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INSTITUTE of HYDROLOGY

MORUPULE POWER STATION

GROUNDWATER STUDIES

VOLUME 1

MORUPULE POWER STATION

GROUNDWATER STUDIES

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PREFACE

This report describes the work carried out during the second phase of the exploration of the Cave Sandstone aquifer north of Serowe. It deals primarily with the drilling and test pumping operations, the interpretation of these data, and their synthesis within a mathematical model of the aquifer system.

Field operations were carried out jointly by the Institute of Hydrology and Aqua Tech Groundwater Consultants (Pty) Limited. Broadly, responsibility for the borehole construction was undertaken by Aqua Tech, with pumping test and well logging by the Institute.

Interpretation and modelling has been carried out at the Institute. This work has been to a December deadline, with several weeks time lost due to delays in the pumping test programme. To a large extent interpretation and modelling is an interactive exercise, each lending support to the other, involving testing of ideas and concepts within data which do not necessarily have a unique solution. Consequently, this report expresses the views of the Institute of Hydrology.

We would wish to acknowledge the considerable assistance provided by the Director of the Botswana Geological Survey. Earlier work by his staff and the GS10 Underground Water Resources Project provided the foundation upon which our exploration programme was built.

CHAPTER 1

STUDY OBJECTIVES

1.1 Introduction

This report is concerned with the programme of investigations aimed at identifying sufficient groundwater from the Cave (Escarpment) Sandstone aquifer to provide for the needs of the proposed Morupule Power Station. Water demands are for wet cooling operation, together with associated developments to the year 2010 when supplies averaging 19,500 m^3/d ($7.1\ m^3/yr \times 10^6$) would be required.

The groundwater investigations have been made in three phases primarily in the Serwe Pan - Paje area identified in our pre-feasibility study of January 1980[1]. Geophysical and photogeological exploration was undertaken during March and April 1980 and were reported in May 1980[2]. From these studies a drilling programme of 27 boreholes was developed to examine various hydrogeological conditions through pumping tests at 8 separate locations. These field operations were completed early in November and from these, together with a re-analysis of existing information, we have developed a mathematical model of the aquifer to bring together all the known factors which influence groundwater availability.

Broadly the new exploration work confirms our January 1980 estimates of aquifer properties, in fact these appear to be better than our early predictions. Evidence for recharge to the aquifer through the Kalahari Beds in the Serwe Pan area is much stronger and we now suggest regular replenishment of groundwater resources in the area of interest. We can conclude from our studies that sufficient groundwater is available within the aquifer to meet the demand of $7.1\ m^3/yr \times 10^6$.

Morupule Power Station, Groundwater and Surface Water Resources Studies, Sir Alexander Gibb & Partners (Botswana), Jan 1980.

Morupule Power Station Groundwater Investigations, Interim Report, Geophysical and Photogeological Studies, Sir Alexander Gibb & Partners (Botswana), May 1980.

However our exploration results are disappointing in two respects. The geological structure of the aquifer has proved to be far more complex than existing information suggested and also we have not been able to locate aquifer conditions which significantly improve borehole yields. These constraints indicate the groundwater from the Cave Sandstone will be expensive. Large numbers of boreholes are required throughout quite extensive areas to meet the water demands and we are uncertain that supplies would be maintained beyond 2010 without new wellfield construction.

The results of the investigations are presented in two volumes. Details of the field programme (drilling and test pumping) together with interpretation of these data site by site are presented as an appendix. In this main volume we are concerned with bringing together all the information relating to the aquifer in the area of interest by developing an assessment of groundwater availability through a conceptual model describing the nature of the aquifer and a mathematical model which predicts the effects of various abstraction strategies. In this way we are able to separate the detail of an enormous amount of primary data from the synthesis of the main conclusions which can be drawn from them.

1.2 Project Setting

The area of interest is 4000 km^2 on the north-eastern edge of the Kalahari Plateau immediately north of Serowe. This is predominantly a flat sand-veld area at an elevation of about 1250m AOD. The principal topographic feature of the area is a 90m to 150m high escarpment bounding the plateau area and separating it from lower lying ground in the east. The aquifer is exposed at the surface along the foot of this escarpment bounding the plateau area and separating it from lower lying ground in the east. The aquifer is exposed at the surface along the foot of this escarpment and dips north and westwards beneath the plateau where it is overlain by volcanic basalts and hidden by a complete cover of sand.

Location and hydrogeological information in map form are not bound within this volume, but provided separately in a map portfolio.

Plan I shows the setting for the study in a 1:200,000 scale LANDSAT image. This was developed from a separate programme of research discussed in detail in Appendix A.2. It shows clearly the contrast between the relatively featureless sand covered Kalahari Plateau and the excavated geology along the foot of the escarpment from which a large number of small ephemeral streams drain eastwards. Within the plateau few drainage features exist, the topography is dominated by a stabilised dune field and various vegetation expressions. The main villages are located along the foot of the escarpment developing water supplies from the Cave Sandstone aquifer beneath a thin sand cover which obscures much of the geological detail at outcrop. Throughout the plateau widely scattered boreholes provide for stock watering from the Cave Sandstone. The principal boreholes operating in 1975, the date of the imagery, can be located from grazing patterns appearing through the remains of numerous fire burns that sweep across the area each year.

To the east of the escarpment drainage is well developed. The main watershed separating these from the poorly drained westerly sloping plateau is just within the escarpment. This is an area of low relief and the main catchment divide is to all intents marked by the escarpment, a feature caused by active erosion of the many ephemeral streams which arise along it.

1.3 Geological Setting

The geological sequence within the framework of this study is relatively simple. It comprises:

	Kalahari Beds	Sand, calcrete and silcrete
	Unconformity	
Karoo Supergroup	Drakensberg Lava	Basalt
	Unconformity	
	Cave Sandstone	Sandstone with minor silty sandstones
	Unconformity	
	Ecca Series	Mudstone and siltstone

In our pre-feasibility study we referred to the aquifer as the Escarpment Sandstone in anticipation of a nomenclature review currently being undertaken. This has not yet been implemented and we have therefore reverted in this report to the older and widely used terminology of Cave Sandstone.

Whilst the geological sequence in the study area is simple, by contrast, the geological structure is most complicated. The aquifer and the overlying basalts are extensively faulted and intruded with occasional large dykes and numerous smaller dyke swarms. These present the greatest challenge to both interpretation of the primary data and to construction of a conceptual model to describe the nature of aquifer system as a whole. The structure influences all aspects of major groundwater development in the area, from individual borehole performance, to location of any well fields. A coherent and spatially continuous description of this has formed the initial framework for the groundwater model. In Chapter 2 concerned with the nature of the aquifer, the geological structure of the area is therefore described in some detail to provide a setting for the hydrogeological characteristics of the Cave Sandstone.

The distribution of the principal rock formations is shown in Plan II without the complication of the detailed structure. Cave Sandstone is exposed along the foot of the escarpment from Serowe northeastwards through Paje and Mabeleapodi where small areas of basalt cap the aquifer at Tebele and Taukome hills. The approximate position of the base of the aquifer is given although throughout most of the outcrop area it is hidden. Within the escarpment, marked by the eastern limit of the Kalahari Beds, the Cave Sandstone is overlaid by up to 230 m of basalt. In three locations the Kalahari Beds directly overlie the aquifer, the basalts having been removed by erosion, or possibly not even extruded in these areas.

1.4 Field Exploration Programme

A drilling and pumping test programme provides the main source of new primary data contained within this report. Details of 27 boreholes at twelve separate sites are given in the appendix. The sites were selected to investigate specific hydrogeological topics primarily concerned with how the aquifer behaves within the complicated structural setting.

Five drill sites were located on the plateau to investigate hydrogeological conditions associated with faulting or dyke intrusion located by the geophysical survey completed in May 1980. One of these locations had to be abandoned due to geological conditions but a new site was found for the test. This group of boreholes, TS2 to TS6, (TS1 was abandoned) each comprised a test well and one or two observation wells. Short-term pumping tests were made at each. A four or five stage step drawdown test established production and well characteristics and was followed by a constant rate test to determine aquifer properties.

Longer-term testing was carried out at 3 additional sites. These were concerned with examining the Cave Sandstone under water table conditions to determine the unconfined storage coefficient. Two sites, SYA and SYB, were chosen from existing borehole information. These were located on the plateau at sites where groundwater levels were at about the basalt/sandstone contact. They were designed to determine the conditions in the upper part of the aquifer. The third site, SYC at outcrop, similarly examined specific yield but in the lower portion of the aquifer under true water table conditions without overlying basalt. Three exploration boreholes (Ex 7, Ex 9 and Ex 10) were used to locate a suitable site for this test.

Tests of between 24 and 32 days duration were completed at these sites using two or three observation wells. At site SYB unconfined conditions developed only in the abstraction well but specific yield estimates were obtained at SYA and SYC.

Borehole locations and reference numbers are shown on Plans I and II. Non-project boreholes are located and numbered from Cheyney[1] and we have adopted this system for ease of reference throughout our report.

1.5 Re-interpretation of Interim Report Geophysics

In our interim report we described a complex pattern of extensive east-west faulting across the area. Many faults with throws of up to 40 m were indicated extending over short distances paralleling several larger and persistent structures with throws of up to 150m. Whilst our drilling programme was designed to investigate specific groundwater situations, it also provided a check on the geophysical predictions of geological structure. Before developing a picture of the structure

[1] *Cheyney C.S., A Groundwater Inventory of the GS10 Serowe Block. Dept of Geological Survey, Botswana, Record GS10#3, 1979.*

throughout the area as a whole it is useful to examine the reliability of the predictions within the smaller area of our geophysical survey.

Table 1.1 compares results for the two prime targets, base of Kalahari Beds and base of basalt, at each of the exploration drill sites on the plateau. Vertical electrical soundings were used to determine the depth of Kalahari Beds, information we considered important in respect to interpretation of gravity data used to estimate the thickness of basalt. Details of the methods and interpretation of the results were fully reported in our Interim Report of May 1980. Here we are concerned only with updating this published work.

The thickness of the Kalahari Beds have proved to be greater than we predicted at all sites. However even in drilling the base is normally difficult to define with a gradational contact from calcareous sandstone into heavily weathered basalt. Comparisons between predicted and actual depths to the base of the basalt were to better than ± 20m at three sites (SYB, TS3 and TS4) whilst at the others our geophysical interpretation again underestimated depths. This implies that the structures are probably more complex than we originally postulated with even larger throws on the various faults.

In order to provide a geological base for the mathematical modelling of the system, these drilling results presented a straight choice between incorporating the results into a reinterpretation of the corrected gravity data, or alternatively, going back into the primary gravity information and re-running the geophysical models with alternative density data. We concluded that although a better structural fit between the geophysical and drilling data could be achieved by complete re-analysis, the improvements may only have been marginally better than re-interpretation.

Preliminary trials of modelling also had a bearing upon this decision. It became necessary to simplify the geological structure to keep the number of model elements to manageable proportions. Our model had to be divided into over 400 elements to represent the aquifer system described by only the major faulted and dyke elements. These had to be revised to accommodate the larger scale faulting proved by the drilling and a model to represent the complete faulted picture was totally impractical being beyond the efficient operation of the computer facilities available.

TABLE 1.1

THICKNESS OF KALAHARI BEDS AND BASALT
AT EXPLORATION DRILL SITES

(m)

SITE	DEPTH OF KALAHARI BEDS PREDICTED	DEPTH OF KALAHARI BEDS ACTUAL	DEPTH OF BASE OF BASALT PREDICTED	DEPTH OF BASE OF BASALT ACTUAL
SYA Test Well)		26	)	82
OW1)	38*	28	) 92*	82
OW2)		38	)	82
C5)		38	)	92
SY3 Test Well)		44	)	98
OW1)	24	44	) 84	98
OW2)		46	)	96
OW3)		46	)	94
TS1	15	32	118	200+
TS2 Test Well)		66	)	132
OW1)	11	66	) 105	132
OW2)		72	)	160+
TS3 Test Well)	18	32	) 88	98
OW1)		32	)	87
TS4 Test Well)		52	108	94
OW1)	36	50	155	122
OW2)		48	108	90
TS5 Test Well)		45	)	128
OW1)	34		) 69	76+
OW2)		44	)	134
TS6 Test Well)	24	28	) 108	144
)		26	)	150

* Predicted depths taken from borehole information at the site not from geophysics

The re-interpreted geophysical data are presented in Figures 1.1 - 1.6. The most significant structural revision concerns the large downthrow of about 100m at TS1 on geophysical traverse 2. A westward extension of the deeply faulted zone at Serwe Pan (traverse 1) is clearly indicated. This was predicted in our Interim Report but we had been reluctant to postulate persistence of such a narrow and deeply faulted structure. The nature of the processes which could lead to such a feature are still obscure. Elsewhere the re-interpretation retains the essential structural character with upthrown zones in the south and through the middle zones of the traverses.

Gravity and Magnetic Model of Traverse 1

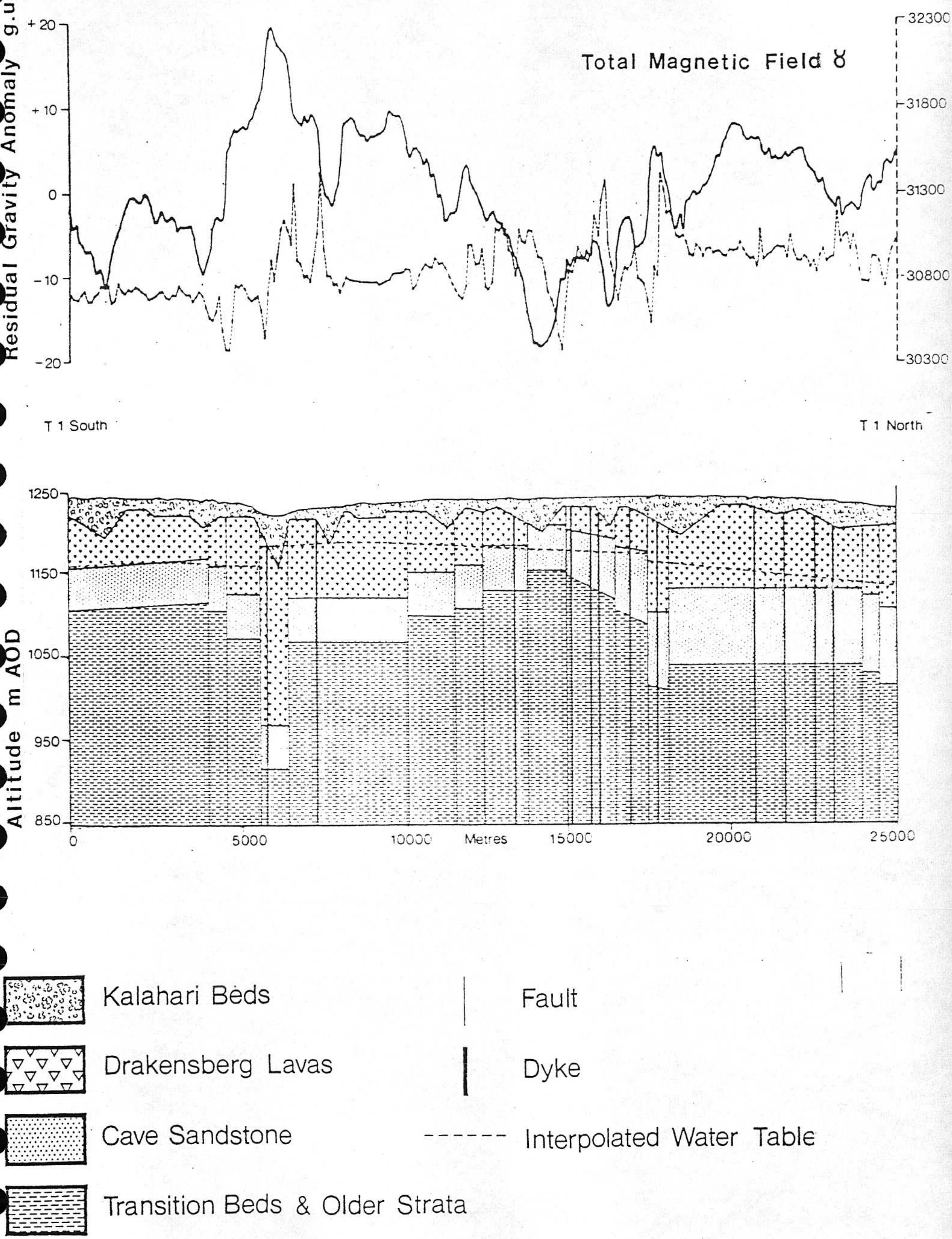


Figure 1.1

Gravity and Magnetic Model of Traverse 2

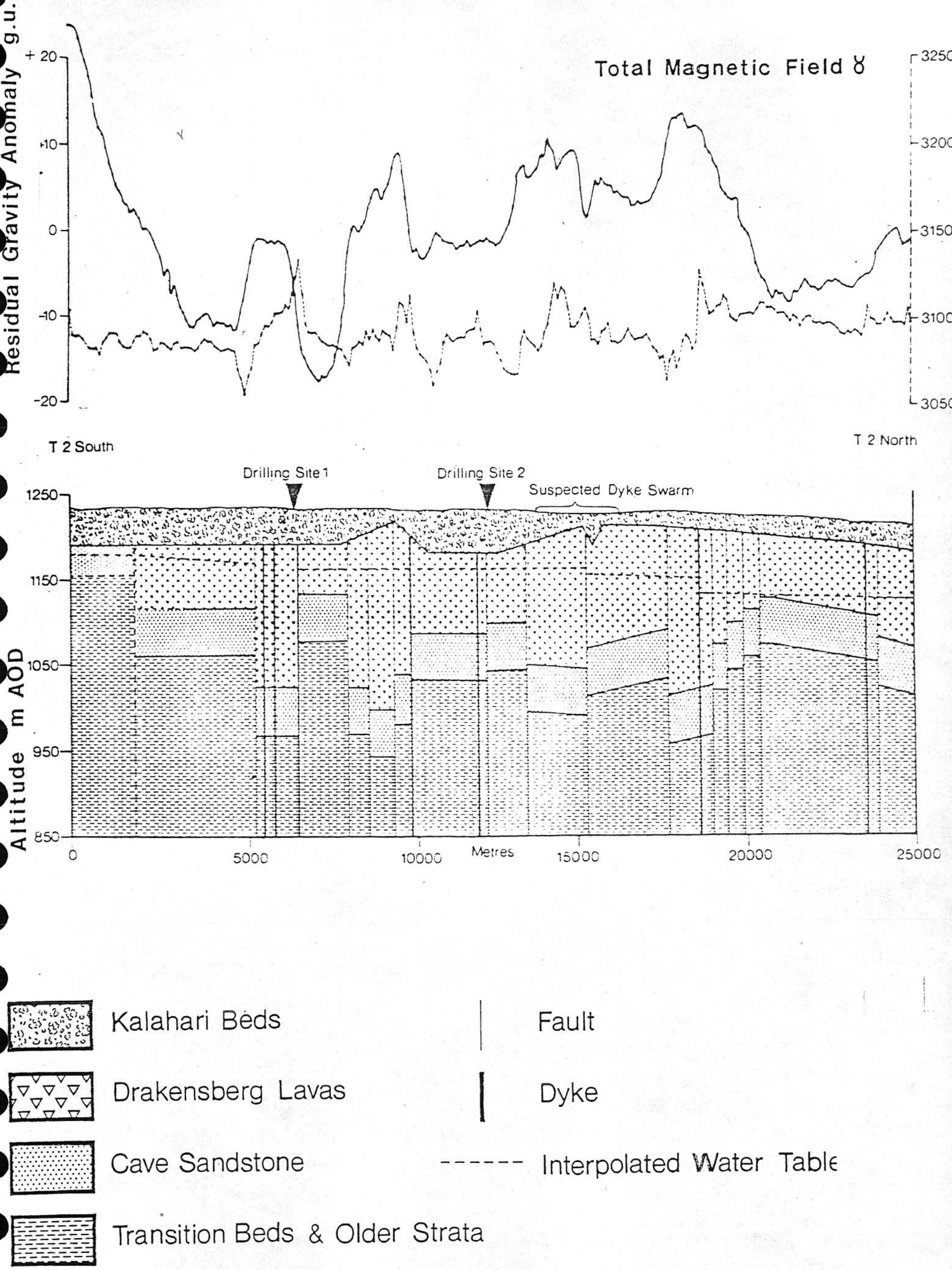
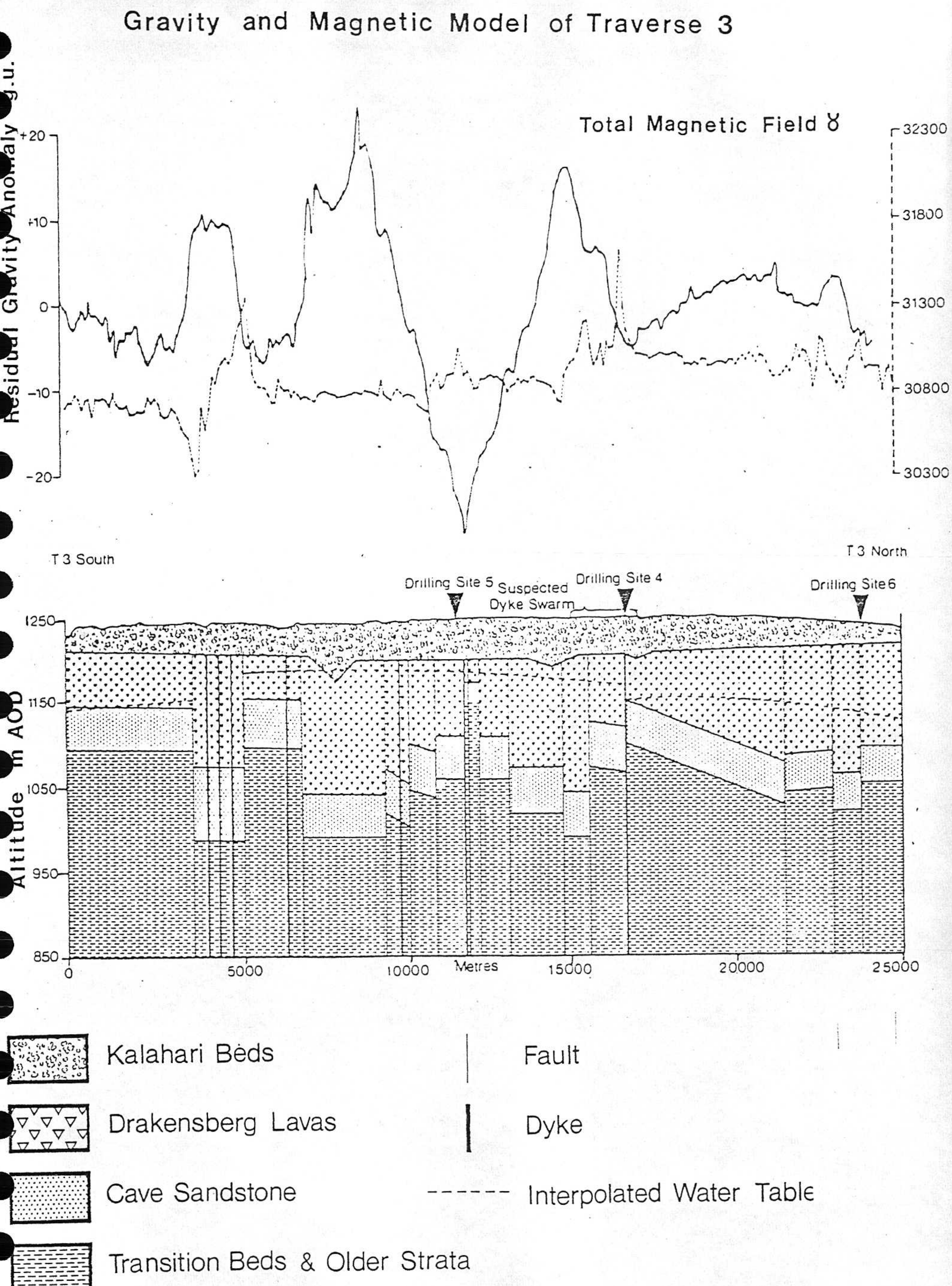


Figure 1.2



Gravity and Magnetic Model of Traverse 3
Total Magnetic Field γ
Residual Gravity Anomaly g.u.
+20
+10
0
-10
-20
32300
31800
31300
30800
30300
T 3 South
T 3 North
Drilling Site 5
Suspected Dyke Swarm
Drilling Site 4
Drilling Site 6
Altitude in AOD
1250
1150
1050
950
850
0
5000
10000
Metres
15000
20000
25000
Kalahari Beds
Drakensberg Lavas
Cave Sandstone
Transition Beds & Older Strata
Fault
Dyke
Interpolated Water Table

Figure 1.3

Gravity and Magnetic Model of Traverse 4

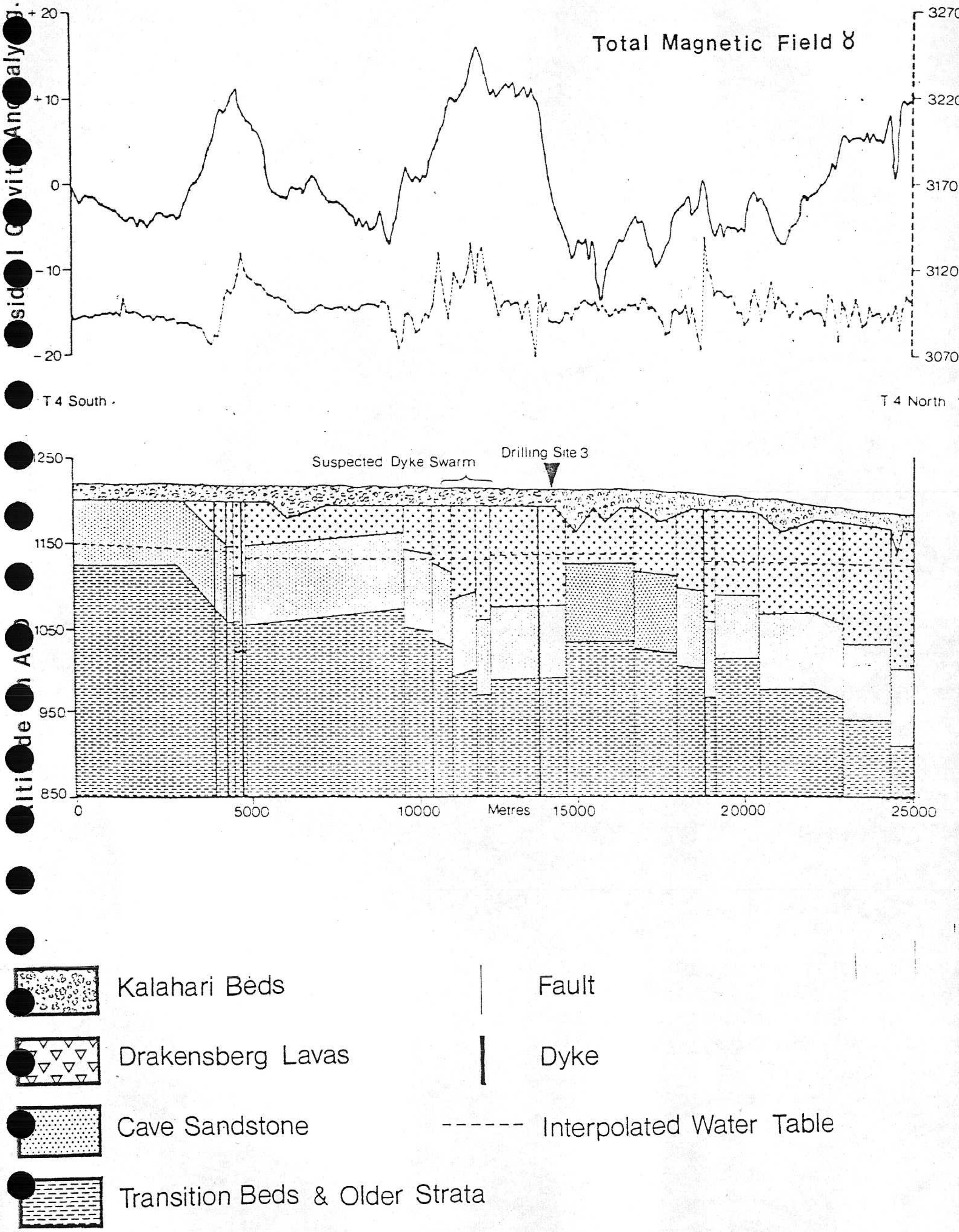
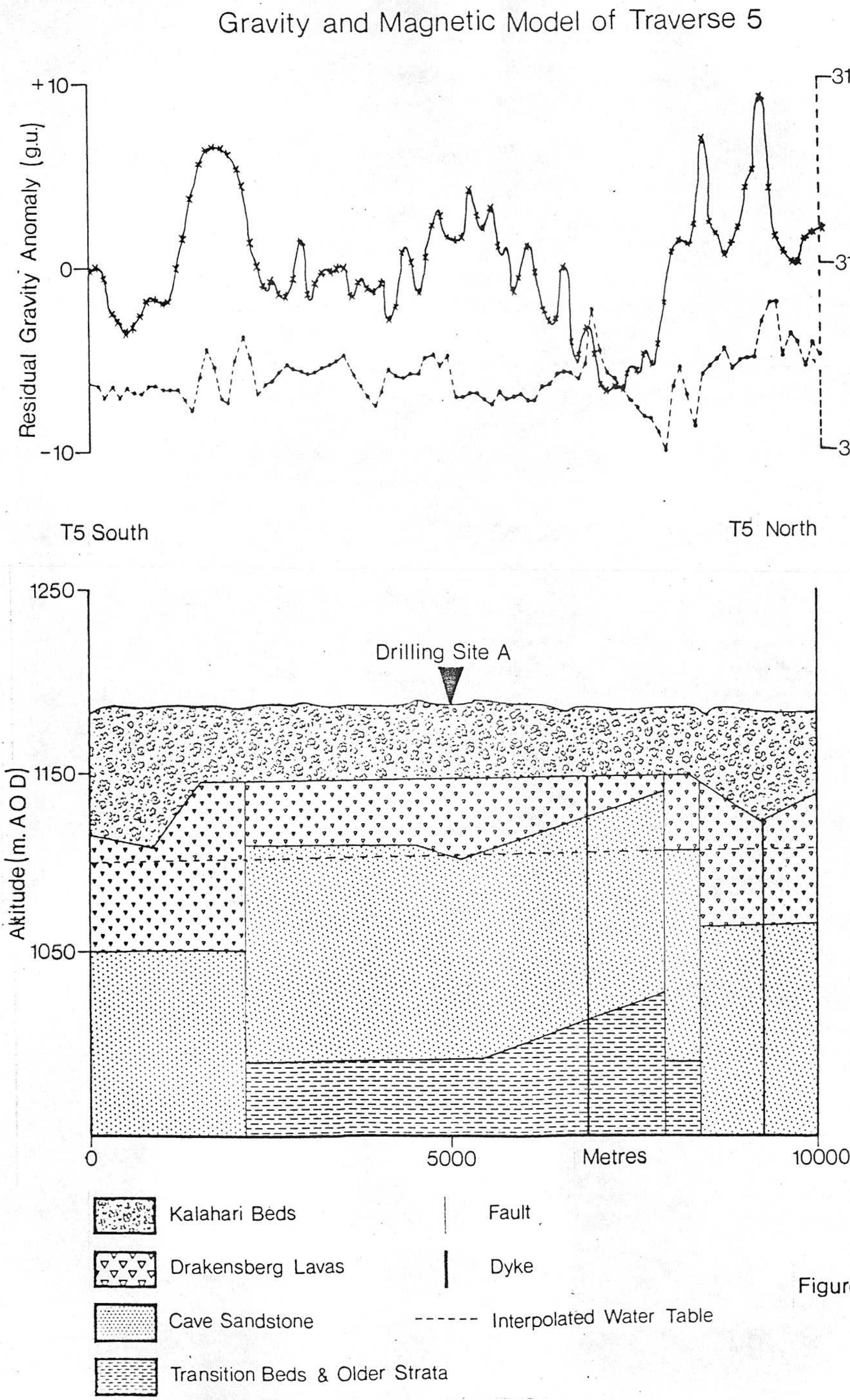


Figure 1.4



Gravity and Magnetic Model of Traverse 5
+10
0
-10
Residual Gravity Anomaly (g.u.)
31700
31200
30700
Total Magnetic Field γ
T5 South
T5 North
1250
1150
1050
Altitude (m. AOD)
Drilling Site A
0
5000
Metres
10000
Kalahari Beds
Drakensberg Lavas
Cave Sandstone
Transition Beds & Older Strata
Fault
Dyke
Interpolated Water Table

Figure 1.5

Gravity and Magnetic Model of Traverse 6

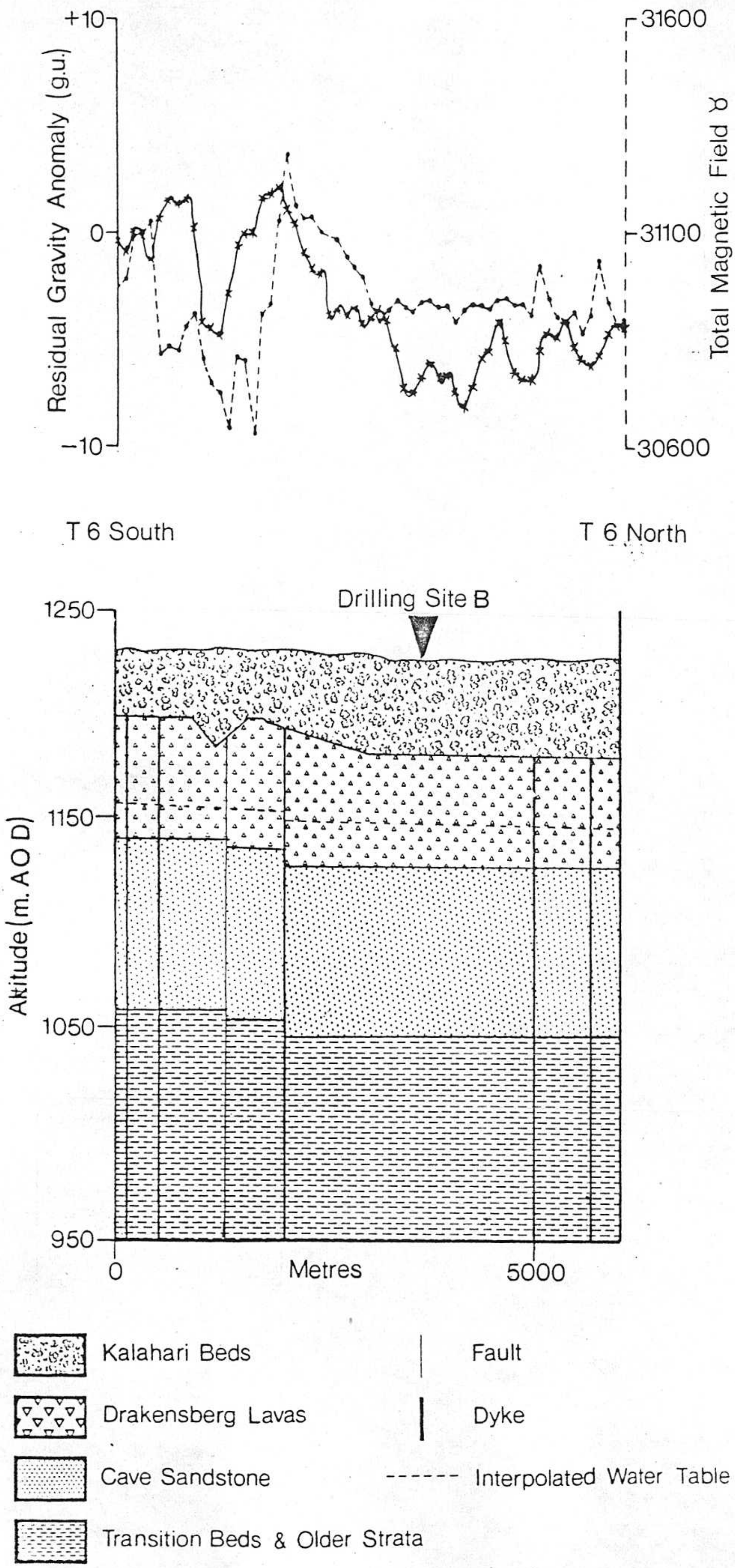


Figure **1.6**

CHAPTER 2

THE NATURE OF THE AQUIFER

2.1 Geological Structure

All of the geophysical, drilling and mapping data are brought together in a structure contour plan on the base of the basalts (Plan III). Some of the detail seen in the geophysics, small fault sets and dykes or dyke swarms without apparent persistence, have been omitted to produce a coherent expression of the main structural units. We have relied heavily upon the reconnaissance aeromagnetic survey for guidance in this interpretation using the reported geology and position of all boreholes to complete the picture outside our exploration area.

Major faulting extends throughout the area and is not confined solely to the zone of recent drilling and geophysical exploration. Outside these areas we are unable to determine the structure in such broad detail and we consider it unlikely that large simple fault blocks exist west for example of Serowe. Widely spaced drilling records just do not allow the true complexity to be seen here.

The main structural trend is west-northwest rather than due west dividing the area into a series of parallel fault-bounded blocks extended across the whole area. Generally the base of the basalt tends to dip northwards within each of the blocks and to be at greatest depth in the most northerly area.

The largest and most prominent feature shown on Plan III is the area without basalt between Serwe Pan and Serowe, identified as the Serowe Upthrown block. This is an area of relative stability bounded by faults down throwing the basalts up to 200 m on either flank.

The northern boundary is the most complicated structural zone in the area involving a series of sub-parallel and apparently coalescing faults with large individual throws. At Serwe Pan a narrow block is is downfaulted to a depth of over 200 m. The abandoned drillsite TS1 proves the westward extension of this unusual, rather "rift" like feature. Equally large up faulting can also be inferred within this complex near drillsite Ex 10 below the foot of the escarpment. Throughout, this fault complex appears to be heavily intruded with dykes, and overall forms the most spectacular feature of the geology.

Such extensive downfaulting in a narrow block, immediately adjacent to a large upthrown block, must seriously impede groundwater movement across it. The structure therefore virtually divides the area into two separate hydrogeological zones with the main exploration target to the north of the Serwe fault complex.

Most of the geophysical survey and much of the drilling has taken place across a 12 km wide zone immediately north of the Serwe fault complex. We have had to simplify the geophysical data, omitting small fault sets and minor dykes, in order to present the structure in map form. Overall we have a picture similar to that described in the Interim Report and the geophysical cross-sections (Figures 1.1 to 1.6). A central upfaulted block runs through this zone from Photsana at the outcrop across the whole area with the base of the basalts dipping off this axis to north and south. To the north the boundary faulting does not appear to be as complex as that in the south, but is nevertheless complicated. The direction of faulting changes from a southern downthrow at Shashane near the escarpment to a northerly downthrow in the west. Dykes appear to be intruded throughout its length and at drill site TS4 we were able to demonstrate that it was an impermeable boundary to groundwater flow.

North of this Shashane fault, structures appear less complicated, and regionally the aquifer seems to dip north and northwestwards without major faulting or extensive dyke intrusion. The northern limit of our study has been taken at the edge of the escarpment marked by two prominent dykes probably intruded into fault zones. There are few boreholes in this area but the simple structural pattern, built-up largely from the geophysical sections, makes it an attractive prospect for groundwater development.

In our Interim Report we proposed that the structure of the area formed under tension along an approximate north-south axis perhaps influenced by deeper basement features. It is not necessary for us to expand this interpretation. We are, however, surprised both by the scale and severity of the faulting. Perhaps in conclusion we should also point out that we can find no facet of the structure which is advantageous to groundwater development. Generally all aspects contrive to hinder exploitation, either indirectly by confusing interpretation due to the complexity, or directly by creating conditions which impede groundwater movement.

2.2 Geology of the Cave Sandstone

The sandstone is generally fine grained, white, buff or pinkish red in colour, composed predominantly of quartz grains cemented by a fine crystalline matrix. At many of our drill sites the sequence becomes finer grained with depth grading into silty sandstones, passing gradually into siltstones and shales of the underlying Ecca Series. Broadly we are able to distinguish an upper zone of sandstone underlain by a sequence of silty-sandstones. We have defined the base of the Cave Sandstone mainly on the basis of the appearance and persistence of coloured siltstones. Our identification is essentially that of an aquifer unit rather than of a precise geological formation. Throughout our drilling programme depths were tightly controlled by recognition of a few metres of coloured siltstones. Pace and direction of the exploration programme within the project timetable demanded this.

The aquifer has proved to be thinner than expected. Existing borehole evidence had suggested 100 - 120m of sandstones above the siltstones of the Ecca, we recorded between only 36m and 113m in our exploration. The aquifer appears to be thickest at the most easterly and westerly drillsites, 118m at Ex 9 and 95m at SYA. Between these the aquifer thins to 52 - 82m and is reduced to only 36m in the north-east at TS6. These variations are associated mainly with changes in the thickness of the upper sandstone horizon.

In Table 2.1 we summarise the geological data from the drilling programme. Several broad trends are evident.

On the plateau, beneath basalt in both confined and unconfined aquifer conditions, silty-sandstones were not encountered when sandstones exceeded 60m (Sites SYA, SYB, TS3 and Ex 10). Elsewhere an upper sandstone horizon, 14 - 32m thick, was underlain by silty-sandstones of about equal thickness. Total aquifer thickness varied from 36m to 95m beneath 24 - 120m of basalt. The thickest basalt overlies the thinnest aquifer and an inverse relationship might exist here.

At outcrop under water table conditions the aquifer is generally thicker in terms of both the sandstone and silty-sandstone horizons. However,

TABLE 2.1

THICKNESS OF CAVE SANDSTONE AND

BASALT AT PROJECT DRILL SITES
(metres)

	Basalt	Sandstone	Silty-sandstone	Total aquifer Thickness*
CONFINED CONDITIONS				
TS2	60 - 88+	14 - 20	34	54
TS3	52 - 64	85		85
TS4 OW1	72	28	28	52
TS5 OW2	88	32	34	
TW	84	22	35+	
TS6 TW	116	22	16	
OW1	120	16	20	
EX 10	24	60		60
SYB	48 - 54	80		82
UNCONFINED CONDITIONS BELOW BASE OF BASALT				
SYA	44 - 56	95		95
TS4 (W and OW2)	42 - 44	28	24	
WATER TABLE CONDITIONS AT OUTCROP				
SYC		30 - 38	50 - 66	80
EX 7		37	41	78
EX 9		96	22	118

*Minimum at site

here our drill sites were chosen on structural grounds to encounter the thickest aquifer conditions. On the plateau drill site locations were more widespread.

The sandstones are generally regarded as aeolian in origin, terrestrial deposits formed under conditions similar to those encountered in the Kalahari today. The appearance of silty-sandstones suggests a phase of sedimentation associated with wetter conditions in the north east of the study area.

Variations in the total thickness of the aquifer, or of the sandstones, are difficult to interpret. These may reflect primary depositional conditions but could equally be an expression of the pre-basalt topography of the original Cave Sandstone dune field. We are unable to distinguish between these two alternative explanations. Changes in the thickness of basalt, apparently inversely with total aquifer thickness, favour a topographic control. Removal of 60 - 80m of sandstone is implied by this interpretation. However unless a strong stratigraphic control can be established over a relatively large area it is impossible to determine whether primary sedimentary changes account for the variation. In view of the structural complexity this cannot be established from the existing data.

2.3 Occurrence of Groundwater During Drilling

Information concerning the strike and make of water during drilling provides important evidence of hydrogeological conditions. Surprisingly water was struck at the basalt contact in only 3 sites (TS3, TS1 and Ex. 10). Elsewhere the main appearance of groundwater was below the contact, normally within about 20m, and associated with the upper sandstones. Details of this borehole construction information are given in Table 2.2, the sites are grouped according to the position of the water level at completion. Unconfined conditions describe the aquifer where basalt is present but a water table exists below the contact. Confined conditions concern a true artesian situation with a piezometric level above the base of the confining basalts.

Water strikes at or near the contact occurred mainly at sites with thick sandstones (TS3, SYA and Ex. 10). Elsewhere it was suppressed until boreholes had penetrated up to about 25m into the sandstone. Only at drill site TS4, and at the test well at TS5, was water first encountered in the silty-sandstones. However at many sites water flow developed rapidly during drilling through the silty-sandstones and everywhere water levels stood above the water strike on completion of drilling.

TABLE 2.2

GROUNDWATER OCCURRENCE AT PROJECT DRILL SITES

(metres)

	Depth to water struck below basalt	Artesian head above water strike	Main source of water
CONFINED CONDITIONS			
TS2	5[1]	61 - 67	Silty-sandstones
TS3	2[1]	18 - 28	Sandstones
TS4 OW1	42[2]	41	Silty-sandstones
TS5 OW2	13[1]	79	Silty-sandstones
TW	30[2]	90	Silty-sandstones
TB6 TW	4[1]	42	Silty-sandstones
OW1	+10[3]	32	Silty-sandstones
Ex 10	2[1]	13	Sandstone
SYB	13 - 24[1]	16 - 24	Sandstone
UNCONFINED CONDITIONS BELOW BASE OF BASALT			
SYA	5 - 13[1]	6 - 8	Sandstone
TS4	25 - 28[1-2]	28	Sandstone/Silty-sandstone
WATER TABLE CONDITIONS AT OUTCROP			
SYC	23*[1]	10	Silty-sandstone
Ex 7	35*[1-2]	13	Sandstone/silty-sandstone
Ex 9	35*[1]	10	Sandstone

*Basalt absent, depth below surface

1 Water strike in sandstone

2 Water strike in silty-sandstone

3 Water strike in basalt

We do not believe these results imply that the Cave Sandstone is partly dewatered over large areas of the plateau. Suppression of the water strike is thought to be a function largely of the nature of the aquifer in this area. Borehole geophysics indicates the virtual absence of joints, fractures or solution cavities in the upper sandstone unit of the aquifer. This supports the findings of Cheyney and Farr[1] from the GS 10 logging, core analysis, and aquifer testing in the area. Water entry into the boreholes must therefore be controlled largely by the permeability of the rock matrix itself without any contribution from secondary structures. Initially water inflow must be restricted by a skin effect developed by the construction techniques. We used rock hammer, with foam injection for drill cutting recovery. Records of existing boreholes constructed using other drilling techniques also indicate suppression of water strike below the basalt. In all 16 other sites listed in the groundwater inventory for our area show similar effects.

We must conclude from our drilling records that the basalt/sandstone contact is not generally the major water producing horizon in this area. This supports observations from Serowe and is in contrast to aquifer conditions in the Cave Sandstone to the west at Orapa. In our study area the whole sequence of sandstone and silty-sandstones appear to contribute more or less evenly to provide groundwater supplies.

We have had to develop the pattern of permeability variation within the various aquifer types for our modelling studies. These are discussed elsewhere, but it is useful to summarise these findings here since they provide a more detailed explanation of the construction data. We believe the permeability in the top 5-15 m of sandstone to be slightly greater than that in any deeper sandstone. Permeability in the silty-sandstones appears also to be slightly higher than in the lower part of the sandstones, with a tendency for preferred flow-paths or localised higher permeabilities, to be developed around variations in the silt content of the aquifer. Overall the scale of these variations is small, less than an order of magnitude. We have not been able to determine the precise nature of the preferred flow pathways in the silty-sandstones. However during drilling it is here that skin effects are overcome and the main make of water develops.

2.4 Aquifer Characteristics

These have been established from 16 pumping tests. Details of each test,

[1] *Cheyney C.S. and Farr J.L., Results of borehole logging, core analysis and aquifer testing in the Serowe Study Block, GS10 Technical Note No.7, Dept. Geol. Surv. Botswana, 1980.*

the various solutions employed and interpretation at each site are contained in the appendix. Here we are concerned with the regional characteristics of the aquifer with regard to transmission and storage of groundwater.

A summary of the pumping test results is given in Table 2.3. Average values obtained from both pumped and observation boreholes are shown. Permeability has been calculated using the minimum aquifer thickness and the average transmissivity at each site.

Transmissivity, 7 m^2/d to 71 m^2/d, is somewhat higher than we predicted in our pre-feasibility study where regional values of less than 20 m^2/d were developed from modelling studies. The storage coefficient for artesian conditions varies from 0.01 per cent to 0.07 per cent. Our original resources calculations were based on a value of 0.02 per cent and here again we appear to have slightly under-estimated the aquifer in our pre-feasibility studies.

At drill sites SYA, SYC and TS4 we have obtained estimates of the storage coefficient for water table conditions in the Cave Sandstone. These specific yield data were one of the primary objectives of our field exploration programme. Values of between 2.4 per cent and 3.6 per cent were reliably obtained despite structural complexities affecting some solutions. Three sites (SYA, SYB and SYC) were originally selected for examination of specific yield under relatively long-term testing. Site SYB did not develop water table conditions and SYA was seriously influenced by boundary effects. Only at SYC on the outcrop was a full delayed yield condition monitored. Additional information concerning water table conditions were fortuitously obtained at drill site TS4, originally chosen to examine conditions close to the Shashane fault. Here our solutions are obtained from a shorter pumping test programme.

An average specific yield of 14 per cent ranging between 4 and 17 per cent was reported by Cheyney and Farr from centrifuged core testing. Our results suggest that during the period of 30 day pump testing gravity drainage does not develop the specific yield to this extent. However, for the purposes of our resources study we have obtained initial values for this parameter. In our pre-feasibility study we used a specific yield of 1 per cent, a value which now appears to be a small underestimate.

Permeability values have been obtained from the pumping tests for the full sequence at each site. These vary between 0.12 m/d and 0.74 m/d.

TABLE 2.3

SUMMARY OF PUMPING TEST RESULTS

	Confined conditions				
	TS2*	TS3	TS5*	TS6*	SYB
Transmissivity (m^2/d)		44	11	26	36
Confined storage coefficient(%)	0.021	0.034	0.01	0.067	0.026
Min. thickness of aquifer at site (m)	54	85	66	36	82
Permeability (m/d)	0.12	0.52	0.17	0.72	0.44

	Unconfined conditions		
	TS4	SYC	SYA*
Transmissivity (m^2/d)	22	36	71
Specific yield (%)	2.4	3.6	3.0
Confined storage coefficient	0.01	0.038	
Min. saturated thickness of aquifer at site (m)	54	58	95
Permeability (m/d)	0.41	0.62	0.74

* Sites where boundary barriers present

These field values compare favourably with those obtained from core analysis by Cheyney and Farr, ranging from 0.2 to 1.7 m/d and averaging 0.66 m/day for a complete sequence. Generally the higher values are associated with the drill sites in the main sandstones and the lower values with the thinner and silty sequences.

Several of the pumping tests were affected by dykes behaving as impermeable boundaries. Sites TS2 and TS5 were most strongly influenced by these barrier effects and the transmissivity values of 7 m^2/d and 11 m^2/d, the lowest obtained, may be under-estimates. The mean permeability at the remaining sites is about 0.5 m/d.

The concept of permeability as opposed to transmissivity (permeability times saturated thickness) plays an important role in the evaluation of the groundwater resources for Morupule. The basic premise of our pre-feasibility study was that groundwater would only be available by mining. Artesian heads, where they exist would fall rapidly and the aquifer would have to be partly dewatered to sustain the required supply. Our pump test transmissivities relate to full saturation conditions and throughout our modelling we have to simulate decreasing saturated thicknesses with the appropriate permeability.

We have therefore used a numerical modelling technique to test the reliability of the conventional pump test results for the water table aquifer conditions. This computer simulation allows permeability to be varied within a pumping simulation until a match is obtained with field results. Lateral and vertical variations of permeability can be interrogated by this method. The tests at SYA, SYC and TS4 have been simulated using this technique.

At TS4, Figure 2.1, water levels were depressed from the basalt contact to about 20m into the sandstone horizon. The best curve match gives permeability (K) dropping from 0.52 m/d after 15m of dewatering to 0.36 m/d below about 20m. This in good agreement with the average of the pumping test solutions.

For site SYA (Figure 2.2), again entirely within sandstone, the curve fitting method indicates a reduction in permeability with depth, from 0.34 m/d to about 0. 1 m/d below 20m. These are significantly lower than the pumping test average of 0.74 m/d. This was the most difficult of all our tests to analyse due to large barometric responses in water level masking observation well drawdowns for several days plus the complication of strong boundary effects. The curve matching technique implies that we have over-estimated transmissivity and hence permeability. Regionally the transmissivity at SYA

BOTSWANA MORUPULE POWER STATION PROJECT
STEP TEST AT BOREHOLE 154

STARTING PUMPING RATE 156 METRES PER DAY

OBH RADIUS 75

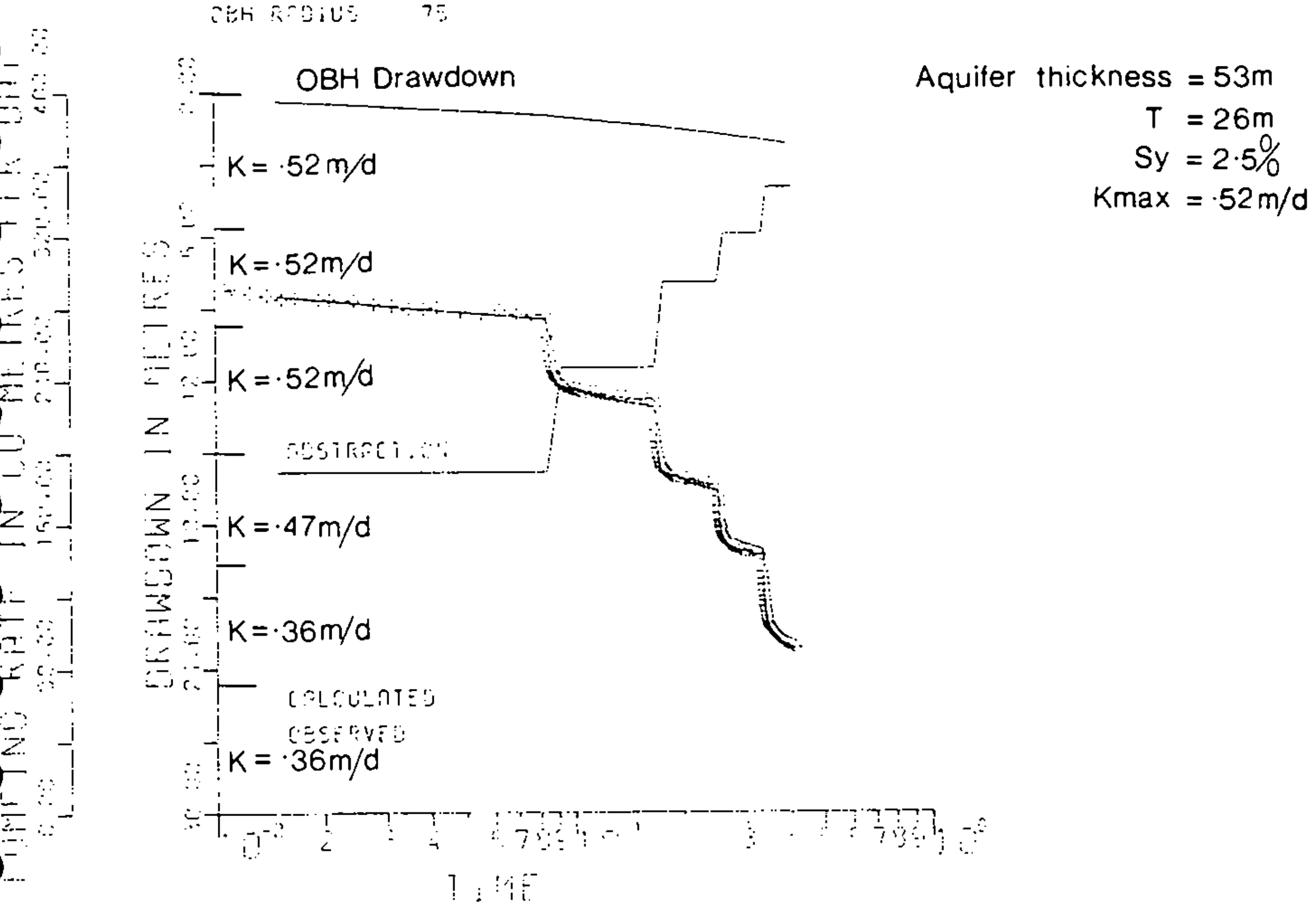


Figure 2·1

BOTSWANA MORUPULE POWER STATION PROJECT
STEP TEST AT BOREHOLE SYA

STARTING PUMPING RATE 205. CU.METRES PER DAY

OBH RADIUS 75. M

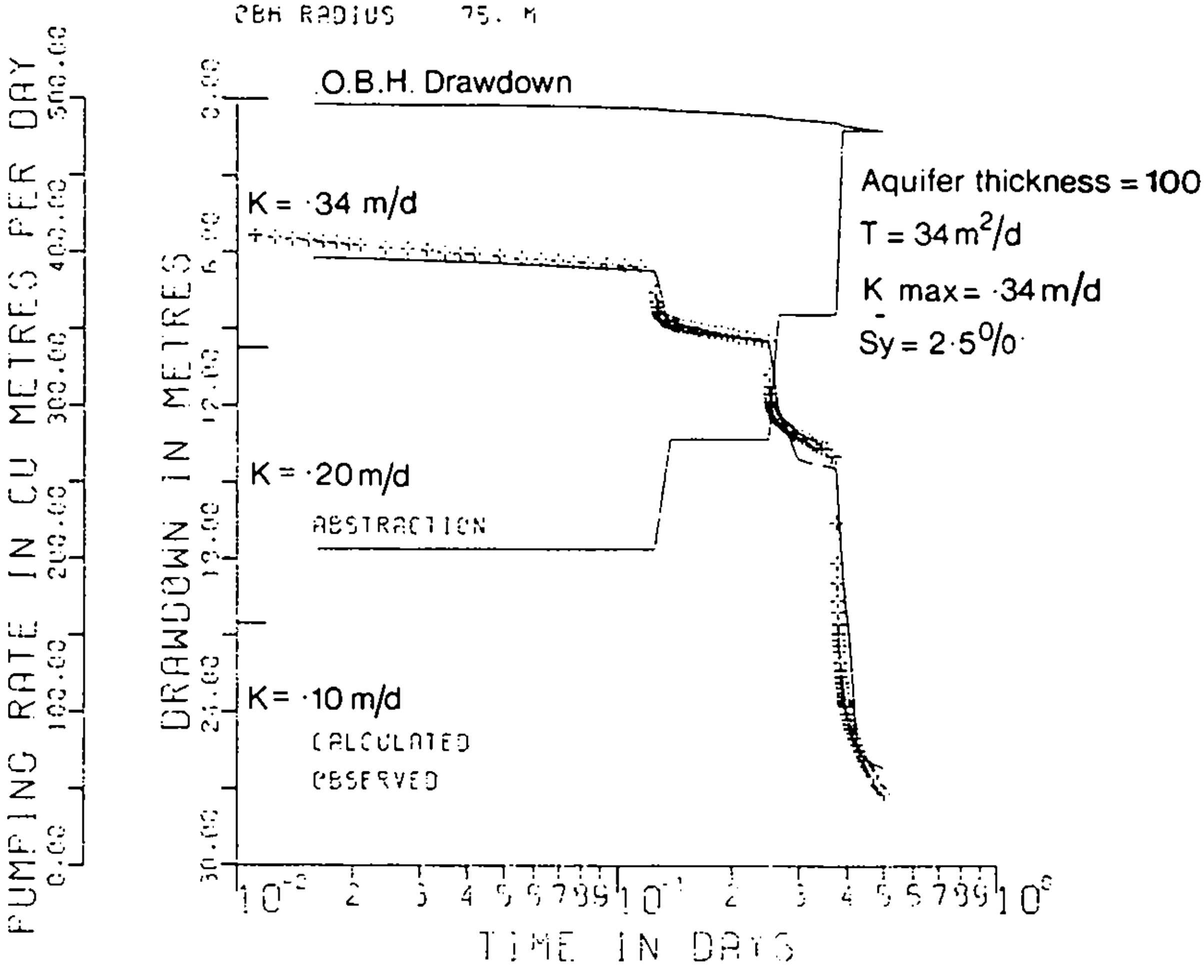


Figure 2·2

is about 34 m^2/d and permeability 0.34 m/d immediately below the contact.

Site SYC, Figure 2.3, demonstrates a further advantage of the curve modelling technique in relation to pumping test interpretation. Individual values of 15 m^2/d, 42 m^2/d and 97 m^2/d for transmissivity were obtained at the production borehole and observation boreholes. Our best curve fit was given by a transmissivity of 12 m^2/d at the test well but with a regional value of 40 m^2/d beyond a radius of 15m. At this site we must postulate either a very locally developed low permeability at the pumped borehole, or in fact, only partial development of the production site. Regionally, a permeability of 0.69 m/d is obtained for a saturated thickness of 58m, values of 0.15 - 0.12 m/d relating to some unknown and exceptional condition.

In summary values of permeability ranging between 0.52 m/d and 0.34 m/d can be attributed to the aquifer in the upper 10-20m of sandstone immediately below the basalt. At depth permeability decreases to between 0.10 m/d and 0.36 m/d in the deeper sandstone. Local variations giving regional values of 0.7 m/d at best, to 0.1 m/d can however be expected.

2.5 Borehole Yields

Various abstraction rates of between 150 m^3/d and 550 m^3/d were employed in our pump tests. The relationships between yield and water level depression for all step-drawdown tests are shown in Figure 2.4. Borehole TS3 gave the best operating performance producing 500 m^3/d for less than 20m drawdown. The poorest performance, TS1, gave 250 m^3/d at a drawdown of 50m.

Linear relationships between yield and drawdown are shown over the tested rates for these two sites and also at TS5 and TS6. These are in the main artesian area. The other boreholes exhibit breakaway characteristics, as yield increases the drawdowns become proportionally larger. This group, SYA, SYB SYC and TS4, are in water table conditions or in very close proximity to such.

The range of yield/depression characteristics for both groups are similar. Abstractions from either artesian or water table conditions are likely to produce boreholes with about the same wide variations in yield. The best producers in each group, TS3 and SYA, have the thickest sandstone sequences, 85m and 95m respectively, and no silty-sandstones. However, the second best in each group, TS6 and TS4, have the least sandstone and are

BOTSWANA MORUPULE POWER STATION PROJECT
STEP TEST AT BOREHOLE SYC

STARTING PUMPING RATE 125. CU.METRES PER DAY
REST WATER LEVEL : 22.25 METRES BELOW GROUND LEVEL
OBH RADIUS 75. M

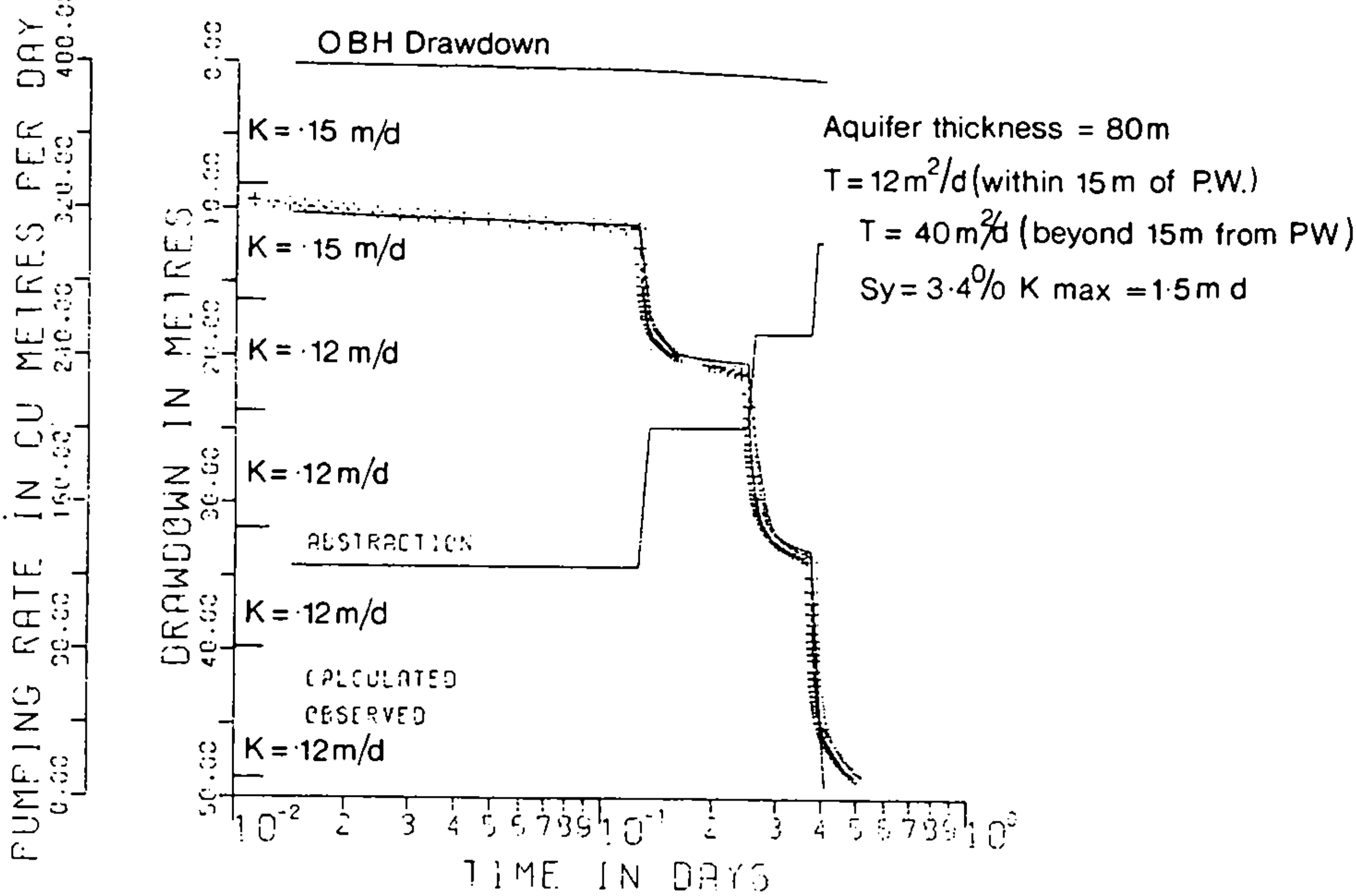
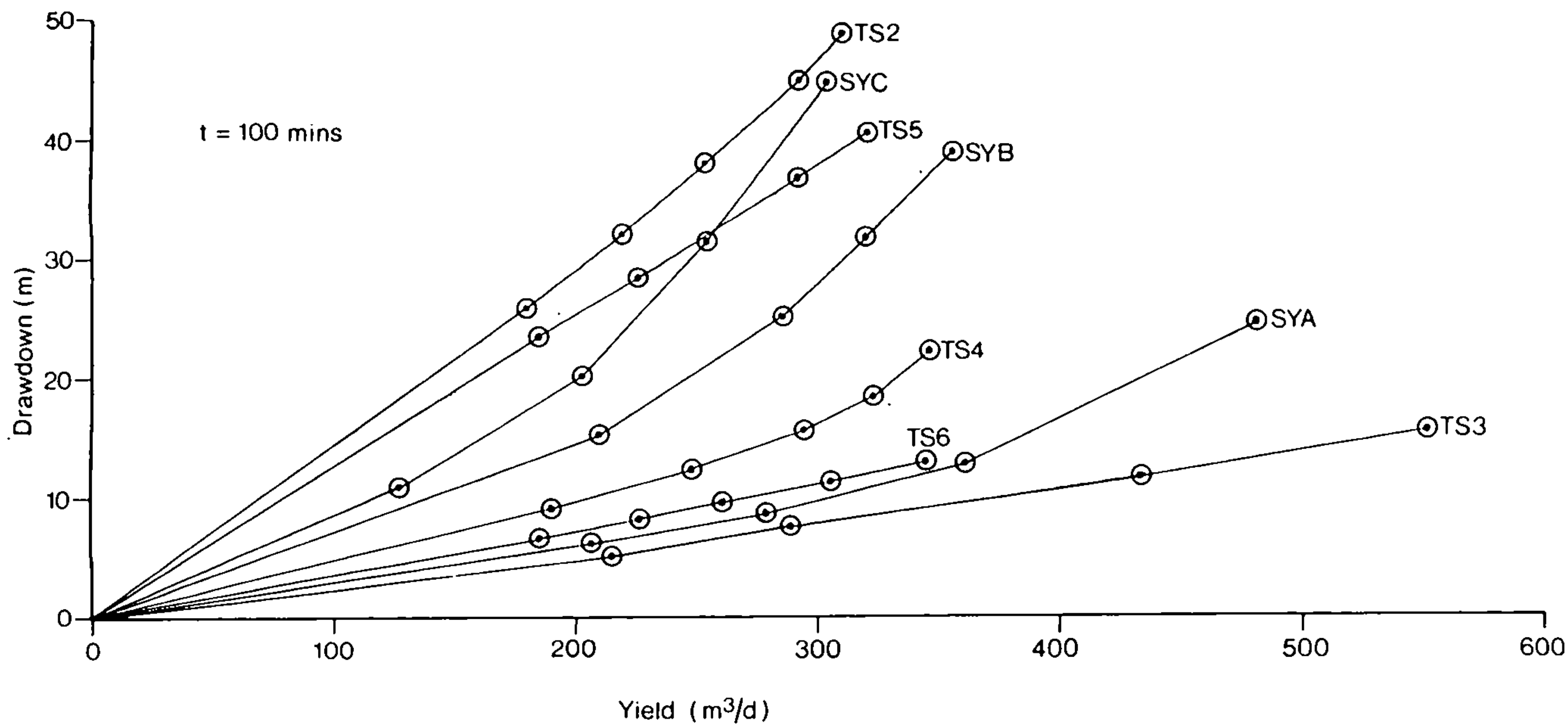


Figure 2·3



YIELD-DEPRESSION CHARACTERISTICS OF PROJECT BOREHOLES

Figure **2.4**

the thinnest aquifers. Production performance is not therefore related simply to thickness or to the proportions of sandstone and silty-sandstone. Minor variations in the permeability distribution throughout the aquifer must play a part.

Analysis of production performance in terms of specific capacity (yield divided by drawdown) improves our understanding of the aquifer. These vary from over 40 m^3/d/m to about 6 m^3/d/m (Table 2.4). Cheyney (1979) assessed specific capacity of existing boreholes in the area. A maximum of 12 m^3/d/m with a 50 per cent probability of only 2 m^3/d/m was indicated. In our pre-feasibility study we suggested these were low since many boreholes did not meet optimum design characteristics. By comparison with the Cave Sandstone aquifer at Orapa we suggested values of about 17 m^3/d/m for the area. Our pump test results show 20-35 m^3/d/m for the best conditions in both artesian and water table situations, and 6 - 9 m^3/d/m for the worst conditions.

The differences between the confined and water table performances are brought out by an analysis of the composition of the drawdown. This comprises two elements, an aquifer loss related to the ability of the aquifer to transmit water and a well loss due to turbulent flow in and adjacent to the borehole. Details of the method are given in the appendix, here we summarise the results as well efficiency, given as the percentage of total drawdown attributed to aquifer loss. 100 per cent efficiency describes a perfect borehole with no well losses. 80 per cent efficiency or more is desirable for efficient production wells.

Our results are plotted in Figure 2.5. The artesian boreholes have efficiencies of between 83 per cent and 95 per cent, decreasing with yield by a few per cent per hundred m^3/d. The water table boreholes on the other hand appear to be operating at below the 80 per cent criteria, apparently losing 20 per cent efficiency per 100 m^3/d of abstraction. In fact this is an aquifer loss effect demonstrating the fundamental and important difference between the two aquifer conditions. Efficiency analysis of this form does not apply in this case.

Under confined conditions pumping levels remain above the base of the basalt, the aquifer is not dewatered, and supplies are obtained by compaction of the aquifer and expansion of water through lowering of pressure. In the

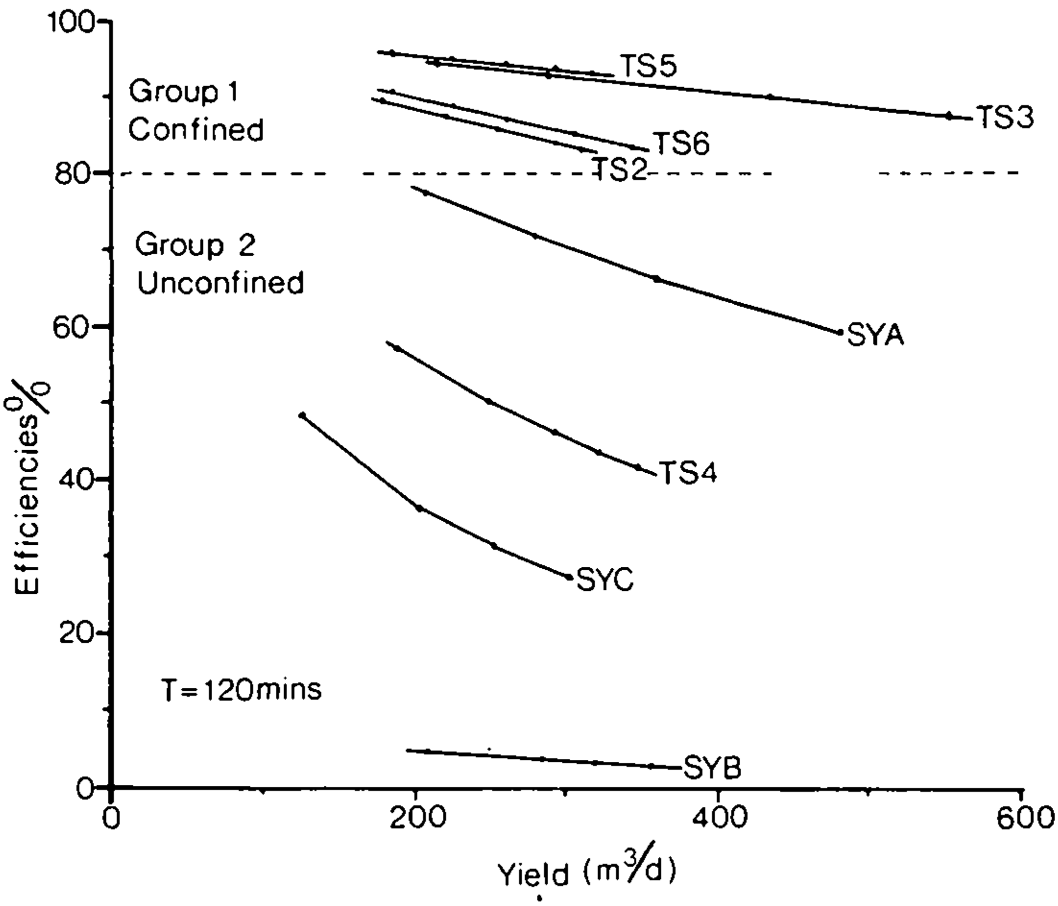
TABLE 2.4

STEP DRAWDOWN PUMPING TEST AND SPECIFIC CAPACITIES

	Aquifer Thickness (m)	Step 1	Step 2	Step 3	Step 4	Step 5
		Specific Capacity (m^3/d/m)				
CONFINED CONDITIONS						
TS3	85	41	37	36	35	
TS6	36	28	28	27	26	26
TS5	66	8	8	8	8	8
TS2	54	7	7	7	7	6
WATER TABLE AND SEMI CONFINED CONDITIONS						
SYA	95	33	29	28	19	
TS4	52	20	20	19	17	16
SYB	82	14	11	10	9	
SYC	80	12	10	8	7	

	Artesian Head (m)					
CONFINED CONDITIONS				Drawdown (m)		
TS3	28	5	8	12	16	
TS6	126	6	8	10	12	13
TS5	76	24	28	33	37	41
TS2	61	26	32	38	45	49
WATER TABLE AND SEMI-CONFINED CONDITIONS						
				Per Cent Dewatered		
SYA	-4		10	14	26	
TS4	2	17	23	31	36	42
SYB	6	17	28	36	47	
SYC	58*	19	34	55	78	

*Saturated thickness at start of test



WELL EFFICIENCIES

Figure **2·5**

water table boreholes, water is being taken from storage, and the aquifer is becoming thinner as it is progressively dewatered. As a result the amount of water obtained for unit drawdown under water table conditions is very much greater than under confined. The percentage dewatering of the aquifer, at each step of all the tests is given in Table 2.4. The falling efficiencies, and in fact the overall order of the performance of this group is determined by the percentage dewatered except at SYB where the storage coefficient changes to unconfined conditions between steps.

Command of the Cave Sandstone groundwater for Morupule by mining from storage will have to operate at these relatively low specific capacities unless more highly productive zones can be located. This now seems unlikely, our exploration has been widespread in extent and searching in detail. In Chapter 4 we use the permeability curve matching model described in 2.4 above to extend predictions for individual production boreholes to much longer times, up to 27 years. We have to conclude that individual yields of only 200 m^3/d per borehole are a realistic extrapolation of our short-term exploration pumping test results.

2.6 Groundwater Contours

In our pre-feasibility study we drew attention to the configuration of the piezometric surface in the Cave Sandstone. The main feature of the contour pattern was a series of groundwater mounds forming a subsurface divide within the plateau area just west of the escarpment. The configuration implied movement of water from the aquifer beneath basalt and Kalahari beds eastwards under the escarpment towards the aquifer at outcrop. This was unexpected. It suggested either active recharge on the plateau, or perhaps the preservation of a fossil groundwater situation from an earlier and wetter climate.

Our recent exploration has provided good confirmation of the piezometric surface configuration reported in our pre-feasibility and Interim reports. Generally the groundwater mount in the vicinity of Serwe Pan is confirmed by drilling together with the steep south-easterly hydraulic gradient off this mound beneath the escarpment. A shallower north-westerly hydraulic gradient beneath the main plateau area is also confirmed.

All water level data are combined together in Plan IV show a groundwater contour map of the piezometric surface and water table throughout the area.

For our drilling area we have modified previous work by inclusion of our new data. Elsewhere the basic information is unaltered but we have interpreted the data with a knowledge that the main dykes restrict groundwater movement. Some faults of over 50m throw have also been considered as barriers in our interpretation.

Within our exploration area the main modification to previous interpretation concerns the difference of 13m in piezometric level at TS4 across the dyke intruded Shashane fault. We can now recognise two separate groundwater mounds on either side of this fault. Southwards to Serwe Pan the piezometric surface currently rises to an elevation of about 1185m A.O.D. To the north a second mound, displaced westwards, rises to about 1150 m A.O.D. Two separate recharge conditions may be inferred from this configuration.

A third groundwater mound, at Mahatana on the Serowe Upthrow Block; to an elevation of 1190 m A.O.D. has previously been reported. We show the contours displaced across the Serwe Fault Complex to emphasise our general contention that this is an impermeable barrier to groundwater movement. However, we must point out that head differences are small across the boundary structures to north and south of the upthrown block.

A fourth shallow groundwater mound at an elevation of 1140m AOD is suggested by the piezometry in the north-west. In our modelling studies we demonstrate that recharge in this general area is necessary to achieve a model calibration. Generally this explanation of the piezometric elevation as an expression of groundwater mounds requiring modern recharge to sustain them is of prime importance to an understanding of the nature of the aquifer system. Their position relative to the beds' thickness and distribution of basalt and of the Kalahari Beds provide a possible explanation of the nature of the processes. Water level fluctuations and chemical data also support the contention that some recharge currently occurs beneath these mounds.

2.7 Evidence for recharge

In our pre-feasibility study we suggested a monthly rainfall of about 100mm as a threshold for groundwater replenishment in the outcrop area of the aquifer. This was based upon evidence from water level and chemical data for Serowe. For the plateau area where Kalahari Beds and basalt provide a barrier to recharge we drew attention to several lines of evidence which seemed to indicate active recharge. No direct evidence was available but from our groundwater modelling, we inferred a recharge of 1 $m^3/yr \times 10^6$ to sustain the piezometry in the Serwe Pan area. We shall rely again upon modelling studies to derive new recharge estimates but have also obtained additional and direct evidence of recharge during our study period.

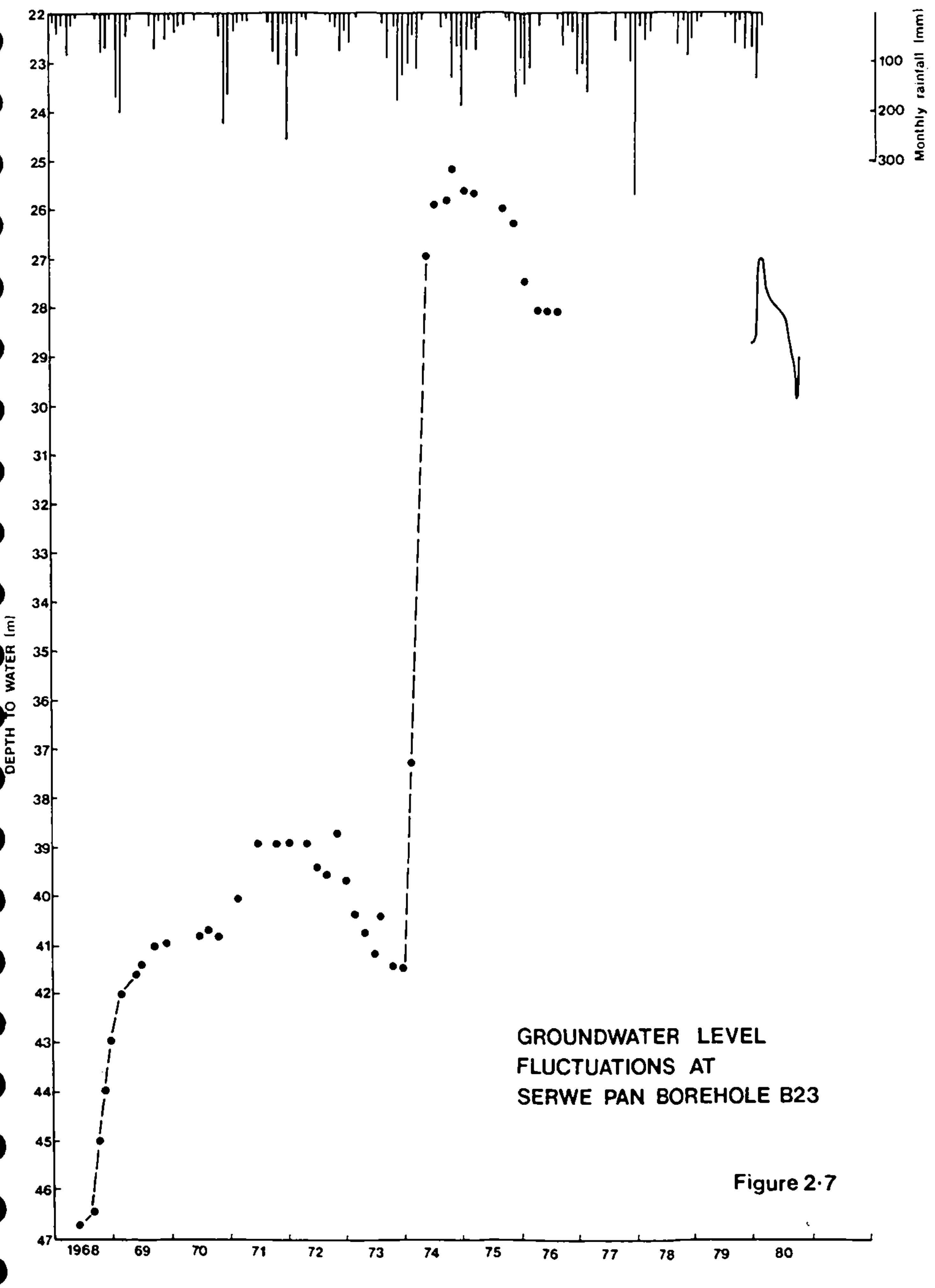
Water levels in borehole B23 at Serwe Pan show two recharge events in February and October 1980 of 1.8m and 1.2m separated by an 8 month recession of 3.0m. (Figure 2.6). Rainfall data for Serowe indicate 133.5 mm in February, well above the average of 82mm for the month, and in excess of the postulated recharge threshold. October rainfall was low only 59mm were recorded at Serowe. Surprisingly this seems to indicate a recharge potential as good, if not better, than for outcrop, despite great depth to the aquifer (252m) at the observation borehole.

Earlier water level data for the site, collected by Geological Survey between 1968 and 1976, show current water level recoveries to be small by comparison with 1968/69 and 1974 when 6m and 16m respectively were recorded (Figure 2.7). No simple relationship appears to exist between the groundwater fluctuations at Serwe Pan and the monthly rainfall at Serowe. Inspection of the records show daily falls of over 100mm arising from thunderstorms, which are generally very localised, and extrapolation from Serowe to Serwe Pan cannot be made for detailed analysis of water level response.

On a broader scale an interesting relationship can however be demonstrated. The cumulative departure of annual rainfall from the mean is shown in Figure 2.8 for Serowe. For over a decade in the 1960's and early 1970's rainfall was generally below average. 1974 marks the onset of several years with much higher rainfalls. The 16m recovery in water level in 1974, and the probable maintenance of this high storage level at Serwe Pan, reflects the wetter conditions of recent years. Regional recharge rather than a local or site peculiarity is needed to produce and sustain such a long-term relationship and we interpret these data as proof of occasional replenishment of the aquifer within the Kalahari area. Large falls in water level are also implied. Rest water level data from the GS10 Groundwater Inventory of the Serowe Block suggest up to 20m variation under confined conditions in the area whilst over 30m of natural fluctuation must be expected on the groundwater mound at Serwe Pan.

WELL HYDROGRAPH
SERWE PAN
BOREHOLE B23
WATER LEVEL
(metres below casing top)
27 0m
28·0m
29 0m
30 0m
RAINFALL (mm)
100
75
50
25
0
APRIL → AUGUST
RAINFALL = 0
October Rainfall
Total 58 5
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER

Figure 2 6



GROUNDWATER LEVEL FLUCTUATIONS AT SERWE PAN BOREHOLE B23

Figure 2·7

SERÖWE RAINFALL [1922-79]
CUMULATIVE DEPARTURE
FROM THE MEAN

Figure 2·8

The geometry of the piezometric surface and the water level fluctuations indicate that the recharge area most probably lies close to the watershed just within the escarpment. This is an area characterised by virtually no drainage features. Physiographically, small depressional hollows and the larger depressions in grass pan areas, form one of the main topographic features of this zone. These vary in overall depth, from about 1m, to over 10m at Serwe Pan, where the main depressional area extends over several kilometres. During heavy rainfall surface water is concentrated into these depressions. The coincidence of the surface water divide and the groundwater mounds in close proximity to the small depressional hollows is shown on Plan IV. They appear to be an unexplained feature and are worth further investigation to examine their origin and possible role in recharge.

Additional and regular observations of water level fluctuation in the study area are vitally important to this problem of recharge in terms of when and where such events take place. Borehole B23 provided the only site near the escarpment for water level observations at the start of our study. Regular observations using water level recorders should be undertaken now on the project boreholes and if possible include rainfall observations on the plateau at Serwe.

It is appropriate to examine the possible mechanisms for recharge in view of these water level fluctuation data. Our interest in this respect must centre on the basalts and the Kalahari Beds since these are the formations through which recharge must occur.

2.8 Drakensberg Lava

The greatest thickness of basalt proven within the study area is 240m at the Serwe Pan observation borehole B23. Project drilling encountered at least 168m in the abandoned drill site TS1 confirming the westward extension of this deeply downfaulted block. Here, as elsewhere throughout the area, the structural pattern controls the depth to aquifer and hence the thickness of basalt.

Plan V shows the very variable distribution that exists. Removal of up to 200m of basalt from the major upthrown blocks is implied but we find no evidence of any erosional products to suggest the age of nature of this phase of development. The geological structure prevents identification of the pre-basalt topography at the contact with the aquifer. It is known to be irregular and individual small exposures along the escarpment suggest several metres of variation at any point. At our drill sites the thickness of basalt within each borehole array of up to about 400m separation varies from 4m to in excess of 28m at TS2. At outcrop elevational movement of about 50m is implied but this is difficult to confirm due to lack of clear exposure of any extent. Overall we have to conclude that we still have little knowledge of the regional nature of the landsurface upon which the basalts were extruded, and we cannot even be certain they originally extended throughout the whole area.

The principal hydrogeological significance of the basalts concern their role as the confining formation leading to confined aquifer conditions in the Cave Sandstone. The contact zone is not extensively hardened and the effect of the original basalt extrusion is thought to extend only throughout about 2m depth. Low permeability is reported for this contact zone by Cheyney and Farr. This appears to be a remarkably thin zone to confine effectively the aquifer throughout the area. An unknown number of separate lava flows form the total basalt sequence. Thin interflow soils should mark the junction between flows but were not very evident. Generally the basalts are variably weathered presumably in relation to the length of climatic exposure between successive outpourings.

Detailed identification of such features were beyond the scope of the project since we did not encounter any groundwater in even the most weathered basalt zones. Occasionally we suspected minor traces of water but there was insufficient flow to obtain any discharge measurements. With artesian heads of tens of metres over large areas we have to conclude that the basalts immediately above the sandstones effectively confine the aquifer on a regional scale.

The distinction between basalt and intruded dyke or sill material has been difficult to determine. Grain size, texture, magnetic anomaly and geological relationships have been variously used for field identification. X-Ray diffraction and thin section investigations were also employed from drill samples at TS2 where dolerite intrusion was suspected in an attempt to provide diagnostic characteristics for identification. All samples investigated had a similar mineralogy; labradorite and clinopyroxene, in a very fine-grained ground mass containing clay minerals (smectites). We have therefore tended to be extremely cautious in our interpretations. A basis for distinction should be sought if a major groundwater development is to take place. Site decisions regarding whether or not a borehole is in basalt above the aquifer, or alternatively is in dyke material and perhaps should therefore be abandoned are extremely difficult to judge with any certainty.

The exploration programme gave little information regarding the specific nature of fracture zones. We assume they are steeply dipping, nearly vertical, and relatively sharp and narrow in extent. We can find no evidence for the existence of shatter belts in the basalt which might provide a particularly attractive groundwater prospect. Equally there is little we can add to the Interim Report regarding the occurrence and distribution of dykes. In our structural map the most persistent as deduced from all geophysical data sources are shown. Where these are believed to be offset from faults, but nevertheless in close proximity, we have had to combine them for modelling purposes.

Dykes were unequivocably encountered in drilling only at site SYA. At others our borehole patterns are believed to have straddled dykes or were adjacent to them. Clear evidence regarding their hydraulic characteristics were however obtained from the exploration programme.

At site TS4 our drilling pattern straddled a fault/dyke occurrence on or close to the main Shashane fault. Here a 13m difference in water level elevation was recorded across the structure which acted as a barrier to pumping in the nearby test well. Other than data provided by Robins[1] for a groundwater discontinuity across the major dyke intrusion at Serowe, this appears to be the only other specific evidence of their hydraulic behaviour. Boundary effects were also recorded in our pumping tests at sites SYA, TS2, TS5 and TS6. These are also attributed largely to the occurrence of dykes.

The distribution of the groundwater head relative to the structural component has been summarised in Plan VI. This shows the height of the piezometric level above the top of the aquifer and identifies those unconfined areas where water levels exist below the basalt.

North of the Serwe fault complex unconfined conditions (water levels below basalt) occur on the north-east escarpment, on the crest of the upthrown block through the centre of our detailed exploration area, and in the extreme

[1] *Robins, N.S. Geohydrology of the Serowe area. Unpubl. Report Geol. Surv. Botswana, 1972.*

west. Only in this western area is the aquifer apparently dewatered to any extent. Here the piezometry and structure predict water levels up to 60m below basalt in an area where the Cave Sandstone is expected to be 100m thick. Elsewhere confined heads of up to 140m exist tending generally to increase from the escarpment westwards.

South of the Serwe fault complex, the most significant feature is the apparent dewatering of the aquifer to 60m or 80m depth within the Serowe upthrown block. In view of the thinning of the aquifer from west and east recorded by our drilling, the Cave Sandstone may be virtually dewatered in parts of this basalt free area. At Mahatana, beneath the groundwater mound, a fully saturated sequence is postulated and here water levels may be within the Kalahari Beds.

This zone has an important influence on development strategy for Morupule. Groundwater is unlikely to be available in any quantity, this is proven by the problems of obtaining good supplies at Serowe north of the boundary fault. Abstraction to the south would possibly interfere with the Serowe water supply and any development strategy must therefore concentrate within the zone to the north of the Serwe fault complex.

2.9 Kalahari Beds

These comprise the shallowest geological formation, through which any recharge must infiltrate. Their composition and distribution is therefore of importance to our study. Our drilling programme encountered up to 70m of these deposits. All of the drilling records are brought together in Plan VII which shows the elevation of the base of the deposits and variations in thickness. Minor changes in thickness at drill sites are ignored as are local thickenings over fault zones postulated from geophysics. In this diagram we attempt to provide an overview of the regional picture since this has a bearing on recharge and the maintenance of the groundwater mounds.

The Kalahari Beds, comprising sands overlying silcrete, sandstone, limestone and ferricrete completely cover the underlying Karoo formations in the area west of the escarpment. The surface member is a fine grained, well rounded and frosted quartz sand up to 12m thick ranging in colour from orange-yellow to brown. Essentially these sands comprise a stablised dune field supporting a well established vegetation with occasional silts in pan areas.

Siliceous sandstones form the bulk of the underlying section of the Kalahari beds and appear to be a cemented form of the overlying aeolian sands. They often grade into silcretes and in many places there is only a fine distinction between sandstone and silcrete. At the base of the Kalahari Beds there is often a thin band of pink to brown calcareous sandstone, similar in appearance to the Cave Sandstone, but frequently cut by numerous subvertical tubular holes. Machacha[1] (in press) has named this sandstone the Mohise Formation from erosion resistant outcrops along the escarpment where it occurs as a very hard, brittle silcrete. In drilling, the base of the Kalahari Beds is normally difficult to define, with a gradational contact into heavily weathered basalt which in appearance is very similar to the calcareous sandstone.

Thicknesses of between 50m (TS4) and 70m (TS2) are recorded from our drilling suggesting the greatest accumulation of these beds between geophysical traverses 1 and 2 with up to 54m in a second area due west of Serowe. The beds thin rapidly to less than 20m in the north-west and south-west of the area. Elsewhere 20m - 40m of Kalahari Beds underlie the plateau.

The topography of the base of the Kalahari Beds broadly reflects that of the surface. Along the escarpment the Mohise Formation outcrops at about 1220m AOD dipping northwards and westwards to an elevation of 1140 m A.O.D. However, the thickest accumulations occur in broad, fairly shallow depressions as two northward draining valleys. These are separated by a spur rising 60m above the level of the valleys providing evidence of the pre-Kalahari land surface.

Although no groundwater was encountered in the Kalahari Beds during our drilling operations the piezometric head in the Cave Sandstone is at, or just above, basal calcareous sandstones and silcretes at Serwe Pan and at Mahatana. These locations are shown on Plan VII which also gives the outline of the four groundwater mounds. Only at Serwe Pan can a true Kalahari groundwater be claimed (BH B26) which does not penetrate to the Cave Sandstone. Further evidence is provided at Serwe by a hand-dug well close to the deep observation borehole B23. A water level elevation of about 1188m A.O.D. was recorded here by comparison with a contemporaneous piezometric

[1] *Machacha, Geology of the Serowe Area, Dept. Geol Surv. Botswana.*

level of 1186m A.O.D. in the adjacent deep Cave Sandstone borehole. Here we must conclude from the piezometry in the deep borehole and the water level in the hand-dug well, that aconnection exists between the two aquifers. The rise in water level recorded in February and October 1980 may therefore not be a Cave Sandstone response but a Kalahari Bed aquifer fluctuation.

This situation is remarkable similar to a proposed model of the groundwater regime in the Cave Sandstone at Orapa (Mazor et al,. 1977)[1]. Both describe a perched Kalahari water table aquifer above largely impermeable basalt requiring occasional isolated links to the Cave Sandstone at depth. The main difference between the two situations concerns only the regional head distribution. At Serwe Pan the Kalahari aquifer is on a piezometric high, head potentials lead to a flow into the Cave Sandstone and away from the area. Orapa is at the other end of the system where groundwater flow should be from the Cave Sandstone to the Kalahari aquifer.

Quantitative statements concerning recharge at Serwe are difficult largely because the extent of any contributing area seems impossible to define. Published topographic maps suggest an area of up to 150 km^2 which drain internally to the pan. The groundwater mound encompasses a smaller area of 48 km^2, whilst comparison of piezometric levels and structure contours suggest a possible Kalahari bed aquifer of only 10 km^2 extent. In our modelling studies we conclude from the calibrated model that an average annual recharge of about 2.5 $m^3 \times 10^6$ is required to sustain the piezometry. If we consider only the area for which a Kalahari aquifer is proposed, 10 km^2, the recharge inferred by a water table rise of 1.8m can be obtained if a specific yield is available. On the basis of geological similarity with the Cave Sandstone, a value of 3 per cent may be reasonably evoked. A recharge event of 0.5 $m^3 \times 10^6$ would then be indicated for February 1980.

Given uncertainties regarding the extent of the aquifer and the specific yield this is of the order required to meet the modelling predictions. The borehole hydrograph at B23 shows at least two recharge events, one at the end of a wet season, one immediately after the dry season. Regular recharge events throughout the wet season seem therefore possible to meet a 2.5 $m^3 \times 10^6$ annual average replenishment.

The absence of Kalahari groundwaters in the boreholes elsewhere in the

[1] *Mazar E. et al, Northern Kalahari Groundwaters, Journ. Hyd. Vol 34, No 3/4, 1977*

area does not preclude the possibility of local recharge. In fact, the position of the groundwater mounds in relation to the thickness and elevation of the Kalahari Beds suggests a regional pattern which may relate to the processes.

In the northeast the two mounds lie between the escarpment and the area of thickest deposits extending from the surface watershed westwards beneath the dipping base of the Kalahari Beds. This geometry is consistent with recharge and subsequent groundwater movement westwards through the Kalahari Beds leading eventually to percolation into joints, fissures and weathered zones within the basalt. At Mahatana the third groundwater mound coincides with an area of basalt-free Cave Sandstone beneath about 30m of Kalahari deposits, again extending with the dipping base southwestwards, from close to the surface watershed toward an area of thick Kalahari accumulation. This mound straddles one of the largest faults in the area without major dyke intrusion. In the northwest the fourth groundwater mound underlies the area where the Kalahari deposits appear to be thinning over a fairly extensive area to less than 20m. Here the piezometric surface is up to 30m below the top of the basalts and deep percolation through the Kalahari Beds would account for the absence of any shallow groundwater.

The only missing element to complete a description of the nature of the Cave Sandstone aquifer concerns the interconnecting zones which must be postulated through the basalts. No field evidence exists at Serwe, or at Orapa, to describe their nature. If they exist, and we have to conclude they do, water levels within them must be at atmospheric pressure. Groundwater must stand at the height of the piezometric surface within the vicinity leading to local aquifers in either the basalts or the Kalaharibeds according to the structure at the sites.

2.10 Chemistry and Isotope Studies

The chemical composition of 57 water samples collected during our drilling programme, and stable isotopes (oxygen-18 and deuterium) from 59 samples are recorded in the appendix. These were collected during our study mainly to examine the processes of recharge. We are unable to present our interpretation of this data here. The pace required to arrive at a conclusion regarding the availability of the total resource by December 1980 has concentrated our efforts mainly toward a reconciliation of the structure and aquifer properties within the mathematical model.

These findings, presented in Chapters 3 and 4, are helpful for interpretation of the chemical data. We have been left with no time to consider these implications. Our complete data set has been together only since early November and a calibrated model for a much shorter time. The chemical data deserve serious analysis and we propose therefore to present them as a separate appendix some time in the future. Their implications do not affect the quantitative findings of our study, in fact they support our other lines of evidence regarding the nature of the aquifer.

CHAPTER 3

MODELLING THE GROUNDWATER SYSTEM

So far we have discussed the results of the field investigations that we have carried out in this study. The development of a groundwater model now enables us to bring this information together into a single analytical framework; one that will identify the principal factors affecting the yield of the aquifer and the design and location of wellfields. These factors are the areal variations in the hydraulic properties and saturated thickness of the Cave Sandstone aquifer, the effects of the dolerite dykes and geological faults which dissect the aquifer into a series of poorly connected blocks, and the amount of natural groundwater recharge.

3.1 Description of the Model

Numerical, computer based, groundwater models solve the differential equations of groundwater flow by subdividing the study area into a number of adjacent subareas in which aquifer conditions are assumed to be similar. They also ensure that recharge, abstractions and flow across the boundaries of the model are in balance with the changes in storage caused by changes in the level of the water table. Usually one or more of these variables is unknown; in this study the recharge to the system cannot be adequately defined from the field data alone. However, given the field data collected by Cheney and water level and transmissivity measurements made during our study, we can, by systematically adjusting the model parameters, determine reasonable estimates of the unknown variables. This procedure is known as model calibration.

Initially the model is used in a time varying sense to demonstrate that natural infiltration from rainfall is recharging the aquifer. Next it is desirable to consider the aquifer in a steady state, that is one where changes in storage are zero and flows into and through the aquifer can be considered constant. This simplifies the computation considerably at the calibration stage and the simplification is acceptable where groundwater levels are not changing rapidly. The resulting recharge estimates will therefore be average values consistent with the observed water level configuration. Once the model has been calibrated satisfactorily it may be used to determine the best location and pumping rates from wellfields to meet the projected demand for water at Morupule. Subsequently, a time-varying model is used to examine the changes in storage and the development of cones of depression associated with the new wellfields.

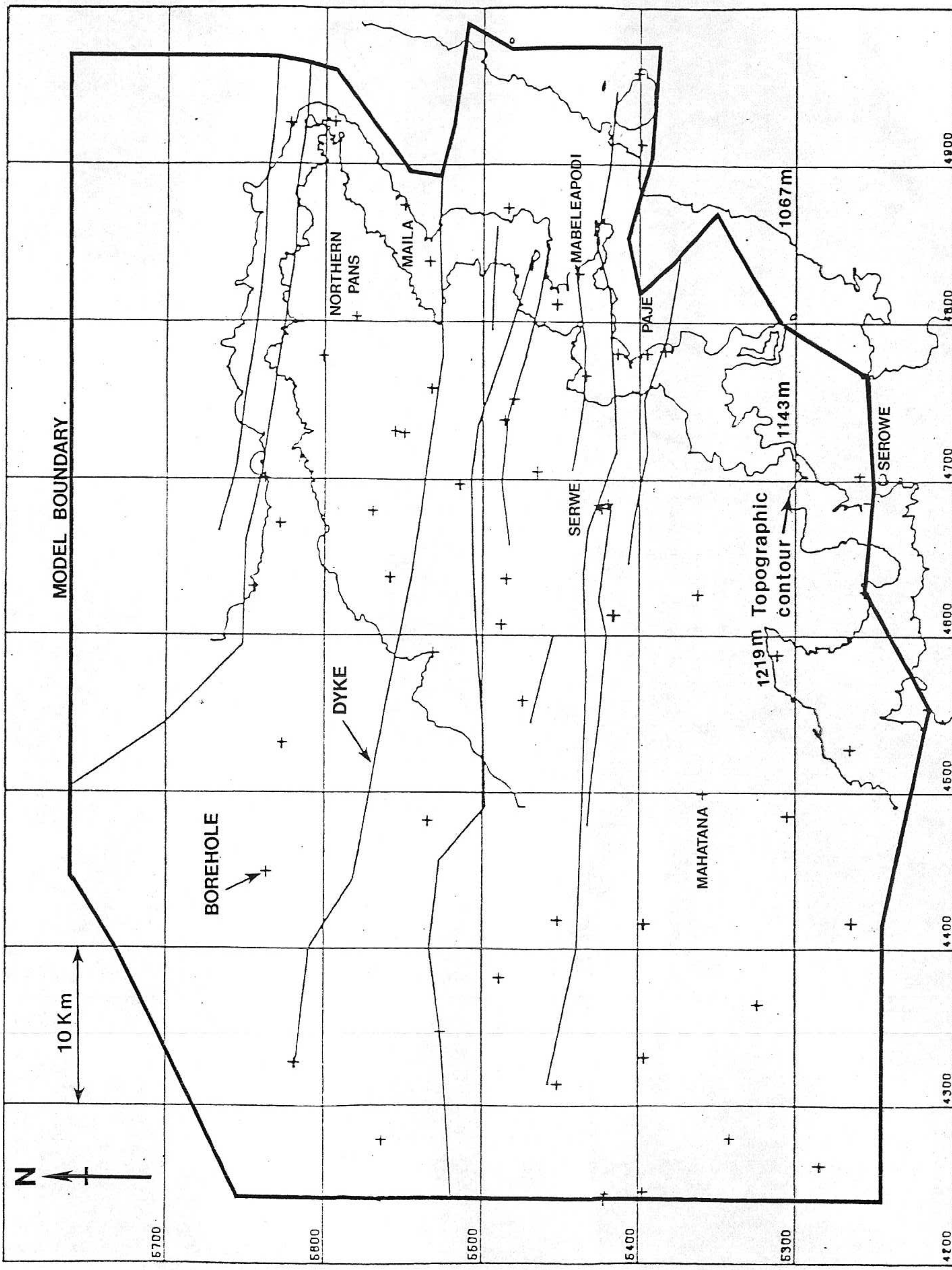
The groundwater model covers the area shown in Figure 3.1. The eastern boundary of the model corresponds to the eastern limit of the Cave Sandstone outcrop. The northern, western and southern edges of the model are constant-flow boundaries and have been chosen to be sufficiently far away from the potential wellfield sites for changes in the boundary flows caused by the proposed pumping to be negligible. The model area extends south east to Serowe so that we can compute the likely effects of pumping on the groundwater levels in this area.

The dolerite dykes and faults in the Cave Sandstone exert a strong control on the flow of groundwater in the aquifer. Figure 3.1 shows the position of the most important dykes and faults that have been identified on the basis of borehole records, the geophysical survey and the photogeological survey of the area of Cave Sandstone outcrop. Figure 3.2 shows the locations of boreholes which have provided water level and lithological information in the model area.

The groundwater model uses Galerkin's finite element method to simulate regional groundwater flow. Pinder and Frind[1] were the first to apply this method to aquifer analysis and the theory has been described in detail by Pinder and Gray[2]. In this study we have made use of a triangular finite element scheme, shown in Figure 3.3. We have changed from the finite difference model used in the pre-feasibility study to a finite element scheme in order to represent accurately the positions of the dolerite dykes and faults cutting the aquifer. Triangular elements also allow the concentration of model effort into those regions of the study area where water levels vary most rapidly and in areas where there is the most data. Model accuracy is therefore expected to be greatest in the area shown in Figure 3.3 where the triangular elements are smallest. The apices of the elements form the nodes of the groundwater model. Plan VIII shows the node and element numbering system for the groundwater model to the same scale as the structural maps. There are 255 nodes and 466 elements in the model, which covers an area of approximately three thousand km^2.

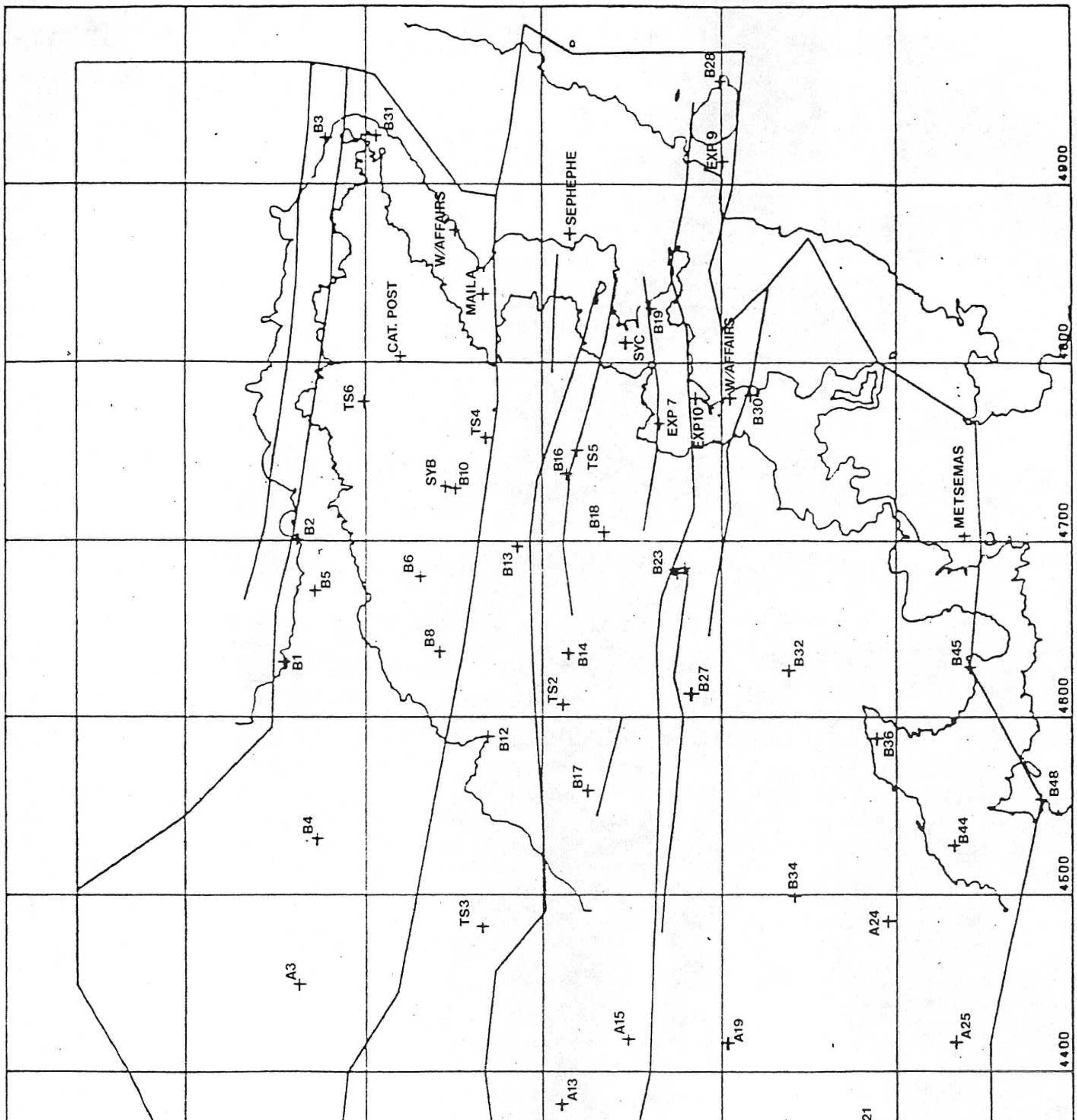
1 *Pinder, G.F. and Frind, E.O. 1972. Application of Galerkin's Procedure to Aquifer Analysis. Water Resources Research 8(1), 108-120.*

2 *Pinder, G.F. and Gray, W.G. 1977 Finite Element Simulation in Surface and Subsurface Hydrology. Academic Press, New York.*



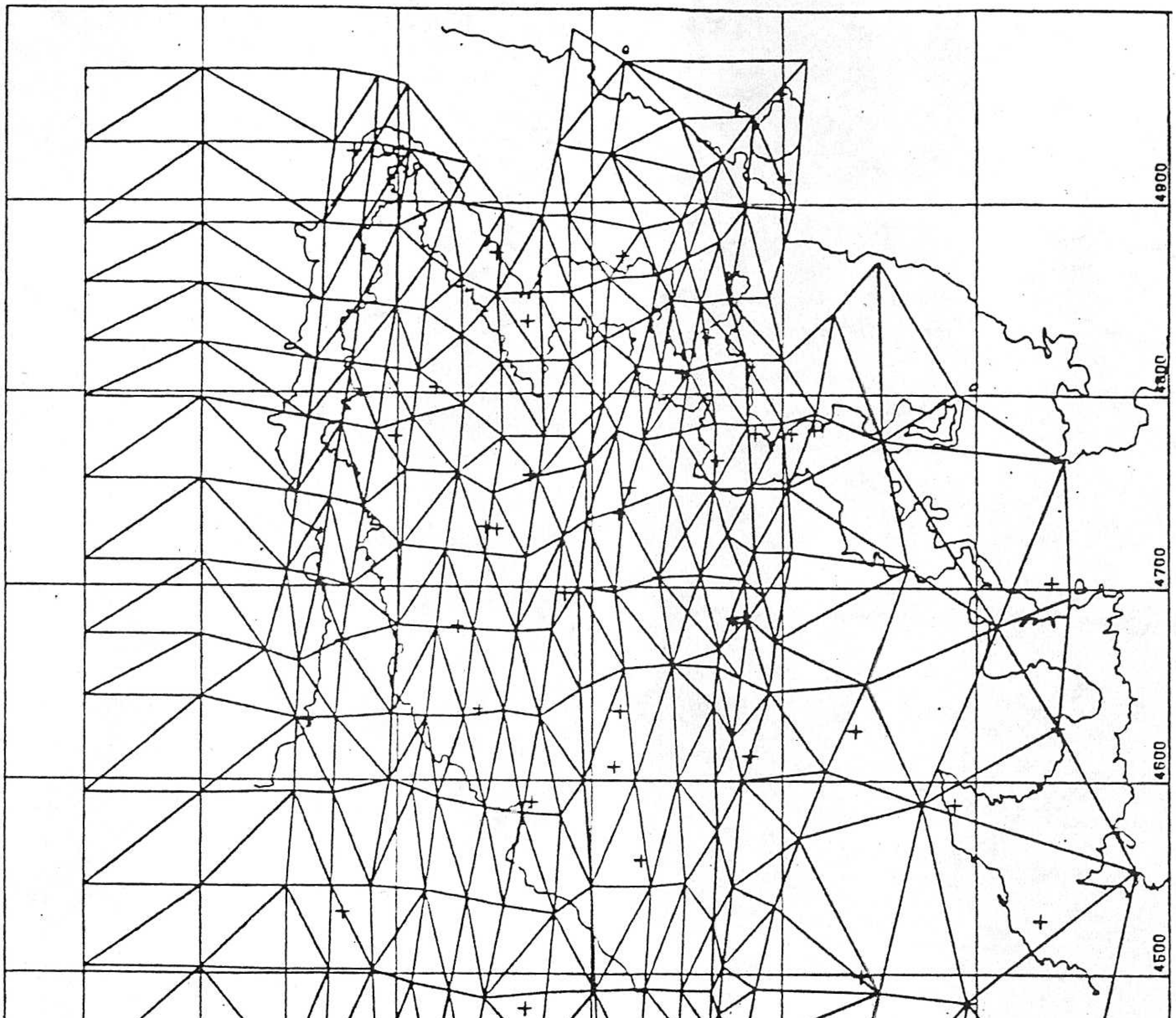
THE GROUNDWATER MODEL AREA

Figure 3·1



LOCATION OF BOREHOLES

Figure 3·2



DETAILS OF THE GROUNDWATER MODEL

Figure 3·3

3.2 Model calibration of aquifer properties

The model distributions of permeability and saturated thickness have been interpolated from the field data listed in Table 3.1 using an inverse squared weighting technique. Field values of permeability are remarkably uniform throughout the study area, except for measurements at TS2 and TS5 which were almost certainly reduced because of their proximity to major dolerite dykes. The mean permeability at the remaining sites is 0.5 m/d, and this value has been assumed to be a reasonable estimate of permeability in the vicinity of SYA, TS2 and TS5. The field values of saturated aquifer thickness vary considerably over the model area as described in section 2.2.

The aquifer transmissivity in each element of the model is the product of the average permeability and the saturated aquifer thickness. Allowance is made in the model for the decline of transmissivity with decreasing saturated thickness where the Cave Sandstone is unconfined and water levels are depressed due to pumping. The average transmissivity of the aquifer in the model area is 32 m^2/d in the unpumped state.

The effect of the dolerite dykes on the groundwater flow pattern in the aquifer is simulated in the model by reducing the transmissivity of elements bordering dykes. Only the transmissivity in a direction normal to the dykes (T_n) is affected; the transmissivity of the Cave Sandstone in a direction parallel to the dykes (T_c) is unaffected by their presence. The model representation of dykes in the finite element scheme is shown in Figure 3.4. The value of T_n is the harmonic mean of the transmissivity of the Cave Sandstone (T_c) and the transmissivity of the dyke (T_d) weighted for the differences in the width of the dyke (W_d) and the width of the element (W_e).

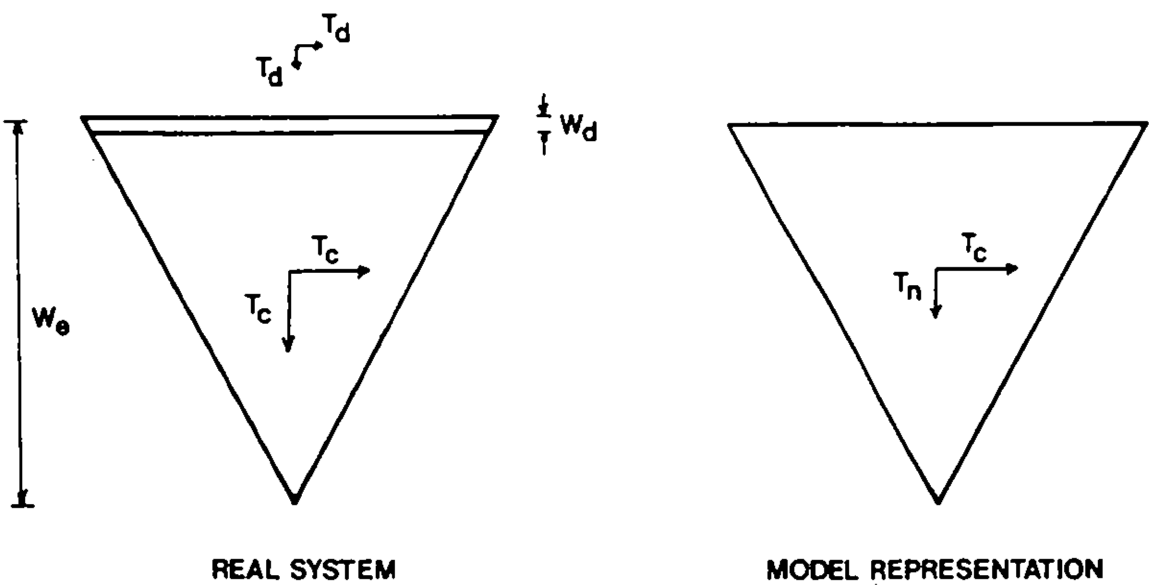
The field studies at site TS4 indicated that flow through the dolerite dyke at this site was negligible during the duration of the pumping test. The Cave Sandstone is unconfined at site TS4, and a water level difference of 12 m was observed across a dyke passing between observation wells 1 and 2, although the pumping cone of depression actually failed to intersect the dyke. Regional groundwater gradients in the Cave Sandstone are about 3 m/km in this area, and the thickness of the dyke has been estimated from our surface geophysical survey as being about 50 m thick in this locality.

TABLE 3.1

AQUIFER PROPERTIES AT TEST WELLS USED IN MODELLING STUDIES

Site	Saturated Thickness (m)	Transmissivity (m^2/d)	Permeability (m/d)	Specific Yield per cent	Confined Storage Coefficient
SYA	100			3.0	
SYB	86	41	0.47		$2.8*10^{-4}$
SYC	60	35	0.58	3.6	$3.8*10^{-4}$
TS2	62		0.11		$2.1*10^{-4}$
TS3	90	30	0.35		$3.5*10^{-4}$
TS4	54	25	0.47	2.4	$1.1*10^{-4}$
TS5	66	11	0.17		$9.7*10^{-5}$
TS6	37	26	0.70		$6.7*10^{-4}$
EX7	59				
EX9	54				
EX10	60				

* Note. The aquifer parameters listed here differ from the individual site results. We have derived these values by inspection of the test results taking into account various hydrogeological constraints.



W_d	Width of Dyke
W_e	Width of Element
T_c	Transmissivty of Cave Sandstone
T_d	Transmissivity of Dolerite Dyke
T_n	Weighted Harmonic Mean Transmissivity of Dyke and Cave Sandstone

MODEL REPRESENTATION OF DYKES

Figure 3·4

From this information we can estimate the ratio of the transmissivity of the dyke and the Cave Sandstone aquifer. Since water is conserved, in the steady state

$$T_d \quad \frac{\Delta h}{\Delta x}\bigg|_d \qquad\qquad T_c \quad \frac{\Delta h}{\Delta x}\bigg|_c \qquad\qquad 3.1$$

where T is the transmissivity, $\frac{\Delta h}{\Delta x}$ is the groundwater gradient, and the subscripts d and c refer to the dyke and the Cave Sandstone respectively. Thus

$$\frac{T_d}{T_c} \qquad \frac{3}{1000} * \frac{50}{12} \qquad 10^{-2} \qquad\qquad 3.2$$

Since T_c is known from field measurements, the ratio given in equation 3.2 gives the maximum realistic value of dyke transmissivity at site TS4. We have no other information with which to quantify the overall effect of the dykes on the groundwater system and we have therefore taken this value to be typical of the aquifer as a whole. Since the average transmissivity of the Cave Sandstone is 32 m^2/d, the model value of dyke transmissivity has been taken as 0.3 m^2/d.

There is considerable indirect field evidence from the area of Cave Sandstone outcrop to support our hypothesis of non-zero transmissivity of the dolerite dykes when they are considered in the regional context. At outcrop the dykes are fractured and often discontinuous along part of their lengths. This effect is shown by the dyke which runs east-west along the south side of Tebele hill where the dyke thickens from about 5 m thick to more than 15 m thick within a distance of less than a kilometre. The dyke forming the north side of Tebele hill is particularly thick, probably about 100 m, but can only be traced for about a kilometre. Most of the other major dykes observed were about 10 m thick, and this figure has been applied to all the dykes shown in Figure 3.1 which are incorporated into the model.

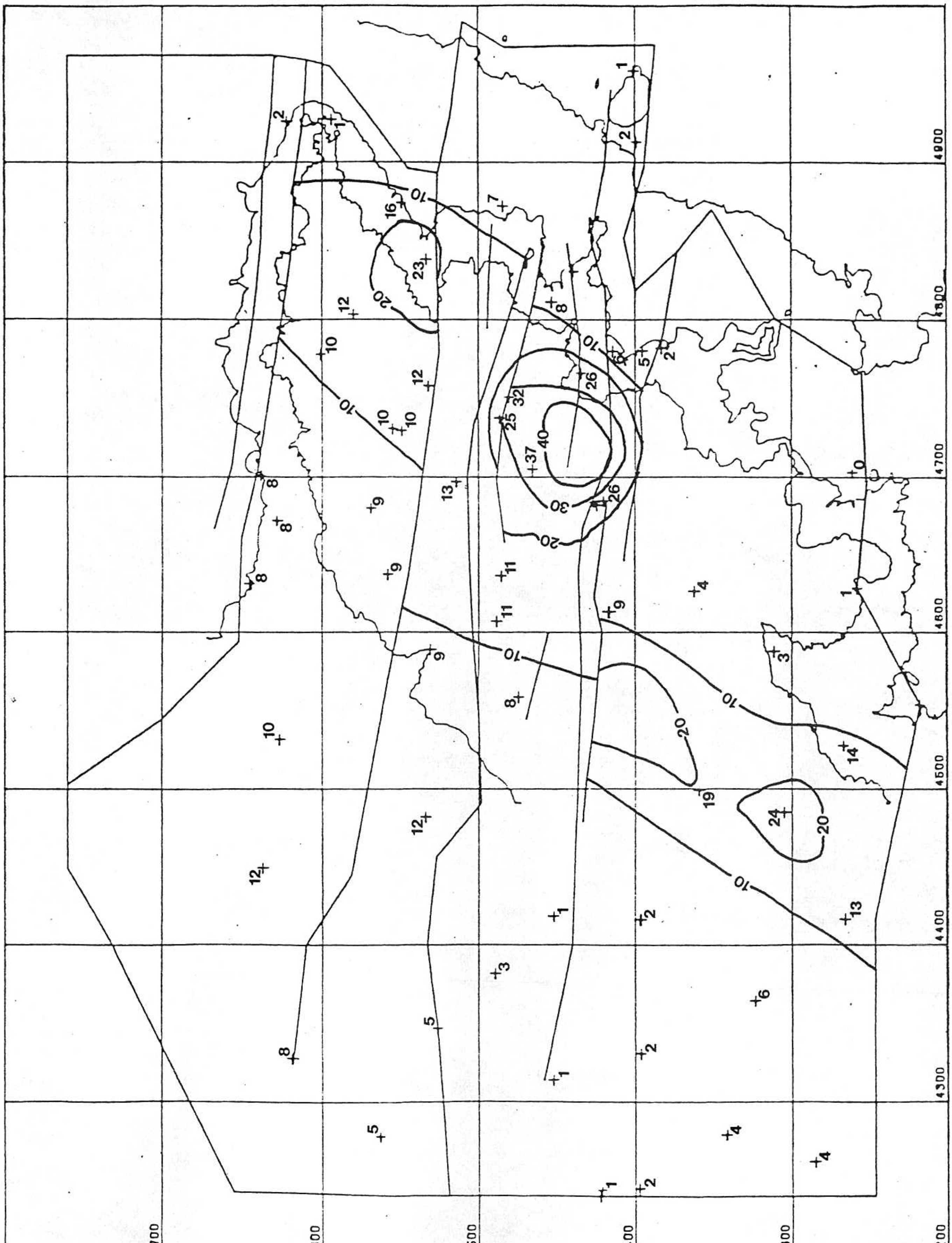
The specific yield of the Cave Sandstone is 3.0 per cent at site SYA, 3.6 per cent at site SYC and 2.4 per cent at TS4. These data are not sufficient for reliable conclusions to be drawn about the areal variations in specific yield, and a value of 3 per cent has been assumed to apply to the whole area of the groundwater model. These field values are relatively low for a poorly consolidated sandstone such as the Cave Sandstone, and it is possible that the low transmissivity of the aquifer extends the effects of gravity drainage of the saturated pores of the rock beyond the period of 32 days of the pumping tests. If this further drainage does take place then the model predictions of regional drawdown due to long-term pumping will be overestimates.

Field values of confined storage coefficient are shown in Table 3.1 These values also show no significant areal variation, and a value of 0.02 per cent has been assigned to the complete model area.

3.3 Evidence for Natural Groundwater Recharge to the Cave Sandstone aquifer

Many workers, particularly those involved in field surveys, have suggested that natural groundwater recharge is negligible in this part of Botswana. As a result the water in the Cave Sandstone has often been considered to be "fossil" groundwater derived from precipitation during previous, wetter, geological time periods. However, the strong correlation between the groundwater hydrograph observed at Serwe pan (borehole B23) and the measurements of daily rainfall at Serowe suggests that significant natural recharge is infiltrating to the aquifer in this area. The groundwater model is able to confirm this hypothesis by showing that the present pattern of groundwater level contours, shown in Plan IV, would fall relatively rapidly if no recharge were to take place.

Figure 3.5 shows the computed drop in water levels that may be expected to occur if no recharge were to take place for 25 years. The maximum fall in levels would be more than 30 m in the area of Serwe Pan, where there is a major groundwater mound and the Cave Sandstone aquifer is confined by the overlying Drakensberg basalt. The computed decline in the unconfined groundwater levels would be less rapid, due to the difference in the storage coefficient, and water levels in the escarpment area would probably fall by several metres per decade. This fall would become significant over historical time, and the results of the model simulation suggest that the bulk of the Cave Sandstone would have been dewatered by the natural movement of groundwater during the time since the last wet climatic period if no natural recharge had taken place. Since the Cave Sandstone is still largely fully saturated where it is overlain by basalt, we conclude that natural recharge is taking place.



PREDICTED DECLINE OF WATER LEVELS (m) DURING A PERIOD OF 25 YEARS WITH NO RECHARGE (contour interval 10m)

Figure 3·5

3.4 Model Calibration of Recharge

Field investigations to determine the magnitude and extent of natural groundwater recharge to aquifers in arid regions are difficult to undertake and often give unreliable results when they are used to calculate the volumes of recharge over large areas. They have, therefore, not been attempted in this study. Instead, the amount and areal distribution of natural groundwater recharge has been determined using a new method developed during the course of this study.

In order to calculate the amount of recharge to the aquifer the model is divided into a number of subareas in which uniform recharge is believed to be taking place. Areas of evaporation and groundwaterloss are also included in the model subdivision, as well as model boundaries where water is leaving (or entering) the model area. For each subarea in turn, the model computes the groundwater head distribution that would result from a recharge of unity being applied to that subarea, while everywhere else received no recharge. The computed head distributions are then combined so that the final groundwater head distribution minimises the sum of the squares of the errors in the computed water levels at data points. The proportion of each of the different head distributions in the final least squares solution gives the amount of net recharge to each subregion. This technique, involving the decomposition of the problem into a number of smaller problems, is similar to that used by Cooley[1] and Birtles and Morel[2].

The 64 water level observations that have been used to calibrate the groundwater recharge are shown in Figure 3.6 and are listed in Table 3.2. The reliability of the measurements at the different data points has been included in the least squares solution by assigning a weighting parameter to each of the observations. Water level measurements during this study were made during a relatively short period of time in comparison with those collected by Cheney, some of which may also have been affected by pumping. We have therefore assigned a relative weighting factor of ten to the variance of the observations made in our study compared to those collected by Cheney. This gives a relative weight of 3.1 (= $\sqrt{10}$) for any one of our observations.

1 *Cooley, R.L. 1977 A method of estimating parameters and assessing reliability models of steady state groundwater flow, 1, Theory and numerical properties. Water Resources Research, 13(2), 318-324.*

2 *Birtles, A.B., and Morel, E.H. 1979 Calculation of Aquifer Parameters from Sparse Data. Water Resources Research, 15(4), 832-844.*

TABLE 3.2

COMPARISON OF OBSERVED AND CALCULATED WATER LEVELS AT DATA POINTS

Key:

OBS H = Observed water level

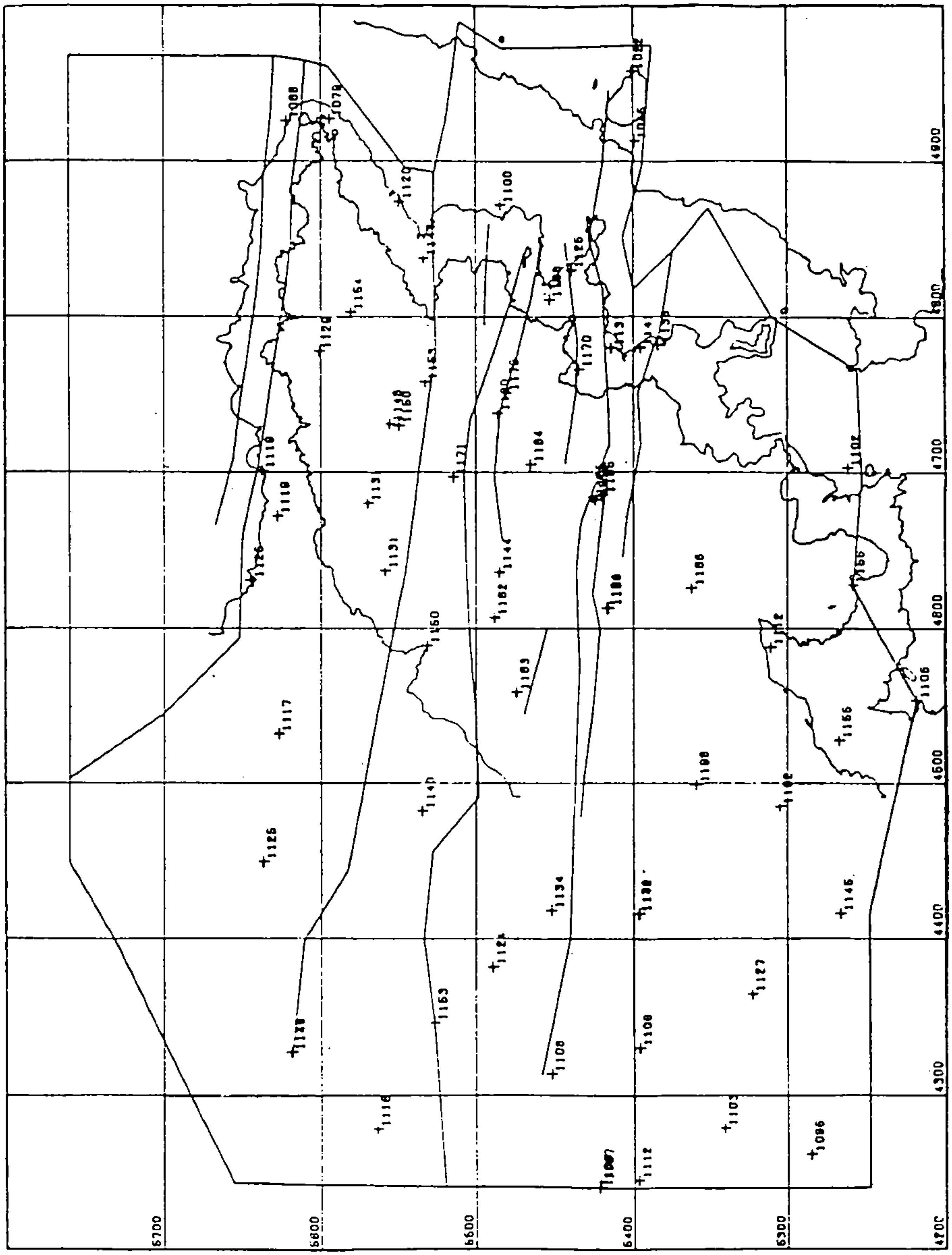
EST H = Calculated water level

ERROR = OBS H - EST H

WEIGHT = weighting parameter in model calibrations

W ERROR = weighted error

GRID	REF	OBS H	EST H	ERROR	WEIGHT	* ERROR	
4244.	5421.	1096.83	1101.59	-4.76	3.93	-9.42	SYA/PW
4731.	5555.	1147.70	1145.76	1.94	3.93	3.85	SYB/PW
4811.	5453.	1137.80	1138.74	-.94	3.93	-1.87	SYC/PW
4607.	5488.	1161.77	1161.61	.16	3.92	.32	TS2/PW2
4482.	5534.	1139.63	1144.29	-4.66	3.93	-9.23	TS3/PW
4758.	5532.	1153.02	1153.28	-.26	3.93	-.52	TS4/PW
4751.	5480.	1178.96	1180.50	-1.54	3.93	-3.04	TS5/PW
4778.	5601.	1128.52	1130.03	-1.51	3.93	-2.99	TS6/PW
4766.	5434.	1169.80	1166.51	3.29	3.93	6.51	EX7
4913.	5399.	1045.79	1045.09	.70	3.93	1.38	EX9
4760.	5414.	1131.47	1133.15	-1.68	3.93	-3.33	EX10
4838.	5523.	1147.00	1147.38	-.38	.39	-.24	MAILA WE
4872.	5484.	1100.00	1096.98	3.02	.39	1.89	SEPHEPHE
4780.	5395.	1140.95	1131.46	9.49	.39	5.95	WATER AF
4874.	5549.	1120.00	1120.76	-.76	.39	-.47	WATER AF
4803.	5580.	1154.00	1138.86	15.14	.39	9.49	CATTLE P.
4245.	5397.	1112.05	1101.23	10.82	.39	6.78	A40
4240.	5422.	1099.88	1100.82	-.94	.39	-.59	A58
4262.	5285.	1096.11	1099.32	-3.21	.39	-2.01	A47
4276.	5563.	1116.14	1104.22	11.92	.39	7.47	A7
4279.	5341.	1103.16	1106.77	-3.61	.39	-2.26	A20
4314.	5452.	1108.03	1114.24	-6.21	.39	-3.89	A35
4328.	5618.	1143.02	1109.20	33.82	.39	21.19	A4
4328.	5619.	1126.18	1108.45	17.73	.39	11.11	A5
4331.	5396.	1106.25	1118.35	-12.10	.39	-7.58	A59
4347.	5526.	1152.57	1119.18	33.39	.39	20.92	A8
4365.	5323.	1126.60	1123.84	2.76	.39	1.73	A21
4382.	5489.	1124.00	1129.04	-5.04	.39	-3.16	A13
4416.	5266.	1145.40	1132.84	12.56	.39	7.87	A25
4416.	5396.	1142.13	1142.49	-.36	.39	-.22	A19
4416.	5397.	1138.75	1142.46	-3.71	.39	-2.33	A54
4418.	5452.	1134.49	1139.91	-5.42	.39	-3.40	A15
4449.	5637.	1124.90	1119.93	4.97	.39	3.12	A3
4488.	5305.	1192.37	1166.91	25.46	.39	15.96	A24
4499.	5359.	1197.50	1182.81	14.69	.39	9.20	B34
4528.	5267.	1154.70	1146.31	8.39	.39	5.26	B44
4532.	5627.	1117.00	1124.03	-7.03	.39	-4.40	B4
4554.	5218.	1105.70	1124.94	-19.24	.39	-12.05	B48
4559.	5474.	1163.20	1160.33	2.87	.39	1.80	B17
4568.	5311.	1111.60	1150.35	-38.75	.39	-24.28	B36
4589.	5531.	1150.20	1148.25	1.95	.39	1.22	B12
4613.	5416.	1158.20	1171.10	-12.90	.39	-8.09	B27
4613.	5417.	1164.30	1171.11	-6.81	.39	-4.27	B53
4626.	5362.	1165.80	1160.28	5.52	.39	3.46	B32
4628.	5258.	1155.80	1120.38	35.42	.39	22.19	B45
4631.	5645.	1126.04	1119.70	6.34	.39	3.97	B1
4636.	5485.	1144.10	1158.90	-14.80	.39	-9.27	B14
4637.	5558.	1131.00	1141.57	-10.57	.39	-6.62	B8
4672.	5628.	1118.70	1124.08	-5.38	.39	-3.37	B5
4680.	5569.	1131.10	1140.11	-9.01	.39	-5.65	B6
4682.	5624.	1188.50	1177.80	10.70	.39	6.70	B25
4684.	5428.	1184.50	1180.64	3.86	.39	2.42	B23
4685.	5420.	1185.90	1176.00	9.90	.39	6.20	B26
4697.	5514.	1171.20	1159.74	11.46	.39	7.18	B13
4701.	5638.	1119.10	1120.61	-1.51	.39	-.54	B2
4705.	[illegible]	1184.10	1189.94	-5.84	.39	-3.66	B18
4730.	5549.	1150.30	1147.46	2.84	.39	1.78	B10
4734.	5466.	1159.7[illegible]	1175.61	-15.91	.39	-9.97	B16
4782.	5393.	1129.50	1131.76	3.76	.39	2.36	B30
4763.	5281.	1102.80	[illegible]	-9.99	.39	-6.26	METSEMAS
4831.	5439.	1124.30	1123.00	1.62	.39	1.02	B19
4926.	5622.	1068.20	1071.74	-3.54	.39	-2.22	B3
[illegible]27.	5596.	1078.80	1074.70	4.10	.39	2.57	B31
[illegible]	5401.	1122.80	[illegible]29.25	-6.89	.39	-4.32	B28



GROUNDWATER LEVELS AT DATA POINTS

m above Ordnance Datum

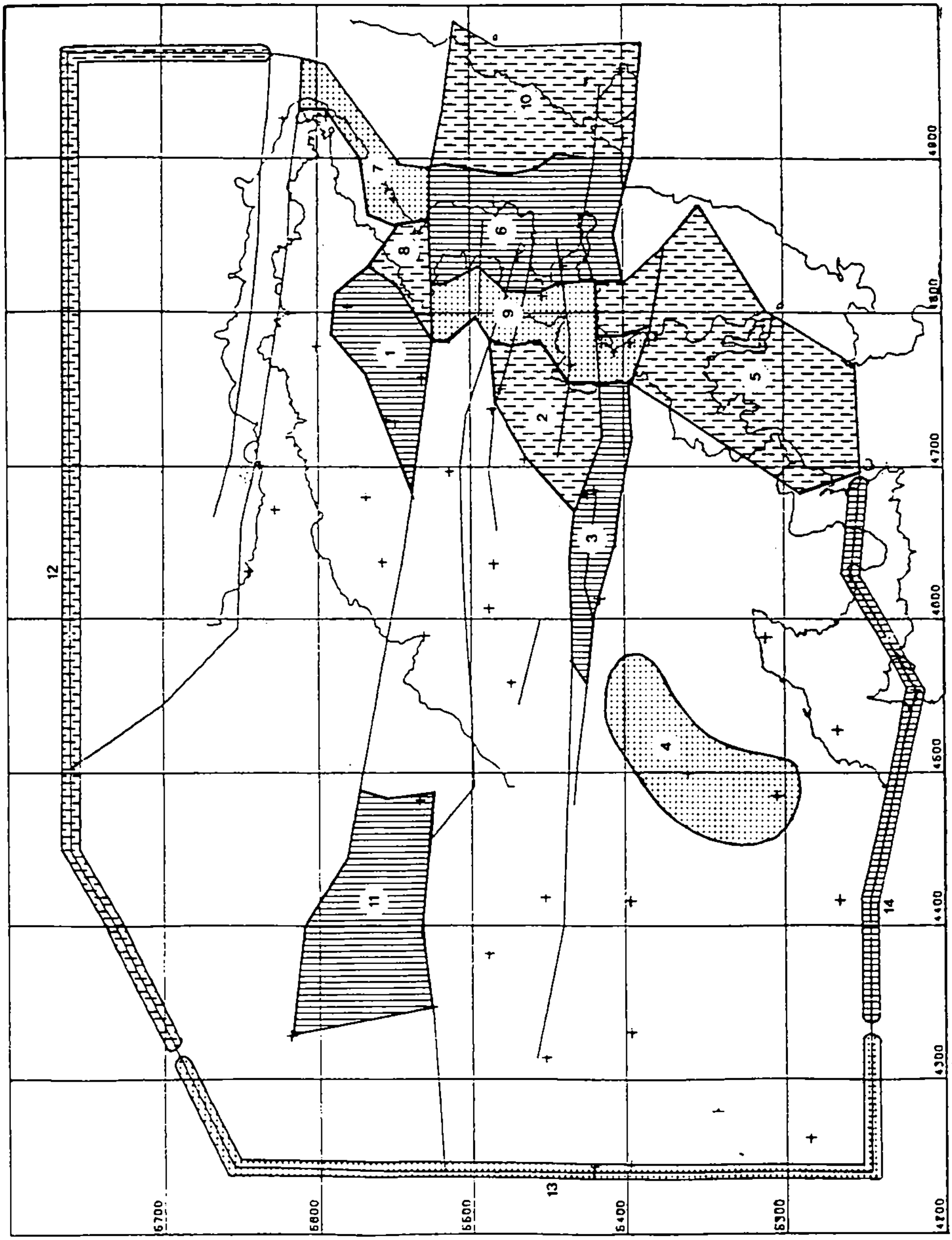
Figure 3·6

The number of subdivisions in the model depends largely on the quality of the groundwater level data, and on the modellers' knowledge of the areal variations in aquifer transmissivity. In the Morupule Cave Sandstone aquifer we have chosen 14 subareas, shown in Figure 3.7, including the three model flow boundaries. Each of the subareas numbered 1 to 11 shown in Figure 3.7 consists of several model elements. Subareas 12 to 14 consist of lines of nodes along the model boundaries. The net recharge or discharge to the remainder of the model area is assumed to be negligible. The computed recharge (+ ve) or discharge (- ve) to the 14 subareas is listed in Table 3.3, and the computed groundwater heads at data points are listed in Table 3.2. Figure 3.8 shows the interpolated groundwater head distribution in the Cave Sandstone aquifer, and the error at each data point.

The overall accuracy of the model is described by the root mean square error between the calculated and observed water levels at data points corrected for the number of degrees of freedom (which is equal to the number of data points minus the number of subareas). The root mean square error (s) for all data points is 10.9 m. The range of groundwater levels (Δh) in the water level data in the model area is 177 m, so that the value of $s/\Delta h$ is about 6 per cent. The root mean square error at the test sites drilled in this study is, however, much smaller ($s = 2.6$ m), and the corresponding value of Δh is 133 m, so that the value of $s/\Delta h$ is about 2 per cent. This value may be compared with a value of $s/\Delta h$ of about 1 per cent which Cooley and Sinclair[1] obtained for their model of the Truckee Meadows alluvial aquifer of Nevada, where Δh was about 400 m and s about 4 m. It is worth noting in this context that the storage coefficient of the Cave Sandstone is much less than is generally the case for alluvial aquifers so that the volumes of water involved in the error are proportionally smaller in this study.

The largest errors in the computed heads in the model occur in boreholes located in the south and west of the study area where the model mesh is coarsest. The main reason for these errors, apart from errors in the data, is that in these areas large differences in groundwater level occur within short distances, which the model is unable to resolve owing to the linearisation of the head distribution between the nodes of the finite element grid. In order to simulate more accurately the water level at each borehole in these areas,

[1] *Cooley, R.L. and Sinclair, P.J. 1976. Uniqueness of a model steady-state groundwater flow. Journal of Hydrology, 31, 245-269*



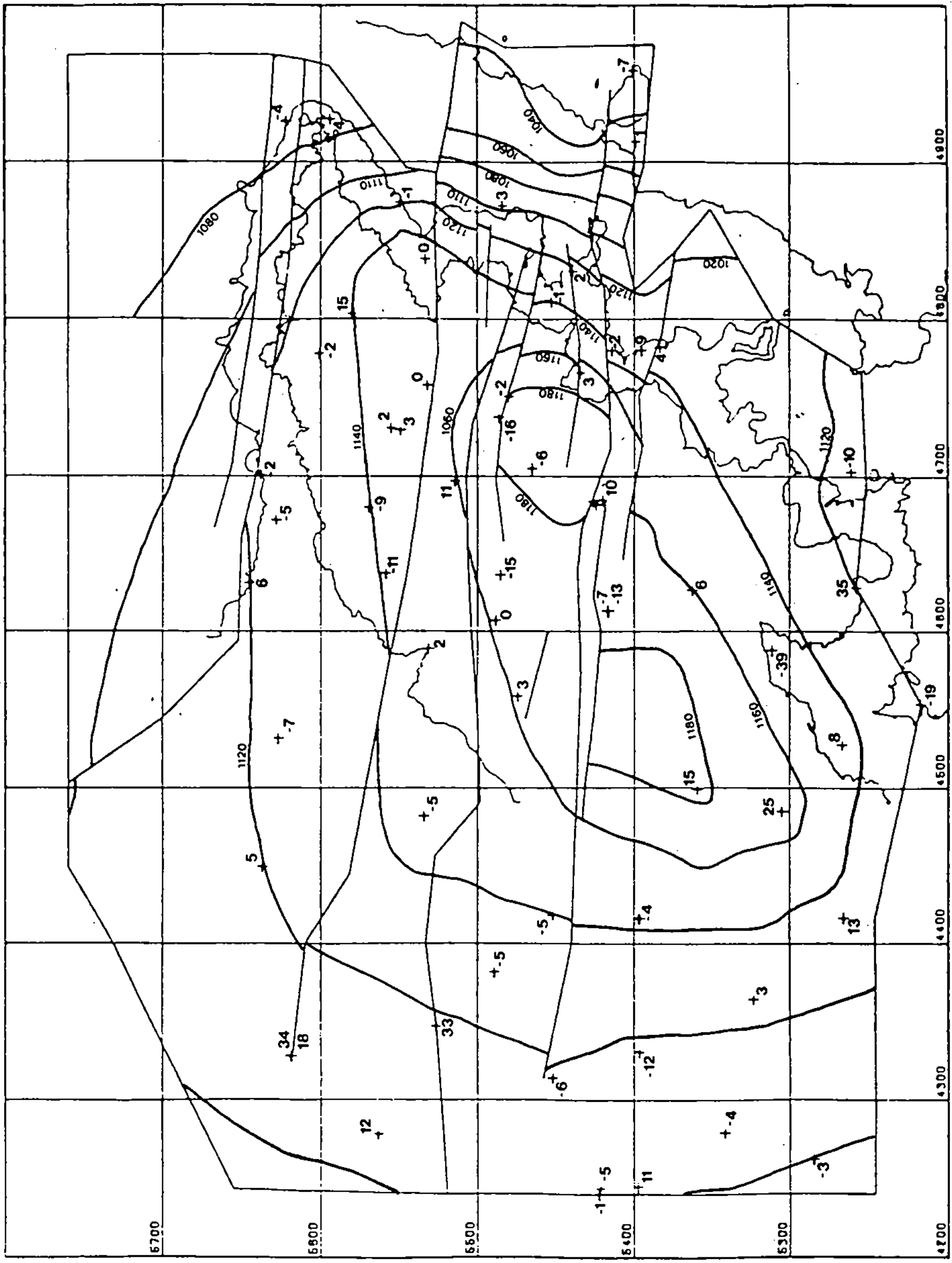
SUBAREAS RECEIVING NET RECHARGE

Figure 3·7

TABLE 3.3

COMPUTED NET RECHARGE TO THE CAVE SANDSTONE AQUIFER

Subregion	Area	Net Recharge	
	(km^2)	($10^3 m^3/d$)	(mm/year)
1. Northern Pans	50	0.3	2
2. Serwe	48	6.9	53
3.	39	- 0.7	- 7
4. Mahatana	100	7.5	70
5.	160	- 2.0	5
6.	95	3.2	12
7.	36	- 2.2	23
8. Maila	18	5.4	109
9.	56	1.3	9
10.	105	5.6	19
11.	105	1.4	
12. Northern boundary		- 4.6	
13. Western boundary		3.4	
14. Southern boundary		- 4.6	



INTERPOLATED GROUNDWATER HEADS AND ERRORS AT DATA POINTS (contour interval 20m)

Figure 3·8

the model would require a rather finer mesh size. However, as the calibration procedure used to calculate the recharge distribution obtains a least squares solution to the observed groundwater levels the method has the advantage that the model reproduces the average spatial behaviour of the aquifer and therefore reduces the need for a smaller mesh in areas distant from potential wellfield sites.

The computed net recharge to each of the subregions is listed in Table 3.3. The principal areas receiving significant natural groundwater recharge are the area located to the north east of Serwe Pan (subregion 2), the area to the north west of Maila (subregion 8), and the upthrown block of Cave Sandstone situated near Mahatana in the south of the model area (subregion 4). The amount of recharge to the area north of Maila (subregion 8) has probably been overestimated at the expense of underestimating recharge to the area of northern Pans (subregion 1) but the sparse water level data in this area are not sufficient to be able to resolve this difference. The boundary flows out of the model are small, and equal about 75 m^3/d/km in the north and west of the area. The total net recharge of 120 m^3/d represents the computed spring flow at Paje.

The most important result obtained from the model calibration studies is the demonstration that natural recharge is reaching the aquifer. The values of net recharge listed in Table 3.3, are, however, small relative to the average annual rainfall which was 462 mm/year at Serowe during the time period 1922-79. Rainfall during the last decade has been wetter than average, more than 500 mm/year, so that the net recharge to the Serwe recharge area represents only 10 per cent of the annual rainfall. The total computed recharge to the aquifer is approximately 25 thousand m^3/d, which represents an annual infiltration rate of about 3 mm/year over the whole of the model study area.

The mechanism by which the Cave Sandstone is recharged by natural infiltration is not exactly clear in the areas where the aquifer is covered by basalt. Mazor et al suggested that leakage of groundwater between a thin unconfined aquifer at the base of the Kalahari Beds and the Cave Sandstone took place via interconnected cracks and fissures in the basalt. This leakage would result in smaller drawdowns being observed during pumping tests than would be expected for fully confined conditions. The results of our analysis of the pumping tests at site SYB indicate that the maximum permeability of the basalt is about 10^{-3} m/d in this vicinity. This value is similar to that obtained from a regional appraisal of water level contours in the Serwe recharge area: The average computed groundwater leakage Q to an aquifer of area A is given by

$$Q \approx A K' \frac{\Delta h}{\Delta z} \qquad 3.3$$

where K' is the permeability of the basalt, Δh is the head difference between the Kalahari and Cave Sandstone groundwater systems, and Δz is the thickness of basalt. A typical value of Δz is about 50 m in the Serwe area, and water levels in the Cave Sandstone are about 2 m below those in the Kalahari Beds, so substitution of the results for subregion 2 listed in Table 3.3 gives

$$K' \approx \frac{6900\ m^3/d}{48\ km^2} * \frac{50\ m}{2\ m} \approx 3x10^{-3}\ m/d \qquad 3.4$$

which is the same order of magnitude as the value of K' observed at site SYB.

The above discussion suggests that sufficient leakage of groundwater could take place through the basalt to maintain the observed groundwater head distribution in the Cave Sandstone aquifer. We therefore accept the model calibration of groundwater recharge as being realistic.

CHAPTER 4

WELLFIELD LOCATION AND MANAGEMENT

4.1 Model Objectives

The groundwater model described in the previous chapter is now used to determine the drawdown in each node corresponding to any given pattern of abstractions. By optimising the magnitude and location of the abstractions it is possible to minimise the size of the wellfields required to meet the projected demand while maintaining water levels in the production boreholes at practicable levels. The main constraint on wellfield design is that excessive drawdowns may be experienced in pumping boreholes even though the draught on regional groundwater storage may be relatively small.

Initial model studies have indicated that the potential long-term safe yeild of the Cave Sandstone aquifer, which depends solely on the natural groundwater recharge and aquifer transmissivity, is very limited, and is almost certainly less than 1000 m^3/d from the whole of the model study area. This result confirms our previous assertion that the demand for water at Morupule will have to be met by "mining" the groundwater storage in the aquifer. The rest of this chapter describes how the projected demand till the year 2010 can be met.

The amount of groundwater released from storage depends on the storage coefficient of the aquifer. The unconfined storage coefficient of the Cave Sandstone (3 per cent) is more than a hundred times greater than the confined storage coefficient (0.02 per cent). Thus a metre drop in groundwater head over an area of 1 km^2 would release 30000 m^3 from the unconfined aquifer but only 200 m^3 from the confined aquifer. The major resource of groundwater therefore lies in the saturated thickness of the Cave Sandstone, and the optimisation procedure which we have adopted is designed to make the best use of the available unconfined storage in the aquifer.

In order to be able to make predictions of wellfield behaviour, the groundwater model is simplified in the optimisation procedure. Firstly, it is assumed that the demand for water will be constant from the start of the scheme in 1986 until 2010, a period of 24 years. Secondly, the confined storage in the aquifer is assumed to be negligible compared to the unconfined storage. These simplifications lead to overestimation of the drawdown in the aquifer, and the optimisation model forms a conservative basis for the management studies. After the optimisation model has been run, a "time varying simulation" is carried out to show the way in which the groundwater level drawdown may be expected to develop within the time span under consideration in this study, and to provide data with which the model can be checked as yields are developed.

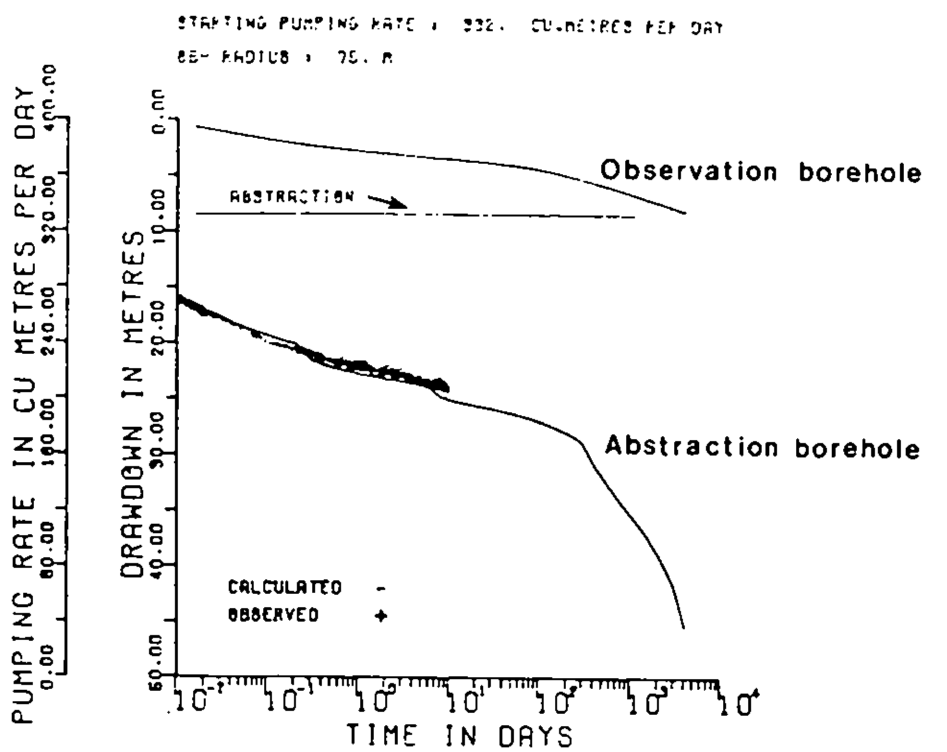
4.2 Constraints on wellfield yield

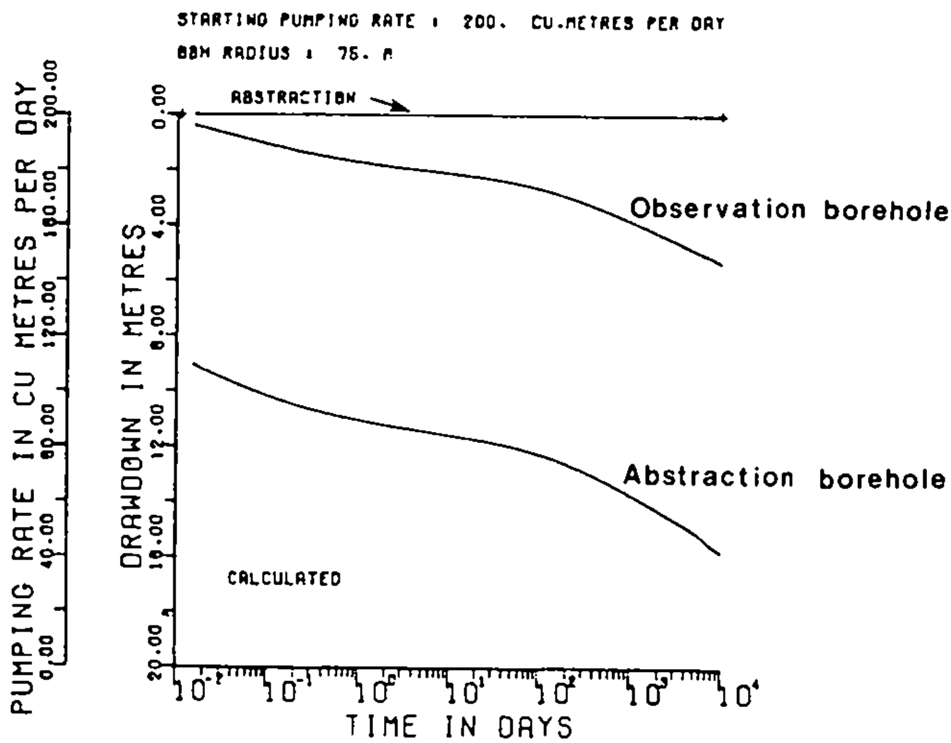
Before discussing the potential of the Cave Sandstone for large scale regional groundwater developments, it is useful to consider the likely effects of long-term pumping from a single unconfined abstraction borehole. This analysis will enable us to determine the maximum regional drawdown that may be developed by a reasonable number of abstraction boreholes without producing excessive drawdown in the pumped boreholes. For this purpose we will consider the behaviour of the abstraction borehole at test site TS4, a typical test well in the unconfined Cave Sandstone aquifer.

The results of the geophysical logging and analysis of the step test carried out during our field investigations indicate that the effective thickness of the aquifer at TS4 is about 50 m, and that the permeability of the Cave Sandstone decreases gradually with depth from about 0.5 m/d to 0.35 m/d. Figure 4.1A shows the groundwater drawdown observed during the constant rate test at TS4, and the model prediction of subsequent drawdown if the pumping were to be continued indefinitely at 332 m^3/d. The extended curve is, in fact, hypothetical as barrier effects have not been included in the analysis, but it indicates that water levels would decline relatively rapidly after about a year's operation due to the decline of transmissivity with decreasing saturated aquifer thickness, and that pump suction would be reached after about ten years. The results shown in Figure 4.1A suggest that abstractions from boreholes in the wellfields proposed in this study will probably have to be less than 330 m^3/d, and Figure 4.1B shows the predicted drawdown during 10^4 days' (27 years) hypothetical pumping at TS4 at a rate of 200 m^3/d. Breakaway conditions are not predicted at this abstraction rate, and the final drawdown in an observation well located 75 m from the pumped well would be about 6 metres.

The actual drawdown experienced in an abstraction borehole pumping in a productive wellfield is the sum of the drawdown due to pumping from that borehole and the combined interference effects of all the other boreholes.

A





B

GROUNDWATER DRAWDOWN AT TEST SITE TS4

Figure 4·1

If the drawdown in the abstraction borehole, all other effects excluded, is 16 m after 24 years' operation, taken from Figure 4.1B then assuming a regional aquifer thickness of about 50 m, and a safety factor of 10 m to allow also for the pump equipment leaves a net exploitable regional drawdown of about 25 m. Management schemes which would lead to greater regional drawdowns have been rejected because they would probably lead to excessive drawdowns being developed in the abstraction boreholes.

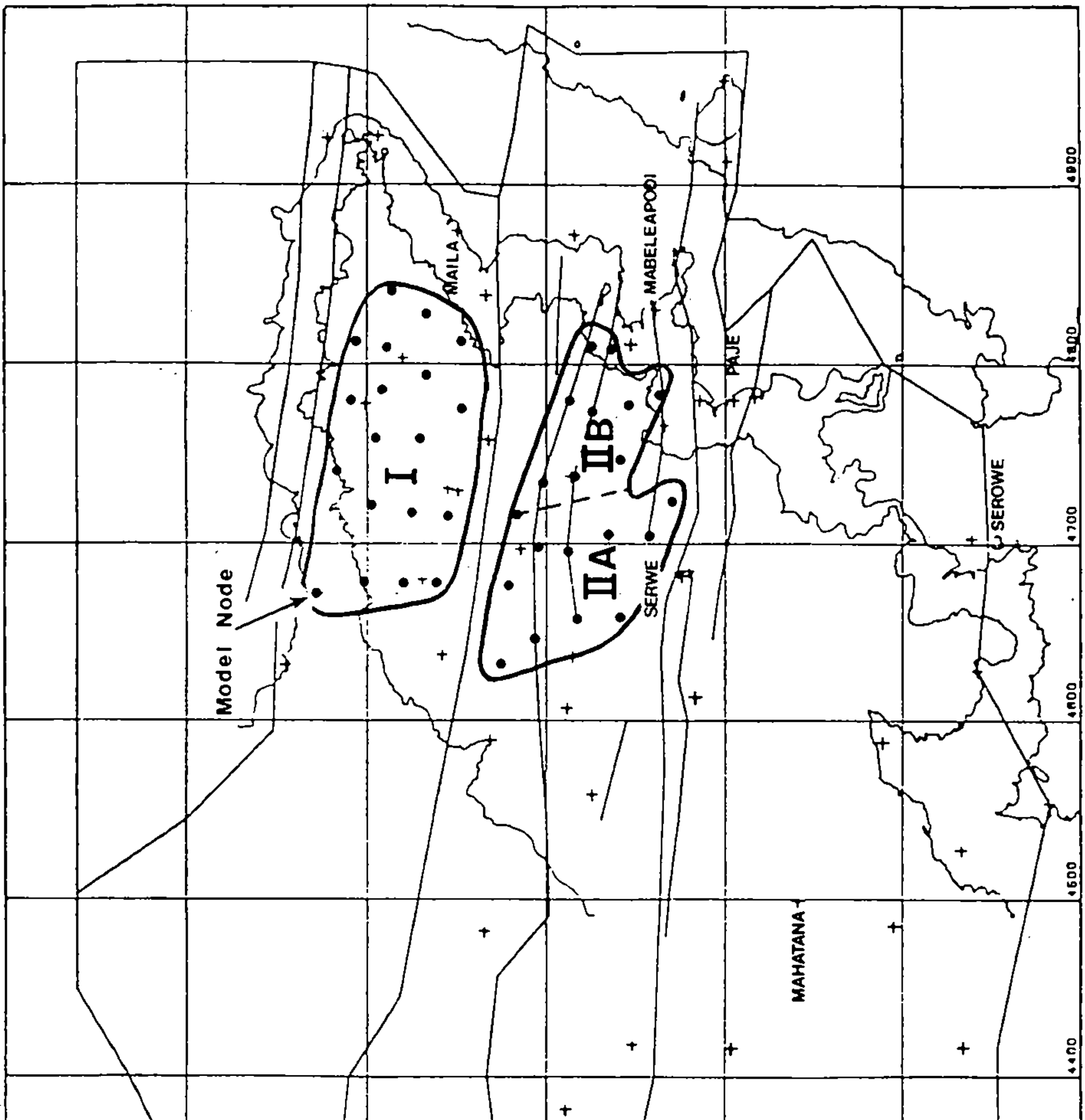
4.3 Suggested management strategy

The demand for water for wet cooling at Morupule will be about 20000 m^3/d in the year 2010. This figure has been obtained by extending the estimated demands listed in Table 2.6 of the Pre-feasibility Report (1979). Since each production borehole will support an abstraction rate of about 200 m^3/d, approximately 100 production boreholes will be required to meet the demand in 2010.

The best wellfield design is the one which minimises the cost of water at Morupule. Pipeline costs form a major part of the capital costs of large scale groundwater developments such as the proposed scheme, and the best potential wellfield locations would appear to be those closest to the demand. The unconfined Cave Sandstone in the outcrop area is closest to Morupule, but has been rejected as a potential source of water as the field surveys have indicated that the saturated thickness of aquifer is too small to be able to support large-scale abstractions. Instead, we have concentrated our management investigations into the area north east of Maila, and the area north of Serwe Pan. These areas, shown as potential wellfields I and II in Figure 4.2A,are at present confined, so that the full sequence of Cave Sandstone is at present saturated with groundwater. Figure 4.2A also shows the model nodes at which groundwater abstraction has been assumed to take place. Each wellfield covers an area of about 100 km^2.

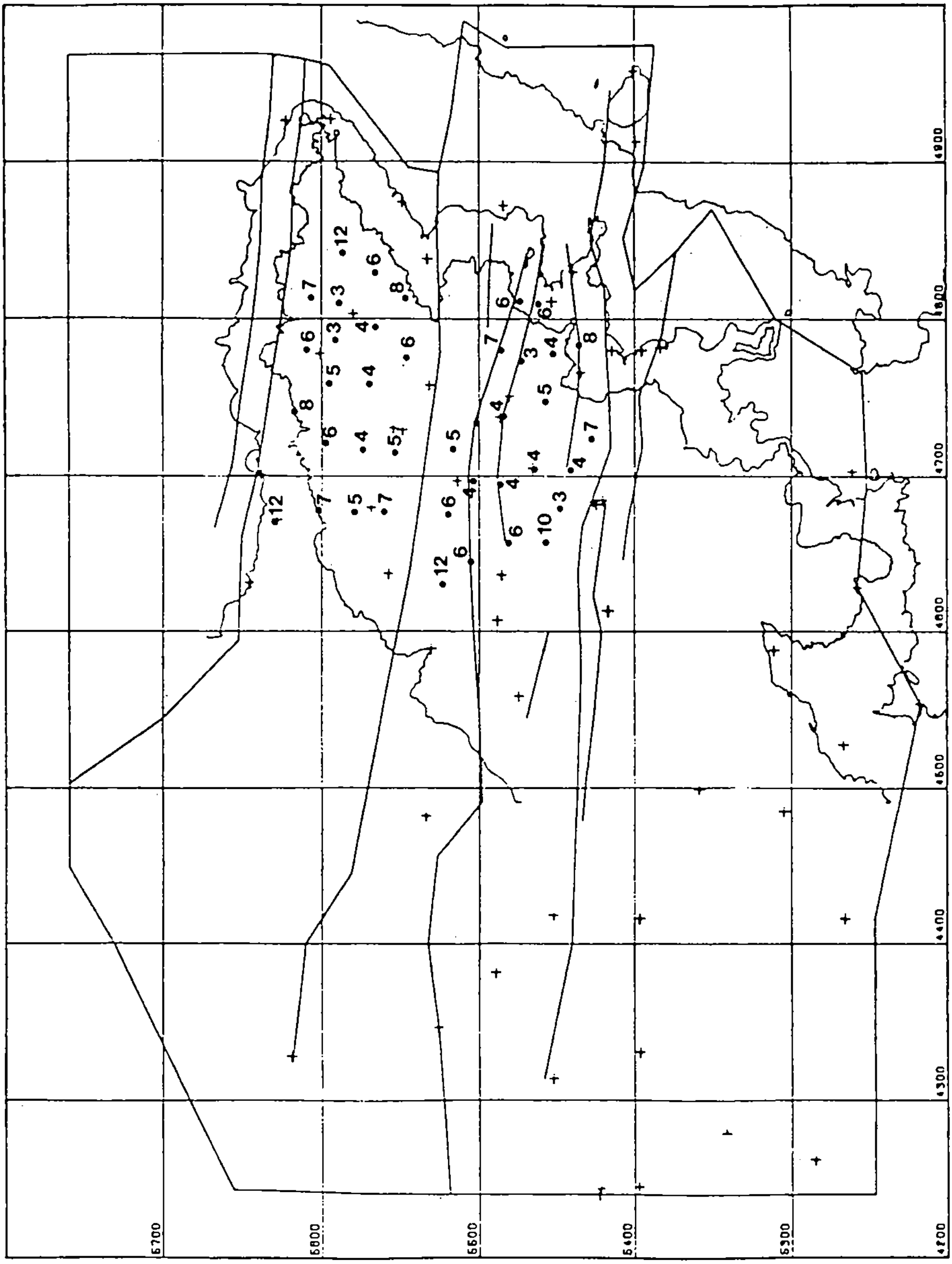
Initially, we make use of a theoretical, linear programming, method to determine the maximum abstraction that could be sustained from each node representing the two wellfields during the period 1986 to 2010. The computed maximum yield of each wellfield is about 12000 m^3/d, and the total yield would be 24000 m^3/d over the 24 year period.

Figure 4.2B shows the nodal abstraction rate computed by the linear programming procedure. The abstraction rates are generally greatest for nodes



POTENTIAL WELLFIELD LOCATIONS

Figure 4·2A



NODAL PUMPING RATES

[100 m^3/d]

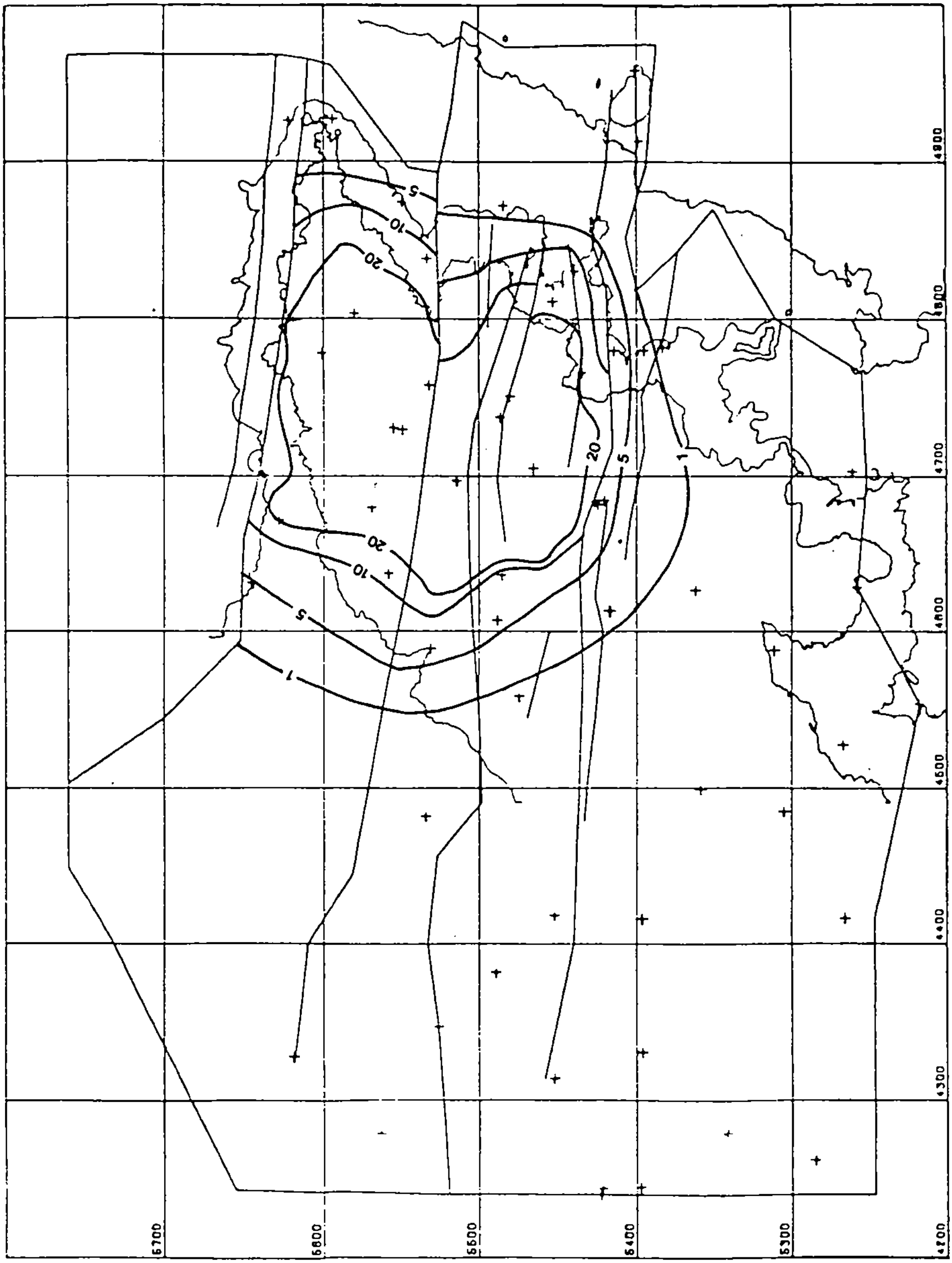
Figure 4.2B

located at the apices of relatively large model elements, since these elements represent larger volumes of groundwater storage. The average nodal abstraction rate, corrected for the size of the elements, is about 120 $m^3/d/km^2$. This figure implies that the production boreholes comprising the proposed wellfields will have to be separated from each other by about 1.3 km if each borehole is to maintain a yield of 200 m^3/d for 24 years.

Figure 4.3 shows the computed decrease in saturated aquifer thickness, corrected for the effects of the reduction of transmissivity with decreasing saturated aquifer thickness, and indicates that the draught on unconfined storage will be restricted to the wellfield area. The reduction on unconfined storage will be small in areas distant from the proposed wellfields, less than 5 m at a distance of 5 km. These results suggest that the proposed wellfields will be sufficient to meet the demand for water at Morupule until the year 2010.

The projected demand for water for wet cooling is shown in Figure 4.4, and builds up from about 7500 m^3/d in 1986 to 20000 m^3/d in 2010. We would therefore suggest a phased development of the groundwater resources of the Cave Sandstone aquifer. Demand during the first six years of operation, 1986 to 1994, could be met by either of the two wellfields, or a combination of both. There are advantages and disadvantages associated with both of the two wellfields. The northern wellfield is located in an area with relatively simple geological structure and few major dolerite dykes. However, the depth to the Cave Sandstone is quite large, and borehole pumping lifts may exceed 120 m in this area. The geological structure of the southern wellfield is complicated, and the area contains many dykes, but pumping lifts may be less in those parts of the wellfield where the basalt is thin. As a result the operating costs may be less for this wellfield.

In view of the need to provide a reliable supply we would suggest that the northern wellfield (number I in Figure 4.2A) is constructed first in the area of simpler geological structure, with wellfield II being constructed in stages as demand increases. The field experience gained during the construction of wellfield I will prove invaluable in the detailed design of wellfield II.



COMPUTED DECREASE IN SATURATED AQUIFER THICKNESS [m]

pumping 24 thousand m^3/day for 24 years

Figure 4·3

4.4 Time Simulation of Aquifer Behaviour 1986 to 2010

The effects of the proposed management strategy have been simulated in a time-varying description of the aquifer's response during the period 1986 to 2010. A pumping scheme has been devised solely to examine the order of the magnitude of the drawdown. The actual plan of development of the wellfields must take into account engineering and economic factors outside the scope of our present study, but could be included at a later date. The suggested scheme is summarised in Table 4.1 and would lead to supply just keeping up with the predicted average daily demand during the period under consideration. The total rate of groundwater abstraction is shown in Figure 4.4.

The initial conditions for the model simulation are the steady state groundwater heads shown in Figure 3.8, and groundwater recharge during the model simulation is at the average rates given in Table 3.3

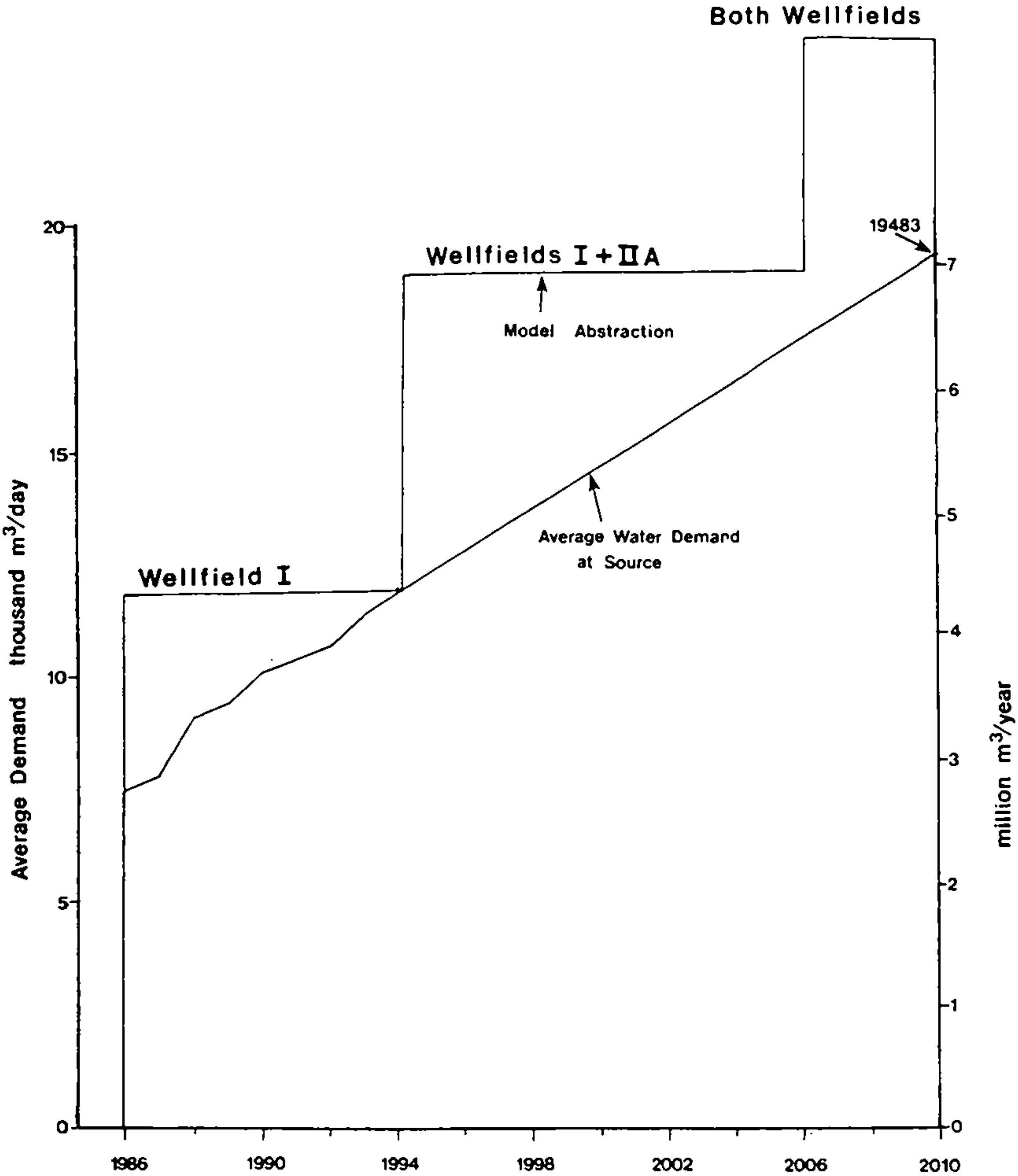
The computed drawdown after 24 years' pumping is shown in Figure 4.5 and final heads are shown in Figure 4.6. Drawdown is greatest (more than 40 m) in the north of the region because pumping from the northern wellfield has been sustained longer in this area. The model results indicate that groundwater levels will be drawn down significantly over a considerable area where the Cave Sandstone aquifer is confined, but that drawdowns in the area of Cave Sandstone outcrop are likely to be small, less than 5 m at Maila and 1 m at Mabeleapodi. Drawdowns south of the Serwe Pan fault and dyke complex are also likely to be small, as shown by the position of the 1 m contour in Figure 4.5. Water levels in Serowe are unlikely to be affected by the proposed developments in the time span under consideration in this study.

Water levels are likely to fall rapidly after the onset of pumping in the confined aquifer until the groundwater head falls to the top of the Cave Sandstone aquifer, and then decline more slowly as the unconfined storage of the sandstone is developed. Figure 4.7 shows the computed drawdown that would develop in the vicinity of site SYB during the first four years' operation of the proposed scheme. The effect of the change in storage coefficient from confined (S = 0.02 per cent)to unconfined conditions (S = 3 per cent) is shown after about 220 days when the water level falls to the top of the Cave Sandstone and there is a marked decrease in the rate of groundwater drawdown. After 220 days the rate of decline decreases gradually as the cone of depression gradually widens.

TABLE 4.1

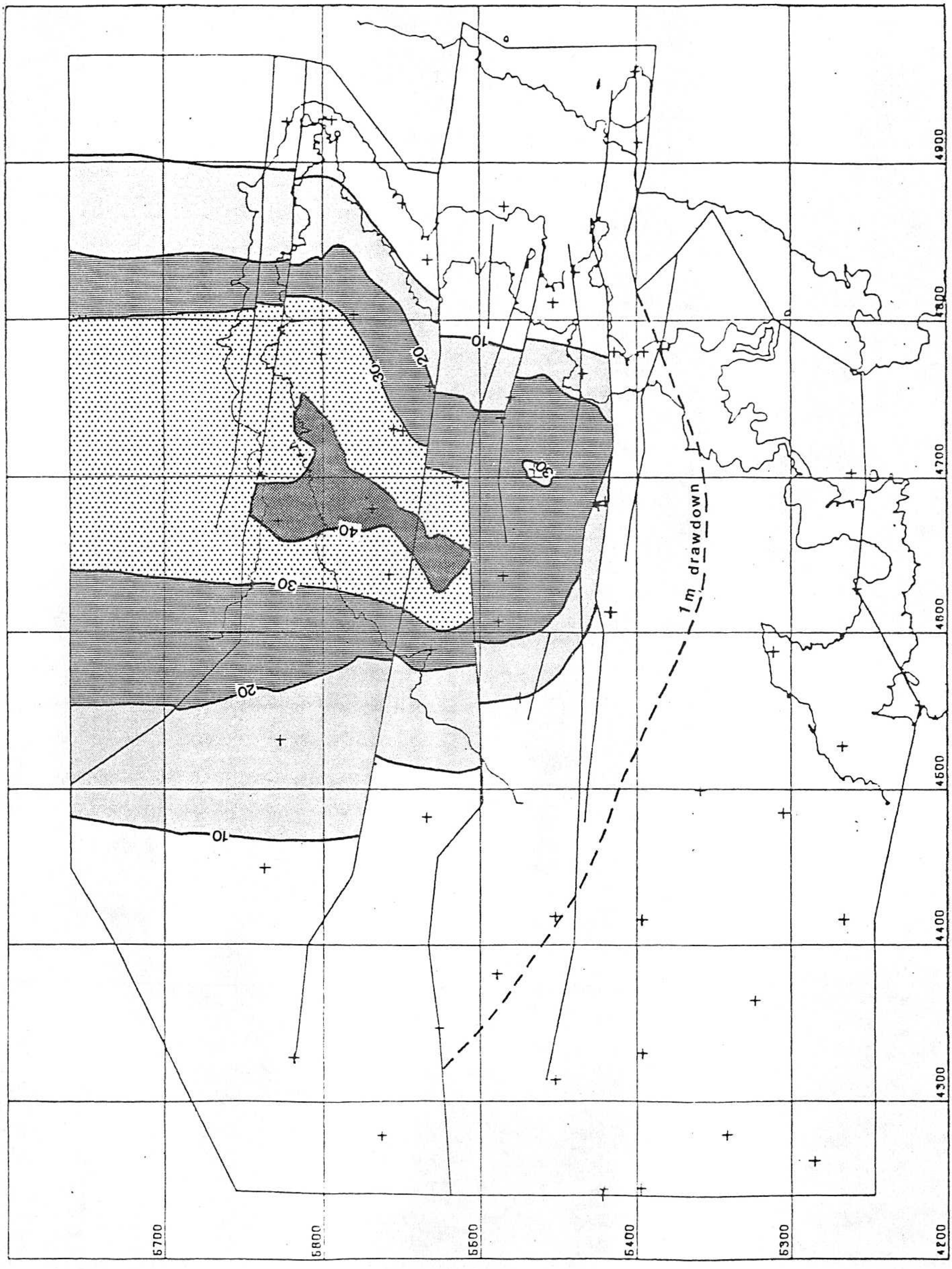
SUGGESTED PUMPING RATES FROM THE PROPOSED WELLFIELDS

Dates	Wellfield	Pumping Rate thousand m^3/d
1986-1994		12
1994-2006		12
	IIA	-
2006-2010		12
	IIA	
	IIB	



PROJECTED DEMAND AT SOURCE, WET COOLING 1986 - 2010

Figure 4·4



COMPUTED GROUNDWATER DRAWDOWN AFTER 24 YEARS PUMPING

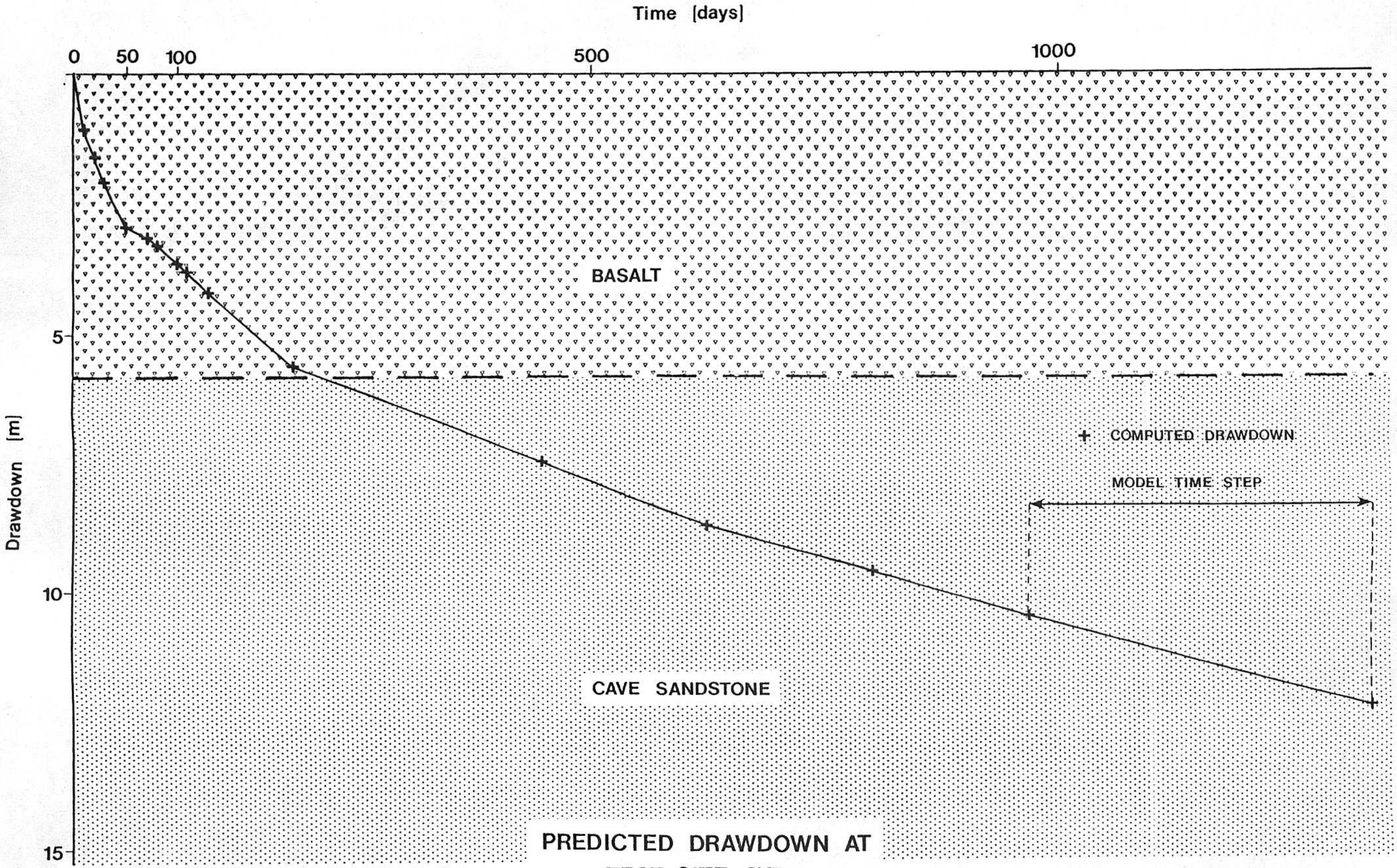
[m]

Figure 4·5

COMPUTED GROUNDWATER LEVELS AFTER 24 YEARS PUMPING

m above Ordnance Datum

Figure 4·6



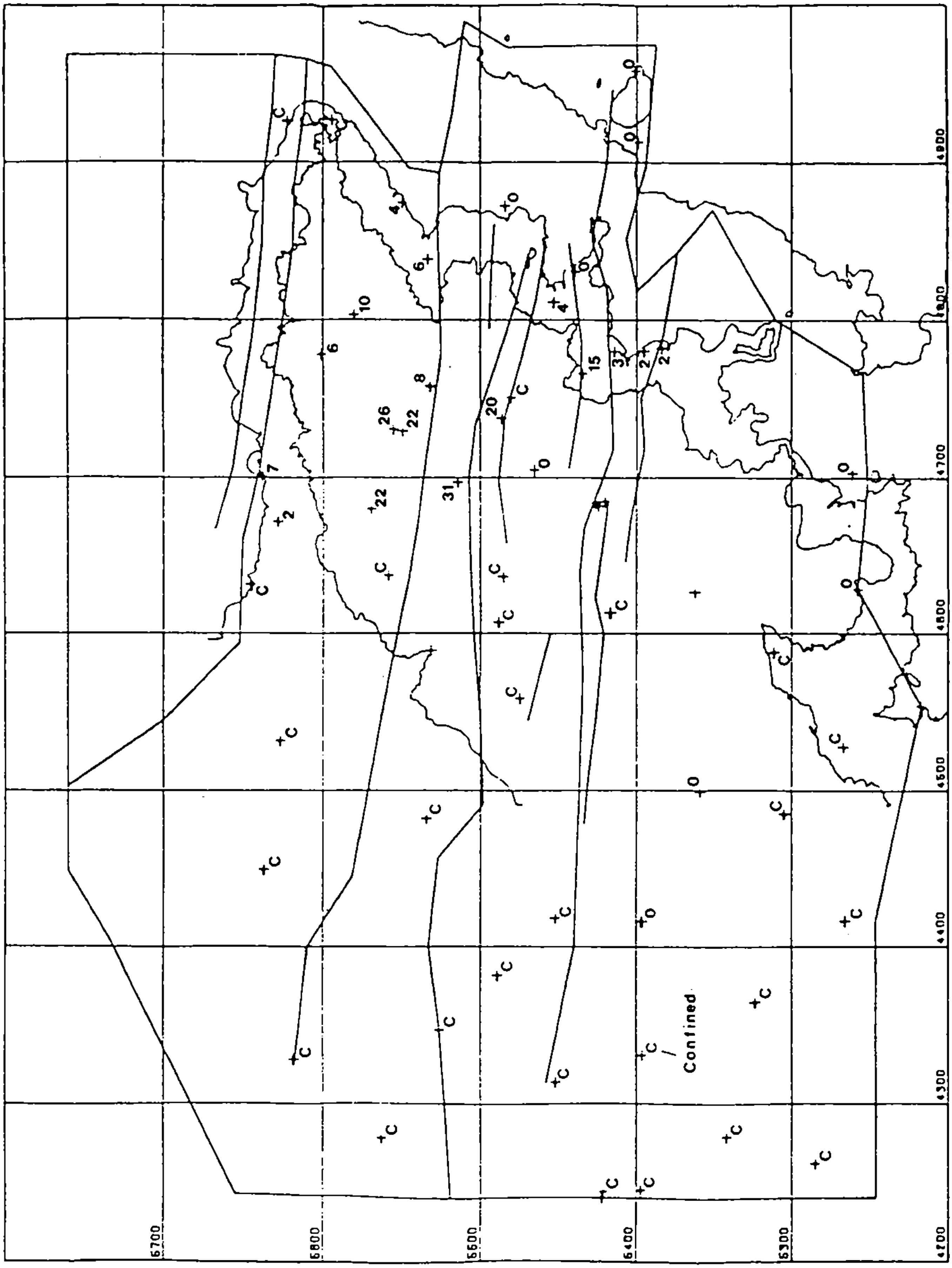
PREDICTED DRAWDOWN AT
TEST SITE SYB

Figure 4·7

The great difference in the value of the confined and unconfined storage coefficient of the Cave Sandstone means that most of the abstracted groundwater will be derived from partial dewatering of the sandstone aquifer below the basalt. Because of the regional differences in the elevation of the basalt/Cave Sandstone interface (shown in Plan III), there are significant areal variations in the dewatered thickness of sandstone. However, it is not a simple matter to produce contours of these areal variations. This is because the groundwater model has been constructed so that the top and the bottom of the aquifer are assumed to be horizontal within each model element. (This approximation was made because of the need to calibrate and run the model in the short space of time following the end of our field survey, but the model could be improved at a later date to show these contours.) The groundwater model does however compute the amount of dewatering at data points.

Figure 4.8 shows the computed dewatering of the Cave Sandstone at data points. The maximum dewatering (about 30 m) would be expected in the vicinity of borehole B 13 (The Serwe Farms Brigade borehole) where the initial computed water level lay at the Cave Sandstone/basalt interface. The computed dewatering at this site is 30 m which is similar to the value of 28 m obtained by the optimisation procedure. Elsewhere, the computed dewatered thickness is less than the maximum drawdown allowed in the optimisation procedure, mainly because of the ability to develop larger groundwater drawdowns and head gradients in the confined aquifer. The thickness of dewatered Cave Sandstone is expected to be small, about 5 m, in the north west of wellfield I as the depth to the top of the Cave Sandstone is at least 120 m in this area, and large confined regional drawdowns of more than 30 m may be expected. Little or no dewatering of the Cave Sandstone is predicted in the initially confined areas located south and west of the wellfield areas. Boreholes expected to remain confined during the period 1986 to 2010 are marked 'c' in Figure 4.8

Large local variations in the thickness of dewatered Cave Sandstone may be expected where the Cave Sandstone has been extensively faulted. The geological structure is complicated in the vicinity of test site TS5 and borehole B16, and a fault, downthrown to the south, is believed to pass between the two boreholes. As a result the Cave Sandstone is predicted to become dewatered by about 20 m at B16, but remain confined at TS5 although the final confining head may be very small (1 or 2 m).



COMPUTED DEWATERING OF CAVE SANDSTONE [m] AFTER 24 YEARS PUMPING

Figure 4·8

4.5 Factors affecting the reliability of our conclusions

We have commented throughout this report on the reliability or otherwise of the data. Inevitably in reaching definite practical conclusions on the scope for groundwater development, in both this and the previous chapters we have had to make a considerable number of assumptions based on hydrogeological judgement, which must affect the reliability of the conclusions reached. Although sensitivity analyses have been carried out in many stages of the modelling study, it is not possible to express the reliability of the groundwater response in a simple fashion. We would therefore strongly advise continued monitoring of water table levels in order to test the validity of the model predictions, and if necessary, the recalibration of the model should be carried out from time to time to improve the predictions as more data be come available.

The predicted groundwater level drawdowns depend largely on the assumed values of the aquifer transmissivity and storage coefficient. In particular the value of unconfined storage coefficient incorporated into the groundwater model (3 per cent) is small relative to the average specific yield of the aquifer (about 15 per cent). If as Cheney and Farr suggest, about 50-80 per cent of the specific yield of the Cave Sandstone will eventually be available from gravity drainage, a more appropriate figure for the unconfined storage coefficient would be about 10 per cent. If this figure is found to be more appropriate the actual groundwater drawdown and depletion of saturated aquifer thickness that would be developed would be less than the values predicted by the groundwater model. However, we have tried to devise a relatively safe management strategy, and, in the absence of hard field information, we would hesitate to raise the model value of unconfined storage coefficient above 3 per cent.

Another major factor, about which there is insufficient field information, is the time distribution of recharge. It is possible that, were the data to be adequate, we would have been able to relate the water levels measurements recorded by Cheney, and those made in this study, to the time distribution of rainfall. We would then have been able to adjust the water level measurements in the model calibration procedure to a common recharge condition, and also to have more confidence in the precise values of recharge predicted by the model in Chapter 3. We would also have been able to examine the likely effects of prolonged wet periods and droughts on the performance of the proposed well-fields. In the absence of these data, we have had to assume replenishment to the aquifer would be constant during the period represented by the model simulations.

In order to make model predictions, we have had to simplify the geological and geophysical evidence for the structure of the Cave Sandstone aquifer. The main simplification has been to assume that the dolerite dykes have a non-zero transmissivity when they are considered in the regional context. The model is therefore believed to be a reasonable representation of the gross features of the groundwater system, but it is not able to resolve the detailed variations of aquifer parameters that would be required to predict accurately the response of individual boreholes in the proposed groundwater developments. It is unlikely that this goal could ever be achieved without the field information provided by the construction of the proposed wellfields.

The groundwater model has demonstrated the hydrogeological feasibility of meeting the projected demand for wet cooling at Morupule during the period 1986 to 2010. It is, therefore, our belief that, economic and engineering considerations being satisfactory, the proposed wellfields should be constructed without further large-scale field investigations.

The pumping scheme used to predict the effects of the proposed management strategy was devised solely to examine the order of the magnitude of the drawdown. The actual plan of development of the wellfields must take into account engineering and economic factors outside the scope of our present study, but could be included at a later date. If these model re-runs were undertaken, it would also be worth analysing the time distribution of rainfall as described above so that the model could be recalibrated, and then used to investigate the likely effects of droughts on the proposed management strategy.

The groundwater model simulations have indicated that the groundwater drawdowns are likely to be almost negligible in the area south of the Serwe fault and dyke complex, and relatively small over much of the west of the study area. There is therefore likely to be considerable merit in the construction of another, more detailed, groundwater model with which to predict the future development of drawdown and depletion of saturated storage in the proposed wellfield areas. This model should include the known locations of dykes, and also the detailed lithological information that would be available from the geological and geophysical logging of the production boreholes. The model could include the areal variations of permeability and storage coefficient that would be available from pumping tests at each production borehole, and the model should be recalibrated as the wellfield performance was re-evaluated during the operation of the scheme.

CHAPTER 5

CONCLUDING REMARKS

Our analysis has shown that the demand for water for wet cooling at Morupule between 1986 and the year 2010 could be met by the groundwater resources of the Cave Sandstone in the study area.

The average demand for water for wet cooling builds up from about 7500 m^3/d in 1986 to 20,000 m^3/d in 2010. We have therefore suggested a phased development of the groundwater resources of the confined area of Cave Sandstone situated between Serwe Pan and the northern escarpment of the Kalahari Plateau. We propose that two wellfields, each about 100 km^2 in areal extent, are constructed, one either side of a major east-west structural feature passing through Maila. In view of the need to provide a reliable supply we would suggest that the northern wellfield (number I in Figure 4.2A) is constructed first in the area of simpler geological structure.

The wellfields cover a relatively small area where there are unlikely to be major sedimentotological variations within the Cave Sandstone, although the aquifer thickness may vary considerably from site to site. However, enormous structural variations and numerous, impersistent, dolerite dykes will affect individual borehole yields and performance within the proposed wellfields. Each production borehole will be unique, having its own particular production characteristics, although these will probably be in the range encountered during our field exploration and pumping tests.

In order to command the resource by mining the groundwater, the abstraction boreholes will have a separation of about 1.3 km. This is due to the low transmissivity and high specific yield of the Cave Sandstone aquifer, and the relatively long time scale under consideration in this study.

Production boreholes should be sited as far as possible from the dolerite dykes to minimise the effects of barrier boundaries. We would therefore recommend that a detailed ground magnetic survey is carried out throughout the whole of the proposed wellfield areas to locate the positions of the dykes.

We have given very serious throught to the possibility of other further large-scale geological and geophysical surveys in the proposed wellfield areas (resistivity, gravity etc). Given the background knowledge that we have obtained from the geophysical surveys carried out in this study, there is no doubt that any further geophysical surveys would provide additional information about the structural setting of the area. However, they would be unlikely to alter significantly the precision of our predictions concerning the thickness and nature of the aquifer or the potential yield of individual borehole locations. Drilling these boreholes would also provide the only reliable and accurate information about the geological structure. We therefore suggest that, other engineering and economic factors being satisfactory, the wellfields are constructed without further major field surveys being undertaken.

We have also considered the possibility of a new programme of exploration drilling in the proposed wellfield areas. However, in view of the large numbers of exploration boreholes that would be necessary to define the structure accurately, we see no reason why these should not be part of the final production wellfields.

Each production borehole will need to be geologically logged during drilling, and then subjected to geophysical and test pumping procedures to determine its role within the wellfields. The abstraction rates set at production boreholes will have to be flexible to allow good producing boreholes to develop their maximum potential. Poor producers might become part of an observation network, which will be required to monitor the overall performance of the wellfields.

The construction of each wellfield should be in three phases.

1. Broad drilling across the area of the wellfield (say one third of the wells) to determine the broad structure

2. Construction of the second third of the boreholes, filling in the best locations determined during phase 1.

3. Final infilling drilling, either to obtain the required capacity or to command additional resources.

During these three phases there would be considerable benefit to be gained from the construction of a detailed model of the wellfield area.

Construction of the model should begin in phase 1. The model should then be updated with the additional field information obtained during phase 2, and used to determine the optimum locations for the remaining boreholes. Later, the model could be further improved and used to optimise the pumping at each borehole to meet the demand at Morupule. While this would inevitably prolong the period of wellfield construction, it does avoid a costly exploration programme.

We have not considered the effects of peak demands in our study. These are expected to be 28000 m^3/d in 2010, 46 per cent greater than the average demand. We know nothing of the timing or persistence of the demands, but it is obviously inefficient to attempt to provide for the peak demands by the construction of further boreholes. It is possible that short-term demands could be met from greater abstraction within the proposed wellfields. Otherwise an engineering solution would be more appropriate, with fluctuations in demand being met by storage at Morupule.

The proposed development will dewater the aquifer significantly in the wellfield areas, and lower the piezometric surface elsewhere. All existing abstractions in the wellfield areas will be affected, and most will lose their existing supply. Our model predicts that the effect in the villages along the escarpment will be small to begin with, but will build up after a prolonged period of wellfield operation. A similar diminution in spring flow will also gradually become apparent at Paje and elsewhere in the ephemeral springs along the escarpment.

Finally, we would emphasise that our model predicts that the northern wellfield may be largely exhausted by 2010. This may mean that more drilling will be needed at some time in the future. This conclusion is necessarily based on our interpretation of the sparse data available, and on a number of assumptions set out in the report. If long-term dewatering develops additional gravity drainage then the proposed wellfields will have a more prolonged life beyond 2010.

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