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THE HYDROGEOLOGY AND HYDROGEOCHEMISTRY OF THE AQUIFERS
OF THE HEX RIVER VALLEY, CAPE PROVINCE

PETER NIGEL ROSEWARNE



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SYNOPSIS

The Hex River Valley is one of the main centres in South Africa for cultivation of table grapes of export quality. The vines require irrigation water, which must be low in dissolved solids. Approximately two thirds of the annual irrigation requirement is obtained from boreholes and the balance from surface water sources.

During the early 1960s a deterioration in the quality of the groundwater was noticed, becoming critical in some areas, and borehole yields also declined. The main objectives of this study were therefore to obtain an understanding of the hydrogeological and hydrogeochemical processes operating in the valley to explain the derogation of the groundwater resource and enable optimum utilisation and management of the resource in the future.

To achieve these objectives, field work involving exploration drilling, aquifer tests, hydrocensus, long-term monitoring of groundwater levels and surface water flows and extensive sampling of the ground and surface waters was carried out. Analysis of these data gave quantitative information on groundwater occurrence, aquifer hydraulic properties, groundwater recharge and storage, chemical characteristics of the ground and surface waters and sources of dissolved species.

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To my Mother and Father

THE HYDROGEOLOGY AND HYDROGEOCHEMISTRY OF THE AQUIFERS
OF THE HEX RIVER VALLEY, CAPE PROVINCE

1 INTRODUCTION

This thesis describes the hydrogeology and hydrogeochemistry of the aquifers occurring in the Cape Supergroup and Tertiary to Recent deposits of the Hex River Valley, Cape Province. The data collection and field phase of this investigation was carried out between 1976 and 1979.

The Hex River Valley is situated in the district of Worcester in the Cape Province. De Doorns is the main town in the valley and is 145 km ENE from Cape Town on the main road and rail links between Cape Town and Johannesburg (Fig 1). The valley trends north-east south-west, is 23 km in length and up to 5 km in width between the bordering mountain fronts.

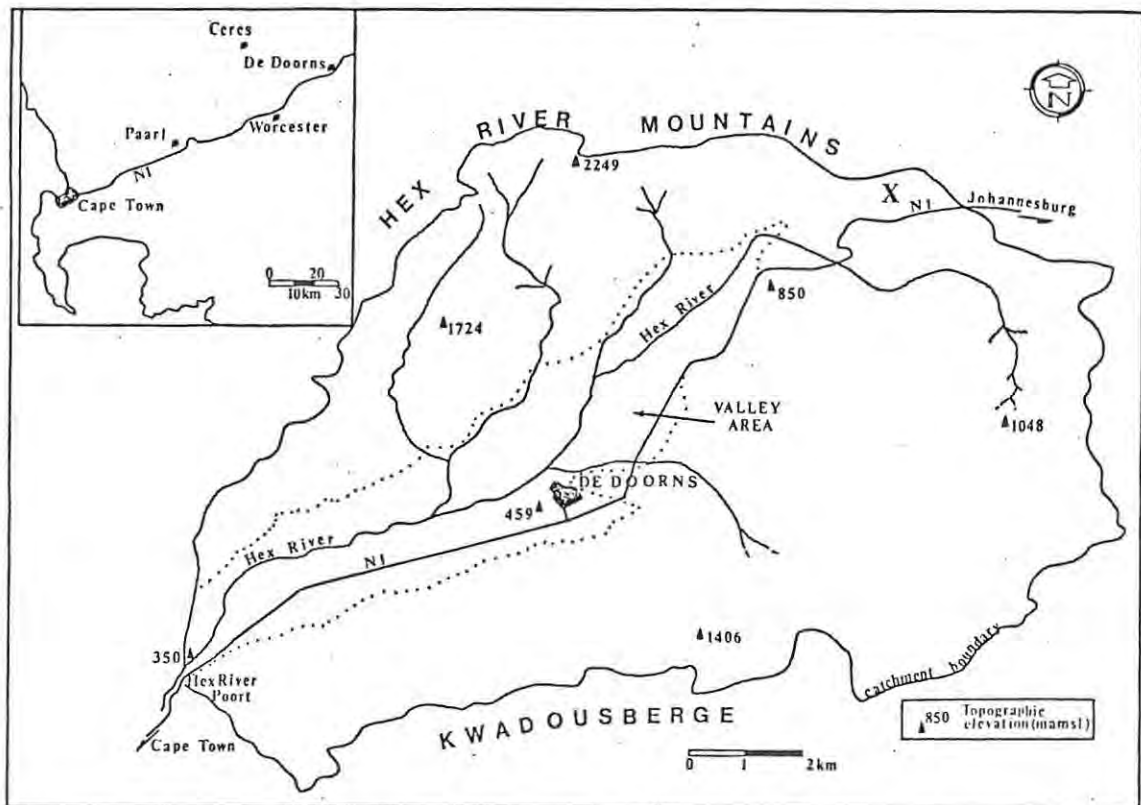


FIG 1 : LOCALITY MAP

The Hex River Valley is one of the main centres for cultivation of table grapes of export quality. Approximately 50% of the total area under table grapes in the western Cape is situated in the Hex River Valley (Pienaar et al, 1972). In 1980 there were 2 900 hectares of vines under irrigation.

The general physiographic features of the study area are shown in Fig 2, an aerial view of the Hex River Valley facing to the south-west from the point marked X on Fig 1.

Kwadousberge

Hex River
Mountains



FIG 2 : OBLIQUE AERIAL VIEW OF THE HEX RIVER VALLEY, FACING SOUTH-WEST

2 THE STUDY AREA

2.1 Relief

The Hex River Valley is surrounded by rugged mountain ranges, which are:

- . in the north and north-east, the Hex River Mountains
- . in the south and south-east, the Kwadousberge.

The mountains rise up to 1 637 m above the valley floor, with the highest peak, the Matroosberg, being 2 249 m above mean sea level. The Hex River Valley is an example of concordant morphology with the valley sides conforming to the limbs of a synclinal structure. The surrounding mountains are dissected by steep gorges eroded by tributaries of the Hex River, the main ones being Sandhoekkloof, Grootthoekkloof and Rooielskloof in the Hex River Mountains. The Hex River has breached the surrounding mountains, at the south-western end of the valley, at the Hex River Poort.

2.2 Surface drainage

The Hex River drains tertiary catchment H14 (Pitman et al, 1981) and flows into the Breë River near Worcester, 20 km downstream from the Hex River Poort. The Hex River and its tributaries drain a catchment area of 265 square kilometres up to the Hex River Poort. The mean annual runoff from this area is $13 \times 10^6 \text{ m}^3$ (Pitman et al, 1981) representing 8 per cent of the mean annual precipitation over the catchment.

2.3 Climate

The study area lies within the winter rainfall region and tends towards a mediterranean climate. The average annual rainfall recorded in the central valley area is 321 mm for the period 1908 to 1980. According to the published 1:250 000 scale map (1965) annual rainfall on the highest peaks of the Hex River

Mountains may reach 2 400 mm (Fig 3). Indeed, the highest mean annual precipitations in the country are experienced in the Hex River Mountain complex (Pitman et al, 1981).

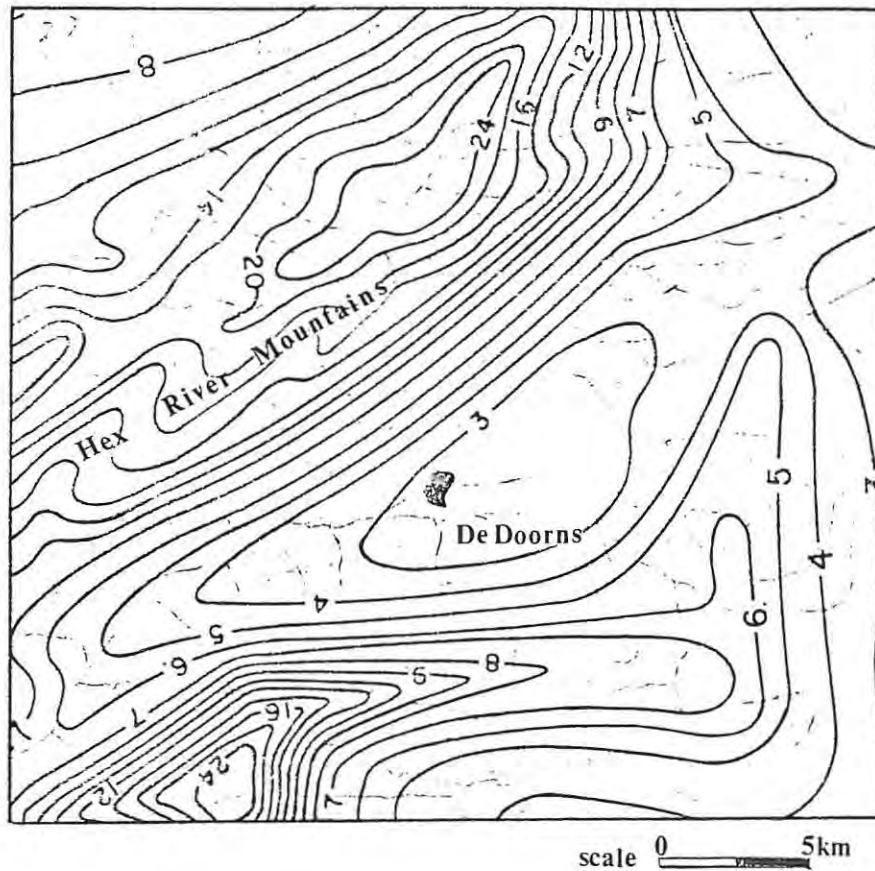


FIG 3 : AVERAGE ANNUAL RAINFALL ISOHYETS ($\text{mm} \times 10^2$)

The mean annual potential evaporation (A pan) measured at De Doorns is 2 426 mm for the period 1965 to 1977. Eighty per cent of this occurs during the period September to March.

3 GEOLOGICAL FEATURES

3.1 General statement

The Hex River Valley has developed along a synclinal fold axis within the Cape Supergroup. Rocks of the Cape Supergroup outcrop in an L-shaped area along the southern and south-western coastal margins of the Cape Province (Fig 4).

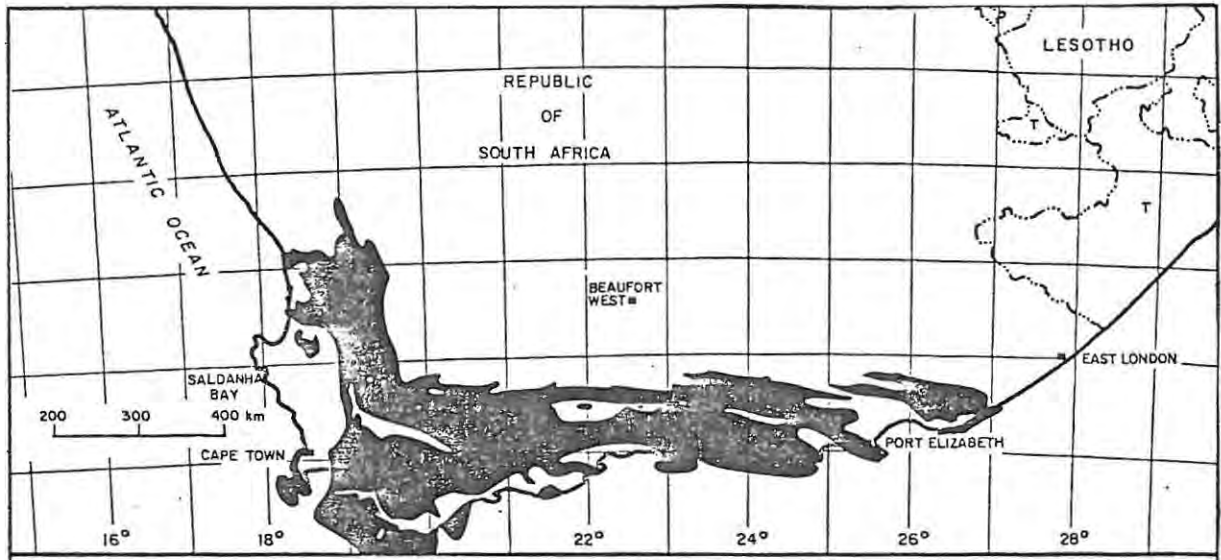


FIG 4 : OUTCROP AREA OF THE CAPE SUPERGROUP (from SACS, 1980 p 525)

Only the lower two members of the Cape Supergroup are present in the study area, viz the Table Mountain Group and the Bokkeveld Group. The former consists predominantly of quartzitic sandstones while in the latter, mudrocks predominate. Extensive alluvial deposits have been laid down over the Valley floor, ranging in lithology from clayey sand to sand and gravel of considerable thickness, the latter along the flanks of the Valley.

3.2 Structural history

After deposition of sediments of the Cape Supergroup, a period of major tectonic movement was initiated (Brink, 1979). Tectonic stresses from the south and west of the continent



LANDSAT MOSAIC OF THE SOUTH-WESTERN CAPE (after Brink 1979)

FIG NO 5

resulted in the formation of two major mountain belts; a shorter western belt striking N-S from Nieuwoldtville to Ceres and a longer southern belt striking E-W from Ceres to Port Alfred (Fig 5).

The structural trends of the western and southern fold belts converge in the vicinity of Ceres, which is 30 km north-west of De Doorns. The rugged topography and well developed jointing and fissuring of the Hex River Mountains owe their existence to the tectonic conflict at this convergence of the western and southern fold belts (Brink, 1979).

3.3 Geological succession

The lithostratigraphy of the Cape Supergroup in the Hex River Valley is shown in Table 1 (after SACS, 1980). The surface geology of the area outlined in Fig 1 is depicted in Fig 6 (after Theron, 1972).

Group	Formation	Thickness (m)	Lithology
BOKKEVELD	Boplaas Sandstone	30	Sandstone
	Tra-Tra Shale	180	Shale
	Hex River Sandstone	70	Sandstone
	Voorstehoek Shale	220	Shale
	Gamka Sandstone	35	Argillaceous Sandstone
	Gydo Shale	140	Shale
TABLE MOUNTAIN	Nardouw Sandstone	500	Sandstone
	Cederberg Shale	120	Shale
	Pakhuis	40	Sandstone, diamictite
	Peninsula Sandstone	1 550	Sandstone

TABLE 1 : LITHOSTRATIGRAPHY OF THE CAPE SUPERGROUP IN THE HEX RIVER VALLEY (after SACS, 1980)

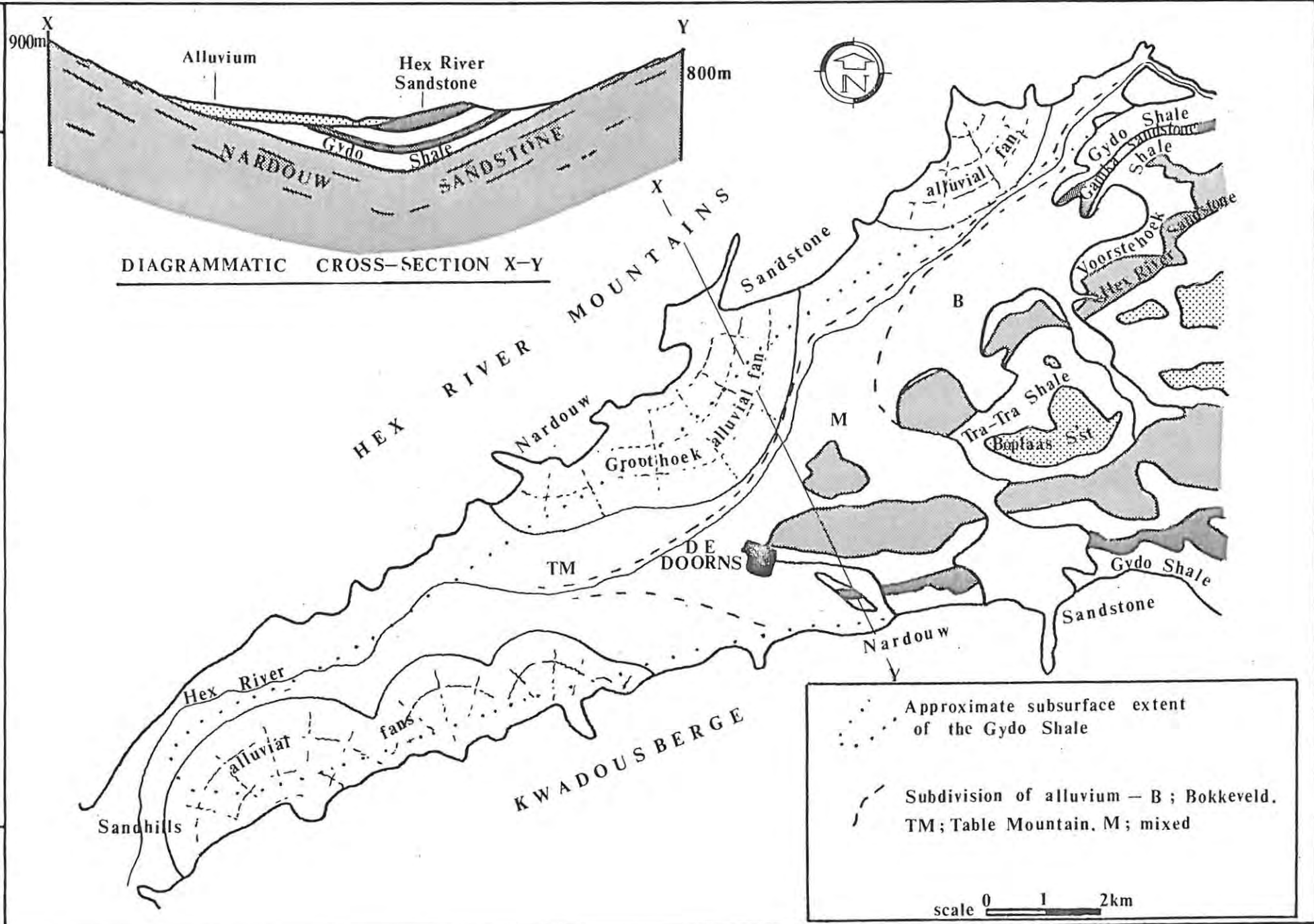


FIG NO
6

3.3.1 Table Mountain Group

The base of the Group is not seen in the Hex River Valley. The lowermost exposed member, the Peninsula Sandstone, is the same formation that builds Table Mountain at Cape Town. Separating the lower Peninsula Sandstone from the upper Nardouw Sandstone are the predominantly argillaceous Cederberg Shale and Pakhuis Formation. These formations are generally poorly exposed and form a green vegetated swath that contrasts very clearly with the barren rocky surfaces of the quartzites above and below (Truswell, 1977).

In the Hex River Valley the most important member of the Table Mountain Group is the Nardouw Sandstone, as this is the only formation of this Group penetrated by boreholes and it also directly underlies the lowermost shale of the Bokkeveld Group. Fig 7 shows the typical appearance of the Nardouw Sandstone with well developed bedding planes and fissures.



FIG 7 : OUTCROP OF THE NARDOUW SANDSTONE SHOWING WELL DEVELOPED FISSURES

The Table Mountain Group forms the envelope of the Hex Valley syncline and dips at 20° in the north-east, steepening to 60° in the south-west.

3.3.2 Bokkeveld Group

Conformable with the Table Mountain Group and occupying the core of the syncline is the sequence of alternating shales and sandstones of the Bokkeveld Group. This group is only exposed to the east and north-east of De Doorns, being concealed beneath alluvial deposits elsewhere. Evidence from borehole logs (Vegter, 1974) indicates that the lowermost shale formation extends to the south-east almost as far as Sandhills (Fig 6).

The unweathered shales are typically dark grey in colour, micaceous and locally contain abundant pyrite. The sandstones are impure, micaceous and fine to medium grained. The lowermost sandstone, the Gamka Sandstone, is poorly developed in the Hex River Valley and is hardly distinguishable from the shales in percussion drill samples.

3.3.3 Alluvium

As one of the study aims is to evaluate the exploitation potential of the alluvial deposits and because of their considered importance hydrogeologically, the alluvium will be described in some detail here.

From surface observations and detailed logging of exploration boreholes it has been possible to subdivide the alluvial deposits on the basis of their source rock and mode of deposition (Fig 6). The subdivisions recognised are (Rosewarne, 1978):

- . alluvium derived from the Table Mountain Group
- . alluvium derived from the Bokkeveld Group

- . alluvium of mixed origin derived from both the above sources.

With regard to mode of deposition the alluvium may be further subdivided into:

- . piedmont deposits (comprising a mixture of colluvial and coarse alluvial material)
- . normal fluvial deposits (comprising well rounded and moderately sorted alluvial material).

Alluvium derived from the Table Mountain Group is the most extensive of the alluvial deposits and is predominantly quartzitic and typically off-white to light brown in colour. The greatest thicknesses are found in the piedmont deposits of the alluvial fans built up along the flanks of the Valley at the mouths of gorges cut in the Table Mountain Sandstones (Fig 8).



FIG 8 : SECTION THROUGH TOE OF AN ALLUVIAL FAN IN THE SANDHILLS AREA

A borehole log typical of this alluvium is as follows:

G30987:

- 0 - 33 m : A matrix of very fine to very coarse silty sand with gravel up to cobble/boulder size.
- 34 - 42 m : Mainly silty sand with some fine gravel.
- 43 - 54 m : A matrix of silty sand with gravel up to cobble/boulder size.
- 55 m : Bedrock.

Alluvial deposits derived from the Bokkeveld Group are much less extensive and on average are thinner. The alluvium has been derived from both shales and sandstone. The shales have given rise to a silty clay matrix with coarser grains of sandstone up to pebble/cobble and, rarely, boulder size. Appreciable quantities of mica are present and the alluvium is reddish-brown in colour. A typical log is as follows:

G30858:

- 0 - 36 m : Silty clay with micaceous sand and gravel up to pebble size.
- 37 m : Bedrock.

Alluvium of mixed origin contains material derived from both Table Mountain and Bokkeveld sources. It consists typically of a silty and sometimes clayey matrix with sand and gravel up to cobble/boulder size and is buff coloured.

A typical borehole log is given below:

G30889:

- 0 - 30 m : A silty sand matrix with gravel up to boulder size.
- 31 - 40 m : Silty clay matrix with sand.
- 41 m : Bedrock.

3.4 Summary

The foregoing sections have described the geological formations of the Hex River Valley which constitute the potential aquifers of the study area. Even at this stage some extrapolation can be made regarding the broad aquifer characteristics of these formations. These are:

- . the Table Mountain and Bokkeveld Group rocks constitute secondary aquifers where groundwater flow and storage are controlled by fracture development
- . the alluvial deposits constitute primary, intergranular aquifers with groundwater flow and storage largely controlled by orientation of clay minerals.

These theories will be expanded and quantified in Chapter 7.

4 STUDY AIMS AND OBJECTIVES

The overall objective of the study is to obtain an understanding of the hydrogeological and hydrogeochemical processes operating in the Hex River Valley to explain the observed deterioration in quality and quantity of the groundwater over the past 20 years and to assist in future groundwater resource management. The specific aims of the investigation can be summarised as follows:

- . define the utilisation of ground and surface water and their individual contributions to the annual irrigation requirements
- . identify aquifer units, their geometry and hydraulic connections, with particular reference to the alluvial deposits
- . quantify the hydraulic parameters of the aquifer(s), principally transmissivity, storage and leakage
- . assess the exploitability of groundwater within the alluvial deposits by means of boreholes equipped with well screens
- . identify and quantify recharge mechanisms and principal areas
- . define the interrelationships between the surface water and groundwater
- . obtain an understanding of the hydrogeochemistry of the ground/surface water system, relating this to sources of dissolved species, groundwater flow patterns, groundwater abstraction, influent and effluent seepage, recharge mechanisms, irrigation practice and age of the groundwater.

5 HYPOTHESES

Based on previous work carried out in the study area and application of basic hydrogeological principles, the following hypotheses have been formulated.

. Hydrogeology

- 1 There is hydraulic connection between the Table Mountain Group, the Bokkeveld Group and the alluvial deposits with aquifer conditions ranging from unconfined to semi-confined with leakage.
- 2 Discrete units exist within the Bokkeveld Group, with shales acting as aquicludes to the sandstone aquifers.
- 3 Structural control of permeability in the Table Mountain/Bokkeveld formations results in anisotropic groundwater flow conditions.
- 4 Recharge is mainly effected by rainfall infiltration on the mountainous areas of the Table Mountain Group.
- 5 Leakage from the alluvial deposits to the underlying bedrock is an important recharge mechanism.

. Hydrogeochemistry

- 6 Groundwater in the Bokkeveld Group is inherently of poor quality whilst that in the Table Mountain Group is of good quality.
- 7 The quality of the groundwater in the Bokkeveld Group improves with proximity to the Nardouw Sandstone.
- 8 Over-exploitation of the aquifer(s) has resulted in intrusion of poor quality water into the pumped aquifer(s).

6 INVESTIGATION APPROACH

The data collection phases of the investigation comprise a series of activities designed to satisfy the aims and objectives of Chapter 4 and test the hypotheses outlined in Chapter 5. The activities are presented in the logical sequence of execution.

6.1 Review of available information

The hydrogeology of the Hex Valley has been extensively investigated (Dziembowski, 1970; Vegter, 1974; Rosewarne, 1978, 1979). These investigations have provided a framework on which the aims and objectives and the hypotheses have been formulated. The above data are all site specific, however, and a broader overview is necessary of similar hydrogeological areas within South Africa to put the proposed investigation in a more 'global' context.

6.2 Hydrocensus

A census of all existing water points, eg boreholes, surface water abstraction points, generally marks the first field phase of a regional hydrogeological investigation. Borehole locations, depths, yields and pumping rates were ascertained as well as surface water usage from river pumps, diversion weirs etc.

6.3 Exploration drilling

Exploration drilling is carried out to obtain detailed information on the hydrogeology and hydrogeochemistry of the hard rock and alluvial formations. At each selected drilling site two boreholes were drilled. The first borehole was drilled through the alluvium, which was cased off, into the underlying bedrock formations. Where a substantial thickness of saturated alluvium was present, a second borehole was drilled to the base of the alluvium only. The latter boreholes were equipped with

well screens at sites selected for aquifer tests or with slotted casing where used for water level and water quality monitoring only.

6.4 Aquifer tests

A programme of constant discharge (followed by recovery) aquifer tests was undertaken on exploration boreholes penetrating both hard rock and alluvial formations, to provide data on hydraulic parameters for the various hydrogeological conditions thought to exist in the Valley. Appropriate analysis of aquifer test data provided transmissivity, storage and leakage values for use in quantitative hydrogeological and hydrogeochemical assessments.

6.5 Periodical measurements

Water level measurements in boreholes are available from as far back as 1962. Since 1975, monthly monitoring of approximately 150 private observation boreholes has been carried out. One of the prime uses of such data is the compilation of piezometric/water table contour maps. A number of important hydrogeological inferences can be made from such maps, chief among them being groundwater flow directions, recharge areas, groundwater/surface water relationships and aquifer response to pumping. In the Hex River Valley the months of September and April will be of most interest for compiling such maps as this corresponds to the beginning and end, respectively, of the pumping season, ie 'high' and 'low' water conditions within the aquifer(s). Piezometric maps can be superimposed to produce water level change maps to highlight recharge/discharge areas (Davis and De Wiest, 1966).

6.6 Water sampling

Ground and surface water quality is a very important aspect of the investigation. Adequate sampling is therefore essential

to provide a sound data base on which to make hydrogeochemical assessments. Groundwater samples are collected during exploration drilling at water intersections, during aquifer testing at the start, middle and end of the test and from private boreholes in the valley at the beginning and end of the pumping season. Surface water samples are also collected from stream gauging points. Samples may be collected for three types of analysis:

- . normal chemical analysis for pH, TDS and major cations and anions
- . tritium analysis for age dating
- . carbon 14 analysis, also for age dating.

In conjunction with the results of the hydrogeological study these data will give a higher level of confidence in the validity of conceptual aquifer and river/aquifer models.

7 HYDROGEOLOGY

7.1 Previous work

Hydrogeological investigations in the Hex River Valley have been carried out since 1961 by geologists and hydrogeologists of the Geological Survey and Department of Environment Affairs. Numerous reports have been produced, which are briefly summarised in the following paragraphs. As most of these investigations involved hydrogeology and hydrogeochemistry, both aspects have been included in this section.

Nieuwoudt (1961) carried out a hydrocensus during which hydrogeological data on 538 boreholes were obtained. Two aquifers were recognised, viz alluvial deposits and the Bokkeveld formations. Groundwater storage in the alluvium was estimated at $10 \times 10^6 \text{ m}^3$.

Vegter (1965) proposed the following action for continuation and extension of groundwater research in the Hex River Valley:

- . developing groundwater supplies in alluvial deposits by experimenting with well screens and aquifer tests
- . estimating the total available groundwater supplies
- . artificial recharge by excess flood waters during the winter months.

In 1966, seven boreholes were drilled along profiles in the Orchard and Buffelskraal areas. The boreholes were drilled to the base of the alluvium and limited hydrogeological data collected.

Van der Spuy (1970) and Dziembowski (1970) carried out a survey of shallow wells penetrating only the alluvial deposits, obtaining water levels and water samples from 50 wells. The

groundwater potential of the alluvium, recharge mechanisms and water quality were investigated.

Pienaar et al (1972) sampled groundwater from all pumping boreholes in 1970 and again in 1971 to determine any quality changes during the pumping season. No significant changes in quality were noted.

Vegter (1974) reviewed the available information on the hydrogeology and hydrogeochemistry of the Hex River Valley. Water levels were found to have dropped an average 32,6 m between July 1961 and July 1973. The range of TDS in the aquifer formations was 15 - 131 mg/ℓ in the Table Mountain Group; 70 - 1 684 mg/ℓ in the Bokkeveld Group and 19 - 1 298 mg/ℓ in the alluvium.

An Interdepartmental Committee report (1975) also analysed previous work and questionnaires sent out to 161 farmers in the Valley. Total annual water-use was estimated to be $29 \times 10^6 \text{ m}^3$ of which 70% was obtained from groundwater sources, viz Table Mountain/Bokkeveld formations.

Rosewarne (1978) reported on the results of a new exploration programme initiated in 1975. The programme involved drilling, extensive monthly water level measurements in boreholes, surface water gauging and water sampling.

Bredenkamp (1979) concentrated on the hydrogeochemical aspects of ground and surface water in the Valley employing radioactive (^3H and ^{14}C) and stable (^{18}O) isotope studies to supplement normal chemical data.

Rosewarne (1979) investigated groundwater conditions in the Groothoek area with particular reference to aquifer response to pumping, water level fluctuations and groundwater occurrence in the alluvium. Six exploration boreholes were drilled.

7.2 Exploration drilling

7.2.1 Principles of exploration drilling

Exploration drilling is carried out to satisfy two objectives (Johnson Division, 1972): the work may be part of the hydrogeological study of an area, or it may be preliminary to design and construction of one or more wells at a particular site. In the present study the former is the case; drilling was carried out to obtain specific hydrogeological and hydrogeochemical information, well screens, for example, being removed from alluvial "production" boreholes after completion of aquifer tests.

In exploratory water borehole drilling, the primary data to be obtained are (Johnson Division, 1972):

- . log of the strata penetrated
- . representative samples of the strata penetrated
- . depth to water intersections, estimation of yields and variation with drilling depth
- . samples of groundwater from water intersections for field testing of pH and conductivity and/or laboratory chemical analysis

The drilling method employed was the cable-tool percussion method. The alternative drilling method commonly used in South Africa, air rotary drilling, could not be used owing to the large thickness of unconsolidated alluvial deposits at most of the drilling sites. Drilling with air as the circulating fluid can only be done in consolidated materials (Johnson Division, 1972).

7.2.2 Exploration drilling programme

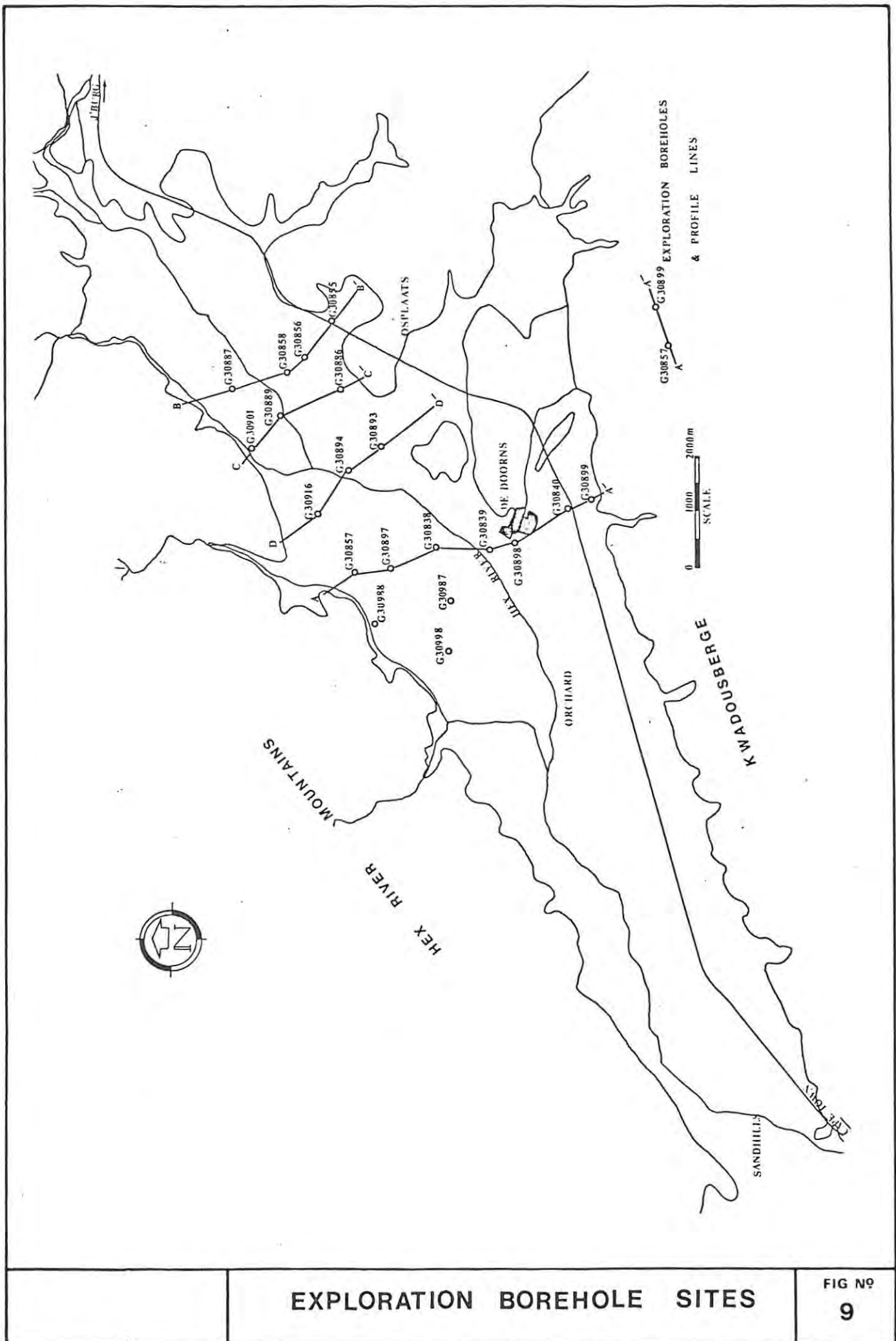
Exploratory drilling was carried out along four profiles A to D, between De Doorns and Buffelskraal (Fig 9). The profiles are presented in Appendix A. The De Doorns/ Buffelskraal area was chosen for the drilling as this was one of the main areas affected by deteriorating groundwater quality and existing observation boreholes were sparse, especially in the alluvial deposits and south of the Hex River. The exploration drilling was carried out in profiles normal to the valley trend for the following reasons:

- . a line of test holes normal to a valley trend is more likely to disclose important variations in thickness of alluvial material than if drilling is done parallel to the trend of the valley (Johnson Division, 1972)

- . the valley trend parallels the trend of the synclinal structure, therefore, drilling along profiles normal to this trend would yield most information on hydrogeological and hydrogeochemical variation in the aquifer formations.

The first borehole at each site was drilled through the alluvium, which was cased off, into the underlying bedrock formations to varying depths (84 m to 187 m). The bedrock was left uncased below the top few metres of weathering. Where there was saturated alluvium present, a second borehole was drilled to the base of the alluvium and slotted casing was installed so that the borehole could be used as a piezometer.

Alluvial boreholes selected for aquifer tests were equipped with Johnson well screens. The slot sizes were selected on the basis of size analyses carried out on



EXPLORATION BOREHOLE SITES

FIG NO
9

sand samples obtained with a sample tube. As the alluvial deposits are poorly sorted ranging from silt to coarse gravel, the boreholes could be naturally developed. Screen slot sizes were chosen to retain 40% of the aquifer. Slot No 20 (0,5 mm) was found to be suitable for four of the boreholes, G30889B, G30894, G30897, G30916 while the fifth production borehole G30839E was equipped with slotted casing.

As the alluvial aquifer was thought to be essentially a water table aquifer, the bottom third of the aquifer was screened providing the optimum design for this situation. (Johnson Division, 1972).

Some general statistics of the drilling programme are given in Table 2.

Number of boreholes drilled	56
Boreholes for aquifer testing	12
Observation boreholes at aquifer test sites	27
General exploration/observation boreholes	17
Total metres drilled	3 563
- in alluvium	1 381
- in bedrock	2 182

TABLE 2 : GENERAL STATISTICS OF THE DRILLING PROGRAMME

7.3 Hydrocensus

The inventory of all farms in the Hex Valley during January to April 1980 produced the following general information:

- . farms inventoried : 141
- . private boreholes : 621 of which 401 were in use
- . wells : 24 of which 8 were in use
- . river points : 9 (pumps, diversion weirs, irrigation schemes)

The total surface under irrigation is 3 100 ha made up as follows:

vines - 2 913 ha
 fruit - 104 ha
 grass - 70 ha
 vegetables - 13 ha

Therefore a total of 94% is occupied by vineyards.

Groundwater is obtained in the main by deep boreholes penetrating through the alluvium, which is cased off, into the underlying bedrock. The survey showed that little use is made of wells in the alluvium at the moment. In 1961 there were 16 wells in use while in January/April 1980 only 8 were being pumped. All existing wells only partially penetrate the alluvial aquifer and in the Groothoek area are often above the water table. The wells normally consist of pits 5 m to 7 m deep and 1,5 m in diameter equipped with centrifugal pumps. Yields of 3,6 l/s to 5 l/s are average, rising from 25 l/s to 38 l/s in the Sandhills area.

Most of the boreholes have been drilled by the percussion method and are generally of 152 mm diameter. The depths (production boreholes only) are as follows:

Depth (m) of boreholes	<99	100-149	150-199	200-249	>250
%	14	27	40	15	4

TABLE 3 : DEPTHS OF BOREHOLES

This contrasts with an earlier survey when only 1,7% of existing boreholes (>500 at the time) were more than 150 m deep (Nieuwoudt, 1961). The present survey shows that the figure is

now 59%. This indicates that existing boreholes have been deepened and new ones drilled to greater depths than was previously the case, most probably due to diminishing yields at shallower depths due to a combination of increase in abstraction, interference between closely spaced boreholes and reduced natural recharge.

Most boreholes are equipped with submersible pumps. Present yields of boreholes are given in Table 4. The yield here is taken as that supplied by the farmers for current usage and is not the tested yield.

Yield ℓ/s	< 2,5	2,6-5,3	5,4-8,0	8,1-10,8	10,9-13,6	>13,7
%	11	31	22	16	11	9

TABLE 4 : YIELDS OF BOREHOLES

When compared to the figures for the 1961 survey, it can be seen that the number of high-yielding boreholes has decreased. At that time 36% of boreholes had yields of more than 10,9 ℓ/s . In 1980 the figure was 20%.

The data obtained during the 1980 borehole inventory on yields and the duration of pumping enables an estimate of the annual groundwater abstraction to be made. The figure obtained by this method is $31 \times 10^6 \text{ m}^3$.

However, random borehole yield measurements taken during the hydrocensus showed an average 35% decrease in yield from that given by the owner. If the estimation for annual groundwater abstraction is adjusted for an average decrease in yield of 35%, a figure of $20 \times 10^6 \text{ m}^3$ is obtained. This figure will be used in later estimations of natural recharge.

Surface water is utilised by a number of Irrigation Boards and a few river pumps extract water from the Hex River. An estimation of the average quantity of surface water utilised annually was made from surface water gaugings and dam capacities. The figure derived for average annual surface water consumption was $10 \times 10^6 \text{ m}^3$.

7.4 Aquifer tests

Aquifer tests may be carried out to satisfy two main objectives; firstly to test the performance of the pumped borehole and secondly, to obtain information on aquifer hydraulic properties (Johnson Division, 1972).

The first type of test, known as a step drawdown test, involves increasing the pump rate in a borehole in a step-wise fashion over equal time increments whilst measuring the accompanying fall in water level in the pumped borehole. Appropriate analysis of the drawdown/discharge data allows differentiation of the two components of the total drawdown in a pumped borehole, namely aquifer losses and well losses (Jacob 1947). The well loss calculation is essential in the analysis of constant discharge aquifer tests on pumping boreholes with no observation boreholes. Knowledge of the well loss component of drawdown allows correction of drawdown data to yield the true aquifer drawdown (Clarke 1977). The calculation of transmissivity in solitary boreholes ignoring the well loss leads to underestimation of transmissivity. As there was a minimum of one observation borehole at each test site and the pumped boreholes were not intended for permanent production status, step drawdown tests were not carried out in this investigation.

The second type of test involves pumping a borehole at a constant discharge, for a period of at least 24 hours, and preferably longer, while measuring the decline in water level in nearby observation boreholes, as well as the pumped borehole. Appropriate analysis of this data allows computation

of the aquifer hydraulic properties, principally transmissivity and storage. Water level recovery is usually measured after the pump is shut off at the end of a constant discharge test. The data so obtained provide a check on the transmissivity computed from the drawdown data and are often more reliable as fluctuations in pumping rate are eliminated (Kruseman and De Ridder 1979). Constant discharge and recovery tests were the only aquifer tests carried out during this investigation.

7.4.1 Aquifer test programme

Constant discharge tests were carried out on 12 boreholes during the investigation. The test sites were selected mainly on the basis of lithological logs and water intersections, to provide a comprehensive coverage of expected aquifer conditions, ie fractured rock aquifer(s) within the Table Mountain/Bokkeveld formations, leaky fractured rock aquifers in areas overlain by saturated alluvium and the different types of alluvial deposits. Details of the aquifer test sites are given in Table 5.

Borehole No	Test duration (hrs)		Observation boreholes	Discharge l/s	Formation
	Drawdown	Recovery			
G30840	72	72	3	8,3	Gydo Shale
G30855	37	48	2	6,7	Voorstehoek Shale
G30898	25	72	2	5,5	Voorstehoek Shale
G30899	72	72	2	6,8	Gydo Shale/Nardouw
G30987	24	24	1	6,5	Voorstehoek Shale
G30998	20	4	2	8,0	Voorstehoek Shale
G30839	24	24	2	0,5	Mixed alluvium
G30889	49	49	2	2,0	Mixed alluvium
G30894	25	24	2	4,0	Mixed alluvium
G30897	24	6	1	7,3	TM alluvium
G30916	72	24	2	2,6	TM alluvium
G30987B	10	10	1	8,0	TM alluvium

TABLE 5 : AQUIFER TEST DETAILS

A pumping duration of 24 hours was taken as an absolute minimum but at G30998 and G30987B this was not possible, because of mechanical breakdown of the pump and interference by nearby private pumping boreholes.

Discharge rates were selected from yields obtained during development work in the case of alluvial boreholes, and from short duration (4 hours) 'drillers' pump tests in the case of boreholes in the Table Mountain/Bokkeveld formations.

Selected examples of drawdown response to pumping are illustrated in Section 7.4.3. The remaining test results are presented in Appendix B.

7.4.2 Theory of aquifer test analysis

When a borehole in a confined aquifer is pumped at a constant rate, the 'cone' of influence of the discharge extends outwards with time. The rate of decline of head multiplied by the storage coefficient and summed over the area of influence is equal to the discharge (Todd, 1980). The applicable differential equation is (Todd, 1980):

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r} \frac{\partial h}{\partial r} = \frac{S}{T} \frac{\partial h}{\partial t} \quad \dots (1)$$

where h is head, r is radial distance from the pumped borehole to the point of observation, S is the storage coefficient, T is transmissivity and t is time since pumping started.

Theis (1935), in what can be considered as a fundamental breakthrough in the science of hydrogeology (Freeze and Cherry, 1979), derived a solution to Eq (1) based on analogy to the conduction of heat. The Theis, or non-steady state, equation may be written as:

$$h_0 - h(r,t) = \frac{Q}{4\pi T} \int_u^\infty \frac{e^{-u}}{u} du \quad \dots (2)$$

$$\text{where } u = r^2 S / 4Tt \quad \dots (3)$$

The parameters of the Theis equation are illustrated diagrammatically in Fig 10.

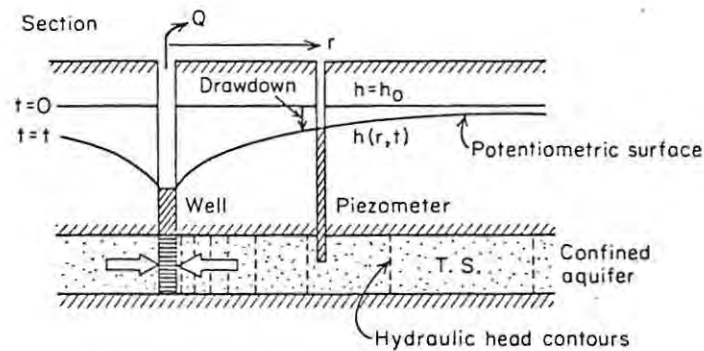


FIG 10 : PARAMETERS FOR THE THEIS EQUATION (from Freeze and Cherry, 1979)

The integral in Eq (2) is called the exponential integral. For the specific definition of u given in Eq (2) the integral is known as the well function, $W(u)$. With this notation Eq (2) becomes:

$$h_0 - h = \frac{Q}{4\pi T} W(u) \quad \dots (4)$$

The Theis solution is based on the following assumptions (Theis, 1935):

- . the aquifer is homogeneous and isotropic
- . the aquifer has infinite areal extent (practically its boundaries are beyond the effects of the pumping borehole)
- . the discharging well penetrates the entire thickness of the aquifer
- . the borehole has infinitesimal diameter, ie storage in the borehole can be neglected
- . the water removed from storage is discharged instantaneously with decline in head.

Rewriting Eq (3) and (4) the storage and transmissivity may be determined from:

$$S = \frac{4Tt}{r^2} \frac{1}{u} \quad \dots (5)$$

$$\text{and } T = \frac{Q}{4\pi h_0 - h} W(u) \quad \dots (6)$$

Direct solutions to Eq (5) and Eq (6) are not possible. Theis developed a graphical method of superposition that makes it possible to obtain solutions to these equations.

If the discharge Q is constant, then the drawdown $h_0 - h$ is related to t in a similar manner to the relation of $W(u)$ to $1/u$. A plot of $W(u)$ against $1/u$ is known as a type curve (Fig 11). Because of the relationship

described above, a plot of the observed drawdown against time will be similar to the type curve. The observed data plot is placed over the type curve and, keeping co-ordinate axes of both data plot and type curve parallel, the position of best fit between the two is located. An arbitrary match point is then selected and the co-ordinates $W(u)$, $1/u$, h_0-h and t are determined for this point. Substitution of these values into Eq (5) and Eq (6) enables determination of T and S .

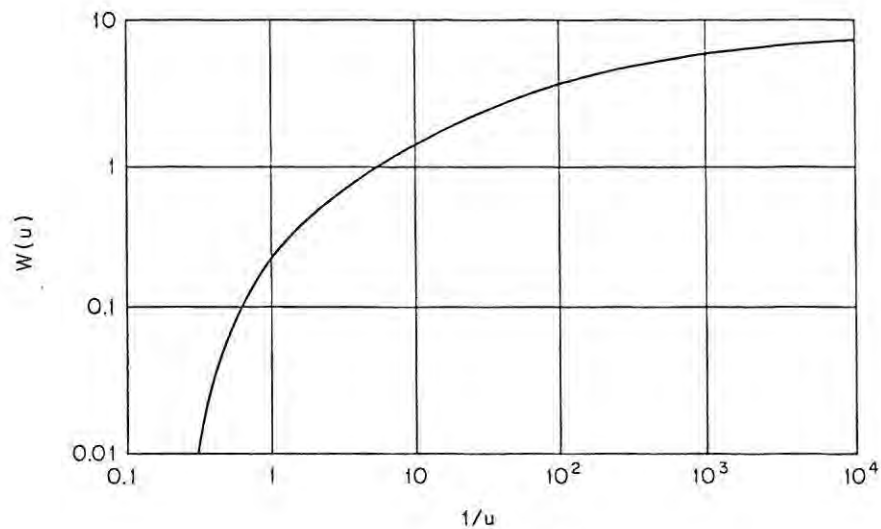


FIG 11 : THEIS TYPE CURVE

The assumption inherent in the Theis solution, ie that the formations overlying and underlying a confined aquifer are completely impermeable, is seldom satisfied (Kruseman and De Ridder, 1979). Aquifers that receive groundwater inflow from adjacent beds are called 'leaky' or semi-confined aquifers. The modified Theis equation applicable to these aquifers is (Walton, 1962):

$$h_0 - h = \frac{Q}{4\pi T} W(u, r/L) , \quad \dots (7)$$

Where $W(u, r/L)$ is the well function for leaky aquifers and L is the so-called leakage factor, which determines the distribution of the leakage into the semi-confined aquifer (Kruseman and De Ridder, 1979). Large values of L indicate that the influence of leakage will be small. Walton (1962) developed a similar graphical method of solution as for the Theis equation but instead of one type curve there is a type curve for each value of r/L (Fig 12).

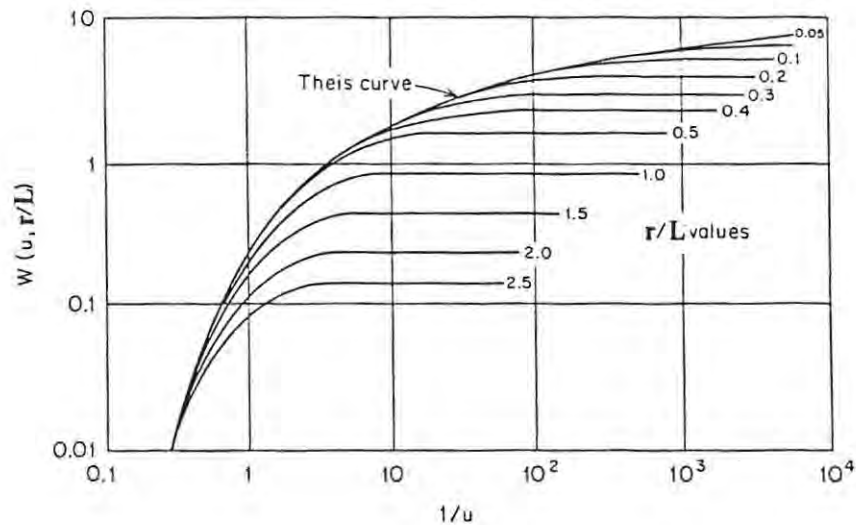


FIG 12 : WALTON 'LEAKY' AQUIFER TYPE CURVES

A second assumption of the Theis solution, that water is released from storage instantaneously with decline in head, is also not satisfied in some aquifers (Boulton, 1963). These aquifers are termed unconfined aquifers with delayed yield. In these aquifers gravity drainage from pore interstices is not instantaneous. Boulton (1963) introduced a method of analysing aquifer test

data in which allowance is made for delayed yield from storage due to slow gravity drainage. The applicable equation is:

$$h_0 - h = \frac{Q}{4\pi T} W(u_{AY}, r/B) \quad \dots (8)$$

where $W(u_{AY}, r/B)$ is the 'well function of Boulton' and B is the drainage factor and is analogous to the leakage factor of semi-confined aquifers. Large values of B indicate a fast drainage. As with the Walton method of analysis, there is a family of type curves for each value of r/B (Fig 13).

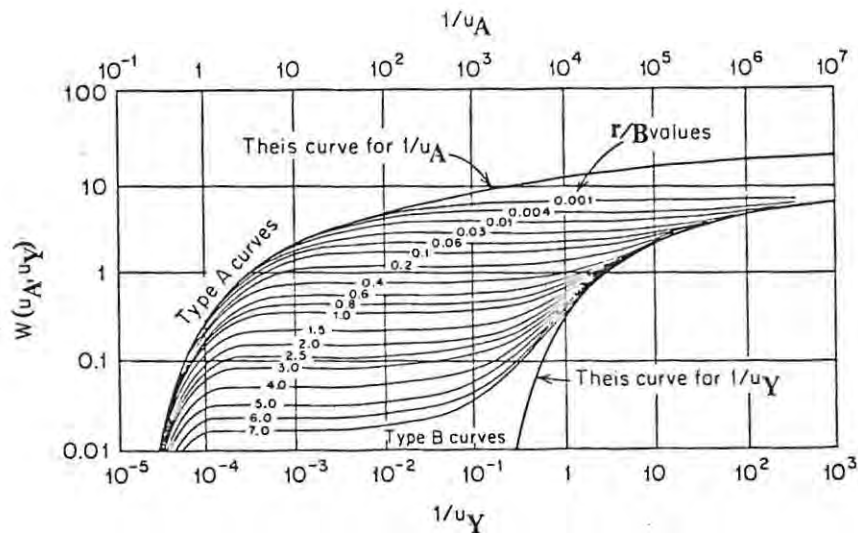


FIG 13 : BOULTON TYPE CURVES

Once the pump has been shut down the water level in a borehole will cease dropping and start rising again towards its original position. This is the so-called recovery of the borehole. This recovery can be measured as residual drawdown $\Delta s''$, which is the difference

between the original water level prior to pumping ($t = 0$) and the water level measured at a certain time t' since pumping stopped.

According to Theis (1935) the transmissivity is given by:

$$T = \frac{2,30 Q}{4 \pi \Delta s} \quad \dots (9)$$

Residual drawdown, $\Delta s'$, is plotted on semi-logarithmic paper versus t/t' (where t is time since pumping started) and a straight line fitted through the points. The term $\Delta s'$ is the residual drawdown difference per log cycle of t/t' . No value for storage can be obtained with this method.

The above discussion of aquifer test solutions is strictly applicable only to homogenous, isotropic aquifers. Use of these methods to analyse aquifer test data from naturally fractured aquifers can lead to significant errors (Gringarten and Witherspoon, 1972). The flow of groundwater in a fractured rock aquifer may be linear towards a natural production surface (fracture) rather than radial towards a pumping borehole (Jenkins and Prentice, 1982). Gringarten and Witherspoon (1972) have developed a practical method for such aquifer test analysis where the pumped borehole intersects either a vertical or a horizontal fracture.

The type curves are characterised by an initial half unit slope indicating linear flow from the reservoir matrix into the fracture, with the latter part of the curve corresponding to the Theis solution.

The following relations are valid for a vertical fracture situation (Gringarten and Witherspoon, 1972).

$$\sqrt{T_x T_y} = \frac{Q S_D}{4\pi s} \quad \dots (10)$$

where $\sqrt{T_x T_y}$ is the geometric mean of the maximum and minimum transmissivities,

$$\text{and } \frac{T_x}{S x_f^2} = \frac{t_D}{t} \quad \dots (11)$$

where S = storage and x_f is the half length of the vertical fracture. The second equation can be solved if a value for S is available. The type curve is illustrated in Fig 14.

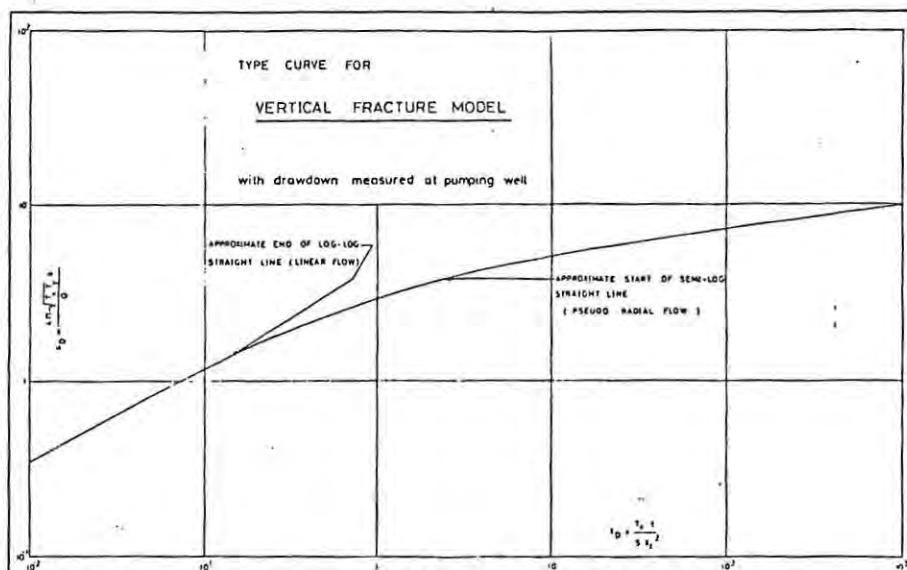


FIG 14 : VERTICAL FRACTURE TYPE CURVE

For the horizontal fracture case the following relations are valid:

$$\sqrt{T_r T_z} \text{ rf} = \frac{Q S_D}{4\pi s} \quad \dots (12)$$

where rf is the horizontal fracture radius,

$$\text{and } \frac{Tr}{S_s r_f^2} = \frac{t_D}{t} \quad \dots (13)$$

where S_s is specific storage.

The term H_D is also used which represents dimensionless aquifer (fracture) thickness. The type curve is illustrated in Fig 15.

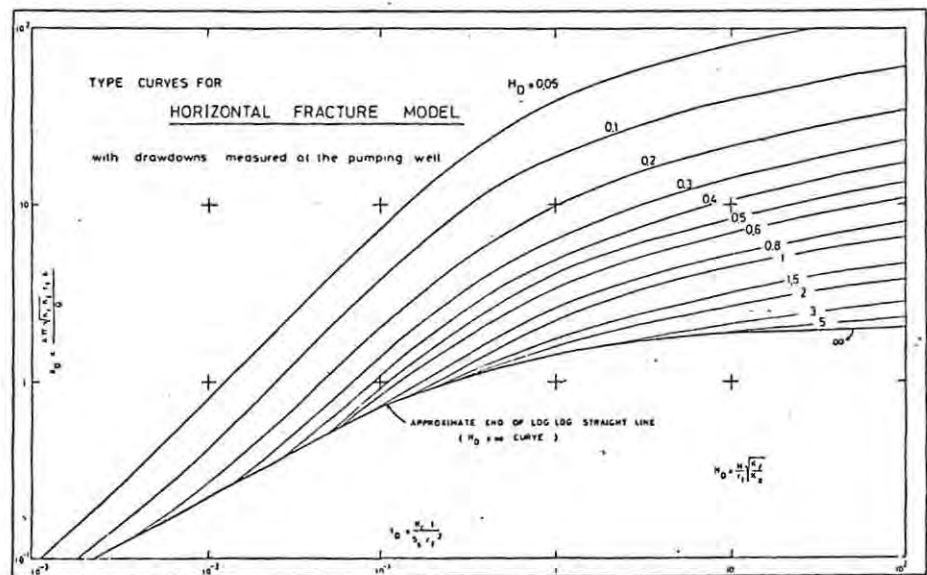


FIG 15 : HORIZONTAL FRACTURE TYPE CURVES

The subscripts x , y , z and r refer to the x , y , z or r directions in the aquifer, and D = dimensionless.

The expressions on the left hand side of the equations can only be completely solved if data are available from observation boreholes from which values of T_x , T_r , S and S_s can be calculated. This is possible if the observation boreholes are far enough from the pump borehole and do not intersect the same fracture. In this case the Theis method of analysis can be used, as drawdown is the same as that created by a line source well in a homogeneous reservoir with isotropic radial permeability, K_r (Gringarten and Witherspoon, 1972).

7.4.3 Aquifer test results

The transmissivity and storage parameters presented in this section are the averages calculated from the Theis non-equilibrium and Theis residual drawdown methods of analysis. In the case of leaky or fractured aquifer response, the drawdown data were analysed with appropriate type curve matching only. The hydraulic parameters calculated from analysis of the alluvial aquifer tests are presented in Table 6. These parameters will be used for quantitative hydrogeological assessments in Chapters 7 and 8.

Borehole No	Saturated thickness (m)	Transmissivity (m^2/day)	Permeability (m/day)	Storage coefficient (specific yield for unconfined aquifer)
G30839E	3	20	7	1×10^{-3}
G30889B	27	252	9,3	9×10^{-3}
G30894	29	220	6,1	$3,2 \times 10^{-3}$
G30897	18	250	14	$S_A=8,10^{-3}$ $S_y=1 \times 10^{-1}$
G30916	18	220	12,2	2×10^{-2}
G30987B	29	280	9,9	$1,3 \times 10^{-2}$

TABLE 6 : HYDRAULIC PARAMETERS - ALLUVIUM

The range of transmissivity is large in the alluvial deposits, ranging from 20 to 280 m^2/day . As the saturated thickness of the alluvium varies considerably and transmissivity is the product of saturated thickness and permeability, comparison of permeability, K, is particularly relevant. The range of K is 6 m/day to 14 m/day, with the higher values obtained in alluvium derived from the Table Mountain Group.

The storage coefficients, or specific yields, calculated are representative of unconfined to semi-confined conditions, ie within the range 1×10^{-3} to 1×10^{-1} . No true confined aquifer conditions were encountered, where storage coefficients are usually in the range 10^{-4} to 10^{-5} .

Differing aquifer responses to pumping are illustrated in Fig 16 and Fig 17. Fig 16 shows a time-drawdown plot for observation borehole G30894C (mixed alluvium). The observed data show a very good match with the Theis type curve, although the computed storage coefficient of $3,2 \times 10^{-3}$ is rather high for true confined aquifers. The Theis solution can be applied to unconfined aquifers if the reduction in aquifer thickness, and therefore transmissivity, with fall in head is taken into account. This is achieved by applying a correction to the observed drawdown, which is given by (Jacob, 1944):

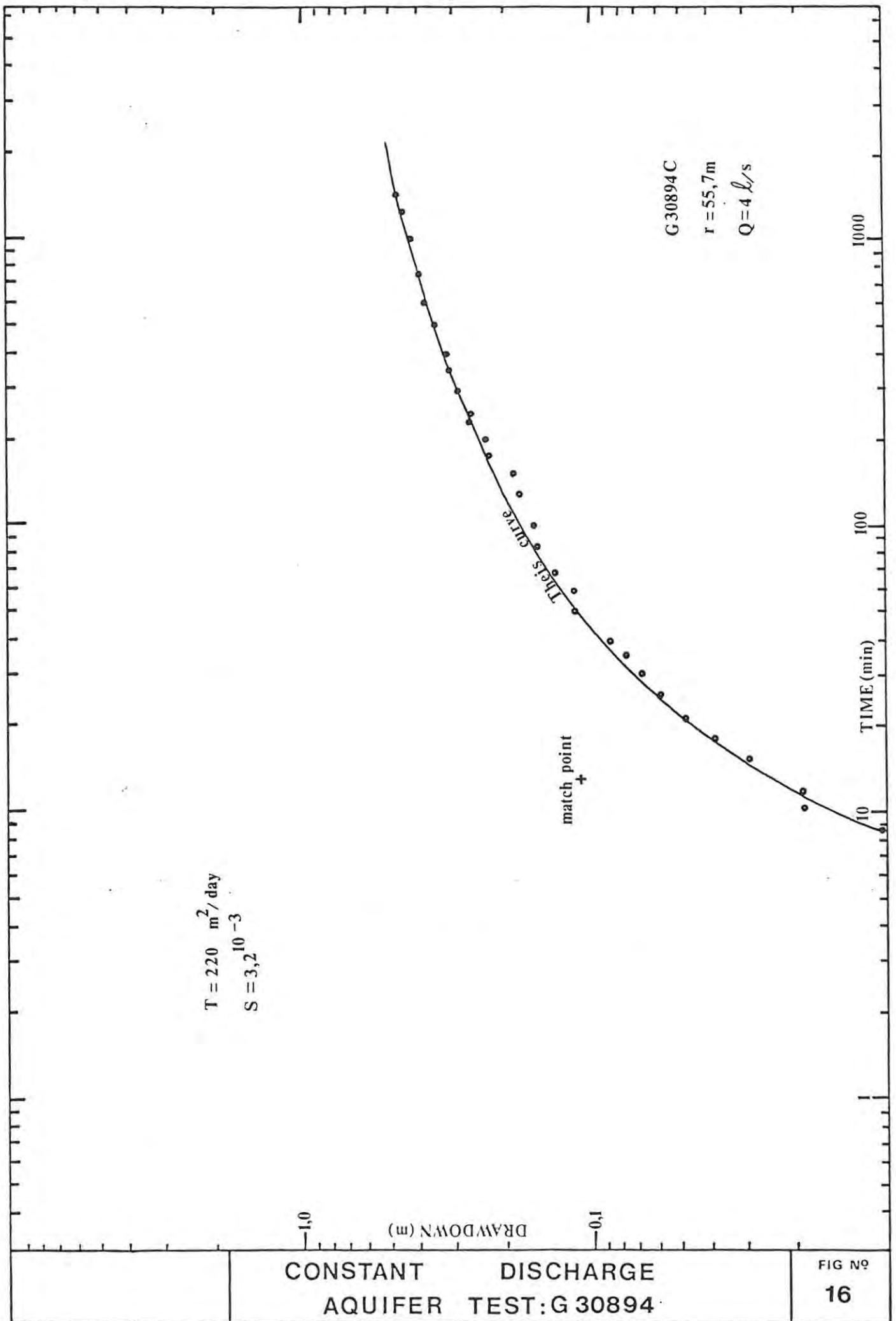
$$s_c = s - \frac{s^2}{2D} \quad \dots (12)$$

where s_c is corrected drawdown and D is saturated aquifer thickness prior to the test.

However, in the case of G30894C, no correction was applied as the ratio of drawdown to original saturated thickness is very small (1:40).

Fig 17 shows a time-drawdown plot for observation borehole G30897 (Table Mountain alluvium).

The first segment of the curve follows a typical 'Theis' response, indicating that an unconfined aquifer reacts initially in the same way as a confined aquifer. Water is released instantaneously from storage by compaction of the aquifer and expansion of the water. The second segment of the curve shows a decrease in slope because



CONSTANT DISCHARGE
AQUIFER TEST: G 30894

FIG No
16

of gravity drainage from the interstices above the cone of drawdown. The third segment again conforms to the predicted Theis response and there is equilibrium between gravity drainage and the rate of fall of the water table.

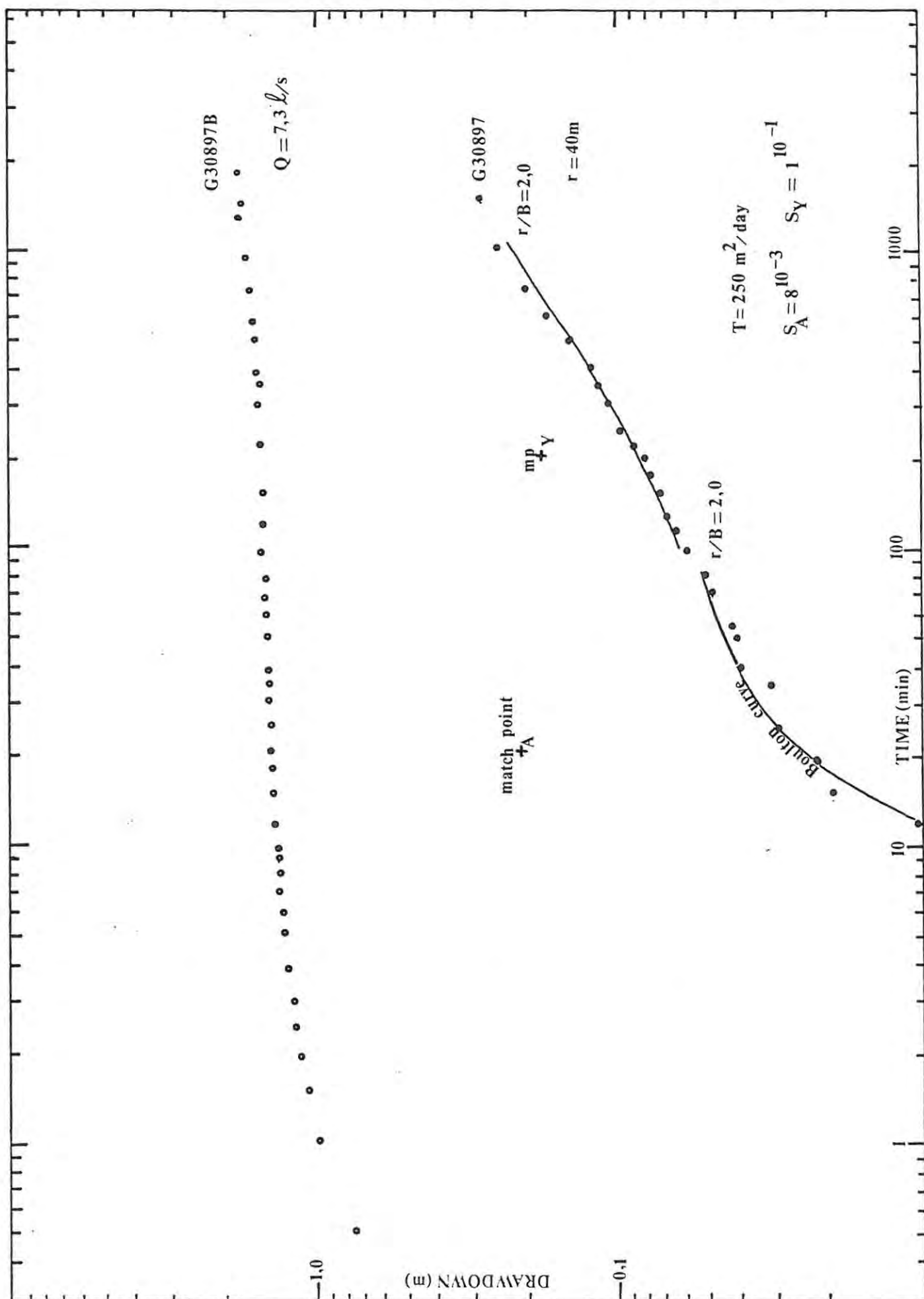
Aquifer tests carried out in Table Mountain alluvium of the Rawsonville/Goudini area, near Worcester, indicated similar aquifer responses to pumping (BRGM, 1976; Rosewarne, 1981)

The hydraulic parameters of the fractured rock aquifers, calculated from aquifer test analysis, are given in Table 7.

Borehole No	Tr m ² /day	Tx m ² /day	Tz m ² /day	S	rf (m)	xf (m)	L (m)	c (days)
G30840	40	-	-	3x10 ⁻³	-	-	-	-
G30855	23	-	1,8x10 ⁻³	1,3x10 ⁻⁴	73	-	-	-
G30898	32	-	-	3x10 ⁻⁴	-	-	-	-
G30899	-	55	1	-	-	47	-	-
G30987	56	-	-	1x10 ⁻³	-	-	135	304
G30998	110	-	-	3,5x10 ⁻⁵	-	-	10 066	10 577

TABLE 7 : HYDRAULIC PARAMETERS - BEDROCK AQUIFER

The transmissivity (Tr) range is 23 m²/day to 110 m²/day and therefore apparently lower than that of the overlying alluvial deposits. The storage coefficients are mostly indicative of confined aquifer conditions.



CONSTANT DISCHARGE
AQUIFER TEST: G30897

FIG NO
17

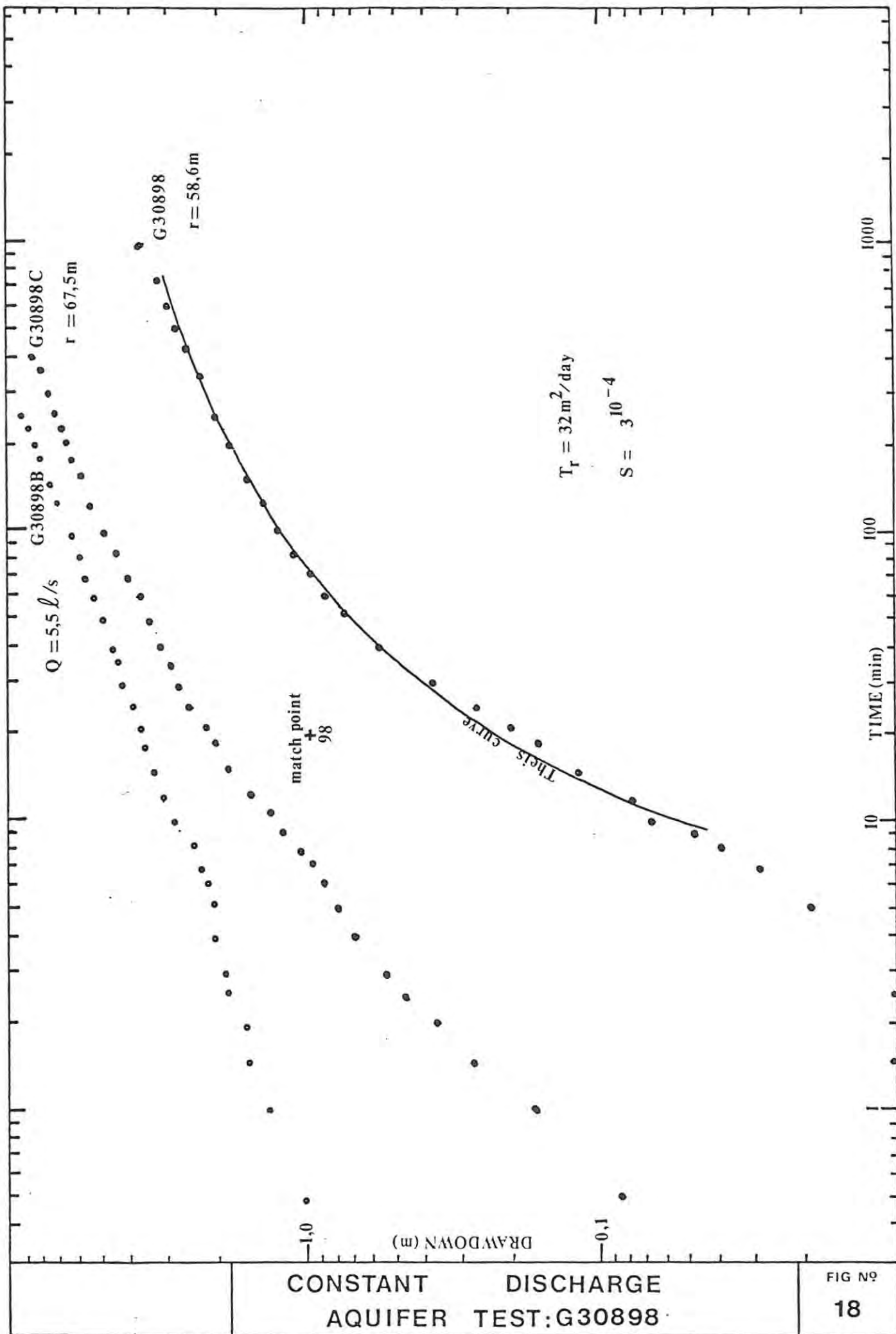
The fractured rock aquifer(s) showed a more varied response to pumping than did the alluvium. Some examples are discussed below.

The boreholes at site G30898 were drilled into the Voorstehoek Shale and there is no saturated alluvium overlying the bedrock at this site.

The drawdown in observation borehole G30898C is very interesting. Its drawdown is larger than observation borehole G30898B although it is situated further from the pumped borehole. Fig 18 shows that from about 10 minutes after pumping started the drawdown at G30898C is only slightly less than in the pumped borehole. If well losses at G30898B were taken into account the difference in drawdown would be even less. This type of response indicates that borehole G30898C is located on the same fracture as G30898B (Bonnet, 1977). The drawdown plot of G30898B shows a half unit slope straight line at early time, indicating that the borehole is located inside a fracture (Gringarten and Witherspoon, 1972).

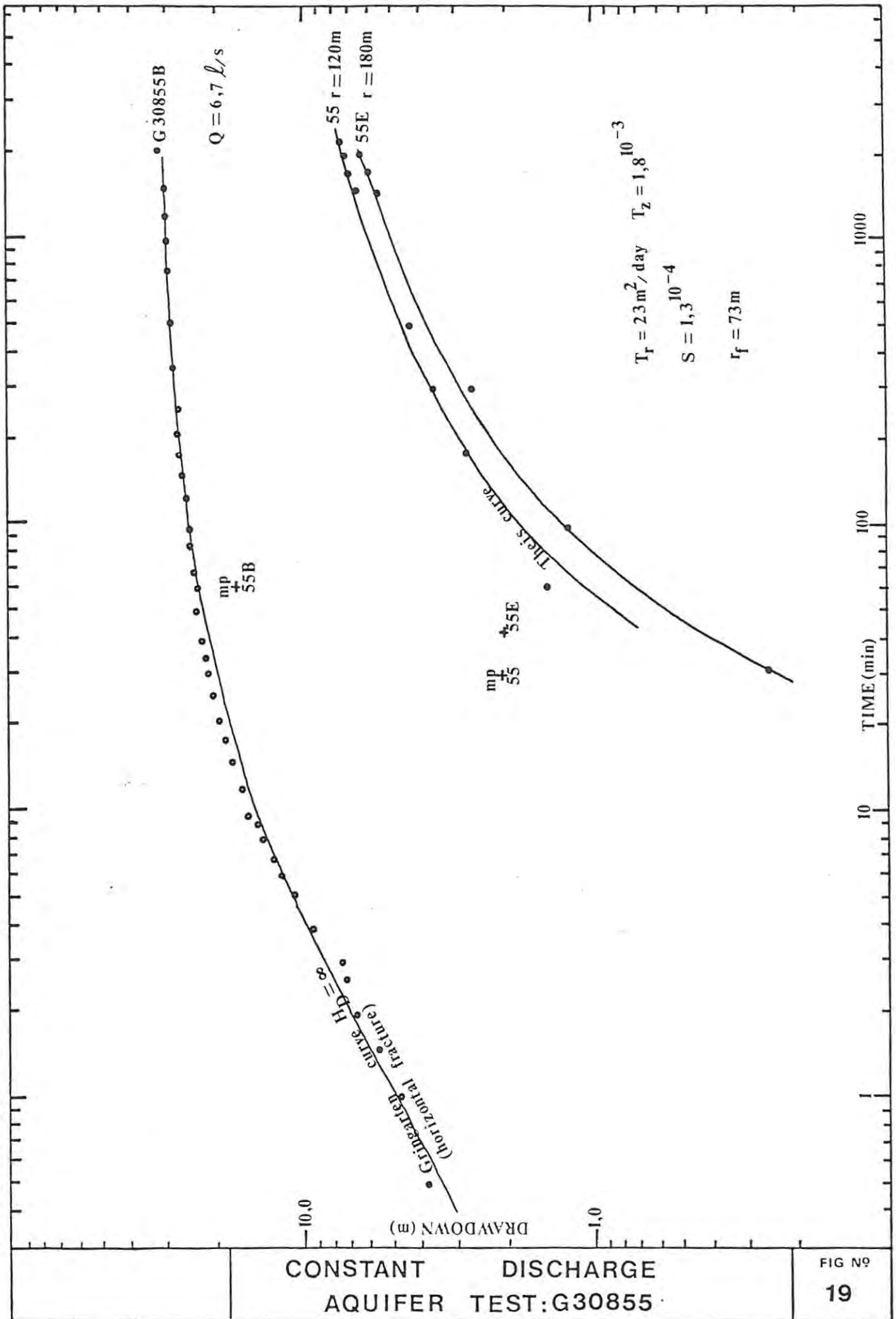
The drawdown plot for G30898 shows a fairly typical Theis response and indicates that the borehole is not located on the same fracture and that radial flow conditions are predominant. The Theis method of analysis was used for this borehole. Drawdown response at this site gives evidence of the anisotropic nature of the fractured aquifer. Further evidence of anisotropy is discussed in the section on groundwater levels.

A time drawdown plot for site G30855 (Fig 19) also shows an initial half unit slope and thereafter shows a drawdown response typical of a borehole intersecting a horizontal fracture (Gringarten and Witherspoon, 1972). The mere fact that a good match is obtained with a particular type of curve is no indication that the



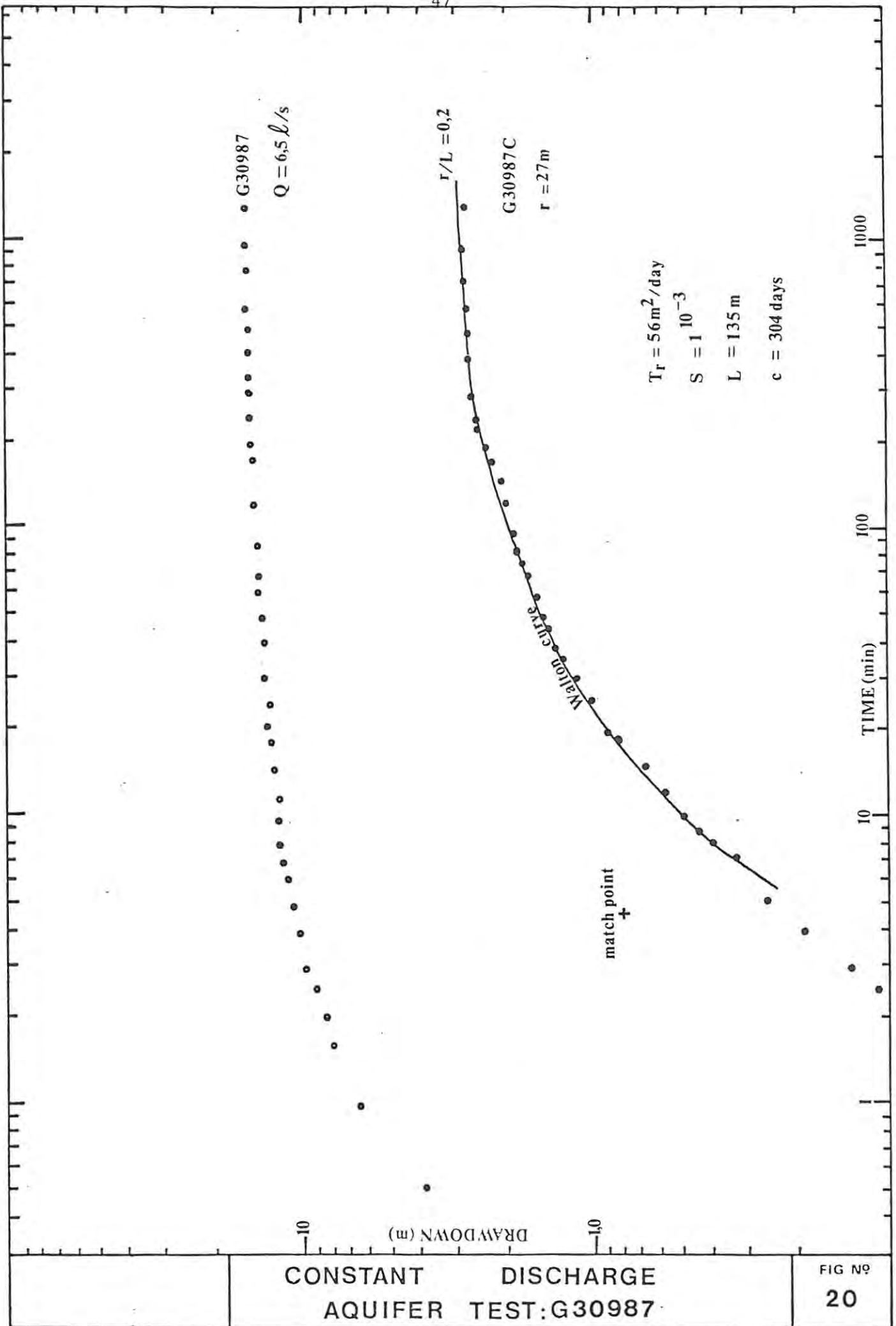
CONSTANT DISCHARGE
AQUIFER TEST: G30898

FIG Nº
18



governing conditions for application of a particular method of analysis are satisfied (Gilding, 1979). However, evidence from water intersections at this site and the shallow dip of the strata (18°), plus the observed response to pumping, suggests that G30855B has intersected a sub-horizontal fracture probably developed along a bedding plane. The responses of G30855 and G30855E have been matched with the Theis type curve, as suggested by Gringarten and Witherspoon (1972). Substitution of match point co-ordinates into Eq (12) and Eq (13) gives a fracture radius of 73 m.

The drawdown response to pumping at test site G30987 is shown in Fig 20. The drawdown of both the pumped borehole and the observation borehole G30987C shows a distinct levelling off and departure from the predicted Theis response. The pump rate was kept constant, there were no rainfall events prior to or during the test and the abstracted water was discharged 300 m 'downstream' of the test site. Therefore recirculation can be ruled out. Both G30987 and G30987C penetrate the Gydo Shale, which is overlain by 30 m of saturated alluvium at this site. This fact and further hydrogeologic evidence discussed in Sections 7.5 and 7.7 indicates that the drawdown in the Gydo Shale is being affected by leakage from the overlying alluvium. The drawdown data from the observation borehole, G30987C, was therefore matched with Walton type curves for leaky artesian aquifers. The leakage factor, L , was calculated to be 135 m. This is a low figure, indicating that leakage is an important mechanism at this site (Kruseman and De Ridder, 1979). The hydraulic parameters calculated at this site and G30998, where a similar response to pumping was noted, are used for quantitative estimation of leakage in Section 7.7.



A final example of response of the fractured aquifer to pumping is that of site G30899. There is no saturated alluvium at this site and the main water intersection was at 90 m, at the transition from the Gydo Shale to the Nardouw Sandstone. The drawdown plot of the pumped borehole is shown in Fig 21. The plot shows a half-unit slope typical of a pumped borehole intersecting a fracture. The Gydo Shale/Nardouw Sandstone contact is dipping at about 45° at this site. The pumped borehole therefore does not truly intersect a vertical fracture. However, the drawdown at G30899 shows a good match with the Gringarten and Witherspoon type curve for a vertical fracture and this type of analysis was used. Substitution of match point co-ordinates and a storage coefficient averaged from G30855 and G30898 indicates a fracture length of 94 m.

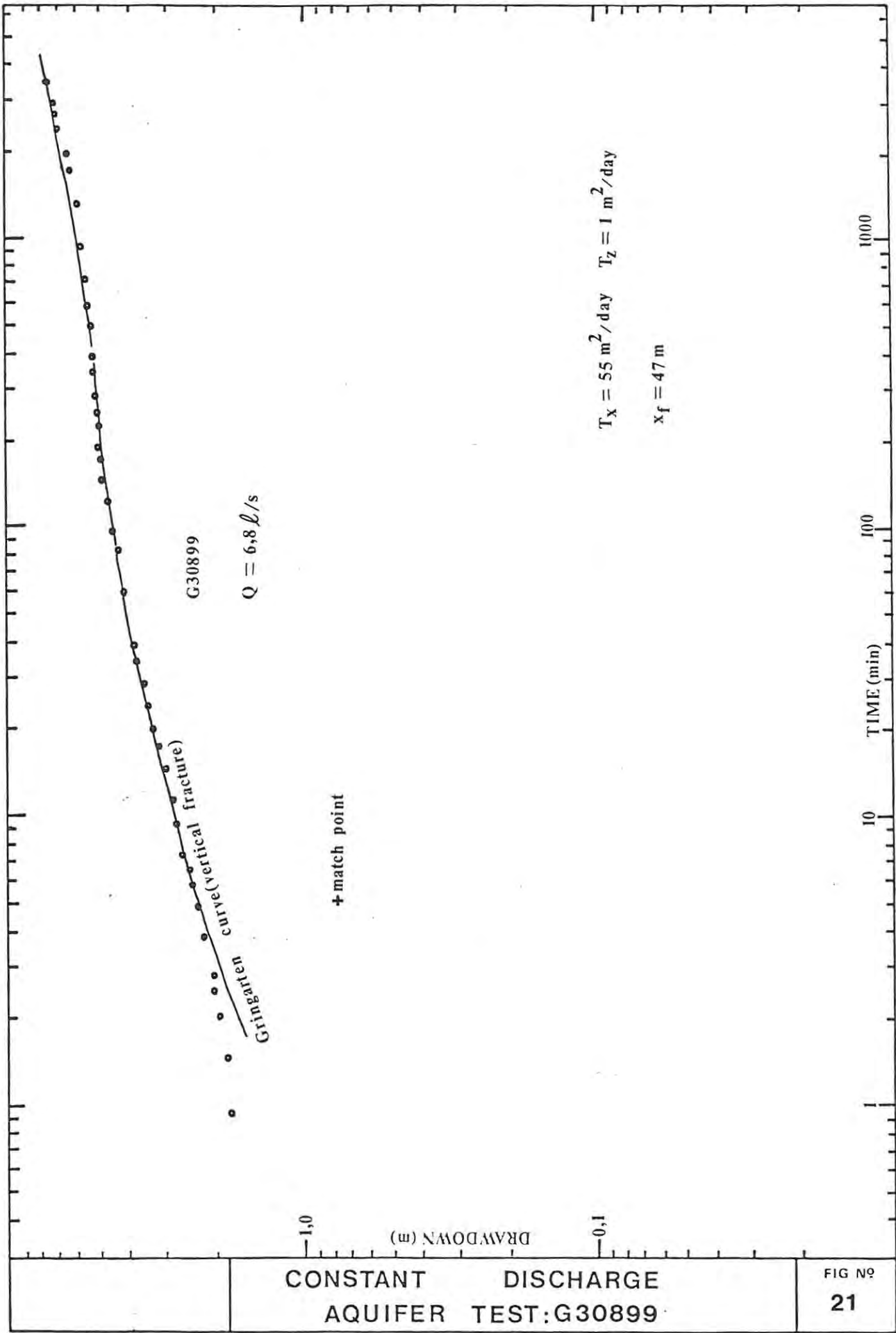
7.5 Groundwater levels

Monthly water level measurements have been taken in an observation borehole network since 1976 in the present investigation. This network comprises:

- . 17 exploration boreholes in the bedrock formations (commencement of record depends on date of drilling)
- . 16 exploration boreholes in the alluvial deposits
- . 103 private boreholes in bedrock formations
- . 20 private wells in alluvial deposits.

7.5.1 Groundwater level fluctuations

Borehole hydrographs have been drawn up, representative of the varying hydrogeological conditions in the valley, to show water level response to recharge, pumping and leakage (Figs 22 and 23).

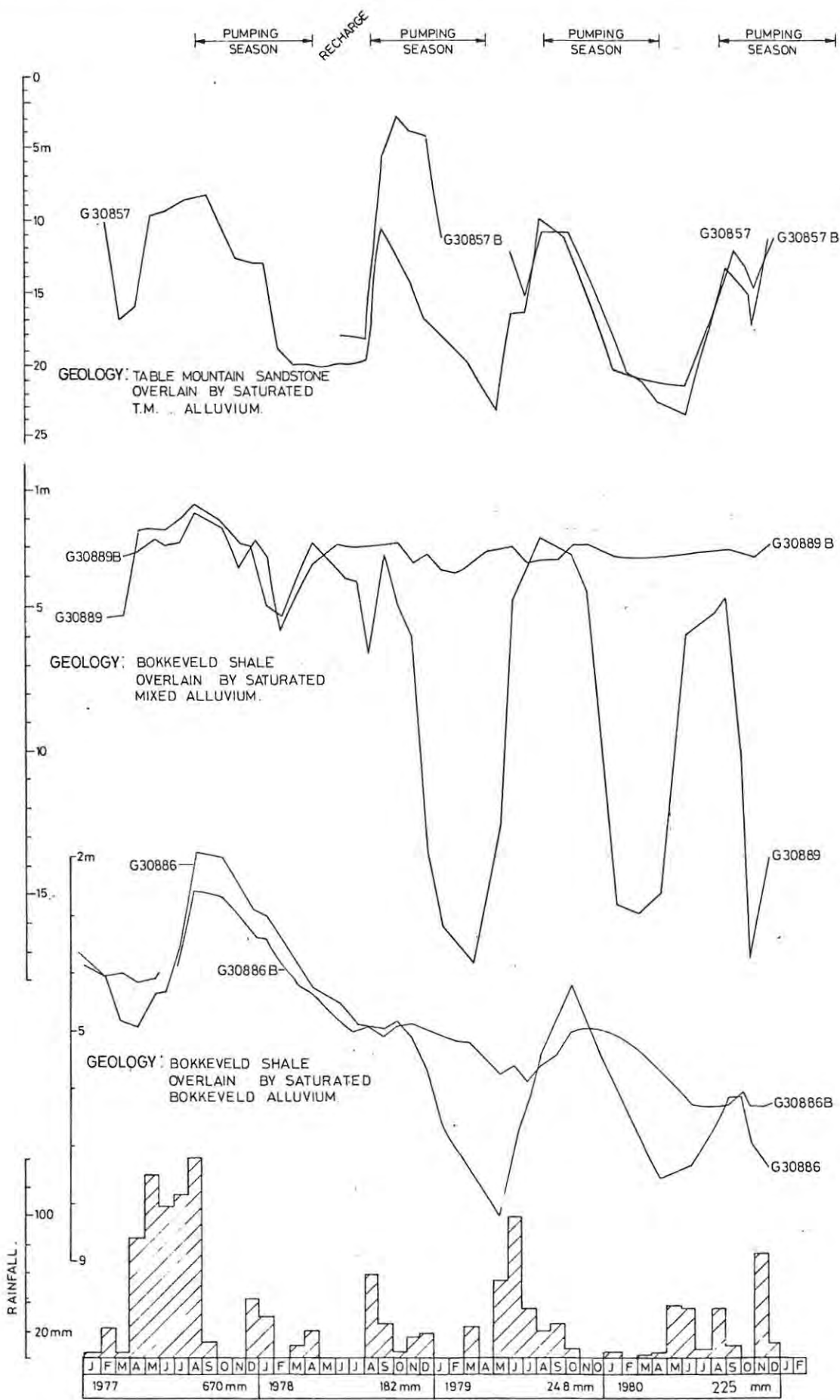


CONSTANT DISCHARGE
 AQUIFER TEST: G30899

The hydrographs illustrate the seasonal fluctuations of the water levels with drawdown during the summer irrigation period and recovery during the winter months. The water levels of October 1977 were generally the highest since measurements were started, eg Fig 23, G30840, after the heaviest winter rainfall recorded since 1908. Twenty three of the observation boreholes showed artesian flow at this time, with flows of up to 10 l/s. However, the hydrographs show that the effects of this recharge were not lasting, eg Fig 23, G30899, despite the fact that abstraction during the 1977-1978 irrigation season was approximately 50% of that during more average conditions. The aquifers behave as if there is a certain threshold above which they cannot retain water in storage. The high hydraulic gradients over much of the valley can explain loss of recharged groundwater in these areas due to rapid subsurface drainage. Water is also lost from storage by spring and artesian borehole flow.

Large fluctuations in the water levels of boreholes in bedrock formations occur over most of the valley with the exception of the area to the north-east of De Doorns, where there is little groundwater abstraction and the Sandhills area. Drawdown of over 30 m may occur in observation boreholes from the start to the finish of the pumping season, eg Fig 23, G30899. Some figures for maximum recorded seasonal drawdowns are as follows (see Fig 24 for localities).

- . Buffelskraal area : 5 m (490-5) to 40 m (G30887)
- . Osplaats area : 3 m (G30886) to 7 m (G30856)
(very little groundwater abstraction in this area)
- . Groothoek area : 14 m (G30857) to 52 m (326-1)



BOREHOLE HYDROGRAPHS

FIG NO
22

- . De Doorns : 9 m (G30898) to 40 m (379-2)
- . Orchard area : 11 m (270-4) to 43 m (270C-2)
- . Sandhills area : 2 m (202-1) to 4 m (226-1).

Most water level fluctuations are sharply defined. In the case of drawdowns this is a rapid response to pumpage in the vicinity of the observation boreholes, especially where located on the same fracture as the pumped borehole (eg G30898). The sharp recoveries, although apparently synchronous with rainfall occurrence, are due initially to the cessation of pumping and lateral flow of groundwater already in storage into the areas of pressure relief, as discussed in Section 7.7. After a time lag, during which infiltrating rainwater has had time to percolate to dewatered fissures, further recovery takes place.

In certain areas the piezometric level of the Bokkeveld aquifer falls to about the same level, or below, the base of the saturated alluvium. Such areas are the Buffelskraal, Groothoek and Orchard areas. The effect of this is most marked in the Groothoek area where the largest seasonal fluctuations in the alluvial water levels occur, presumably due largely to leakage from the alluvium to the underlying bedrock, as there is only one borehole abstracting groundwater directly from the alluvium in this area. Elsewhere, in the Buffelskraal and Orchard to Sandhills area, the alluvial water levels show only small seasonal fluctuations, of less than 2 m, compared with over 14 m in the Groothoek area. The low fluctuations could be due to a combination of higher horizontal permeability and storage in this alluvium, slower downward leakage due to an aquitard of low permeability at the base of the alluvium or top of the bedrock, and lower hydraulic gradients and therefore slower natural subsurface drainage (assuming a constant T).

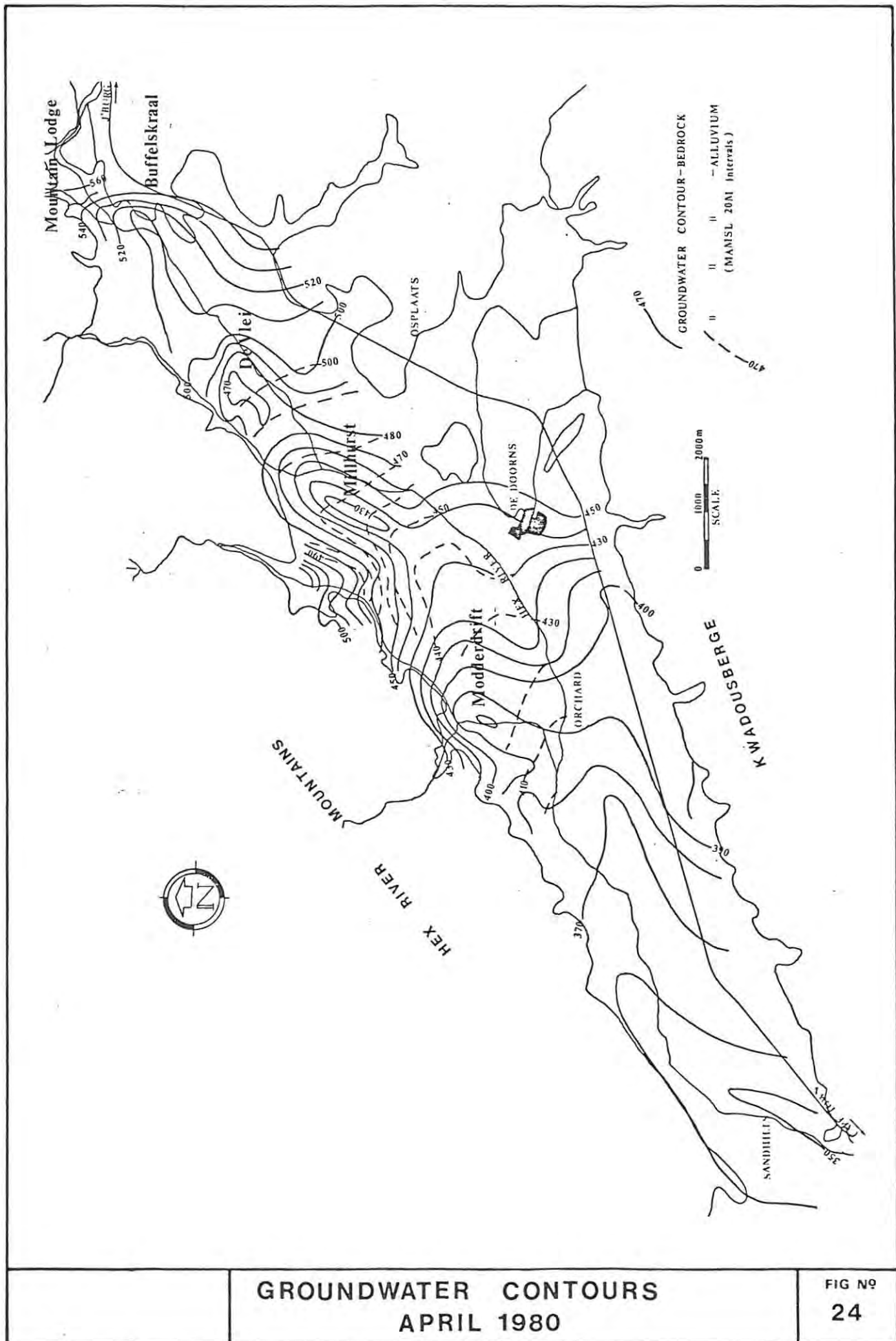
7.5.2 Piezometric surface

The groundwater level fluctuations discussed in the preceding section indicate that the piezometry of the aquifers can be broadly divided into two stages, representative of differing seasonal conditions. Water levels in September generally represent "high waters" conditions in the aquifers after recharge and recovery has taken place, due largely to the winter rainfall in the preceding months.

During October to March intensive withdrawals of groundwater are made for irrigation of vineyards during the growing season. The water levels recorded in April therefore represent "low waters" conditions in the aquifers. Piezometric maps have been drawn up to represent these seasonal conditions for April and September 1980.

The piezometric map for April 1980 (Fig 24) shows the piezometry of the aquifers at the end of the pumping season with water levels generally at their lowest. With regard to the piezometry of the Table Mountain/Bokkeveld aquifer the map shows:

- . groundwater flow in a southerly direction from the Hex River Mountains; in a westerly direction from the eastern areas; in a generally south-westerly direction along the central parts of the valley
- . groundwater troughs have developed in the Buffelskraal, De Vlei, Millhurst and Modderdrift areas in response to heavy pumping. The trough in the Millhurst area is the most pronounced
- . generally high hydraulic gradients. Values range from 8×10^{-2} in groundwater troughs, decreasing



GROUNDWATER CONTOURS
APRIL 1980

FIG NO
24

towards the Sandhills area to $8 - 4 \times 10^{-3}$. The drop in the piezometric level from Mountain Lodge to Sandhills is 210 m or an average gradient of 1×10^{-2} . The wider spacing of the piezometric contours in the Sandhills area suggests that transmissivities are higher here which is supported by the generally higher yields and smaller drawdowns of the area.

It is interesting to note that the drawdown caused by groundwater abstraction gives rise to elongated, trough-like depressions in the piezometric surface. This contrasts with the cones of drawdown referred to in groundwater texts where discussion is concerned with isotropic aquifers. These 'troughs' provide further evidence of the anisotropic nature of the fractured aquifer, discussed initially in the section on aquifer tests. The orientation of these troughs and the direction of anisotropy at C30898 is sub-parallel to the strike of the geological formations, ie NE-SW in the northern limb of the syncline and WNW-ESE in the southern limb. This suggests that transmissivity is strongly related to fissures developed along bedding planes in the Table Mountain/Bokkeveld aquifer system.

Whittingham (1976) concluded that fissure trends were parallel to the regional strike of the Table Mountain and Bokkeveld formations in the Klein Swartberg Valley, viz east-west. This observation was based on borehole yields, responses to pumping and groundwater contour configurations.

With regard to the piezometry of the alluvium Fig 24 shows:

- . a depression in the piezometric surface developed in the Millhurst area, superimposed on the one present

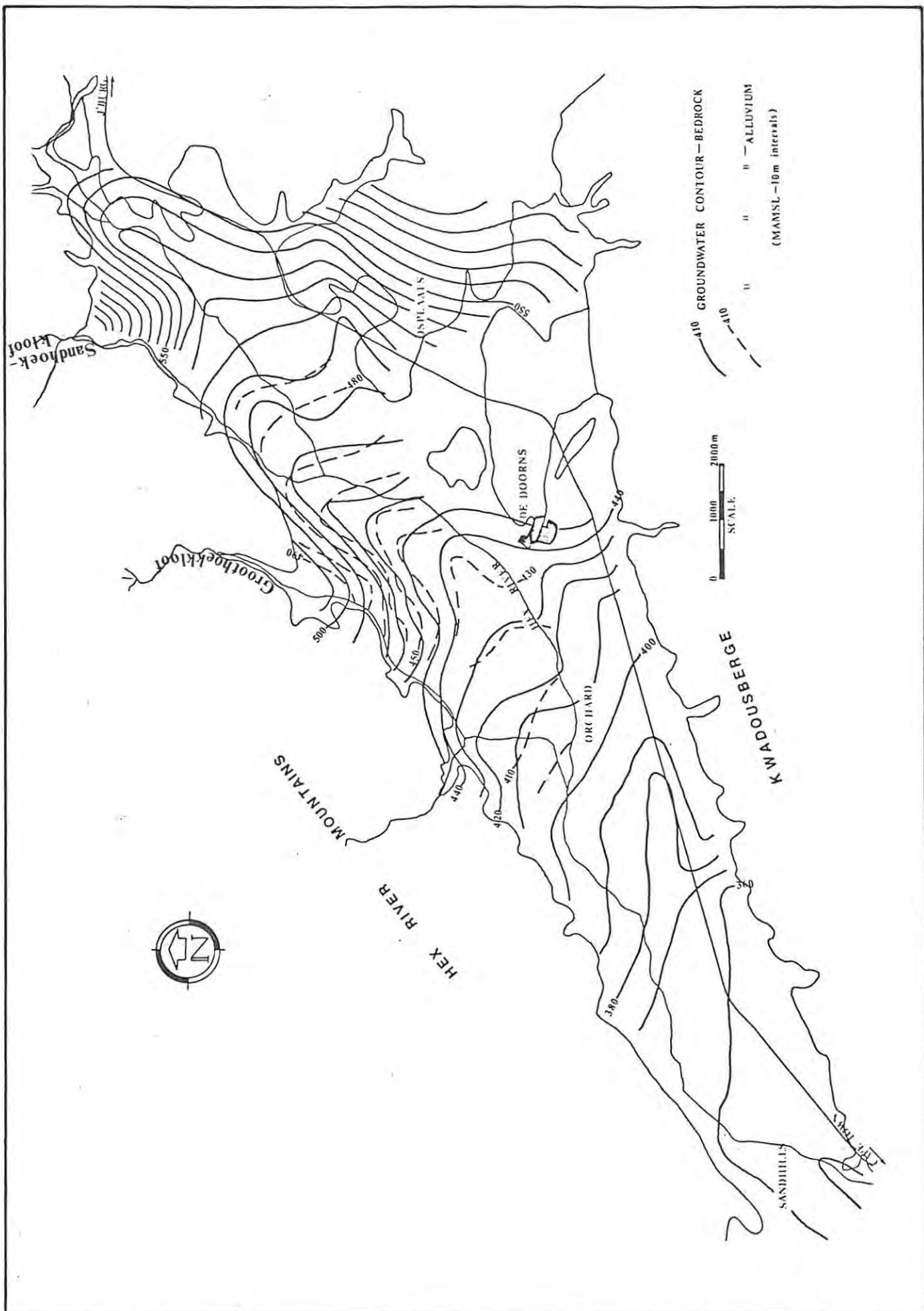
in the underlying bedrock, the latter having induced leakage from the alluvium. This depression has set up a reverse gradient from the Hex River to the water table between R5 and R7. The groundwater troughs in the bedrock of the De Vlei and Modderdrift areas do not visibly affect the piezometry of the alluvium

- . upstream from De Doorns the water table is at about the same elevation as the bed of the Hex River and the groundwater contours are approximately normal to the river. As stated above, from R5 to R7, the groundwater contours indicated flow from the Hex River to the water table on the right bank of the river. Downstream of this area the contours are concave in an upstream direction indicating effluent seepage from the alluvium to the river. These observations have been confirmed by surface flow gaugings in the Hex River
- . high hydraulic gradients; gradients range from 8×10^{-2} near the Groothoekkloof to 1×10^{-2} in the central Valley area
- . recharge from the Groothoekkloof area, indicated by the groundwater contours being convex in a downstream direction in this area.

The piezometric map of September 1980 (Fig 25) illustrates the piezometry of the aquifers after recharge and recovery, by mechanisms which are discussed fully in Section 7.7.

Regarding the piezometry of the Table Mountain/Bokkeveld aquifer the map shows:

- . recharge areas or groundwater mounds, below the Groothoek and Sandhoekkloofs



GROUNDWATER CONTOURS
SEPT '1980

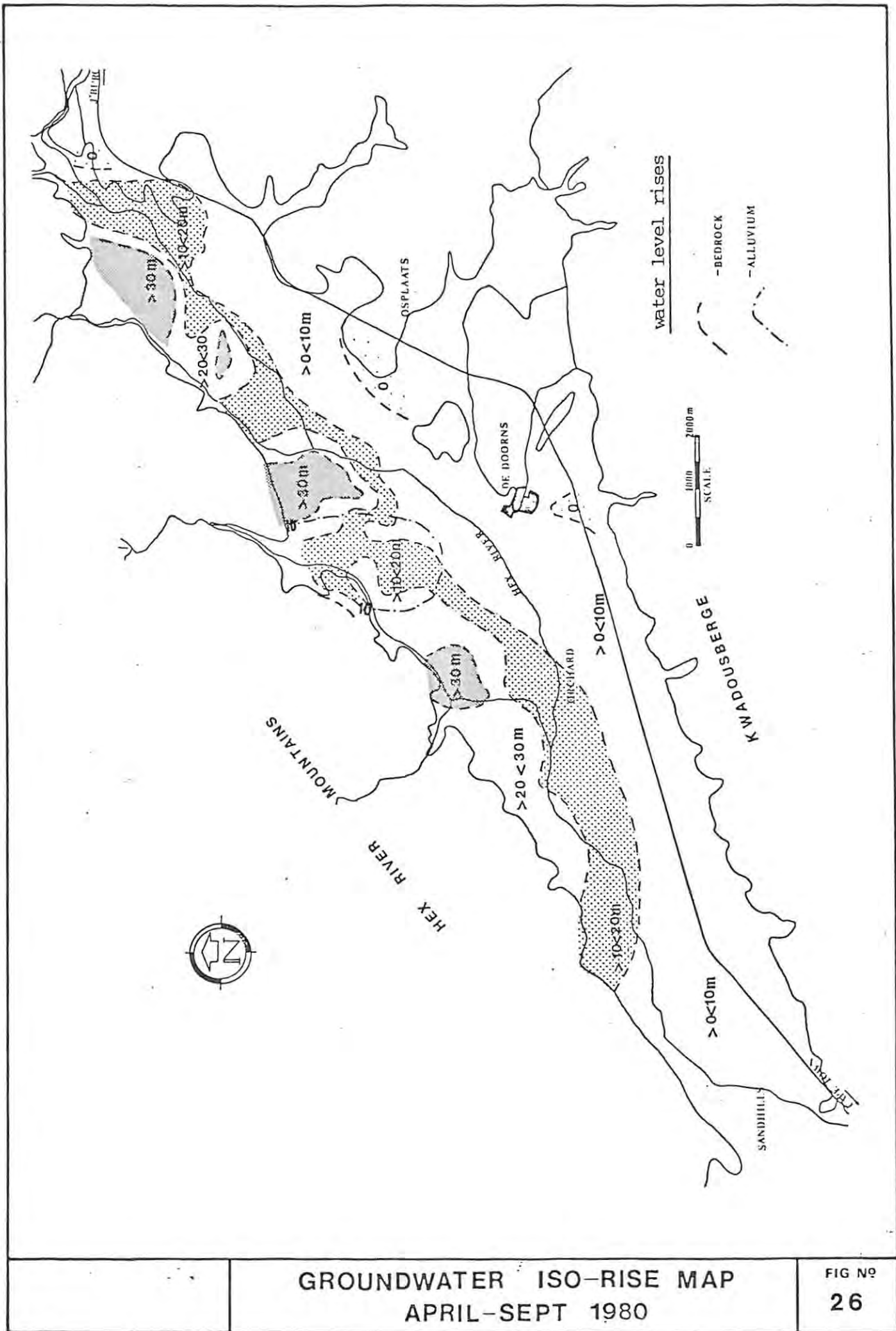
FIG No
25

- . the troughs of pressure relief in the Buffelskraal, De Vlei, Millhurst and Modderdrift areas are still apparent but are generally less sharply defined
- . the hydraulic gradients have generally flattened out but are still high. In the Groothoek and Sandhoek areas the gradient is 5×10^{-2} and in the central areas of the valley, 2×10^{-2} .

The piezometry of the alluvium is similar to that of April 1980.

An iso-rise map has been drawn up by overlay of the two piezometric maps to show water level rises between April and September 1980 for the bedrock water levels (Fig 26). The map shows that the main recharge fronts are located along the northern flanks of the valley adjacent to the Hex River Mountains, where rises of over 30m occur. The eastern and southern areas of the valley are areas of little or no rise. The piezometric contours shifted in a downstream direction between April and September indicating a general rise in water levels.

Comparison of the piezometric contours of the alluvium shows that the main water level rises occur in the Groothoek alluvial fan (Fig 26) where rises of up to 10 m take place, decreasing in a radial direction from the intake area of the fan. Upstream and downstream from the Groothoek area the water level rises are small (less than 1 to 2 m). The piezometric contours have also moved in a downstream direction between April and September, most markedly in the upstream part of the Groothoek alluvial fan.



GROUNDWATER ISO-RISE MAP
APRIL-SEPT 1980

FIG NO
26

7.6 River/aquifer relationships

Spot gaugings, using a current meter, have been carried out at 17 sites on the Hex River and its tributaries (Fig 27). The measurements carried out during the summer months are of most significance to this study as these will give information regarding:

- . baseflows in the rivers when flow is totally derived from groundwater
- . rates of influent and effluent seepage.

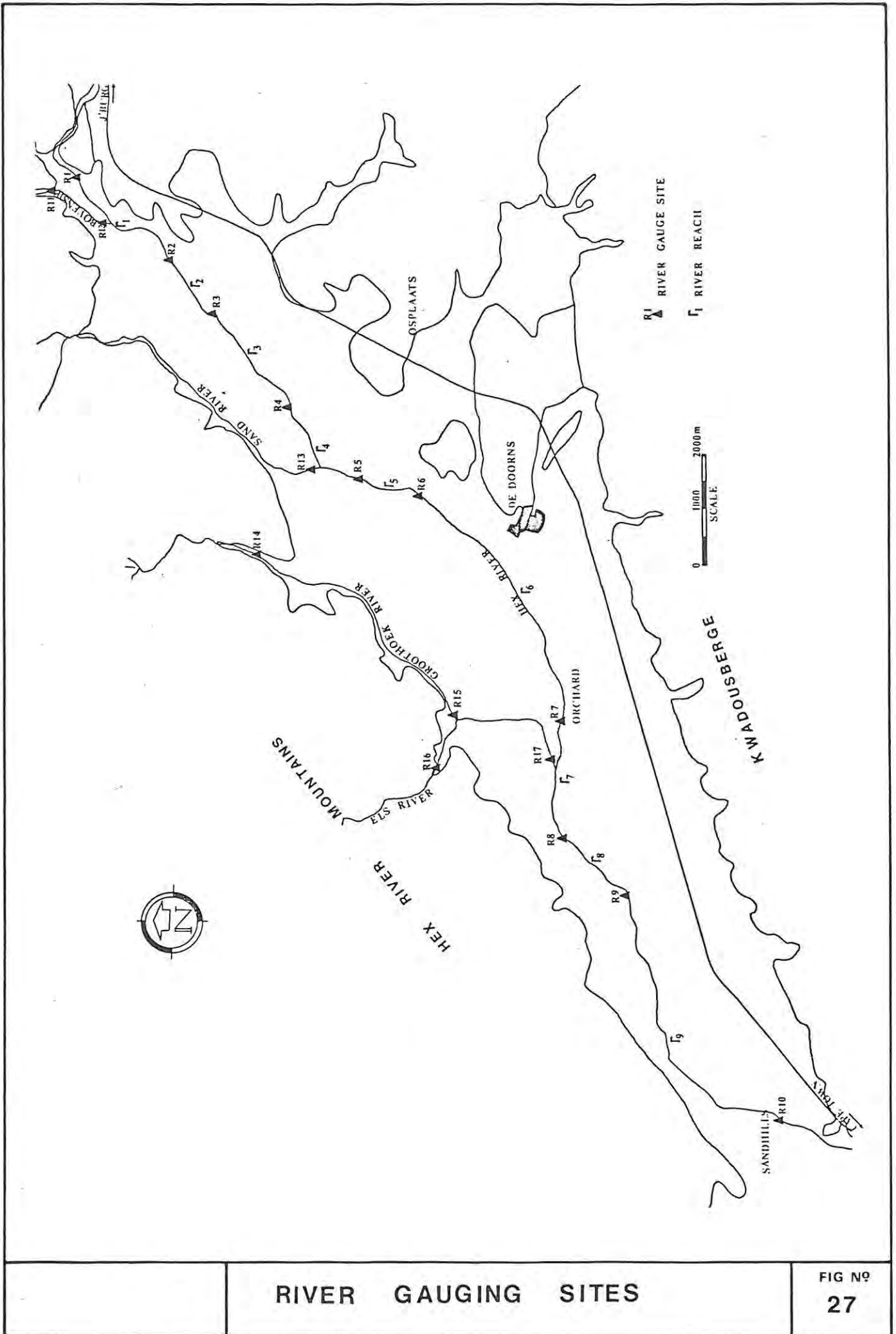
The average flows in the Bovenste, Groothoek and Els Rivers when flow is derived only from groundwater sources have been estimated for the period September 1980 to February 1981. The averages are listed below:

- . Bovenste : 22 l/s
- . Groothoek : 160 l/s
- . Els : 160 l/s

Allowing for flow in the Sand River and other minor streams the average base flow in tributaries issuing from the Hex River Mountains was of the order of 400 l/s for the period. Influent seepage rates of up to 200 l/s were measured between R14 and R15 on the Goothoek River.

The flow measurements carried out at 10 gauging sites on the Hex River, R1, to R10, show the inter-relationships between the river and the alluvial aquifer. The River has been divided into 9 reaches r_1 , r_2 etc corresponding to R1-R2, R2-R3 etc (Fig 27). The flow increments (effluent seepage), or, in some cases, deficits (influent seepage), for each reach are given in Table 8 for specified times.

The measurements show that the river/aquifer system is in a non-steady state condition which can be explained by changes in



RIVER GAUGING SITES

FIG NO
27

River reach	Reach length (m)	Flow increment (+) or deficit (-) ℓ/s					
		28/08/80	30/09/80	23/10/80	23/01/81	10/02/81	06/05/81
r ₁	2 300	No flow	No flow	No flow	No flow	-9	No flow
r ₂	1 600	No flow	No flow	No flow	No flow	+10	+11
r ₃	2 350	+2	+4	No flow	No flow	+2	+25
r ₄	1 600	+8	0	+7	+3	+16	0
r ₅	1 050	+2	+5	-5	0	+2	+18
r ₆	5 550	+40	+6		+39	+63	-15
r ₇	1 700	0	+1	+52	+4	-11	+52
r ₈	1 550	+28	+55		-8		+137
r ₉	5 350		0			+66	+127
Total increment ℓ/s		+80	+71	+54	+38	+148	+355

TABLE 8 : RIVER/AQUIFER RELATIONSHIPS FOR REACHES r₁ - r₁₀ HEX RIVER

head difference between the alluvium and the Hex River with time. The main causes of these differences are the influences of direct pumpage from the alluvium by wells near to the river course and leakage from the alluvium into the bedrock. These effects are mainly confined to the right bank of the Hex River. Pumpage and leakage will tend to flatten the gradient between the water table and the river and, in some cases may produce a reverse gradient from the river to the water table.

The main reaches to be affected by pumpage will be r7 and r8 where most production wells are located. Table 8 shows that deficits do occur at times in these reaches. However, pumpage will be compensated to some extent by irrigation return flows.

7.7 Groundwater recharge

7.7.1 Qualitative considerations

Natural recharge to the Table Mountain/Bokkeveld aquifer may take place by the following mechanisms:

- . natural recovery by lateral movement of groundwater already in storage in the bedrock into dewatered fissures in the pumped aquifer at the end of the pumping season
- . infiltration of precipitation on the Kwadousberge and Hex River Mountains and, to a lesser extent, on areas of exposed Bokkeveld rocks, mainly during the winter months. This water will percolate downwards through fissures under the influence of gravity into the groundwater reservoir
- . downward leakage of groundwater stored in overlying saturated alluvium, where present.

The first mechanism is apparent from the borehole hydrographs where initial rapid water level rises occur after cessation of pumping. The second mechanism will come into operation after a time lag during which infiltrating rainwater has had time to gravitate to dewatered fissures. The third mechanism probably operates to a greater or lesser extent at all times where there is a pressure differential between the water levels in the bedrock and alluvial aquifer. This recharge will increase as the bedrock piezometric surface declines and the vertical head loss increases. If the head in the alluvial deposits remains constant, the recharge rate per unit area will be at a maximum when the piezometric level is at the base of the alluvium through which the leakage is occurring (Walton, 1970).

Evidence for this type of leakage can be seen in the configuration of water level contours in the alluvium, as discussed in Section 7.6, and from pumping tests discussed in Section 7.4.

Over much of the area, the piezometric surface declines to the base of the saturated alluvium during the pumping season (eg the Groothoek alluvial fan area). Leakage will be at a maximum in these places, although in the Groothoek area the head also declines in the alluvial deposits. Elsewhere the head in the alluvial deposits remains fairly constant. Artificial recharge is not practised in the Hex River Valley.

There are also three possible mechanisms for recharge to the alluvial aquifer. These are:

- . direct infiltration of rainfall on the alluvial surface and also by over-irrigation

- . recharge from influent streams and run-off from the bordering mountain slopes
- . recharge by vertical or lateral movement of water from fissures in the bedrock aquifer.

Recharge by rainfall infiltration will depend upon such factors as: duration and intensity of the rainfall, soil moisture content, evapotranspiration, soil character and depth to water table. Influent seepage is confined to the upper reaches of streams entering the Valley from the bordering mountains, where the stream bed is above the water table. The Groothoek River is the most important in this respect. Influent seepage also takes place in reaches r_5 and r_6 of the Hex River as discussed in Section 7.5.

Just as downward leakage is postulated to occur at times of head difference between the alluvium and bedrock aquifers during the pumping season, upward leakage also occurs when the piezometric surface (bedrock) recovers and is above the water table. This would explain rapid recovery of alluvial water levels in the Groothoek area when pumpage from the bedrock ceases. The recoveries are too large and rapid to be due to rainfall infiltration or influent seepage alone, especially as there would be a time lag involved with the former recharge. Lateral subsurface recharge from the bordering Hex River Mountains is probably also important. Water table contours parallel the mountain front in places eg the Groothoek area, instead of being normal to it as would be the case if this were an impermeable boundary.

7.7.2 Quantitative estimates of recharge

One of the most difficult parameters to quantify in a regional groundwater investigation is the natural

recharge. This is no less the case with the Hex Valley. However, information obtained during the course of the investigation enables some speculation as to the quantities involved. Recharge to the Table Mountain/Bokkeveld aquifer system will be considered first, followed by a discussion on recharge to the alluvium.

Evidence for downward leakage from areas of saturated Table Mountain alluvium to the underlying bedrock has already been put forward under sections on piezometry, periodical measurements and pump tests. This mechanism is now discussed quantitatively.

Leakage is given by: (Bear, 1979)

$$L = \frac{K'(h' - h)}{D} \quad \dots (15)$$

where

K' is the vertical permeability and D' the thickness of the deposits through which leakage is taking place, $(h'-h)$ is the head difference between the bedrock and the alluvium.

From pump test results it is evident that K' varies over the area and from drilling results it is noted that D' also varies (from 0-10 m). Water level measurements show that $(h'-h)$ is also variable in time and space. It would therefore be incorrect to assume a uniform rate of leakage over the Valley. The Groothoek area has therefore been chosen for leakage calculation as most information is available for this area regarding K' , D' and $(h'-h)$. To enable the most accurate calculations the area has been subdivided by a grid system into elementary areas $(\Delta A)_i$ through which the average leakage $(\bar{L})_i$ is calculated for a period Δt . The expression $\Delta t \sum_i (\bar{L})_i (\Delta A)_i$ then gives the total inflow into the bedrock aquifer by leakage during Δt (Bear, 1979).

The grid system is shown in Fig 28 where $(\Delta A)_i = 1 \text{ km}^2$. Δt is taken as the period September 1979 to April 1980, 212 days. This corresponds to the pumping season when the head loss between the bedrock and alluvial water levels, and therefore leakage, will be at a maximum.

The leakage calculations are given in Table 9 below.

TABLE 9 : LEAKAGE CALCULATIONS IN THE LOWER GROOTHOEK AREA

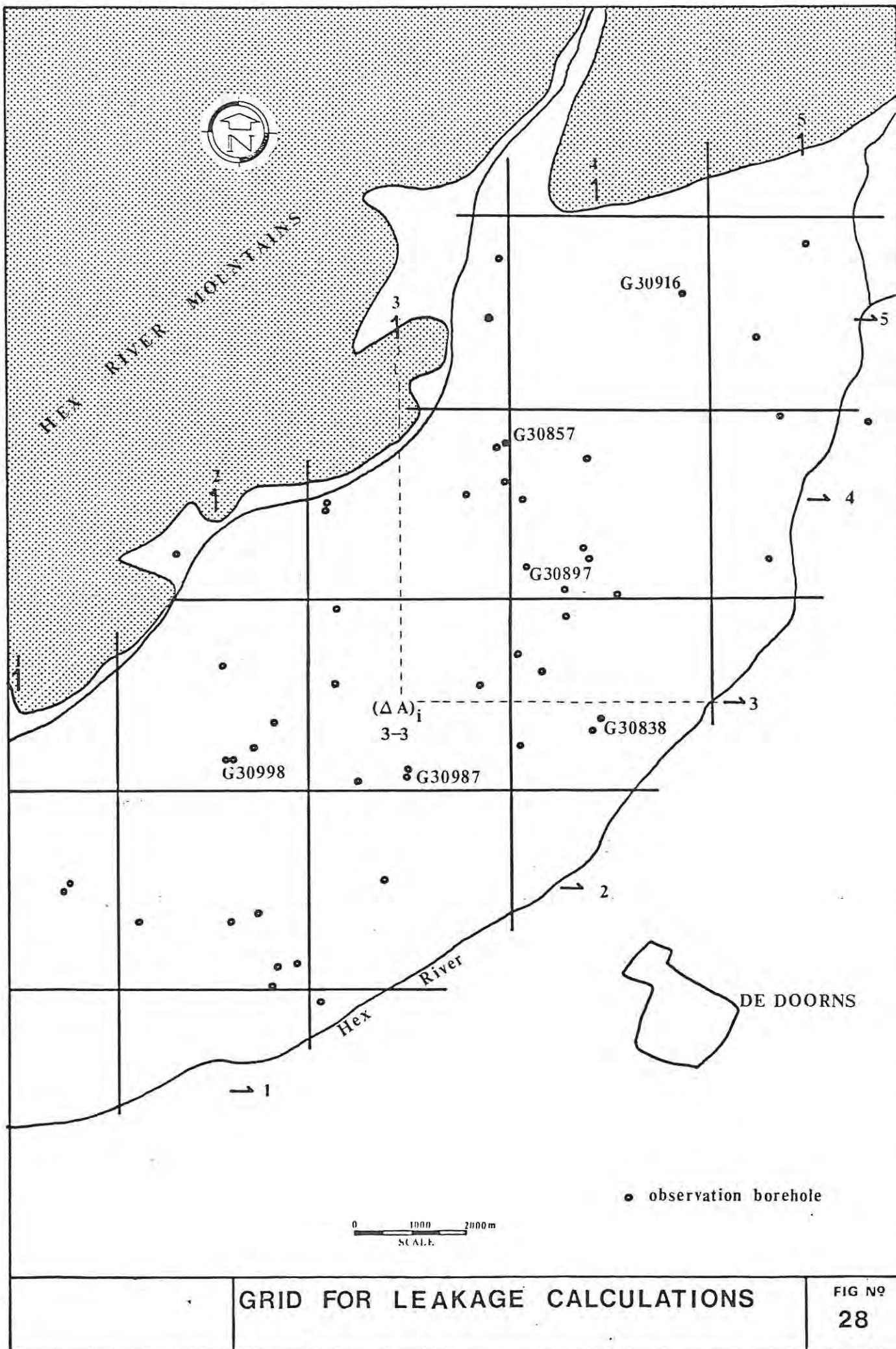
Grid No	$(\Delta A)_i$ ($\text{m}^2 \times 10^6$)	$\Delta t(\bar{L})_i(\Delta A)_i$ (m^3)
5-5	1	33 920
-4	0,6	114 480
-3	0,5	21 200
4-5	1	106 000
-4	1	169 600
-3	0,9	212 000
3-4	0,8	169 500
-3	1	212 000
-2	0,8	84 800
2-4	0,6	220 480
-3	1	133 560
-2	1	106 000
-1	0,4	42 400
1-3	0,3	95 400
-2	0,6	190 800
-1	0,5	106 000
TOTAL LEAKAGE		$2 \times 10^6 \text{ m}^3$

The accuracy of this calculation can be checked by comparison with the change in storage within the alluvial aquifer for the same time period. The change in storage, ΔS , in the Groothoek area is given by:

$$\Delta S = \Delta h(15 \text{ m}) \times S_y(0,02) \times A(12,5 \text{ km}^2) \quad \dots (16)$$

$$\therefore \Delta S = 3,8 \times 10^6 \text{ m}^3$$

A balance equation for change of storage in the Groothoek area is given by:



$$\Delta S = L + Q + E_s + P \quad \dots (17)$$

where

L = leakage and has been calculated as $2 \times 10^6 \text{ m}^3$

Q = subsurface flow and is computed at $1 \times 10^6 \text{ m}^3$
for the period

E_s = effluent seepage to the Hex River and is calculated from surface water gaugings to be $5 \times 10^5 \text{ m}^3$

P = direct pumpage from the alluvium and is of the order of $1,5 \times 10^5 \text{ m}^3$.

Thus ΔS from this calculation is $3,65 \times 10^6 \text{ m}^3$ which gives good correlation with that calculated from Eq (16). Therefore the estimated leakage of $2 \times 10^6 \text{ m}^3$ in the Groothoek area for the period September 1979 to April 1980 appears in good agreement with supplementary hydrogeological data.

Although not strictly a correct procedure, extrapolation of this figure over the whole area overlain by saturated Table Mountain alluvium indicates that leakage is of the order of $5 \times 10^6 \text{ m}^3/\text{year}$. This leakage explains why, in years of below average rainfall, water levels in the bedrock aquifer in areas overlain by saturated alluvium still show good recovery.

Leakage in areas overlain by saturated mixed and Bokkeveld alluvium has not been calculated. In these areas the piezometric surface is at times above that in the alluvium eg G30893, in other words $(h' - h)$ is negative. This indicates that upward leakage from the bedrock to the alluvium is taking place.

Direct recharge from precipitation is rather more difficult to quantify. The water level recoveries in the Table Mountain/Bokkeveld formations of 1978 and 1979 were very similar which indicates that recharge to the pumped aquifers during the winter of 1979 was roughly

equivalent to abstraction in the 1978/79 irrigation season. It has been calculated in Section 7.2 that $\pm 20 \times 10^6 \text{ m}^3/\text{year}$ of groundwater is abstracted. Allowing for $5 \times 10^6 \text{ m}^3/\text{year}$ of leakage from the alluvium, the recharge in 1979 was of the order of $15 \times 10^6 \text{ m}^3$.

The average rainfall over the Hex River catchment area is 610 mm (Pitman et al, 1981). This is for an area of 265 km^2 . Subtracting the alluvial surface area gives 200 km^2 for the exposed Table Mountain/Bokkeveld formations. The average precipitation over this area is $122 \times 10^6 \text{ m}^3$. Thus natural recharge of $15 \times 10^6 \text{ m}^3$ is equivalent to 12 per cent of the average precipitation.

Another means of estimating recharge to the Table Mountain/Bokkeveld aquifer system is the water level rise method using the following relationship:

$$R = S A \Delta h \quad \dots (18)$$

where S = storage coefficient, A = surface area of the aquifer and Δh is the rise in water level.

A figure of 1×10^{-3} is used for the storage coefficient. Referring to the water level rise map in Fig 26 the following calculations can be made.

Average Δh	Area (km^2)	Recharge (m^3) Apr-Sept 1980
35 m	4,1	143 500
25 m	9,0	225,000
15 m	13,6	204,000
5 m	35,5	177,500
Total		750 000 m^3

TABLE 10 : RECHARGE CALCULATIONS : WATER LEVEL RISE METHOD

This is obviously a very low figure and indicates that the water level rises recorded in boreholes in the valley do not represent the total recharge to the catchment area. The model put forward here is that the main recharge by rainfall takes place on the Hex River Mountains and, due to the highly fissured nature of the Table Mountain Sandstones, and therefore storage capacity, the infiltration increment is largely retained within these sandstones. This water will then be available for lateral and vertical movement into the pumped aquifer during and at the end of the pumping season. This hypothesis is further substantiated when one considers the volume of Bokkeveld rock that would have to be dewatered to yield $15 \times 10^6 \text{ m}^3$ (estimated annual abstraction minus leakage). The piezometric level in the Bokkeveld would have to be drawn down by 240 m over the entire surface area of 62 km^2 to yield this volume. This is about five times the maximum drawdown occurring in the area.

Recharge in areas of exposed Bokkeveld formations will be small in comparison to the Table Mountain Sandstones. One reason for this is the much lower rainfall, eg Matroosberg station, average 234 mm. Also over much of the area, clayey soils are developed and slopes developed on shales are often steep and smooth (see Fig 2) promoting runoff rather than infiltration. The main areas of infiltration are probably along drainage channels where semi-pervious alluvium or exposed bedrock is present. A perennial spring on the Hex River Pass gives an idea of the low recharge. The flow of this spring ranges from 0,93 to 0,3 l/s.

Water levels in boreholes in the Osplaats area show only small rises in water level in response to recharge during the winter months. At G30855 for instance, the water level rise between April and September 1980 was

4 m. The storage coefficient here is $1,3 \times 10^{-4}$. Extrapolating these figures over the area of exposed Bokkeveld formations of 90 km^2 gives a recharge of $47\,000 \text{ m}^3$ for the period April to September 1980.

Recharge to the alluvial aquifers is now considered. The Groothoek alluvial fan is taken as an example to assess the magnitude of recharge to the alluvium. Influent seepage from streamflow in the apex area is usually considered to be the main source of recharge to alluvial fans (Tolman, 1937; Clyde et al, 1981).

Stream gaugings on the Groothoek River between R14 and R15 give an indication of the volume of influent seepage to the Groothoek alluvial fan. Observed rates of influent seepage varied up to 200 l/s during the investigation.

A water balance equation for recharge to the Groothoek alluvial fan can be written as follows:

$$R = Q + L + P + E_s + \Delta S \quad \dots (19)$$

where

Q = subsurface flow

L = leakage

P = direct pumpage from the alluvium

E_s = effluent seepage, in this case to the Hex River

ΔS = change in subsurface storage

The period April to September 1980 will be taken for calculation purposes. Q is estimated with Darcys law, which can be written as follows:

$$Q = WT \frac{dh}{dL} \quad \dots (20)$$

Where W is width of the aquifer, T is transmissivity and dh/dL is the hydraulic gradient. The computed flow is 108 l/s or $1,4 \times 10^6 \text{ m}^3$ for the period in question.

L for the period April to September is of the order $1 \times 10^6 \text{ m}^3$.

P can be disregarded as negligible.

E_S can be calculated between R6 and R7 and is 30 l/s or $4 \times 10^5 \text{ m}^3$.

ΔS is estimated by the water level rise method using an average specific yield of 2×10^{-2} . This gives a volume of 1×10^6 .

Substitution of these values into Eq (19) gives:

$$1,4 \times 10^6 + 1 \times 10^6 + 4 \times 10^5 + 1,4 \times 10^6 = 3,8 \times 10^6 \text{ m}^3$$

= recharge to the Groothoek alluvial fan.

7.8 Groundwater storage

The estimates of storage are of most importance in areas where groundwater of acceptable quality for irrigation of vines occurs, ie where the conductance is less than 80 mS/m (see Chapter 8). It should be emphasised here that the calculations for the bedrock formations are approximate at best and should be viewed as an indication of the relative amounts of groundwater involved only.

The Table Mountain Sandstones are the most important reservoir for groundwater storage in the valley mainly by virtue of their great thickness and areal extent and the excellent quality of the associated groundwater. The thickness of the Nardouw Sandstone is 500 m. This Sandstone forms the envelope of the syncline and stresses during folding may have led to open fractures extending to the base of the formation. The existence of high yielding thermal springs in the Table Mountain

Group at places such as Brandvlei and Goudini indicates that fissures may persist to great depths (Whittingham, 1976). The storage coefficient calculated for Bokkeveld shale at G30987B was 1×10^{-3} . For the Nardouw Sandstone this would probably be higher. Taking a value of $S = 5 \times 10^{-3}$ for a total volume of rock of $11 \times 10^{10} \text{ m}^3$ (area underlain by sandstone = $212 \text{ km}^2 \times 500 \text{ m}$) gives an available storage of $555 \times 10^6 \text{ m}^3$. Even with a conservative value of $S = 1 \times 10^{-3}$, available storage is still $276 \times 10^6 \text{ m}^3$. Obviously the whole volume of rock is not saturated. Also, it can only be speculated as to what depth the groundwater in the Nardouw Sandstone influences the water supply in the pumped part of the aquifer by lateral or vertical movement. Vertical influence is indicated by artesian flow from boreholes, observed after high rainfall on the Hex River Mountains.

The formations within the Bokkeveld Group containing water of suitable quality for irrigation of vines are the Gydo shale, Gamka Sandstone and, in the Groothoek area only, Voorstehoek Shale. The thicknesses of these formations are 140 m, 35 m and 220 m respectively and they occupy a surface area of 21 km^2 . The average storage coefficient calculated from G30987B and G30998 is 9×10^{-4} . Taking an average saturated thickness of 200 m gives a figure of $2,8 \times 10^6 \text{ m}^3$ in storage.

The average annual abstraction from the bedrock aquifer has been estimated at $20 \times 10^6 \text{ m}^3$ from which must be subtracted $5 \times 10^6 \text{ m}^3$ derived from leakage from the overlying alluvium. If there is a maximum of $2,8 \times 10^6 \text{ m}^3$ available from storage in the Bokkeveld in the area of abstraction, the remainder must be derived from lateral and vertical inflow of groundwater stored in the Nardouw Sandstone, ie $12 \times 10^6 \text{ m}^3$. A rough idea of the thickness D , of Nardouw Sandstone required to supply this water can be obtained from:

$$D = \frac{V(14 \times 10^6 \text{ m}^3)}{S(0,005) \cdot A(37 \times 10^6 \text{ m}^3)} \quad \dots (21)$$

where

V = volume of groundwater

A = area of Nardouw Sandstone

S = storage coefficient

∴ D = 75 m.

The area of saturated alluvium derived from the Table Mountain Group is 24 km². With an average specific yield of 2×10^{-2} (computed from pumping tests) and an average saturated thickness of 20 m (from exploration borehole logs), the volume of water stored is $9,5 \times 10^6 \text{ m}^3$.

The area of saturated mixed alluvium is 5,2 km². The average storage coefficient is $4,4 \times 10^{-3}$ and average saturated thickness is 20 m. This gives a storage volume of $5 \times 10^5 \text{ m}^3$. However, this groundwater is too brackish for the irrigation of vines, as is that contained in the Bokkeveld alluvium.

7.9 Summary

The aquifers directly exploited for groundwater supplies are the lower formations of the Bokkeveld Group, viz the Gydo Shale, Gamka Sandstone and Voorstehoek Shale. However, the volume of groundwater in storage within these formations is insufficient to meet the annual average draft on this groundwater reservoir of about $20 \times 10^6 \text{ m}^3$. The deficit is made up by leakage from the underlying Nardouw Sandstone (60%) and the overlying Table Mountain alluvium (25%).

Aquifer test results and groundwater contour configurations gave evidence of anisotropic flow conditions in the bedrock aquifers, with a direction of maximum transmissivity sub-parallel to the regional strike of the geological formations, which is approximately east-west.

The alluvial aquifers are in hydraulic connection with the surface water in the Hex River and its tributaries. Along the Hex River, effluent seepage is mainly taking place, while in the upper reaches of tributaries such as the Groothoek River, influent seepage takes place.

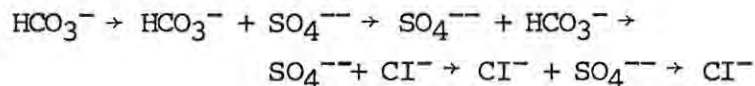
These hydrogeological conclusions will be further expanded in the hydrogeochemistry discussions in Chapter 8 and used in Chapter 9 to test the hypotheses formulated in Chapter 5.

8 HYDROGEOCHEMISTRY8.1 Theory of the chemical evolution of groundwater

Nearly all groundwater originates as rain or snowmelt that infiltrates through soil and rock into flow systems in the underlying geologic formations. Rain and snowmelt are extremely dilute, slightly to moderately acidic and oxidising solutions (Freeze and Cherry, 1979). During infiltration through the soil profile and migration along flow paths in the saturated zone, increases in total dissolved solids (TDS) and most of the major ions normally occur.

In a normal groundwater environment there is a change from a bicarbonate to chloride character as the groundwater moves from recharge to discharge zones. Chebotarev (1955) suggested the following sequence of changes in the dominant anion species:

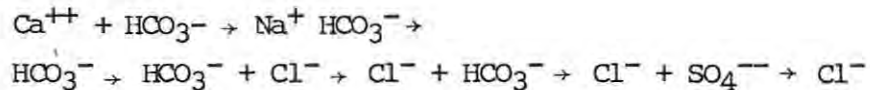
Travel along flow path: →



Increasing age: →

These chemical changes occur as the water moves from shallow zones of active flushing through intermediate zones into zones of sluggish flow where the water is old.

A generalisation of major cation evolution sequences in groundwater is of less significance as there would be so many exceptions to the rule (Freeze and Cherry 1979). Cation exchange, for example, commonly causes alteration or reversals in the cation sequences. However, Johnson (1975) suggested the introduction of cations into the early part of the anion sequence to give the following:



The sequences for chemical evolution of groundwater given above can be described in terms of three main zones, which correlate in a general way with depth (Domenico, 1972 Johnson, 1975).

- . An upper zone with active flushing through well leached geological formations. Groundwater in these recharge areas has a $\text{Ca}^{++}.\text{Mg}^{++}(\text{HCO}_3^-)_2$ character. Further along the flow path the groundwater may acquire an $\text{Na}^+\text{HCO}_3^-$ character due to exchange of Mg^{++} and Ca^{++} ions in solution for Na^+ ions adsorbed on clay minerals. The water maintains this $\text{Na}^+\text{HCO}_3^-$ character as long as the hydraulic gradient and/or transmissivity is high.
- . An intermediate zone with less active groundwater circulation with an increase in TDS and Cl^- (SO_4^{--} the dominant anion according to Chebotarev, 1955).
- . A lower zone with very sluggish groundwater movement. SO_4^{--} precipitates out of solution and the groundwater has a high TDS and Cl^- character.

Travel distance and age of the groundwater tends to increase from the upper zone to the lower zone.

8.2 Interpretation of chemical analyses

The main techniques of numerical and graphical interpretation of water quality data can be grouped into four categories (Zaporozec, 1972); classification methods, correlation methods, analytic methods and synthetic & illustrative methods. The water quality data from the Hex River Valley will be analysed using classification and analytic methods, namely the Kurlov Formula and the Piper Diagram, respectively.

Classification methods are used for basic characterisation of the chemical composition of ground and surface waters and differentiate chemical types of water and identify the dominant types. In the original Kurlov Formula (1928) the chemical composition is represented by a fraction, with anions and cations as the numerator and denominator respectively. The different ions are taken as percentages of the total milliequivalents per litre in descending order of concentration. The total dissolved solids precedes the fraction and other parameters, such as pH, follow after the fraction. An example is given below:

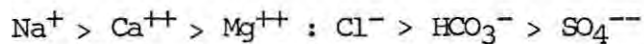
$$560 \frac{\text{Cl}(85)\text{HCO}_3(8)\text{SO}_4(5)}{\text{Na}+\text{K}(78)\text{Ca}(18)\text{Mg}(3)} \quad 7,3$$

This representation is rather cumbersome for displaying a large number of analyses on a map. In an earlier hydrogeochemical study of the Hex River Valley, Bredenkamp (1979) used a modified Kurlov formula that is more amenable to plotting on a map. The denominator is the TDS (mg/l) and the numerator consists of a letter and a number indicating the relative concentrations (in me/l) of the major cations and anions, as follows:

<u>Cations</u>	<u>Symbol</u>
$\text{Na}^+ > \text{Ca}^{++} > \text{Mg}^{++}$	A
$\text{Na}^+ > \text{Mg}^{++} > \text{Ca}^{++}$	B
$\text{Ca}^{++} > \text{Na}^+ > \text{Mg}^{++}$	C
$\text{Ca}^{++} > \text{Mg}^{++} > \text{Na}^+$	D
$\text{Mg}^{++} > \text{Na}^+ > \text{Ca}^{++}$	E
$\text{Mg}^{++} > \text{Ca}^{++} > \text{Na}^+$	F

<u>Anions</u>	<u>Symbol</u>
$\text{Cl}^- > \text{HCO}_3^- > \text{SO}_4$	1
$\text{Cl}^- > \text{SO}_4^{--} > \text{HCO}_3^-$	2
$\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{--}$	3
$\text{HCO}_3^- > \text{SO}_4^{--} > \text{Cl}^-$	4
$\text{SO}_4^{--} > \text{Cl}^- > \text{HCO}_3^-$	5
$\text{SO}_4^{--} > \text{HCO}_3^- > \text{Cl}^-$	6

This enables a chemical analysis to be represented by a composite symbol indicating its character; for example, water type Al/500 has the following relationships:



and a TDS of 500 mg/l.

Principles of graphical interpretation of chemical analyses of groundwater are based on the relationships of ions, or groups of ions, forming a chemical type of water (Zaporozec, 1972). One of the most widely used graphical representations of chemical analyses of groundwater is the trilinear diagram developed by Piper (1944). He proposed that groundwater be treated as though it essentially contains three cation constituents, Na^+ , Ca^{++} and Mg^{++} , and three anion constituents Cl^- , SO_4^{--} and HCO_3^- . The less abundant constituents are lumped with the major constituents to which they are related eg $\text{Na}^+ + \text{K}^+$. The diagram consists of three plotting fields; two triangular fields, one each for the cations and anions, and a central diamond field combining the cations and anions into a single plotting point (Fig 29). All the plotting fields have scales of 0 to 100 per cent of total milli-equivalents per million.

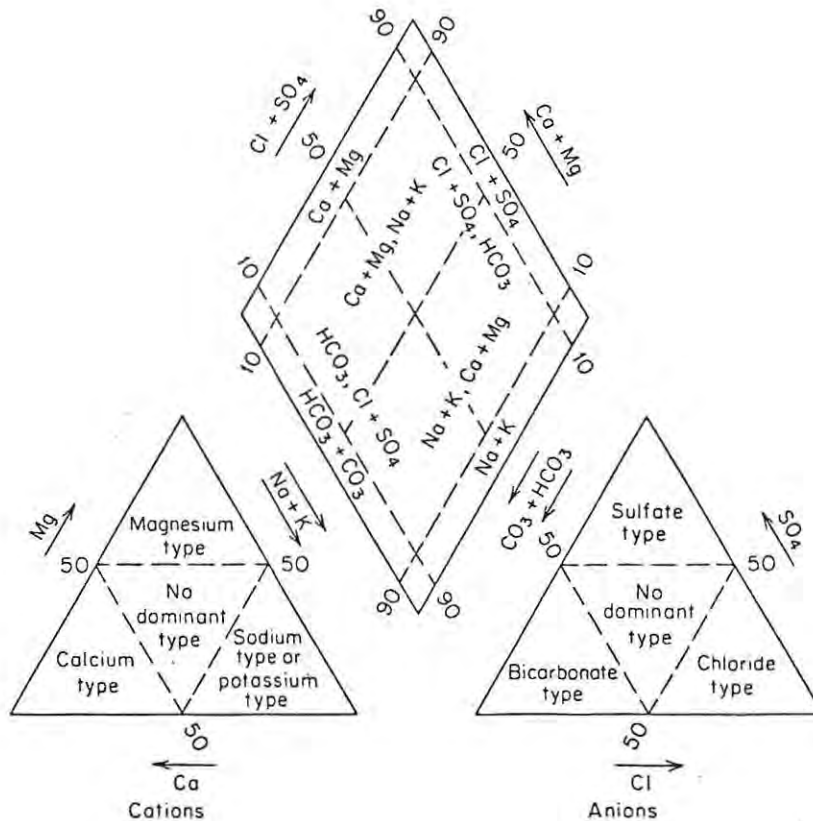


FIG 29 : PIPER DIAGRAM FOR CLASSIFICATION OF CATION AND ANION FACIES (after Back, 1966)

The plotting position of a chemical analysis within the central diamond field thus gives an indication of the chemical character of the groundwater in relation to its environment. In general, analyses plotting in the top half of the diamond field represent stagnant waters while the lower half represents waters normally found in a more dynamic environment. These can be tentatively correlated with the lower and upper zones described in the preceding section. One disadvantage of the trilinear plotting technique proposed by Piper is that waters with widely differing TDS can plot at the same point.

8.3 Analytical results

8.3.1 Electrical conductivity

It is recommended that water with an electrical conductivity of more than 80 mS/m should not be used for the irrigation of vines (Pienaar et al, 1972). This can be taken as a general guideline for evaluation of water quality in the Hex River Valley as other factors such as an ionic concentration of specific salts, soil type and drainage also need to be considered.

The measurements taken during the hydrocensus of January to April 1980 will be used for consideration of the geological and spatial variation in conductivity of groundwaters in the Hex River Valley. The range of conductance of groundwater from the various geological formations is given in Table 11.

Formation	Electrical conductivity (mS/m at 25°C)
Nardouw Sandstone	2,2 - 94
Gydo Shale	10 - 236
Gamka Sandstone	22 - 192
Voorstehoek Shale	20 - 270
Hex River Sandstone	255
Tra-Tra Shale	109 - 489
Table Mountain alluvium	8 - 38
Mixed alluvium	150 - 284

TABLE 11 : CONDUCTIVITY RANGE OF GROUNDWATER IN GEOLOGICAL FORMATIONS OF THE HEX RIVER VALLEY, JANUARY - APRIL 1980

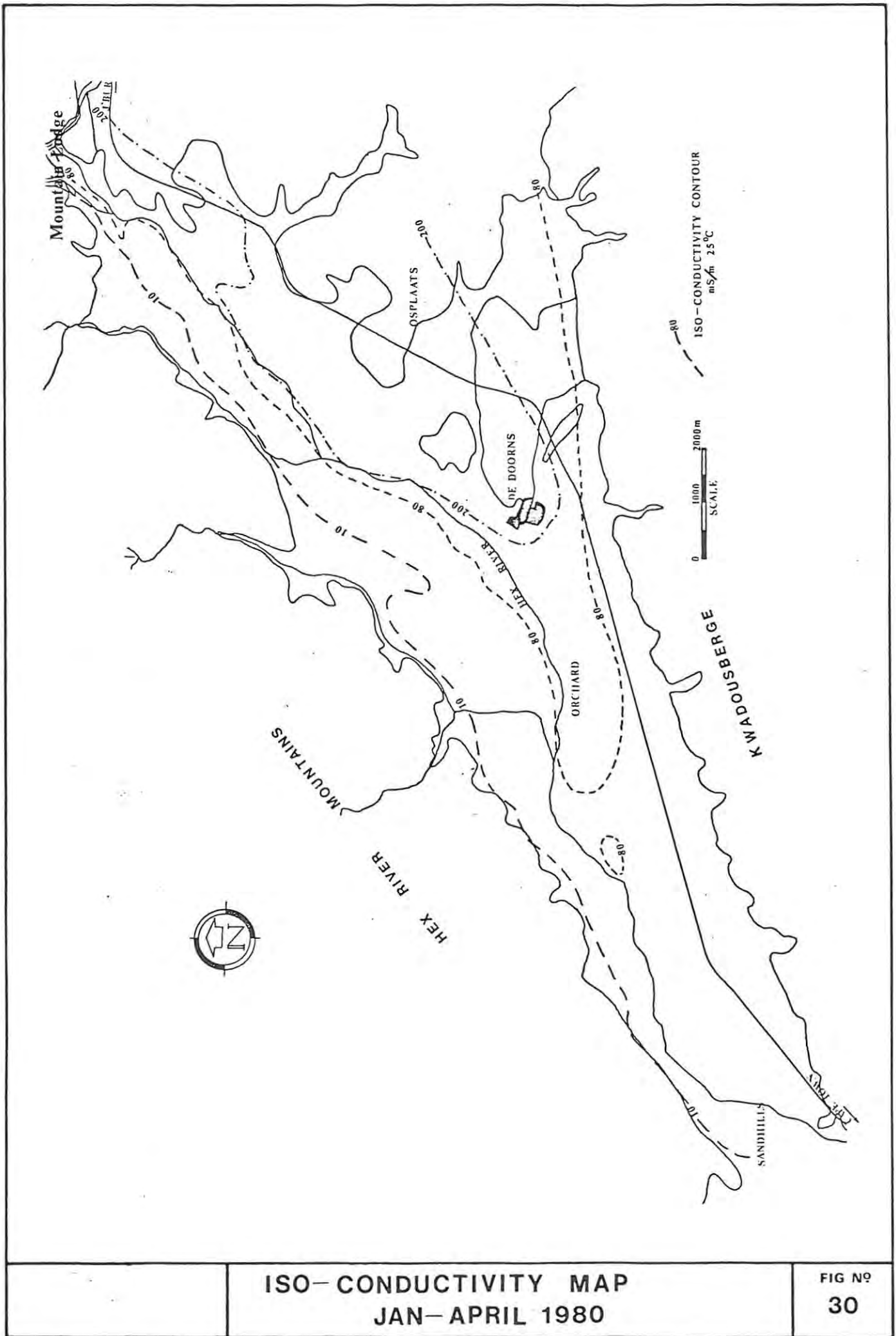
The table shows that groundwater with the lowest conductance occurs in the Nardouw Sandstone and its associated alluvial deposits. The Nardouw Sandstone is largely siliceous in nature and the absence of soluble

compounds explains the observed low conductance. Rocks of the Bokkeveld Group are predominantly pelitic in nature and, as such, contain more soluble material, partly explaining the observed higher conductivities of the associated groundwater.

An iso-conductivity map is shown in Fig 30 to illustrate spatial variation in electrical conductance in the Table Mountain and Bokkeveld formations. Fig 30 shows that groundwater with the lowest conductance is obtained from boreholes on the northern flanks of the Valley and in the Sandhills area where the water is derived from the Nardouw Sandstone and its associated alluvial deposits. The conductivity increases towards the centre of the Valley where the underlying bedrock is Bokkeveld shale and sandstone and the overlying alluvium is of mixed and Bokkeveld origin. Rosewarne (1981) concluded that groundwater with the lowest conductance was found in boreholes peripheral to the mountain fronts of the Breë River Valley, ie Table Mountain Sandstones and associated alluvial deposits. A similar trend was reported by Whittingham (1976) in the Klein Swartberg Valley.

Groundwater with a conductance greater than 80 mS/m occupies a tongue shaped area, mainly within the Bokkeveld Group, extending from Mountain Lodge and De Doorns to the Orchard area. Inflows of low conductivity groundwater are apparent in the Groothoek area, causing local southward deflection of the poorer quality groundwater. Groundwater samples were taken during the exploration drilling at water intersections and at frequent intervals through the saturated profile. Conductivity profiles are shown in Appendix A. There is no apparent tendency for conductivity to increase or decrease with depth.

Water samples were taken during the aquifer tests at the start, middle and end of the pumping period. The data are presented in Table 12.



ISO-CONDUCTIVITY MAP
JAN-APRIL 1980

FIG No
30

Borehole No	Aqulfer type	1st Sample		2nd Sample		3rd Sample		% Devia- tion
		mS/m	mln	mS/m	mln	mS/m	mln	
G30839	Mixed alluvium	146,0	50	150,0	700	150,0	1 400	2
G30889	Mixed alluvium	173,2	40	173,9	1 500	173,8	2 940	0
G30894	Mixed alluvium	286,1	60	284,0	750	284,0	1 500	0
G30897	TM alluvium	7,9	40	8,4	750	8,6	1 500	8
G30916	TM alluvium	47,9	35	38,9	2 500	37,2	4 320	22
G30840	Gydo shale	203,9	50	182,7	2 500	171,0	4 320	16
G30855	Voorstehoek shale	281,3	50	298,7	2 000	-	-	6
G30898	Voorstehoek shale	210,2	30	232,0	750	246,8	1 500	17
G30899	Gydo shale/Nardouw sandstone	28,5	40	28,5	2 250	29,0	4 320	2
G30987	Gydo shale	15,6	40	27,4	750	30,8	1 440	97

TABLE 12 : VARIATION OF CONDUCTIVITY DURING AQUIFER TESTS

In six of the ten tests, the variation in conductivity was less than 10 per cent. To assess possible longer term variations in conductivity, measurements taken from 1975 to 1980 are shown in Table 13.

Comparing the 1976 and 1980 conductivities for which the most comprehensive data are available, the boreholes in the Nardouw Sandstone show an increase in average conductivity from 21,2 mS/m to 27,3 mS/m, while the boreholes in Bokkeveld formations (Gydo Shale up to the Voorstehoek Shale) show an increase in average conductivity from 56,8 mS/m to 65,6 mS/m, or 15 per cent. In only four of the boreholes in Bokkeveld formations was the increase in conductivity potentially critical, ie above 80 mS/m.

Conductivity measurements have been taken at 10 points along the course of the Hex River (designated R1-R10) and on the major tributaries (R11-R17, Fig 27).

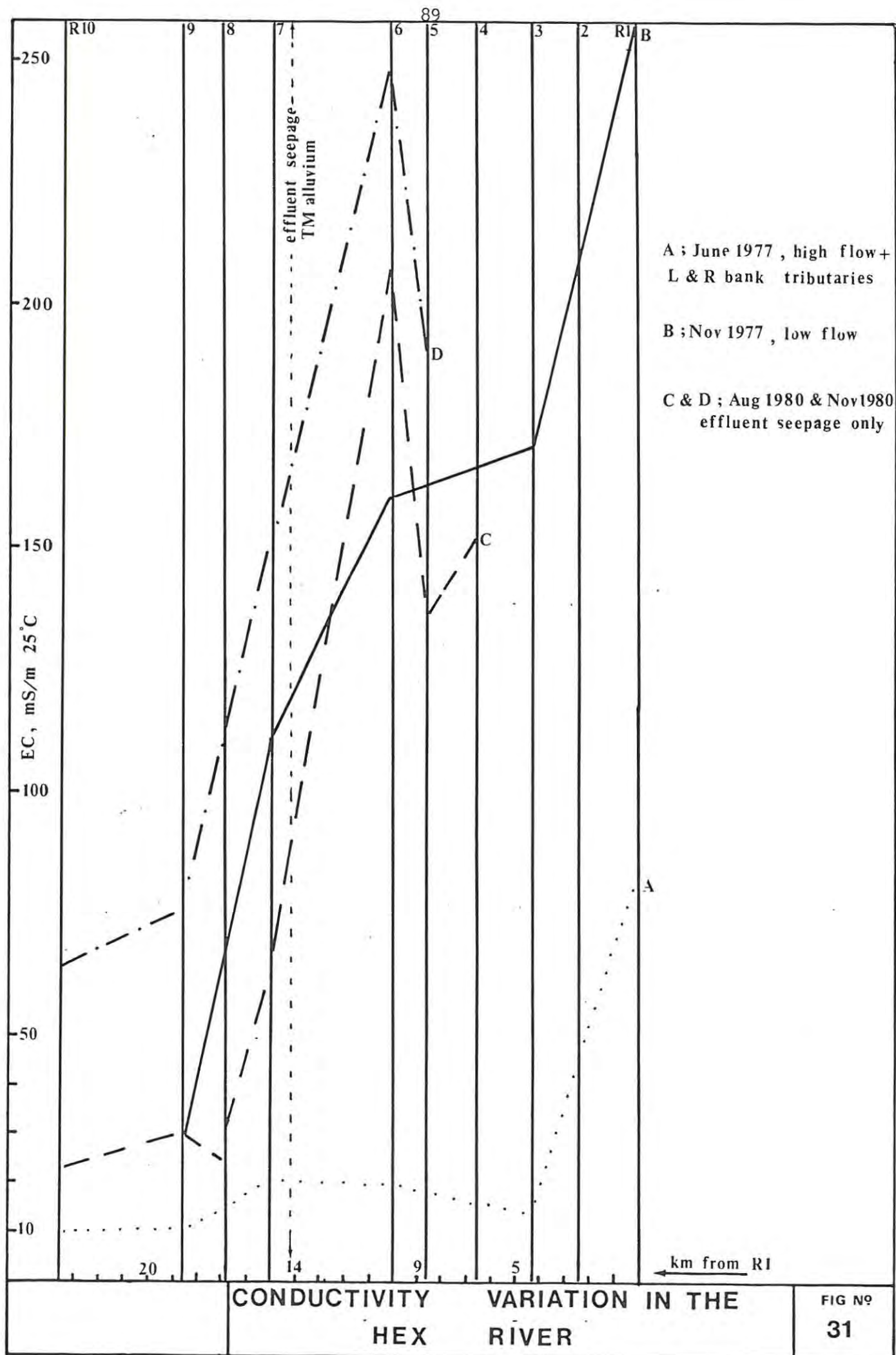
Formation	Borehole No	Date sampled and EC in mS/m at 25°C					
		Sep/Oct '75	Jan/Feb '76	Jan/Feb '77	Mar '78	Mar/Apr '80	
TABLE MOUNTAIN	221-4	2,0	4,6	5,7	-	5,9	
	238-2	-	35,7	42,8	-	29,6	
	406-2	-	21,8	3,6	2,8	3,8	
	406A-2	4,2	1,7	2,8	2,9	5,4	
	472-1	-	53,0	64,6	52,4	83,4	
	480-1	6,7	40,8	69,6	21,7	9,6	
	438-5	-	9,8	8,5	-	72,0	
	452-2	-	2,2	9,7	8,2	8,7	
	Total			169,6			218,4
	Average			21,2			27,3
BOKKEVELD	244-1		23,8	21,5		21,4	
	244-5		74,3			76,5	
	248-4		42,3	46,9		65,3	
	267-2		39,1			36,0	
	268-3		76,5	74,0	70,2	75,5	
	268-5		28,5	13,7		31,0	
	270B-2		48,8	60,5		50,0	
	270H-4		107,8			122,0	
	350-8	63,4	79,0	29,1		66,7	
	362-1	55,0	32,1	29,3	30,8	42,2	
	363-6	55,1	66,6			89,0	
	363-3	78,0	85,3	88,8	87,8	93,5	
	388-2		132,2	48,9	185,5	103,0	
	406E-4	28,2	27,8	22,8	28,5	33,5	
	436-1		22,8	60,4	16,2	193,0	
	346-2	46,8	47,3		58,9	48,9	
	436-3	58,8	61,3		39,1	29,4	
	446-1	22,7	21,5	34,2	18,7	66,0	
	446-2		46,0			28,9	
	464-1		152,0	144,8		100,8	
	466-4	26,8	9,8		35,4	18,2	
	466-5	26,0	24,2	20,9	42,2	52,8	
	Total			1 249,0			1 443,6
Average			56,8			65,6	

TABLE 13 : LONG-TERM VARIATION OF GROUNDWATER CONDUCTIVITY

The flow in the Hex River is derived from three main sources. During the summer months, September to March/April, the flow is normally derived entirely from groundwater inflows from the alluvium downstream from Mountain Lodge. Occasional summer storms may cause runoff in the tributaries for short periods. During the winter months, May to August, the flow is supplemented by runoff from the tributaries on the right bank. During this period heavy rainfall may also cause flow in the Hex River upstream of Mountain Lodge and, rarely, in left bank tributaries.

The variations in conductivity along the Hex River for varying seasonal conditions have been plotted in Fig 31. The influence of the different inflows are quite marked. The runoff from areas of exposed Bokkeveld formations (R1) has a high conductivity which increases at times of lower flows. The highest conductivity recorded at R1 is 250,0 mS/m in November 1977 and the lowest 83,0 in June 1977. Conversely the runoff from the Hex River Mountains has a very low conductance. The average conductivity for three main tributaries, the Bovenste, Groothoek and Els Rivers are 1,8; 2,0 and 1,7 mS/m respectively. Inflows from these sources will tend to lower the conductivity in the Hex River as can be seen in Fig 27 between R7 and R8.

Effluent seepage from the alluvium tends to vary in conductance. Upstream from R6 the Hex River flows through alluvium of mixed origin which contains water with a high conductance, eg 174 mS/m near R4 (G30889) and 290 mS/m near R5 (G30894). Downstream from R6 this type of alluvium becomes less important and the river flows through alluvium derived from the Table Mountain Group. This alluvium contains water with a generally low conductivity. The effects of these different inflows can be seen in plot D of Fig 31 ie an increase in



conductivity between R5 and R6 where the Hex River is flanked by mixed alluvium, and a decrease in conductivity between R6 and R9 where the Hex River is flanked by alluvium derived from the Table Mountain Group. The highest conductivity recorded when flow is derived totally from groundwater sources is 250,0 mS/m in November 1980 at R6. The lowest conductivity, 10 mS/m in June 1977 at R10, was recorded during a period of very high flow, with significant contributions from right bank tributaries.

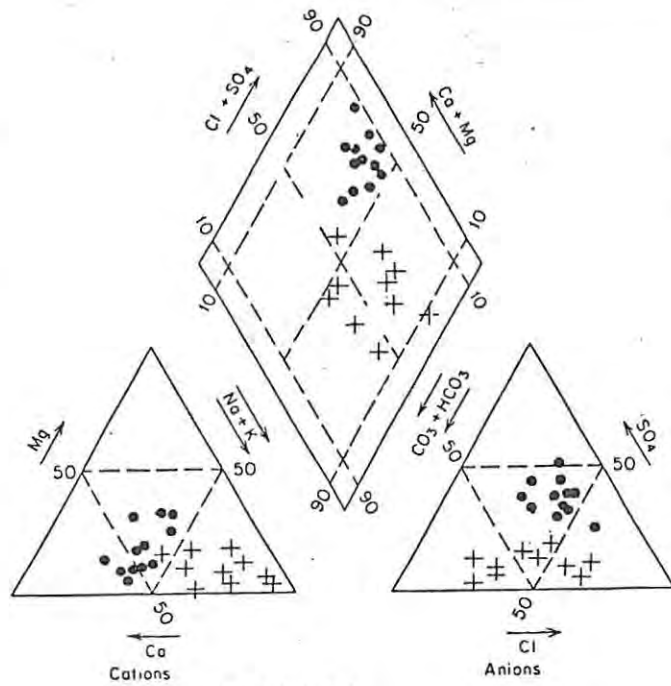
8.3.2 Chemical characteristics

The samples collected during the hydrocensus of 1980 are used for evaluation of the chemical characteristics of the ground and surface waters. Ionic concentrations of the cations and anions have been converted to percent milli-equivalents per litre and plotted on Piper Diagrams in Fig 32. The chemical analyses are presented in Appendix C.

The groundwaters from the Nardouw Sandstone and Bokkeveld formations plot in separate zones in the central diamond field. The Bokkeveld groundwater plots in the upper half of the diamond field, this zone being indicative of a stagnant environment according to Johnson, 1975. These groundwaters can be classed as $\text{Na}^+ + \text{Ca}^{++}$, $\text{Cl}^- + \text{SO}_4^{--}$ types and have TDS of above 200 mg/l. The groundwater from the Nardouw Sandstone plots in the lower half of the diamond field, this zone being indicative of a more dynamic environment, according to Johnson, 1975. These groundwaters can be classed as Na^+ , $\text{Cl}^- + \text{HCO}_3^-$, types and have TDS of less than 60 mg/l.

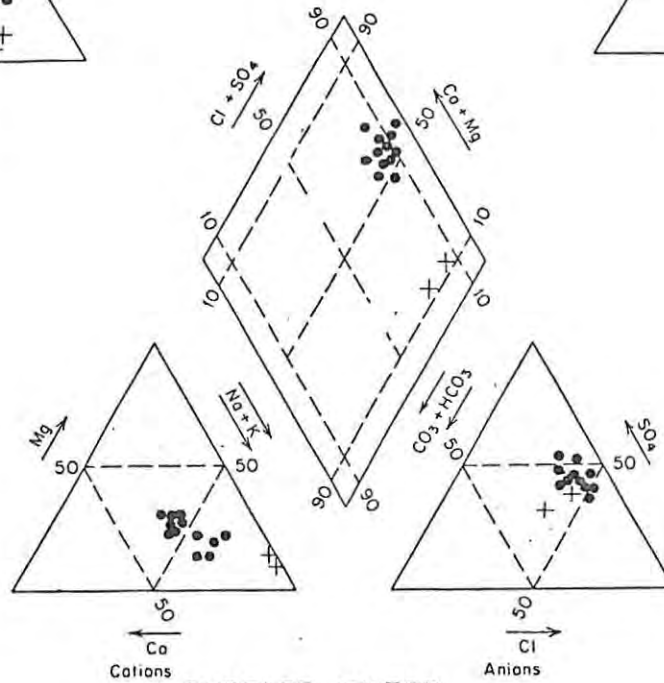
The alluvial groundwaters all plot in the upper half of the diamond field, and there is less distinction in chemical characteristics of the alluvial types as compared to their parent rocks.

PIPER
DIAGRAMS



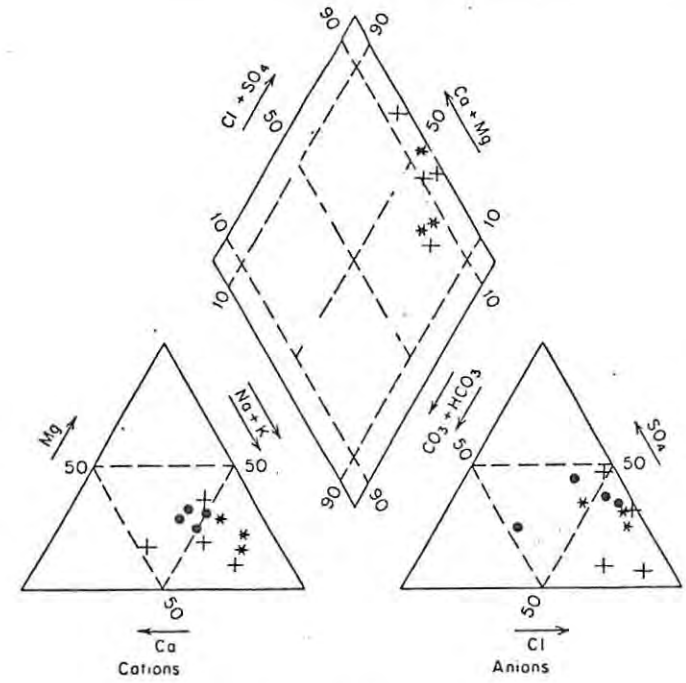
**a. BEDROCK
GROUNDWATER**

- + Nardouw Sandstone
- Bokkeveld



c. SURFACE WATER

- Hex river
- + Tributaries



**b. ALLUVIAL
GROUNDWATER**

- + Table Mountain
- Mixed
- * Bokkeveld

The alluvium derived from the Table Mountain Group, for example, shows a $\text{Ca}^{++} + \text{Mg}^{++} + \text{Cl}^{-} + \text{SO}_4^{--}$ character, quite different from the Nardouw Sandstone although the TDS is still comparatively low. The chemical modification of groundwater in the alluvial deposits is discussed in Section 8.3.

Chemical analyses from the Hex River plot in the upper half of the diamond field in a zone overlapping that of the alluvial and Bokkeveld groundwaters. This is not surprising as the flow of the Hex River is largely derived from effluent seepage from the alluvium and runoff from Bokkeveld formations. The water can be classed as a $\text{Ca}^{++} + \text{Mg}^{++}, \text{Cl}^{-} + \text{SO}_4^{--}$ type. Water from tributaries issuing from the Hex River Mountains (ie Nardouw Sandstone) plot in the lower half of the diamond field in the vicinity of the groundwater from the Nardouw Sandstone.

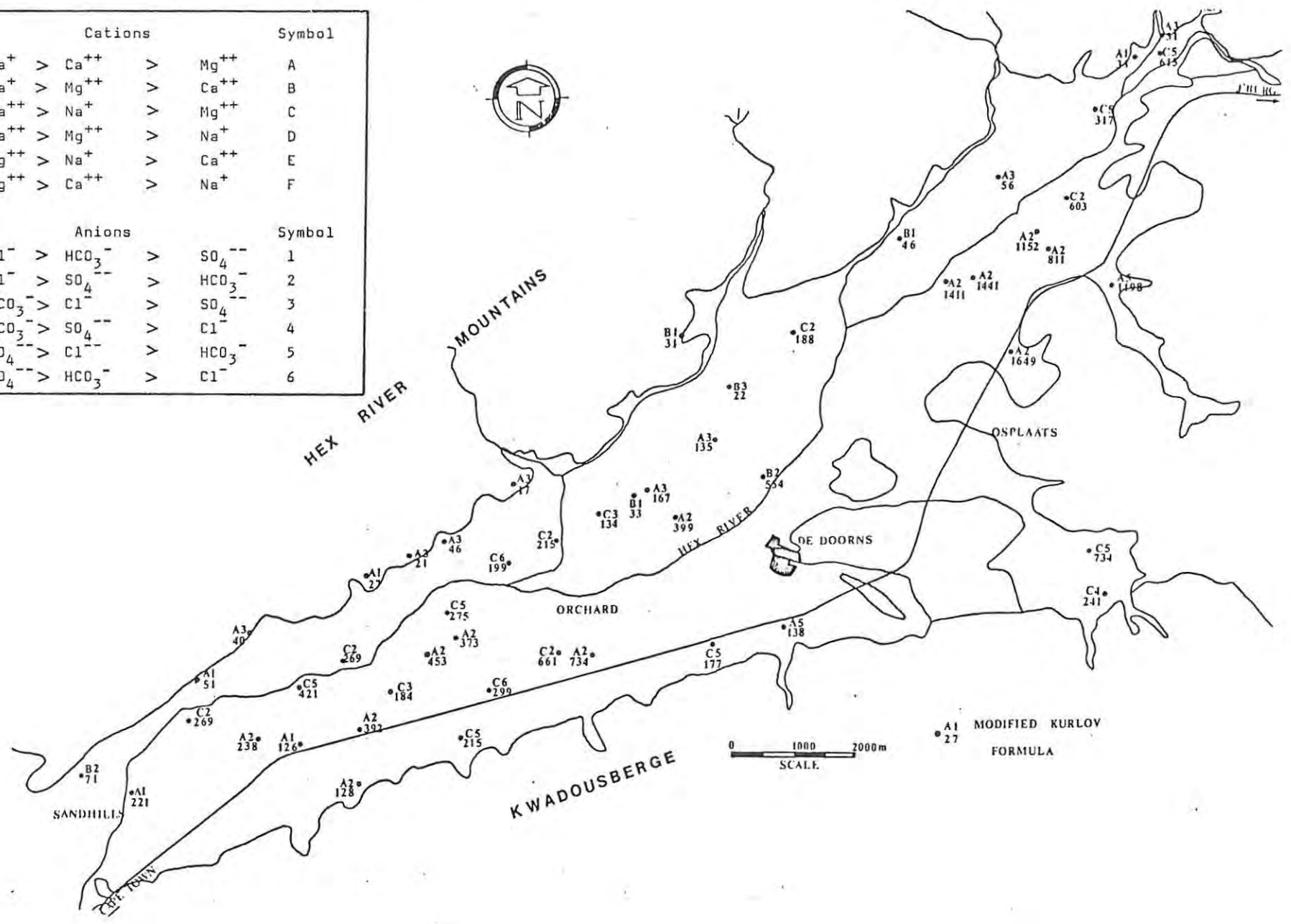
Having defined certain hydrogeochemical groundwater 'facies' it is appropriate at this stage to look at the regional distribution of these facies in the Hex River Valley. This is attempted by use of a modified Kurlov formula (Fig 33) as described in Section 8.2. The regional hydrogeochemical trends can be summarised as follows:

- . the groundwater along the northern flanks of the Valley is characterised by water types A1 and A3 and a TDS generally less than 50 mg/l ;
- . towards the central parts of the Valley, in the Orchard area, water types A2, C2 and C5 predominate with TDS of 200 mg/l to 600 mg/l ;
- . in the upper Valley area, north-east of De Doorns, type A2 predominates but the TDS is much higher, being in the range 800 mg/l to 1 650 mg/l .

HYDROGEOCHEMICAL FACIES

Cations			Symbol
Na ⁺	> Ca ⁺⁺	> Mg ⁺⁺	A
Na ⁺	> Mg ⁺⁺	> Ca ⁺⁺	B
Ca ⁺⁺	> Na ⁺	> Mg ⁺⁺	C
Ca ⁺⁺	> Mg ⁺⁺	> Na ⁺	D
Mg ⁺⁺	> Na ⁺	> Ca ⁺⁺	E
Mg ⁺⁺	> Ca ⁺⁺	> Na ⁺	F

Anions			Symbol
Cl ⁻	> HCO ₃ ⁻	> SO ₄ ⁻⁻	1
Cl ⁻	> SO ₄ ⁻⁻	> HCO ₃ ⁻	2
HCO ₃ ⁻	> Cl ⁻	> SO ₄ ⁻⁻	3
HCO ₃ ⁻	> SO ₄ ⁻⁻	> Cl ⁻	4
SO ₄ ⁻⁻	> Cl ⁻	> HCO ₃ ⁻	5
SO ₄ ⁻⁻	> HCO ₃ ⁻	> Cl ⁻	6



• A1 27 MODIFIED KURLOV FORMULA

These hydrogeochemical facies should be evaluated in the light of the earlier theoretical discussion on chemical evolution of groundwater as proposed by Chebotarev (1955), Johnson (1975) and Domenico (1972).

The northern flanks of the Valley were put forward as a main recharge zone in Chapter 7. This would correspond with the 'upper zone' as described by Domenico (1972) and the expected hydrogeochemical facies here would be a D3 type, ie $\text{Ca}^{++} + \text{Mg}^{++} + \text{HCO}_3^-$. The early incorporation of Na and Cl into the groundwater, resulting in A1 and A3 being the dominant types, can be explained by proximity of the Hex River Valley to the Atlantic ocean, from whence comes the moist air supply for precipitation on the Hex River Mountains.

The A2, C2 and C5 and higher TDS facies of the central Valley area can be correlated with the intermediate zone of Domenico. The Ca^{++} and SO_4^{--} character of the water can be explained by solution of calcite and oxidation of pyrite present in the Bokkeveld formations.

The A2, high TDS groundwater occurring in the upper Valley area can be correlated with the lower zone of Domenico. There is very little abstraction or recharge of groundwater in this area and groundwater movement is therefore sluggish and residence time relatively long compared to elsewhere in the Valley. Under these conditions the groundwater will acquire an $\text{Na}^+ + \text{Cl}^-$ and high TDS character.

8.3.3 Sources of dissolved species

The sediments of the Bokkeveld Group were originally deposited in a marine environment. It is therefore possible that some connate water and saline residues still remain in pore spaces and attached to mineral grains. The sluggish movement of groundwater in the

eastern and north-eastern parts of the Bokkeveld aquifer, due to low permeability, low recharge and small annual abstraction, is probably responsible for the failure of any connate water and soluble residues to have been removed by flushing. The Cl/Na ratio of 2:1 commonly observed in Bokkeveld formations is typical of sea water. The higher recharge and abstraction in the northern flanks of the valley results in a more rapid circulation of groundwater. The Bokkeveld formations in this area have been more thoroughly flushed and groundwater with a TDS of between 100 to 300 mg/l may be obtained compared with up to 3 200 mg/l in the eastern and north-eastern parts of the Hex River Valley.

Groundwater entering the Valley from the eastern catchment area has also travelled greater distances through Bokkeveld formations than that entering from the north. Reference to flow directions deduced from piezometric contours (see Fig 24 and 25) indicates that the former water may have come more than 10 km through Bokkeveld formations, compared to a maximum of 2 km for the latter, thus having more opportunity to acquire salinity.

One of the features of the Bokkeveld groundwater in the eastern and north-eastern areas of the Valley is the generally high SO_4^{--} concentrations. One source is thought to be from the oxidation of pyrite which is a common constituent of the Bokkeveld shales. Chemical weathering of the exposed shales would provide a ready source of sulphate to be dissolved in infiltrating rain and surface water. It may be of significance that recharging groundwater in the northern areas of the Valley does not pass through a similarly weathered zone. The area of exposed Bokkeveld formations can largely be classified as being a semi-arid area. In such areas the soils are not fully leached and soluble salts produced by weathering tend to accumulate in the soils. The

amount of drainage water leaving this area is a small proportion of the volume of water in which it can be carried away. Although low rates of runoff affect other constituents, sulphate is the anion most commonly affected (Hem, 1970). Samples of surface water taken in the area around Matroosberg station indicate that runoff water in this area soon acquires a high salinity. Values of 600 to 1 140 mg/l were measured. As a part of this water will infiltrate as recharge to the Bokkeveld aquifer, the high salinity in the eastern areas is not surprising. After rainfall in this area a white film of salt residues can be observed on soil surfaces, especially along drainage channels, where surface water has evaporated. Thus a ready supply of soluble salts is available for subsequent incorporation into the ground and surface waters.

The discussion so far has been concerned with natural sources of contamination. Significant modification of the alluvial groundwater and surface water may occur due to the activities of man.

The extensive development of irrigation in the Hex Valley means that vast quantities of salts are added to the soil each year, both as salts already present in the irrigation water and by the addition of fertilizers. In Section 7.3 it was calculated that approximately $20 \times 10^6 \text{ m}^3$ of groundwater and $10 \times 10^6 \text{ m}^3$ of surface water per annum was used for irrigation. The surface water used has an average TDS of 11 mg/l which means that in the region of 111 000 kg of salts/year are added in this way. To obtain a figure for salts added by groundwater used for irrigation is not so simple as the quality is very variable. However, taking an average of 250 mg/l, the total salts added to the soil by this means is in the region of $5 \times 10^6 \text{ kg}$ annually.

A survey of farming practices in the Hex Valley, during the hydrocensus, has indicated that the following quantities of fertilizer are applied each year:

CaCO_3 - 1 000 kg/ha

LAN (lime, ammonium, nitrate) - 210 kg/ha

KNO_3 - 210 kg/ha

Mg/SO_4 - 105 kg/ha

manure - 1 100 kg/ha

A fertilizer known as 3:2:1 is also occasionally used. This consists of nitrogen, phosphate and potassium in the above ratio.

For a surface area of 3 100 hectare a total of $4,73 \times 10^6$ kg of chemical fertilizers are added each year, plus $3,4 \times 10^6$ of organic fertilizer. Adding the totals for chemical fertilizers and the natural salt content of the irrigation water gives a total of approximately 10×10^6 kg of salts added to the soil annually.

The amount of salts taken up by plants from irrigation water is a small proportion of the amount in the water and consists largely of calcium and magnesium (Eaton, 1954) Likewise, evaporated water is also essentially free of salts. Thus most of the soluble matter originally in the irrigation water will either remain in the soil or be removed by infiltrating water to reach the water table and the Hex River.

It is appropriate at this stage to consider the salt balance equation which can be written in the simplified form (Franklin, 1980):

$$V_i C_i - V_d C_d = 0 \quad \dots (22)$$

where V_i and V_d are volumes of irrigation and drainage water (Hex River and alluvial underflow) respectively, having the corresponding salt concentrations C_i and C_d .

The term $V_i C_i$ has been previously estimated to be 10×10^6 kg. The right hand side of the equation is more problematical. Gaugings and quality measurements on the Hex River have been carried out from 1978 to 1980 and analysis of this data gives an estimated average of 87 440 mg/s or $2,8 \times 10^6$ kg/year at R10. Inflows at R1 have been subtracted from the total but are in any case generally insignificant. Subsurface flow in the alluvium must also be taken into account. An estimate of the subsurface flow, Q , can be made by application of Darcy's law, (Eq 20).

The width of the saturated alluvium at R10 is 1,5 km. This alluvium is the type derived from the Table Mountain Group. Values of transmissivity calculated from pump tests in this alluvium near De Doorns gave values of 280, 250 and 220 m^2/day . The hydraulic gradient is 0,0065. Substituting these values into Eq (20), taking T as 280 m^2/day gives:

$$Q = 2\,730\,000\, m^3/day.$$

Assuming an average TDS for this alluvial groundwater of 200 mg/l gives 2×10^6 kg/year of salts leaving the area as subsurface flow. Addition of the subsurface and surface estimates gives $\pm 4,8 \times 10^6$ kg/year of salts leaving the area. Substitution of the estimated values in Eq (22) gives:

$$10 \times 10^6\, kg - 4,8 \times 10^6\, kg = + 5,2 \times 10^6\, kg.$$

While the estimations are obviously subject to error it would appear that the salt balance is unfavourable with a considerable residue of salts failing to be removed from the area each irrigation season.

8.3.4 Radiometric dating of the groundwater

Water samples were collected for Tritium (^3H) and Carbon 14 (^{14}C) dating during pump tests and drilling operations in 1979/80. The samples were analysed by the National Physical Research Laboratory of the CSIR, Pretoria. The results are presented in Tables 14 and 15, overleaf.

The main conclusions to be drawn from the analyses are:

- . the groundwater in the Bokkeveld formations in the southern and eastern areas of the Valley is relatively old, eg G30840, G30855 and G30898. Tentative estimations of age from the ^{14}C analyses indicates that the groundwater in these areas may be thousands of years old;
- . the groundwater in the alluvial deposits is recent (Table Mountain and mixed alluvium). ^{14}C and ^3H analyses suggest that this groundwater is less than 20 years old. There is some evidence from G30897 and G30998 that the groundwater in the upper parts of the alluvium is somewhat younger than that in the lower parts;
- . the low TDS groundwaters are young while the higher TDS waters are old and stagnant. The exception to this is groundwater in mixed alluvium, eg G30839, G30889 and G30894 which have a high TDS (900 to 1 704 mg/l) but are recent waters according to the ^{14}C and ^3H analyses. This indicates fairly

Borehole No	Depth (m)	Formation	^3H (TU)	^{14}C (%)	Age
G30897	40	TM alluvium	$8,8 \pm 1,2$	-	-
G30897	43	TM alluvium	$10,3 \pm 1,2$	-	Very young
G30897	46	TM alluvium	$8,2 \pm 1,1$	-	Very young
G30998	21	TM alluvium	$11,1 \pm 1,1$	-	Very young
G30998	43	TM alluvium	$6,9 \pm 1,2$	-	Very young
G30998	50	Bokkeveld shale	$8,8 \pm 1,2$	-	Old water
G30886	26	Bokkeveld shale	$-1,6 \pm 1$	-	Old water
G30839B	80	Bokkeveld shale	-	$66,4 \pm 0,5$	3 000 yrs
G30858	Artesian	Bokkeveld shale	-	$70,4 \pm 0,6$	3 000 yrs
G30838C	-	TM alluvium	-	$133,6 \pm 0,6$	Very recent

TABLE 14 : TRITIUM (^3H) AND CARBON 14 (^{14}C) ANALYSES OF GROUNDWATER IN THE HEX VALLEY

Borehole No	Formation	Pumping time (min)	^3H (TU)	^{14}C (%)	Age
G30839E	Mixed alluvium	45	$7,4 \pm 1,1$	$122,47 \pm 0,62$) 20 yrs
G30839E	Mixed alluvium	1 500	$7,8 \pm 1,1$	$121,64 \pm 0,61$)
G30840	Bokkeveld shale	2 000	$0,4 \pm 1,0$	$43,71 \pm 0,44$	7 000 yrs
G30840	Bokkeveld shale	4 300	-	$47,37 \pm 0,41$	6 500 yrs
G30855	Bokkeveld shale	-	$1,1 \pm 1,0$	-	Very old
G30889B	Mixed alluvium	-	$6,8 \pm 1,1$	-	Young water
G30889B	Mixed alluvium	-	$6,6 \pm 1,1$	-	Young water
G30889B	Mixed alluvium	40	$6,5 \pm 1,0$	$114,68 \pm 0,75$	20 yrs
G30894B	Mixed alluvium	1 410	$6,1 \pm 1,1$	$113,23 \pm 0,70$	20 yrs
G30901C	TM alluvium	40	$6,8 \pm 1,1$	$121,25 \pm 0,87$	20 yrs
G30898	Bokkeveld shale	70	-	$79,08 \pm 0,51$	2 000 yrs
G30898	Bokkeveld shale	750	-	$78,62 \pm 0,52$	2 000 yrs
G30898	Bokkeveld shale	1 440	-	$79,86 \pm 0,54$	2 000 yrs
G30916	TMS alluvium	4 300	-	$126,05 \pm 1,12$	20 yrs

TABLE 15 : TRITIUM (^3H) AND CARBON 14 (^{14}C) ANALYSES OF GROUNDWATER TAKEN DURING
AQUIFER TESTS

rapid contamination and may be further evidence of the unfavourable salt balance in the Valley.

8.4 Summary

The groundwaters in the aquifers of the Hex River Valley exhibit a varied range of chemical characteristics. The chemical quality of the groundwater is influenced by lithology, position within the chemical evolution sequence of major species and mans' activities.

Groundwater associated with the predominantly siliceous Table Mountain Group rocks has the lowest TDS and can be classed as Na^+ , $\text{Cl}^- + \text{HCO}_3^-$ in character. Groundwaters associated with the predominantly pellictic rocks of the Bokkeveld Group have a higher TDS and are $\text{Na}^+ + \text{Ca}^{++}$, $\text{Cl}^- + \text{SO}_4^{--}$ in character. The TDS of the Bokkeveld groundwaters appears to improve with proximity to the Nardouw Sandstone.

The alluvial groundwaters show similar characteristics to their parent rocks with regard to TDS trends but their chemical characteristics have been altered by mans' activities, principally fertilizer application. A salt balance calculation for the Hex River Valley indicates an unfavourable situation with $\pm 5 \times 10^6$ kg/year of residual salts in the unsaturated zone.

The ^{14}C and ^3H age determinations on the groundwater provides further confirmation of hydrogeological and hydrogeochemical arguments discussed in Chapters 7 and 8. The low TDS waters are relatively young (tens of years) while the high TDS waters are relatively old (thousands of years). The groundwaters of the Nardouw Sandstone and its associated alluvium is of the young age type, whilst that in the Bokkeveld formations of the central and eastern areas of the Valley is of the older age type.

The data presented in this chapter will be examined critically in the next chapter to test the validity of the hydrogeochemical hypotheses listed in Chapter 5.

9 HYPOTHESIS TESTING

9.1 Hydrogeology

. Hypothesis 1

There is hydraulic connection between the Table Mountain Group, the Bokkeveld Group and the alluvial deposits, with aquifer conditions ranging from unconfined to semi-confined with leakage.

Calculations of groundwater storage within the lower Bokkeveld formations gave a figure of $2,8 \times 10^6 \text{ m}^3$ (Section 7.8). Groundwater abstraction, mainly from the Bokkeveld formations, was calculated to be $20 \times 10^6 \text{ m}^3$ annually (Section 7.3). The deficit is made up of $12 \times 10^6 \text{ m}^3$ from the Nardouw Sandstone and $5 \times 10^6 \text{ m}^3$ from alluvial deposits, by way of leakage. Prolonged heavy rainfall on the Hex River Mountains results in flowing artesian conditions in many boreholes penetrating only the Bokkeveld formations. This provides further evidence of hydraulic connection between the Table Mountain and Bokkeveld Groups. Aquifer tests at G30897, G30987 and G30998 gave evidence of a range of aquifer conditions with delayed yield in the alluvium to semi-confined with leakage in the Bokkeveld formations (Section 7.4). The hypothesis is therefore accepted.

. Hypothesis 2

Discrete aquifer units exist within the Bokkeveld Group with shales acting as aquicludes to the sandstone aquifers.

In the Hex River Valley, boreholes are mainly exploiting groundwater within the lower formations of the Bokkeveld Group, namely the Gydo Shale, Gamka Sandstone and Voorste-hoek Shale. This is because of the poorer quality groundwater and more elevated and rugged topography of the higher

formations. The Gamka Sandstone is poorly developed in the Hex River Valley and hardly distinguishable from the shales in drill samples. Yields of up to 45 m³/h (12,5 l/s) are obtained from the Gydo and Voorstehoek Shales. Therefore, in the lower formations of the Bokkeveld Group, the hypothesis is rejected. Conditions may be different in the higher Bokkeveld formations where the sandstones are much more prominently developed, eg the Hex River Sandstone. The hypothesis may hold true here, although if similar yields are still obtainable from the shales, they could hardly be classed as aquicludes.

. Hypothesis 3

Structural control of permeability in the Table Mountain/Bokkeveld formations results in anisotropic groundwater flow conditions.

Aquifer tests carried out at G30855, G30898 and G30899 indicated that fractures had been intersected (Section 7.4). Drawdown 'curves' combined with geological observations indicated that these fractures ranged from sub-horizontal to sub-vertical. At 30898 drawdown in the pumped borehole and an observation borehole 66 m distant were almost identical whereas the drawdown in an observation borehole only 55 m from the pumped borehole was sixty per cent less.

The piezometric contour maps indicate that 'troughs' of drawdown develop in the Bokkeveld formation in response to pumping rather than cones of drawdown observed in isotropic formations (Section 7.5). The hypothesis is therefore accepted. The direction of this anisotropy appears to parallel the strike of the geological formations, ie NE-SW and E-W.

. Hypothesis 4

Recharge is mainly effected by rainfall infiltration on the mountainous areas of the Table Mountain Group.

In Section 7.7 recharge to the Table Mountain/Bokkeveld Group rocks was calculated at $15 \times 10^6 \text{ m}^3$ (excluding leakage from the alluvium) in 1979. The water level rise method of recharge calculation gave a figure of $7,5 \times 10^5 \text{ m}^3$ for recharge to the Bokkeveld formations. This is obviously a very low figure and indicates that water level rises recorded in the Valley do not represent the total recharge to the catchment area. The average annual rainfall on the Hex River Mountains may be as high as 2 400 mm. The model put forward here is that, due to the highly fissured nature of the Nardouw Sandstone, rainfall infiltration mostly takes place into this formation. This water will then be available for lateral and vertical movement into the pumped aquifer during and at the end of the pumping season. This model is further substantiated when one considers the volume of Bokkeveld rock that would have to be dewatered to yield $15 \times 10^6 \text{ m}^3$ (estimated annual abstraction minus alluvial leakage). The piezometric level in the Bokkeveld would have to be drawn-down by 240 m over the entire surface area of 62 km^2 to yield this volume. This is about five times the maximum drawdown observed in the area.

The hydrogeochemical data discussed in Section 8.3 also supports the hypothesis, with groundwaters with the lowest conductance being obtained from the Nardouw Sandstone and the lowermost Bokkeveld formations. The hypothesis is therefore accepted.

Hypothesis 5

Leakage from the alluvial deposits to the underlying bedrock is an important recharge mechanism.

In Section 7.7 it was calculated that recharge from rainfall infiltration to the Table Mountain/Bokkeveld aquifer system was $15 \times 10^6 \text{ m}^3$ in 1979. Leakage from the Table

Mountain alluvium into the underlying bedrock formations was calculated at $5 \times 10^6 \text{ m}^3$ annually, which is 25% of the total recharge to the Table Mountain/Bokkeveld aquifer. The hypothesis is thus accepted.

9.2 Hydrogeochemistry

. Hypothesis 6

Groundwater in the Bokkeveld Group is inherently of poor quality whilst that in the Table Mountain Group is of good quality.

The Bokkeveld rocks are mainly pelitic in composition and also contain minerals such as calcite and pyrite. There is therefore a ready supply of material available for solution by circulating groundwater. The Table Mountain Group, on the other hand, is mainly silicious in nature and, as such, contains little soluble material.

One would therefore expect the Bokkeveld groundwater to have a higher dissolved mineral content than groundwater associated with the Table Mountain Group, under natural conditions. The upper formations of the Bokkeveld Group, undisturbed by large scale groundwater abstraction or fertilizer application, do have much higher total dissolved solids than the Nardouw Sandstone of the Table Mountain Group. In the Tra-Tra Shale for instance, the TDS range is 700 mg/l to 3 200 mg/l, consisting largely of $\text{Na}^+ + \text{Cl}^- + \text{SO}_4^{--}$. In the Nardouw Sandstone of the Hex River Mountains the TDS is generally below 60 mg/l and may be as low as 10 mg/l. The hypothesis is therefore accepted.

. Hypothesis 7

The quality of the groundwater in the Bokkeveld Group improves with proximity to the Nardouw Sandstone.

Measurements taken in January/April 1980 showed that the higher formations of the Bokkeveld Group, ie the Voorstehoek Shale and succeeding formations, have a conductivity greater than 80 mS/m and reaching up to 490 mS/m (Section 8.3). There is little groundwater abstraction or cultivation taking place in these areas which may have had an adverse effect on the water quality. Such a range in conductance can therefore be considered normal for groundwater associated with Bokkeveld rocks. Groundwater associated with the lower members of the Bokkeveld Group, eg the Gydo Shale, however, has conductivities as low as 10 mS/m along the northern flanks of the Valley. Groundwater in the underlying Nardouw Sandstone may have a conductivity as low as 2,2 mS/m. It has been calculated that $12 \times 10^6 \text{ m}^3/\text{year}$ of this good quality groundwater leaks into the overlying Gydo Shale in response to pressure relief caused by large scale groundwater abstraction by boreholes. This active flushing of the lower Bokkeveld formations will have removed soluble minerals from the major fissures and matrix interstices, resulting in only a limited increase in conductivity of groundwater as it flows from the Nardouw Sandstone through the Gydo Shale. The hypothesis is therefore accepted.

. Hypothesis 8

Over-exploitation of the aquifer(s) has resulted in intrusion of poor quality water into the pumped aquifer(s).

Conductivity measurements of January/April 1980 revealed a zone of relatively high conductivity groundwater (EC of more than 80 mS/m) extending from the head of the Valley, near R1 to the Orchard area and back towards De Doorns. This zone forms a tongue-shaped intrusion into the lower conductivity groundwaters of the Nardouw Sandstone and lower Bokkeveld formations. These groundwaters are of good quality owing to the active recharge and flushing of these rocks and the

siliceous, low solubility nature of the Nardow Sandstone. Groundwater in the eastern areas of the Hex Valley has a conductance of up to 490 mS/m, however. The piezometric maps (Figs 24 and 25) show that groundwater flow takes place from the north, south and eastern parts of the Valley. It can be seen that high recharge from the northern flanks of the Valley will tend to keep a pressure differential between the northern and southern piezometric levels, which should prevent the intrusion of the high conductivity groundwater from the east.

However, since about 1958, the average rainfall has dropped by 14 per cent resulting in reduced recharge. Development of new vineyards has continued, however, with corresponding greater abstraction of groundwater for irrigation. These factors have caused a lowering of the piezometric pressure differential allowing the lateral migration of high conductivity groundwater from the east into the adjacent pumped aquifer. The bedrock aquifer was found to be anisotropic with respect to transmissivity, with a T_{max} in an approximately east-west direction. This characteristic facilitates the intrusion of high conductivity groundwater from the east. The hypothesis is therefore accepted.

10 CONCLUSIONS

The conclusions drawn from this investigation will be presented under sub-headings corresponding to the study aims outlined in Chapter 4. These are:

. Ground and surface water utilisation

The hydrocensus revealed that there are 401 production boreholes and 8 production wells in the Valley. Sixty per cent of these boreholes are over 150 m in depth and twenty per cent yield more than 10 l/s. Annual groundwater abstraction and surface water usage is of the order of $20 \times 10^6 \text{ m}^3$ and $10 \times 10^6 \text{ m}^3$, respectively.

. Aquifer characteristics

Groundwater abstraction takes place principally from boreholes penetrating bedrock formations, namely the Nardouw Sandstone (Table Mountain Group), Gydo Shale (Bokkeveld Group) and, to a lesser extent, the Gamka Sandstone and Voorstehoek Shale (Bokkeveld Group). Groundwater abstraction from alluvial deposits is limited to those derived from the Table Mountain Group. There is hydraulic connection between all of these aquifer units.

Transmissivity ranged from $20 \text{ m}^2/\text{day}$ to $280 \text{ m}^2/\text{day}$ in the alluvial deposits, with the alluvium derived from the Table Mountain Group having the higher transmissivities. Storage coefficients ranged from 1×10^{-3} in mixed alluvium to 1×10^{-1} in Table Mountain alluvium, representative of semi-confined to unconfined conditions respectively. Aquifer conditions were found to be more varied in the bedrock formations, with leakage and anisotropy with respect to transmissivity. The range of transmissivity was $23 \text{ m}^2/\text{day}$ to $110 \text{ m}^2/\text{day}$. The higher transmissivities were found in the Gydo Shale on the northern flanks of the Valley. The direction of anisotropy, corresponding to maximum transmissivity, is in an

approximately east-west direction and is thought to be linked to fissures developed along bedding planes. The storage coefficient ranged from 1×10^{-3} to $3,5 \times 10^{-5}$, representative of semi-confined to confined aquifer conditions in the bedrock formations, respectively.

Leakage of groundwater from the Table Mountain alluvium and Nardouw Sandstone to the Bokkeveld formations is an important mechanism and is discussed further under recharge.

• Exploitation of alluvial groundwater

The only alluvium containing groundwater of suitable quality for irrigation of vines is that stored in the Table Mountain alluvium. It has been estimated that the volume of groundwater in storage within this alluvium is of the order of $9,5 \times 10^6 \text{ m}^3$. A yield of 7 l/s was obtained from an alluvial borehole G30897, which compares favourably with yields from deeper bedrock boreholes. The economics of an alluvial borehole, both construction and running costs, are also more favourable than for a bedrock borehole, eg shallower drilling depth, reduced pumping lifts. However, a detrimental effect of increased exploitation of alluvial groundwater would be a reduction in leakage to the underlying bedrock formations as the hydraulic head in the alluvium is lowered.

The groundwater stored in the mixed alluvium could possibly be utilised by dilution with better quality water. Alternatively, this groundwater could be used directly for irrigation of such crops as lucerne.

• Natural recharge

A number of recharge mechanisms were found to be important in the Hex River Valley. Leakage of groundwater from Table Mountain alluvium to the underlying Bokkeveld formations was calculated to be $5 \times 10^6 \text{ m}^3/\text{year}$. Recharge to the bedrock formations in

the area of groundwater withdrawal was estimated at $15 \times 10^6 \text{ m}^3$ for 1979. This represents 12% of the mean annual rainfall. Recharge by influent seepage to the alluvium of the Groothoek fan, between R14 and R15, was measured up to 200 l/s. During the period April to September 1980 natural recharge to the Groothoek fan was calculated to be $3,8 \times 10^6 \text{ m}^3$.

Discussion of natural recharge is an appropriate place to introduce the concept of 'perennial yield'*. The perennial yield of a groundwater unit has been defined (Todd, 1980) as 'the rate at which water can be withdrawn without producing an undesired result'. Five factors are generally considered for the determination of perennial yield (Todd, 1980), namely: water supply available to the unit; economics of pumpage; quality of the groundwater; water rights in and near the unit and land subsidence caused by lowering groundwater levels. The first three factors are of importance in the Hex Valley. From the groundwater hydrographs it is obvious that since records were started in 1961 the annual draft on the groundwater reservoir (bedrock) has often exceeded the mean annual water supply to the area. This statement should perhaps be qualified by saying the mean annual water supply available to the withdrawal area as a large percentage of the recharge to the Table Mountain Group rocks of the Hex River Mountains does not enter the pumped aquifer.

The quantity and rate concept of safe yield can therefore be applied here, where total recharge to the area may be equal to or exceed the annual draft but the rate at which this water moves into the area of withdrawal does not. A possible factor to be considered here is the occurrence of shale bands within the Table Mountain Group which will tend to retard the lateral flow of groundwater.

With regard to pumping costs the situation does not appear to be critical as yet. Although many boreholes have had to be

* preferred to the term 'safe yield', (Todd, 1980)

deepened, new ones drilled and to greater depths than was formerly the case, pumping levels increased and wells have dried up, the economics of export table grape farming are still favourable.

In respect of quality of groundwater the perennial yield has definitely been exceeded. This is evidenced by the poor quality groundwater that has been drawn into the pumped aquifer from the eastern areas of the valley. This type of degradation of the quality resource is usually economically irreversible for most practical situations (Hall, 1980). While on the subject of perennial yield a conclusion drawn from an earlier report on the Hex Valley (Vegter et al, 1975) is appropriate. This states that, 'there is a disproportionate availability of water in the Hex Valley rather than a general shortage'. Thus the perennial yield of one area of the Valley may not be the same as for others. An example is the Sandhills area, as there are no problems here of groundwater availability or quality. In this area there is a surplus of groundwater in both the bedrock and alluvium which, if proper management was initiated, could possibly be beneficially distributed to farms experiencing shortages as and when they occur.

. Water quality

The best quality groundwater is obtained from the Nardouw Sandstone on the northern flanks of the Valley and in the Sandhills area. The Gydo Shale, Gamka Sandstone and Voorstehoek Shale (the latter in the Groothoek area only) of the Bokkeveld Group also contain good quality groundwater. In the alluvial aquifer, only the alluvium derived from the Table Mountain Group contains water suitable for the irrigation of vines. These groundwaters have a conductivity of less than 80 mS/m and may be less than 10 mS/m in the Nardouw Sandstone. A tongue-shaped intrusion of poorer quality water extends from Mountain Lodge and De Doorns to just west of Orchard. Groundwater in this area may have a conductivity of up to 490 mS/m (January - April 1980 survey). This

encroachment of poor quality water has been caused by a lowering of the pressure differential between the northern and eastern piezometric levels due to high groundwater abstraction, allowing the lateral migration of the brackish water into the pumped aquifer.

The quality of the water in the Hex River is poor up to R6 (more than 100 mS/m) and unsuitable for irrigation of vines. Downstream from R7 the quality improves due to effluent seepage of groundwater from the Table Mountain alluvium and is suitable for irrigation of vines. The quality of the tributary water issuing from the Hex River Mountains is excellent, having an average conductivity of 1,8 mS/m.

The salt balance in the Valley appears to be unfavourable. It was calculated that the residual salts amount to approximately 5×10^6 kg annually. If this is a true reflection on conditions in the Valley then the long-term repercussions could be serious with areas becoming unsuitable for cultivation owing to saline soils.

• Water resources management

From the information presented in this report on the conditions prevailing in the Hex River Valley it appears obvious that some form of management of the water resources of the area is desirable, if not essential. The Valley is a very rich farming area and irrigated area and production could be increased and more assured if proper management was initiated. The present situation of continuous drilling of new boreholes and unmonitored groundwater abstraction can only have deleterious effects on the long-term future of the Valley as one of the major producing areas of table grapes of export quality in South Africa.

Surface water management has been practiced for decades in the Valley in the form of Irrigation Boards and other schemes but groundwater development has been, and still is, haphazard and

uncoordinated. The effects of this can be seen in the intrusion of poor quality groundwater into the pumped aquifer, water shortages in some areas and surpluses in others.

Clearly there is a need for the groundwater resource of the Valley to be optimally managed as a dependent unit and not as independent sub-units (individual farms). Morel-Seytoux (1980) suggested the following four steps in the formulation of a typical management plan.

Physical : Planning of optimum network of high yield production boreholes to reduce mutual interference of troughs of pressure relief. Development of more alluvial production boreholes eg the Groothoek area. Cessation of pumping of boreholes peripheral to the brackish water area to try and contain further encroachment of poor quality groundwater. Selection of high yielding boreholes in the Sandhills area as a supply source for the Upper Valley and consideration of a distribution system for this water. Conjunctive use of the ground and surface water resources.

Legal : Possible declaration of the Hex River Valley as a groundwater control area. Legal aspects of pumping groundwater from one property to another.

Economic : Cost of transport of groundwater from source to consumer. Fixing of the price of this 'imported' water to farmers. Cost of monitoring groundwater abstractions eg water meters. Possible drilling of new boreholes in the Sandhills area and alluvial boreholes in the Groothoek area.

Administrative : Re-allocation of Government Water Scheme quotas. Monitoring groundwater abstractions. Allocation of surplus water.

Implementation of a management plan involving the above components would be bound to run into difficulties. Farmers who are liable to experience water shortages could probably be convinced

that the redistribution of the groundwater resource of the Hex Valley was in their best interests. However, farmers who are quite happy with the present set-up and who do not experience problems of water quality and shortage would be unlikely to agree to increased groundwater abstraction on their farms for export to other areas. If they cannot be convinced that their groundwater resource will be maintained and perhaps enhanced, they are certain to insist on the present status-quo with the power of current law on their side.

. Concluding remarks

The results of this investigation have provided a hydrogeological framework on which future work in the Hex River Valley, particularly aquifer management, can be based. It is also hoped that extrapolation of results to other areas of a similar nature may be possible.

Examples of such areas are the Breë River Valley, Klein Swartberg Valley, Ceres Basin and Tulbach Valley. These are all intermontane valleys, underlain by Bokkeveld and alluvial formations, surrounded by mountain ranges composed of Table Mountain Group Sandstones and extensively engaged in viticulture. These physiographic, geological and agricultural similarities suggest that hydrogeological conditions will also be similar. Preliminary hydrogeological surveys of the Breë River Valley (BRGM, 1976; Greef, 1980 and Rosewarne, 1981) and the Klein Swartberg Valley (Whittingham, 1976) suggest that this is broadly the case. Examples of such similarities have been given in this report.

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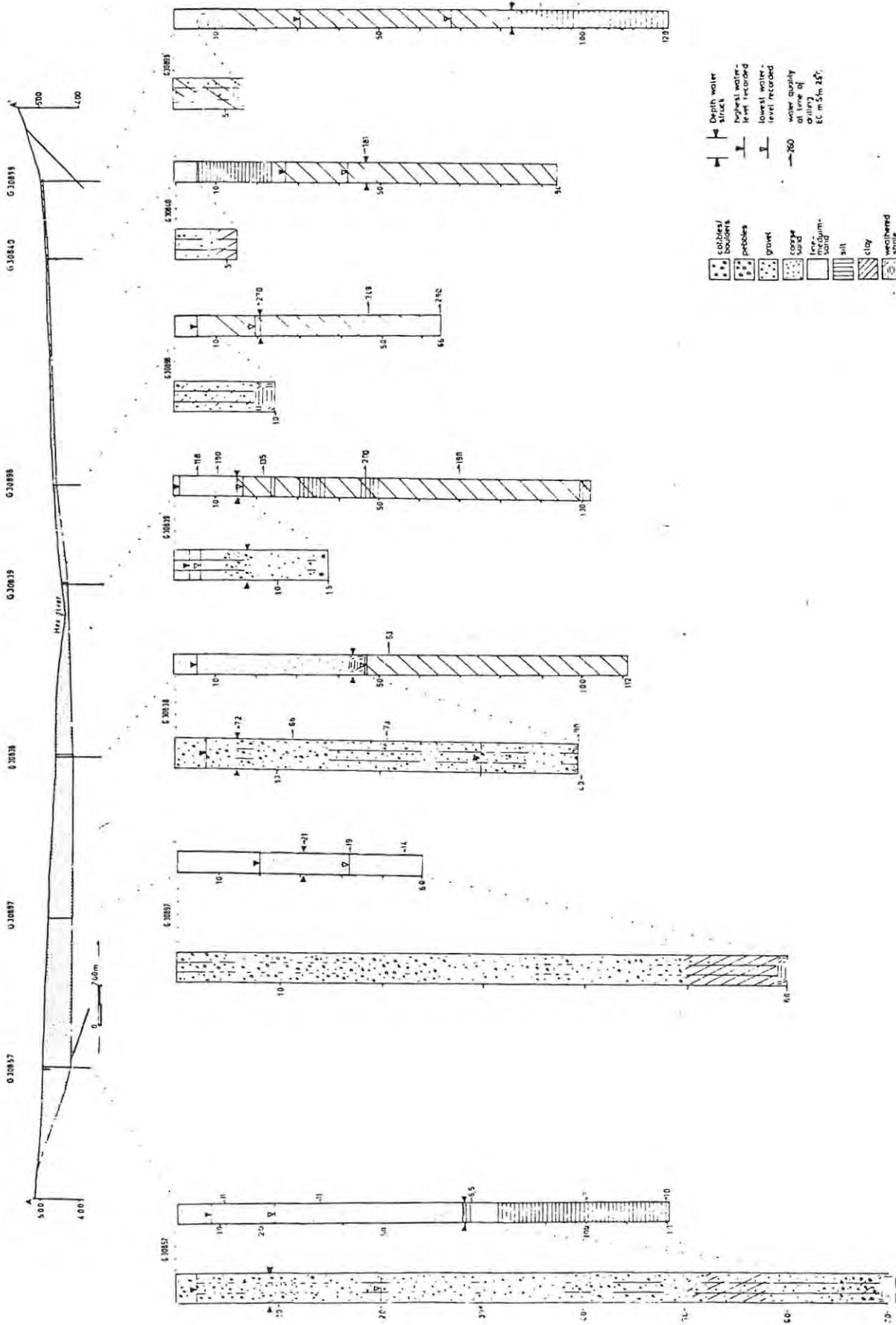
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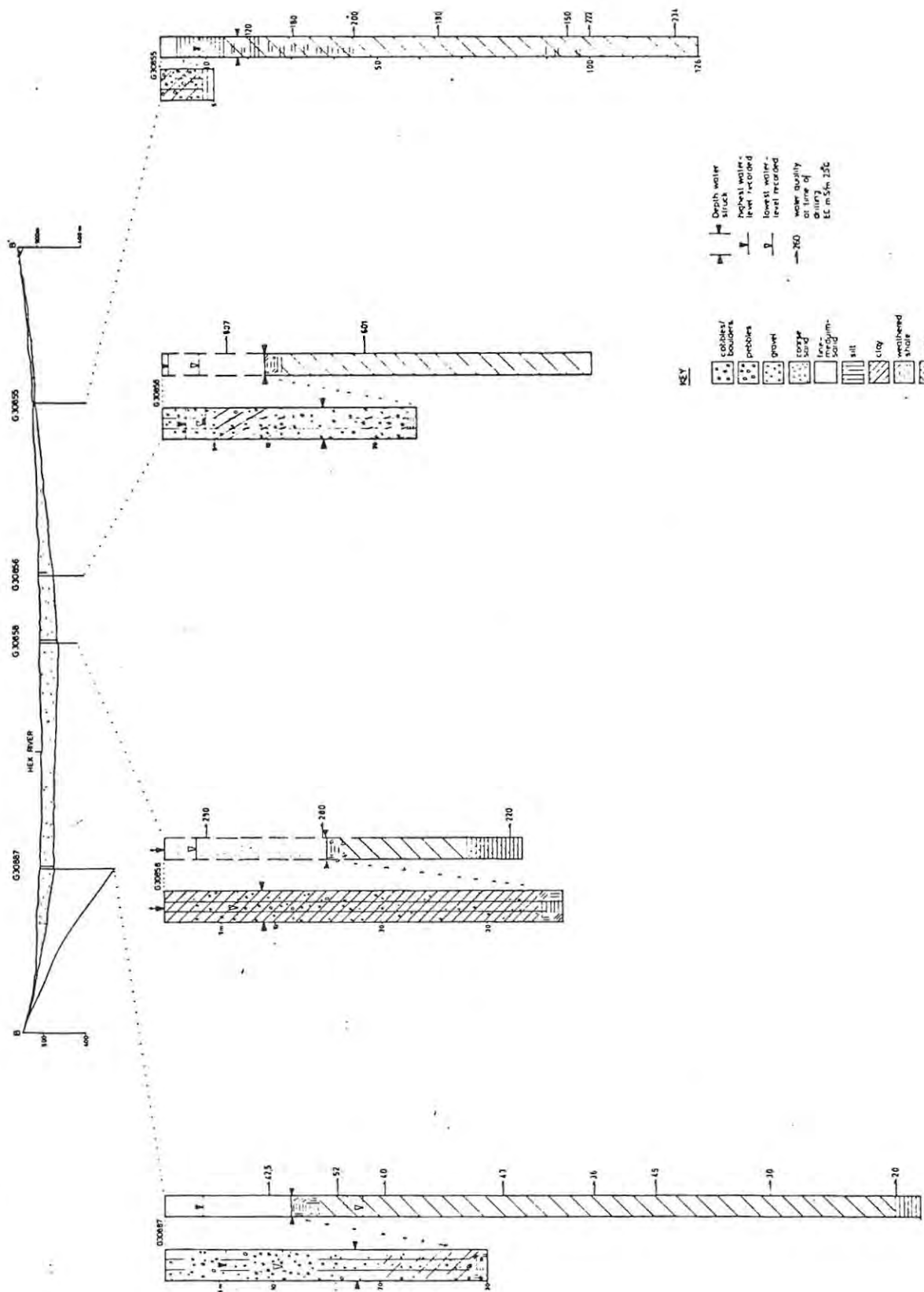
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APPENDIX A

EXPLORATION BOREHOLE PROFILES

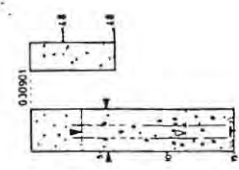
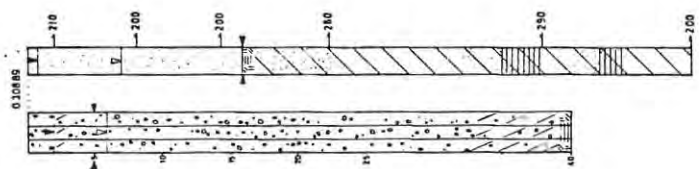
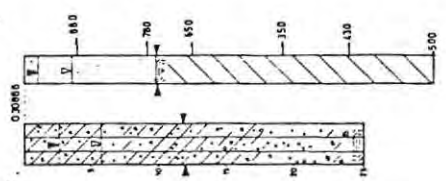
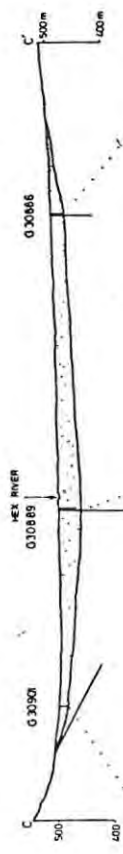


EXPLORATION BOREHOLES
PROFILE A-A



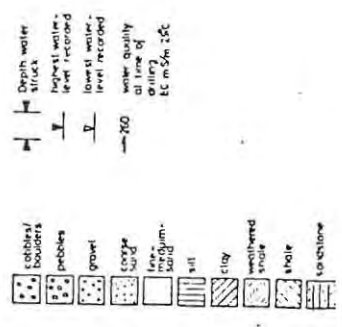
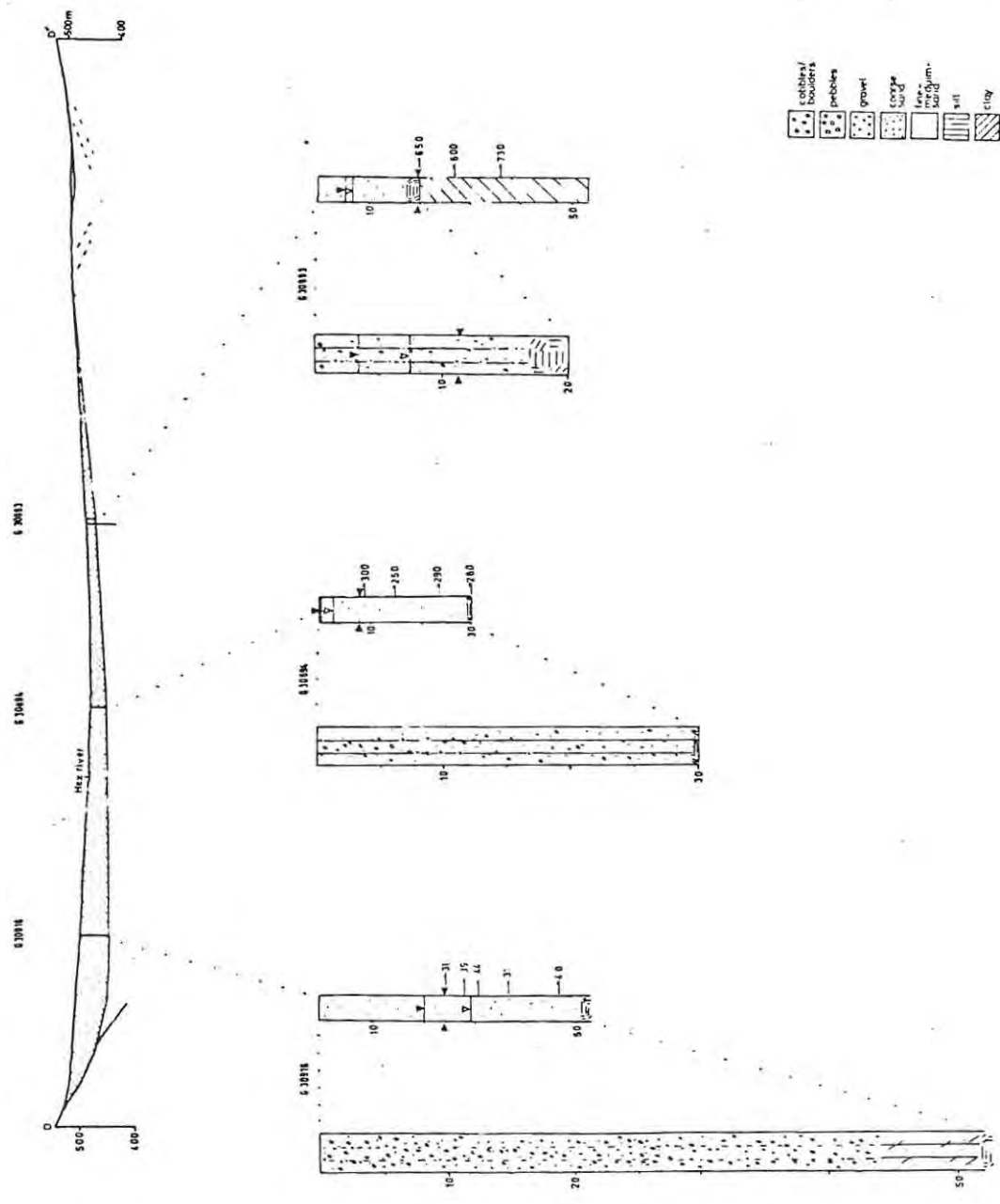
- KEY**
- cobbles/boulders
 - pebbles
 - gravel
 - coarse sand
 - fine sand
 - silt
 - clay
 - weathered shale
 - shale
 - tochiow
- Depth water stuck
 - High water level retained
 - Lowest water level retained
 - Water quality at time of drilling
 - 260
 - 100
 - 150
 - 272
 - 171
 - 180
 - 170
 - 127
 - 60
 - 210
 - 280
 - 210
 - 12.5
 - 57
 - 10
 - 11
 - 16
 - 15
 - 10
 - 20

EXPLORATION BOREHOLES
PROFILE B-B'



- KEY**
- cobbles/boulders
 - pebbles
 - gravel
 - coarse sand
 - fine-medium sand
 - silt
 - clay
 - weathered shale
 - shale
 - sandstone
- Depth water struck
 - Highest water level recorded
 - Lowest water level recorded
 - Water quality data at 250m
- EC m. S/m. 25°

**EXPLORATION BOREHOLES
PROFILE C-C'**



EXPLORATION BOREHOLES
PROFILE D-D'

APPENDIX B

AQUIFER TEST DATA PLOTS

CONSTANT DISCHARGE
AQUIFER TEST: G30839

G30839

G30839D r = 25,87 m

G30839C r = 36,18 m

Q = 0,5 l/s

39C : $T = \frac{43}{12,56 \times 0,17} \times 1 = 20 \text{ m}^2/\text{d}$

$S = \frac{80 \times 0,008}{669} \times 1 = 1,1 \times 10^{-3}$

39D : $T = \frac{43}{12,56 \times 0,2} \times 1 = 17 \text{ m}^2/\text{d}$

$S = \frac{68 \times 0,03}{1309} = 1,4 \times 10^{-3}$

THIS CURVE

X match point D

X_C

DRAWDOWN (m)

1,0

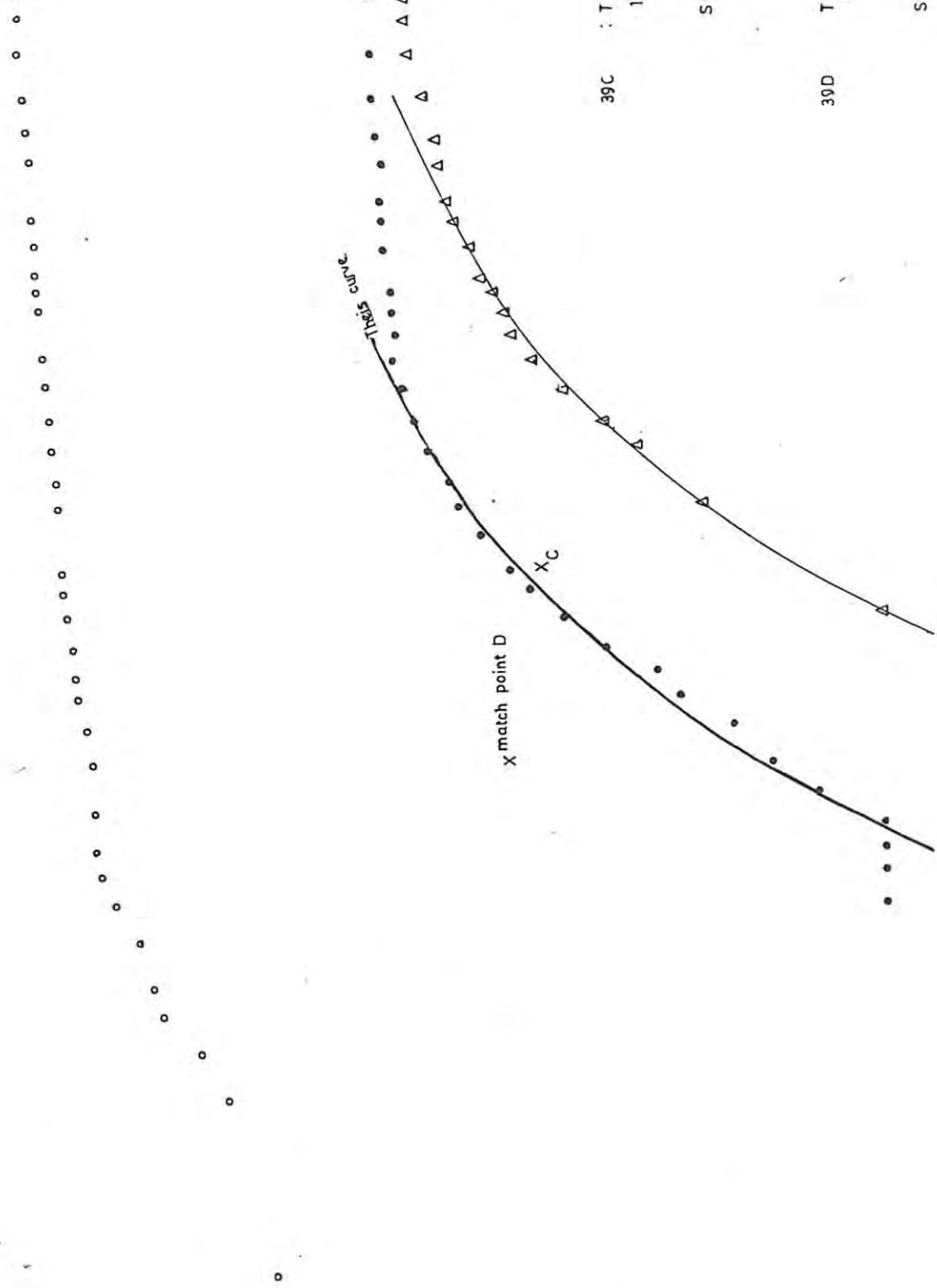
0,1

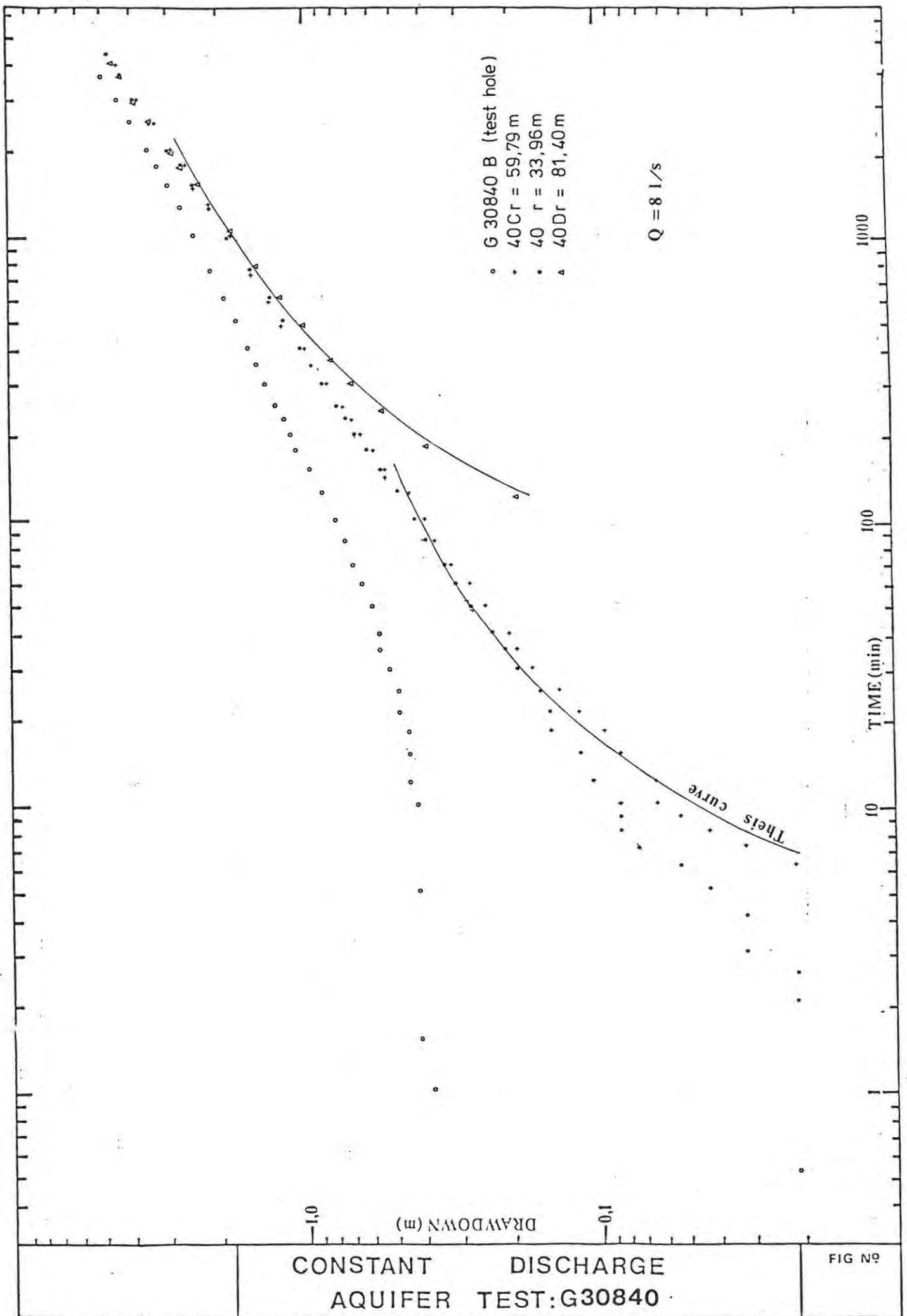
TIME (min)

1000

100

10





CONSTANT DISCHARGE
AQUIFER TEST: G30889

$T = 274 \text{ m}^2/\text{day}$
 $S = 9 \cdot 10^{-3}$

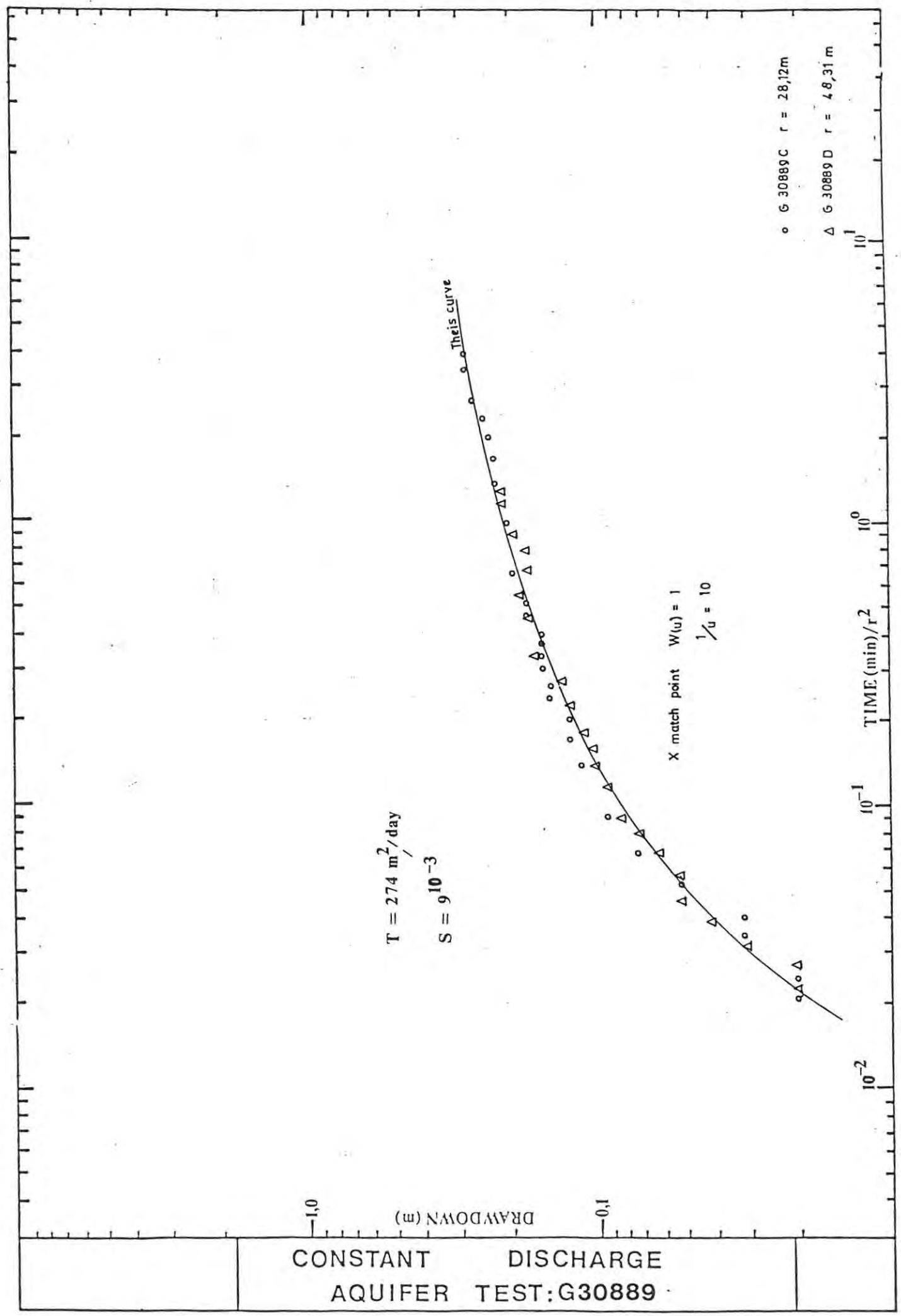
Theis curve

X match point $W(u) = 1$
 $1/u = 10$

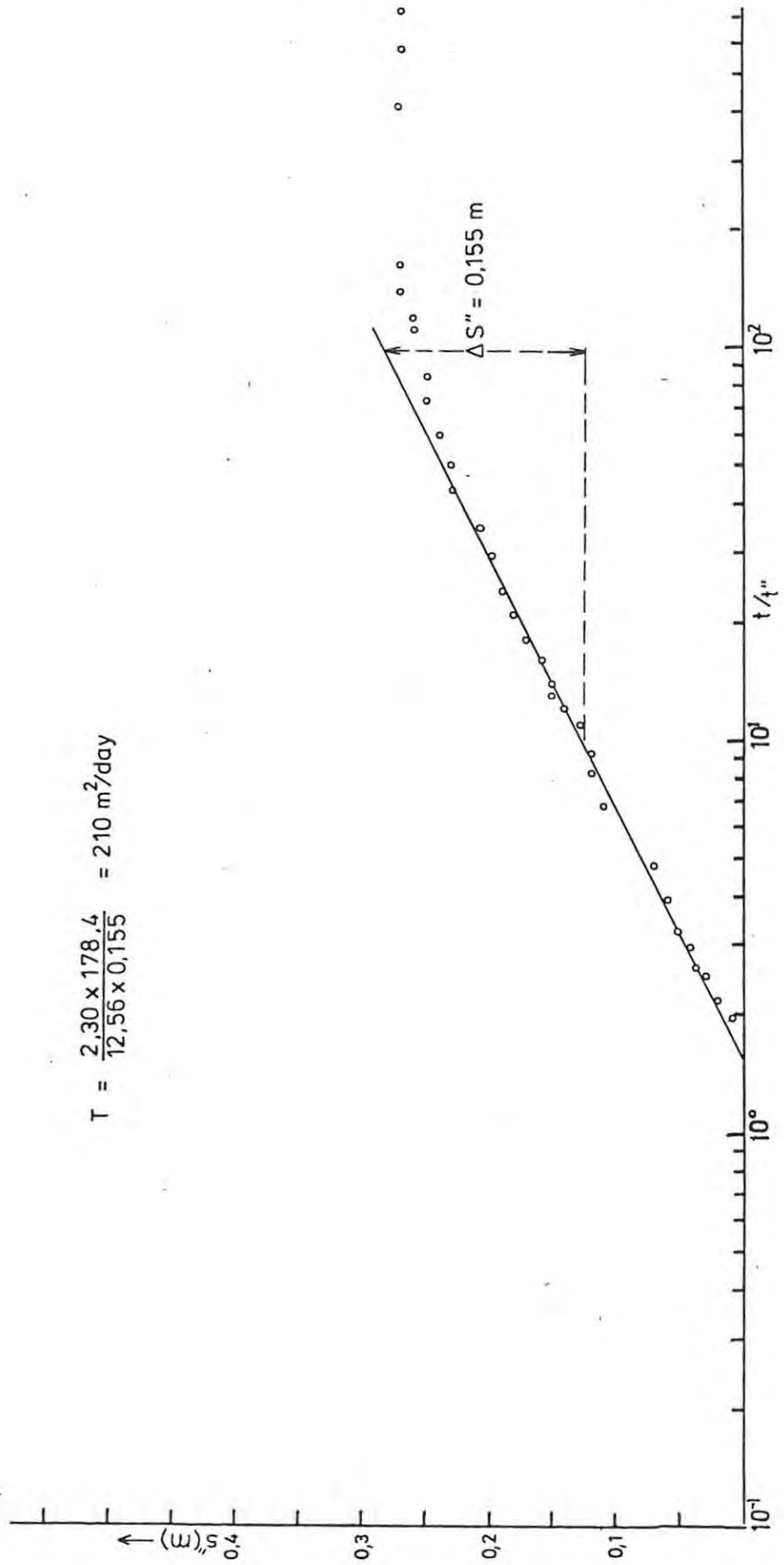
o G 30889 C $r = 28,12\text{m}$
 Δ G 30889 D $r = 48,31\text{m}$

DRAWDOWN (m)

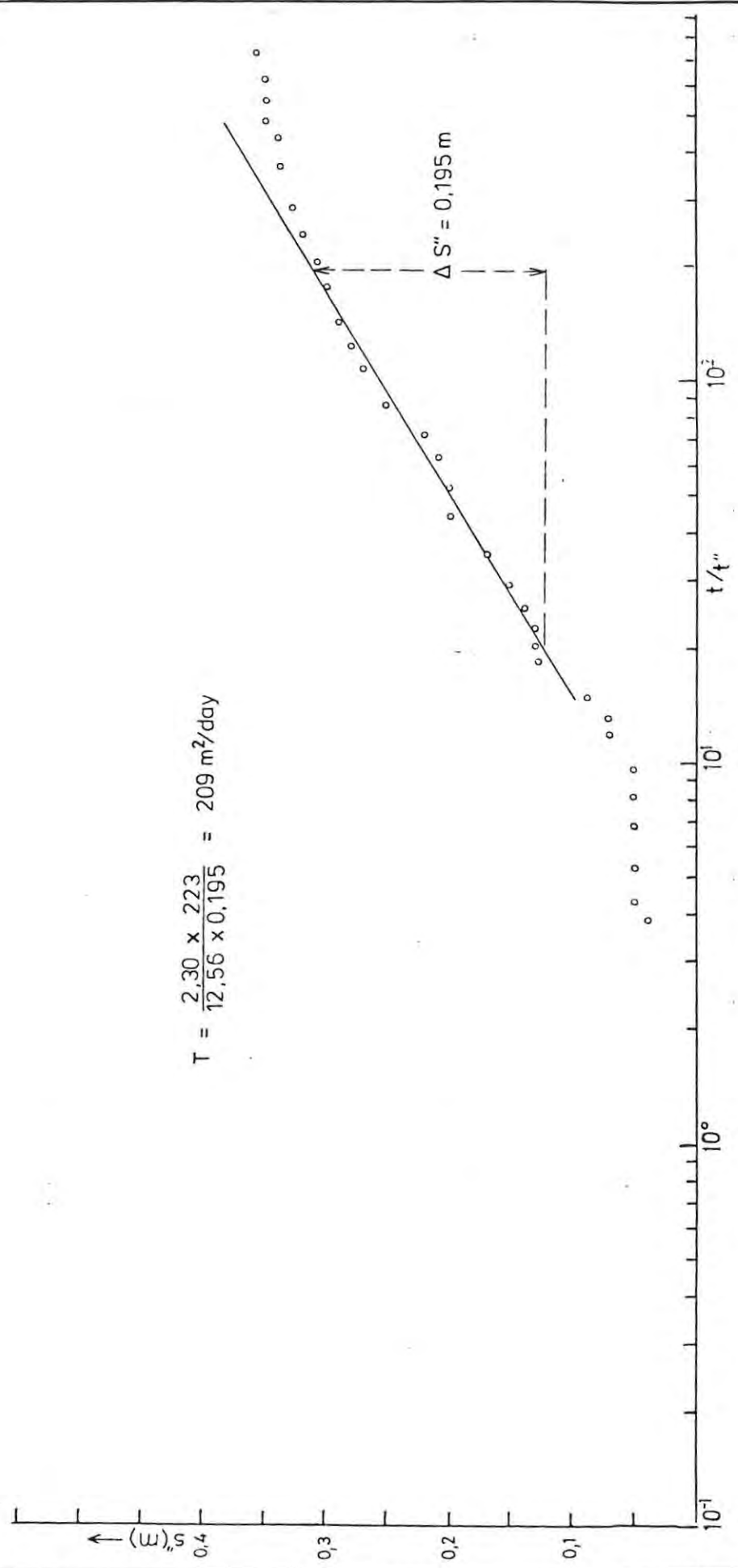
TIME (min)/ r^2



$$T = \frac{2,30 \times 178,4}{12,56 \times 0,155} = 210 \text{ m}^2/\text{day}$$

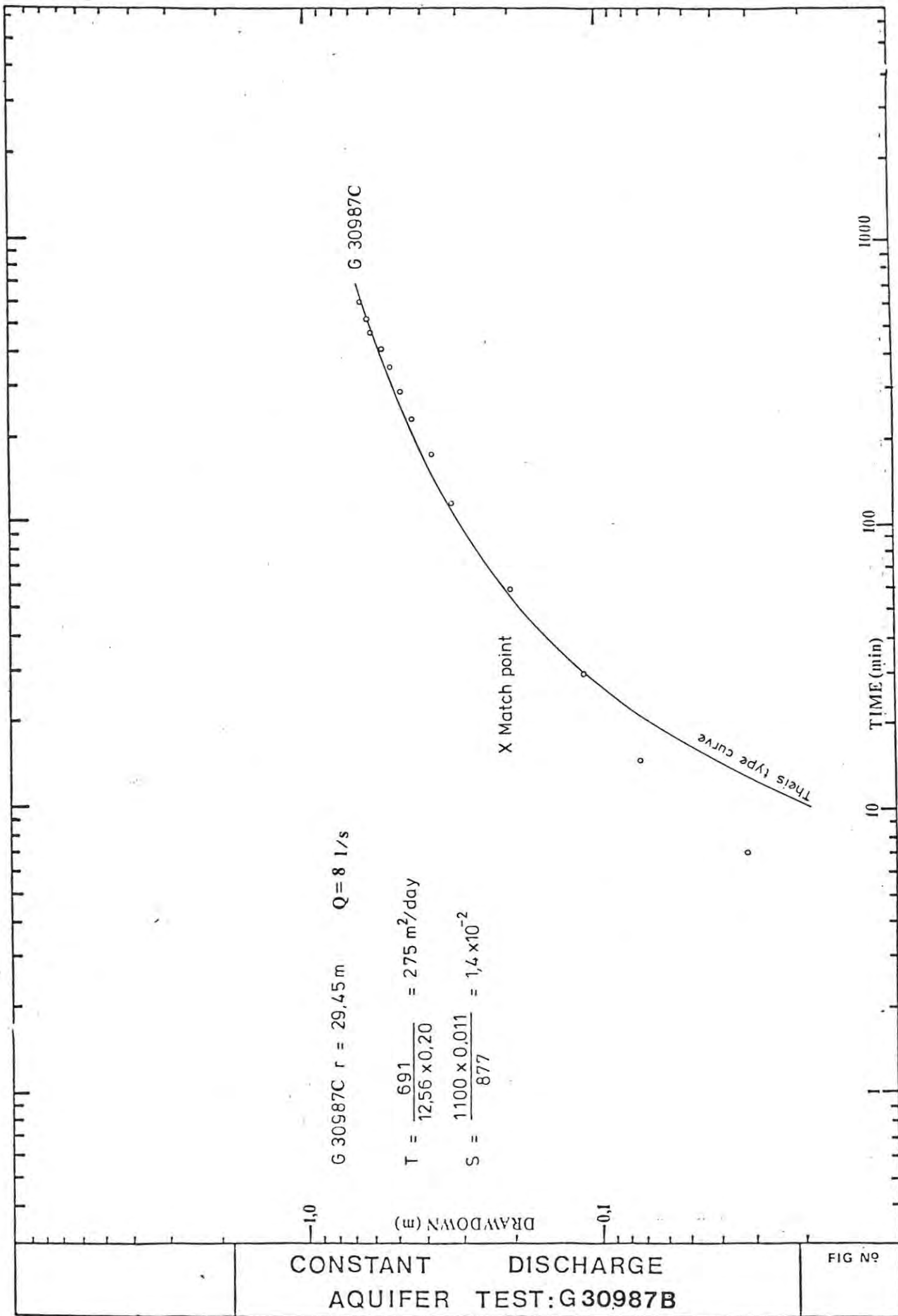


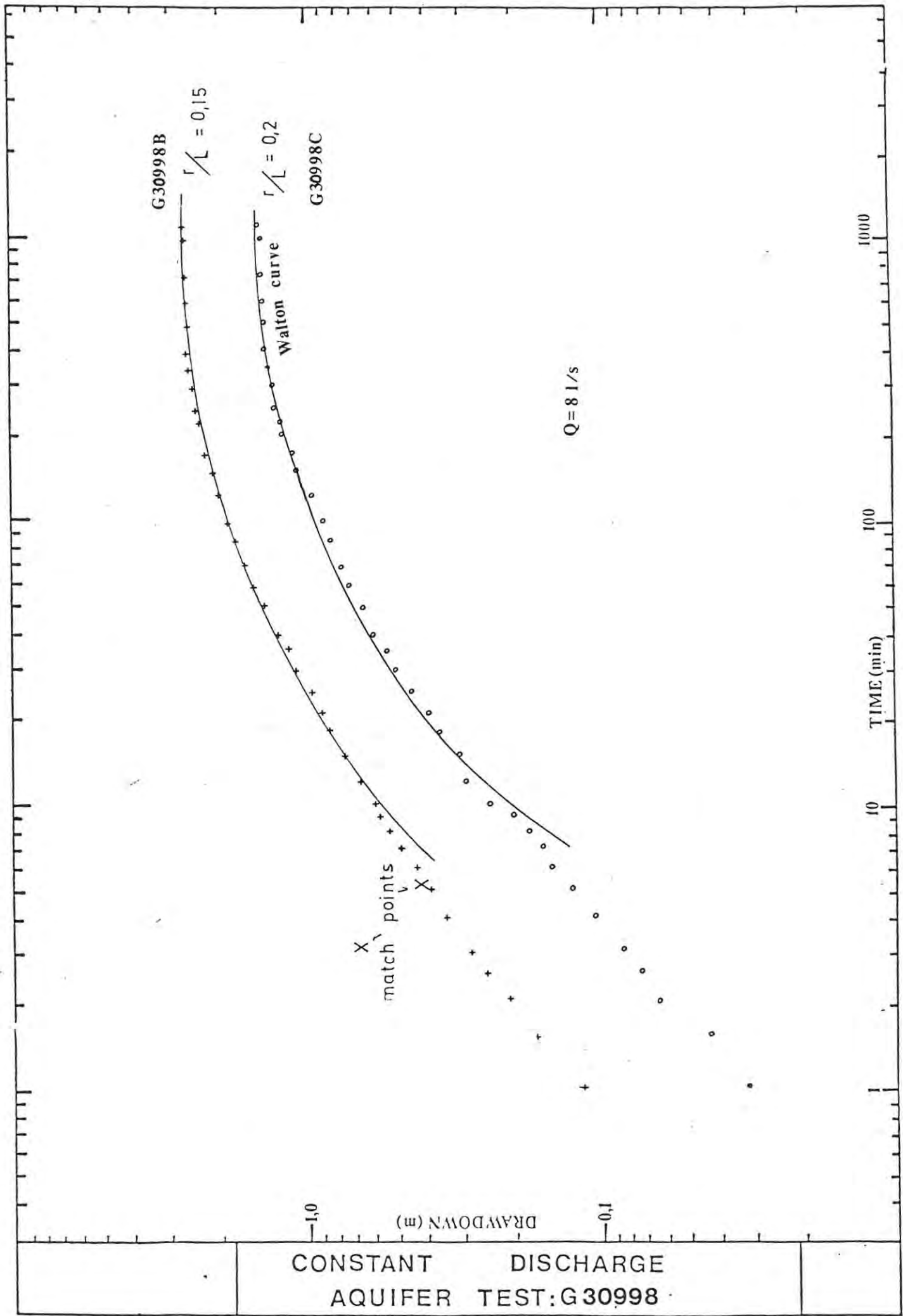
RESIDUAL DRAWDOWN
G 30889



$$T = \frac{2.30 \times 223}{12.56 \times 0.195} = 209 \text{ m}^2/\text{day}$$

RESIDUAL DRAWDOWN
G 30916





APPENDIX C

CHEMICAL ANALYSES

CHEMICAL ANALYSES OF GROUNDWATER FROM THE NARDOUW SANDSTONE USED IN COMPILATION OF THE PIPER DIAGRAM, FIG 32

Borehole No	CONSTITUENTS (me/l)								TOTAL	
	Na	Ca	Mg	K	Cl	SO ₄	HCO ₃	NO ₃	Cations	Anions
	254-4	0,19	0,14	0,06	0,04	0,14	0,04	0,23	0,00	0,43
251-2	0,29	0,18	0,00	0,05	0,30	0,02	0,18	0,05	0,52	0,55
275-1	0,14	0,09	0,06	0,02	0,10	0,00	0,17	0,001	0,31	0,27
438-5	0,23	0,05	0,08	0,10	0,26	0,10	0,20	0,02	0,46	0,58
452-3	0,16	0,02	0,005	0,08	0,17	0,04	0,20	0,00	0,26	0,48
472-1	2,13	4,59	1,27	0,12	2,93	3,72	1,04	0,00	8,11	7,69
472-3	0,18	0,08	0,02	0,12	0,22	0,07	0,23	0,00	0,40	0,54
475-7	0,23	0,03	0,01	0,14	0,32	0,04	0,12	0,00	0,41	0,53
480-1	0,31	0,10	0,07	0,01	0,40	0,05	0,25	0,00	0,58	0,70
480-6	0,17	0,05	0,05	0,10	0,15	0,06	0,30	0,00	0,40	0,52

CHEMICAL ANALYSES OF BOKKEVELD GROUNDWATER USED IN COMPILATION OF THE PIPER DIAGRAM FIG 32

Borehole No	CONSTITUENTS (me/l)								TOTAL	
	Na	Ca	Mg	K	Cl	SO ₄	HCO ₃	NO ₃	Cations	Anions
	248-11	2,50	2,30	0,85	0,03	2,53	2,10	0,77	-	5,60
267-2	1,10	1,72	1,12	0,12	1,0	1,5	0,54	-	4,10	3,30
270H-3	4,15	4,72	1,12	0,03	6,23	2,30	1,12	0,00	10,02	10,20
288-4	1,04	1,90	0,40	0,35	1,40	1,23	0,35	0,20	3,70	3,30
388-2	3,90	4,90	2,20	0,10	3,05	4,0	3,34	0,00	11,10	10,50
390-5	0,60	0,60	0,23	0,10	0,60	0,22	0,70	0,00	1,50	1,50
428-1	11,0	8,0	5,4	0,15	11,75	7,80	3,74	0,00	24,55	23,30
432-1	3,90	5,70	0,82	0,20	4,60	3,40	1,50	0,00	10,60	10,14
450A-2	2,60	3,92	0,82	0,20	2,45	5,70	1,50	0,00	7,51	7,35
454-3	8,60	6,73	5,95	0,10	9,40	7,53	4,04	0,00	21,32	21,00
464-1	3,90	5,75	2,40	0,20	4,62	4,40	2,34	0,00	12,20	11,40
485-3	11,64	7,84	7,40	0,10	11,10	11,30	4,64	0,00	26,90	27,04

CHEMICAL ANALYSES OF SURFACE WATER SAMPLES USED IN COMPILATION OF THE PIPER DIAGRAM, FIG 32

River point	CONSTITUENTS (me/l)								TOTAL	
	Na	Ca	Mg	K	Cl	SO ₄	HCO ₃	NO ₃	Cations	Anions
	R1	5,50	3,12	3,63	0,13	4,80	5,90	1,45	0,00	12,40
R3	5,93	3,90	6,0	0,05	6,21	7,80	1,80	0,04	15,90	15,85
R5	5,60	3,09	4,40	0,20	5,30	5,60	2,07	0,15	13,10	13,0
R6	8,70	4,03	5,50	0,11	7,71	7,50	3,0	0,10	18,34	18,30
R8	1,50	0,60	1,04	0,12	1,34	1,50	0,50	0,20	3,23	3,52
R9	1,64	0,90	1,07	0,14	1,50	1,70	0,54	0,22	3,70	3,92
R10	1,73	0,75	1,15	0,15	1,60	1,80	0,43	0,20	3,80	4,0
R16	0,12	0,0	0,02	0,01	0,13	0,12	0,05	0,00	0,15	0,30