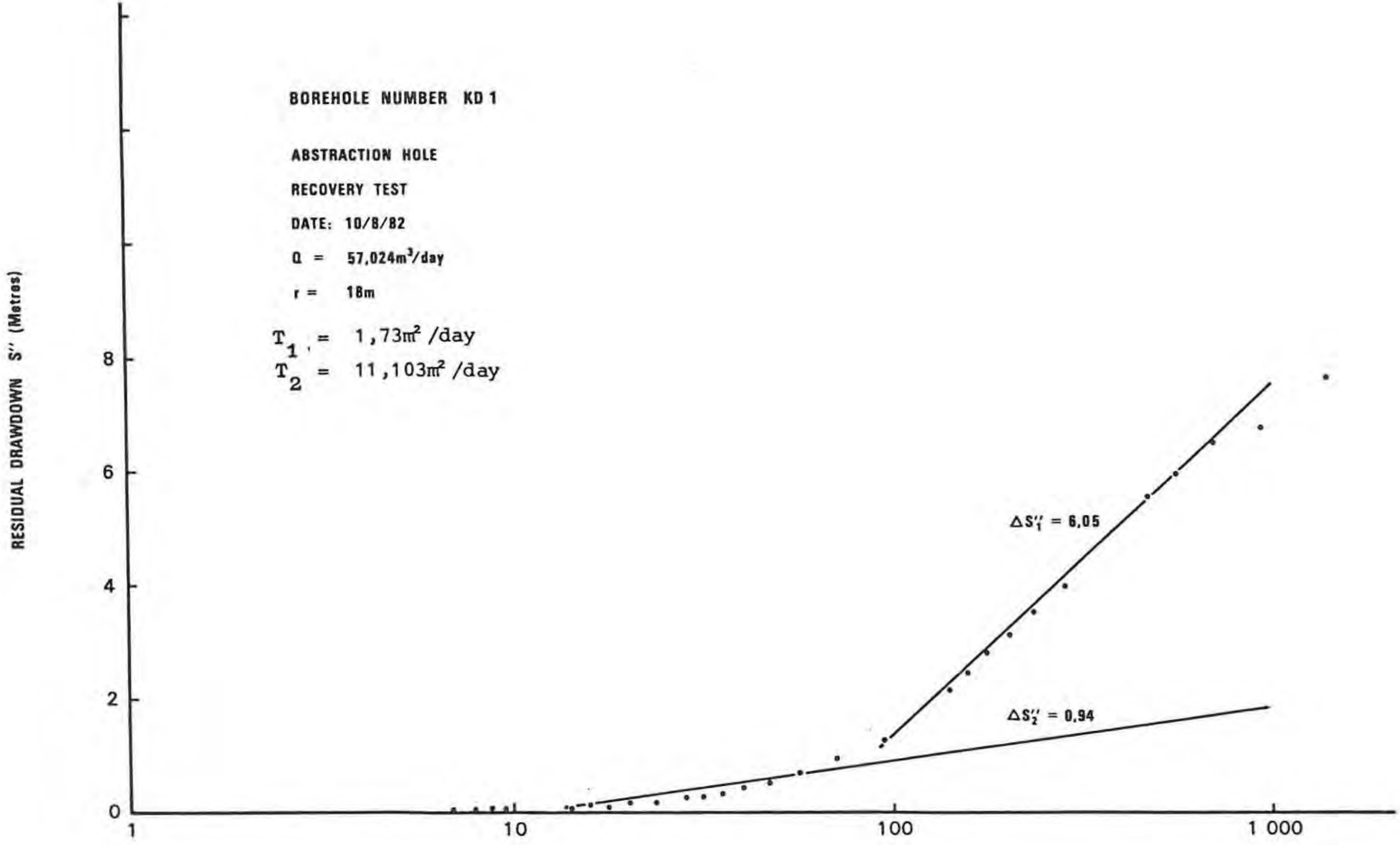
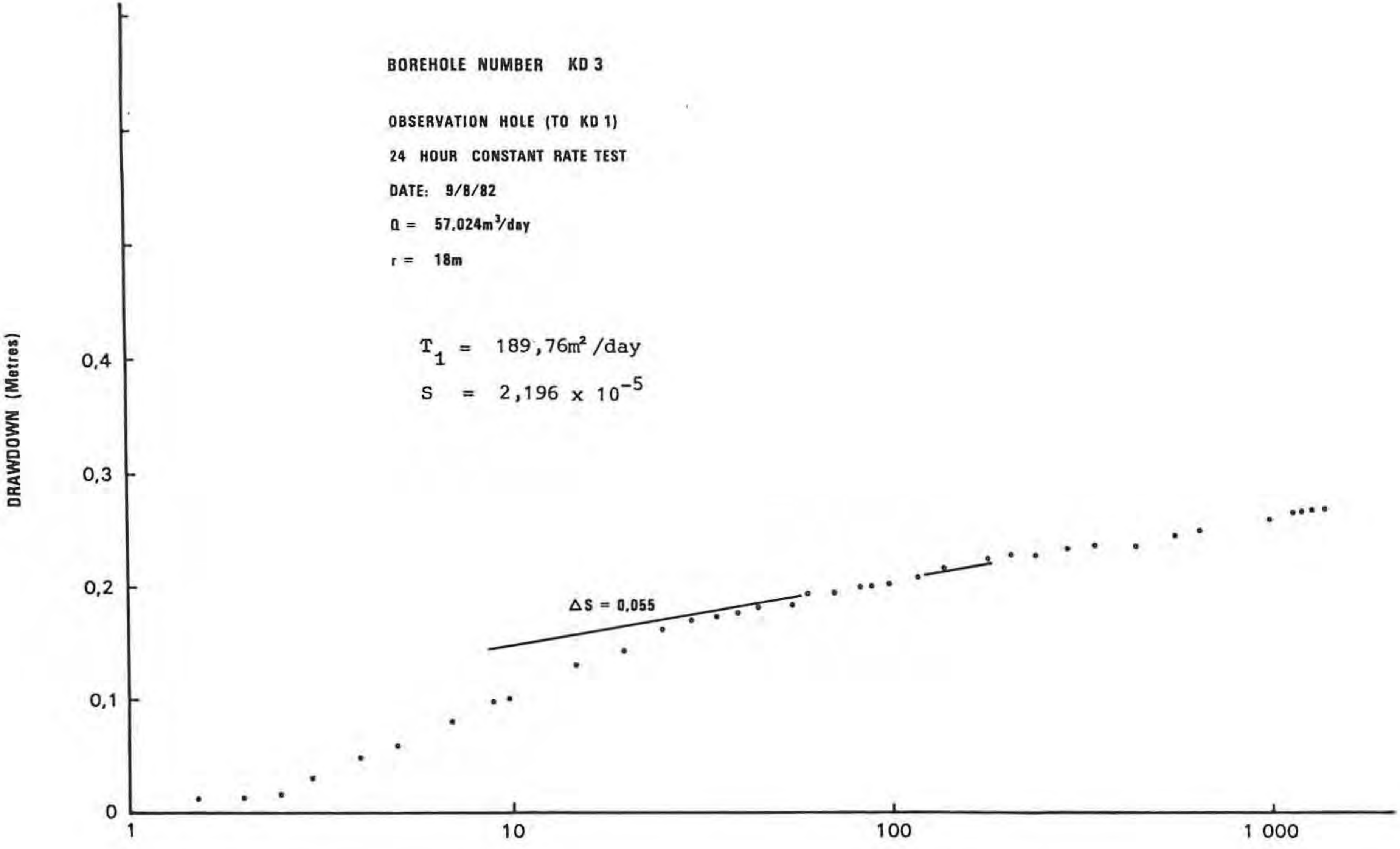


FIGURE C.6 AQUIFER TEST



BOREHOLE NUMBER KD 3

OBSERVATION HOLE (TO KD 1)

24 HOUR CONSTANT RATE TEST

DATE: 9/8/82

$Q = 57{,}024 m^3/day$

$r = 18m$

$T_1 = 189{,}76 m^2/day$

$S = 2{,}196 \times 10^{-5}$

FIGURE C.7 AQUIFER TEST

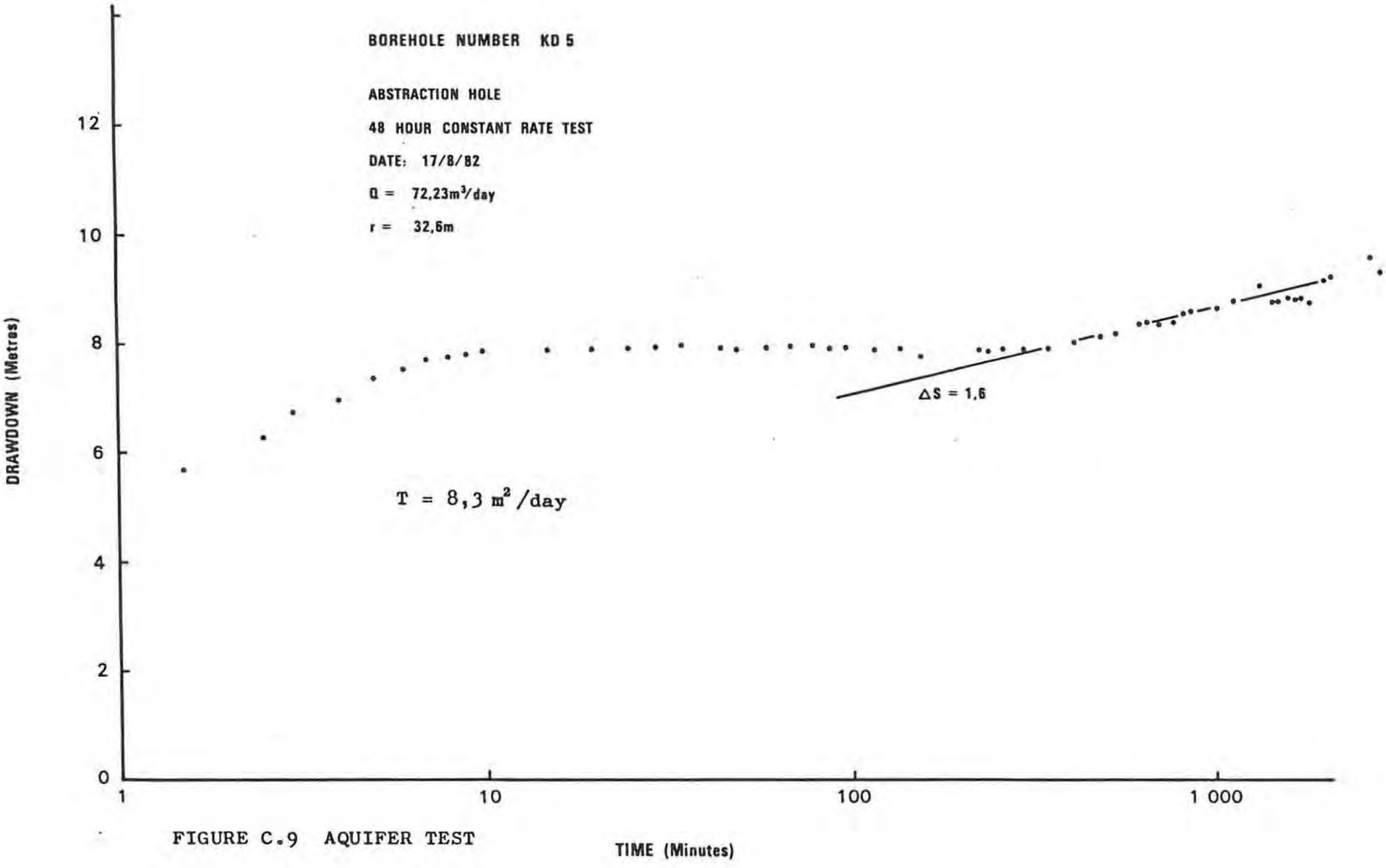


FIGURE C.9 AQUIFER TEST

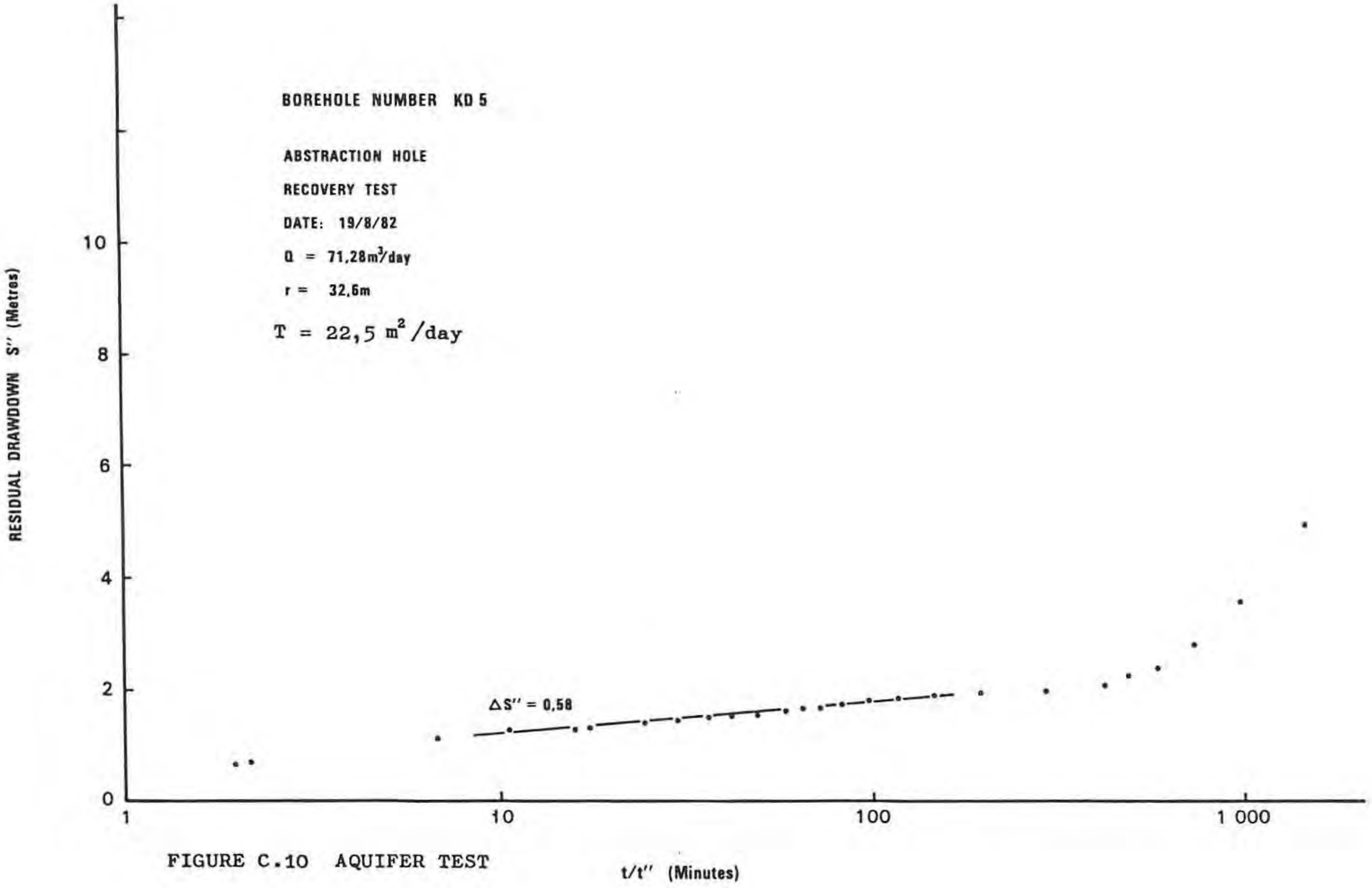


FIGURE C.10 AQUIFER TEST

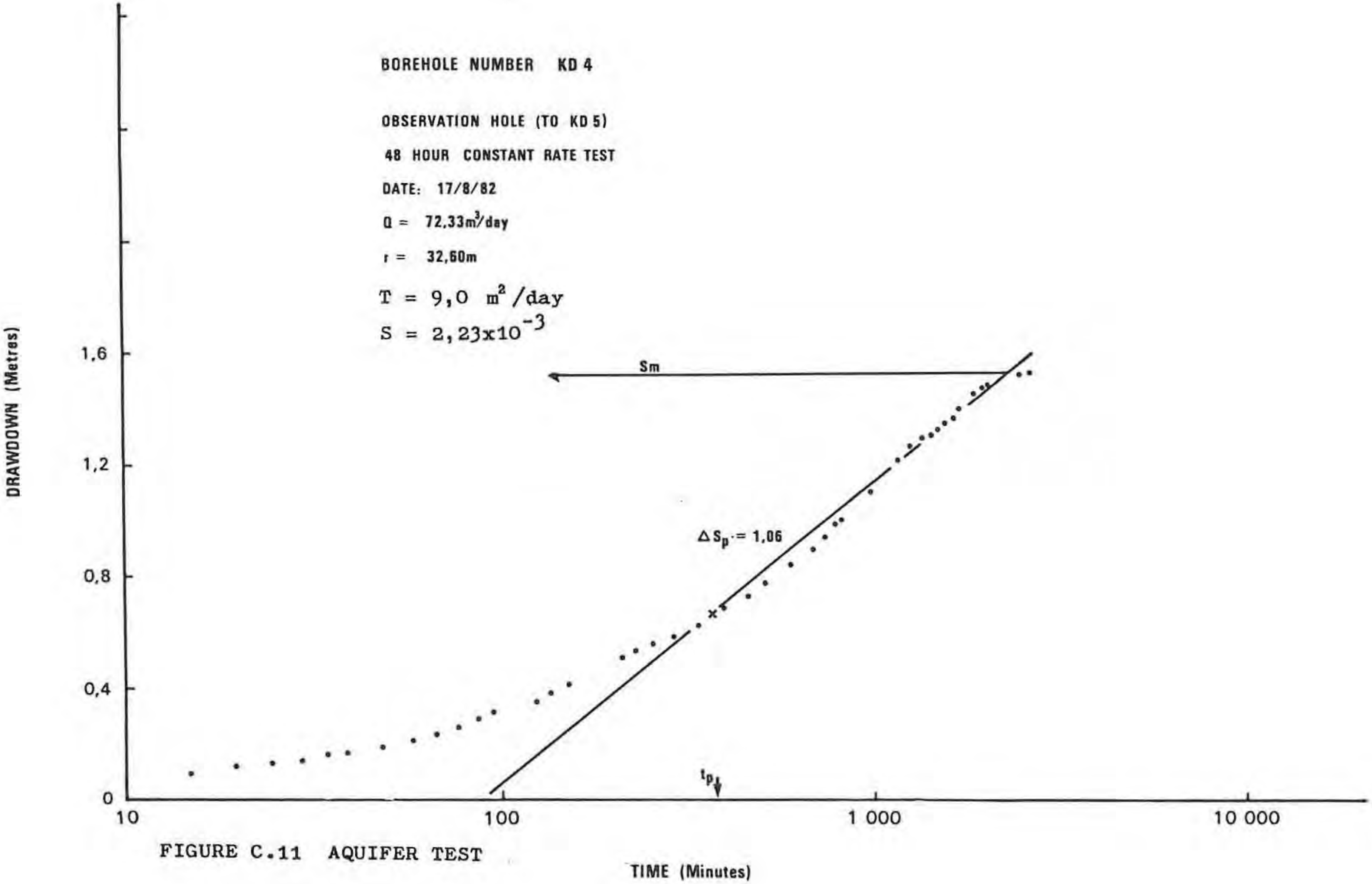


FIGURE C.11 AQUIFER TEST

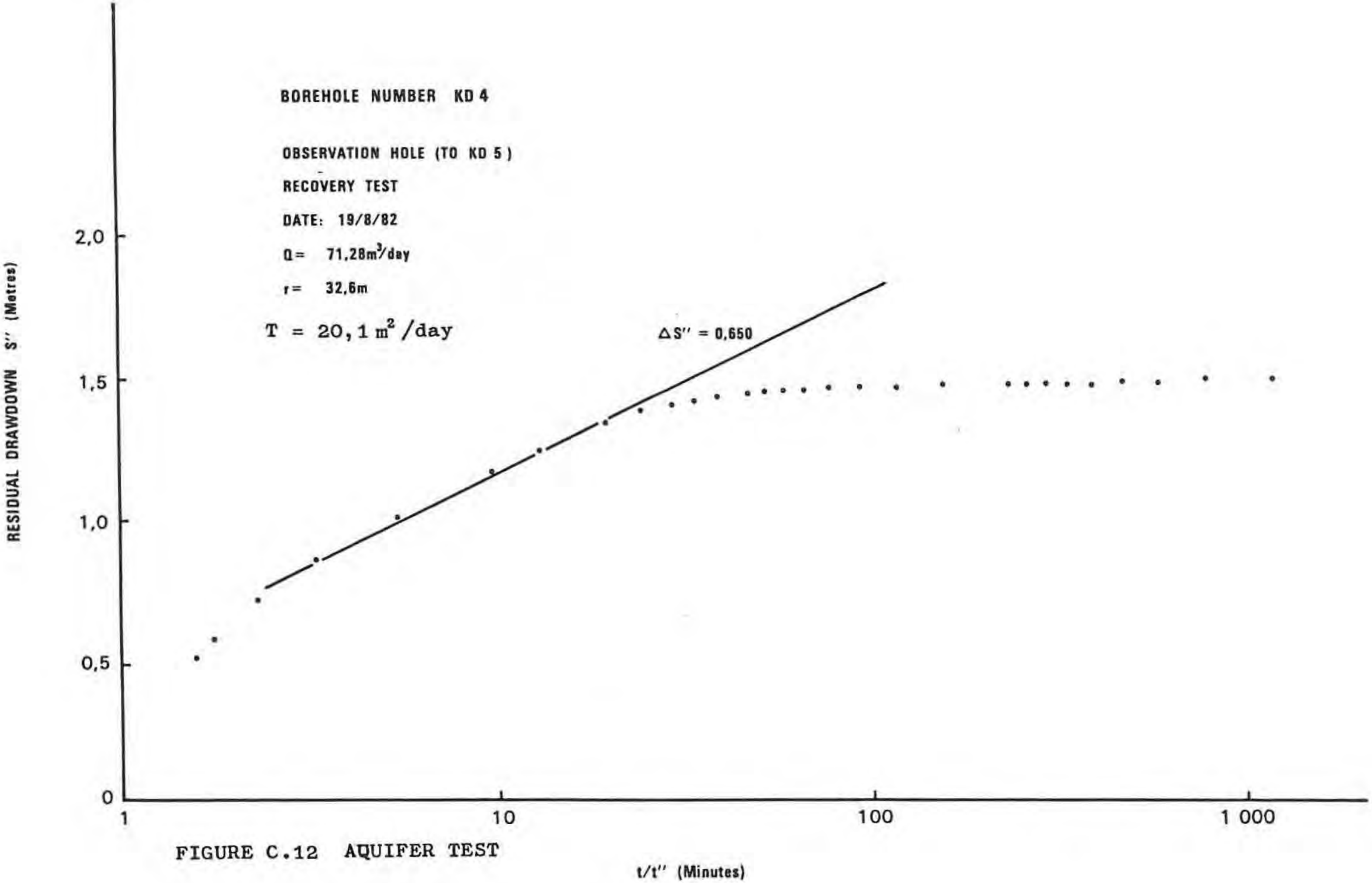
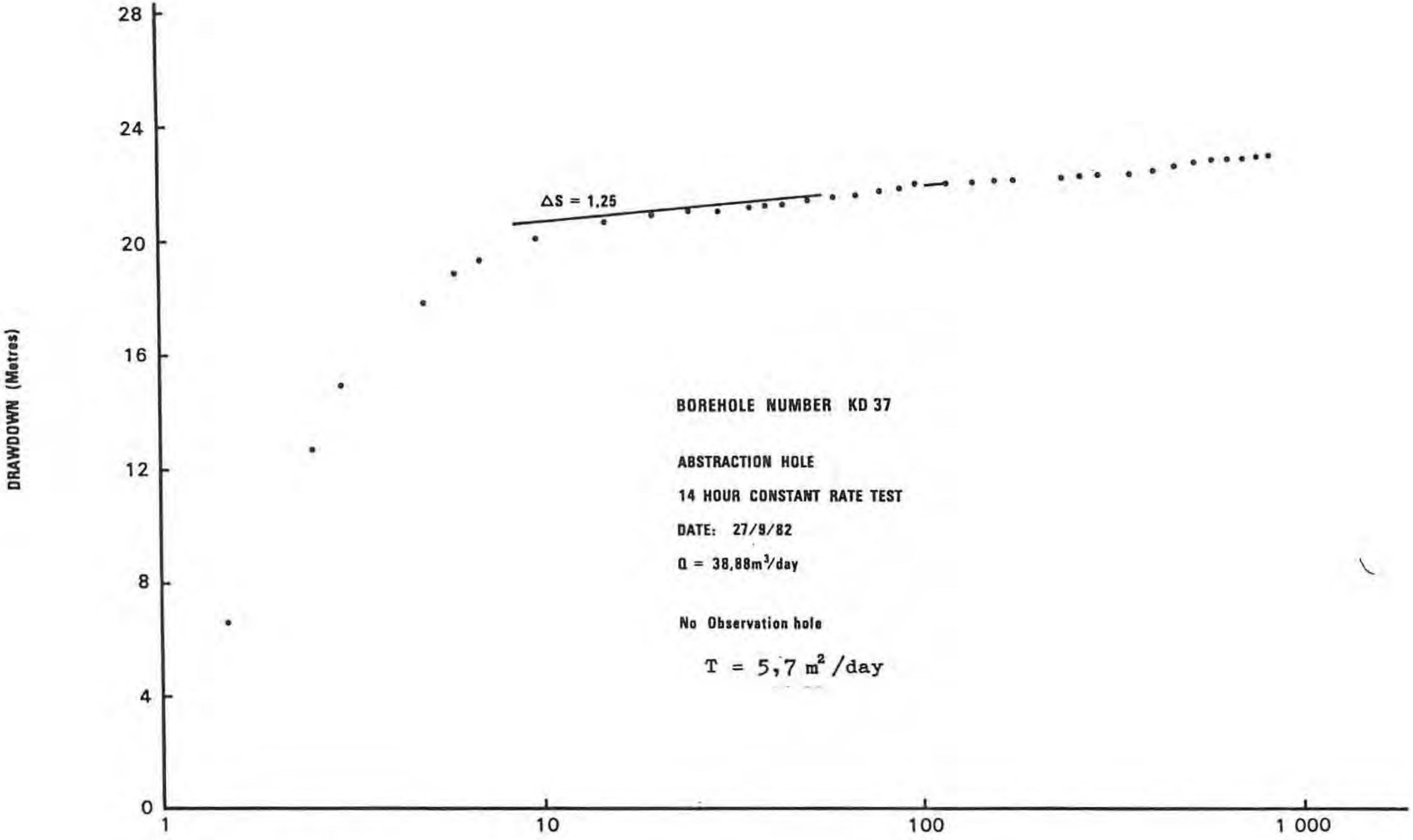


FIGURE C.12 AQUIFER TEST



BOREHOLE NUMBER KD 37

ABSTRACTION HOLE

14 HOUR CONSTANT RATE TEST

DATE: 27/9/82

$Q = 38{,}88 m^3/day$

No Observation hole

$T = 5{,}7 m^2/day$

FIGURE C.13 AQUIFER TEST

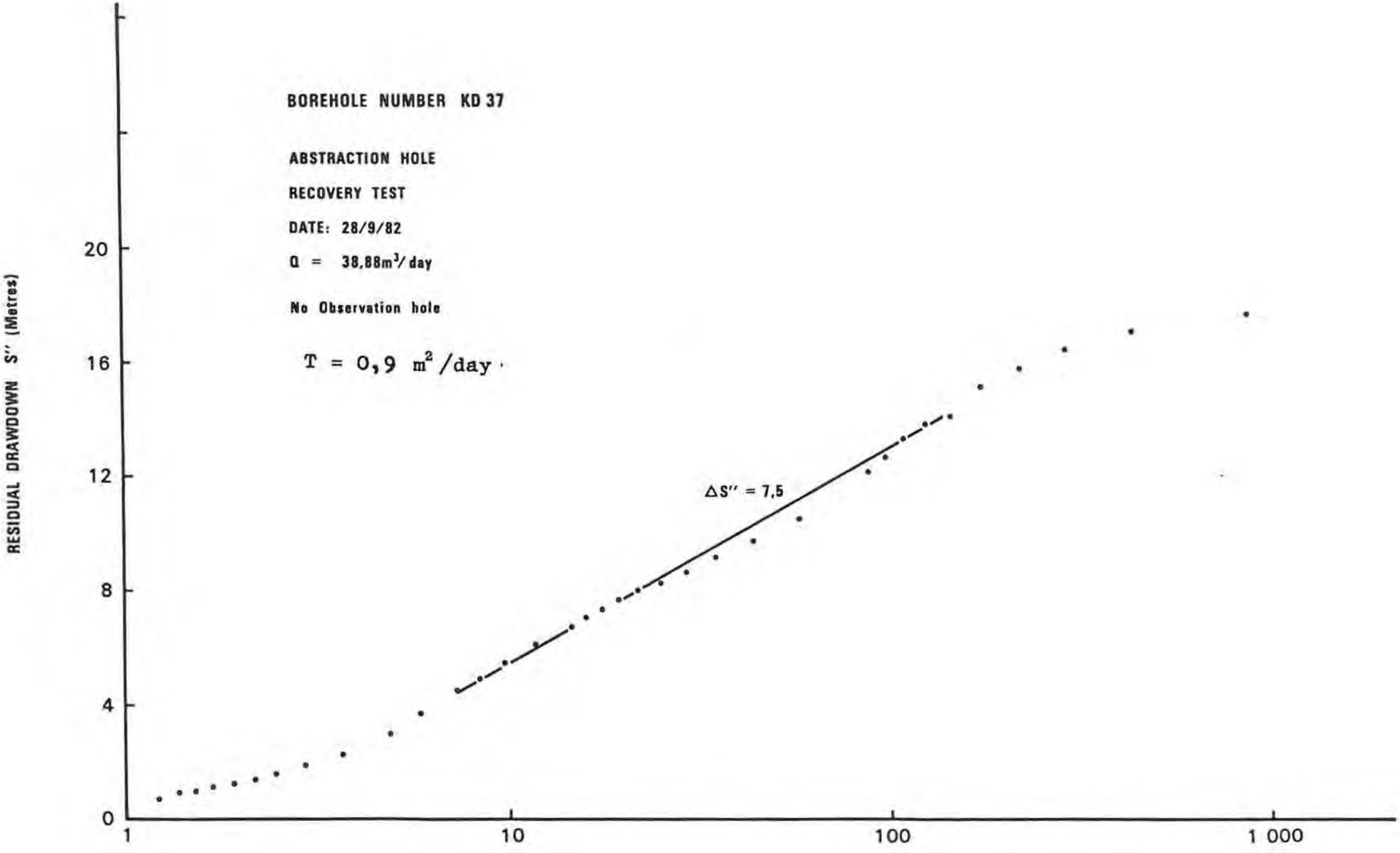


FIGURE C.14 AQUIFER TEST

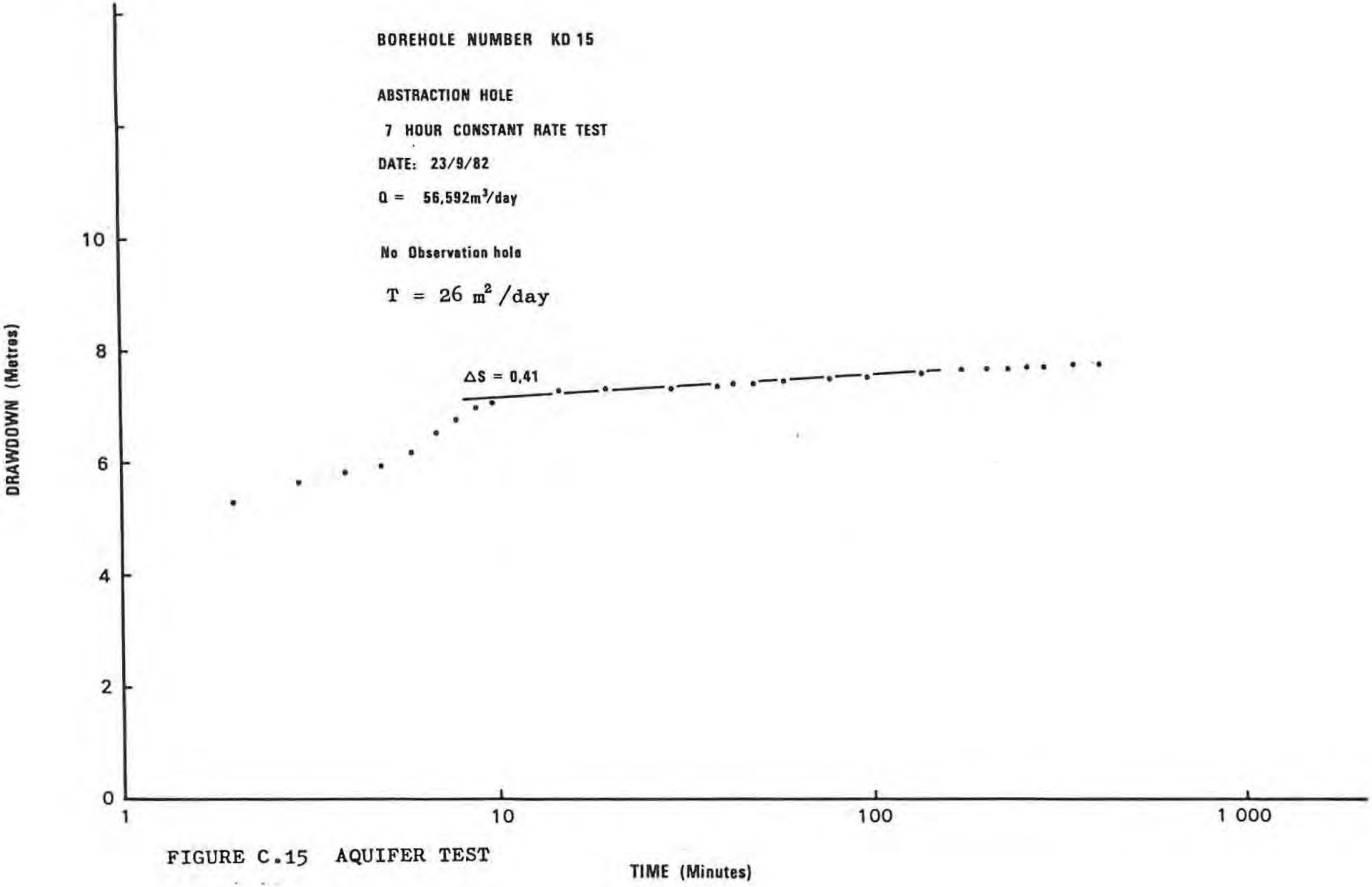


FIGURE C.15 AQUIFER TEST

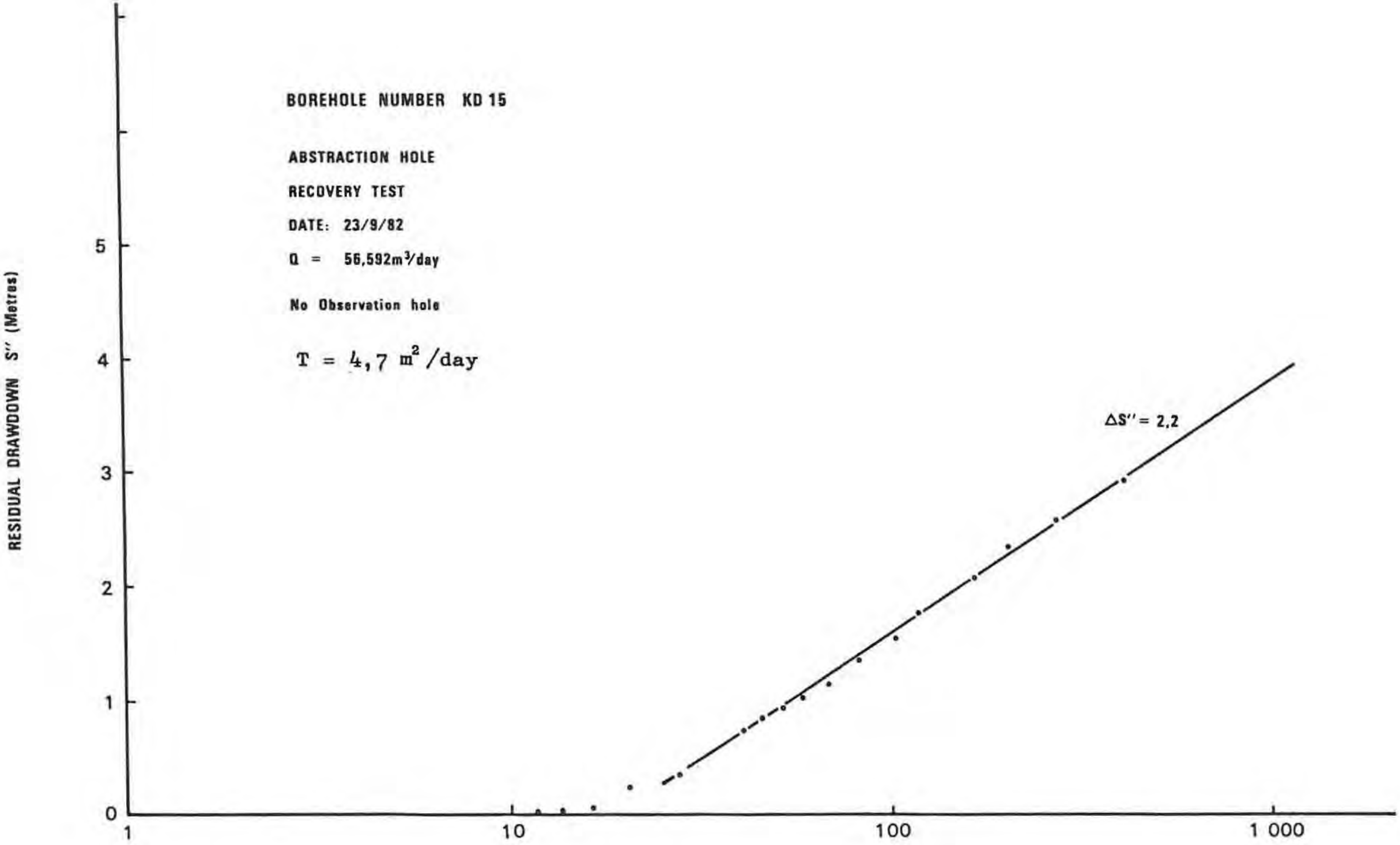


FIGURE C.16 AQUIFER TEST

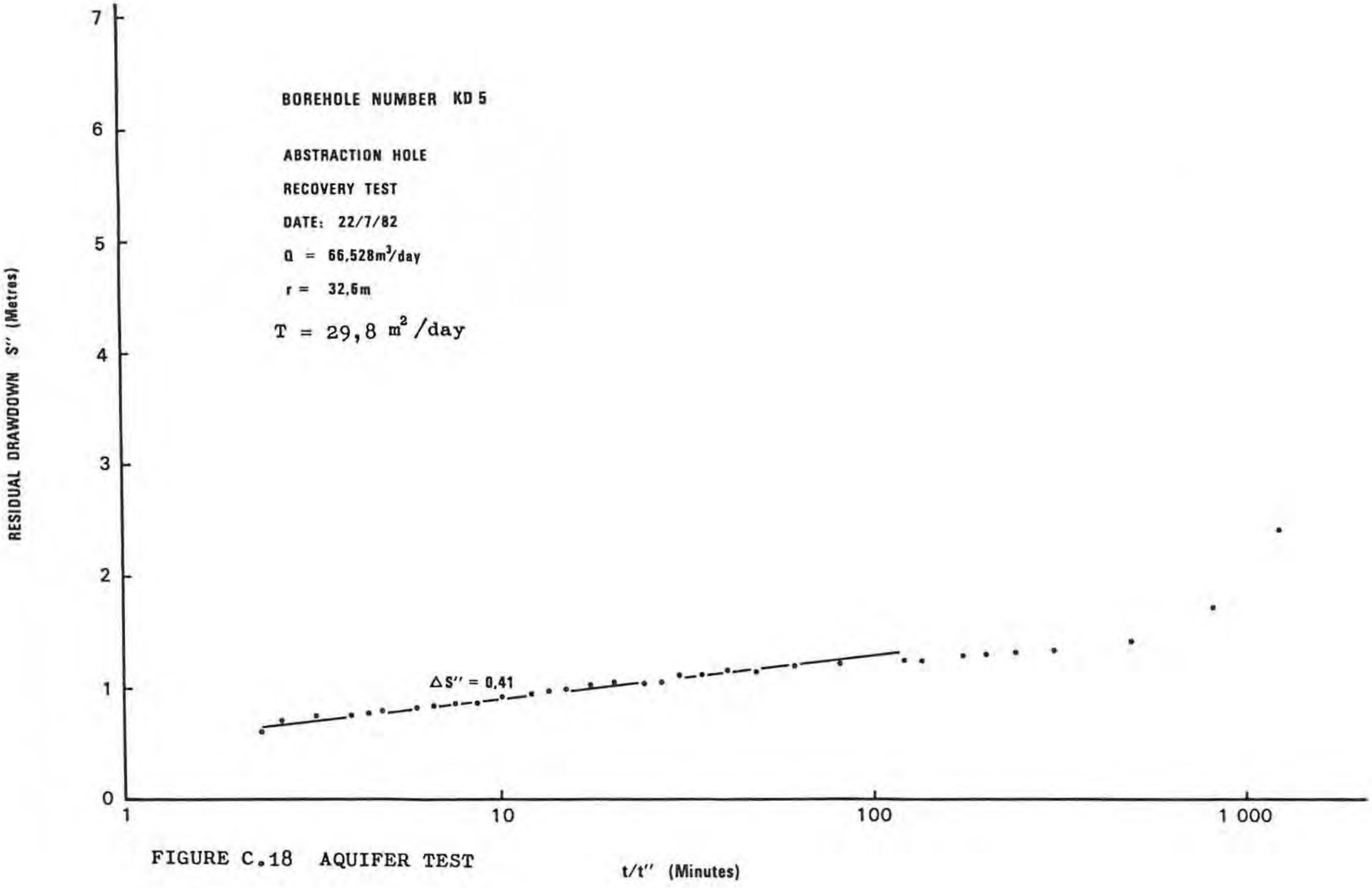


FIGURE C.18 AQUIFER TEST

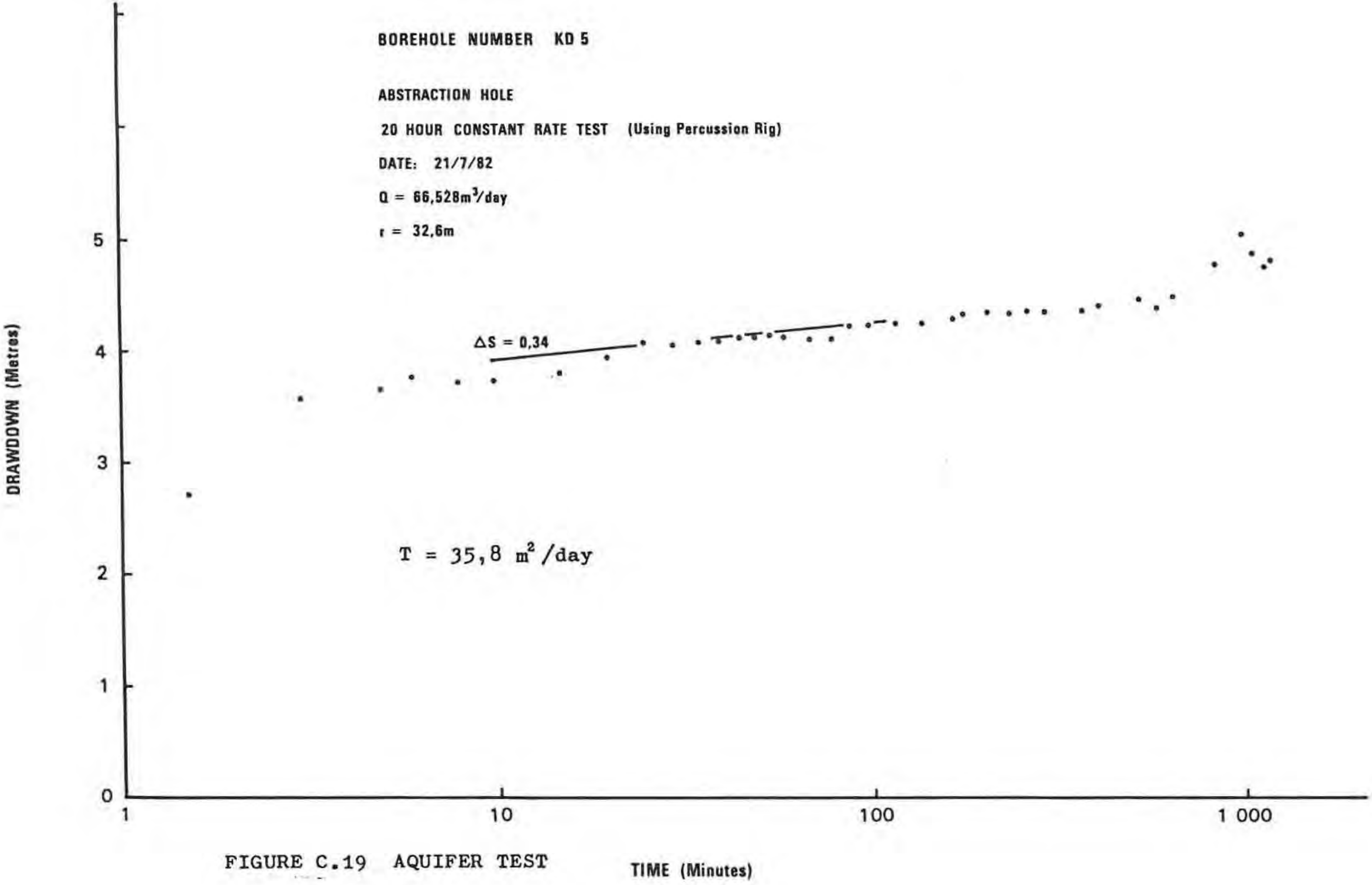
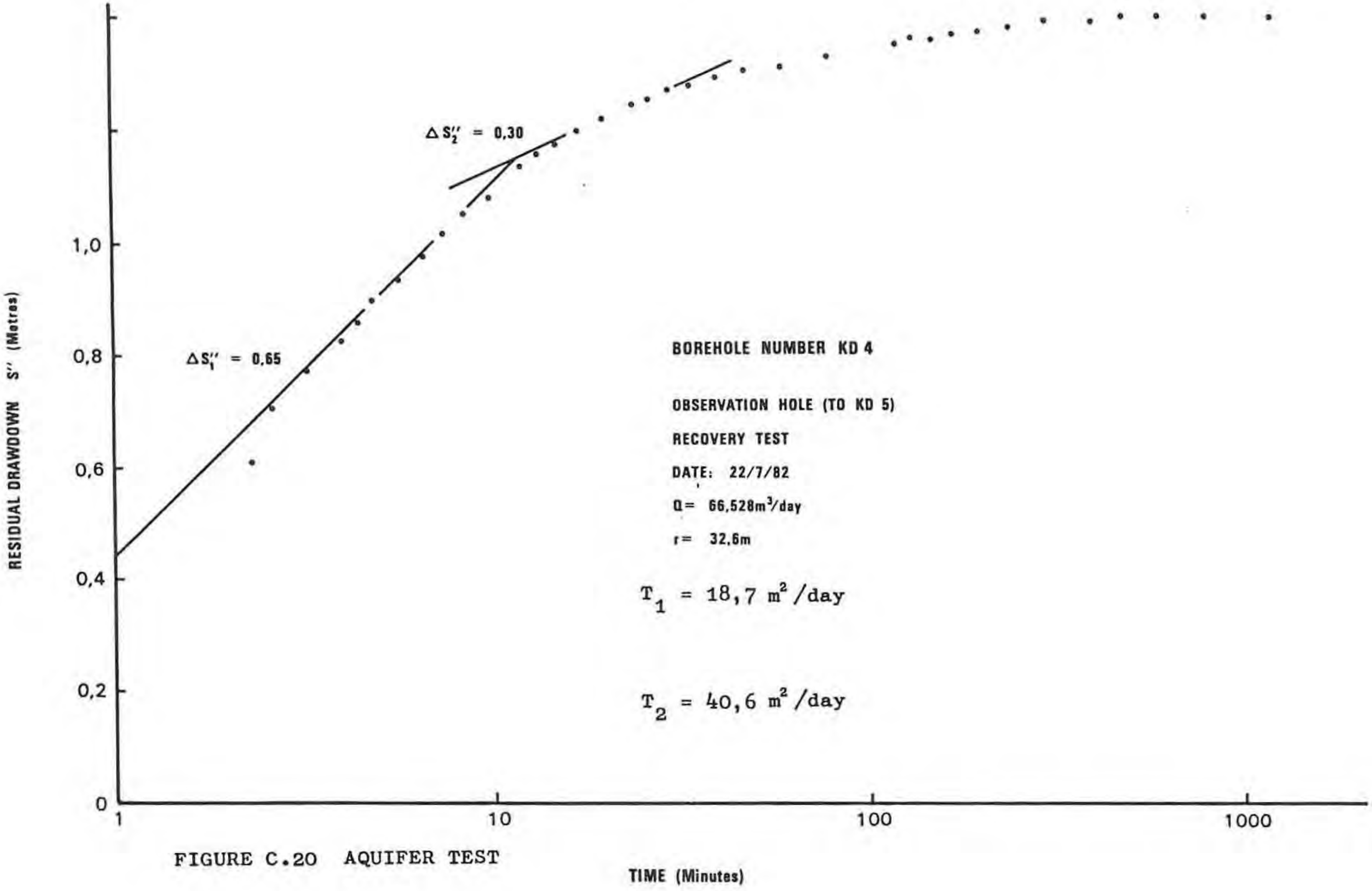


FIGURE C.19 AQUIFER TEST



BOREHOLE NUMBER KD 4

OBSERVATION HOLE (TO KD 5)

RECOVERY TEST

DATE: 22/7/82

Q= 66,528m^3/day

r= 32,6m

$T_1 = 18,7\ m^2/day$

$T_2 = 40,6\ m^2/day$

FIGURE C.20 AQUIFER TEST

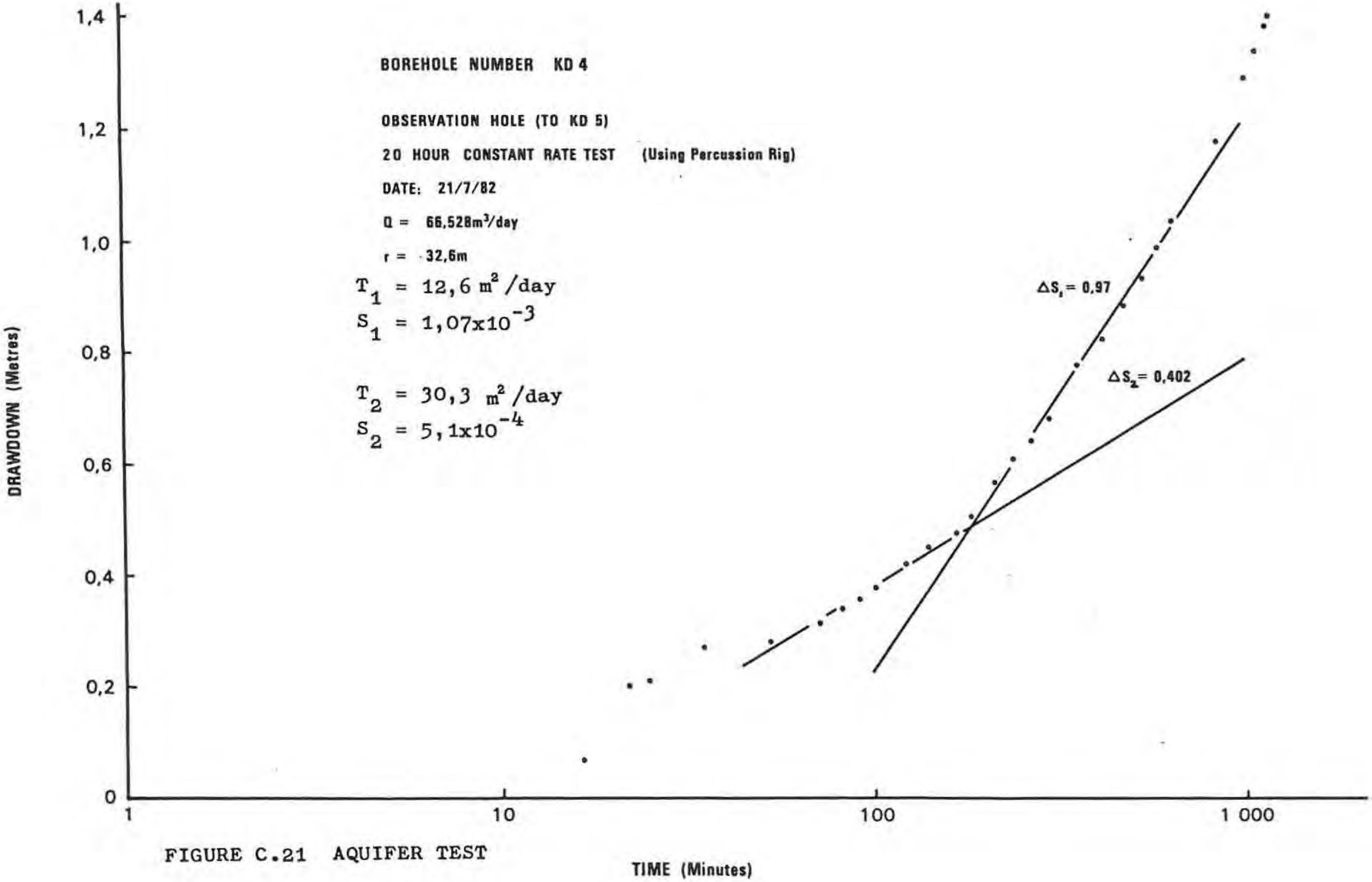


FIGURE C.21 AQUIFER TEST

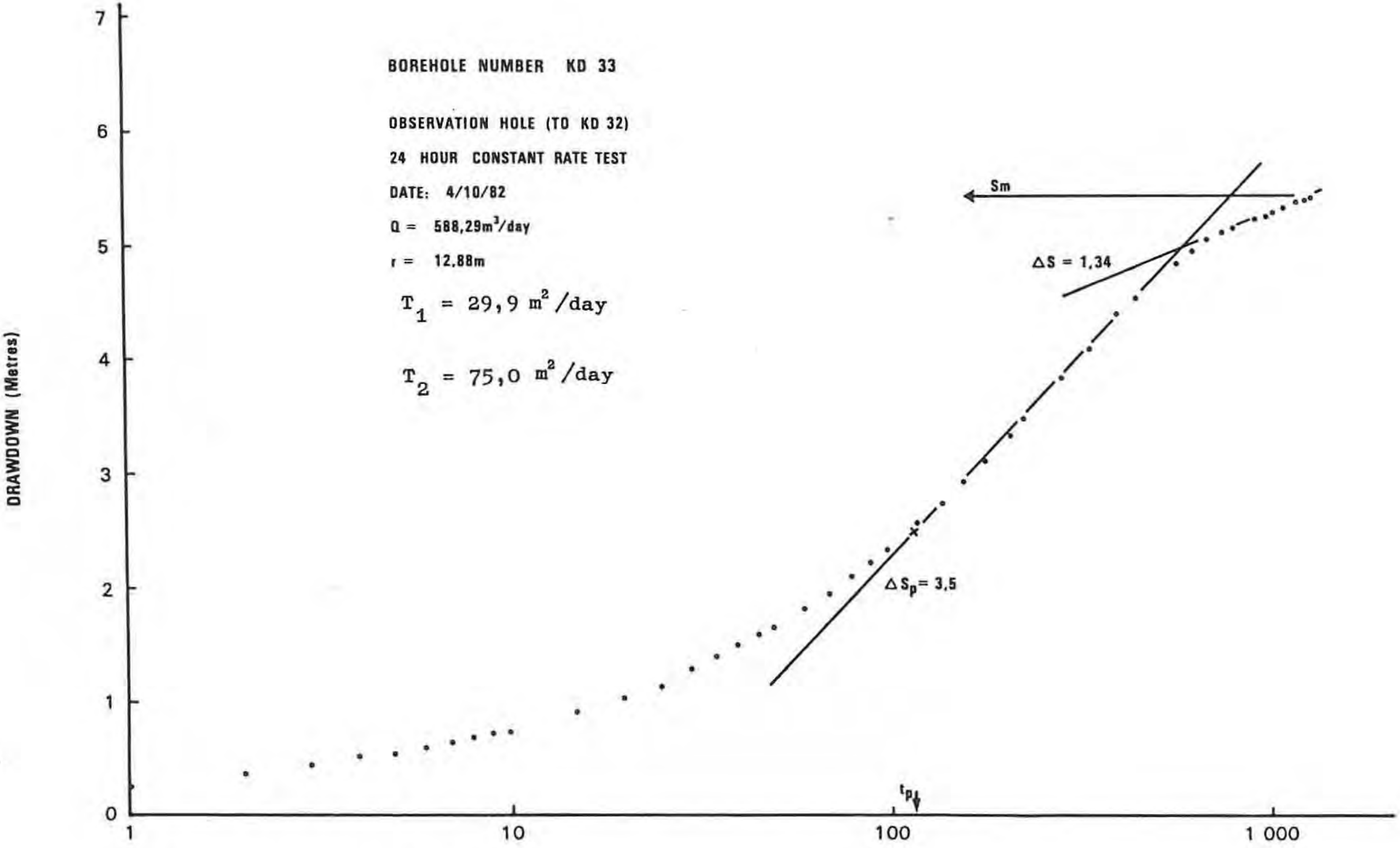


FIGURE C.22 AQUIFER TEST

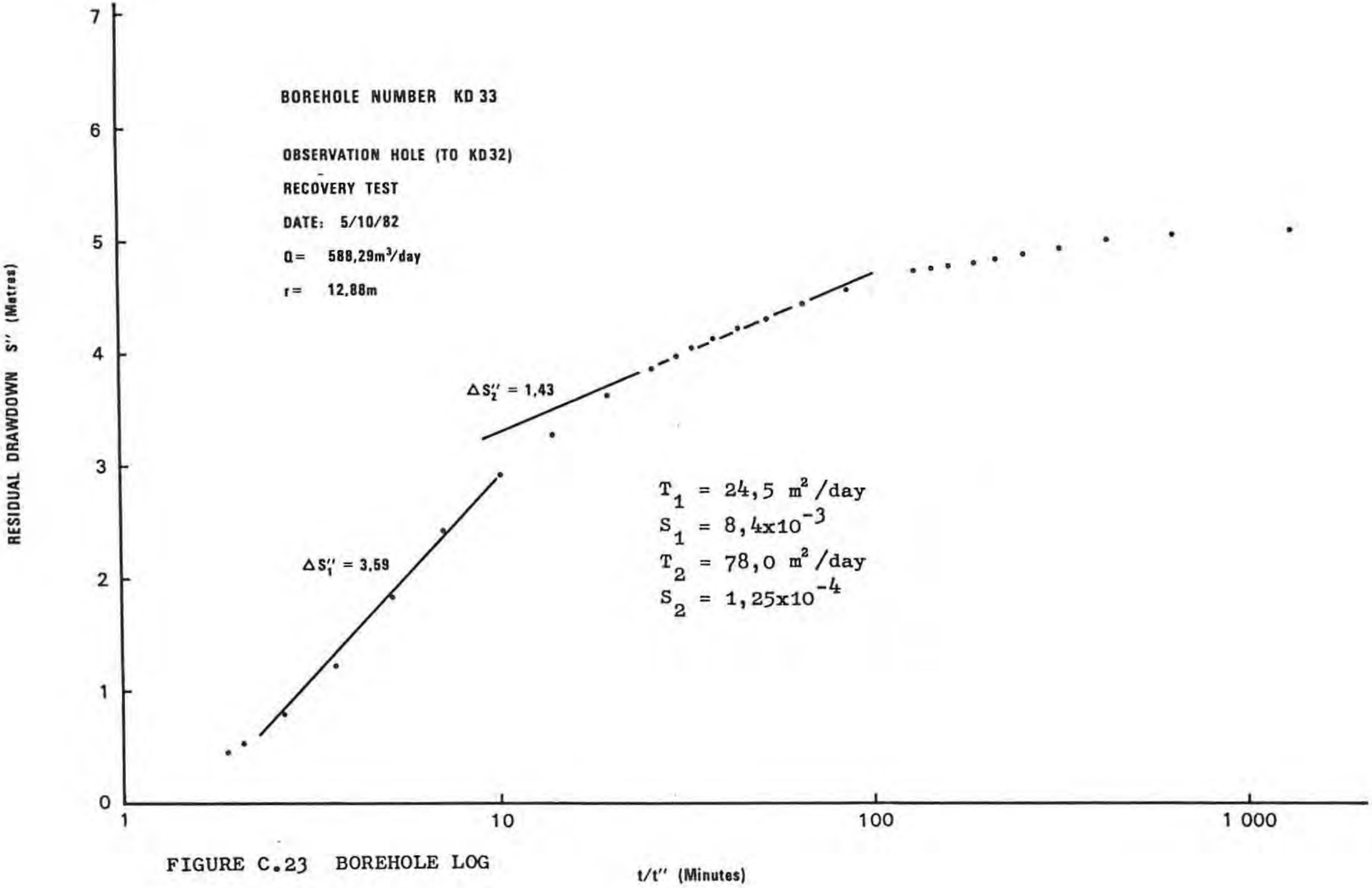
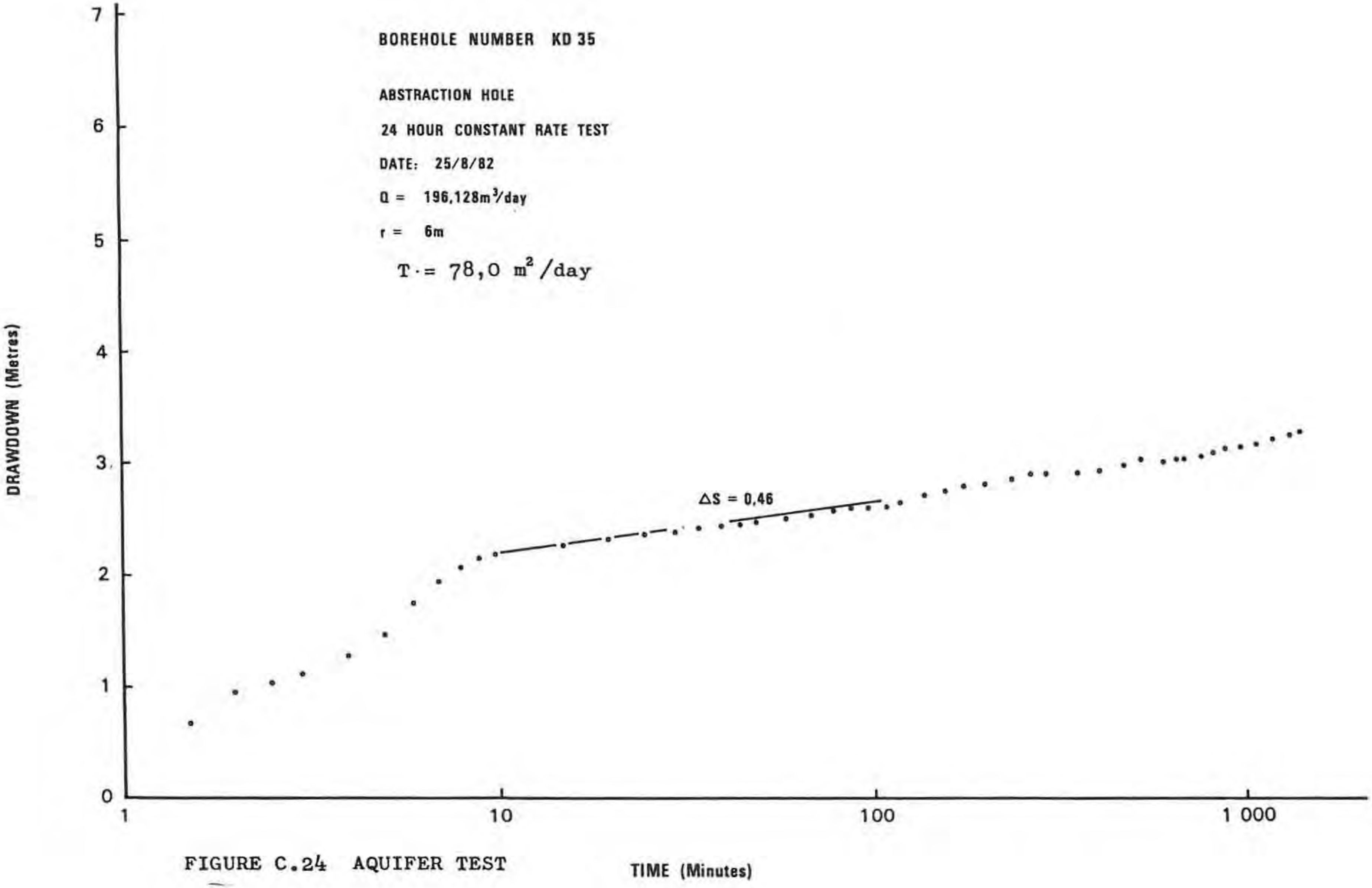


FIGURE C.23 BOREHOLE LOG



BOREHOLE NUMBER KD 35

ABSTRACTION HOLE

24 HOUR CONSTANT RATE TEST

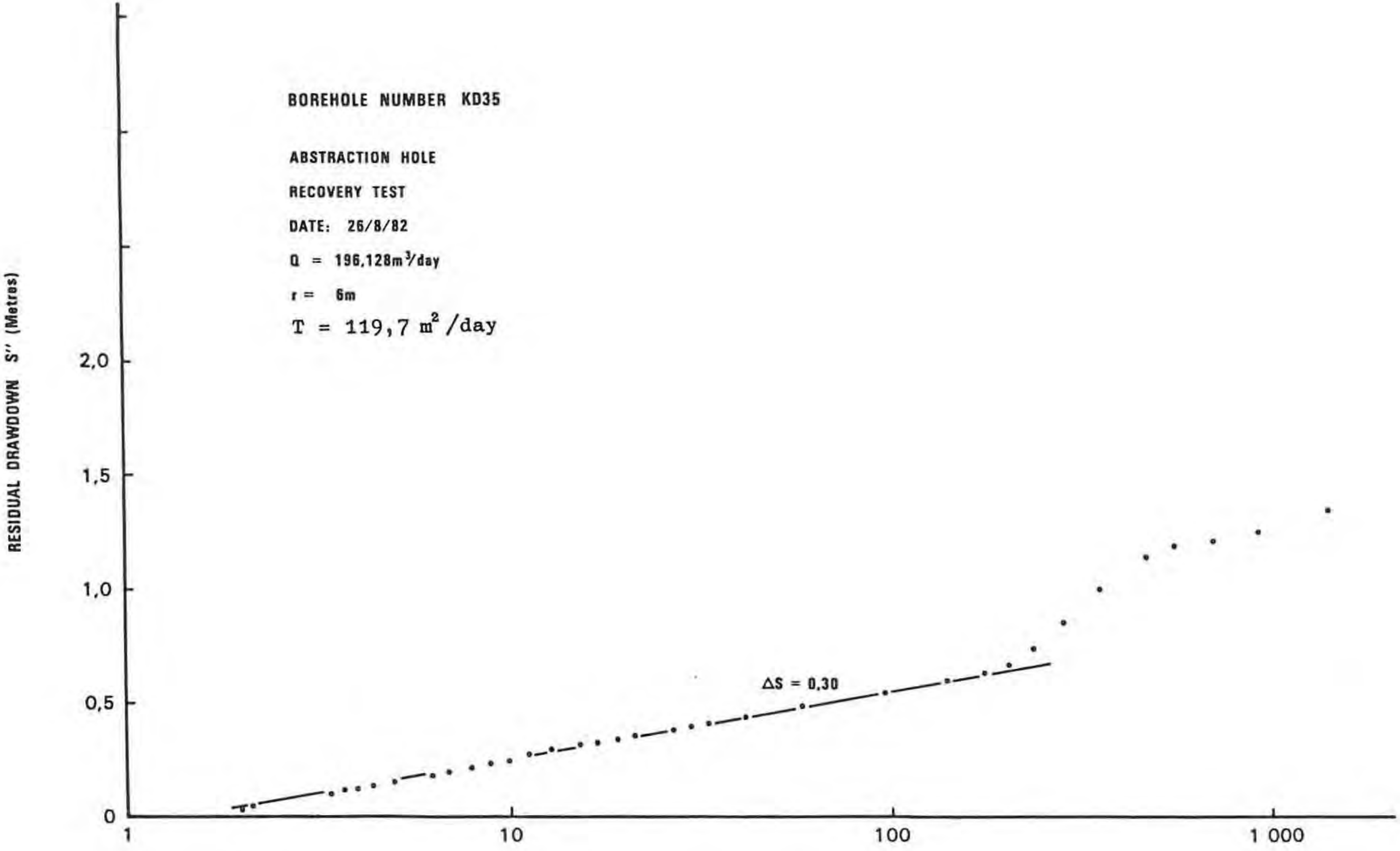
DATE: 25/8/82

Q = 196,128m^3/day

r = 6m

T = 78,0 m^2/day

FIGURE C.24 AQUIFER TEST



BOREHOLE NUMBER KD35

ABSTRACTION HOLE

RECOVERY TEST

DATE: 26/8/82

$Q = 196{,}128 m^3/day$

$r = 6m$

$T = 119{,}7\ m^2/day$

FIGURE C.25 AQUIFER TEST

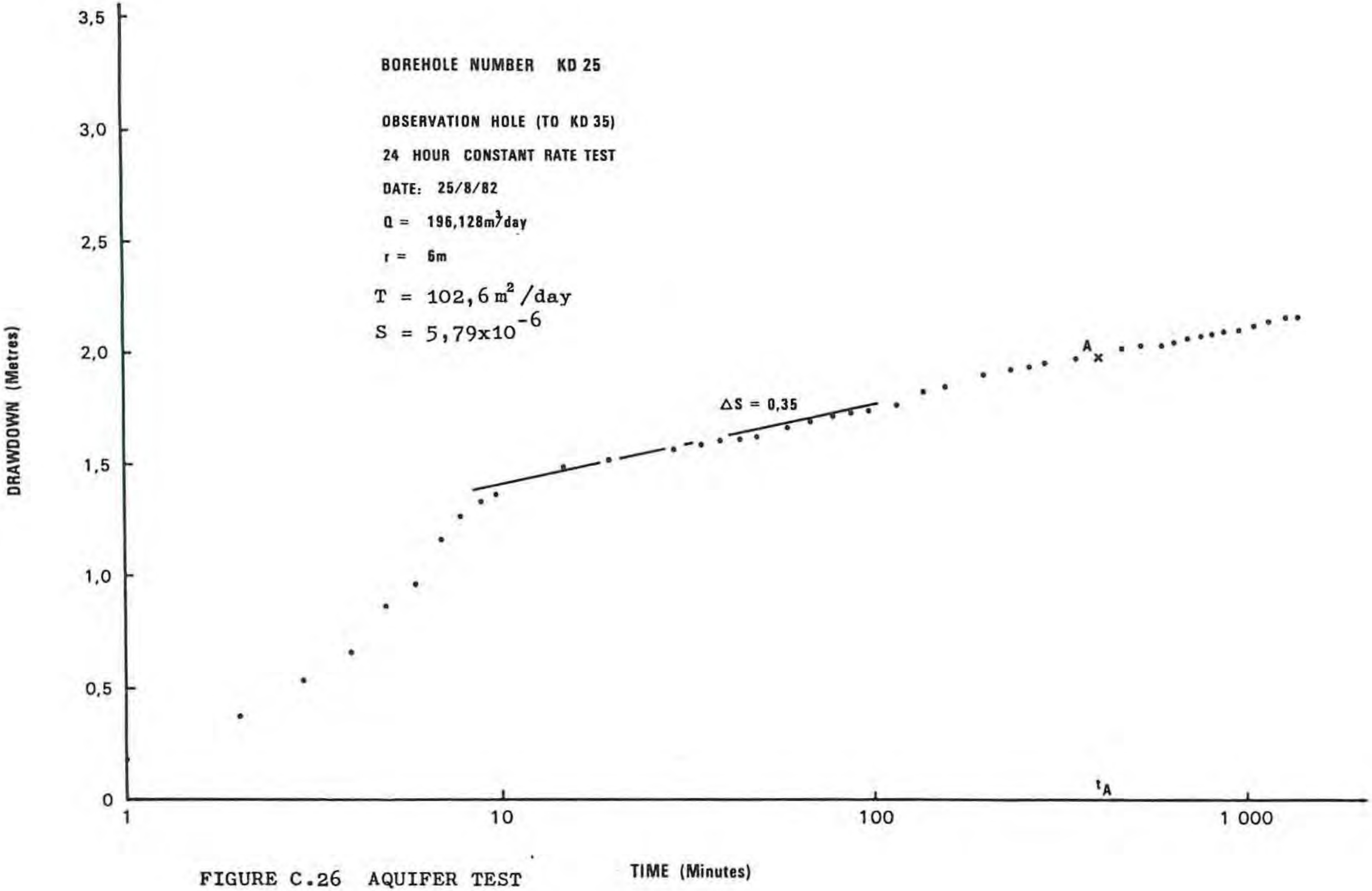


FIGURE C.26 AQUIFER TEST

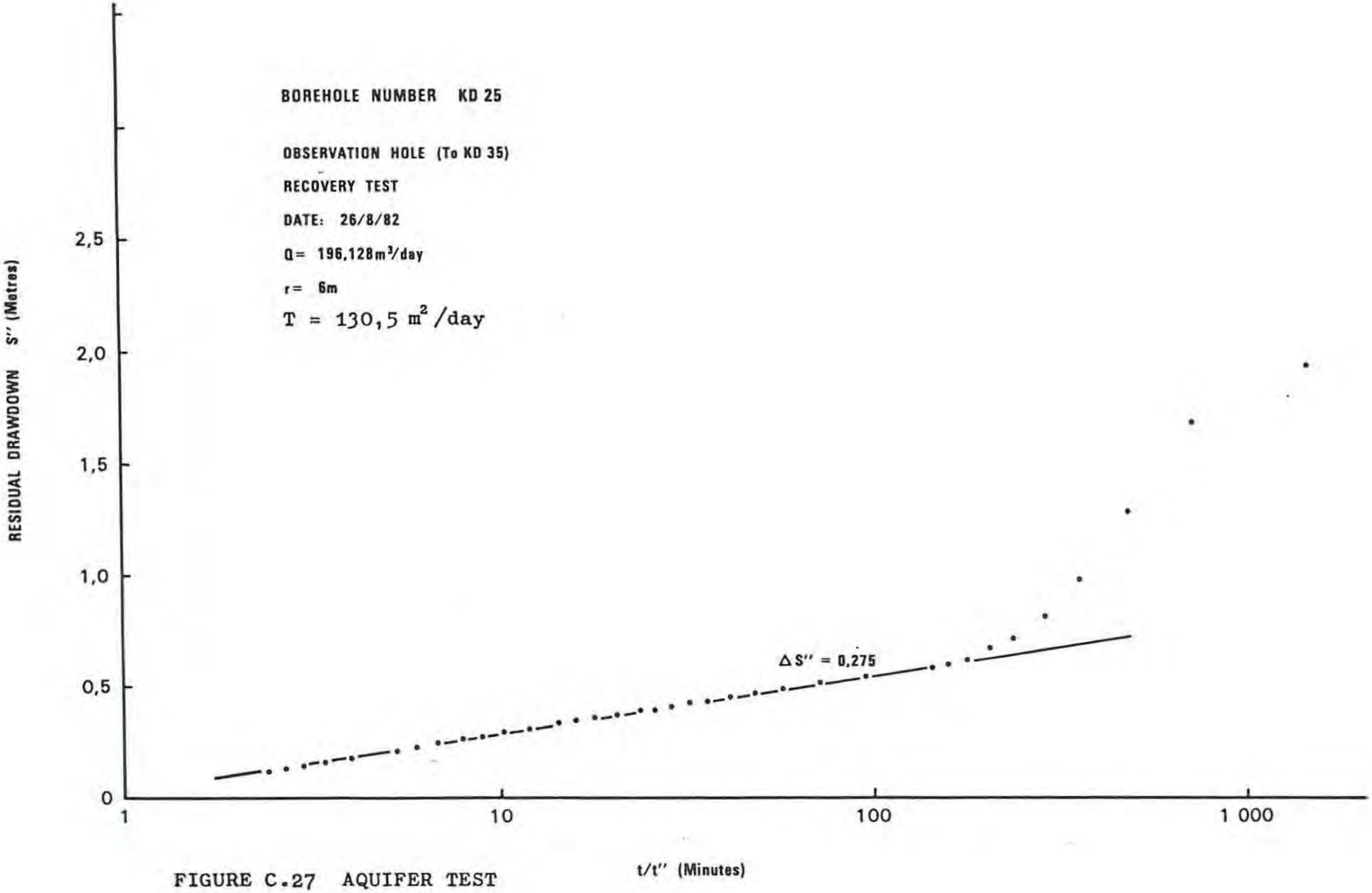


FIGURE C.27 AQUIFER TEST

TABLE C.1 CALCULATED HYDRAULIC PARAMETERS FOR THE FRACTURED ROCK AQUIFERS.

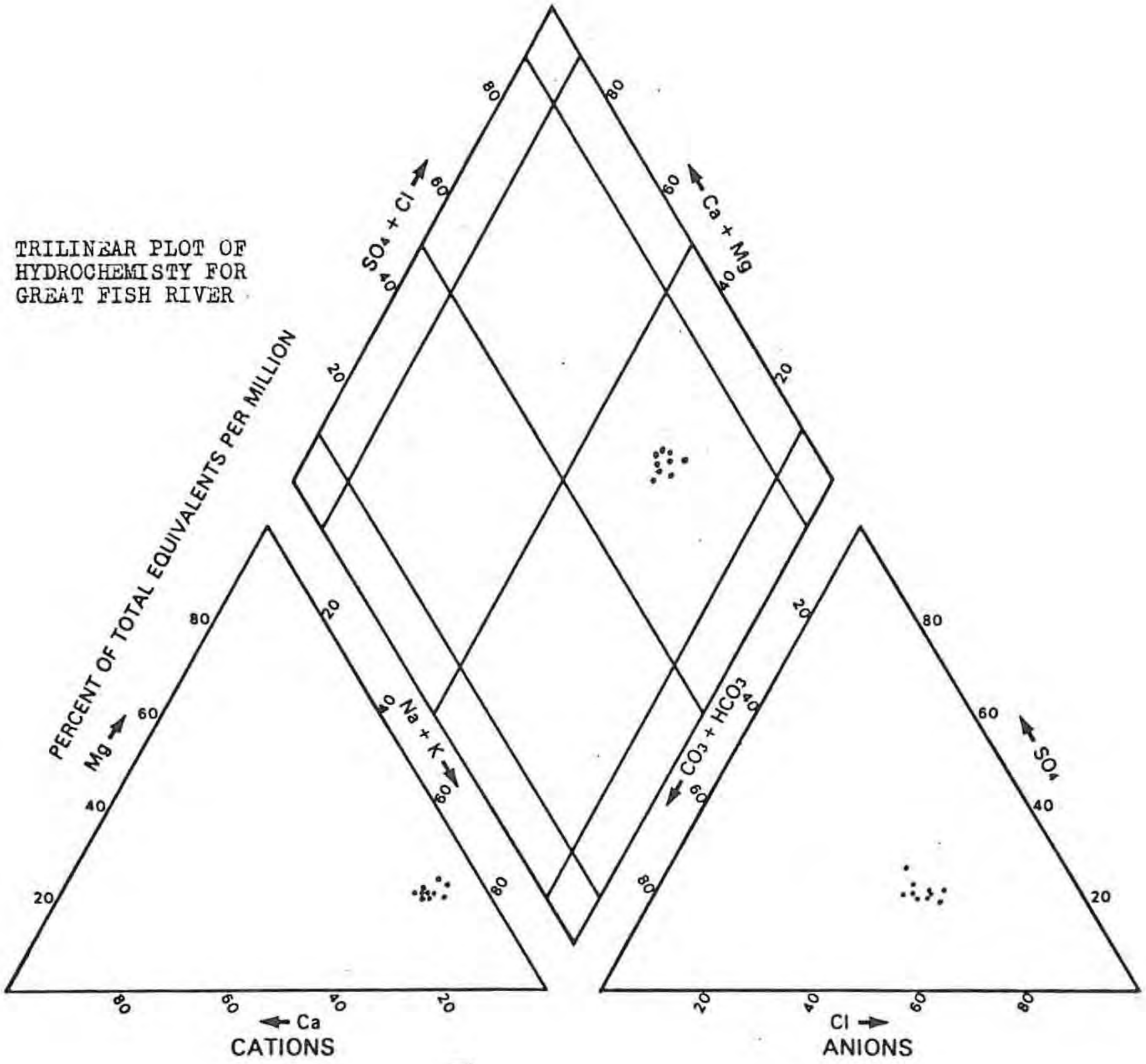
BOREHOLE NUMBER	JACOB METHOD $T = m^2/day$	THEIS'S RECOVERY METHOD	HANTUSH'S IMAGE METHOD	CHOW METHOD	PASCHETTE AND MC ELWEE METHOD
KD 34 ABSTRACTION HOLE	T = 57,3	T = 43,0			T = 34,5 S = 0,0299 rms error = 0,07
KD 22 OBSERVATION HOLE	T = 50,2 $S = 8,69 \times 10^{-6}$	T = 50,2			T = 36,5 S = 0,007 rms error = 0,49
KD 1 ABSTRACTION HOLE	T = 23,2	T = 1,2			
KD 3 OBSERVATION HOLE	T = 189,8 $S = 2,17 \times 10^{-5}$	$T_1 = 35,9$ $T_2 = 298$			T = 92,5 S = 0,076 rms error = 0,04
KD 5 ABSTRACTION HOLE	T = 8,3	T = 22,5			
KD 4 OBSERVATION HOLE		T = 20,1	T = 9,0 $S = 2,23 \times 10^{-3}$		T = 14,9 S = 0,061 rms error = 0,33
KD 37 ABSTRACTION HOLE	T = 5,7 NO OBSERVATION HOLE	T = 0,9			
KD 15 ABSTRACTION HOLE	T = 26 NO OBSERVATION HOLE	T = 4,7			

TABLE C.1 CONTINUED.

BOREHOLE NUMBER	JACOB METHOD $T = m^2/day$	THEIS'S RECOVERY METHOD	HANTUSH'S IMAGE METHOD	CHOW METHOD	PASCHETTE AND MC ELWEE METHOD
KD 5 ABSTRACTION HOLE (USING CABLE TOOL RIG)	$T = 35,8$	$T = 29,8$			
KD 4 OBSERVATION HOLE (USING CABLE TOO RIG)	$T_1 = 12,6$ $S_1 = 1,07x10^{-3}$ $T_2 = 30,3$ $S_2 = 5,1x10^{-4}$	$T_1 = 18,7$ $T_2 = 40,6$			$T_1 = 8,6$ $S_1 = 0,119$ rms error = 0,316 $T_2 = 15,9$ $S_2 = 0,029$ rms error = 0,667
KD 32 ABSTRACTION HOLE	$T_1 = 29,9$ T_2 ==82,6	$T_1 = 24,4$ $T_2 = 78,0$			
KD 33 OBSERVATION HOLE	$T_1 = 29,9$ $T_2 = 75,0$	$T_1 = 24,5$ $S_1 = 8,4x10^{-3}$ $T_2 = 78,0$ $S_2 = 1,25x10^{-4}$			$T = 79,0$ $S = 0,122$ rms error = 1,47
KD 35 ABSTRACTION HOLE	$T = 78,0$	$T = 119,7$			
KD 25 OBSERVATION HOLE	$T = 102,6$ $S = 5,79x10^{-6}$	$T = 130,5$		$T = 102,6$ $S = 4,93x10^{-6}$	$T = 121,4$ $S = 4,78x10^{-5}$ rms error = 0,25

APPENDIX D

FIGURE D.1 TRILINEAR PLOT OF HYDROCHEMISTY FOR GREAT FISH RIVER



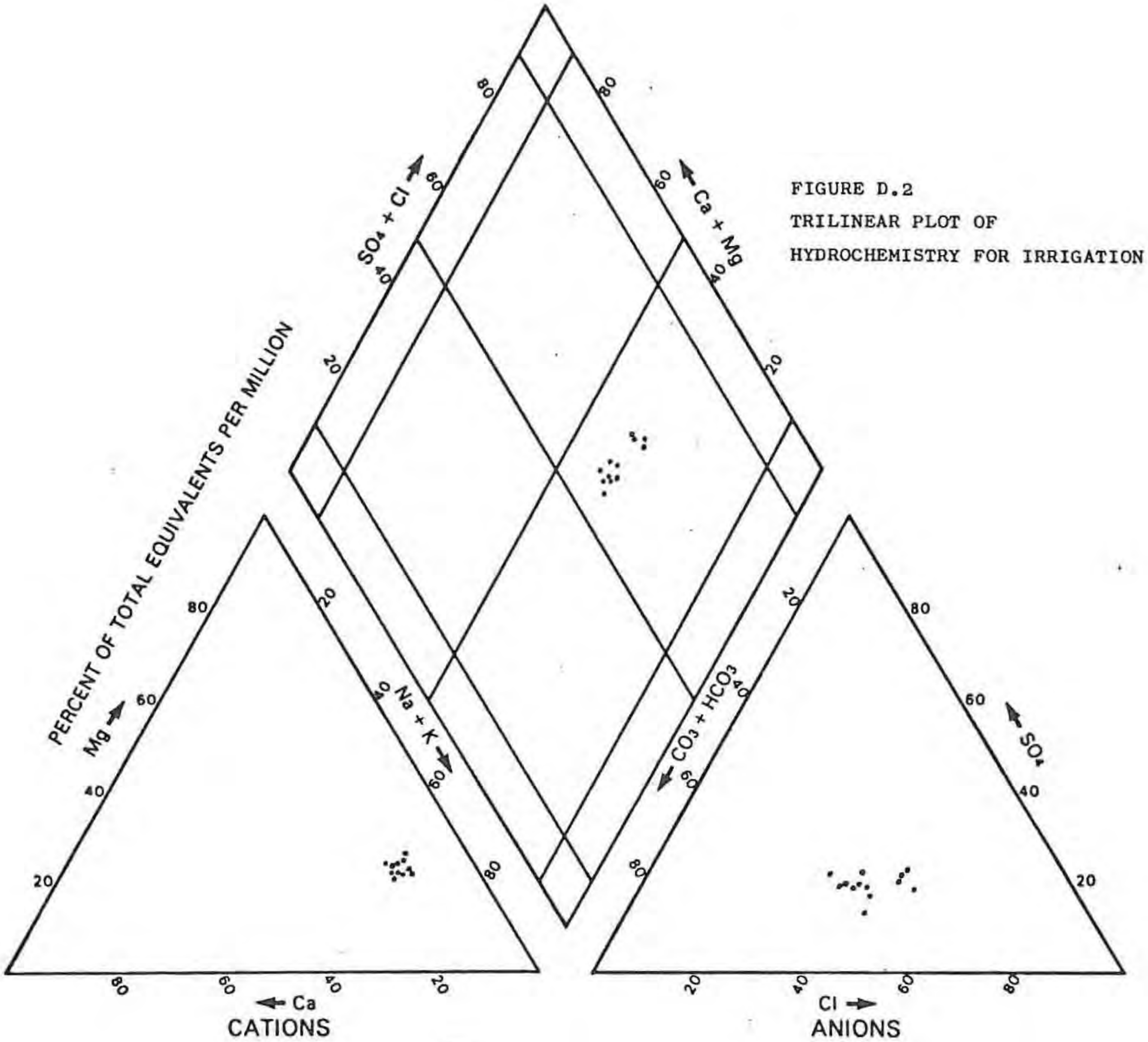


FIGURE D.2
TRILINEAR PLOT OF
HYDROCHEMISTRY FOR IRRIGATION WATER

FIGURE D.3

TRILINEAR PLOT OF HYDROCHEMISTRY FOR SEEPAGE WATERS

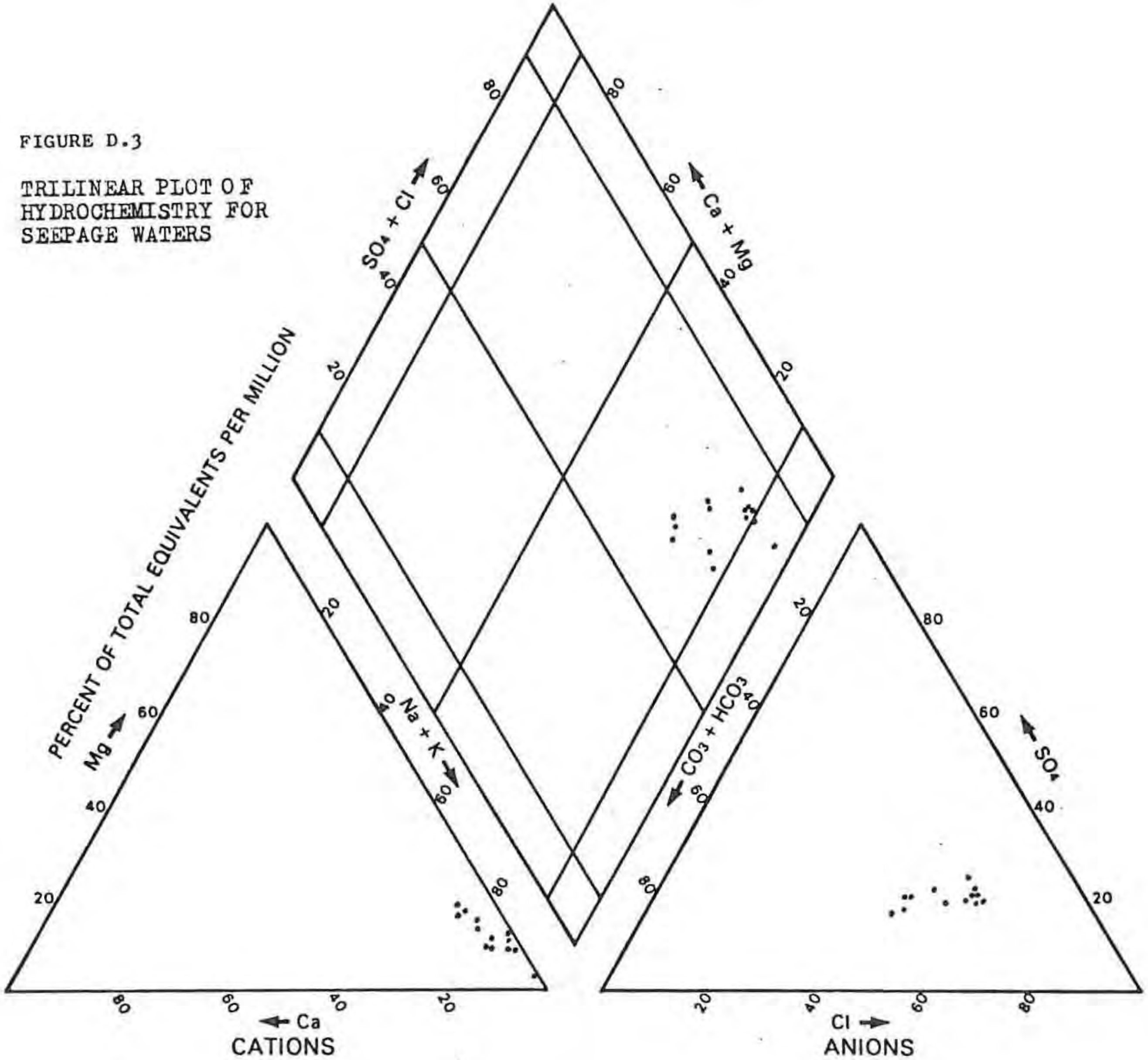


FIGURE D.4

TRILINEAR PLOT OF
HYDROCHEMISTRY FOR
SANDSTONE AQUIFERS

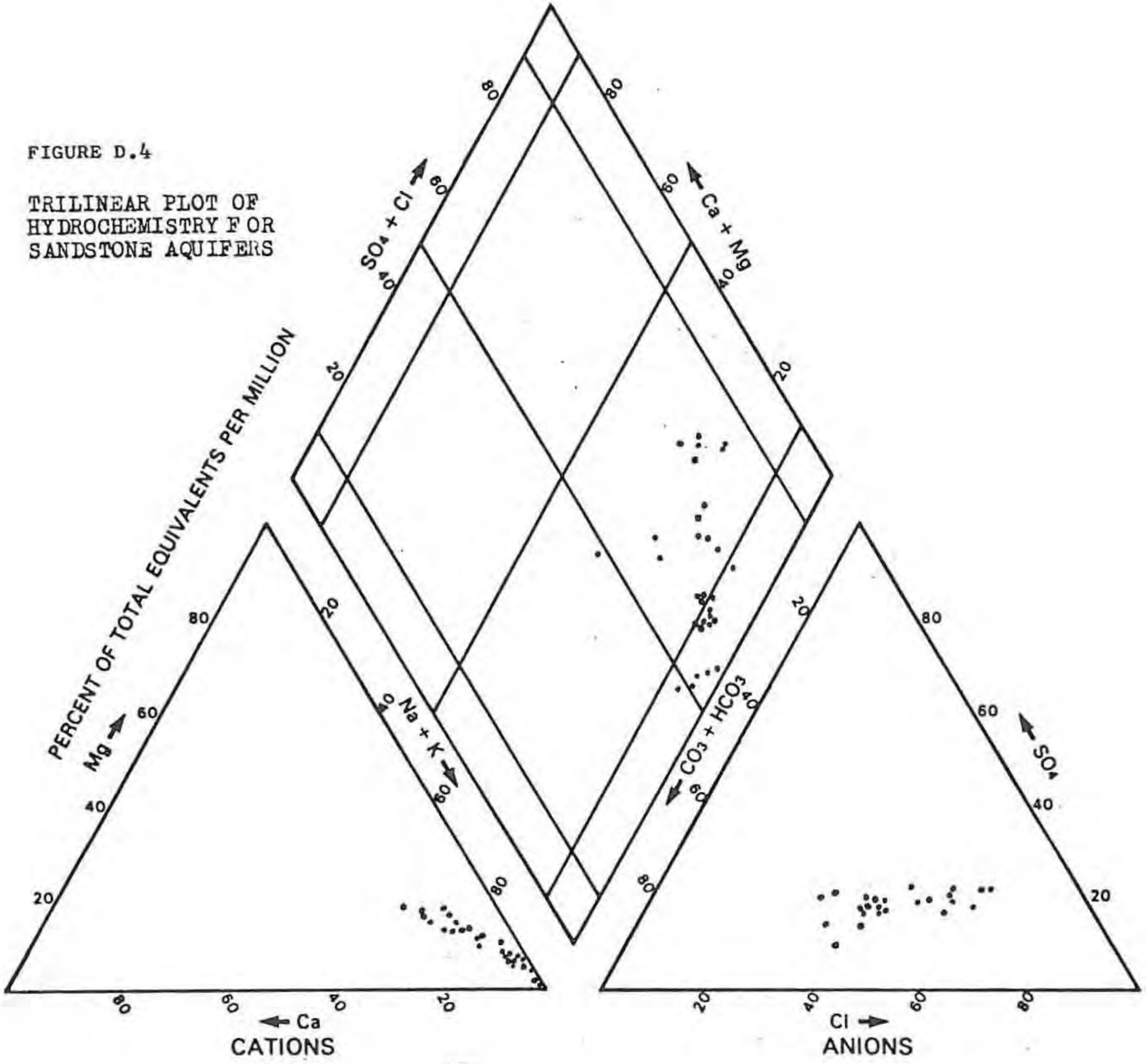


FIGURE D.5

TRILINEAR PLOT OF
HYDROCHEMISTRY FOR
MUDSTONE AQUIFERS

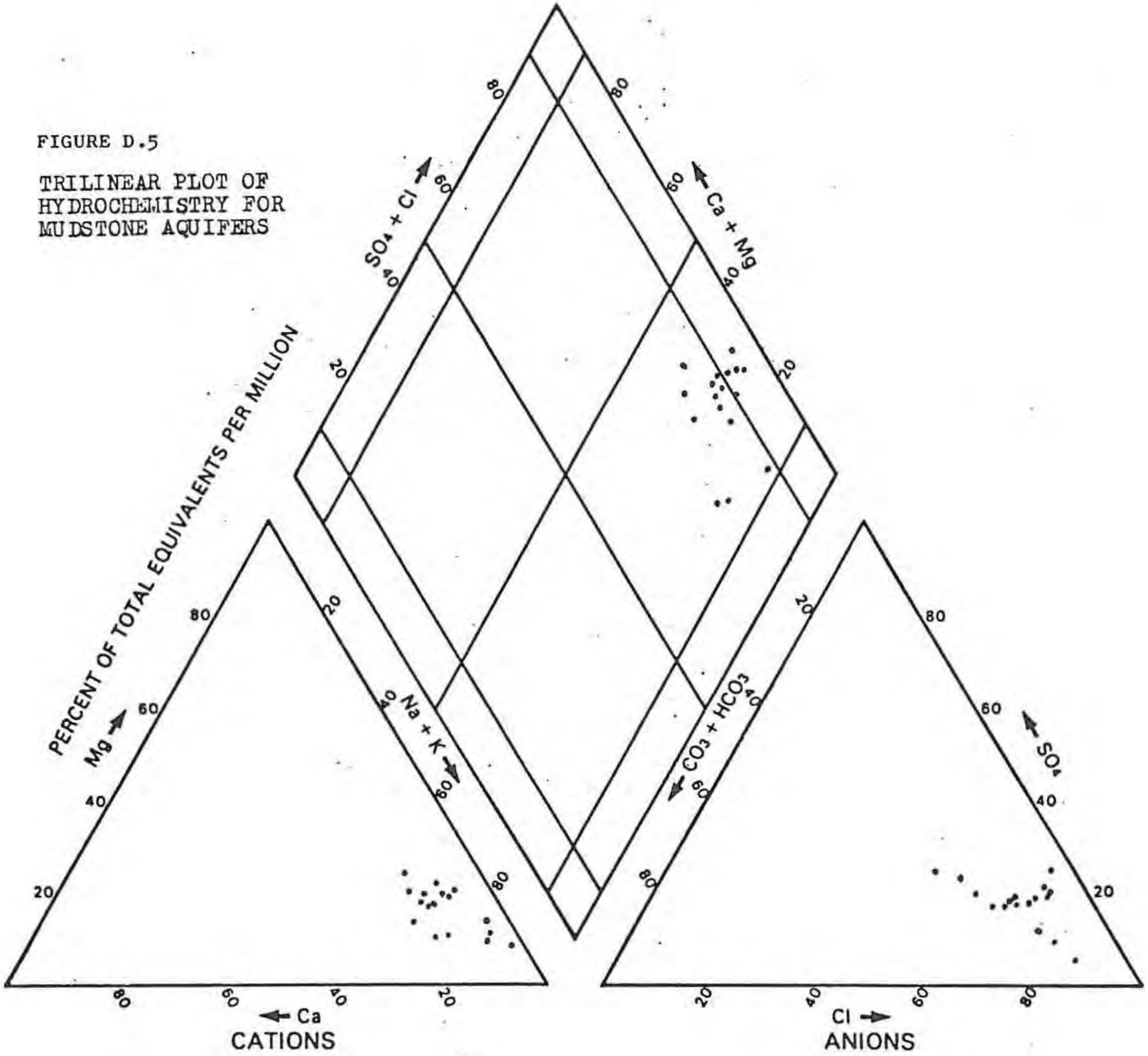


FIGURE D.6 TRILINEAR GRAPH OF IRRIGATION WATER ENRICHED BY EVAPOTRANSPIRATION

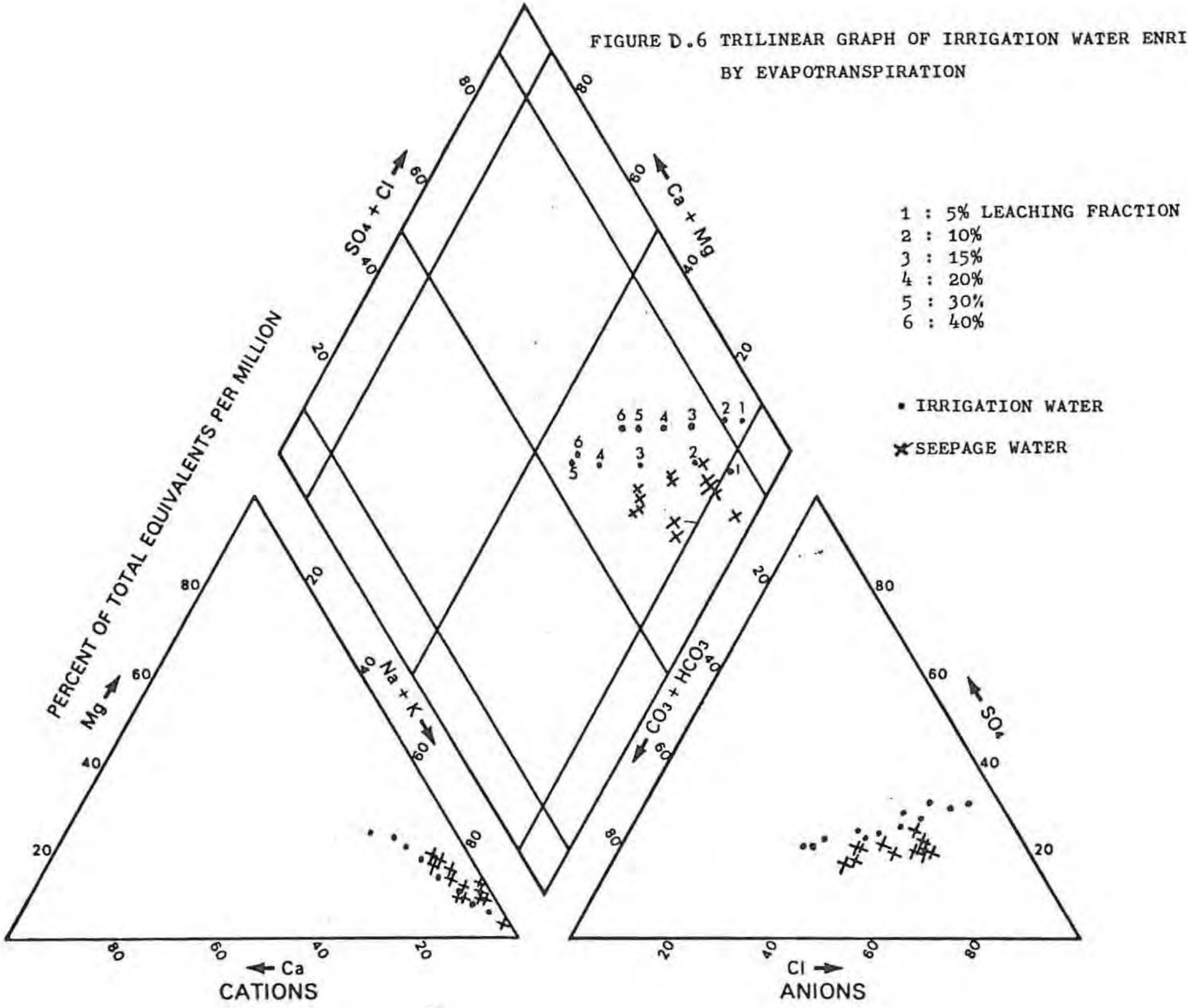
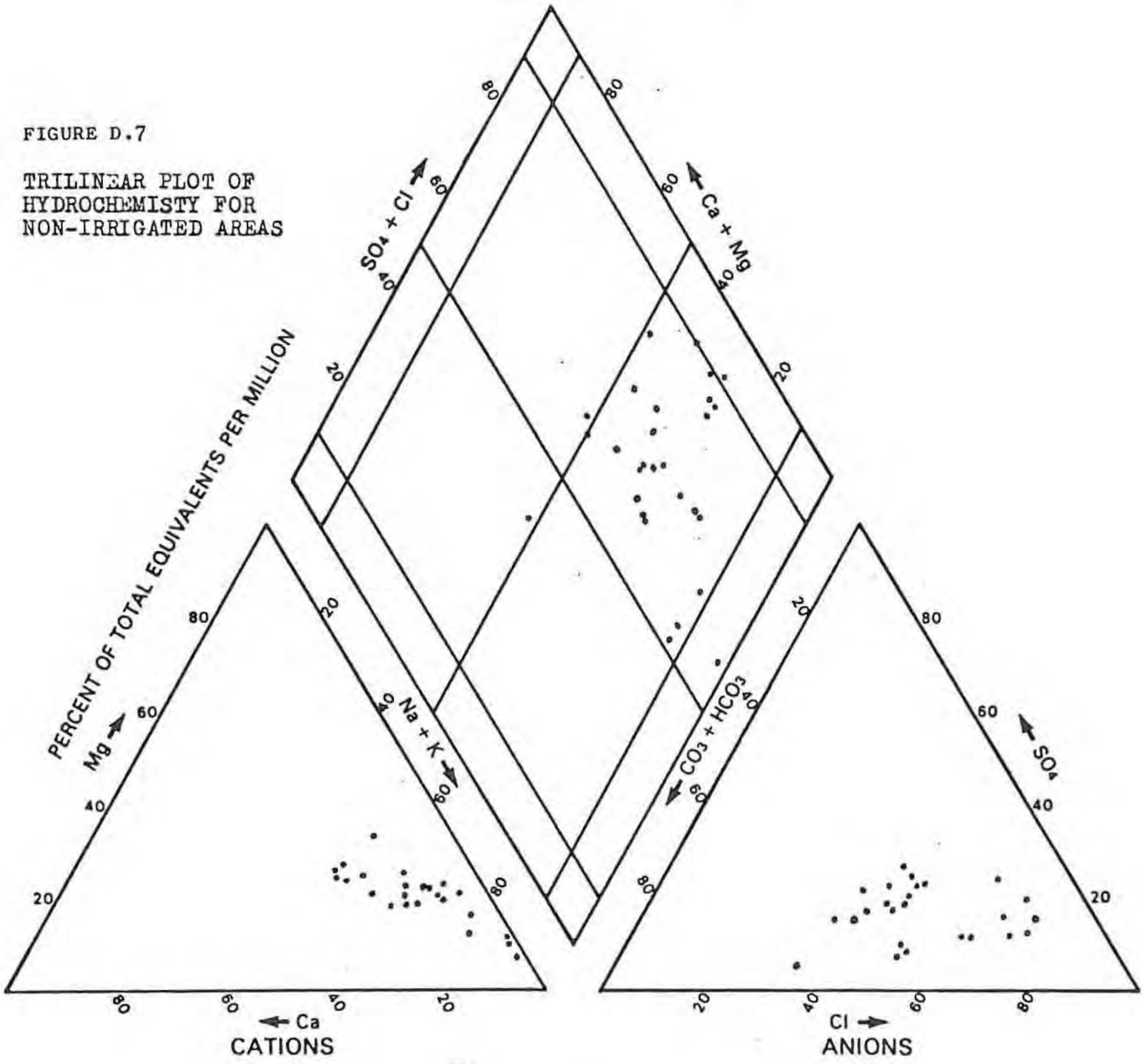


FIGURE D.7

TRILINEAR PLOT OF
HYDROCHEMISTY FOR
NON-IRRIGATED AREAS



APPENDIX E

			TOTAL DISSOLVED SOLIDS (mg/ℓ).																	ADSORBED CATIONS.				
DEPTH (M)	PERCENT MOISTURE	P.S.A. PERCENT SILT + CLAY	TAL	NH$_4$	Ca	Cl	NO$_3$	Na	Mg	F	Si	K	SO$_4$	P	TDS	Na	Mg	K	Ca	CATION CONTENT (mg/ℓ)	Na	Mg	K	Ca (me/ 100g)
3	5,8	14,1																						
4	9,2	20,5	2933	3	67	733	17	2267	0	33	293	113	1267	51	8533	800	800	627	3333	5560	1	2	0,5	5
5	10,8	24,4																						
6	6,2	12,6	2333	3	67	733	17	1399	0	20	187	60	733	10	6067	533	333	300	1667	2833	0,7	0,8	0,2	2,5
7	7,0	12,6	1733	6	200	1867	41	2133	67	20	213	60	933	4	7867	600	1400	267	15067	17334	0,8	3,5	0,2	22,6
8	7,4	8,6	1267	5	400	3333	39	2333	200	20	180	67	800	1,4	9133	533	1533	233	15733	18032	0,7	3,8	0,2	23,6
9	4,8	6,5	1467	2	67	133	3	533	0	20	220	33	533	19	3400	400	1400	500	0	2300	0,5	3,5	0,4	0
10	4,1	8,3	2000	2	133	1333	19	1733	0	27	133	40	800	7,2	6800	600	800	260	2200	3860	0,8	2	0,2	3,3
11	10,3	12,2	3333	3	67	867	6	2333	67	40	207	27	867	17	8533	933	800	347	4133	6213	1,2	2	0,3	6,2
12	9,8	20,1	4267	3	133	1000	7	2733	67	67	327	53	933	16	10533	1533	800	540	6333	9206	2	2	0,5	9,5
13	15	9,9																						

TABLE E.1 VARIATION IN SOIL TEXTURE AND CHEMISTRY WITH DEPTH - BOREHOLE KD 40.

			TOTAL DISSOLVED SOLIDS (mg/ℓ).																	ADSORBED CATIONS.				
DEPTH (M)	PERCENT MOISTURE	P.S.A. PERCENT SILT + CLAY	TAL	NH_4	Ca	Cl	NO_3	Na	Mg	F	Si	K	SO_4	P	TDS	Na	Mg	K	Ca	CATION CONTENT (mg/ℓ)	Na	Mg	K	Ca (me/ 100g)
1	8,1	12,3	2400	4	133	400	6	1467	67	47	267	100	800	15	6200	667	3278	676	25466	30087	0,9	8,1	0,5	38,2
2	9,1	22,6	1467	2	67	1	23	600	67	13	160	40	533	26	3467	399	1741	547	0	5820	0,5	4,3	0,4	0
3	9,1	16,6	2867	5	67	267	1	1267	0	60	200	220	533	3	6067	533	2333	1147	8533	12546	0,7	5,8	0,9	12,8
4	9,7	14,2	2000	5	67	400	1	1400	0	47	153	73	800	2	5333	733	3933	533	4200	9399	1,0	9,7	0,4	6,3
5	6,7	4	1533	3	0	267	0	933	0	40	140	33	667	0,6	4000	867	2467	367	2600	6301	1,1	6,1	0,3	3,9
6	5,3	4,2	1533	3	0	133	0	867	0	20	107	33	667	1	3733	600	2133	307	3133	6173	0,8	5,3	0,2	4,7
7	6,9	8,5	2667	5	67	400	1	1467	67	33	187	67	667	2	6133	467	2067	313	10000	12847	0,6	5,1	0,2	15
8	7,7	8,5	1133	2	0	467	1	1067	0	33	180	47	733	3	3933	1733	2733	433	2400	7299	2,3	6,7	0,3	3,6
9	11,6	18,5	1113	3	67	533	1	1267	0	40	193	40	1067	8	4533	1800	2400	413	1600	6213	2,4	5,9	0,3	2,4
10	12,4	20,5	667	4	67	600	1	1267	0	53	207	33	1067	6	4133	2467	3200	527	1733	7927	3,2	7,9	0,4	2,6
10,5	3,4		933	3	0	400	0	933	0	53	247	40	800	10	3733	2667	3067	547	1600	7881	3,5	7,6	0,4	2,4

TABLE E.2 VARIATION IN SOIL TEXTURE AND CHEMISTRY WITH DEPTH - BOREHOLE KD 41.

				TOTAL DISSOLVED SOLIDS (mg/ℓ).														ADSORBED CATIONS.				
DEPTH (M)	TAL	NH_4	Ca	Cl	NO_3	Na	Mg	F	Si	K	SO_4	P	TDS	Na	Mg	K	Ca	CATION CONTENT (mg/ℓ)	Na	Mg	K	Ca (me/ 100g)
1	1533	7	200	133	14	533	67	7	200	173	467	21	3733	267	1533	887	1440	4127	0,4	3,8	0,7	21,6
2	3067	7	200	67	5	800	67	13	307	507	600	45	6399	667	867	1473	4199	7206	0,9	2,1	1,1	6,3
3	4133	4	67	67	4	1467	67	20	287	880	467	61	8400	667	230	3440	18133	22470	0,9	3,5	2,7	27,2
4	4667	5	67	67	6	1733	0	13	373	1007	733	56	9733	867	867	4047	2733	8514	1,1	2,1	3,1	4,1
5	3800	5	67	267	5	1733	67	13	327	533	733	31	8467	733	267	2073	2533	5606	1	0,7	1,6	3,8
6	2933	3	133	867	5	2000	67	13	267	193	1133	27	8200	800	800	807	2467	4874	1	2	0,6	3,7
7	2600	13	200	1867	5	2600	67	13	253	160	1800	22	10133	867	800	800	2800	5267	1,1	2	0,6	4,2
8	1333	2	67	867	1	1067	67	13	107	13	667	1	4467	400	2533	187	4133	7253	0,5	6,3	0,1	6,2
9	4200	3	67	1733	13	3600	0	27	333	73	1067	48	12067	2067	667	1013	3667	7414	2,7	1,6	0,8	5,5
10	3733	8	67	2933	33	4600	67	47	340	107	2333	71	15333	3600	22200	1000	5667	32467	4,7	55	0,8	8,5
11	3267	4	67	3133	37	4333	0	40	279	100	1733	59	13933	2667	3067	907	8200	14841	3,5	7,6	0,7	12,3
12	333	10	67	2133	10	3000	0	73	307	80	1067	48	10933	1600	22133	900	5800	30433	2	55	0,7	8,7
13	3467	3	67	2133	15	3267	67	93	333	80	1133	42	11467	2267	400	1040	6467	10174	3,0	1	0,8	9,7
14	2933	3	133	1733	3	2733	200	13	233	320	867	30	9800	1133	1800	880	0	3813	1,5	4,4	0,7	0
15	733	5	67	333	2	667	0	67	113	33	467	9	2733	600	2533	433	1400	4966	0,8	6,3	0,3	2,1

TABLE E.3 VARIATION IN SOIL CHEMISTRY WITH DEPTH - BOREHOLE KD 36.

	TOTAL DISSOLVED SOLIDS (mg/ℓ).																ADSORBED CATIONS.				
DEPTH (M)	TAL	NH_4	Ca	Cl	NO_3	Na	Mg	F	Si	K	SO_4	P	TDS	Na	Mg	K	Ca	CATION CONTENT (mg/ℓ)	Na	Mg	K	Ca (me/ 100g)
1	1267	5	267	133	24	400	67	13	73	40	467	20	3133	200	1200	273	13133	14806	0,3	3,0	0,2	19,7
2	3267	4	0	333	5	1733	0	47	187	214	667	5	7200	867	3733	1440	0	6040	1,1	9,2	1,1	0
3	733	2	0	200	1,3	333	0	47	133	33	467	15	2133	267	1600	5200	67	2454	0,4	2	0,4	0,1
5	1667	5	133	67	33	600	67	20	160	93	667	25	4067	533	800	567	2000	3900	0,7	2,0	0,4	3
7	1200	10	467	1533	45	1267	133	20	227	93	933	24	6333	467	733	493	3667	5360	0,6	1,8	0,4	5,5
9	5133	8	0	200	7	2467	0	20	440	167	533	3,5	10133	1199	2000	1313	0	4512	1,6	4,9	1,0	0

TABLE E.4 . VARIATION IN SOIL CHEMISTRY WITH DEPTH - BOREHOLE KD 42.

			TOTAL DISSOLVED SOLIDS (mg/ℓ).																	ADSORBED CATIONS.				
DEPTH (M)	PERCENT MOISTURE	P.S.A. PERCENT SILT + CLAY	TAL	NH_4	Ca	Cl	NO_3	Na	Mg	F	Si	K	SO_4	P	TDS	Na	Mg	K	Ca	CATION CONTENT (mg/ℓ)	Na	Mg	K	Ca (me/ 100g)
1			2533	6	267	333	20	1267	133	87	267	180	533	1,5	6333	600	3467	1313	29667	35047	0,8	8,6	1	44,5
3			3667	3	0	200	3	2000	67	33	493	120	600	2	8000	2399	2799	1287	4667	11152	3	6,9	1	7
4			5067	2	0	267	3	2533	0	33	640	120	667	2	10467	1600	427	60	8867	10954	2	6,4	0,9	13,3
5			3800	3	67	267	4	2000	0	47	580	87	600	3	8333	2267	2667	1240	5733	11907	3	6,6	1	8,6
6			2067	6	67	67	7	800	67	27	200	53	533	20	4333	467	1467	420	0	2354	0,6	3,6	0,3	0
7			5467	3	0	133	3	2467	0	13	400	207	533	3	10467	667	1200	800	2393	5060	0,9	3	0,6	36

TABLE E.5 VARIATION IN SOIL CHEMISTRY WITH DEPTH - BOREHOLE KD 43.

			TOTAL DISSOLVED SOLIDS (mg/ℓ).																	ADSORBED CATIONS.				
DEPTH (M)	PERCENT MOISTURE	P.S.A. PERCENT SILT + CLAY	TAL	NH_4	Ca	Cl	NO_3	Na	Mg	F	Si	K	SO_4	P	TDS	Na	Mg	K	Ca	CATION CONTENT (mg/ℓ)	Na	Mg	K	Ca (me/ 100g)
1			1533	2	67	1733	1	2067	67	20	107	60	800	2	6800	600	230	200	0	1030	0,8	3,5	0,2	0
2			2467	3	0	1600	5	2667	0	33	187	87	1133	3	8733	1399	2000	773	3933	8105	1,8	4,9	0,6	5,9
3			4267	3	0	667	5	2467	0	33	240	87	667	1	9467	933	2267	500	21333	25033	1,2	5,6	0,4	32
4			3000	4	67	933	1	2333	67	27	127	93	1200	1	8533	533	1733	280	22800	25346	0,7	4,3	0,2	34,2
5			2400	4	67	267	1	1333	67	27	127	73	600	1	5467	467	1667	233	14867	17234	0,6	4,1	0,2	22,3
6			2533	2	67	2267	13	3000	67	27	140	100	1067	1	9800	1067	3399	613	22867	27946	1,4	8,4	0,5	34,3
7			2267	3	67	267	2	1133	0	27	170	80	533	3	5000	333	1199	273	8600	10405	0,4	3,0	0,2	12,9
8			400	6	67	400	0	467	0	20	100	47	600	4	2267	1067	800	293	600	2760	1,4	2,0	0,2	0,9

TABLE E.6 VARIATION IN SOIL CHEMISTRY WITH DEPTH - BOREHOLE KD 44.

			TOTAL DISSOLVED SOLIDS (mg/ℓ).																		ADSORBED CATIONS.			
DEPTH (M)	PERCENT MOISTURE	P.S.A. PERCENT SILT + CLAY	TAL	NH_4	Ca	Cl	NO_3	Na	Mg	F	Si	K	SO_4	P	TDS	Na	Mg	K	Ca	CATION CONTENT (mg/ℓ)	Na	Mg	K	Ca (me/ 100g)
M2			1533	4	333	67	47	333	67	27	180	213	467	7	3800	267	1333	800	24667	27533	0,4	3,3	0,6	37
M2			1733	7	400	120	222	1133	133	13	373	553	400	82	7400	467	2800	2253	1900	25067	0,6	6,9	1,7	28,5
M3			6467	5	267	1200	152	2333	67	33	287	4107	1800	92	18800	1067	733	2880	1000	25600	1,4	1,8	2,2	1,5

TABLE E.7 TOTAL DISSOLVED SOLID AND ADSORBED CATION CONTENT OF 3 SURFACE SOILS.

T.D.S. CONTENT - IRRIGATION WATER

ION CONCENTRATION IN mg/ℓ

ION		Ca	Mg	Na+K	Cl	CO_3+HCO_3	SO_4	T.D.S.	S.A.R. *
INITIAL CONCENTRATION		48,4	46	221	257	197,5	149	919,3	5,4
LEACHING FRACTION TREATMENT LEACHING FRACTION TREATMENT (PERCENTAGE OF APPLIED WATER PASSING BELOW ROOT ZONE).	5%	211	204	4429	5143	650	2979	13616	51,6
	10%	149	147	2214	1666	620	1489	6285	30,5
	20%	116	116	1107	1286	587	745	3957	17,3
	30%	193	194	738	857	570	496	2686	12,1
	40%	97	98	554	643	555	372	2319	9,4

* SODIUM ABSORBTION RATIO

TABLE E.8. THE AFFECT OF INCREASED LEACHING FRACTION TREATMENT ON ION CONCENTRATION OF IRRIGATION PERCOLATE. _ SAMPLE 6245

T.D.S. CONTENT - IRRIGATION WATER

ION CONCENTRATION IN mg/ℓ

ION		Ca	Mg	Na+K	Cl	$CO_3 + HCO_3$	SO_4	T.D.S.	S.A.R. *
INITIAL CONCENTRATION		48	51	273	313	266	196	1147	6,55
LEACHING FRACTION TREATMENT LEACHING FRACTION TREATMENT (PERCENTAGE OF APPLIED WATER PASSING BELOW ROOT ZONE).	5%	255	246	5468	6255	643	3920	16787	58,2
	10%	172	169	2734	3128	620	1960	8783	35,3
	20%	128	127	1367	1564	592	980	4758	20,4
	30%	112	112	911	1043	574	653	3405	14,5
	40%	103	104	684	782	563	490	2726	11,2

* SODIUM ABSORBTION RATIO

TABLE E.9 THE AFFECT OF INCREASED LEACHING FRACTION TREATMENT ON ION CONCENTRATION OF IRRIGATION PERCOLATE . - SAMPLE 6847

T.D.S. CONTENT - IRRIGATION WATER

ION CONCENTRATION IN mg/ℓ

ION		Ca	Mg	Na+K	Cl	CO_3 +HCO_3	SO_4	T.D.S.	S.A.R. *
INITIAL CONCENTRATION		48,6	41,1	217	207	275	158	946,7	5,53
LEACHING FRACTION TREATMENT LEACHING FRACTION TREATMENT (PERCENTAGE OF APPLIED WATER PASSING BELOW ROOT ZONE).	5%	93	86	4375	4132	984	3158	12828	78,1
	10%	92	88	2187	2066	790	1579	6802	38,8
	20%	88	86	1094	1033	673	789	3763	19,7
	30%	85	84	729	689	625	527	2739	13,3
	40%	83	83	547	517	600	395	2225	10

* SODIUM ADSORBTION RATIO

TABLE E.10 . THE AFFECT OF INCREASED LEACHING FRACTION TREATMENT ON ION CONCENTRATION OF IRRIGATION PERCOLATE . - SAMPLE 3166

T.D.S. CONTENT - IRRIGATION WATER

ION CONCENTRATION IN mg/ℓ

ION		Ca	Mg	Na+K	Cl	CO_3 +HCO_3	SO_4	T.D.S.	S.A.R. *
INITIAL CONCENTRATION		34,4	28,5	132,5	129	204	89	617,4	4,04
LEACHING FRACTION TREATMENT LEACHING FRACTION TREATMENT (PERCENTAGE OF APPLIED WATER PASSING BELOW ROOT ZONE).	5%	91,6	86,7	2646	2586	832	1789	8031	47,2
	10%	88	86	1323	1293	697	895	4382	23.8
	20%	84	83	662	647	615	447	2338	12,1
	30%	81	82	441	431	581	298	1914	8,1
	40%	86	71	331	323	539	224	1574	6,3

* SODIUM ALSORBTION RATIO

TABLE E.11 THE AFFECT OF INCREASED LEACHING FRACTION TREATMENT OF ION CONCENTRATION OF IRRIGATION PERCOLATE . - SAMPLE 3093

T.D.S. CONTENT - IRRIGATION WATER

ION CONCENTRATION IN mg/ℓ

ION		Ca	Mg	Na+K	Cl	CO_3 +HCO_3	SO_4	T.D.S.	S.A.R. *
INITIAL CONCENTRATION		39	35	165	178	225	95	737	4,5
LEACHING FRACTION TREATMENT LEACHING FRACTION TREATMENT (PERCENTAGE OF APPLIED WATER PASSING BELOW ROOT ZONE).	5%	101	95	3301	3564	831	1891	9783	55,9
	10%	94	91	1651	1782	704	946	5268	28,7
	20%	87	87	825	891	622	473	2985	14,8
	30%	84	84	550	593	588	315	2214	10,0
	40%	82	83	413	446	569	236	1829	7,6

* SODIUM ADSORBTION RATIO

TABLE E.12 . THE AFFECT OF INCREASED LEACHING FRACTION TREATMENT ON ION CONCENTRATION OF IRRIGATION PERCOLATE .- SAMPLE 5126

T.D.S. CONTENT - IRRIGATION WATER

ION CONCENTRATION IN mg/ℓ

ION		Ca	Mg	Na+K	Cl	$CO_3 + HCO_3$	SO_4	T.D.S.	S.A.R. *
INITIAL CONCENTRATION		33,2	26,6	134,3	127,8	195	82	598,9	4,2
LEACHING FRACTION TREATMENT LEACHING FRACTION TREATMENT (PERCENTAGE OF APPLIED WATER PASSING BELOW ROOT ZONE).	5%	51	45	2772	2474	1134	1643	8119	66
	10%	64	60	1386	1237	820	821	4388	29
	20%	71	69	693	618	665	410	2526	13m6
	30%	72	72	462	412	615	274	1907	8,9
	40%	77	67	347	309	570	205	1509	6,8

* SODIUM ALSORBTION RATIO

TABLE E.13 THE AFFECT OF INCREASED LEACHING FRACTION TREATMENT ON ION CONCENTRATION OF IRRIGATION PERCOLATE. - SAMPLE 5029

T.D.S. CONTENT - IRRIGATION WATER

ION CONCENTRATION IN mg/ℓ

ION		Ca	Mg	Na+K	Cl	CO_3 +HCO_3	SO_4	T.D.S.	S.A.R. *
INITIAL CONCENTRATION		57	65	297	352	321	199	1291	6,3
LEACHING FRACTION TREATMENT LEACHING FRACTION TREATMENT (PERCENTAGE OF APPLIED WATER PASSING BELOW ROOT ZONE).	5%	278	304	5934	7036	631	3984	18167	60,5
	10%	183	179	2966	3518	612	1992	9450	37,1
	20%	133	133	1483	1759	590	996	5094	21,6
	30%	115	116	989	1173	570	664	3627	15,4
	40%	106	107	742	880	560	498	2893	12

* SODIUM ACSORBTION RATIO

TABLE E.14 THE AFFECT OF INCREASED LEACHING FRACTION TREATMENT ON ION CONCENTRATION OF IRRIGATION PERCOLATE. - SAMPLE 5223

T.D.S. CONTENT - IRRIGATION WATER

ION CONCENTRATION IN mg/ℓ

ION		Ca	Mg	Na+K	Cl	CO_3 +HCO_3	SO_4	T.D.S.	S.A.R. *
INITIAL CONCENTRATION		37,4	27	149,7	139,5	209,5	96	659,1	4,5
LEACHING FRACTION TREATMENT LEACHING FRACTION TREATMENT (PERCENTAGE OF APPLIED WATER PASSING BELOW ROOT ZONE).	5%	68,8	63	2992	2792	1000	1920	8836	62
	10%	76	73	1496	1396	724	960	4725	29
	20%	78	76	748	698	601	480	2681	14,3
	30%	77	77	499	465	606	320	2044	9,5
	40%	82	68	374	349	552	240	1665	7,3

* SODIUM ABSORBTION RATIO

TABLE E. 15 THE AFFECT OF INCREASED LEACHING FRACTION TREATMENT ON ION CONCENTRATION OF IRRIGATION PERCOLATE. - SAMPLE 1798

T.D.S. CONTENT - IRRIGATION WATER

ION CONCENTRATION IN mg/ℓ

ION		Ca	Mg	Na+K	Cl	CO_3 +HCO_3	SO_4	T.D.S.	S.A.R. *
INITIAL CONCENTRATION		36,6	27,7	149	153	199	91	656,3	4,47
LEACHING FRACTION TREATMENT LEACHING FRACTION TREATMENT (PERCENTAGE OF APPLIED WATER PASSING BELOW ROOT ZONE).	5%	91	85	2985	3060	857	1824	8902	53
	10%	88	86	1492	1530	713	912	4821	26,8
	20%	84	84	746	765	624	456	2759	13,6
	30%	82	82	498	510	588	304	2064	9,2
	40%	87	69	373	383	550	228	1690	7,1

* SODIUM ACSORBTION RATIO

TABLE E.16 THE AFFECT OF INCREASED LEACHING FRACTION TREATMENT ON ION CONCENTRATION OF IRRIGATION PERCOLATE. - SAMPLE 2115.

T.D.S. CONTENT - IRRIGATION WATER

ION CONCENTRATION IN mg/ℓ

ION		Ca	Mg	Na+K	Cl	CO_3+HCO_3	SO_4	T.D.S.	S.A.R. *
INITIAL CONCENTRATION		35,6	27,4	148,1	145,9	173,5	90,2	620,7	4,5
LEACHING FRACTION TREATMENT LEACHING FRACTION TREATMENT (PERCENTAGE OF APPLIED WATER PASSING BELOW ROOT ZONE).	5%	77,4	72	2967	2911	934	1810	8771,4	57,9
	10%	80,8	78	1481	1459	745	902	4745,8	28
	20%	80,2	79,3	740	730	640	452	2721,5	13,9
	30%	79	79	494	487	600	301	2040	9,3
	40%	84,4	68,5	370	205,6	550	226	1504,5	7,2

* SODIUM ALSORBTION RATIO

TABLE E.17 THE AFFECT OF INCREASED LEACHING FRACTION TREATMENT ON ION CONCENTRATION OF IRRIGATION PERCOLATE. - SAMPLE 1216.

T.D.S. CONTENT - IRRIGATION WATER

ION CONCENTRATION IN mg/ℓ

ION		Ca	Mg	Na+K	Cl	CO_3 +HCO_3	SO_4	T.D.S.	S.A.R. *
INITIAL CONCENTRATION		38	32	162	159	200	113	684	4,65
LEACHING FRACTION TREATMENT LEACHING FRACTION TREATMENT (PERCENTAGE OF APPLIED WATER PASSING BELOW ROOT ZONE).	5%	99,6	94	3247	3181	853	2266	9741	55,3
	10%	94	90,7	1623	1590	717	1133	5248	28,3
	20%	87	87	812	795	629	566	2976	14,5
	30%	84	84	541	530	590	378	2207	9,8
	40%	84,6	79	406	398	562	283	1813	7,5

* SODIUM ADSORBTION RATIO

TABLE E.18 THE AFFECT OF INCREASED LEACHING TREATMENT ON ION CONCENTRATION OF IRRIGATION PERCOLATE. - SAMPLE 1730.

T.D.S. CONTENT - IRRIGATION WATER

ION CONCENTRATION IN mg/ℓ

ION		Ca	Mg	Na+K	Cl	CO_3 +HCO_3	SO_4	T.D.S.	S.A.R. *
INITIAL CONCENTRATION		47,4	48,8	262,2	300,7	215,5	181	1055,6	6,4
LEACHING FRACTION TREATMENT LEACHING FRACTION TREATMENT (PERCENTAGE OF APPLIED WATER PASSING BELOW ROOT ZONE).	5%	225,4	216,4	5247	6017	665	3626	16023,8	59,7
	10%	157,4	154	2637	3007	636	1813	8408,4	35,5
	20%	120,6	120	1318	1505	600	907	4570,6	20,2
	30%	107	107,6	879	1002	575	604	3275	14,2
	40%	99,8	101	659	752	570	453	2635	11,0

* SODIUM ABSORBTION RATIO

TABLE E.19 THE AFFECT OF INCREASED LEACHING FRACTION TREATMENT ON ION CONCENTRATION OF IRRIGATION PERCOLATE. - SAMPLE 1232.

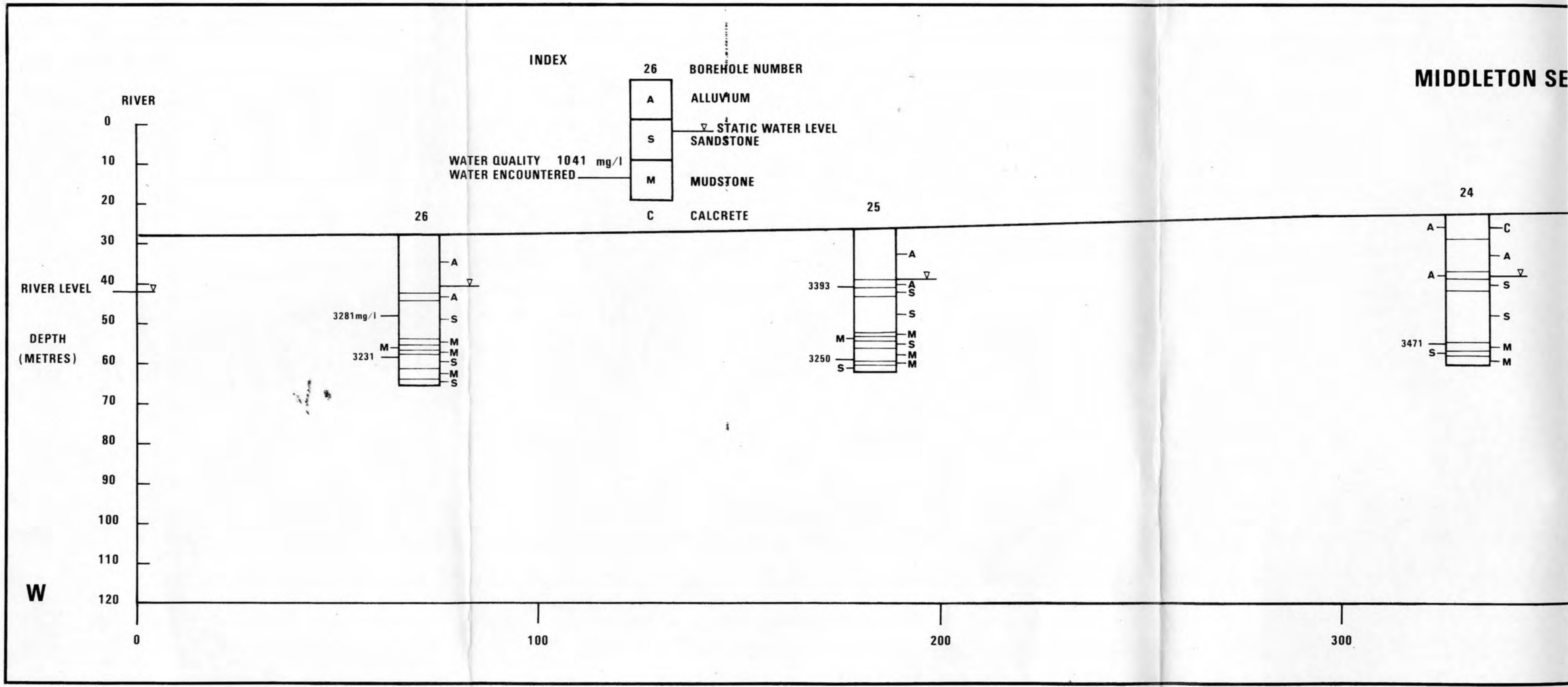
T.D.S. CONTENT - IRRIGATION WATER

ION CONCENTRATION IN mg/ℓ

ION		Ca	Mg	Na+K	Cl	CO_3 +HCO_3	SO_4	T.D.S.	S.A.R. *
INITIAL CONCENTRATION		35,6	34,8	170	186	196	111	733	4,8
LEACHING FRACTION TREATMENT LEACHING FRACTION TREATMENT (PERCENTAGE OF APPLIED WATER PASSING BELOW ROOT ZONE).	5%	135,4	130	3405	3713	735	2221	10339	49,8
	10%	112	110	1703	1856	660	11100	5551	27,2
	20%	96,4	96	851	928	600	555	3126	14,6
	30%	90	91	568	619	575	370	2313	10,1
	40%	87	87	426	464	550	277	1891	7,7

* SODIUM ADSORBTION RATIO

TABLE E.20 THE AFFECT OF INCREASED LEACHING FRACTION TREATMENT ON ION CONCENTRATION OF IRRIGATION PERCOLATE. - SAMPLE 1240.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SANDSTONE
WATER QUALITY 1041 mg/l
WATER ENCOUNTERED
M MUDSTONE
C CALCRETE
RIVER
RIVER LEVEL
DEPTH
(METRES)
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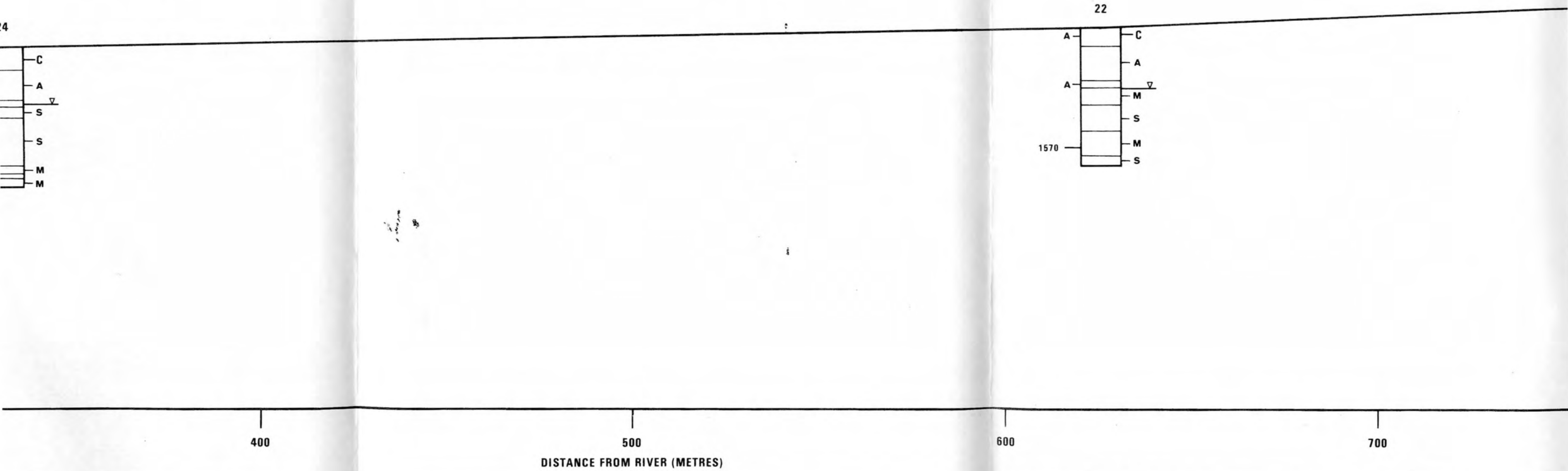
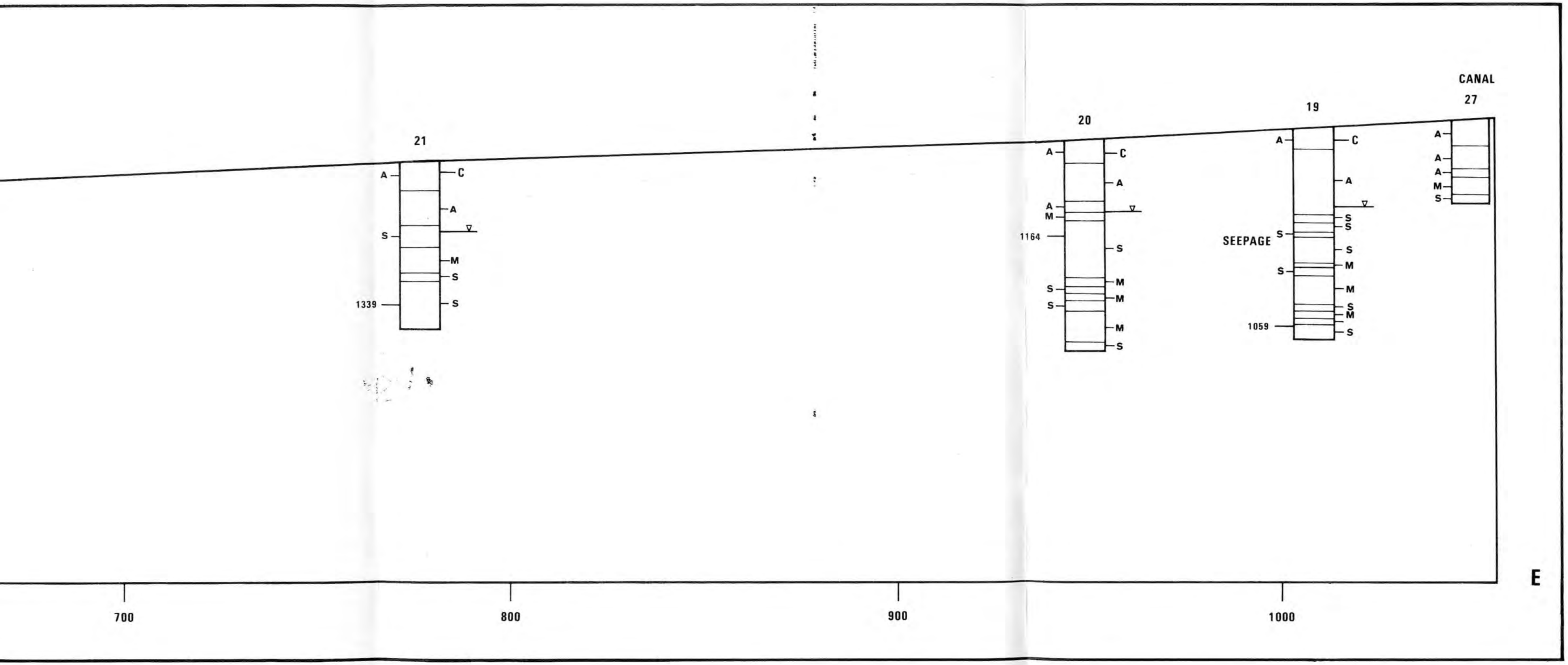
DLETON SECTION C: GEOLOGY PROFILE

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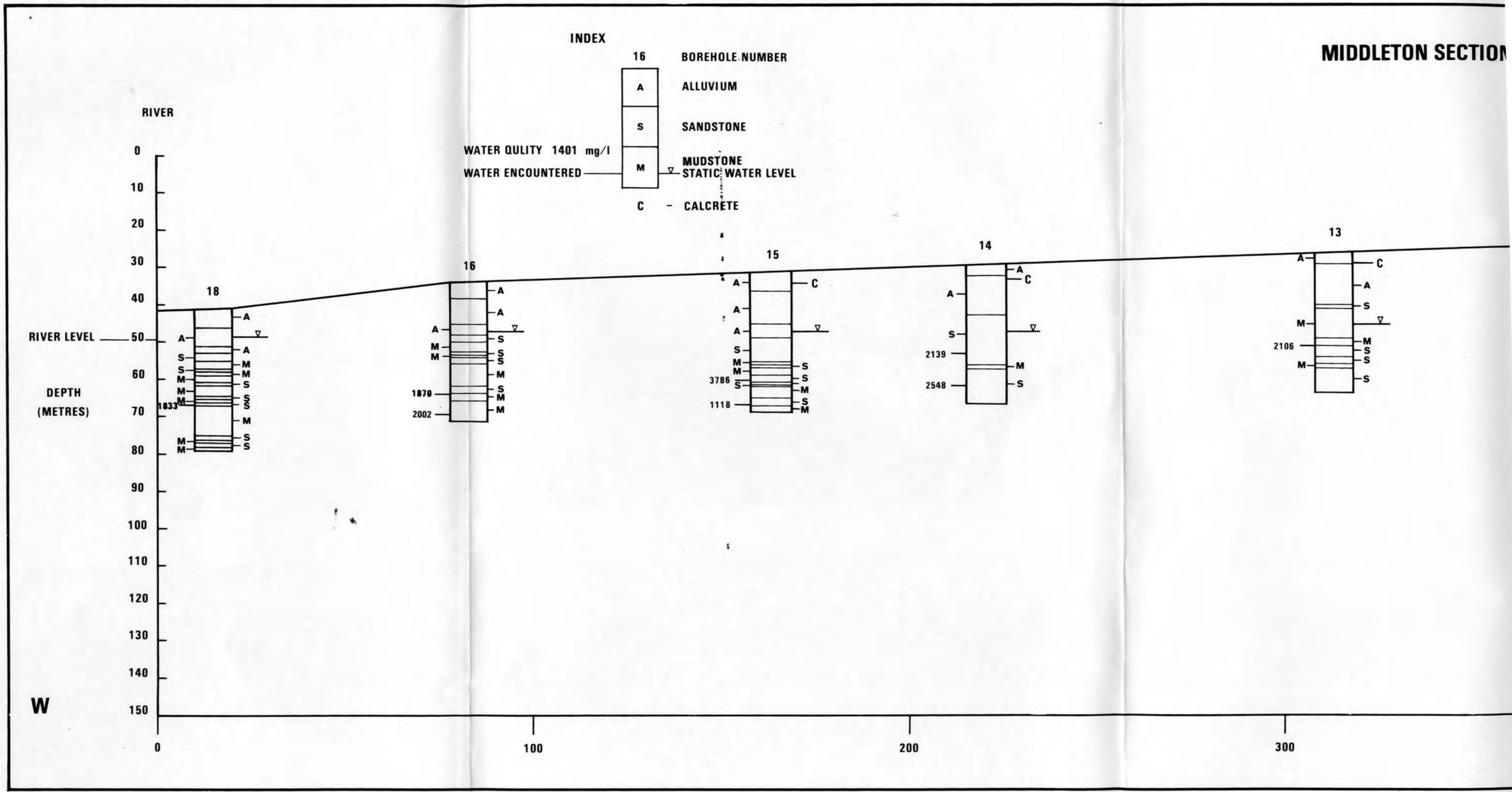
MIDDLETON SECTIO
INDEX
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A ALLUVIUM
S SANDSTONE
M MUDSTONE
▽ STATIC WATER LEVEL
C - CALCRETE
WATER QULITY 1401 mg/l
WATER ENCOUNTERED
RIVER
RIVER LEVEL
DEPTH
(METRES)
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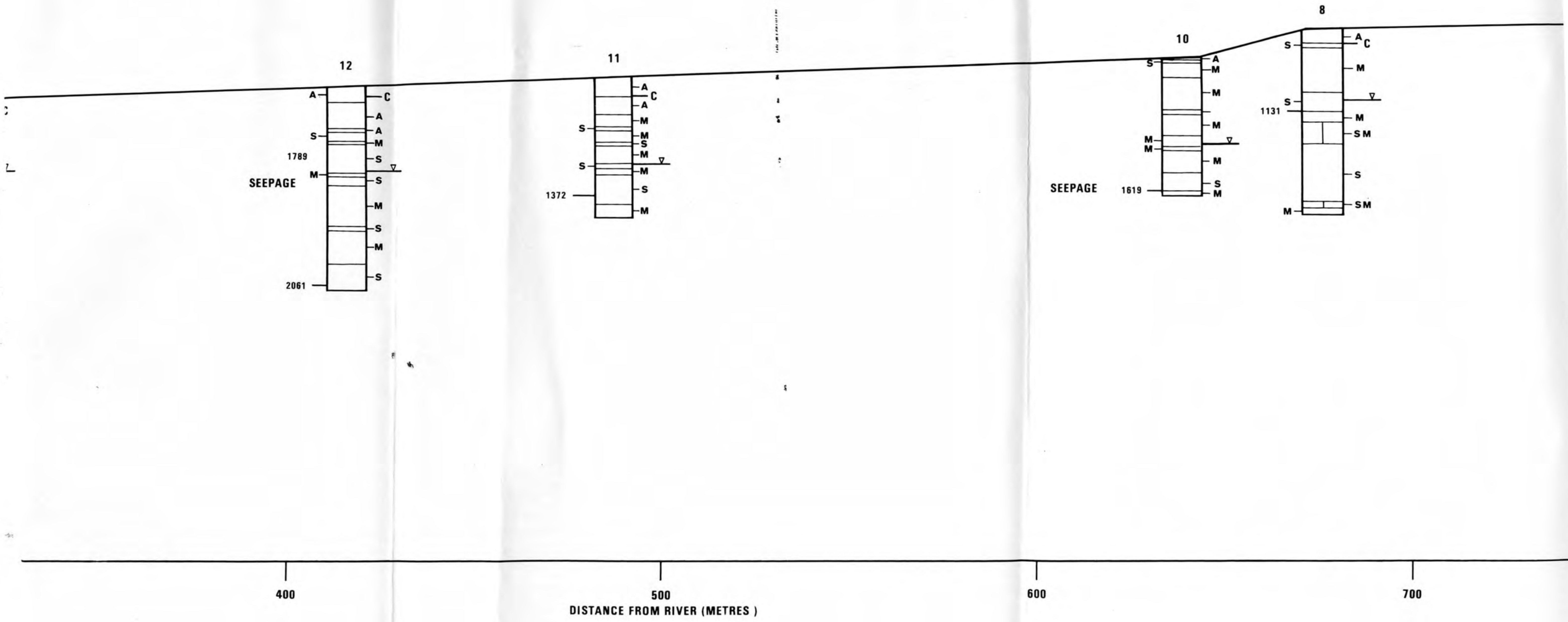
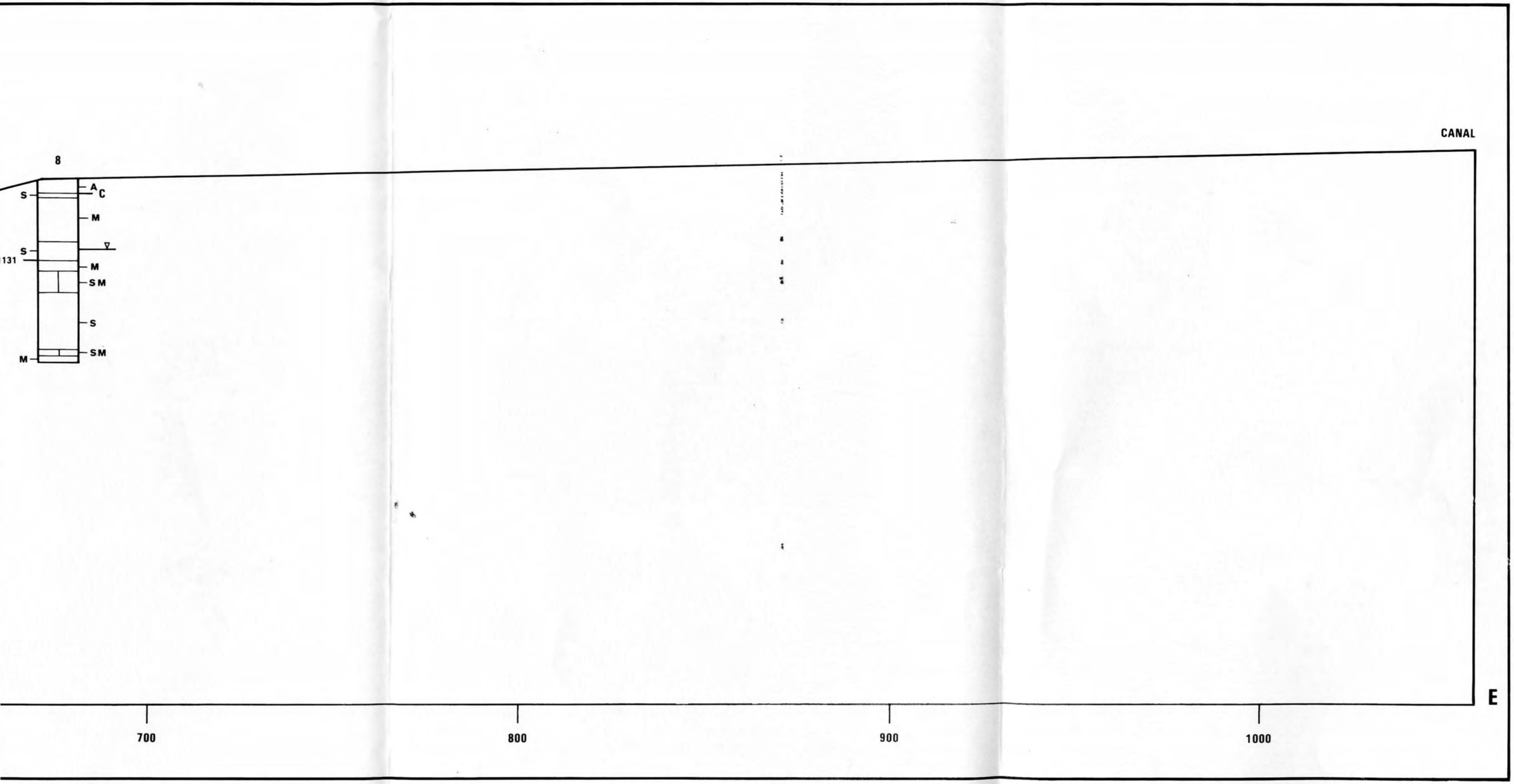
Reynolds

LETON SECTION A: GEOLOGY PROFILE

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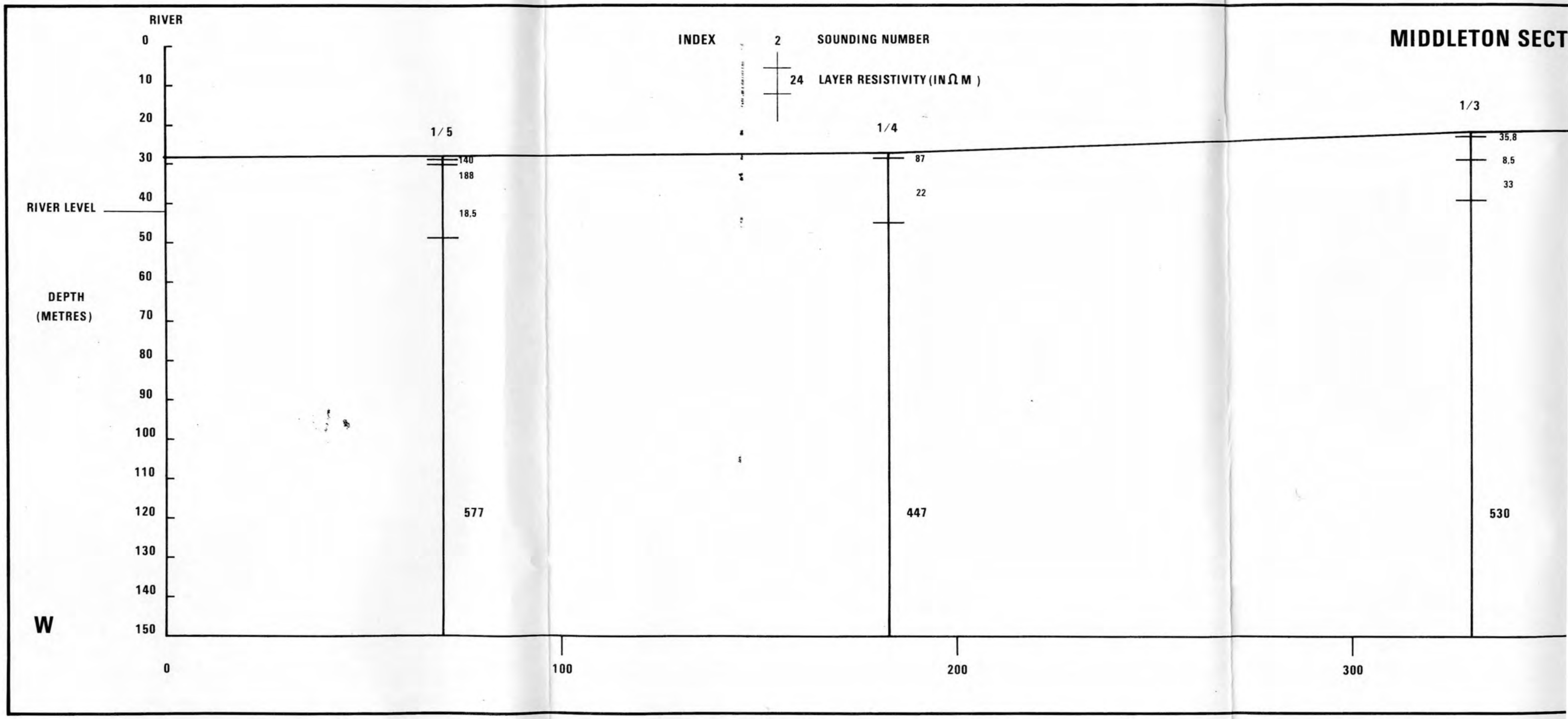
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RIVER LEVEL
DEPTH (METRES)
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140
150
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577
1/4
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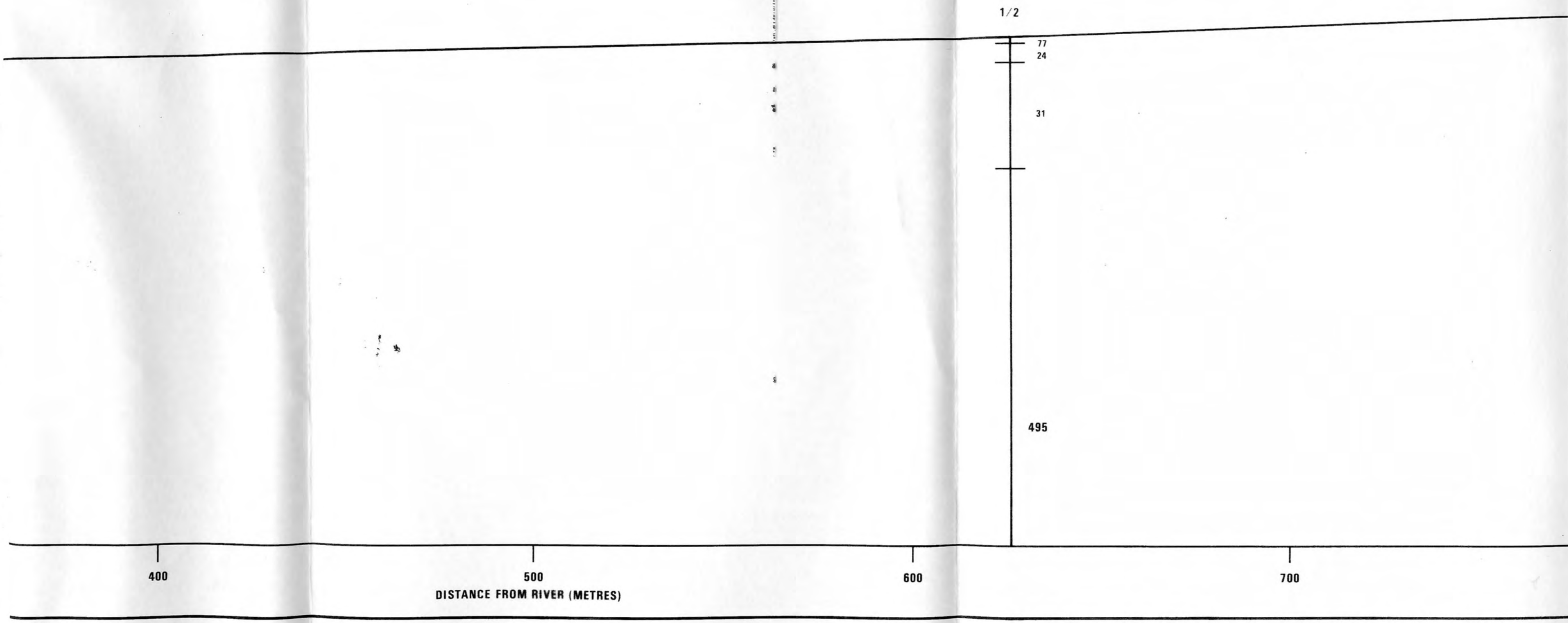
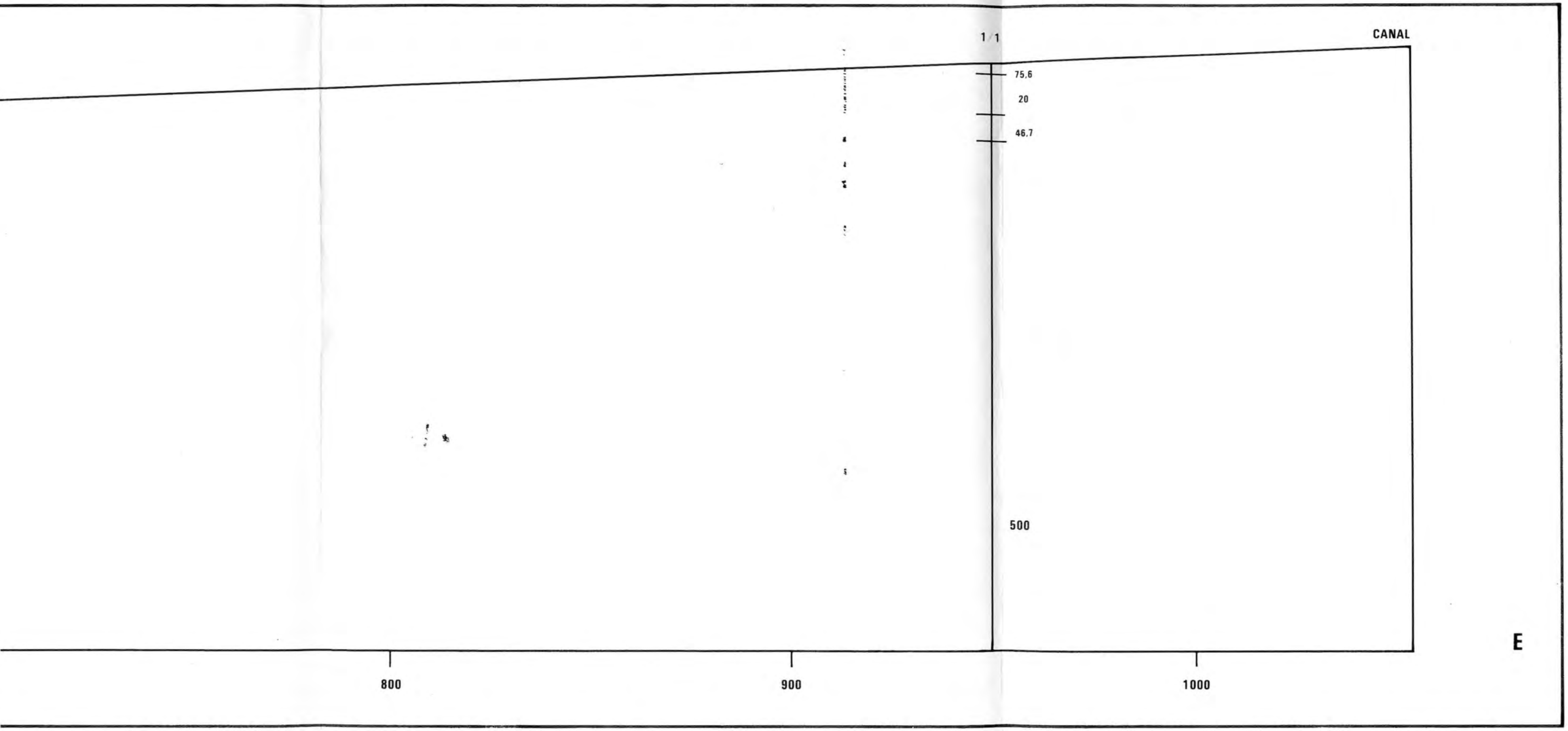
N C: EARTH MODEL BASED ON RESISISTIVITY SOUNDINGS

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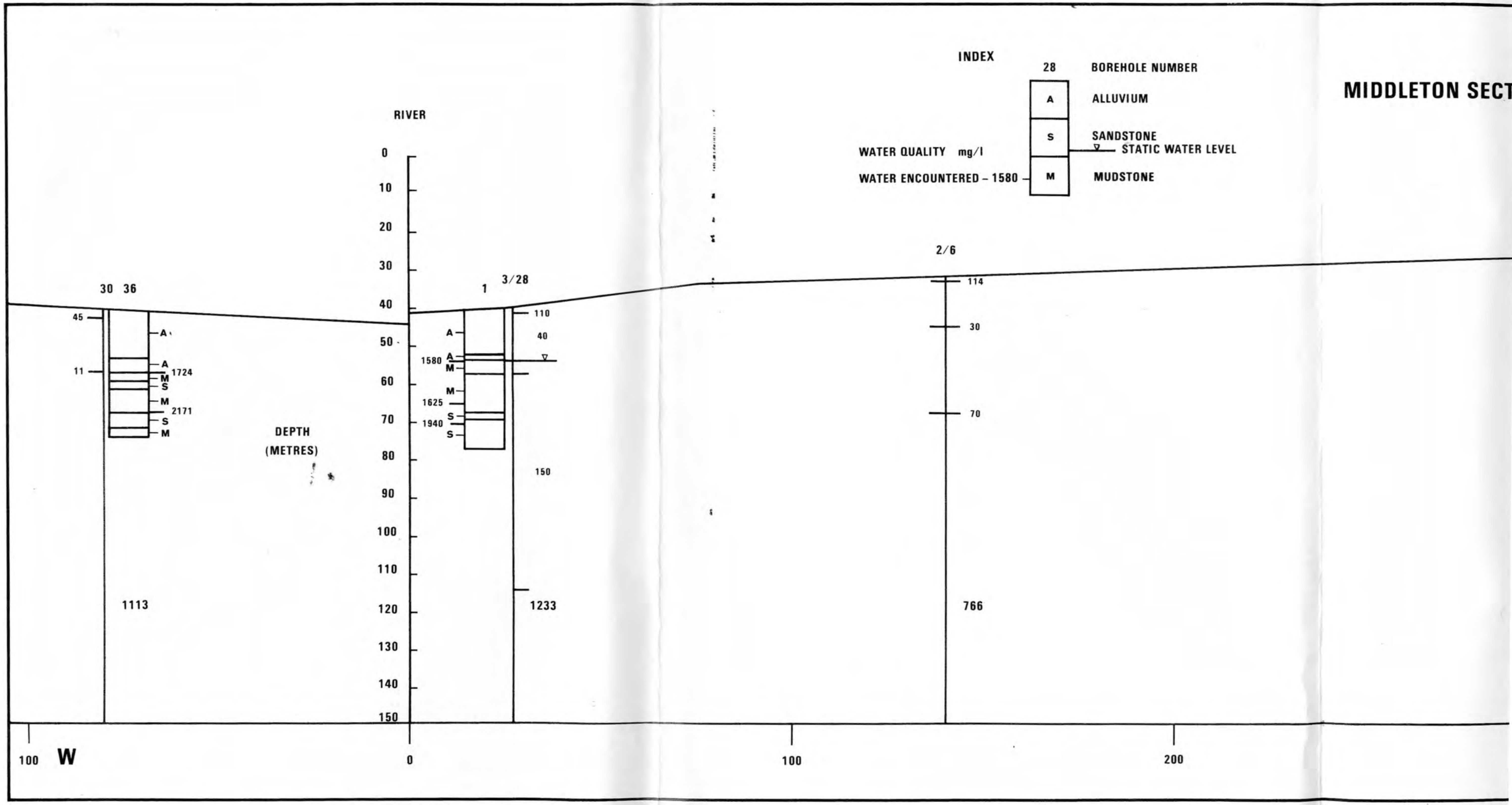
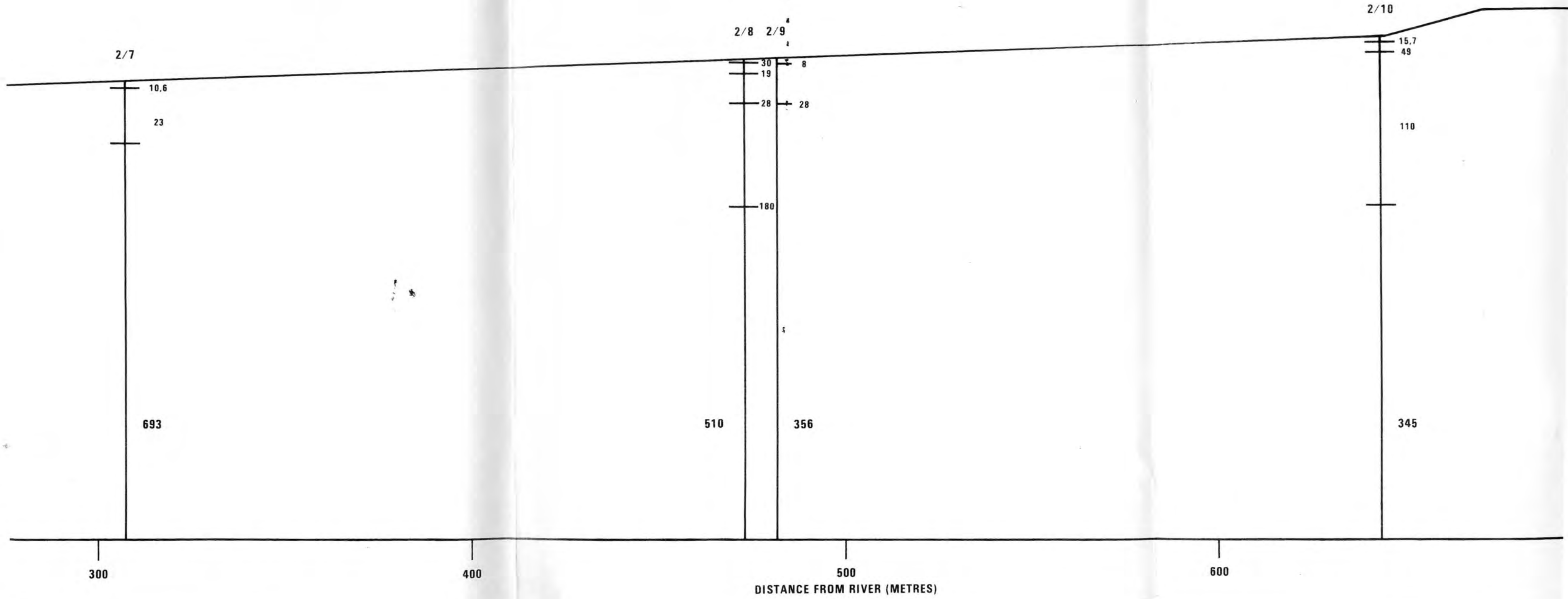
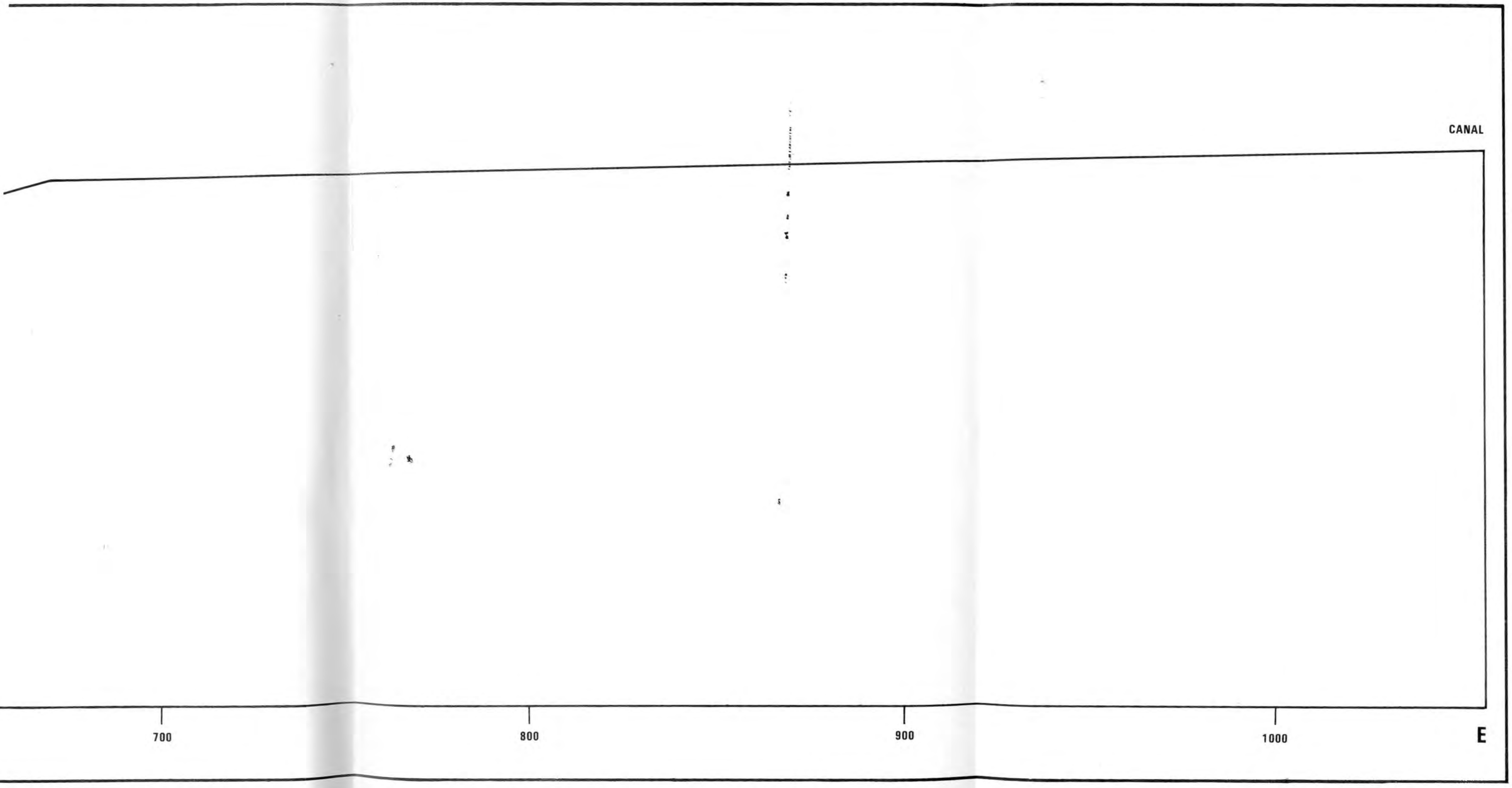
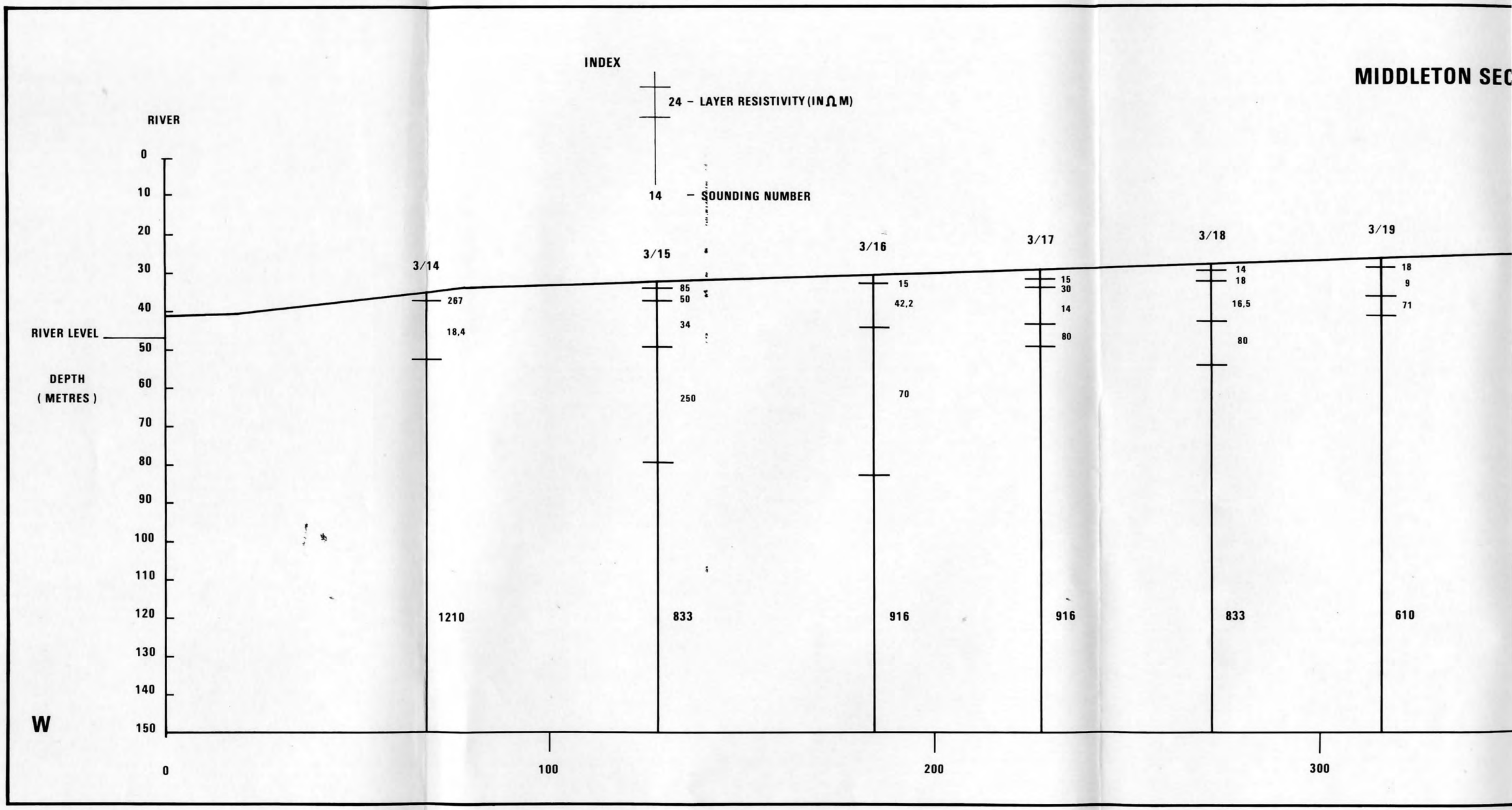
900
1000


MIDDLETON SECT
INDEX
28 BOREHOLE NUMBER
A ALLUVIUM
S SANDSTONE
STATIC WATER LEVEL
M MUDSTONE
WATER QUALITY mg/l
WATER ENCOUNTERED – 1580
RIVER
DEPTH (METRES)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
30 36
45
11
A
A
1724
M
S
M
2171
S
M
1113
1 3/28
A
1580
A
M
M
1625
S
1940
S
110
40
150
1233
2/6
114
30
70
766
100
W
0
100
200

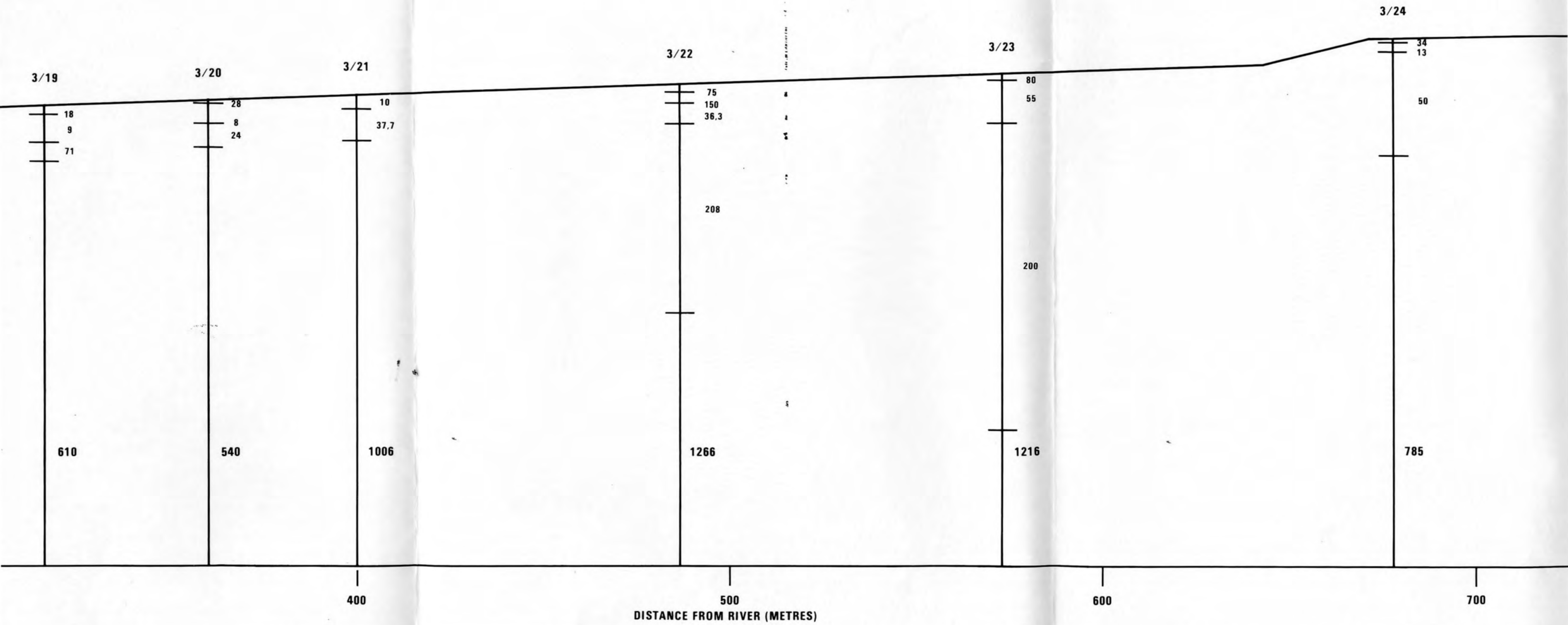
SECTION B: EARTH MODEL BASED ON RESISTIVITY SOUNDINGS

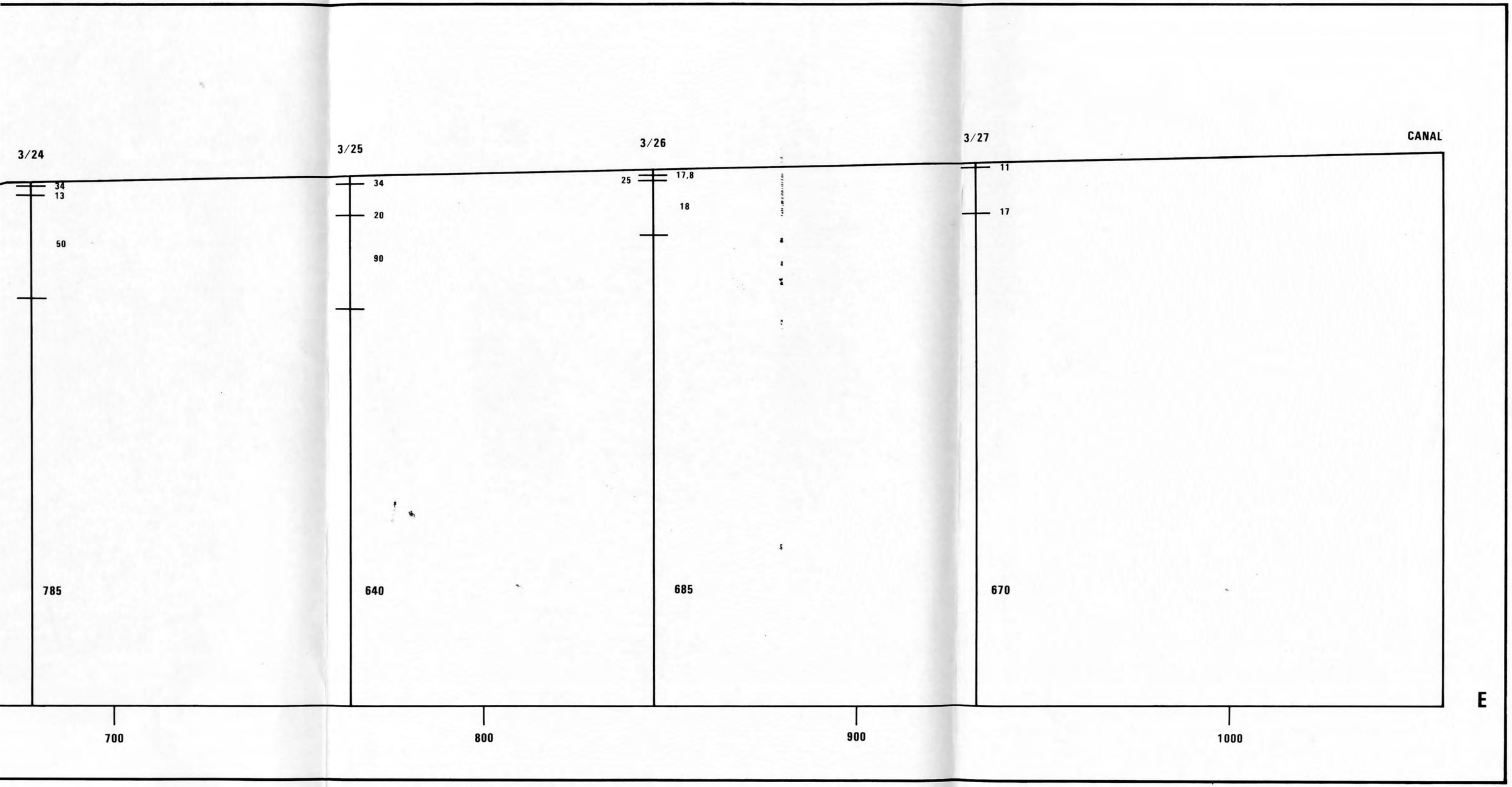



CANAL
700
800
900
1000
E


MIDDLETON SEC
INDEX
24 – LAYER RESISTIVITY (IN Ω M)
14 – SOUNDING NUMBER
RIVER
RIVER LEVEL
DEPTH
(METRES)
W
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
0
100
200
300
3/14
267
18,4
1210
3/15
85
50
34
250
833
3/16
15
42,2
70
916
3/17
15
30
14
80
916
3/18
14
18
16,5
80
833
3/19
18
9
71
610

MIDDLETON SECTION A: EARTH MODEL BASED ON RESISITIVITY SOUNDINGS




3/24
34
13
50
785
3/25
34
20
90
640
3/26
25
17,8
18
685
3/27
11
17
670
CANAL
E
700
800
900
1000