INSTITUTE of
HYDROLOGY

RAMOTSWA WELLFIELD
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DIGITAL MODEL STUDY
AND STORAGE ESTIMATES

Institute of Hydrology
September 1986

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INTRODUCTION

The Ramotswa wellfield, located about 25 km south of Gaberone, is used to supplement the water supply of the capital during periods of drought by utilizing groundwater storage in the Ramotswa Dolomites (RD) and, to a lesser extent, the Lephala Formation shales (LF).

The wellfield has developed gradually since the original high yielding wells drilled by Wellfield Services in 1980. It now comprises ten production wells with a fitted pumping capacity of 1125 m^3/h (27000 m^3/d) intended for a one-year continuous supply (9.0 Mm^3). About 60% of the wellfield capacity is obtained from four wells located along a major linear feature in the southernmost part of the Ramotswa Dolomites. It has not yet been necessary to operate the wellfield at its full design capacity. However, a large-scale pumping test was undertaken for about three months in 1984 during which water levels were monitored to provide an indication of the aquifer response to multiple well abstraction.

In recent years several studies have been undertaken in the Ramotswa area to examine the hydrogeology (1,4), locate additional production wells (2), and study pollution aspects (3). These studies have suggested a potential resource, excluding recharge, of 18 Mm^3 indicating that further supplies could perhaps be developed. However, subsequent groundwater exploration by BRGM (2) did not locate further high-yielding wells despite detailed local investigations. It seems increasingly likely that the main productive area of the dolomite aquifer within Botswana is limited to the linear feature of the present wellfield. However, it has been suggested that this feature may draw upon groundwater in storage in the dolomites which continue eastwards into South Africa.

In March 1986 meetings were held between the Water Utilities Corporation (WUC), Geological Survey (GS) and a visiting consultant hydrogeologist from the Institute of Hydrology to discuss the Ramotswa wellfield supply following an initial review of the available reports for the Ramotswa area by IH.

At the request of WUC we have undertaken a review of the available information with the following objectives:

* to develop a conceptual model of the aquifer system.
* construct a mathematical model incorporating this conceptual interpretation.
* review previous estimates of storage.

The model applied is similar to that developed in 1980 by Wellfield Services but has the advantage of the long term test data as a guide to its development rather than the single, short term test used previously. The new model also benefits from additional information on the aquifer and its response to abstraction but is not intended to be a detailed representation of the region. It has been used to test our interpretation of the nature of the aquifer system by comparison of model predictions against the long-term pumping test data.

The model has also been used to indicate how long the fitted pumping capacity of wells in the main linear zone can be sustained given our interpretation of the hydrogeological data. We have not at this stage examined alternative management strategies, although the new model can be used for this purpose as well as to study recharge aspects.

AQUIFER SYSTEM

2.1 GENERAL

The groundwater investigations carried out over the past five years have been focused mainly on the area adjacent to the Notwane river to locate high yielding wells. However, the BRGM exploration programme was orientated more towards identifying the principal geological controls on groundwater occurrence over a wider area of the catchment. Nonetheless, large areas still remain away from the river where there is only scant information and no information is available concerning the groundwater conditions from the eastern half of the catchment area within South Africa.

The two main aquifers - the Ramotswa Dolomite (RD) and Lephala Formation (LF) - extend over a wide area as part of the Bushveld Basin. surface water catchment defined by WLPU of about 61 km^2 has also been adopted as the groundwater catchment for the Ramotswa area. Both aquifers are considered to be in local hydraulic connection via predominantly N-S trending fracture zones.

The dominant feature of the system is the marked anisotropy associated with high density fracturing. In the dolomites active groundwater circulation has promoted local karstification along structural features producing conditions of high transmissivity and storativity. Elsewhere fissures appear to remain unaffected by solution whilst matrix permeability is essentially non-existent.

The concept of a broad three-layered system, which extends throughout both the RD and LF, has been proposed by previous studies. In the RD this was considered to comprise shallow and deep zones of karstification, each about 20-50 m thick separated by a layer of limited karst development and fissuring about 10-20 m thick. A similar pattern was believed to occur in the LF (but unaffected by karstification) with shallow fissuring 30-40 m thick, deep fissuring about 30 m thick and an intervening poorly fissured layer 25-30 m thick. GS attempted to correlate these layers from a detailed examination of well logs and also mapped the distribution of the major surface karst features.

One or more zones may be encountered in varying combination by a particular well, suggesting that the correlation proposed by GS may be an oversimplification of the situation.

WLPU considered that the deep karst zone may be restricted only to the E-W linear feature of the main wellfield (and possibly to a N-S tensional fault to the south) and BRGM suggested that this may be associated with an abandoned course of the Notwane passing west of Tsokwane Hill and through the main wellfield.

The shallow karst zone is of relatively limited and variable thickness mainly restricted to the immediate area of the river. Cavities in this zone are often infilled with fine sediments and occasionally manganese wad. However, cavities have remained open due to dissolution along the dolomite-infill contact at the base of the upper karst system producing local thin zones of high permeability probably not more than 5-10 m in thickness. The deep karst is generally free of infill material.

The density of fracturing is more likely to control the extent of deeper karst rather than whether the fractures are of tensional or compressional origin. If so, the direction of fracturing would not be a reliable guide for selecting well sites. A high density of fracturing will allow more rapid circulation of groundwater promoting chemical dissolution. Lithostratigraphic factors will also influence the development and density of fissures and thus, indirectly, karstification.

Well 4337 has the highest short term specific capacity of the dolomite wells. At this site a zone of karstification has developed at a depth of 40 m at the Ramotswa Village Slide contact between the LF and RD. The opportunity in Botswana for exploiting this particular zone however is limited.

The above outline serves to illustrate the local complexity of the aquifer system. In the following sections we describe in more detail the main components of the aquifer system with simplifications that can be applied to select hydraulic characteristics for the model describing each of the main aquifers in turn. We then present a basic conceptual representation of the main features.

2.2 LEPHALA FORMATION (LF)

The Lephala Formation outcrops along the southern edge of the catchment, where it is faulted against the dolomites, and as an extensive outlier north-east of Ramotswa. Exploratory drilling has been restricted to two fracture zones in the southern area close to the Notwane.

The sequence, up to 250 m thick, consists mainly of shales which have been sub-divided into the Upper and Lower Argillites. There is no information on the sequence in South Africa but well 4337 encountered 40 m of LF which has confined the underlying dolomites.

In the Upper Argillites, a sequence of predominantly black shales, fracturing appears to be limited to a depth of 50 m. Water is usually encountered at 20-30 m with rest water levels of 10-20 m suggesting confined conditions. The southernmost group of wells (4358, 4340, 4885, 4972) draw supplies from the Upper Argillites. Low yields of 20-25 m^3/h were obtained with pumping water levels of 50-70 m and specific capacities of 5-10 m^2d. Transmissivities from recovery data range from 25-50 m^2d and a storage coefficient of 10^{-4} is suggested by short term tests. Unconfined conditions may occur within the narrow fracture zones.

Production wells Z4406, 4373 and 4347 obtain supplies from the Lower Argillites, a sequence of grey shales with sandstone bands. Water is also encountered in narrow fracture zones at 40-50 m depth with main supplies at 60-80 m. These fractures, which can be infilled with manganese, pyrites or quartz are probably sub-vertical and provide connection with the dolomites to the north. The piezometric surface is usually at a depth of about 10 m and the similarity in elevation suggests possible continuity via fractures throughout the Upper and Lower Argillites or a common recharge source. Specific capacities of 80 m^2/d (4406), 110 m^2/d (4373) and 135 m^2d (4347) are similar to those of the deep zones in the dolomites.

Yields of the LF wells in the southern area depend on the intersection of sub-vertical fissure zones of narrow width, proximity to the river and extent of secondary infill material. Recharge may be restricted to surface run-off via fractures in connection with the Notwane river. The fracture zones will restrict available drawdowns, particularly in the upper zone, but recharge rather than development of storage may determine sustained yields in this formation.

From our review of the Lephala Formation aquifers we have selected the following model values to represent the Lephala Formation unfissured country rock, including the outlier NE of Ramotswa:

Permeability 0.05 m/d Av.T 5 m^2d
Thickness 100 m
Storage coefficient 3 x 10^{-4}

The following values are considered typical for the fracture zones in each part of the Lephala Formation:

Upper Argillites	Av. T ≈ 50 m^2d S ≈ 10^{-3} (?)	
	Thickness = 10 - 30m	
	K = 5 m/d	
Lower Argillites	Av. T ≈ 350 m^2d S 10^{-4}	
	Thickness 20-30 m	
	K = 15 m/d	

However, we have not represented these fracture zones in the model.

2.3 RAMOTSWA DOLOMITES (RD)

There is a marked contrast between the major linear karst feature of the dolomites in which the main wellfield is located and the general surrounding unfractured dolomite country rock. In the following sections we outline separately the principal features of the country rock and the linear feature.

2.3.1 Country Rock

The area north of the Ramotswa Village Slide is characterized by massive dolomites of a lower stratigraphical position than to the south. An internal groundwater divide appears to be present along this fault.

In the north the sequence has less frequent chert or limestone bands, dipping at about 15° SSE, fractures are commonly infilled with calcite. Major faults are generally absent. Low yielding boreholes have been drilled close to the river where an upper karst extends to a depth of 20 m but in which cavities are often infilled with clay. This zone is usually dewatered rapidly at low pumping rates. Away from the river dry boreholes are common in the dolomites north of the Ramotswa Village Slide.

The dolomite area south of the Ramotswa Village Slide appears to be a stratigraphically higher part of the dolomite sequence and contains more frequent chert and limestone horizons. The sequence dips at about 20°SW. In this area fractures are more common and shallow karst features better developed. The dolomite extends eastwards into South Africa south of the LF outlier, which may have acted as a barrier promoting E-W rather than N-S flow giving the opportunity for shallow karst to develop along the RD-LF junction.

The Notwane river follows mainly N-S trending structures through the area. The valley width is about 125-150 m with up to 20 m of clay sand alluvium. It forms a line sink with groundwater flow generally towards and along the river valley. Groundwater outflow is thought to occur beneath the Notwane river (possibly via a major N-S fault). The water table at this location is about 1008 m OD, which can probably be considered as the elevation of the top of the permanent storage. The overall hydraulic gradient is about 1:300 along the line of the river.

The river provides recharge for active dissolution where the underlying bedrock is highly fissured. Away from the immediate area of the river the water table may occur below the base of the shallow karst.

Short pumping tests on boreholes in the dolomite away from the linear feature indicate T values of 5 to 50 m^2d, averaging about 10 m^2d. The higher values appear to represent the upper karst near the river where solution features have been infilled with other material. We have adopted a T value of 10 m^2d for the model study giving an average permeability of 0.1 m/d for the average aquifer thickness of 100 m.

There are very few estimates of storativity relating to boreholes in the country rock. A value of 3×10^{-3} (0.3%) for S was derived from a test on borehole 4162 in the northern part of the dolomites close to the river, although this may relate to the upper aquifer. We would anticipate values between those derived for the lower part of the linear karst feature of about 1% and those obtained from tests in the Lephala Formation of 10^{-4} (.01%). An S value of 10^{-3} would be consistent with this and for the model we have applied 3×10^{-3} or 0.3%. This agrees with a value of 10^{-3} applied by Geological Survey to the areas unaffected by pumping (see Section 4.2). In terms of the model study, our adopted value for storativity of 0.3% is also an order of magnitude different from that of 3.9% used by Wellfield Services for their model. These different storativity values were examined with the model.

2.3.2 Main E-W Linear Zone

(a) Aquifer Geometry

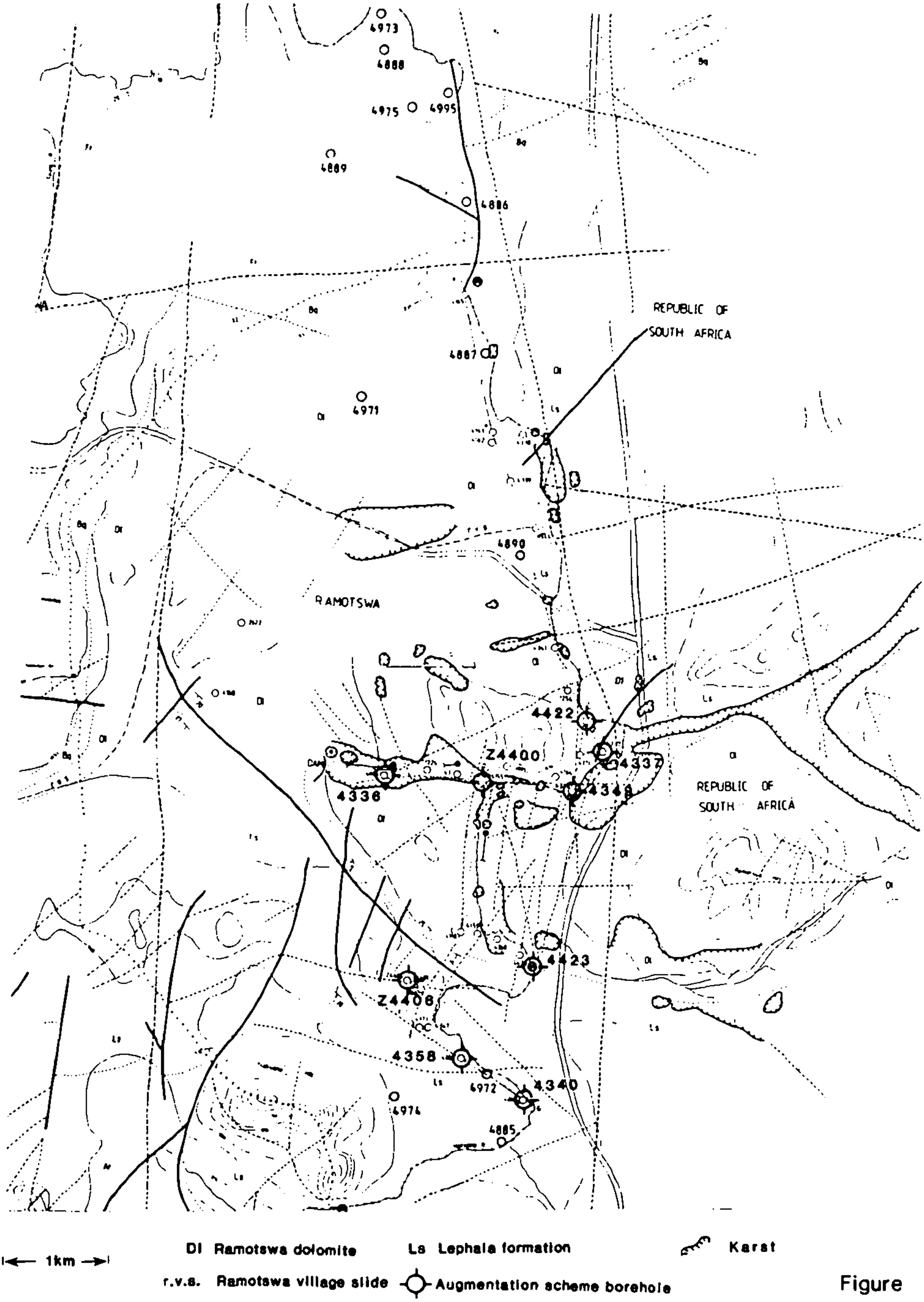
The main production wells are located along a principal E-W karst feature in the southern area (Figure 1). The hydraulic conditions of this feature are more favourable than the surrounding country rock.

The linear feature appears to consist of a dense fracture pattern, with at least several fracture directions, rather than a single major structure. This fracturing, together with recharge from the Notwane and the intersection of minor valleys from the east and west , have produced favourable conditions for enhanced secondary permeability by chemical dissolution. This combination of circumstances would appear to be unique to this particular area for the dolomites in the Ramotswa area of Botswana.

In geological terms the linear zone is considered to be of a similar width to the Notwane valley defining a groundwater feature with a width of about 250 m. It is known to extend for at least two kilometres on the Botswana side of the international border. Areas of shallow karst, which may be an extension of this linear zone, extend NE into South Africa for at least several kilometres but may be separated hydraulically by the major N-S lineation followed by the Notwane. It is not known whether the eastern karst has similar groundwater conditions to the zone in Botswana.

Borehole logs of production wells 4336, Z4400 and 4349 indicate a broad three-fold subdivision of the sequence in the linear zone: an upper aquifer extending to a depth of about 30 m, a zone from 30 to about 50 m where water-bearing fissures are less frequent, and a lower aquifer of

Borehole location, main structural and karst features of Ramotswa area
(from Selaolo, 1985)



Figure

variable thickness between 45 and 100 m depth. The most productive parts of the sequence seem to occur from 10 to 20 m and from 60 to 80 m depth. The drawdown response at a particular time during abstraction is likely to be governed by the hydraulic characteristics of each layer as the sequence becomes dewatered.

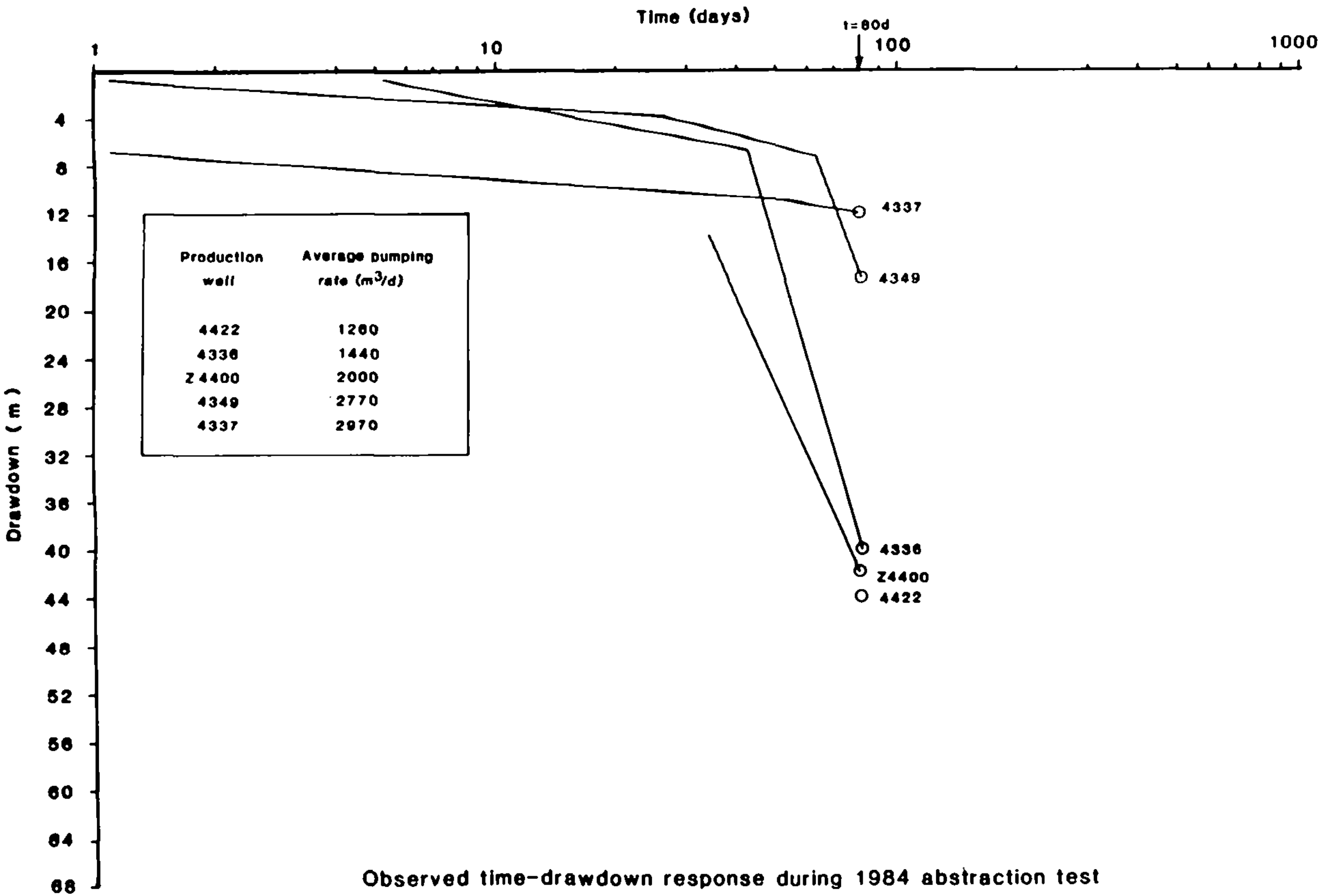
We consider that the shallow karst identified by GS represents the extent of the upper aquifer. The dense fracture patterns identified by BRGM, which occur over a width of some 500 m, may represent the deeper fissured aquifer and as such represent an intermediate zone between the linear feature, where both the upper and lower aquifer are present and the poorly fissured, more massive country rock. This distribution has been taken into account in the model.

(b) *Observed response*

Figure 2 is a plot of the observed time-drawdown response during the long term test for the main dolomite production wells. Wells 4336, Z4400 and 4349 represent the linear feature. At the test rates there is a slow decline in water levels for about one month but as abstraction continues the rate of drawdown increases dramatically producing much greater drawdowns during the next two months. Variations on this generalized response are shown by well 4422, where only the lower zone is present, and at well 4337, where the main producing zone occurs at the RD-LF contact at 40 m.

In the early stages of pumping the cone of depression is extending along the linear feature intercepting storage. Local variations along the feature may produce short duration changes in the rate of drawdown during this phase. As storage becomes depleted the producive horizons in the upper aquifer become dewatered producing a rapid increase in the rate of drawdown (breakaway level).

The onset of these effects depends largely on the pumping rate and the relative contribution of the upper and lower aquifer zones. Whilst high pumping rates can be supported initially these seem unlikely to be sustained for long periods due to increasing dependence upon the poorer characteristics of the country rock and with depth within the feature. Examination of this was a major aim of the modelling studies.



Observed time-drawdown response during 1984 abstraction test

Figure 2

(c) Aquifer Characteristics

Pumping test results for the dolomite production wells are summarized in Table 1, based on analyses undertaken by Selaolo (4a). The breakaway levels at which a marked increase in the rate of drawdown was observed during the long-term tests in 1984 are also included in Table 1.

There is a marked contrast between the transmissivity (T) values derived from the short and long-term tests. A similar contrast is shown by the specific capacities, since this is related partly to transmissivity.

Localized karstic zones in the upper aquifer would account for the exceptionally high T of about 5000 m^2d at well 4336 in the main linear feature. Such high values are not considered representative of the linear feature as a whole. The two other wells in the feature, 4349 and Z4400, have much lower T values of 1400 and 540 m^2d respectively based on the short term test. Different parts of the sequence may be contributing during prolonged pumping and dewatering and this would seem to account partly for the variations in transmissivity. However, it is difficult to distinguish which part of the sequence is being represented by each estimate of T. Nonetheless, by inspection of the results given in Table 1 we have obtained the following general values of T:

Short tests $\approx$ 1500 m^2/d = total sequence, excluding local highly karstified horizons in the upper aquifer

Recovery from long term test $\approx$ 450 m^2/d — lower part of the sequence, after local dewatering of the upper aquifer horizons

Long term tests $\approx$ 300 m^2/d

This would suggest the upper aquifer has an average T of about 1000 m^2/d. The following T values were adopted for the model representation of the linear feature:

Upper aquifer 1000 m^2/d

Lower sequence : 500

Table 1

Summary of Pumping Test Results for Dolomite Production Wells
(based on Selaolo 1985)

Well	Short Tests [1]		Long Tests [2]			
	Specific Capacity (m^2d)	Transmissivity (m^2d)	Specific Capacity (m^2d)	Transmissivity Pumping (m^2d)	Transmissivity Recovery (m^2d)	Breakaway Depth (m)
4337	600	1600	300	300< B1* 135> B2	455	B1=19
4422	87	510	(poor data)		255	LZ only
4349	1030	1320 1435	900< B1 450 B1-B2 200> B2	330< B1 65 B1-B2 65 > B2	470	B1=14 B2=18
Z4400		540	90∿100< B1	(poor data)	240	B1=25?
4336	2735	4650 5730	515< B1 90 > B2	110< B1 10 > B1	120	B1=24
4423	1280 B1 385 B2	1530 1760	N/R		120	B1=9 B2=10.5
4155				120		S∿1.8

Various estimates of storativity have been presented in earlier studies, which are summarized as follows:

Wellfield Services		3.9%
WLPU	average	2.2% (range 1 to 6%)
GS		11.2% (1.3 to 26%)
Well 4155 test (Z4400)		1.8-3.0%

From these estimates a value of 2% was selected to represent the overall storativity of the linear feature.

2.4 CONCEPTUAL REPRESENTATION

Local variations in the degree of fracturing and karstification together with secondary effects, such as karst or calcite infill, have produced a complex anisotropic and heterogeneous aquifer system. To represent this system by a digital model requires certain simplifications.However, this must still retain the inherent features of the system and its response to abstraction.

The basic concept is of a single major linear groundwater feature with high transmissivity and storativity surrounded by and drawing upon fracture and jointed storage in the general country rock. Although extensive in area, this country rock has poor hydraulic characteristics and no matrix groundwater. Abstraction in the main linear zone will initially depend on the contrasting hydraulic characteristics of both the upper and lower aquifers.

A single value for the total saturated thickness of 85 m can be applied to both the linear feature and country rock with overall hydraulic continuity throughout the system. Similarly, the country rock of both the shales and dolomites can be considered as having the same permeability and storativity throughout.

This brief description of our simplified representation of the aquifer system has been used to develop the digital model presented in the following chapter.

3.

MODEL STUDY

3.1 INTRODUCTION

In this chapter we describe the numerical model developed to incorporate our ideas regarding the contrasting hydrogeological characteristics of the main linear feature and the surrounding country rock. To test these ideas we compare drawdown predictions by the model with the observed response during the large-scale pumping test in 1984, which had revealed the aquifer response better than the short term tests available previously. Certain important conclusions are drawn from this simulation with implications for the resource development potential. We then use the model to investigate the importance of storativity and the length of the linear feature on these conclusions.

3.2 MODEL DESCRIPTION

A two-dimensional flow model was used to investigate the regional effect of well abstraction from the aquifer. The model predicts formation drawdown which can be compared with well drawdown after adjustment for well losses. An unconfined aquifer is simulated. Transmissivity varies with saturated thickness and at each time step an iterative procedure is used to calculate the position of the phreatic surface.

The Galerkin finite element method is used to spatially discretise the modelled area. Rectangular elements are used which vary in size to reflect different hydrogeological conditions.

Vertically the model consists of three layers with different hydraulic conductivities. At each node the transmissivity is calculated as the weighted mean of the hydraulic conductivity and saturated thickness in each layer. Since the aquifer has been represented as unconfined the transmissivity will decrease as drawdown occurs. The storativity does not vary in the vertical. A value for storage coefficient is required at each node. Linear basis functions are used in the model; hence the aquifer properties vary in a bilinear fashion across the elements.

Element abstractions rather than nodal abstractions are used since the model is used to predict the regional consequences of abstraction rather than the local effects adjacent to a single well. The model also has a capability to simulate recharge, although this has not been utilised in the present study.

A finite difference time discretisation is used. A twenty (20) day time step has been utilised for all model runs described in this report. Sensitivity analysis was carried out to ensure that the model results are independent of this time step length.

Model boundaries have been located far enough from the area of interest to ensure that the conditions at these boundaries do not influence the model conclusions. Two boundary conditions are used: constant piezometric head and constant flux. Model runs have illustrated that with the chosen boundary locations the type of boundary condition does not influence the conclusions drawn.

3.3 HYDROGEOLOGICAL REPRESENTATION

3.3.1 Model Grid

The model grid is shown in Figure 3. This has been chosen to represent the more important hydrogeological features of the catchment area. A finer grid is used where there are considered to be abrupt changes in characteristics but is coarser elsewhere, particularly where information is scarce. The finest grid is along the main linear feature. A fine grid was also applied along the river (international boundary) to represent a major N-S lineation and to represent a shallow karst feature extending southwards from the main linear feature. This broadly cruciform arrangement was introduced to allow the conditions of the main linear feature at the wellfield to be extended to the N, E or S if required.

3.3.2 Hydrogeological sub-areas

The area was sub-divided into three hydrogeological areas each having similar characteristics:

Model grid

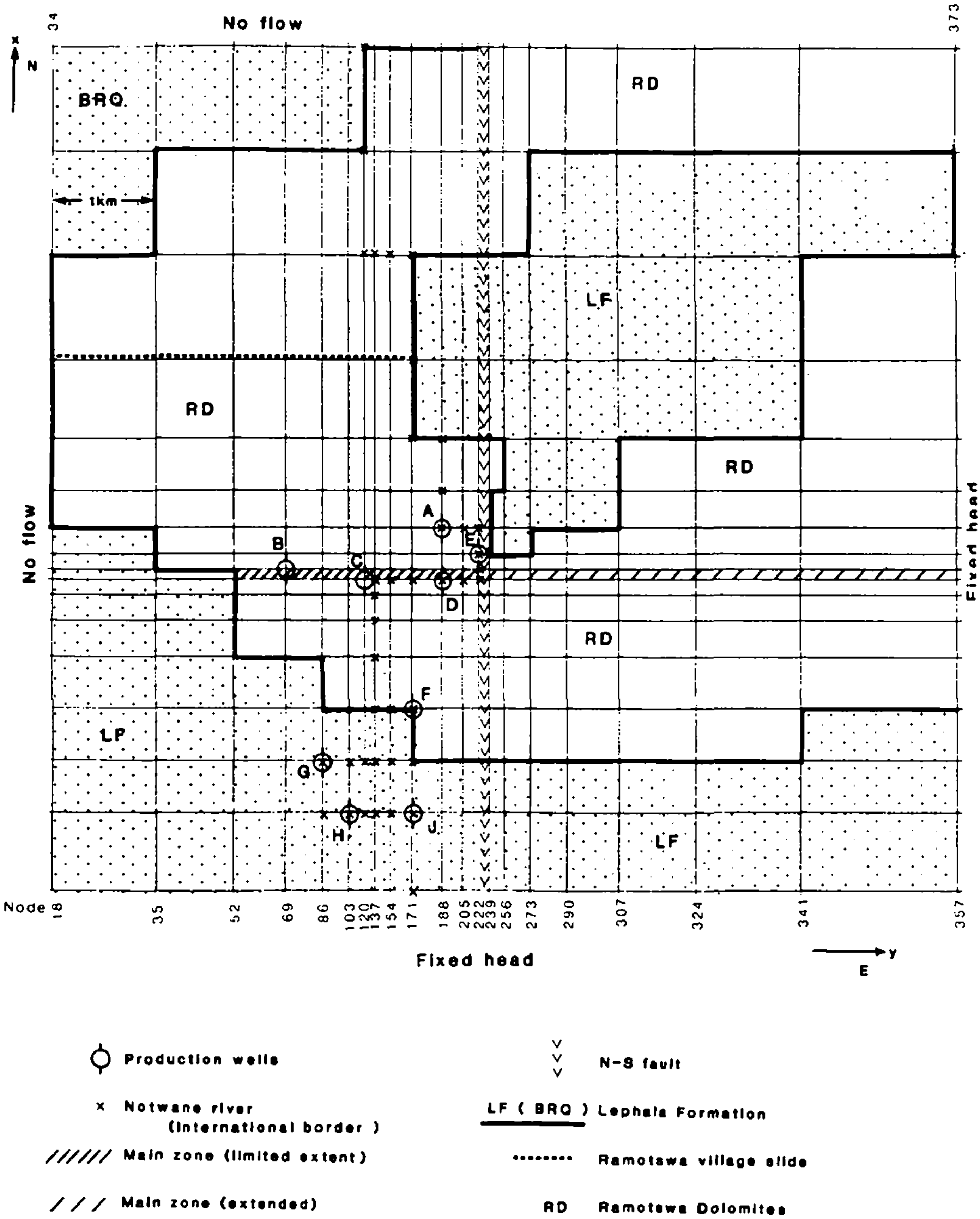


Figure 3

(a) the main E-W linear feature, together with its immediate area

(b) the country rock of the Ramotswa Dolomites

(c) the country rock of the Lephala Formation

(a) E-W linear feature

Rather than attempting to represent localized variations in aquifer characteristics along the feature, we have included the broad properties of the feature along its length over a width of 100 m:

Storativity 2% (0.02)

Total transmissivity 1500 m^2d, distributed vertically as follows ·

	T (m^2/d)	Thickness (m)	Permeability (m/d)
Upper aquifer (K1)	975	15	65
Middle " (K2)	245	35	7
Lower (K3)	245	35	
	1465	85	

To represent the physical characteristics of the marginal area and partly to avoid numerical instability in the model, an intermediate zone of 300 m width was introduced into the grid between the main linear feature and the unfractured country rock. Permeabilities of 10 m/d for the upper aquifer and 5 m/d for the lower aquifers were selected, producing an overall T of 850 m^2/d for the intermediate area.

A sensitivity run was undertaken with a permeability of 30 m/d for the upper aquifer in the linear zone but this showed no signifcant difference in predicted drawdown to the runs where the above distribution was applied.

The fine grid representing the main feature extended from the RD-LF faulted contact near the Ramotswa dam to the eastern model boundary, approximately 7 km. However, for the initial run with the model this zone terminated at the N-S lineation at the international border with country rock aquifer characteristics used for the whole aquifer area in South Africa. This is discussed further in section 3.7.

(b) Dolomite country rock

The dolomite areas outside of the main linear zone are treated as a single unit with the same aquifer characteristics throughout to conform with our basic conceptual model. The input values selected were as follows reflecting the matrix of the more massive dolomites:

Storativity 0.3% (0.003)
Total Transmissivity = 10 m^2/d
K1 = K2 = K3 = 0.1 m/d

(c) Lephala Formation country rock

All geological formations, including the Black Reef Quartzites along the western border of the catchment, other than the Ramotswa Dolomites were included in this hydrogeological sub-division.. The following aquifer characteristics were selected to represent the country rock of the Lephala and associated formations:

Storage Co-efficient 3 x 10^{-4}
Total Transmissivity = 5 m^2d
K1 = K2 = K3 = 0.05 m/d

3.3.3 Model Boundaries

Fixed head boundaries were selected for the south and eastern model boundaries and no flow boundaries were used for the west and northern model boundaries. The former allow the model to draw water from the south and east if the cone of depression extended to these boundaries.

3.3.4 Head and Aquifer Elevations

For certain model input parameters, the same value was applied throughout the whole model. These were as follows:

	Elevation (m OD)	Thickness (m)	Depth (m)
Starting head	1015		
Base upper aquifer	1000	15	30
Base middle zone	965	35	65
Base lower aquifer	930	35	100

The initial head represents an average pre-abstraction condition for June 1984. The approximate elevation of the river bed of 1030 m OD was taken as ground level.

3.3.5 Abstraction and Recharge

Nine nodes (shown as A-H, J in Figure 2) were selected to represent the main production wells in both aquifers. A finer grid was introduced at these points as steeper hydraulic gradients would be expected to occur around them during pumping.

Model runs were undertaken with abstraction from only the main group of four wells in the linear feature of the dolomite aquifer (well 4336 = B, Z4400 = C, 4349 = D, 4337 = E).

The Notwane river is represented by 40 nodes. However, although recharge from this source can be included, this was not applied during the model runs of this study.

3.4 SIMULATION OF LONG TERM TEST

A model run was undertaken with the hydrogeological conditions described above to compare the drawdown predictions with the long term test undertaken through July to September 1984. Only the four main production wells in the linear feature were used for this run (4336, Z4400, 4349, 4337). The average abstraction rate (2400 m^3/d) was derived from the total abstraction from these four wells during the long term test of 0.763 Mm^3. This was then weighted to the actual average daily pumping rate of each well over the test as follows:

Well No.	Element No.	Abstraction Rate m^3/d
4336	56	1500
Z4400	88	2070
4349	152	2870
4337	184	3100

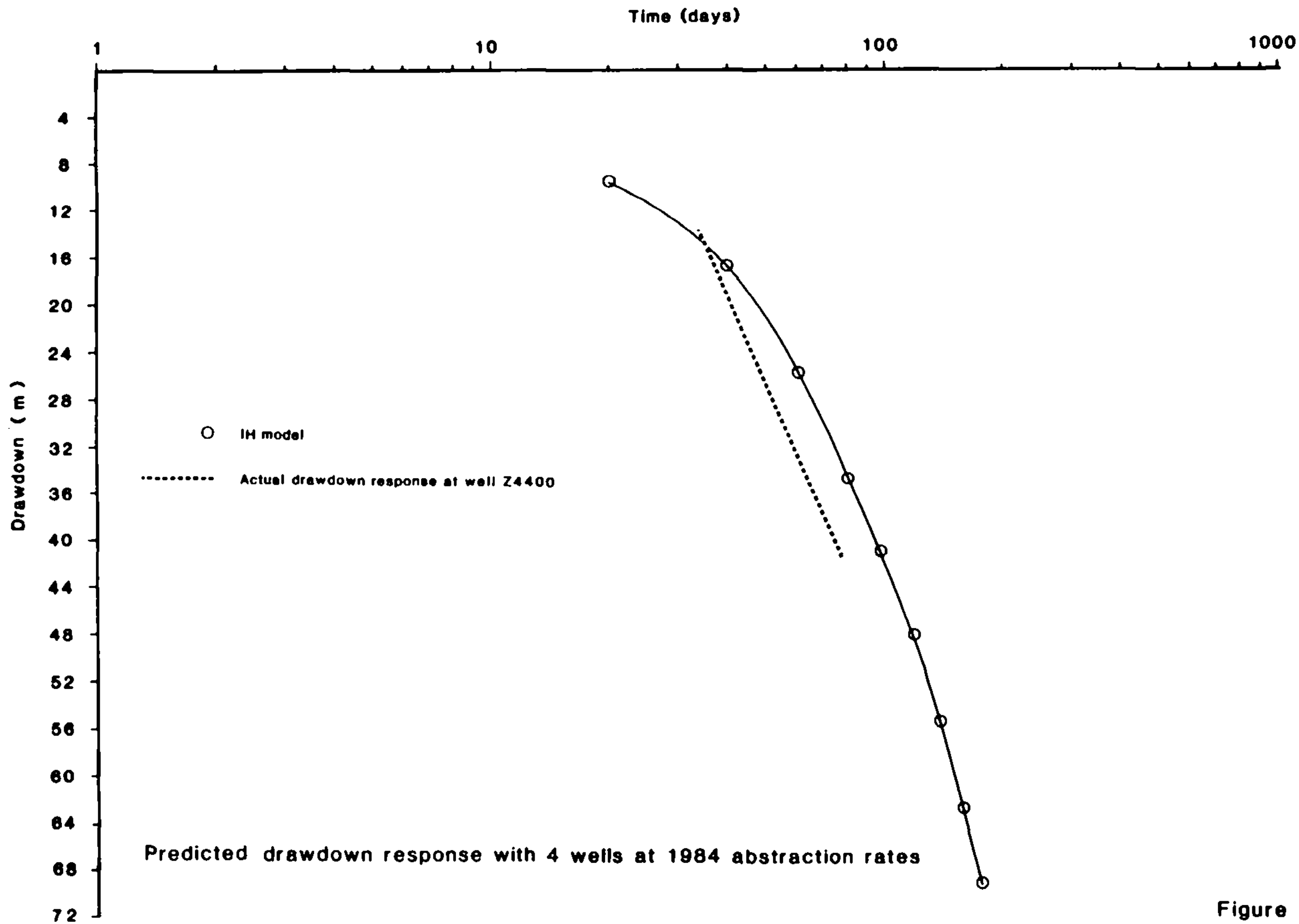
Total abstraction 0.76 Mm^3

In the model the abstraction from each well is simulated by applying the abstraction over the element since the regional consequences of abstraction are being investigated. The specific hydrogeological conditions at each pumping well are not represented in the model nor are periodic shutdowns; only the broad conditions of the linear feature from which the abstraction takes place are included. A precise correlation between predicted and observed response for an individual well would not therefore be expected.

We have compared the model predictions with the drawdown at well Z4400 (node 127) as this is situated near the centre of the feature extent within Botswana. The observed drawdown at this well during the 1984 pumping test was rather erratic due to periodic shutdowns and this well was also pumped prior to the test. However, its overall response based on the short and long term test data is similar to the other two wells 4336 and 4349, in the main liner feature as shown in Figure 2.

The model predicts formation drawdowns whereas the observed drawdowns include formation and well loss components of drawdown. Therefore in order to make comparisons with the observed data we have adjusted the model drawdowns for a 30% well loss. This would seem to be a representative value based on step-drawdown tests described by Wellfield Services.

Figure 4 shows the time-drawdown curve for node 127, which represents well Z4400 (adjusted for well losses of 30%), together with the observed response at Z4400. A close match between the observed and model predicted drawdowns was obtained both in the form of the response and in the actual drawdown values. This was achieved without the need to optimise aquifer parameters, suggesting that the model was a reasonable representation of the hydrogeological conditions. No design alternatives were considered necessary from the closeness of this initial fit of observed and predicted data.



Predicted drawdown response with 4 wells at 1984 abstraction rates

Figure 4

3.5 IMPLICATIONS OF INITIAL RUN RESULTS

After 200 days of abstraction the model predicts drawdowns that approach the base of the aquifer. This would imply that there is a much smaller exploitable resource than predicted previously by other consultants. This is discussed in Chapter 4.

The two major differences in interpretation which have led to this conclusion are the distribution of storativity and the extent of the main linear feature. Subsequent model runs were made to assess the importance of these differences.

3.6 EFFECT OF STORATIVITY DISTRIBUTION

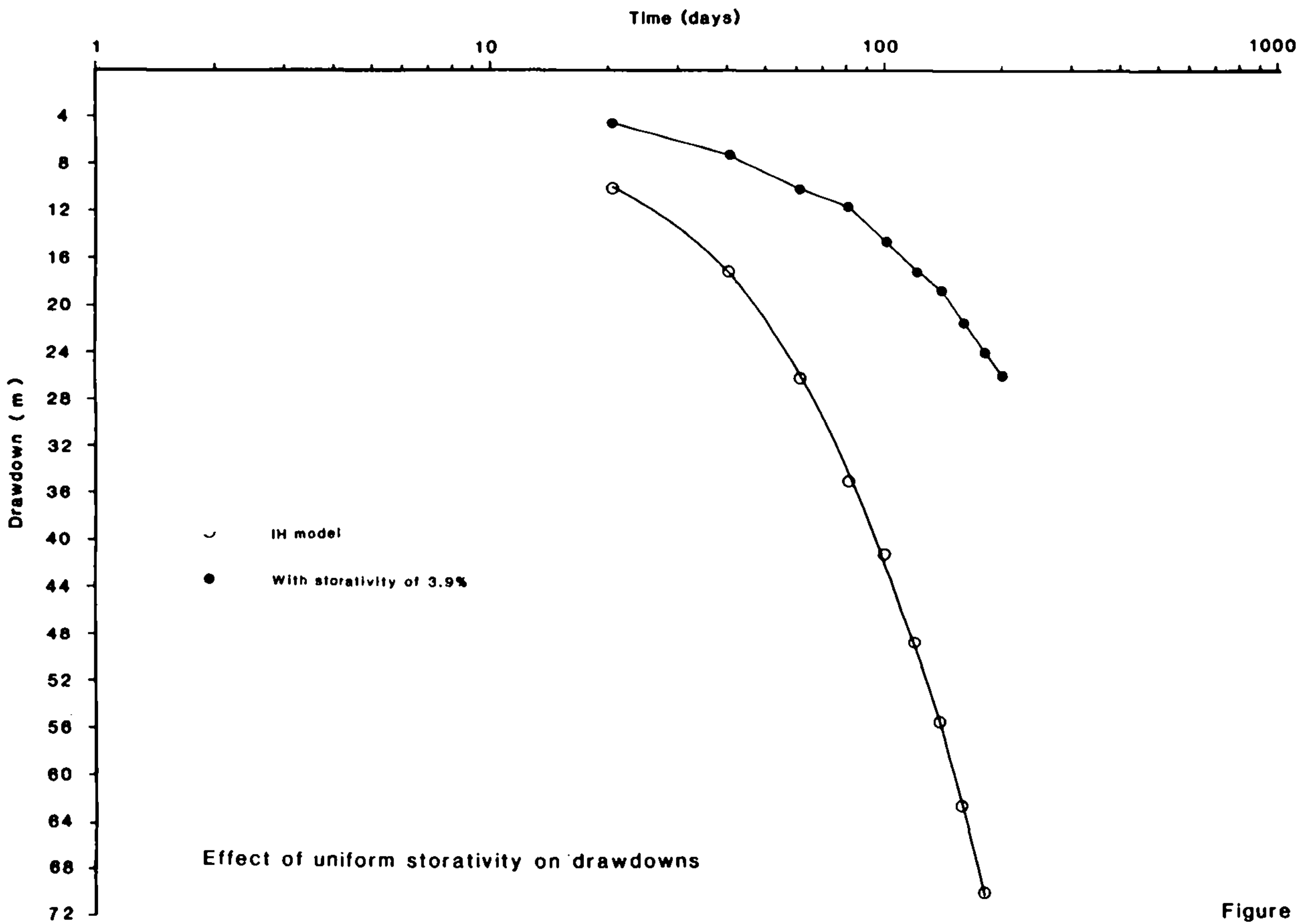
A model run was undertaken substituting a uniform storativity of 3.9% throughout to compare the predicted response with the initial run described above. This value of storativity was applied by Wellfield Services to their model with a single abstraction well. The IH model run was carried out with four abstraction zones and includes the effects of interference drawdown.

The results of this run are shown in Figure 5 where they are compared to the control run. Drawdowns are reduced by 70% after 200 days with a uniform, higher storativity and the form of the time-drawdown response is very different to that observed. This result would suggest that the overall storativity is much less than 3.9%.

3.7 EFFECT OF EXTENDED LINEAR FEATURE

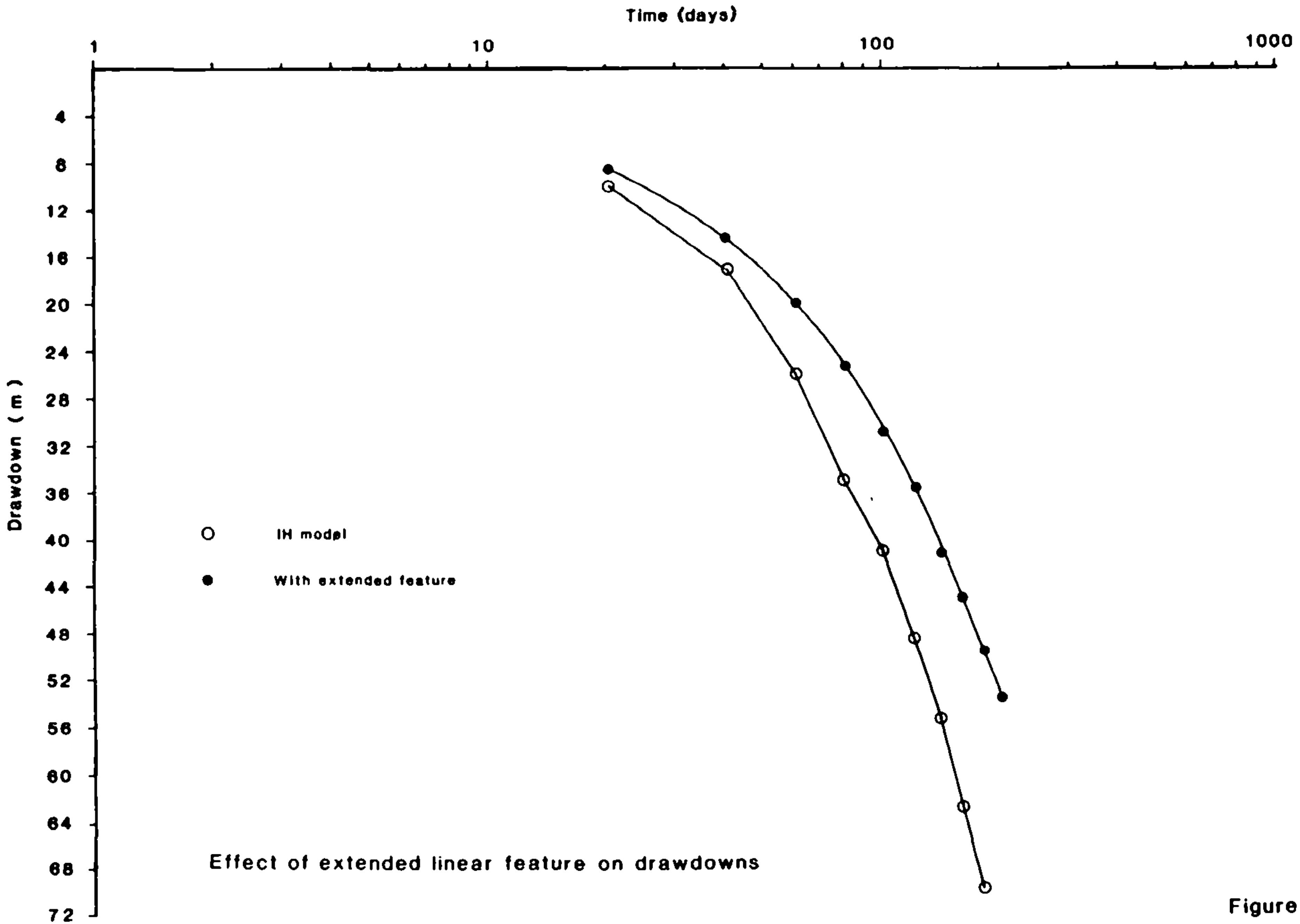
In the control run the linear feature was restricted to the area within Botswana as we have no direct evidence that this feature extends into South Africa. A new run was therefore undertaken extending the linear feature across the international border and 4.5 km into South Africa, retaining the same T and S characteristics used in the control run.

Figure 6 shows the time-drawdown response predicted by the model with an extended zone. Compared to the control run, the drawdowns are reduced by about 30% but the form of the curve is similar to that observed. Had a lower storativity been applied throughout the linear feature, a correlation could also have been achieved with the observed response. It cannot,



Effect of uniform storativity on drawdowns

Figure 5



Effect of extended linear feature on drawdowns

Figure 6

therefore, be concluded that the linear feature is resticted only to Botswana. However, more importantly, the overall implication is that if an extended feature does exist it does not significantly increase the availability of the resources.

3.8 CONCLUSIONS FROM MODEL RUNS

In this chapter we have described how our conceptual interpretation of the aquifer system has been represented by a numerical model. This model provided a satisfactory match to the drawdown response observed during the long term test.

It has been demonstrated that differences in storativity between the linear feature and the country rock must be taken into account. In our model these are 2% and 0.3% respectively. The match obtained with these lower values implies that there is a smaller resource available than has been previously predicted. Resource estimates are presented and discussed in Chapter 4.

The model has also shown that the drawdowns are not significantly reduced by extending the linear feature into South Africa. This also suggests that if this extended feature is present it does not significantly increase the resources availability.

STORAGE ESTIMATES

4.1 INTRODUCTION

In this chapter we present our estimates of the total and available storage and compare these with previous estimates by WLPU(3) and GS (4a,4b). We have based these estimates on a simple division of the aquifer system into the three following areas, which reflect the broad contrasts in storativity:

(a) Country rock - the dolomites or shales where open fissures are infrequent

(b) Intermediate area - where open fissures are frequent

(c) Karst linear feature - in which fissures are further affected by karstification.

Low values of storativity were used in the model for each area. This produced a reasonable match between predicted and observed drawdowns in the linear feature. Recent work in the Pitsanyane Basin dolomites (7) lends support to the values of storativity we have adopted.

In terms of resource evaluation and development we have distinguished total permanent storage and the proportion of this storage which could be recovered due to various development constraints. It was not within the scope of this study to examine how the resource can be exploited. However, the model has been used to illustrate some broad management considerations regarding the development of available storage.

4.3 PREVIOUS ESTIMATES OF TOTAL STORAGE

Total storage is estimated from the product of area, thickness and storativity of the aquifer(s) being considered. Usually it is necessary to make assumptions for one or more of these parameters and this leads to variations in how storage estimates are derived.

Estimates of the total volume of groundwater in storage have been made by WLPU(3) and Selaolo (4a,4b). The WLPU estimate was based on a division of the total catchment area into three layers, each of constant thickness, with different low storativities for each layer in the dolomites or shales. The storativity values represented the fissured area of the aquifer and consequently were applied only to a certain proportion of the total area. Two estimates of total storage were prepared by Selaolo, whereby storativity values, mainly based on the long-term test data, were applied to different aquifer thicknesses in three sub-areas over about half of the catchment area.

4.2.1 WLPU Estimate of Total Storage

The areas of each of the main geological formations within a total catchment area of 60.7 km^2 were measured and then combined into dolomite and shale groups occurring in Botswana or in South Africa. The dolomite and shale formations were divided into upper, middle and lower aquifers and a storativity and thickness assigned to each aquifer. The same thickness was given to each aquifer for both formations (45, 25 and 45 m respectively, totalling 110 m), which gave a weighted mean storativity of 2.2% for the dolomites and 0.88% for the shales. These storativities were selected to represent fissuring within each rock type. An estimate of the area of fissuring ('effective area') was obtained from water balance calculations to be 30% for the dolomites and 50% for the shales.

An estimate of the total storage was then derived from the standard method and presented separately for the dolomites and shales occurring in Botswana and in South Africa.

4.2.2 GS Estimates of Total Storage

Two estimates of storage were produced by Selaolo (4a,4b) using the long-term test data in conjunction with well logs. The same approach was used for each estimate, the assumptions being refined for the second estimate.

The total area selected was about 34 km^2, representing the catchment area within Botswana and a strip varying in width from 1.2 to 2.5 km east of the Notwane river. Consequently, the storage estimate derived does not represent storage within the total catchment, since it would appear that the area selected includes an assumption regarding the area commanded by the wellfield.

The area selected was divided into polygonal elements and classified into three groups:

(i) the areas affected by pumping from the five main dolomite production wells (4422, 4337, 4349, Z4400, 4336)

(ii) the areas affected by pumping from one southern dolomite production well (4423) and three shale production wells (4340, 4358, Z4406)

(iii) areas unaffected by pumping (17 to 23 sub-areas).

These groups approximate to the karst linear zone, intermediate zone and country rock respectively.

The long-term test data were used to define the extent and storativity of the individual elements in groups (i) and (ii). It was assumed that storativity was constant over the area of each element.

For the second estimate storativity values were recalculated and the sequence in the karst area separated into an upper and lower sequence, each 50 m thick. The calculated storativity was then applied only to the top 50 m and 2% assumed for the lower sequence. The area affected by pumping, which was taken to represent the karst area, was decreased from 6.05 km^2 to 3.25 km^2 when the full test results were available with the area unaffected by pumping adjusted accordingly. The volume stored in the upper aquifer (Vu) in the karst area was then computed from

$$Vu = Q\ (m/s)$$

where Q is the total pumpage (m^3), m is the thickness of the upper aquifer and s is the average drawdown.

Elsewhere, and for the lower aquifer, the standard method was used for estimating the storage. An estimate of the aquifer thickness in these elements was based on well logs. In the initial estimate there were 17 elements unaffected by pumping, which were assigned S values of 1 to 0.1% and thicknesses of 10 to 30 m. This was subsequently revised to 23 elements with S values of generally 0.1% and thicknesses of 10 to 40 m.

4.2.3 Comparison of WLPU and GS Estimates of Total Storage

The total volume in storage computed by WLPU was 36.1 Mm^3 within the total catchment area. That computed by Selaolo was 45.3 Mm^3 from the initial approach and 28.5 Mm^3 from the revised estimate both based on about half the catchment area. If it is assumed that the WLPU 'effective area' represents the karst and intermediate zones then the WLPU estimate adjusted to the same area defined by GS reduces to 20 Mm^3, as given in Table 2.

The most important difference between the two previous estimates is the storativity values considered to apply in the karst area. The upper karst in the GS estimate accounts for nearly two-thirds of their estimate of the total volume in storage. WLPU adopted a storativity of 3% for the top 45 m of this area whereas GS assumed that the higher storativity value averaging 11.5% (range 5 to 23%) obtained from the long term test analysis applied to a depth of 50 m, since this was the total drawdown recorded during the pumping tests. This assumption is critical to the storage estimate and is discussed in more detail in subsequent sections.

4.3 IH ESTIMATES OF TOTAL STORAGE

The model represents an area of about 65 km^2, approximately that of the catchment area. Within this area we have distinguished a major linear feature, an intermediate zone of fissuring and the country rock of the dolomites and shales.

It was necessary to simplify the representation of the physical boundaries of each area for the model grid. However, for our storage estimates we have defined and measured each area using 1:25000 scale maps (Selaolo, 1984). The areas included were as follows:

I Karst - the shallow karst mapped by Selaolo extending E-W through the main dolomite production wells and into South Africa.

II Intermediate zones (a) the area of fractured dolomites in the southernmost part of the dolomite outcrop and (b) a zone 500 m wide along the major N-S lineation followed by the Notwane river north of the main karst feature.

III Dolomite country rock - the remaining areas of dolomite outcrop within the area represented by the model

Table 2

GS and WLPU Estimates of Total Storage (1)

Area	GS First Estimate Thickness (m)	GS First Estimate Area (km^2)	GS First Estimate S (%)	GS First Estimate Total Storage (Mm^3)	GS Revised Estimate Thickness (m)	GS Revised Estimate Area (km^2)	GS Revised Estimate S (%)	GS Revised Estimate Total Storage (Mm^3)	WLPU Estimate Thickness (m)	WLPU Estimate Effective Area (2) (km^2)	WLPU Estimate S (%)	WLPU Estimate Total Storage (Mm^3)
Karst	100	6.05	10.5 (av)	38.11	50 U)		11.5	18.2	110		2.2 (dolomite)	
					)	3.2	(av)					
					50 L)		2	3.9				19.6
											0.88 (shales)	
Intermediate	30 ~ 60	2.18	(≈1)	5.49	20 ~ 60	2.2		6.25	110			
Country	10 ~ 20	25.42	0.1	1.72	10 ~ 40	28.4	0.1	0.14	110	21	nil	
		33.65		45.32		33.8		28.5				19.6

(1) These are shown for a part catchment area of 34 km^2

(2) 30% for dolomite, 50% for shales

IV Shale country rock - two areas: (a) the southern outcrop and (b) the outlier east of Ramotswa.

A uniform saturated thickness of 85 m was assumed for the whole catchment area, representing an average water table position of 1015 m OD and aquifer base at 930 m OD. It is likely that open fissures are infrequent below a depth of 100 m. However, at depths of less than 100 m groundwater will occur in open fissures throughout the rock formations producing a general zone of saturation rather than discrete aquifer layers. Boreholes will intersect these fissures at different depths. Hence, we have chosen not to distinguish aquifer layers but have tried to take into account the difference in the density of fissuring by the storativity value; the values adopted being those applied in the model to represent each area.

Table 3 gives our estimates of the volume in total storage throughout the approximate area of the catchment for each sub-area of the aquifer system. This produces a total storage of 16.5 Mm^3, much lower than the estimates by both WLPU or GS for the same area of the catchment.

We have adopted similar storativity values for the karst and intermediate areas to those by WLPU. However, we estimate that such areas represent 17% of the catchment area compared.to 30% adopted by WLPU. GS assume that the area of karst is represented by the cones of depression developed by the long term test, whereas we have attempted to define this area from maps of the shallow karst. Whilst the area of karst is similar in both the IH and GS estimates, these are in fact related to somewhat different areas of the catchment.

We have not included vertical variations in storativity in our simplified model representation, whereas GS have assumed high values of storage extending to a depth of 50 m throughout the karst zone and, consequently, obtain very large estimates of storage. In our opinion, it is more likely that such high storativity values relate only to the top 5 m of the karst aquifer as indicated by the breakaway in the long-term pump test drawdowns. Furthermore, the extent of a shallow, thin aquifer of high storativity (11%) must be very uncertain given the small number and distribution of the high yielding wells. In any case the additional resources that would be contained in a 5 m thick zone extending throughout the <u>whole</u> of our delineated karst area represents about 1.5 Mm^3 extra.

Table 3

Total Storage in Catchment Area

Aquifer	Model Area (km^2)	Mapped Area (km^2)	Storativity (%)	Thickness (m)	Total storage (Mm^3)
<u>DOLOMITE</u>					
Karst	2.7	2.8		85	4.76
Intermediate	3.5	3.7	1	85	3.14
Country	32.2	31.1	0.3	85	7.93
<u>SHALES</u>					
Southern outcrop	16.6	16.6	0.3	85	0.42
Outlier	11.6	11.0	0.3	85	0.28
		65.2			16.53

Certainly, large volumes of storage in the karst area are not suggested by the available evidence. Although recovery following the long term pumping test was relatively rapid this reflects the characteristics of the linear feature rather than indicating large volumes in storage.

4.4 IH ESTIMATES OF AVAILABLE STORAGE

We have estimated the total volume in storage within the catchment area to be 16.5 Mm^3. In this section we discuss the proportion of this storage available for development.

A detailed estimate of available storage was not attempted by WLPU(3). They suggested that only 50% of the total storage within the catchment could in practice be recovered due to the locations of the production wells in the western part of the catchment or 18 Mm^3.

An estimate of available storage was made by Selaolo (4a, 4b) totalling 18.5 Mm^3, as shown in Table 4. In their estimate of total storage they had already assumed that only 34 km^2 of the catchment area represented potential storage available to the wellfield. They then assumed that only a certain proportion of this storage could be recovered in relation to the aquifer thickness: 70% in the karst area, 50% in the intermediate area, and 30% in the country rock areas.

Our estimates of available storage are based on a similar approach:

* we have excluded the area of the catchment in South Africa 2 km east of the Notwane river, which is unlikely to be affected by the wellfield abstraction. This reduces the area to 42.6 km^2.

* only a proportion of the total storage within each of the sub-areas can be recovered before drawdowns in the pumped wells reach critical levels.

Hence, in the absence of recharge, the available storage becomes a function of areal as well as vertical constraints, since these are related to the extent of the multiple cone of depression when the maximum allowable pumping water level is reached in each production well.

We have adopted similar values to GS for the proportion of total storage that can be recovered but have applied these to the total saturated thickness: 70% in the karst area, 50% in the intermediate area, and 20% in

Table 4

GS Estimates of Recoverable Storage

Area	Thickness (m)	Total Storage (Mm^3)	Recovery	Recoverable storage (Mm^3)
Karst	100	22.1	70	15.47
Intermediate	20 ~ 60	6.25	50	3.12
Country	10 ~ 40	0.14	30	0.04
		28.50		18.63

the country rock areas. These values were also adopted for the Pitsanyane dolomite aquifer (7). On this basis we estimate the recoverable storage to be 6 Mm^3 as given in Table 5.

For reasons given in previous sections our estimate of recoverable storage is much lower than that obtained by GS. This relates mainly to the high storativity values and thicknesses adopted by GS for the karst zone.

They have also adopted much reduced thicknesses in the country rock area in particular. Defining the aquifer thickness can be misleading, since this might only represent sub-vertical fissures intersected at some point in each borehole rather than a sub-horizontal layering. To overcome this we have assumed that a zone of saturation extends throughout and then represented variations in the occurrence of open fissures by applying different reduced storativity values.

A very limited storage potential is indicated by our estimates for the shale formations. We have applied a low storativity representing semi-confined conditions: the generally low transmissivities produce local deep cones of depression which may prevent dewatering of large areas of the shale country rock. However, in 1984 0.375 Mm^3 was abstracted from the shale production wells which suggests that our estimate of the recoverable resource may be conservative. However, if a 1% storativity value is assumed for well Z4406, rather than the 12% used by GS, the comparable estimate for the shales in Botswana by GS is about 0.4 Mm^3. Either estimate suggests that abstraction from the shale formtions will depend more on intercepting recharge than by developing storage.

4.5 IMPLICATIONS OF MODEL FOR DEVELOPMENT OF STORAGE

The model is a simplified representation of the key features of the aquifer system. We have not considered recharge, vertical variations in storativity or abstraction from all of the production wells, although the model can be used to examine these aspects as well as alternative strategies for developing the available storage.

Table 5

Available and Recoverable Storage

Aquifer	Area (km^2)	Available Storage (Mm^3)	Recovery	Recoverable Storage (Mm^3)
DOLOMITE				
Karst	2.8	4.8	70	3.4
Intermediate	3.7	3.1	50	1.6
Country rock:				
Botswana	12.4	3.2	20	0.6
S. Africa	8.2	2.1	20	0.4
SHALES				
Botswana	10.0	0.3	20	0.1
S. Africa	5.5	0.1	20	
	42.6	13.6		6.1

The most important implication of the model is the manner in which the intermediate and country rock areas influence the ability to recover storage using wells in the linear feature. This was demonstrated by the long term test in 1984, and confirmed by the model results, which showed that after about 40 days with the high pumping rate conditions the rate of drawdown shows a marked increase. The favourable aquifer conditions suggested by the earlier short term tests are likely to occur over a limited area only.

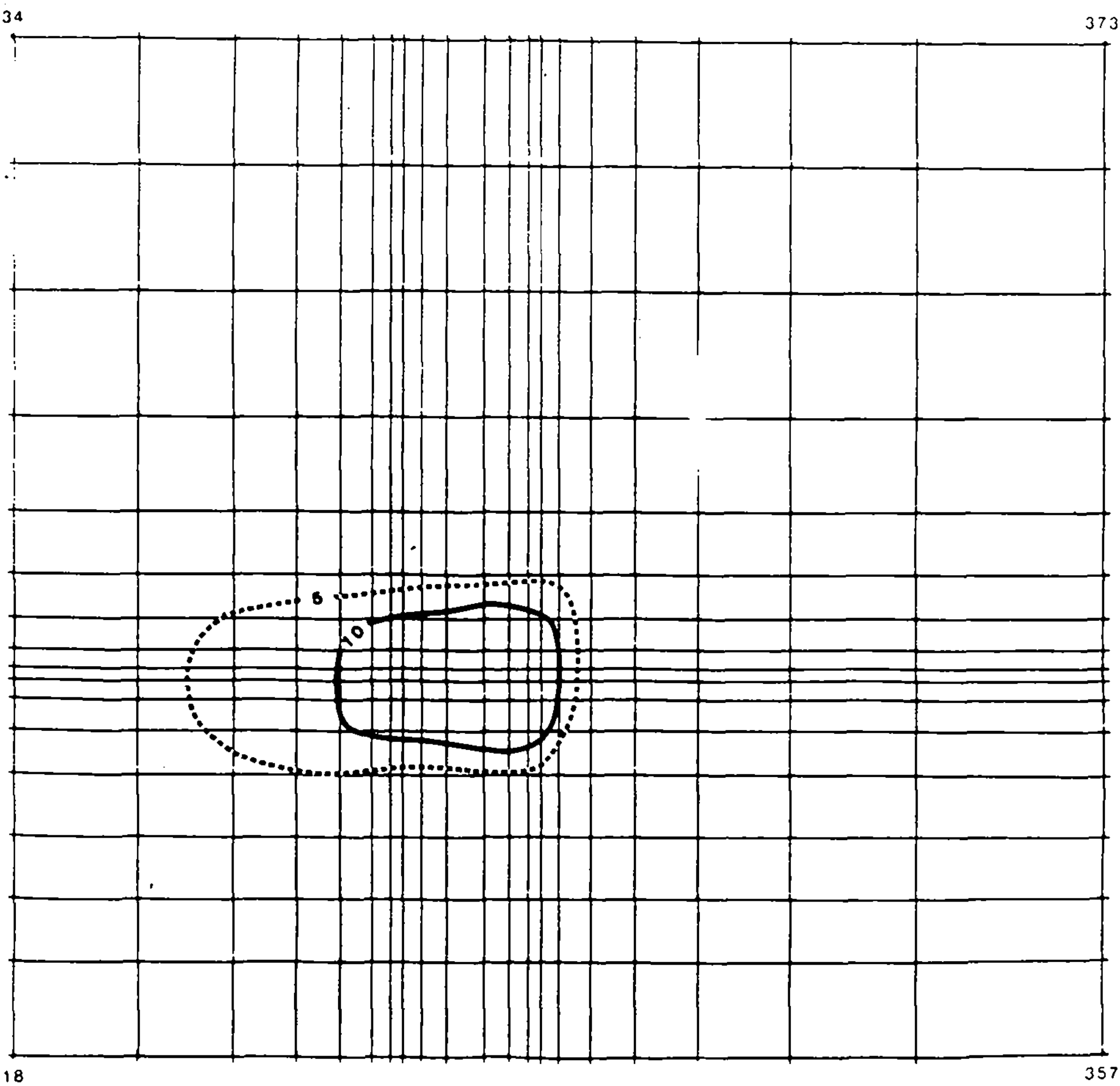
The development constraint imposed by the restricted area of shallow karst, which supports the initially high yields, is demonstrated by the drawdown pattern shown in Figures 7 and 8. These are shown for an abstraction schedule of four wells in the linear feature pumping at the 1984 abstraction rates.

During the first 40 days of abstraction the cone of depression extends rapidly and preferentially along the linear feature. As abstraction continues, the pumping rate is maintained by intercepting storage over a progressively increasing area of the intermediate and country rock areas. However, as these come to dominate the abstraction, drawdowns in the production wells begin to increase rapidly and after 200 days approach the base of the aquifer.

If the same abstraction schedule is applied to a karst feature extending into South Africa a drawdown pattern would result similar to that shown in Figure 9. The cone of depression within Botswana is similar to a feature of limited extent, and, although the cone of depression spreads further into South Africa, the increase is relatively small and large drawdowns still occur at the production wells. This demonstrates that the country rock still dominates the abstraction.

The implication of these results regarding development of storage in the absence of recharge, is a two-phased operational strategy. Initially, high pumping rates can be maintained for a short period but, as drawdowns reach critical levels, these rates will need to be cut-back. To compensate for this, additional wells would need to develop storage in the intermediate areas in particular so that the total abstraction is maintained by a larger number of low yielding, closely-spaced wells to draw levels down as deep as possible. To maximize the command of storage wells should be located to tap the deeper fracture zones.

Drawdown pattern for 4 wells at 1984 abstraction rates after 40 days with limited linear feature.



Figure

Drawdown pattern for 4 wells at 1984 abstraction rates

after 200 days with limited linear feature.

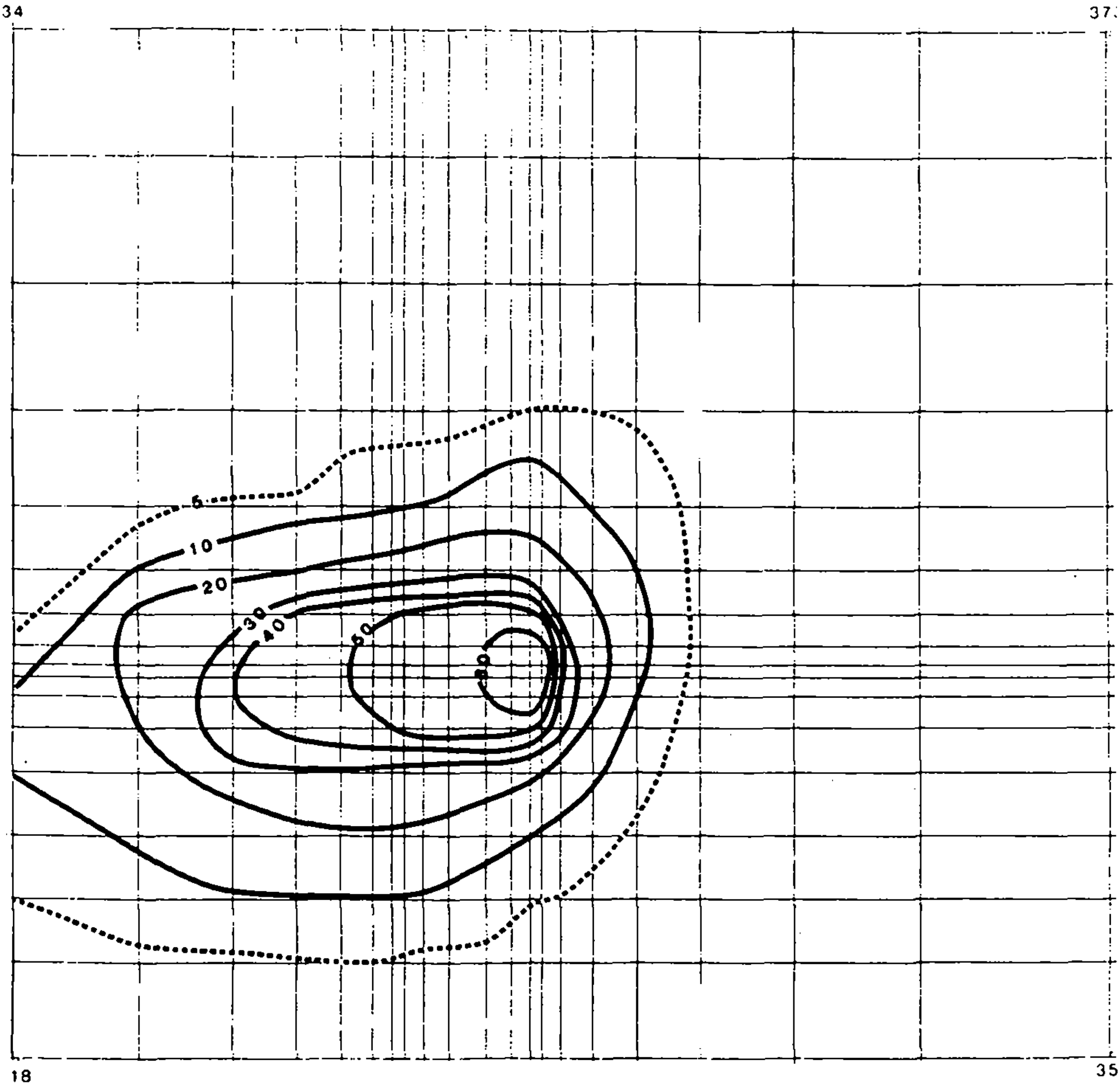


Figure 8

Drawdown pattern for 4 wells at 1984 abstraction rates after 200 days with extended feature.

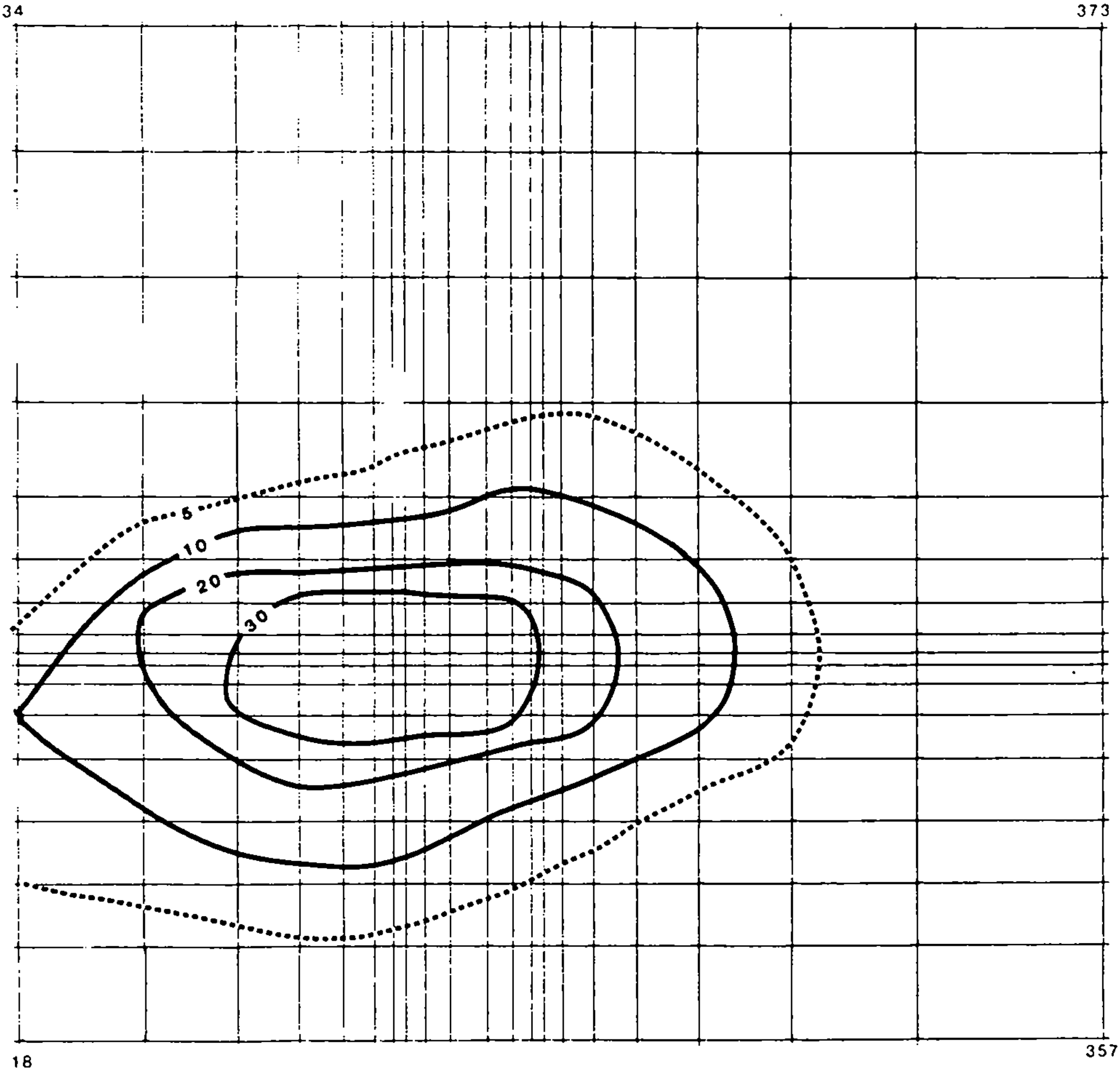


Figure 9

CONCLUDING REMARKS

1. The key features of the aquifer system are as follows: a major linear karst zone, areas of fissuring and the country rock where open fissures are infrequent.

2. The broad hydraulic characteristics of each part of the system were represented in a simplified manner in a numerical model of the catchment. An acceptable match was obtained between the model predicted drawdowns and these observed during the long term test in 1984. This was achieved with low values of storativity.

The model results indicated:

(a) the system response with longer term pumping becomes dominated by the poorer aquifer characteristics of the intermediate and country rock areas.

(b) the linear feature may be restricted to Botswana but, in any case, does not increase the available resources significantly.

4. The recoverable storage is estimated to be about 6 Mm^3. The larger volumes estimated by previous studies were based on a larger area of fissured aquifer and the assumption that high storativities apply to the top 50 m of the karst area. The karst and intermediate areas, together with their vertical variations in storativity and thickness, need to be defined more closely.

5. High rates of abstraction can only be supported for a limited period without recharge. For longer term supplies the abstraction should be spread over a larger number of low yielding wells.

6. *We recommend that a study be undertaken to determine* a suitable operational strategy for the optimum development of the available resources, which should include an evaluation of recharge and vertical variations in storativity. The new model could be adapted for this purpose.

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