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ARAB POTASH PROJECT

GROUNDWATER MODEL STUDY

OF

GHOR SAFI

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SUMMARY

The initial water requirements of the Arab Potash Company potash refinery are to be met by groundwater abstraction from an alluvial fan aquifer at Ghor Safi, the largest of the alluvial fans in the south-eastern ghors of the Dead Sea Rift Valley. The future groundwater supply contribution will depend upon the aquifer response to the planned and the proposed future increase in the industrial water requirements, as well as to changes in recharge that are likely to take place as a result of agricultural development.

This report describes the development of a computer based ground-water model of Ghor Safi to examine the contribution of groundwater supplies for industrial use to aid in the development of the total water resources of this area.

The inherent complexity of the Ghor Safi groundwater system has been revealed during the construction of a steady-state model of the existing conditions. The alluvial fan is now believed to consist broadly of at least two aquifer units separated by a discontinuous clay layer. This clay layer exerts an important influence on the areal distribution of recharge and groundwater flow through the system.

A time-varying model has been constructed to predict the aquifer response to the initial abstraction requirements and to likely alterations in the amount of recharge. Verification of this model indicates that the volume in aquifer storage is about 40 million m^3. Whilst the existing recharge conditions can support the initial water requirements, large-scale agricultural changes which significantly reduce recharge will lead to a depletion in storage such that the existing wellfield would not be able to meet the industrial water requirement. As a result, sole reliance on groundwater for industrial supplies will not be possible and an alternative source of supply will be required. The time when this alternative source of supply will be required is dependent upon the agricultural development programme. If this programme proceeds immediately and is fully implemented in the next three years then an alternative source of supply will be required by 1985.

INTRODUCTION

The initial water requirements of the potash refinery are to be met by a groundwater abstraction scheme at Ghor Safi. Recharge of the aquifer is related to agricultural use of the Wadi Hasa and has been estimated to be similar to these requirements[1,2]. However, major agricultural improvements are being introduced[3] that could reduce recharge significantly and lead to a decline in aquifer storage[4]. As a result, groundwater abstraction may have to be replaced by alternative surface water supplies to an extent dependent upon changes in the present groundwater regime.

This report describes the development of a computer based groundwater model of Ghor Safi that brings together field data into a single analytical framework. This has improved our understanding of the complex groundwater system enabling us to predict subsequently the aquifer response to the planned abstraction and the effects of alterations in recharge. The results could be used to aid the optimum development of the available water resources.

MODEL DEVELOPMENT

The Ghor Safi alluvial fan consists of a variable sequence of coarse and fine material deposited in a shifting network of flood channels. The present agricultural practice and the manner in which water is lost from the system have given rise to a complex hydrological regime.

1 *Final Feasibility Report, Arab Potash Project, Vol IX, Appendix N, Hydrology (Dec. 1977).*

2 *Further Investigations of Ghor Safi, Arab Potash Project, Contract III, Fresh Water Supplies (Apr. 1979).*

3 *Mujib and Southern Ghors Irrigation Project, Feasibility Report (Jan. 1979).*

4 *A Review of the Water Supply to the Arab Potash Project with respect of the Mujib and Southern Ghors Irrigation Project Feasibility Study (Apr. 1980).*

Information on the groundwater system has been assembled largely within the past three years as attention has become focused on Ghor Safi as a source of water supply for both industrial and agricultural development.

The data available at the start of the model study were used to develop a conceptual model of the system as a single hydraulic unit in direct connection with the fan-edge receiving recharge over the whole irrigated area. This interpretation was represented by an initial digital model.

The results of the initial model revealed that the original interpretation was an oversimplification of the aquifer behaviour. As a consequence, the geological conditions were re-assessed by incorporating new information which became available from the wellfield constructed during the study.

The aquifer was shown to consist broadly of at least two hydrogeological units separated over much of the fan area by a layer of low permeability. This layer exerts a dominant control on flow through the system as well as on the distribution of recharge and has led to a revised conceptual model of the aquifer behaviour. The data used for the initial model were re-interpreted to represent the new conceptual model, from which a model of the main aquifer under steady-state, average conditions was constructed and calibrated.

Alterations to the geological model required that the potential recharge to each unit had to be distinguished. Consequently, a complementary review of the previous recharge assumptions was carried out to establish starting values of each recharge component for testing by the model.

MODELLING PROCEDURE

The aquifer can be represented as a grid and the flow between each node described by differential equations. Computer techniques provide a rapid means of solving these equations numerically and of balancing inputs and outputs with storage changes resulting from variations in water levels. However, it is only in recent years that such techniques have developed sufficiently to be applied to a complex aquifer system such as that of Ghor Safi.

Reasonable estimates of unknown variables are produced by the model through a procedure of calibration, where each of the model parameters is systematically adjusted. In this study, the major unknown variables are a detailed distribution of recharge and transmissivity. Each of these variables is given an initial value and the model is fitted iteratively using an optimisation technique until model predicted water levels are in as close agreement as possible with those observed; the goodness of fit is expressed as a root mean square error.

The aquifer is first considered to be in a steady-state where changes in storage are zero and flow into and through the model is considered constant. Although this greatly simplifies the calibration procedure, the resulting values of transmissivity and recharge represent average values consistent with the observed water level configuration.

A time-varying model is developed from the calibrated, steady-state model by introducing storage changes and variations in recharge with time. The model is calibrated by adjusting these parameters until variations in water level predicted by the model match as closely as possible the records of historical water level changes. After the calibration procedure selected schedules of abstraction or alterations in recharge are introduced into the model to predict the water level response at chosen intervals of time. This enables the time-varying model to be used as an aid to management of the aquifer.

ROLE OF GROUNDWATER SUPPLIES

Ghor Safi is the only area of the south-eastern ghors capable of meeting the water supply requirements of the potash process plant. The Wadi Hasa is the major water resource at Ghor Safi, having an 80% reliable baseflow of nearly 24 million m^3/year. The alluvial aquifer forms part of the storage within the Wadi Hasa catchment and is dependent upon the Wadi Hasa for recharge.

The Wadi Hasa is directly utilized as a source of irrigation water for agriculture at Ghor Safi and in order to minimize the effect on the existing agriculture, as well as to assist in developing the water resources more effectively, the initial Stage I water requirements of the process plant of 5.7 million m^3/year are to be met by a wellfield at Safi.

Groundwater abstraction for the potash refinery will begin in 1982 and build up to the full Stage I requirement by 1984. The aquifer response will be monitored to observe whether significant depletion of storage occurs and if water quality deteriorates to an unacceptable level. Should these effects occur other options have been proposed to supply the process plant, which involve the direct utilisation of the surface flow of the Wadi Hasa. In the longer term, it is likely that the Stage II water supply requirement of 9 million m^3/year will require use of the Wadi Hasa to an extent dependent on the proven groundwater supply.

The role of groundwater as a source of supply for APC could be jeopardized by significant improvements in the agricultural use of the Wadi Hasa or by increased groundwater abstraction by other users. Whilst agricultural improvements will reduce recharge, which under existing conditions is estimated to be similar to the initial water requirement of the process plant, they could also lead to greater availability of the Wadi Hasa for APC without affecting agricultural water supplies if agricultural improvements are restricted to the present area.

The hydrological conditions at Ghor Safi are already undergoing change with the construction of six new production wells by other users and by the introduction of drip irrigation by local landowners. In addition, the Mujib and Southern Ghors Irrigation Scheme proposes to fully utilize the Wadi Hasa for agricultural development. The proposals include replacing the existing distribution channels by a piped system and converting the traditional furrow irrigation to drip. The resulting saving in water would be used to reclaim poor quality land and thus extend the area under cultivation.

The change in recharge will depend largely upon the type and extent of agricultural development. Full implementation of the Mujib

Scheme proposals could reduce recharge to that from flood flows and underflow, with potentially serious effects on the use of groundwater for APC supplies, yet will not enable APC to replace their groundwater supply by direct diversion of the Wadi Hasa, which would be fully utilized for agriculture. The possible effects of the Mujib Scheme, which could be completed by 1986, on APC supplies were reported in April, 1980.

We have examined the role of groundwater supplies for the process plant by predicting the aquifer response to abstraction under existing recharge conditions and also under possible changes in recharge. Selected conjunctive use schemes that could develop the total available resources for both industrial and agricultural use have also been examined to indicate a possible long-term role for the wellfield under reduced recharge conditions.

INITIAL MODEL

Our first model of the groundwater system was established from information available at the beginning of the study. For this model the system was represented as a single aquifer unit extending over the whole of Ghor Safi and in direct connection with the fan-edge area. Recharge was assumed to occur over the total irrigated area and along the full length of the Wadi Hasa channel.

SUMMARY OF AVAILABLE INFORMATION

Geological information was available at the beginning of the model study from the following:

- records of existing private boreholes (S1 to S15)
- two exploratory boreholes (BN309, BN300)
- seven observation boreholes (OB1 to 7)
- five shallow observation boreholes (JVA 1, 2, 4, 5, 6)
- several new private and JVA production boreholes
- a geophysical survey of the wellfield area.

However, much of this information relates to the central area of the fan around Safi and there are no deep boreholes in the fan-edge area.

Estimates of potential recharge and its distribution were based on existing records of wadi flow and hydrological information obtained from routine monitoring and periodic surveys of wadi flow distribution. Further information, on crop water requirements in particular, was available from the Mujib and Southern Ghors Irrigation Study. However, losses in the fan-edge area could not be quantified reliably, partly because of the restricted access into this area.

DESCRIPTION OF INITIAL MODEL

The boundaries of the initial model are shown in Figure 1. In order to represent the shape of the fan by a square grid mesh the model grid was orientated in a north-east direction. A nodal interval of 500 m was selected producing a grid of 127 nodes for the whole area of Ghor Safi.

The components of the hydrological cycle are illustrated in Figure 2. Field observations and data from other sources were used to quantify each component, excluding flood flows and shallow groundwater evapotranspiration losses. The total annual input or output of each component was shared equally between the number of nodes involved in the particular component, except for the undiverted baseflow and springflow.

Shallow groundwater evapotranspiration is likely to be a major component of loss from the aquifer in the fan-edge area but cannot be quantified with the available information. As underflow loss will be restricted by impermeable clays and saline water at the fan-edge, the shallow groundwater component was estimated as the difference between total input to the system and the output from springs and borehole abstraction.

The Feasibility Study of 1977 estimated potential recharge for Ghor Safi as a whole to be between 6 and 13 million m^3/year. Subsequent investigations in 1979 indicated that recharge in the area of the well-field alone was about 6 million m^3/year. The total potential recharge used for the initial model was 13 million m^3/year, made up as follows:

Undiverted baseflow	:	2.25 million m^3/year
Canal seepage	:	9.24 million m^3/year
Field seepage	:	1.5 million m^3/year

A permeability of 35 m/d would be required to transmit the annual volume of potential recharge through the aquifer with the present average hydraulic gradient of about 1:200. This permeability is lower than that derived from pumping tests but was adopted as an overall value for the initial model to reflect the increase towards the fan-edge of finer material with a low permeability.

The base of the aquifer was represented as an even surface sloping north-west and the top of the aquifer interpolated from water level data.

RESULTS OF INITIAL MODEL

At first a reasonable correlation between observed and model predicted water levels was produced. However, the constant head boundary along the eastern escarpment was altered to an impermeable boundary to be more representative of Lisan material preventing the transfer of any groundwater flow from the rocks forming the eastern highlands. The model then predicted water levels which diverged markedly from those observed, indicating that heads within the model has been supported by the eastern boundary acting as a recharge source.

Additional recharge or a lower permeability would be required to raise model predicted levels to those observed but neither were consistent with the field data interpretation.

The results from the initial model strongly suggested that some other control on flow must be present within the sequence and, hence, that the system must be more complex than was inferred from the available information on the aquifer conditions.

REVISED CONCEPTUAL MODEL

New information on the aquifer sequence, water levels and aquifer parameters became available from the wellfield being constructed at Safi during the course of the model study. This information enabled local variations in the alluvial sequence to be co-ordinated into two broad hydrogeological units from which a revised conceptual model of the groundwater system was developed.

HYDROGEOLOGICAL INTERPRETATION

The alluvial fan sequence is illustrated in Figures 3 and 4 by geological sections. The sequence consists broadly of two main geological units of coarse and finer material respectively, deposited during periods of different erosional activity. The sequence slopes towards the fan-edge with the result that water is encountered at progressively higher levels within the sequence down the fan. Both units have areas of unconfined and confined conditions, although these areas occur at different elevations across the fan. The two main units may be summarised as follows:

Upper unit — Generally finer-grained deposits but with lenses of gravel of a permeability sufficient to transmit water to the fan-edge to which it is connected.

Lower unit — The main aquifer, consisting of a relatively thick sequence of predominantly coarse material with a high permeability but not directly connected to the fan-edge.

A clay layer, or a series of clay lenses, at the base of the upper unit separates the two units over a large area of the fan and confines the lower unit. This clay has a dominant control on the movement of groundwater through the system.

A revised interpretation of the system as a two-layered aquifer is shown conceptually in Figure 5. This interpretation had the following implications for the model representation of the system:

- the lower unit is unlikely to lose water by underflow and is not connected directly to the fan-edge. However, as the piezometric surface of the lower unit is at a higher elevation than the upper unit, loss from the lower unit must take place by upward leakage through the overlying clay into the upper unit.

- the water table of the lower unit in the unconfined zone is locally in continuity with that of the upper unit. Hence, flow can also occur across the edge of the clay from the lower to the upper unit.

- recharge to each unit only occurs where clay is absent. The areal extent of the main aquifer where recharge could occur was defined in order that the volume of recharge to this aquifer could be estimated.

- separate piezometric surfaces could be distinguished from the borehole records from the depth of penetration in relation to the clay layer. This enabled more reliable water level maps to be prepared than was possible previously, when it had to be assumed that all water levels related to a single aquifer.

BOUNDARIES OF THE MAIN AQUIFER

Whilst the initial model included the whole of Ghor Safi, the main aquifer extends over only part of Ghor Safi and is bounded by the following:

- shallow Lisan Marls, identified by a geophysical survey and at borehole OB7 (see Figure 3), form the southern boundary; only the upper sequence is thought to be present south of this boundary.

- ridges of Lisan deposits of lower permeability than the alluvial fan sequence, project from the eastern escarpment and would have generally prevented the deposition of a significant thickness of sands and gravels in the Wadi Abyad area. The main aquifer is therefore assumed to be generally absent in this area and the foot of the Wadi Abyad fan has been taken as a boundary to the main aquifer.

- northwards, beyond SPB4, the whole sequence consists of finer grained material (see Figure 3).

The boundaries of the initial model were altered to represent the area of the main aquifer.

HYDROLOGICAL COMPONENTS

Revised inputs

For the initial model recharge was assumed to occur across the whole irrigated area. In the revised conceptual model the unconfined zone of the main aquifer unit is distinguished from that of the upper unit. The area of the unconfined zone of the main aquifer receiving recharge is about 3.5 km^2. This area includes the upper 2.5 km of the wadi channel and an irrigated area of about 1.5 km^2.

The assumptions made previously with regard to recharge were examined to re-estimate the potential contribution of each recharge component for subsequent testing by the model calibration procedure. The following assumptions were made to provide initial estimates:

- the wadi channel deposits are not connected with the main aquifer downstream of the clay edge. Consequently, the recharge from undiverted baseflow was proportioned according to the unconfined zone of each unit. Recharge to the main aquifer from this source is estimated to be 1.8 million m^3/year.

- flood flows are irregular in amount from year to year. There is insufficient information to quantify reliably the average recharge contribution from this source, but we believe it is unlikely to exceed more than 0.5 million m^3/year based on water level hydrographs. We have therefore excluded the flood flow recharge component from the model.

- unlined canals, from which seepage occurs, are present over an area of about 1 km^2 between boreholes S2 and SPB1. The volume of seepage of 1.7 million m^3/year was estimated as the difference between available diverted baseflow and the field water requirement at a field efficiency of 30%.

- the deep percolation of water applied to the fields could be effectively prevented by the intermittent application of irrigation water together with high soil moisture deficits. Consequently, this source of recharge was excluded from the model.

Undiverted baseflow, flood flows and canal seepage also contribute recharge to the upper aquifer giving rise to the water table conditions encountered in this aquifer.

Losses

The main aquifer is not in direct connection with the fan-edge area and losses are restricted to the following:

- upward leakage through the confining clay where the piezometric surface of the main aquifer is at a higher elevation than the water table of the upper sequence.

- transfer of water over the edge of the clay into the upper sequence where the water table of the main aquifer in the unconfined zone is in continuity with that of the upper sequence.

- groundwater abstraction from the main aquifer.

Ultimately, recharge to the whole system is lost in the fan-edge areas as springflow and shallow groundwater evapotranspiration from the upper aquifer.

DESCRIPTION OF THE GROUNDWATER MODEL

The revised conceptual model of Ghor Safi is based on a two layered system. Abstraction is to take place from the lower unit, or main aquifer, and more information is available concerning this unit particularly in the wellfield area. The modelling study has concentrated on constructing a model of this aquifer, representing the upper unit only in so far as it influences the direction of groundwater flow through the clay.

The area represented by the groundwater model is shown in Figure 6, which also shows the positions of the observation and production boreholes used as data points. The model covers an area of nearly 20 km^2 of Ghor Safi and consists of 327 nodes in a rectangular mesh of 25 by 21 nodes. A nodal spacing of 250 m was adopted generally, but this spacing was increased to 500 m along the northern boundary, where information is limited, and reduced to 125 m in the upper part of the wadi channel in order to represent this area more adequately.

CONSTRUCTION OF THE STEADY-STATE MODEL

Using the revised conceptual model as a basis, a new set of input data were prepared for each of the major hydrogeological components of the main aquifer system: the elevation of the top and base of the main aquifer, areal variations in aquifer permeability and the factors governing flow between the upper and lower aquifers. It was necessary to extrapolate conditions in the peripheral areas of the model since the field data generally relate to the wellfield around Safi.

Abstraction from existing boreholes was estimated to be 0.75 million m^3/year in 1977, almost all of which occurs in the winter irrigation season. However, 84% of the total abstraction was obtained from one borehole at Safi and this borehole was converted to drip irrigation use in 1979. The total abstraction will now be much smaller, perhaps 5% of the annual recharge to the main aquifer, and for the modelling study abstraction has been excluded.

Top and base of the main aquifer

The elevation of the base of the main aquifer is shown in Figure 7.

The main aquifer sequence was deposited on an eroded surface of Lisan Marl having a generally uniform dip to the north-west. A buried channel has been defined passing beneath the upper part of the present wadi channel through Safi based on the geophysical survey results and the greater thickness of deposits encountered at boreholes S2 and OB2.

In the confined zone the top of the main aquifer is defined by the base of the confining clay layer, as shown in Figure 8, and in the unconfined zone the ground surface forms the top of the main aquifer. Contoured values of the saturated aquifer thickness of the main aquifer are shown in Figure 9. The maximum saturated aquifer thickness of 45m occurs in the buried channel at Safi. We have assumed a minimum thickness of 1 m, in particular along the southern boundary, so as to simplify the model representation of the boundary areas.

Permeability

Pumping tests carried out on the new wellfield boreholes (SPB1 to 5) indicated that high permeabilities occur over a wider area than was inferred previously from the limited programme of aquifer tests carried out in 1977. The results are given in Tables 1 and 2. The permeability of the aquifer varies from about 100 m/d at borehole SPB 4 to 1000 m/d at borehole SPB 5. The median permeability based on the pumping tests results given in Table 2 is about 300 m/d, which is consistent with a sequence of sands and gravels. The very high peremeability at borehole SPB5 may be exceptional, perhaps representing the local occurrence of coarser deposits, such as cobbles or boulders. The average permeability based on the remaining results is about 270 m/d, but we have chosen a more conservative value of 200 m/d as the maximum model permeability to represent those areas where the aquifer sequence consists predominantly of sands and gravels. The proportion of sands and gravels in the sequence decreases towards the fan-edge. The model distribution of permeability has been selected on the basis of borehole logs, giving a minimum permeability of 60 m/d in the fan-edge area west of Safi.

Initially the permeability of the aquifer was assumed to be 200 m/d in the upper part of the Wadi Hasa channel. However, this led to excessive groundwater flows being generated in this region. The records of two boreholes in this area (BN300 and JVA2) suggest that the more

TABLE 1

FIELD VALUES OF AQUIFER PROPERTIES DERIVED FROM PUMPING TESTS

Pumping well	Observation well	Transmissivity (m^2/d)	Confined storage coefficient %	Specific yield %	Saturated thickness (at observation well in m.)	Permeability (m/d)
BN309	BN302	7000	0.02	8	23	305
S2	S2/1, S2/2	7000	-	11 to 34	>23	300
SPB4	OB1	3600	-	17	11.5	315
SPB5	OB1	7000	0.04	-	11.5	610

TABLE 2

FIELD VALUES OF AQUIFER PROPERTIES DERIVED FROM RECOVERY TESTS

Production well	Transmissivity (m^2/d)	Saturated thickness (m)	Permeability (m/d)
BN309	-	23	-
S2	7850	>23	<340
SPB1	-	-	-
SPB2	4000	27.5	145
SPB3	6300	25	250
SPB4	1200	12	100
SPB5	18000	18	1000
S10	3000	not known	-
S18	8400	17	500
S19	4600	not known	-

permeable gravel sequence is unsaturated in this area and that groundwater flow occurs in an underlying sequence of sands or finer material. Consequently, the permeability was reduced in the upper part of the Wadi Hasa channel and a satisfactory calibration was achieved with a permeability of 40 m/d.

The model distribution of transmissivity is contoured in Figure 10. The distribution generally follows that of the saturated aquifer thickness. The highest transmissivity of 7700 m^2/d occurs in the buried channel at Safi, whilst the lowest value of 160 m^2/d occurs at the boundary adjacent to the Wadi Abyad fan.

Confining layer

The level at which water was struck during the construction of each borehole has been taken as the groundwater head in the upper aquifer. Flow through the clay layer is assumed to be vertical and proportional to the head difference between the water level in the upper aquifer and the groundwater head in the lower aquifer. Under present conditions most of the flow through the clay is upwards from the lower aquifer. However, where the groundwater head in the lower aquifer is below the base of the confining clay (ie, the lower aquifer is locally unconfined) groundwater flow downwards through the clay has been assumed to be proportional to the difference in elevation between the head in the upper aquifer and the base of the clay.

The thickness of the confining layer was estimated by interpolation between boreholes. Generally, this layer consists of silty clay with fine sand and occasional gravel. Vertical permeability tests were carried out on 12 shallow boreholes penetrating similar deposits in the Wadi Araba west of Ghor Safi in 1966.[1] These tests gave a range of permeabilities for silty clays of 0.00013 m/d to 0.2 m/d with an average of 0.05 m/d, which is very similar to a value of 0.02 m/d for the confining clay obtained from a pumping test at SPB5. However, the interconnection between the upper and lower aquifers is likely to be dominated by the occurrence of layers with the lowest permeabilities. An initial value of 0.005 m/d was selected on this basis for the permeability of the confining layer and the final value obtained from the model calibration was 0.0015 m/d.

[1] *Report on Soils Investigation. Wimpey International (Aug. 1966).*

Transfer of water occurs over the edge of the clay from the unconfined area of the main aquifer into the upper aquifer, although this occurs only in the areas to the north and south of Safi where the unconfined water level is at a higher elevation than the edge of the clay. The model automatically calculates the locations where overflow is taking place as well as the amount of overflow. It has been assumed that there is a certain resistance to flow over the edge of the clay and that the effective transmissivity of the upper aquifer is about 30 m^2/d in this area.

Underflow input at the weir

For the initial runs of the model recharge was restricted to undiverted baseflow and canal seepage of 1.8 and 1.7 million m^3/year respectively. However, these inputs produced lower computed than observed groundwater heads in the upper wadi channel area; a lower permeability or increased recharge would be required to raise the computed levels in this area. As the deposits in the area are likely to be of a high permeability along the buried channel, the results of the preliminary runs with the model suggested that recharge could be greater in the upper wadi channel area.

The underflow component of recharge through the deposits in the wadi itself is estimated to be less than 0.2 million m^3/year. The Darcy flow equation was used for this estimate with the following values: permeability, 200 m/d; aquifer thickness, 5 m; channel width, 5 m; and hydraulic gradient, 0.0077. This amount was found to be insufficient to raise the computed groundwater heads to those observed. However suitable conditions are present at the diversion weir for surface flow to enter the wadi gravels at this point as the weir extends across only half of the flood channel width and ponds back surface flows. A current meter survey of flow upstream of the weir indicated losses of 57 l/s (4925 m^3/d) over a 230 m length of channel from a point 70 m upstream of the weir. This loss was 6.6% of the total flow at the time of the survey and could lie within the errors of measurement. Other estimates of flow losses have been derived by the difference between total flow and distributed flows at the weir, ranging from 12 to 132 l/s (1035 to 11405 m^3/d) with 69 l/s (6000 m^3/d) being obtained on several occasions. However, these losses relate to the channel immediately upstream of the weir itself and would be an additional loss to that indicated by the current meter survey which was carried out further upstream.

Although estimates of baseflow losses at the weir show a wide range, they suggest that seepage losses are likely to occur at and upstream of the weir. It was decided to use the model to compute the groundwater input at the weir automatically by introducing a fixed head boundary into the model at the weir (node 1, 16) at an elevation of - 325 m AOD. This produced subsequently a more acceptable correlation between computed and predicted groundwater heads in the upper wadi channel area.

VERTIFICATION OF THE STEADY STATE MODEL

Figure 11 shows the steady-state groundwater heads and nodal flows in the main aquifer computed by the groundwater model assuming average groundwater recharge. The groundwater gradients are steeper in the unconfined area in the upper part of the wadi channel, about 1 in 45, than in the confined area around Safi, where the groundwater gradient is less than 1 in 1500. The shallow gradient in the confined area reflects the influence of the low permeability of the clay layer. The head gradient in the unconfined area is determined largely by the gradient of the base of the aquifer as the aquifer permeability in the area is relatively large. Hence, the groundwater head is consistent with the lowest level required to transmit groundwater flow. The groundwater flow vectors illustrate the concentration of flow into the buried channel where the transmissivity is higher.

The accuracy of the model is represented by the root mean square error between model predicted and the observed water levels at each data point. The errors for each data point are given in Table 3 and shown in Figure 12. For all data points the root mean square error (s) is 2.1 m and the range in groundwater elevations (Δh) over the model is 40 m. Hence, the ratio of $s/\Delta h$, which represents the overall accuracy of the model is 5%. This value is considered to be rather high but reflects the difficulties of simulating the complex aquifer conditions with a two-dimensional groundwater model. The greatest errors occur at sites S6, OB4, and S14, where geological control is limited, and together these sites account for more than 75% of the error variance. If these sites are excluded, the root mean square error for the remaining 16 sites is 1.1 m, or a value for $s/\Delta h$ of less than 3% over the range of

GROUNDWATER HEAD ERRORS AT DATA POINTS

Borehole number	Observed groundwater head (mOD)	Calculated groundwater head (mOD)	Difference (m)
OB1	-376.64	-377.10	.46
OB2	-377.57	-377.23	- .34
OB3	-377.46	-377.78	.32
OB4	-368.34	-372.27	3.93
OB5	-376.32	-375.79	- .53
OB6	-377.69	-376.59	-1.10
SPB1	-374.60	-375.37	- .77
SPB2	-376.80	-376.06	- .74
SPB3	-378.35	-376.68	-1.67
SPB4	-377.00	-377.23	.23
SPB5	-376.50	-377.02	.52
BN309	-377.00	-376.42	- .58
BN300	-350.50	-352.54	2.04
S14	-382.00	-378.26	-3.74
S6	-370.58	-376.37	5.79
S2	-374.00	-375.64	1.64
S10	-377.00	-376.33	- .67
S18	-378.00	-376.83	-1.17
JVA2	-339.00	-336.78	-2.22
Root mean square error			2.09

groundwater levels. In the wellfield area around Safi the errors are generally about 1 m and hence the model is considered to be more accurate in the area of the planned abstraction than in the peripheral areas of the model.

Unfortunately, there is no geological information available for borehole S6 with which to ascertain the cause of the large error at this site. At OB4 water was encountered at - 372 m AOD, but on completion of the borehole the rest water level was - 368 m AOD, with the base of the aquifer being penetrated at - 379 m AOD. Although clay was not reported during construction it would appear that the aquifer is locally confined in the vicinity of OB4. The model predicted head at borehole OB4 is equal to the elevation at which water was struck and hence the model saturated thickness is equal to the actual saturated thickness at this site. Large errors are to be expected at borehole S14 which is located close to the edge of the alluvial fan where losses from springflow and groundwater evaporation take place.

Table 4 gives the computed groundwater balance for the steady state simulation for the existing average conditions. Predicted underflow input at the weir is 4350 m^3/d, or 1.6 million m^3/year, and each of the three main recharge components are very similar in magnitude. The total annual recharge is 5.1 million m^3/year, which is slightly less than the planned Stage 1 APC abstraction requirement.

Over 90% of the loss from the main aquifer occurs by upward leakage through the confining layer. Although the vertical permeability of this layer is low, the area through which leakage occurs is extensive and hence a large volume of groundwater can be transmitted through the clay. In comparison flow over the edge of the confining layer is small, about 1070 m^3/d or 0.4 million m^3/year.

One of the main difficulties in the verification of the calibrated model is that the final model is not unique: the same computed groundwater head distribution could be achieved if all the model parameters (permeability leakage, flow over the edge of the clay, and the groundwater recharge) were scaled larger or smaller. The model could be verified in a number of ways, for example if the volume of water entering the aquifer were known accurately, but it has not been possible to identify accurately the amount of canal seepage or seepage from the bed of the Wadi Hasa. Similarly, the flow gauging measurements in the vicinity of the weir are not sufficiently precise to be able to distinguish accurately the amount of groundwater flow

TABLE 4

GROUNDWATER BALANCE FOR STEADY STATE MODEL SIMULATION OF AVERAGE CONDITIONS

Inputs to groundwater system (main aquifer):

Canal seepage	4644	m^3/d
Seepage from bed of Wadi Hasa	4986	
Underflow at Wadi Hasa weir	4352	
TOTAL	13982	

Losses from groundwater system:

Leakage through confining clay	12900	m^3/d
Overflow to upper aquifer	1072	
TOTAL	13972	
Difference (model error)	10	m^3/d

under the weir. The expected losses (4350 m^3/d) represent only 6.6% of the average total flow of the Wadi Hasa (about 66000 m^3/d).

Because of the inter-relationship between the model parameters, the steady state model calibration depends largely on the assumed base value for the permeability of the aquifer. The value of permeability of 200 m/d is at the lower end of the range of field values obtained from recovery and pumping tests in the Safi area, so the model provides a conservative basis for the subsequent management studies.

CONSTRUCTION OF THE TIME VARYING MODEL

The aquifer responds to variations in recharge or pumping in a markedly non-linear fashion. This is due to the variation in aquifer properties with changes in water level, variation in the storage coefficient (depending on the level of the piezometric surface relative to the base of the confining horizon) and to variations in flow across the edge of the confining clay.

The main aquifer is overlain by clay in the Safi area and in this area the appropriate value of storage coefficient (S) depends on the relative positions of the piezometric surface (h) and the base of the confining horizon (h_c). Thus when:

$$h < h_c, \quad S = Sy$$
$$h \geq h_c, \quad S = S_s(b) \qquad (1)$$

where Sy is the specific yield,
S_s is the specific storage of the aquifer
and b is the thickness of the confined aquifer.

It is implicit in equation (1) that the aquifer releases water from storage instantaneously if the piezometric head of the main aquifer falls below the base of the confining clay. However, in reality there is a delayed response as water is released by drainage from the pores of the formation. As this delay is short compared to the duration of the proposed pumping, it has not been included in the model.

The field values of specific yield are listed in Table 1, and range from 8 to 34%. The field data are open to more than one interpretation and are not sufficient to form reliable conclusions about the areal variations of the specific yield of the aquifer. Instead the model distribution of specific yield has been developed from the revised geological interpretation of the groundwater system.

The areal distribution of model specific yield has been obtained using a maximum value of 20%, which is reduced in the fan-edge area to 5% to reflect the likely increase of fine-grained material in this area. The model value of storage coefficient in the confined area has been taken to be equal to 0.01%. The model automatically calculates whether each node is confined or unconfined at the beginning of each time step, and assumes that the conditions remain constant throughout the time step. The time interval is halved and the step repeated if the piezometric head falls below the base of the confining horizon by a preset criterion ε (= 0.1 m).

The transmissivity of the aquifer (T) is the product of the saturated aquifer thickness (b) and the average permeability of the aquifer (K). The permeability has been assumed to be approximately uniform above the base of the aquifer. The explicit determination of transmissivity at the beginning of each time step may lead to inaccurate simulation of the piezometric head and flows in the aquifer if the change in head is a significant fraction of the saturated thickness. The computer model therefore compares the nodal values of the groundwater head distribution in the unconfined area at the beginning and end of each time step. The time interval is halved and the step repeated if the ratio of the head change to the saturated thickness exceeds a preset value ε (= 10%). This check automatically provided the model with the ability to use a large time step when recharge and abstraction are almost constant, up to a maximum of 1 month, but reduces the time step when rapid changes in recharge occur. However, this check was not used at those nodes having a small saturated aquifer thickness as large relative changes in the saturated thickness at these nodes are not significant due to the resulting low transmissivity.

VERIFICATION OF THE TIME VARYING MODEL

Ideally the groundwater model should be verified by comparison with field observations of water level fluctuations during periods of known recharge. However, the temporal and spatial variations in the amount of groundwater recharge to the Wadi Hasa aquifer are not known with sufficient accuracy to be able to undertake detailed comparisons. Instead the model has been verified using the overall changes in water level shown by available borehole water level records given in Appendix 1. The observed seasonal groundwater level fluctuations are generally about 0.75 m, although there are considerable differences from year to year.

The behaviour of the model during a time simulation of four years is illustrated by the computed response of borehole OB2 in the confined area near Safi, and borehole OB4 in the unconfined area (Figure 14). After an initial period of about a year the model water level fluctuations stabilize to follow a uniformly cyclic pattern corresponding to the changing recharge input. The water level variations in the confined area are controlled by those in the unconfined recharge area and are delayed due to the effect of the storage in the aquifer.

The computed hydrographs for boreholes OB2 and OB4 were obtained assuming a base value for the unconfined storage coefficient of 20%. This value is typical of sand containing gravel but little or no clay. An additional model simulation was undertaken with a lower base value of 10% used for previous studies, but this resulted in excessive seasonal head changes at each observation borehole. This suggested that 20% is a more suitable base value for the unconfined storage coefficient.

Using a value of 20% for the unconfined storage coefficient, the total volume of water available from unconfined storage in the main aquifer is estimated to be 40 million m^3. In the area overlain by clay, this water will be released from storage when the piezometric surface declines below the base of the confining clay. Whilst the piezometric surface remains above the base of the clay the aquifer underlying the clay will remain confined. The volume of confined storage is estimated to be 0.031 million m^3 under average conditions assuming a confined storage coefficient of 0.01%.

MODEL PREDICTIONS OF AQUIFER RESPONSE

SELECTION OF MANAGEMENT SCHEDULES

The time varying model has been developed to assess the aquifer response to abstraction under present and altered conditions of recharge. The Mujib Scheme proposals are planned to be implemented at the same time as the APC abstraction is increasing in stages to the full Stage I requirement. However, we have not examined this transitional period as the timing of the agricultural changes likely to affect the present regime cannot be established with certainty. We have not examined the future Stage II APC water requirements for similar reasons. Consequently, the schedules selected for study with the model have been chosen to examine the aquifer response to an extreme change in recharge conditions, but also to examine a possible future role for the wellfield in a conjunctive use scheme involving the Wadi Hasa. The schedules selected are as follows:

Schedule A		Planned Stage I APC abstraction with existing recharge conditions.
Schedule B		Reduced recharge conditions as a result of implementation of the Mujib Scheme proposals:
	B (1)	Without Stage I APC abstraction.
	B (2)	With Stage I APC abstraction.
Schedule C		Reduced recharge conditions with groundwater supplementing Stage II APC demands in a conjunctive use scheme.

Groundwater abstraction is to take place from a wellfield of six production wells (SPB 1 to 5 and S2) designed to provide the daily water requirement. For the model study each production well abstracts at an equal rate of 2500 m^3/d (totalling 5.47 million m^3/year). This abstraction takes place in the model at the node nearest each production well.

The results of each model run are given for a four-year period of abstraction. This period was selected on the basis that a new equilibrium had generally become established by this time. The results of each run are expressed in terms of the changes in the volume of flow into and through the main aquifer, maps of drawdown and flow vectors, and as selected hydrographs for boreholes BN 300 and OB4 in the unconfined zone and borehole OB2 in the confined zone. Storage changes are also quantified and the drawdown (excluding drawdown from well losses) at each production well is compared with the present maximum available drawdown.

The results of the model runs for Schedules A and B indicate that whilst the planned Stage I APC abstraction can be met with existing recharge conditions, it is likely that implementation of the Mujib Scheme proposals would decrease recharge and storage such that the aquifer will be unable to sustain even the Stage I APC requirement. Therefore, APC will need to utilize the Wadi Hasa as a source of supply in the event of reduced recharge. The timing of this supply is discussed in Schedule B.

However, prior analysis has indicated that both APC and agricultural requirements cannot be met by the Wadi Hasa if the Mujib Scheme proposals are fully implemented. Assuming that new land is not developed until additional water supplies are imported from the Wadi Mujib, we have estimated alternative agricultural water demands for various areas of irrigation which also allow for the Stage II APC requirement of 9 million m^3/year. This has then enabled us to use the model to assess a possible conjunctive use scheme using groundwater as a supplementary source. Demand for groundwater for two alternative areas of irrigation development is discussed in Appendix 2.

Whilst the final calibrated model is believed to reasonably represent the average conditions of the main aquifer, the complete groundwater system is not represented and many of the parameters included in the model contain uncertainties. The various factors influencing the model predictions are discussed and it is important that these factors are borne in mind in the following results and conclusions of each model simulation.

MODEL PREDICTIONS OF AQUIFER RESPONSE

Planned APC abstraction with existing recharge conditions (Schedule A)

The model has been used to simulate the effects of pumping the Stage I APC water requirement of about 15000 m^3/d from the Safi wellfield, with existing recharge to the main aquifer in the areas not covered by clay.

The average annual total infiltration to the main aquifer is 5.1 million m^3. The contribution from each of the three main components of recharge (canal seepage, undiverted baseflow seepage along the Wadi Hasa and underflow at the weir) are listed in Table 4. Underflow at the weir is assumed to be constant throughout the year. However, the canal seepage and undiverted baseflow seepage vary in response to agricultural water use. The monthly variation in these two components of recharge used in the time-varying model is shown in Figure 13 as a proportion of the total mean annual recharge from these two components of 3.7 $million^3$.

The model simulates conditions over a four-year time period with a total annual average recharge of 5.1 million m^3 and during which the rate of pumping from each borehole has been assumed to remain constant at 2500 m^3/d.

Figure 15 shows the computed drawdown hydrographs for boreholes OB2 and OB4, which are situated respectively in the confined and unconfined areas of the main aquifer, with existing recharge and the planned abstraction. The hydrographs show the seasonal water level variations superimposed on the drawdown curves associated with the pumping and indicate that water levels will be drawn down rapidly during the first 16 months of operation, after which time the rate of drawdown will diminish. The drawdown at borehole OB2 would be expected to be about 6 to 7 m after pumping for four years and this figure is typical of the drawdown likely to be expected over most of the confined area. The depression of the water table in the unconfined area is likely to vary from zero at the weir on the Wadi Hasa to 6 m at the edge of the confined zone, and would be about 3 m in the vicinity of borehole OB4, as shown in Figure 16.

The computed groundwater head and flow after four years shown in Figure 17 differ significantly from the steady state average with no pumping (Figure 11). The main effect of the pumping has been to lower the groundwater heads in the confined area sufficiently to reduce the upward leakage of water through the confining clay horizon in the vicinity of the fan-edge, and to reverse the direction of flow through the clay in the Safi area.

The computed water balance after pumping for four years is shown in Table 5. This shows that the amount of downward leakage (about 3940 m^3/d)

GROUNDWATER BALANCE AFTER 4 YEARS ABSTRACTION WITH EXISTING RECHARGE CONDITIONS (SCHEDULE A)

Inputs to groundwater system (main aquifer):

Canal seepage[1]	4644	m^3/d
Seepage from bed of Wadi Hasa[1]	4986	
Underflow at Wadi Hasa weir	4499	
TOTAL[2]	14129	

Losses from groundwater system:

Net leakage through confining clay[2]	-535	m^3/d
Overflow to upper aquifer	21	
Pumping	15000	
TOTAL[3]	14486	

Notes: [1] *These figures are averages over the period of pumping*

[2] *Leakage into main aquifer* 3940 m^3/d

Leakage from main aquifer 3405 m^3/d

[3] *Difference in the totals is the depletion in storage*

to the main aquifer is larger than the amount of loss by upward leakage (about 3405 m^3/d), giving a net gain to the main aquifer of about 500 m^3/d, compared to a net loss of about 12900 m^3/d in the absence of pumping.

The effect of the pumping increases the flow of groundwater under the weir on the Wadi Hasa by less than 4% (Table 5). This is a very small change because the effect of pumping in the confined area near Safi has been to lower groundwater levels in the unconfined area lying between boreholes S6 and OB4 almost to the base of the aquifer so that the effective aquifer thickness becomes very small (less than 2 m). Thus, although the groundwater gradient in the unconfined area is large, the possible change in the gradient at the weir is small. Where the saturated thickness is greater (ie, in the buried channel) the drawdown is larger, as shown by the position of the - 375 and - 380 m contours in Figure 17.

The shortfall in the amount of water available from the reversal of flow in the clay horizon is made up by the development of groundwater from storage. The computed change in unconfined groundwater storage after four years is 3.7 million m^3, and the change in confined storage is just less than 0.01 million m^3. These figures, which are equivalent to a steady depletion in storage of 2540 m^3/d and 6.7 m^3/d respectively, show that large-scale groundwater abstraction will need to develop the unconfined storage of the aquifer rather than the confined storage. The decline in the groundwater head leads to change in the position of the confined-unconfined interface as water levels in the previously confined area of the aquifer in the vicinity of Safi fall below the base of the confining clay horzon (compare Figures 17 and 11).

The computed drawdown at each production borehole of the wellfield is given in Table 6. The drawdown at each borehole is within the maximum available drawdown at each borehole, except at SPB 1 where the abstraction rate may have to be reduced. The yields of the other boreholes should not be affected and we conclude from the results of this model simulation that the Safi wellfield can meet the full Stage I water requirement provided that recharge to the aquifer continues at the present level.

TABLE 6

PREDICTED DRAWDOWNS IN SAFI WELLFIELD AFTER 4 YEARS ABSTRACTION[1] WITH EXISTING RECHARGE CONDITIONS (SCHEDULE A)

Production well	Available drawdown[2] (m)	Computed drawdown[1] (m)
SPB1	6	7.8
SPB2	12	7.6
SPB3	13	7.2
SPB4	18	9.0
SPB5	10	7.4
S2	(14)	7.2

Note: [1] *At 2500 m^3/d continuous pumping at each production well*

[2] *The available drawdowns shown in this table (and Tables 7 and 9) include an allowance for the pump with an intake level at the base of the casing and are also controlled by a well design selected to avoid the upconing of deeper, poor quality groundwater.*

Aquifer response to reduced recharge conditions (Schedule B)

Implementation of the Mujib and Southern Ghors Irrigation Scheme will significantly reduce recharge from undiverted baseflow and diverted baseflow by introducing more efficient irrigation methods and by expanding the area of cultivation. As a result, recharge will be derived predominantly from flood flows and underflow entering the Ghor Safi aquifer beneath the weir on the Wadi Hasa. The combined input from these sources is unlikely to exceed an average of 2 million m^3/year. To avoid a salt build-up in the irrigated fields there will be an annual application of pre-planting leaching water. For a total irrigated area of 25000 dunums this represents a total application of 1.24 million m^3/year. However, the irrigated area in the unconfined zone of the main aquifer is only about 6% of the total planned area of irrigation. Hence, the contribution to recharge of the main aquifer from the application of leaching water is considered to be small and has not been included in the model. Similarly, leaching water applied to develop new land towards the fan edge will not contribute significantly to recharge of the main aquifer.

The model has been used to determine the effect of the Mujib and Southern Ghors scheme on present groundwater levels. The effect of this scheme has been simulated during a four-year period with recharge taking place only beneath the weir of 1.8 million m^3/year starting with the steady state average conditions shown in Figure 11. Water level hydrographs for boreholes OB2 and OB4 show that groundwater levels will fall rapidly in response to the reduction in recharge during the first two years in both the confined and unconfined areas of the aquifer (Figure 18). The new steady state thickness of saturated aquifer is likely to be less than 3 m over large parts of the aquifer where it is not covered by clay, particularly in the vicinity of boreholes OB4 and S6. Groundwater flow in the aquifer is expected to be restricted mainly to the position of the postulated buried channel (Figure 19), and the flow under the weir on the Wadi Hasa would be expected to increase to about 4700 m^3/d (a rise of about 8%).

Figure 20 shows that the position of the boundary between the confined and unconfined zones will move further towards the fan-edge with a significant reduction in recharge; this reduction would be more than would result from pumping under existing recharge conditions (see

Figures 11 and 17). Unconfined groundwater storage would decline by 3.8 million m^3 (or about 2600 m^3/d) over a four-year period with a general decline in water levels of about 5 m.

The agricultural developments affecting existing recharge will be phased in from 1982 and be substantially complete by the end of 1984. Hence, the decline in water levels of about 5 m from the natural depletion in storage resulting from the reduction in recharge (as illustrated by Figures 18 and 20) will take place over the period 1982 to 1984. At the end of 1984 the available drawdown at production boreholes SPB 1 and SPB 5 will be exceeded and these boreholes will not be able to sustain their designed abstraction rate.

Aquifer response to reduced recharge conditions with APC abstraction

The planned Stage 1 APC abstraction was superimposed upon reduced recharge conditions, where recharge occurs only at the weir, also commencing with the steady state average conditions shown in Figure 11. The results indicate that groundwater levels will fall rapidly in response to large-scale abstraction from the Safi area under such conditions. Steady state conditions may be expected to be achieved rapidly in the unconfined area after the onset of pumping, as shown by the hydrograph for borehole BN300 (Figure 21), but groundwater levels in the confined area will continue to fall steadily, as shown by the predicted behaviour at borehole OB2 (Figure 21).

As the computed increase in underflow beneath the weir resulting from increased hydraulic gradients is small, less than 10%, most of the planned abstraction would be derived from storage. The computed change in unconfined groundwater storage is about 15 million m^3 (or about 10250 m^3/d) over a four-year period, and the computed change in confined storage would be about 0.024 million m^3 (about 17 m^3/d) over the same period. The position of the confined-unconfined interface would be expected to reach the edge of the alluvial fan within four years, and upward leakage of groundwater from the main aquifer through the confining clay would be expected to decline to zero within this time. Overflow of groundwater from the main aquifer would also cease along the edge of the confining clay.

Table 7 gives the computed drawdowns at each production borehole after a four-year period at the Stage 1 APC water requirement with recharge reduced to the underflow contribution at the weir on the Wadi Hasa. The average drawdown, typified by the hydrograph for borehole OB2 shown in Figure 21, is about 22 m in the wellfield area. However, as this exceeds the available drawdown at each production borehole, the drawdown given in Table 7 would not in practice be possible with the existing wellfield. To accommodate a large-scale, de-watering of the aquifer that would result from a major reduction in existing recharge yet continue to supply the Stage 1 APC water requirement would require a different wellfield design consisting of a large number of low-yielding boreholes. The existing wellfield is not designed for groundwater mining on the scale resulting from the Mujib Scheme agricultural development but to supply the daily Stage 1 APC water requirement from the minimum number of boreholes whilst avoiding the upconing of deeper, poor quality groundwater and therefore the need for a separate potable source of supply.

The existing wellfield would operate at a reduced rate related to the future recharge conditions to supplement an alternative source of supply, such as the Wadi Hasa. From the end of 1984 the total abstraction would need to be reduced to not more than the estimated recharge at the weir, or about 1.8 million m^3/year. It is likely that only a proportion of this recharge will be intercepted by the wellfield and the actual contribution and the role of the wellfield will be determined by monitoring pumping water levels and water quality, which will also determine the future operating regime of the wellfield. With a reduced rate of abstraction water levels will decline more slowly than those illustrated by Figure 21 for borehole OB2, falling by about 5 m after four years (period 1985 to 1988 inclusive) at an abstraction rate of 1.8 million m^3/year.

Modified APC abstraction with reduced recharge conditions (Schedule C)

We have used the model to examine the aquifer response to the use of groundwater by APC to supplement surface water diversion given priority use by the Mujib Scheme to irrigate 25000 du. As the Stage I

TABLE 7

PREDICTED DRAWDOWNS IN SAFI WELLFIELD AFTER 4 YEARS ABSTRACTION WITH REDUCED RECHARGE (SCHEDULE B)

Production well	Available drawdown (m)	Computed drawdown[1] (m)
SPB1	6	22.0
SPB2	12	20.7
SPB3	13	19.9
SPB4	18	21.6
SPB5	10	28.0
S2	(14)	18.9

Note: [1] *At 2500 m^3/d continuous pumping at each production well* abstraction requirement would be small, we have restricted our analysis to that of Stage II. However, the additional abstraction requirement during days of flood cannot be examined with the model.

The monthly abstraction requirements for this simulation are given in Table 8 based on an assessment of the likely groundwater demands discussed in Appendix 2. The available drawdown at each production borehole would be 5 m less at each site due to the reduction in recharge from agricultural development (see Schedule B). Only five wells would still be in commission and the wellfield would be operated discontinuously to meet the monthly abstraction requirement. The operating regime used for the model simulation to supply these requirements is shown in Table 8 with the boreholes brought into use in the following order: S2 or SPB3, SPB4, SPB2 and SPB5. An abstraction rate of 2500 m^3/d per well used for the other schedules was retained for this simulation.

The model simulation represents a period of four years of modified wellfield abstraction under conditions of reduced recharge, beginning with the present steady state average groundwater levels. Figure 22 shows the computed drawdown hydrographs at boreholes OB2 and OB4. Groundwater levels fall rapidly throughout the aquifer during the first two years and, whilst equilibrium conditions are attained in the unconfined area, water levels continue to decline in the confined area. The water level at borehole OB4 is about 0.4 m lower than would have been the case without pumping whereas at borehole OB2 the water level is 2.4 m lower.

The areal distribution of the computed drawdown after four years is shown in Figure 23. Comparison with Figure 19 shows that water levels in the wellfield area are lowered by an extra 2 m than in the case of no pumping and that the confined-unconfined interface moves further towards the fan-edge, particularly in the south of the area. The steep drawdown contours near OB4 are due to the reduction in aquifer thickness upstream of this area. As a result, abstraction is derived partly from storage in the area overlain by clay. It is likely that continued abstraction beyond four years will lower water levels such that upward loss of groundwater through the clay will become very small, and the abstraction will be supported by underflow from the area of the weir.

TABLE 8

STAGE II APC GROUNDWATER REQUIREMENTS TO SUPPLEMENT WADI HASA DIVERSION TO OFFSET PEAK CROP WATER REQUIREMENTS[1] (SCHEDULE C)

	Total monthly groundwater requirement[3] (million m^3)	Simulated wellfield operation[2] to meet monthly requirements					
		S2	SPB3	SPB4	SPB2	SPB5	SPB1
Oct	-						
Nov	0.096	*					
Dec	0.136	*	*				
Jan	0.091	*					
Feb	-						
Mar	0.076	*					
Apr	0.237	*	*	*			
May	-						
June	0.067	*					
July	0.066	*					
Aug	0.223	*					
Sept	0.081	*	*	*			
TOTALS	1.073	0.675	0.225	0.15	(Total wellfield 1.05)[4]		

Notes: [1] *Irrigated area about 25000 dunums (see Appendix II)*

[2] *Each production well pumped at 2500 m^3/d. Those in operation to meet the monthly demand are marked thus* *

[3] *Excludes possible groundwater requirement during flood days - average 12 per year in period Nov. to Apr. totalling 0.187 million m^3/year*

[4] *Difference in requirement and total abstraction due to constant pumping rate of each borehole.*

PREDICTED DRAWDOWNS IN SAFI WELLFIELD AFTER 4 YEARS ABSTRACTION WITH MODIFIED ABSTRACTION AND REDUCED RECHARGE (SCHEDULE C)

Production well	Available drawdown (m)	Computed drawdown[1] (m)
SPB1	6	9.1
SPB2	12	8.8
SPB3	13	8.4
SPB4	18	9.5
SPB5	10	7.7
S2	(14)	9.0

Note: [1] *At 2500 m^3/d at each production well with discontinuous pumping regime to provide monthly requirements in Table 8 for 4 years.*

The computed decrease in unconfined storage after four years is just more than 5 million m^3 (or 3600 m^3/d) and in confined storage about 0.011 million m^3 (or 8^3m /d) over the same period. The change in unconfined storage is 1.2 million m^3 more than the change in storage without abstraction and reduced recharge. As the computed underflow at the weir is identical after four years for both situations (4700 m^3/d), the abstraction is being supported initially by a depletion in storage.

Table 9 indicates that, except for borehole SPB1, the computed drawdown will not exceed the available drawdown at each borehole. Whilst the water levels in the wellfield area would still be falling after four years, we would not expect the final equilibrium water levels to be much lower than the available drawdowns given in Table 9.

The results of this model simulation illustrate a potential role for the wellfield. They indicate that a supply of about 1 million m^3/year, or about 10% of the Stage II water requirement, could be obtained from the aquifer to supplement diversion of the Wadi Hasa given an agricultural development area of 25000 du of a type requiring the water source duty demands given in Appendix 2.

FACTORS AFFECTING MODEL PREDICTIONS

The reliability of the predicted aquifer response to changes in abstraction and recharge depends on how well the model represents the complex conditions of the alluvial fan. Throughout the study, it has been necessary to make a number of assumptions based on hydrogeological judgement to simplify the characteristics of the groundwater system while at the same time ensuring that the main features of its behaviour can be retained to reach practical conclusions regarding aquifer response.

The model assumes that the alluvial fan consist of two semi-horizontal aquifers which are separated by a clay horizon of low permeability. The main aquifer is the lower aquifer, which merges with the upper aquifer in the area east of Safi where the clay horizon is absent. Although the clay horizon is assumed to have the same value of permeability (0.0015 m/d), in practice the 'clay' horizon consists of discontinuous layers of clay which have a negligible permeability (probably less than 10^{-5} m/d), intercalated with more permeable layers of sand and gravel. The generally horizontal nature means that the clay layers are hydraulically more important in establishing the contact between the upper and lower aquifers. However, the contact between the two aquifers will depart locally from the model representation. Furthermore, the available field data concerning the upper aquifer suggests that the clay may be absent locally but this has not been included in the model, due to the uncertainties in the exact location and extent of these areas.

The 'clay' horizon has been assumed to have no groundwater in storage. The simplifying assumption leads to over-estimation of the predicted groundwater drawdowns in the area where the clay layer is present since some storage will be present in the intercalated sand and gravel horizons, and this assumption forms therefore a conservative basis for aquifer management.

The areal extent of the groundwater model is of considerable importance because the predictions of groundwater head drawdown extend to the edges of the model as a result of the high transmissivities. There is little or no direct field evidence to indicate the exact positions of the boundaries of the main aquifer, and the model boundaries have been chosen largely on the basis of the revised hydrogeological interpretation. The areal extent of the model is believed to be a slight underestimate of the actual extent of the main aquifer.

The final calibrated model is believed to be a reasonable representation of the average conditions existing in the aquifer. There is, however, considerable uncertainty in the values of almost all of the parameters included in the model. The uncertainty in the amount and variations of groundwater recharge has limited the ability of the model to be satisfactorily calibrated solely on the basis of the observed water levels and water level fluctuations, and the final choice of model parameter has relied heavily on the field information derived from pumping tests. The data obtained from these tests have provided an acceptable control on the base value of permeability. Since the value of 200 m/d adopted for the permeability in the model is at the lower end of the range of field values, the model should provide a conservative basis for the management studies.

The hydraulic conditions in the vicinity of each test borehole are believed to be too heterogeneous to define accurately the specific yield of the aquifer from the results of the pumping tests. The maximum specific yield value of 20% used for the groundwater model is typical of coarse alluvial fan deposits. Verification of the model implies that this value is more acceptable than the value of 10% used previously for resource estimates. Nevertheless, the model value is based on a particular temporal variation in recharge, which in turn has been estimated from information concerning the present agricultural practice. Other temporal variations with different specific yield values could also produce the same historical water level changes. For example, the same volume of annual recharge with a less marked seasonal change would require a lower specific yield to produce the same historical water level changes. However, there is not sufficient reliable information to establish more precise values for the specific yield or the temporal variation in recharge.

Estimates of the amount, distribution and monthly variation in recharge from canals and undiverted baseflow are based largely on field observations concerning the general operation only of the irrigation, distribution system. Neither flood flow recharge or field seepage are included and our estimates of recharge may therefore be somewhat conservative. The final value of the input as underflow at the weir of 4350 m^3/d assumes a saturated thickness of 5 m and that flow occurs across a distance of 125 m (the minimum nodal interval used in the model), whereas the actual width of the wadi channel at the weir is about 75 m.

The design recharge for the final calibrated model, about 14000 m^3/d, is similar to the planned abstraction from the Safi wellfield of 15000 m^3/d. If the total recharge is found to depart from this design recharge then a correspondingly greater or smaller proportion of the groundwater abstraction will have to be obtained from storage and drawdowns will differ accordingly to those computed. We have considered average recharge conditions only but we do not believe that a prolonged period of drought will significantly alter the volume of recharge, as bedrock storage appears to maintain a consistent volume of baseflow in the Wadi Hasa from year to year. The amount of recharge is more likely to vary due to changes in the agricultural practices.

It should be noted that the transitional period when abstraction builds up and recharge decreases has not been included in the model simulations. Hence, whilst the net effect of the abstraction or alterations in recharge is likely to be the same, the model results are less representative of the intervening period between the present and altered conditions.

CONCLUDING REMARKS

The amount of recharge to the Ghor Safi alluvial fan depends mainly on the use of the Wadi Hasa for irrigation. Our study has demonstrated that the wellfield can meet the Stage I water requirements of the potash plant with the existing recharge situation. However, if the agricultural development proposals of the Mujib and Southern Ghors Irrigation Scheme are implemented, recharge will be reduced significantly and, as a result, the volume of groundwater in aquifer storage will decline also. The wellfield will not be able then to command sufficient groundwater head to support the Stage I water requirements by groundwater mining. Instead, the wellfield could fulfil an alternative role by supplementing direct diversion of water supplies from the Wadi Hasa during days of flood and during periods of peak irrigation demand in a co-ordinated scheme to optimize use of the available water resources of Ghor Safi.

Our analysis has been based on a simplified representation of the complex hydrogeological conditions of the alluvial fan. Broadly, the alluvial fan consists of a lower aquifer, which appears to be continuous across most of Ghor Safi, separated from a thinner, upper aquifer by a discontinuous clay layer through which leakage occurs. The lower aquifer forms the major groundwater resource of the system, and has been modelled explicitly using a distributed parameter, finite difference computer model. Calibration of the model has been achieved in stages by including new information from the wellfield construction and by incorporating the results of each model simulation to further our understanding of the natural aquifer behaviour.

Recharge to the main aquifer occurs where the confining clay is absent. The annual recharge is estimated to be 5.1 million m^3/year, comprising almost equal amounts from undiverted baseflow, canal seepage and a previously undefined input in the area of the weir.

The volume of annual recharge is similar to the planned Stage I water requirements of the potash plant. Consequently, abstraction in excess of the amount of recharge will depend on developing groundwater from aquifer storage, within the capability of the wellfield design. On the basis of the model calibration, the specific yield of the aquifer is about 20%; about twice that adopted for previous estimates of storage. The volume of groundwater in storage in the main aquifer is about 40 million m^3.

Abstraction at the full Stage I water requirement with the existing recharge conditions, is maintained by intercepting groundwater that otherwise would be lost by upward leakage through the clay overlying the main aquifer and also by developing nearly 10% of the volume of groundwater in aquifer storage. The resources of the upper aquifer, which are partly replenished, are also commanded by a reversal in the direction of leakage. Due to the high transmissivity of the main aquifer, pumping causes drawdown effects throughout the area of the aquifer. Water levels decline rapidly at first until the base of the confining clay is reached, whereupon they then decline at a slower rate as dewatering of the main aquifer begins. After a four-year period at the full abstraction rate, a new steady-state situation is established with a drawdown of about 6 m in the wellfield area. This can be accommodated by the available drawdown at each borehole of the wellfield, except perhaps borehole SPB1.

The Mujib Scheme has recognised that agricultural development will reduce recharge significantly and has proposed that groundwater mining should sustain supplies for the potash refinery until alternative supplies are imported from the Wadi Mujib. The model study indicates that without APC abstraction, present water levels will decline by 5 m across the wellfield after four years without recharge from irrigation. This represents a natural depletion of about 10% in aquifer storage. However, with abstraction at the full Stage I water requirement under reduced recharge conditions, the available drawdown at each production borehole, cannot accommodate the resulting rapid and large decline in water levels. The wellfield would have to operate at a reduced rate related to the future recharge conditions but could be used to supplement an alternative supply, such as the Wadi Hasa. The actual contribution and operating regime of the wellfield will be determined from the results of monitoring pumping water levels and water quality.

The model predictions under reduced recharge conditions are based on an instantaneous reduction in recharge with abstraction at the full Stage I requirement. However, abstraction will increase in stages from 1982 to reach full production in 1984, whilst recharge will decrease gradually from 1982 to 1985 or 1986 as agricultural changes are phased in. We cannot yet determine the timing and extent of changes in the hydrological regime during the transitional period until the plans of the Mujib Scheme are finalized. Similarly, information is required to take account of the changes in agricultural practice which are already being widely introduced by landowners and the abstractions plans of other groundwater users.

As the changes to the groundwater regime for the immediate future are not known in sufficient detail, we are not yet able to predict with confidence the timing of the need for alternative surface water supplies. Nevertheless, it is apparent that the Mujib Scheme effects will not enable groundwater mining to support the APC water requirements for more than a short period and if the agricultural development programme begins as planned in 1982 an alternative source of supply from the Wadi Hasa is likely to be required by the beginning of 1985. However, the decision to divert surface water supplies should also take into account the monitoring results from the wellfield during the early years of abstraction.

The present Mujib Scheme proposal to utilize fully the Wadi Hasa for agricultural development will need to be modified if the industrial water requirements, particularly in the longer term, are to be met also from the same source. More effective use of the total water resources could be made by using the wellfield as a supplementary source of supply. We have estimated the likely agricultural water demands for selected levels of development. If agriculture is expanded to that potentially irrigable at Ghor Safi, about 25000 dunums, the wellfield could provide sufficient water to offset periods of peak crop water demand, or about 10% of the Stage II water supply requirements. For this situation, the model predicts a 12.5% decrease in storage or drawdown of 8 m over four years with the existing steady state head conditions. It should also be possible to use groundwater supplies with a slightly modified wellfield to meet the daily requirement of the potash plant during days of flood when surface water supplies could be interrupted.

In reaching definite practical conclusions on the scope for groundwater development we have had to make a considerable number of assumptions based on hydrogeological judgement. Although sensitivity analyses have been carried out in many stages of the modelling study, it is not possible to express in a simple manner the reliability of the model to simulate accurately the groundwater response. We would therefore strongly advise that the model should be recalibrated from time to time to improve predictions as more data become available, to enable particularly the aquifer response during the transitional period to be examined. For these improvements to be possible, we recommend the following:

- detailed monitoring of water levels in each production and observation borehole before and during abstraction together with details of the abstraction regime of each production borehole

- the construction of low-cost, shallow piezometers at selected locations to collect further information on the upper aquifer and to observe the response of this aquifer to abstraction

- construct deep, small diameter exploratory boreholes in the Wadi Abyad fan and in the fan-edge area to examine the extent of the main aquifer in these areas, where information is not available at present

- investigation of the underflow input in the area of the weir, as this should be unaffected by the proposal of the Mujib Scheme to improve the present diversion works. It may be possible to establish the amount of seepage upstream of the weir by detailed flow measurements, but it is likely that these would need to be supported by some exploratory drilling in the bed of the wadi at the weir.

Whilst the model has been used to predict changes in groundwater levels, it cannot be used to examine changes in water quality which could occur due to the upconing of poorer quality water from the Lisan deposits underlying the main aquifer. Groundwater development could be restricted by an unacceptable deterioration in quality. Whilst this situation should be avoided generally by the design of each borehole, the available drawdown has been reduced accordingly and therefore the ability of the wellfield to command aquifer storage has also been reduced. We recommend that the water chemistry at each production borehole and at the collecting tank should be measured at frequent intervals.

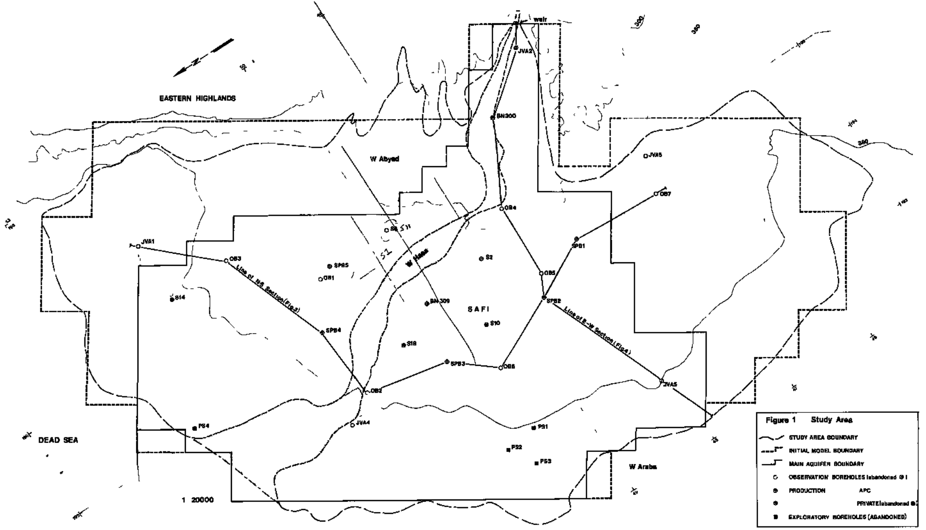
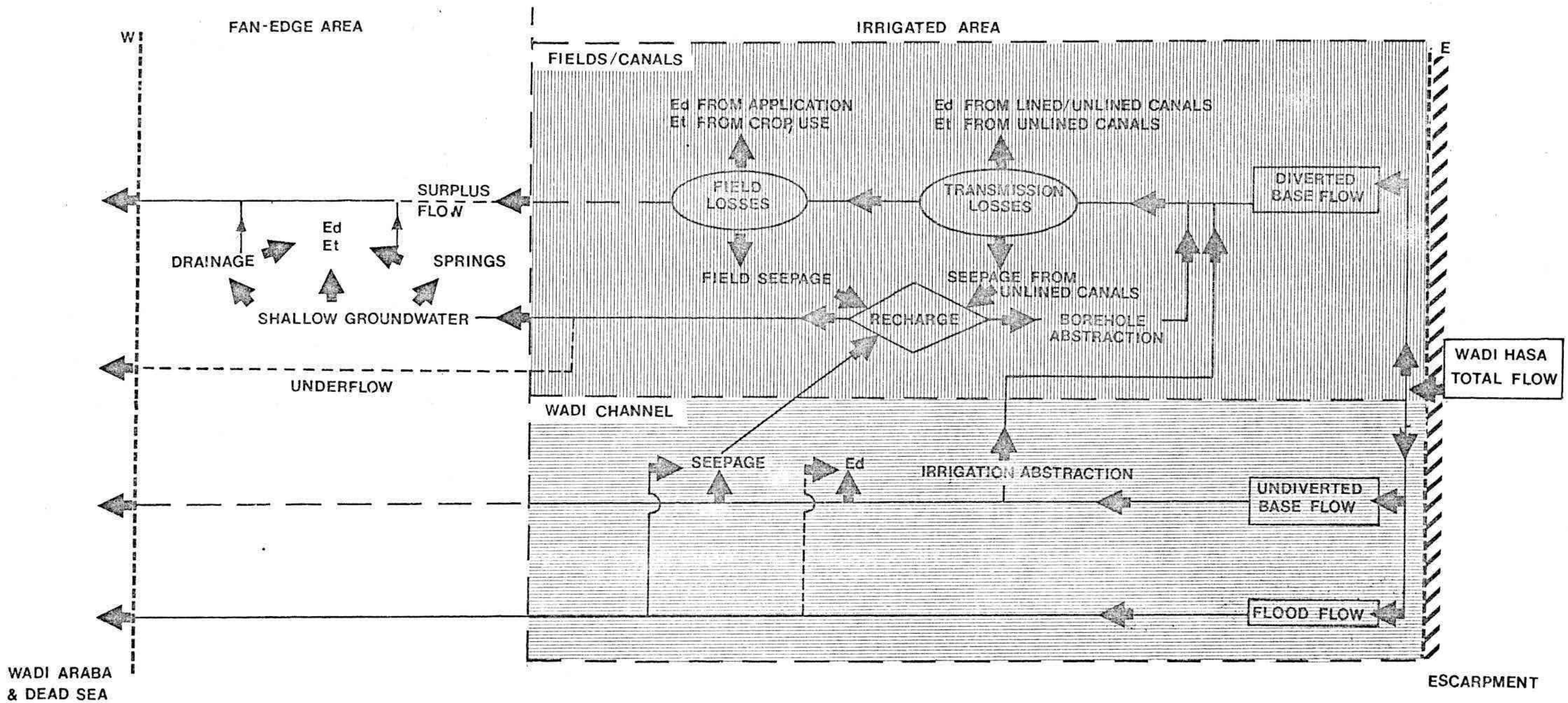


Figure 1 Study Area



NOTES

Ed : DIRECT EVAPORATION

Et : EVAPOTRANSPIRATION

POSSIBLE ADDITIONAL INPUTS OF GROUNDWATER ACROSS ESCARPMENT BOUNDARY OR FROM DIRECT RAINFALL ARE NOT SHOWN

GHOR SAFI ~ SCHEMATIC HYDROLOGICAL CYCLE

Figure 2

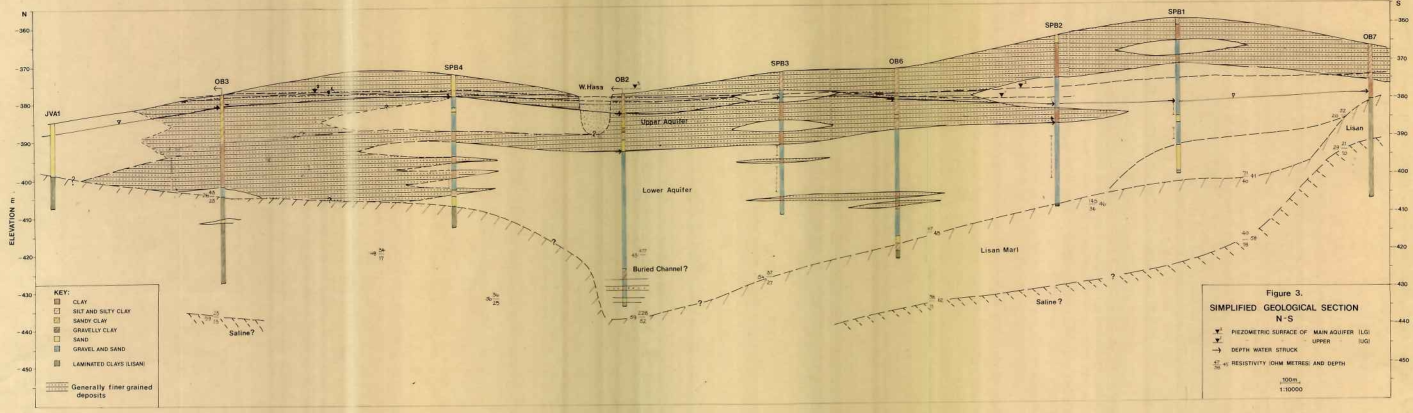


Figure 3.
SIMPLIFIED GEOLOGICAL SECTION
N-S

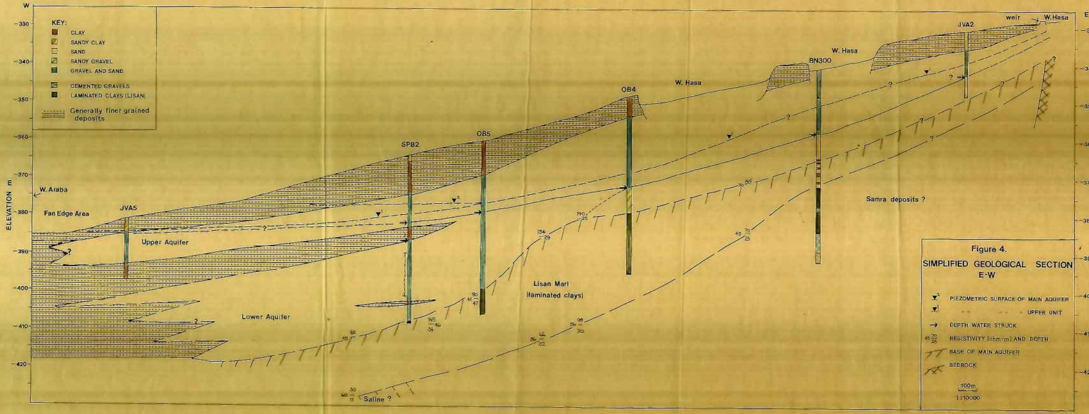
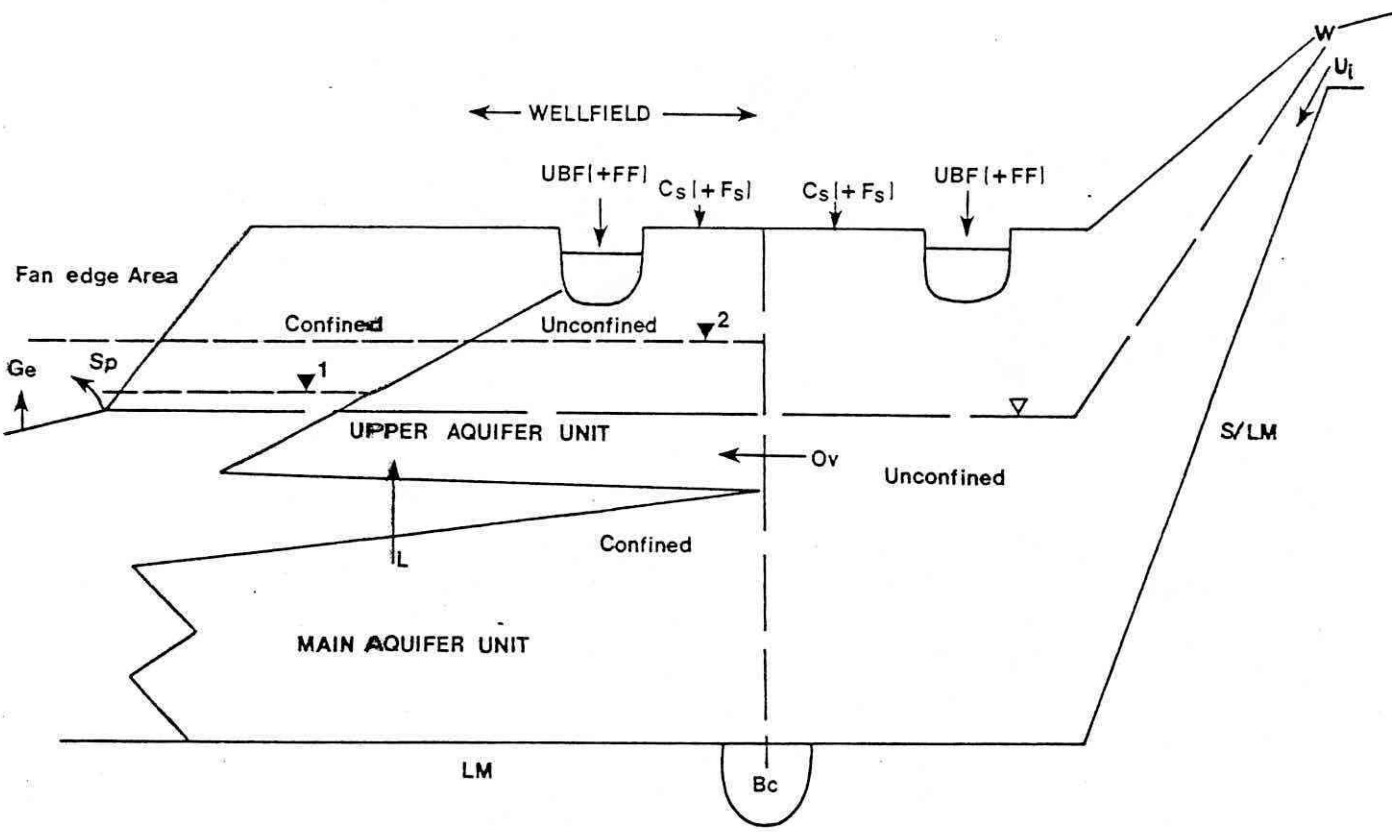


Figure 4.
SIMPLIFIED GEOLOGICAL SECTION E-W

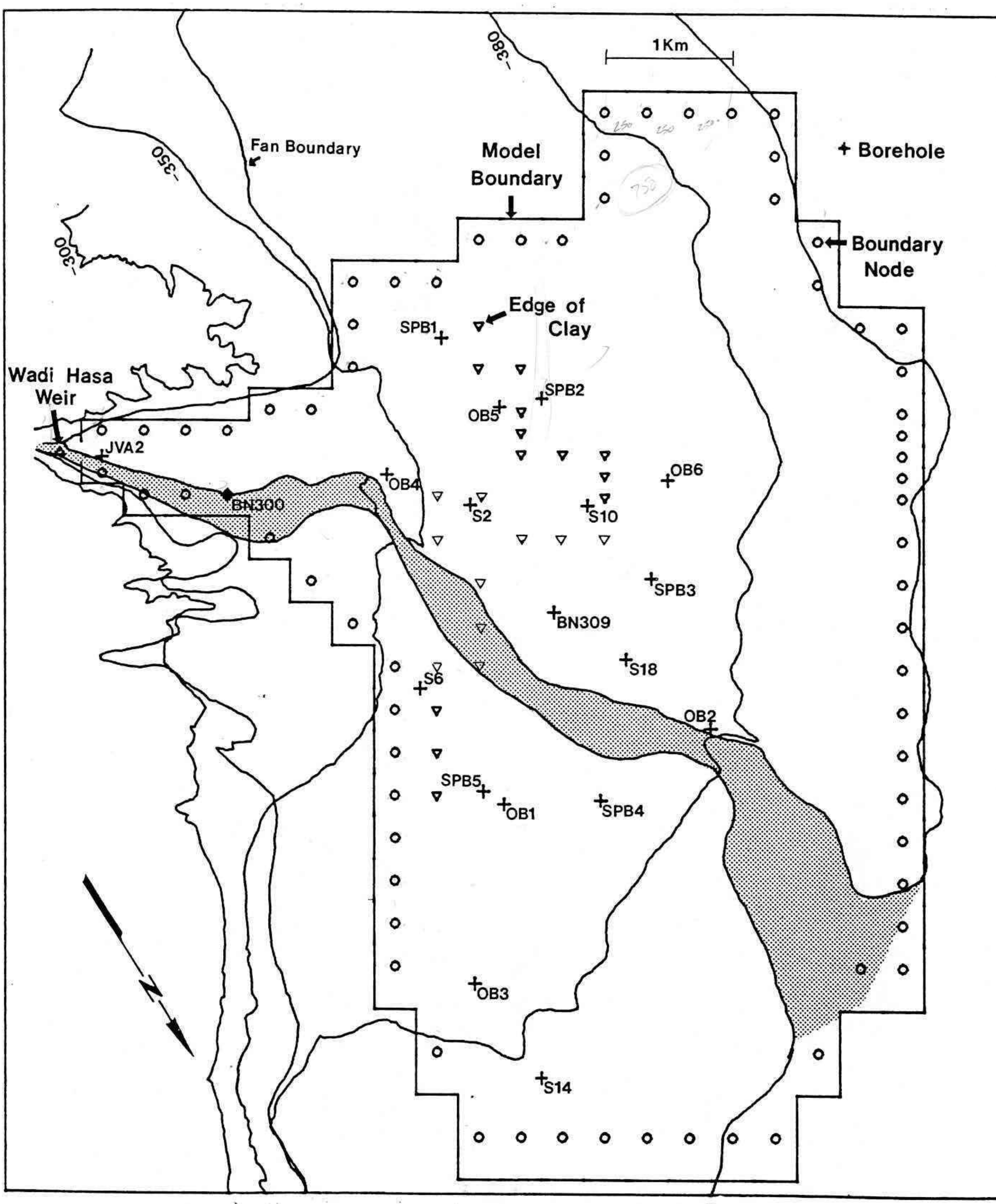


KEY:

U_i	Underflow	Sp	Springflow
UBF	Undiverted baseflow	Ge	Groundwater Evapotranspiration
FF	Flood flow	▽	Water table
C_s	Canal seepage	▼2	Piezometric surface (Lower Unit)
F_s	Field seepage	▼1	Piezometric surface (Upper Unit)
O_v	Overflow	W	Weir
L	Leakage	B_c	Buried Channel
		LM	Lisan Marl
		S	Samra deposits

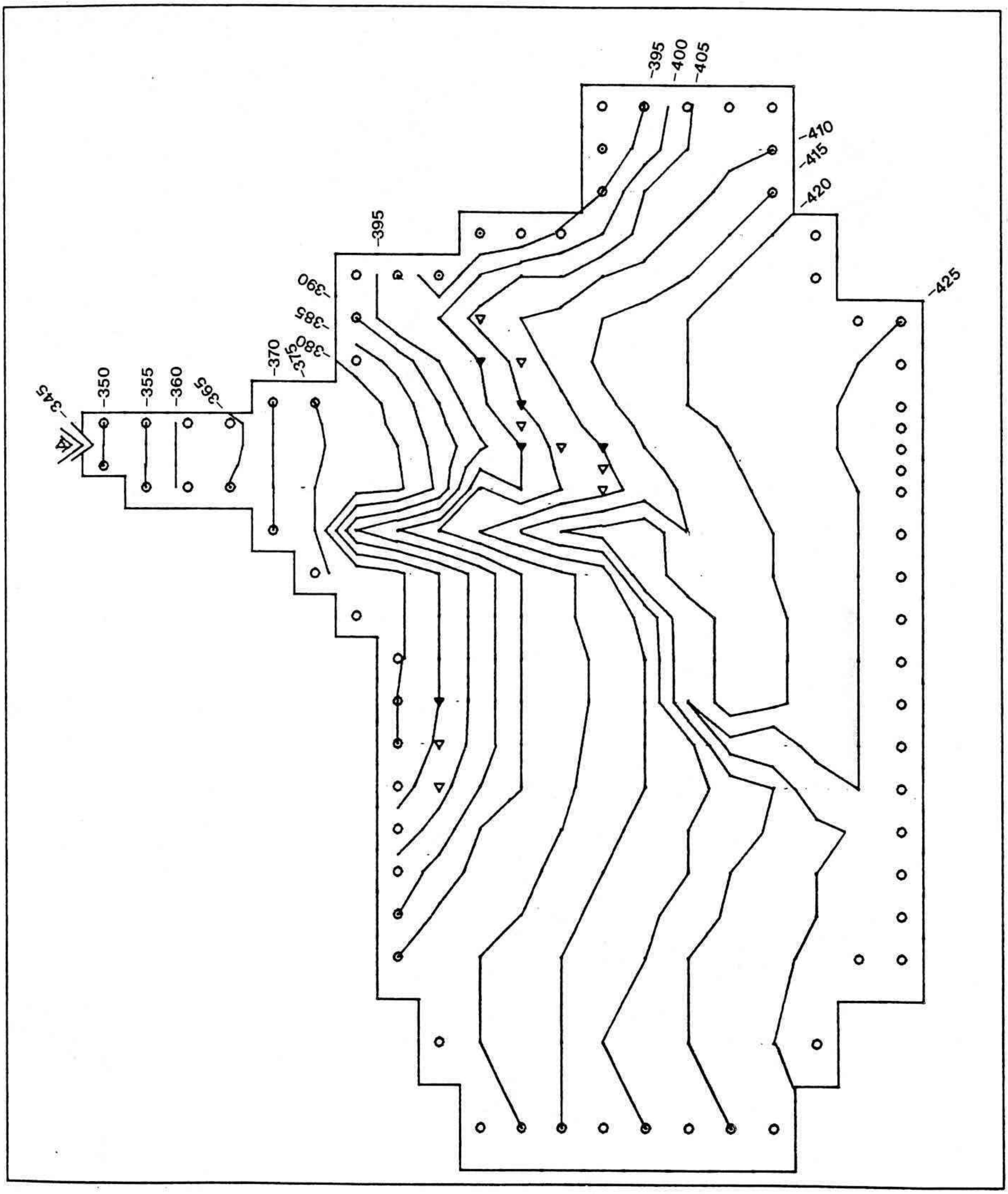
Simplified Representation of Revised Conceptual Model

Figure 5.



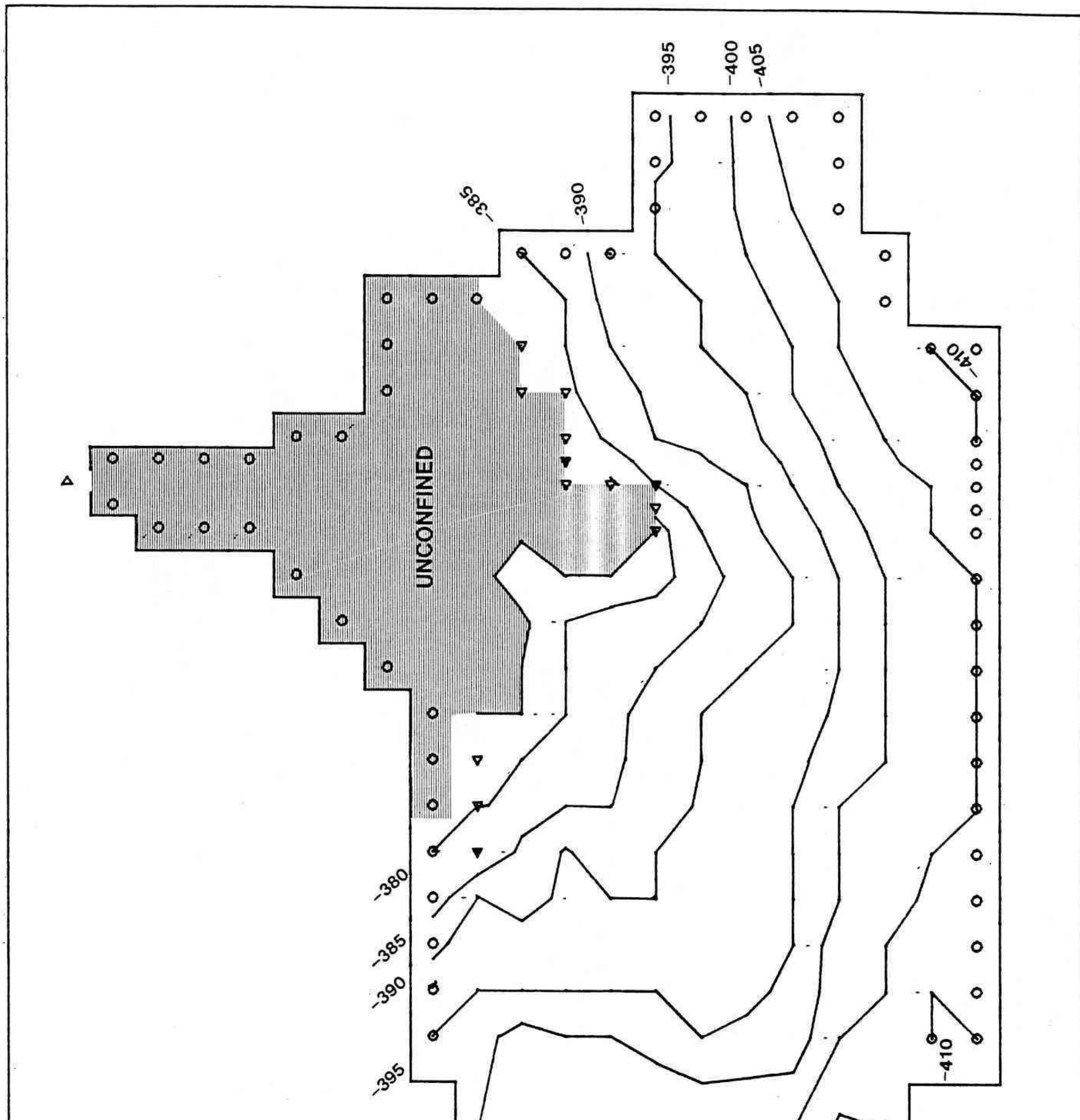
Main Aquifer Model

Figure 6



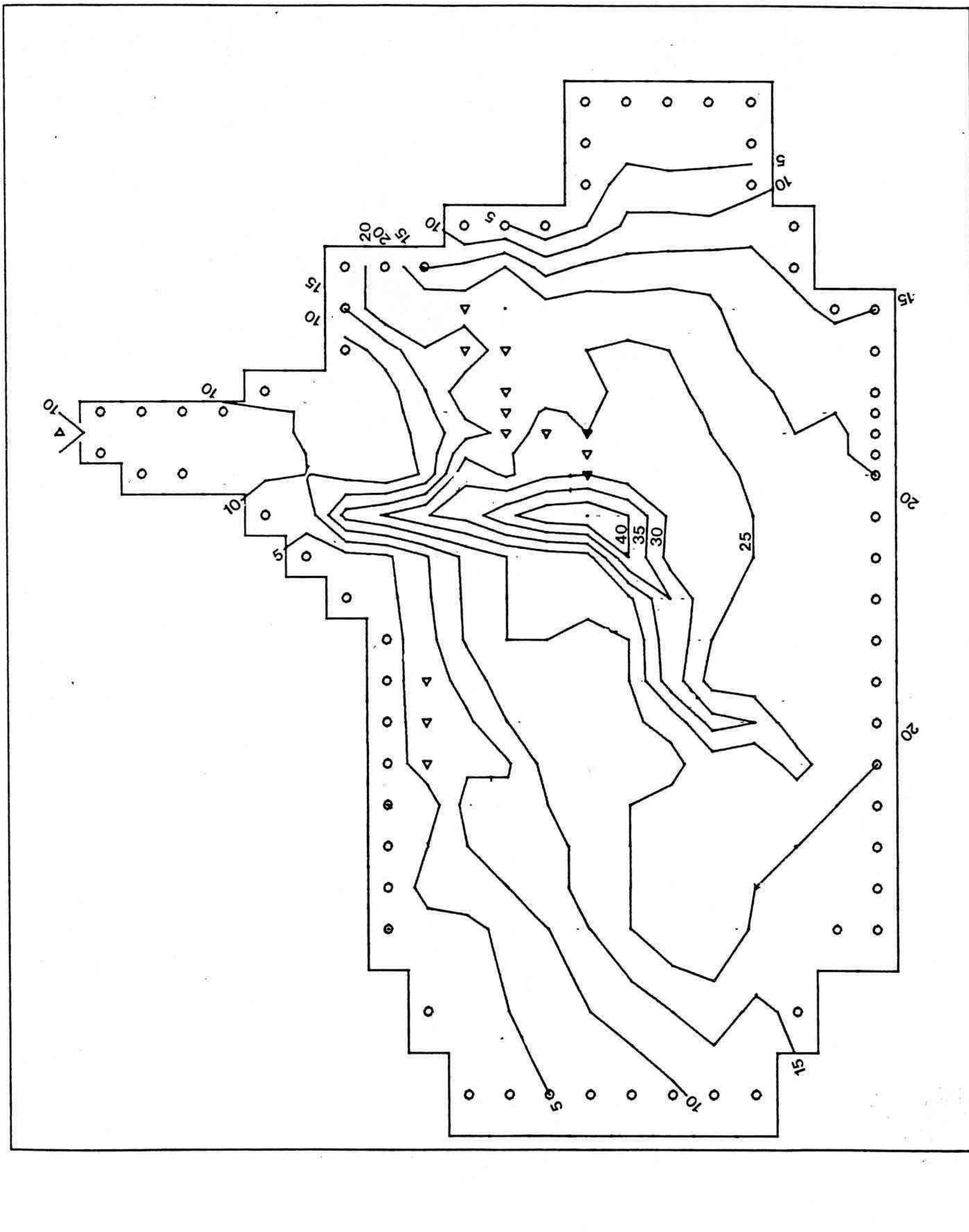
Base of Aquifer [m AOD]

Figure 7

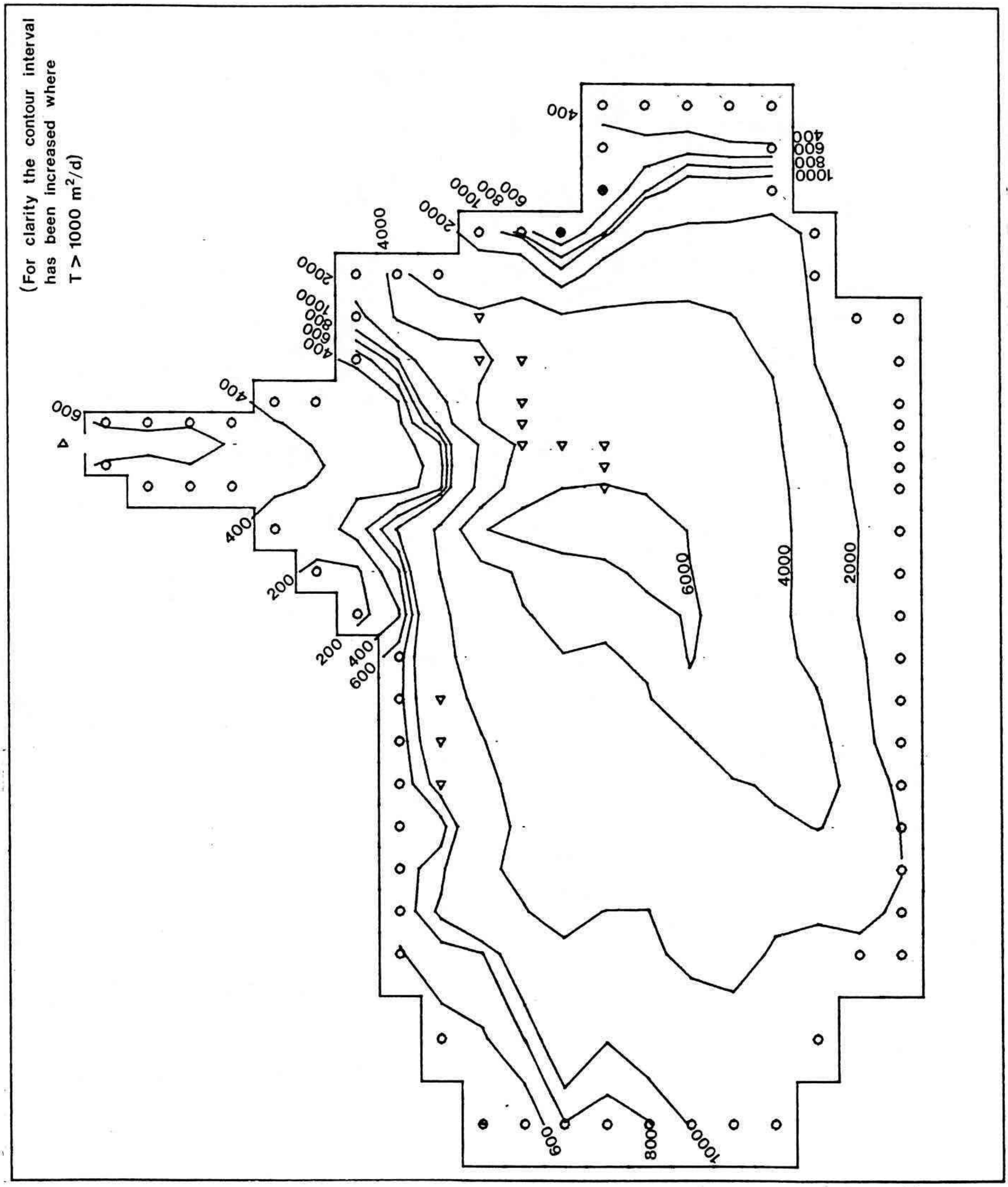


Base of Confining Horizon [m AOD]

Figure 8

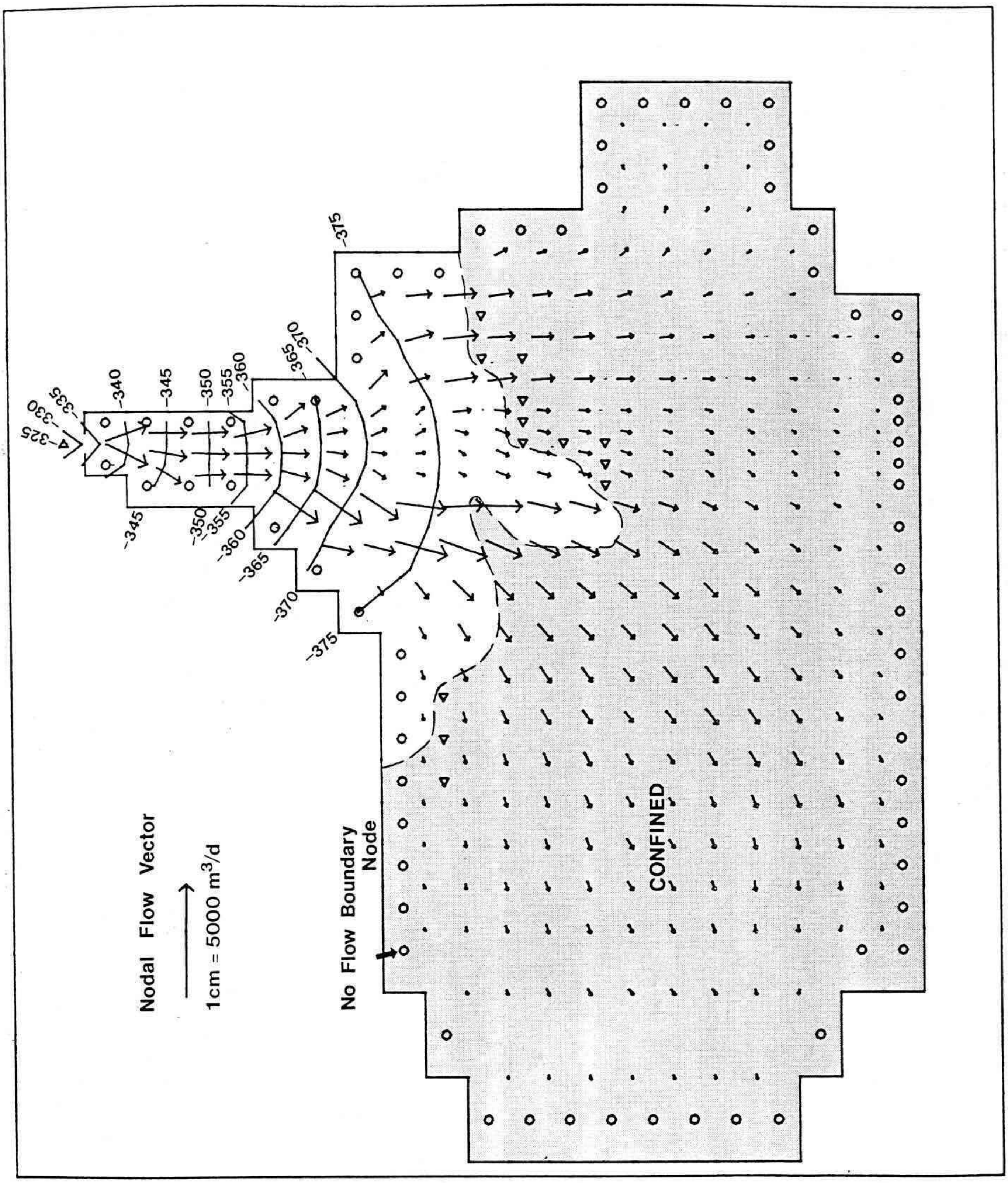


Saturated Aquifer Thickness (m) Under Average Conditions



Model Distribution of Transmissivity [m²/d] Under Average Conditions

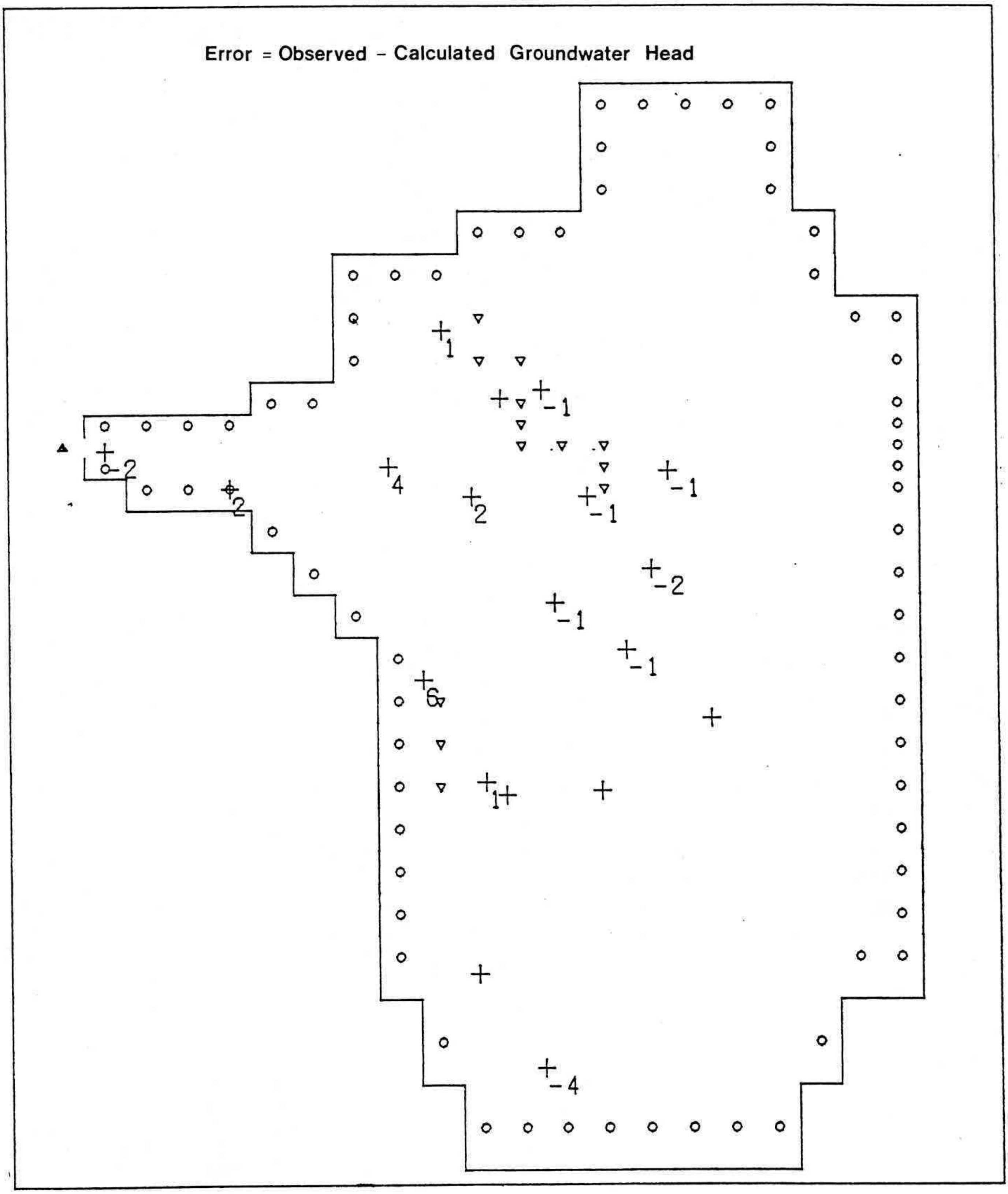
Figure 10



Computed Groundwater Heads [mAOD] and Flow in the Main Aquifer

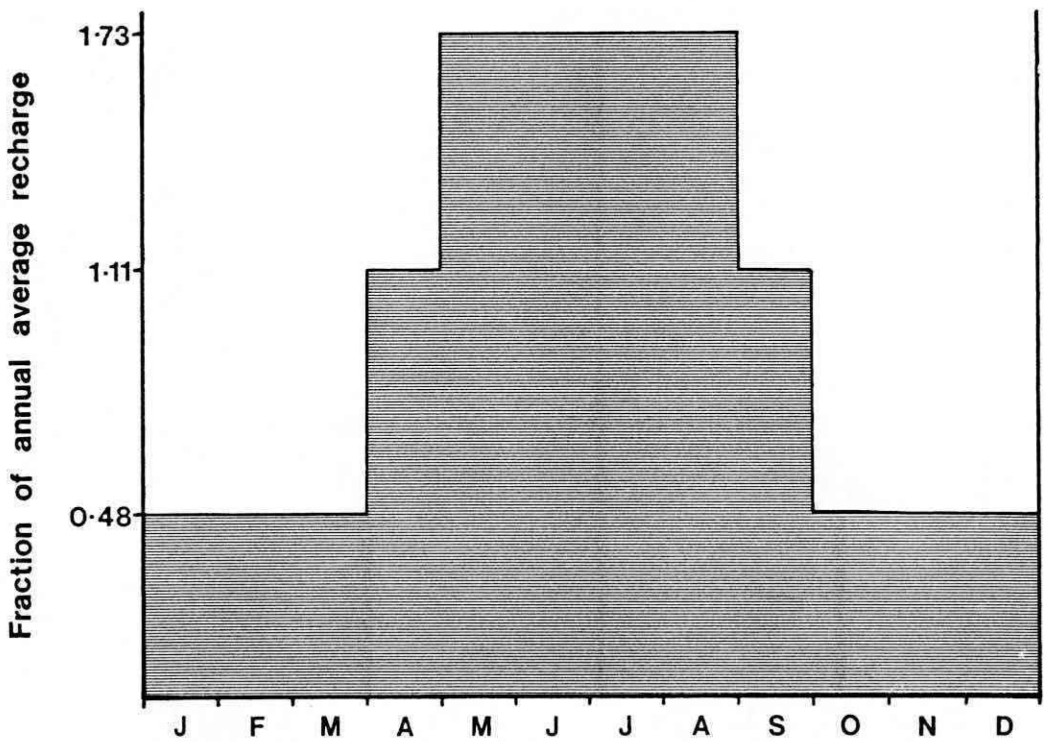
with Existing, Steady - State Conditions

Figure 11



Groundwater Head Errors at Data Points (m)

Figure 12

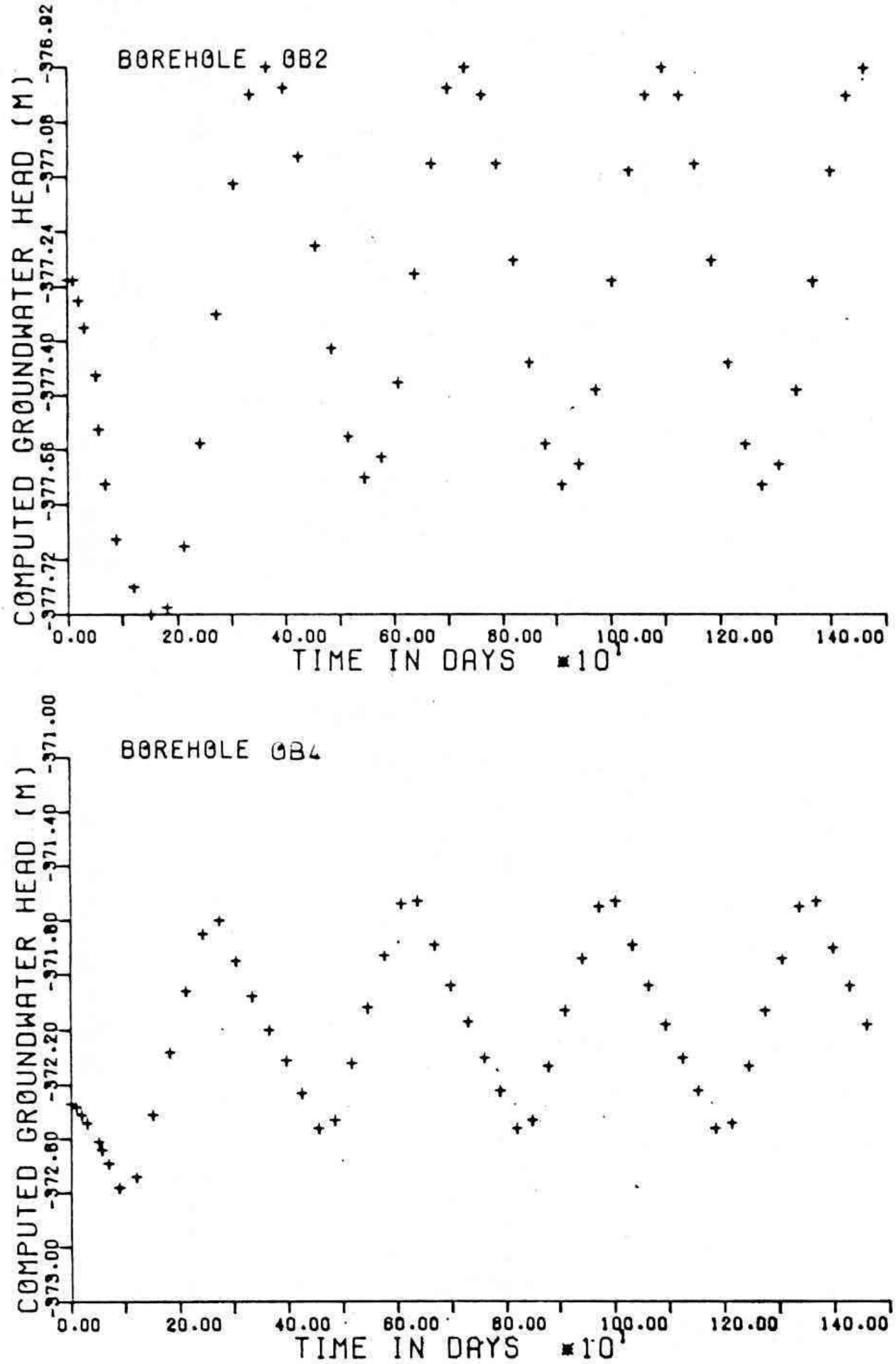


Cyclic Recharge to the Aquifer

Note:

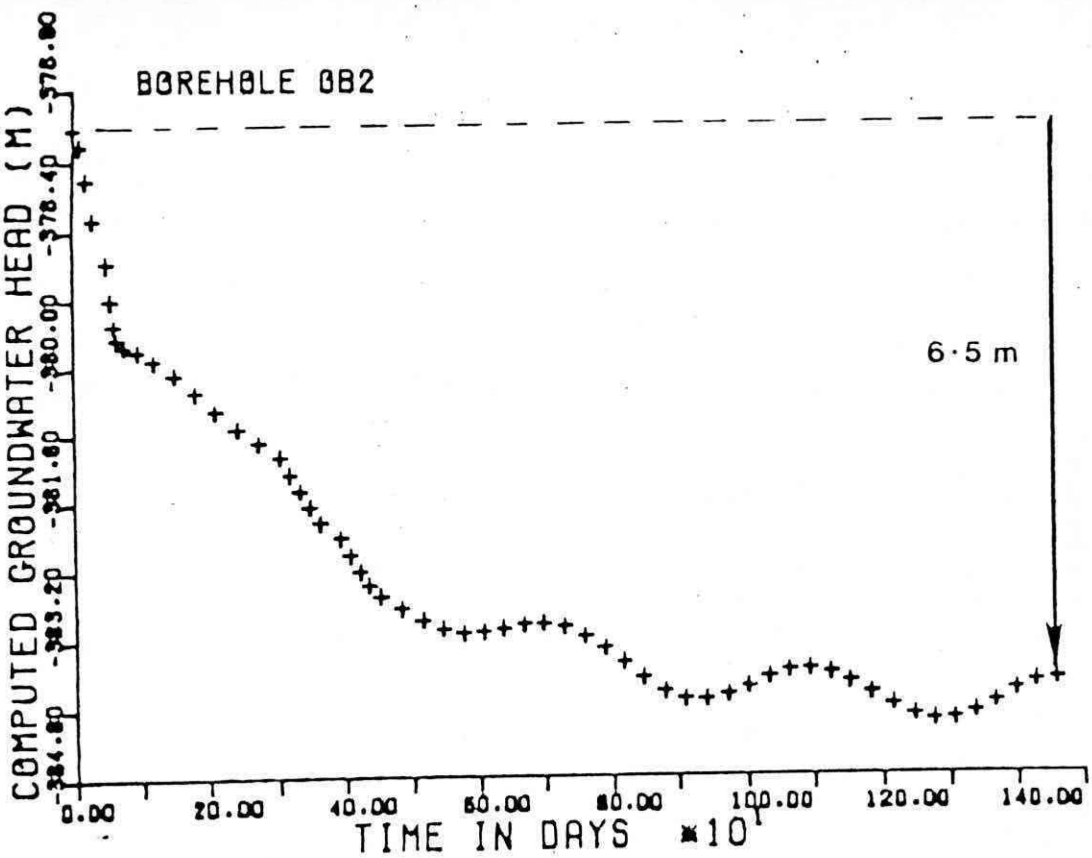
Based on estimated annual total recharge to main aquifer of 3·5 million m^3 from undiverted baseflow and canal seepage

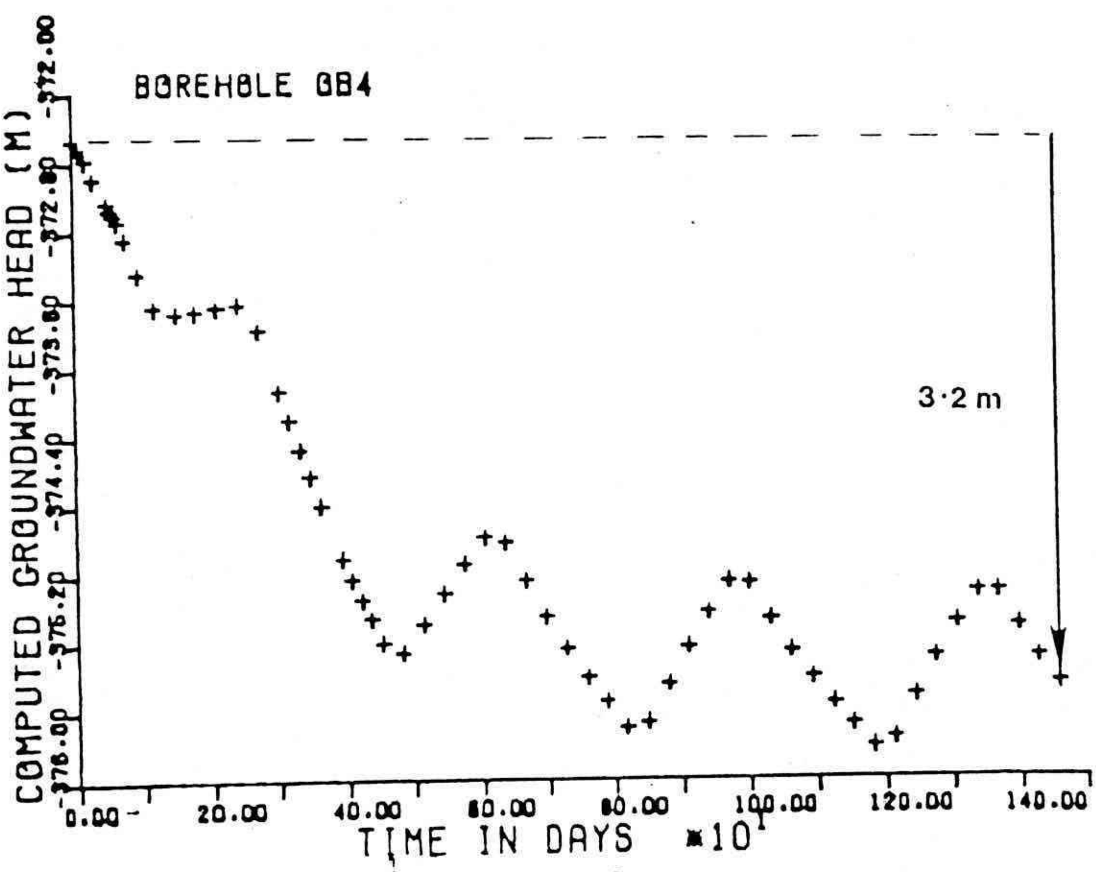
Figure 13



Computed Water Level Hydrographs for Boreholes OB2 and OB4 Under Average Conditions

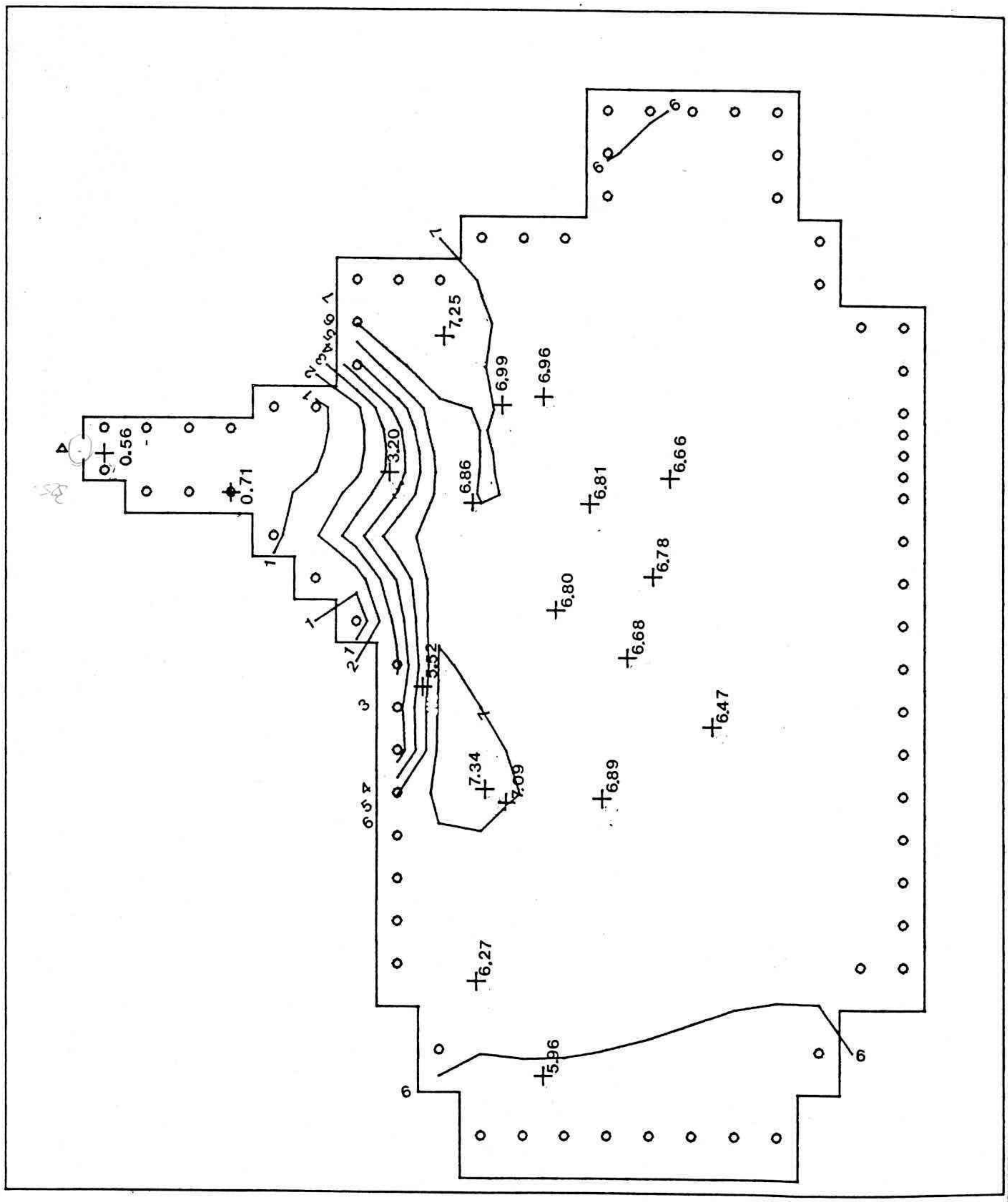
Figure 14





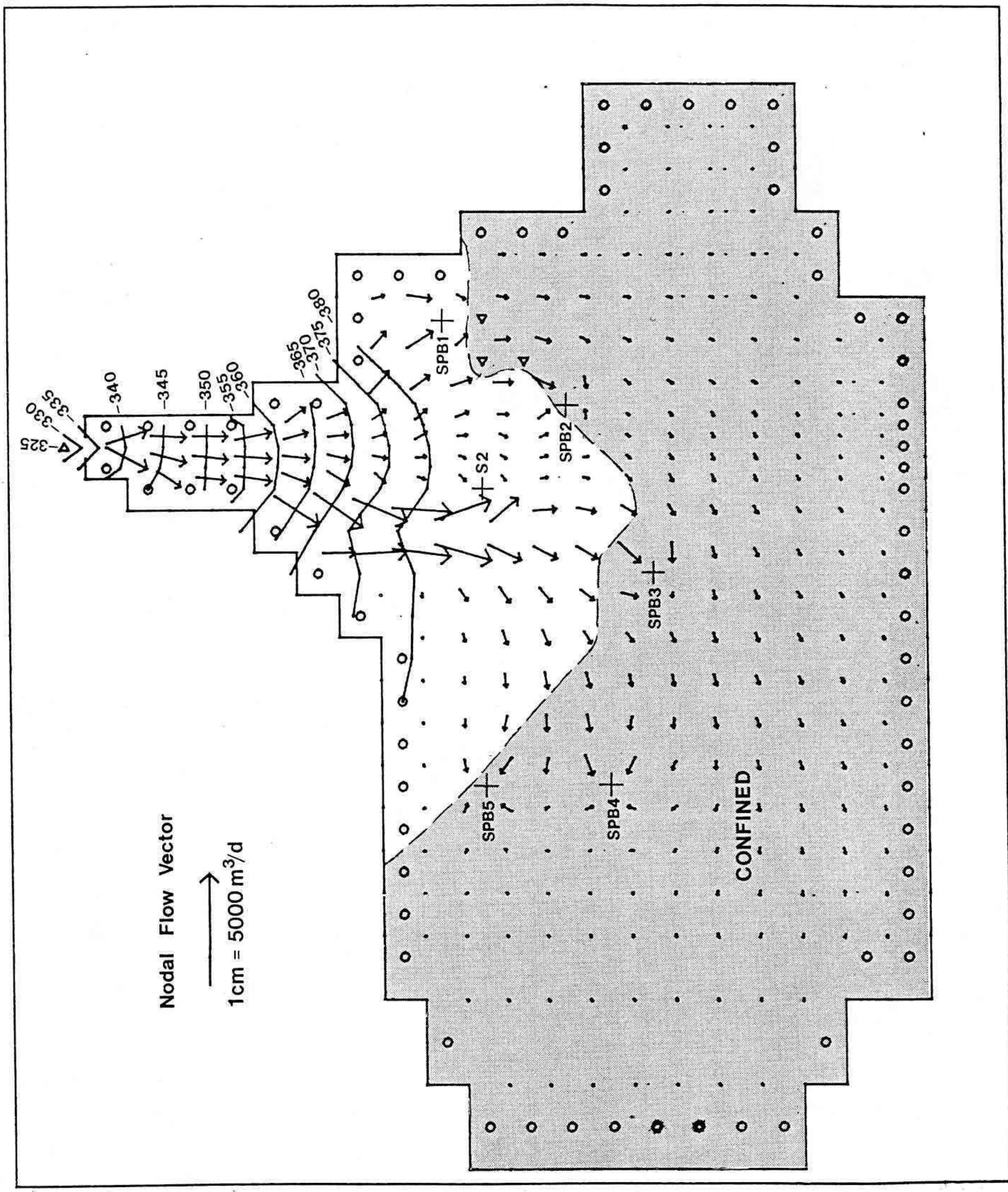
Predicted Decline in Water Levels at OB2 and OB4 with Planned Abstraction and Existing Recharge Conditions [Schedule A]

Figure 15

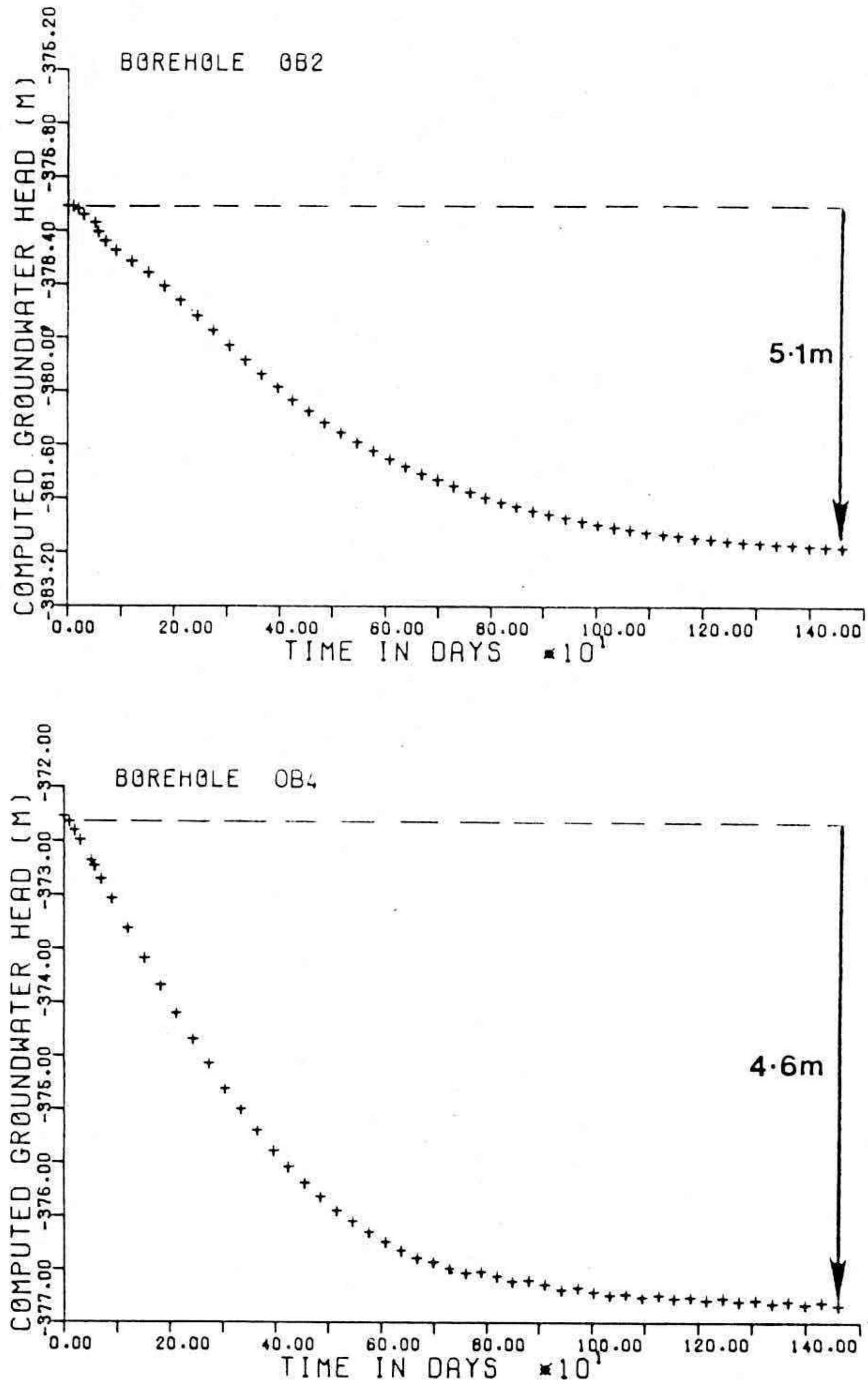


Computed Drawdown After 4 Years Pumping at Planned Abstraction Rate and Existing Recharge Conditions [Schedule A]

Figure 16

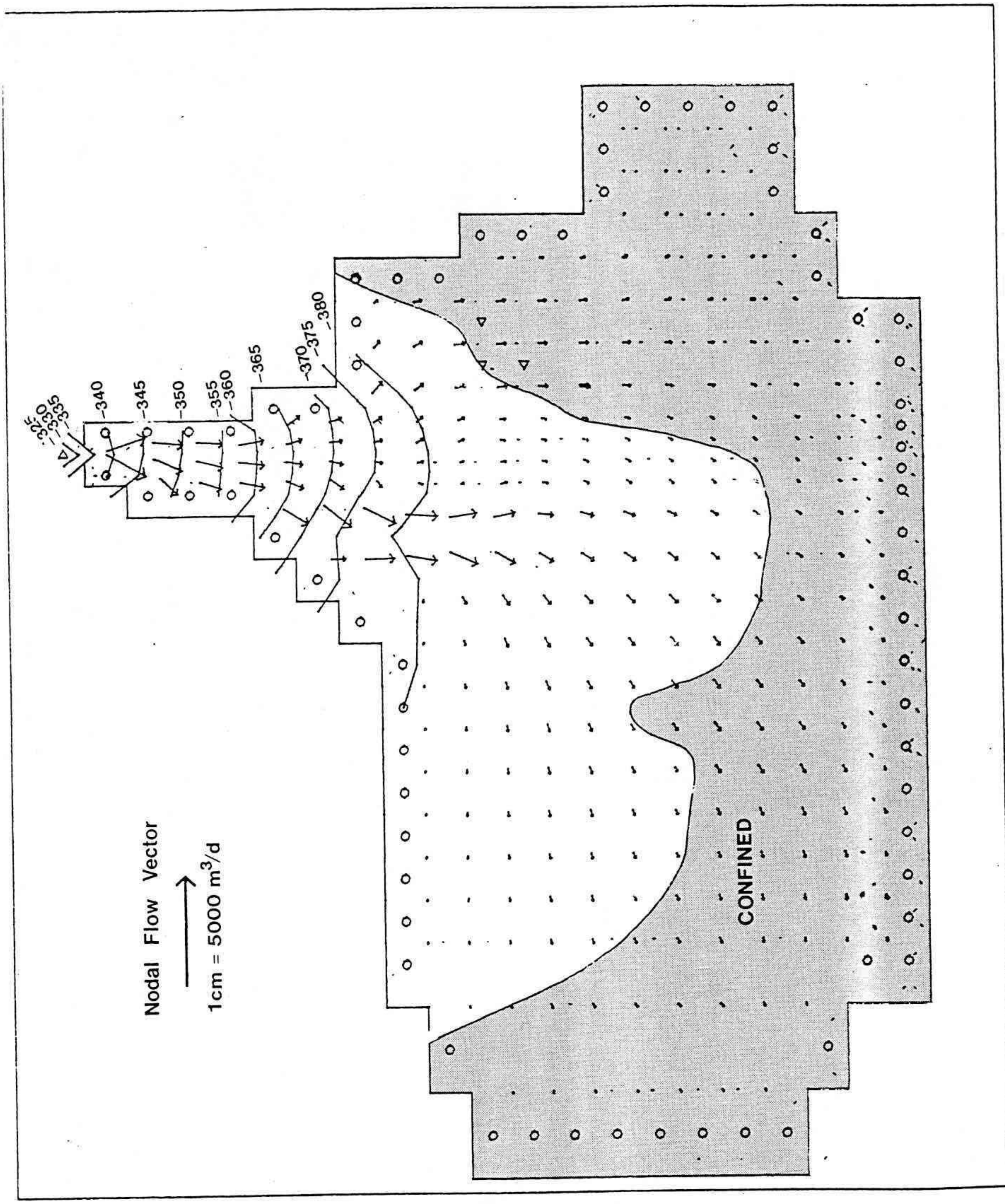


Computed Groundwater Heads and Flow After 4 Years Pumping at Planned Abstraction Rate and Existing Recharge Conditions (Schedule A)



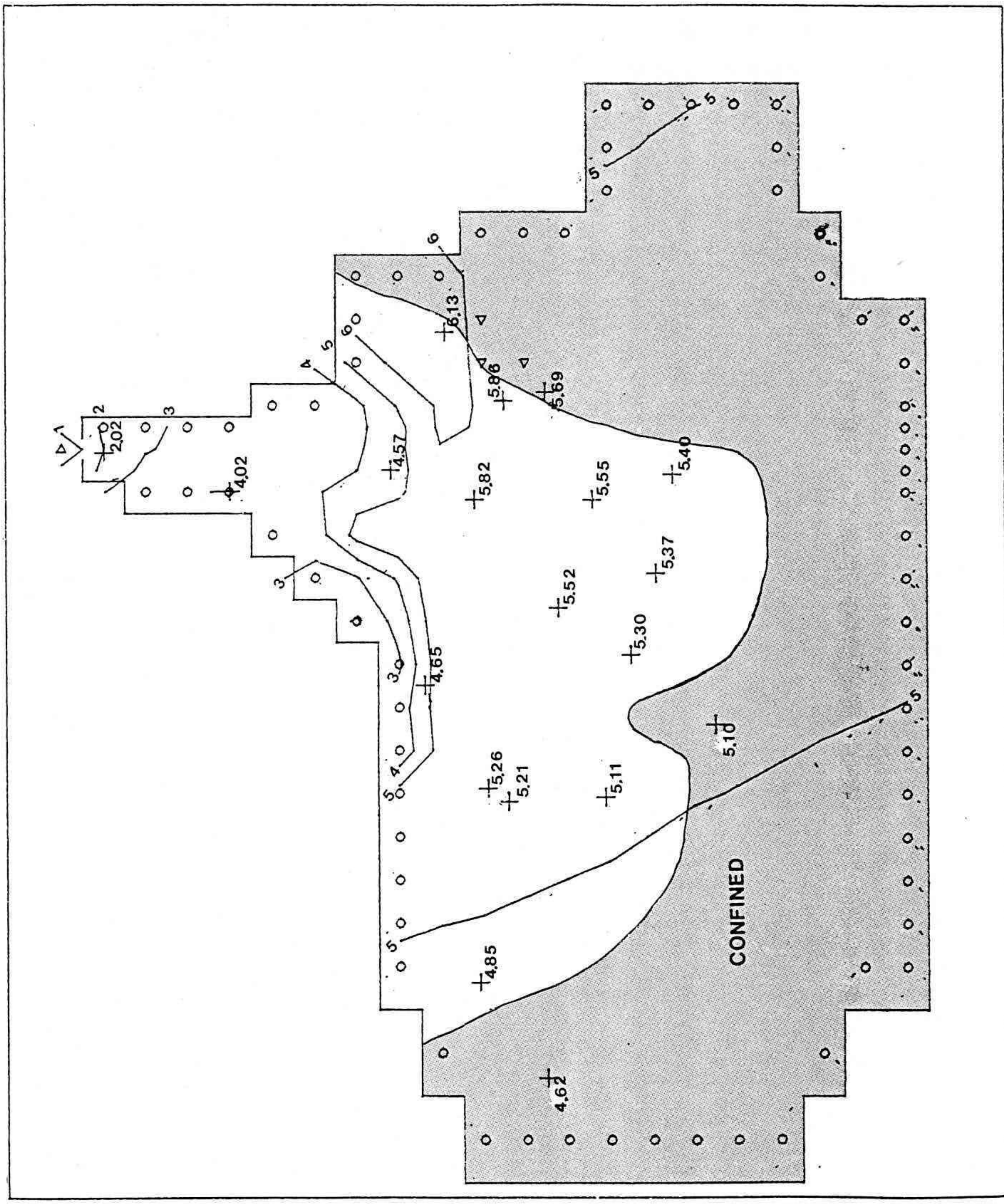
Predicted Decline in Water Levels at OB2 and OB4 with Altered Recharge Conditions and No Pumping (Schedule B1)

Figure 18



Computed Groundwater Heads and Flow After 4 Years

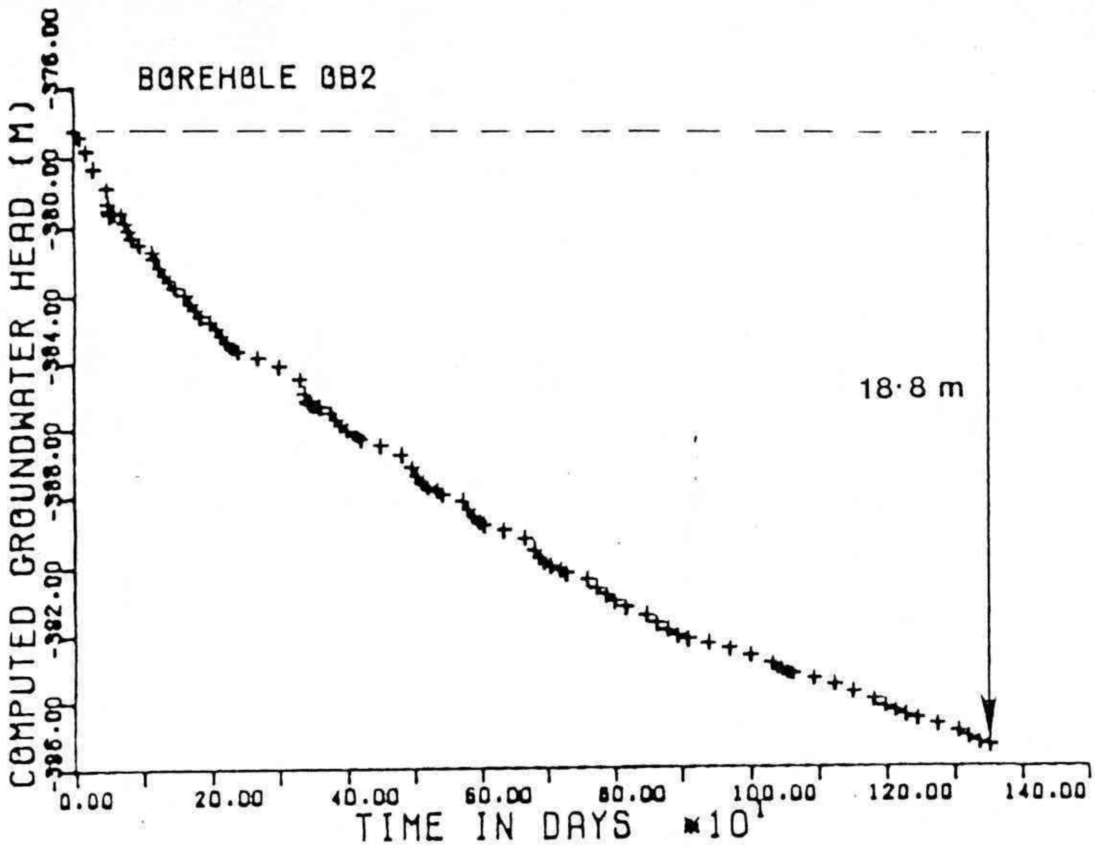
with Altered Recharge Conditions and No Pumping [Schedule B1]

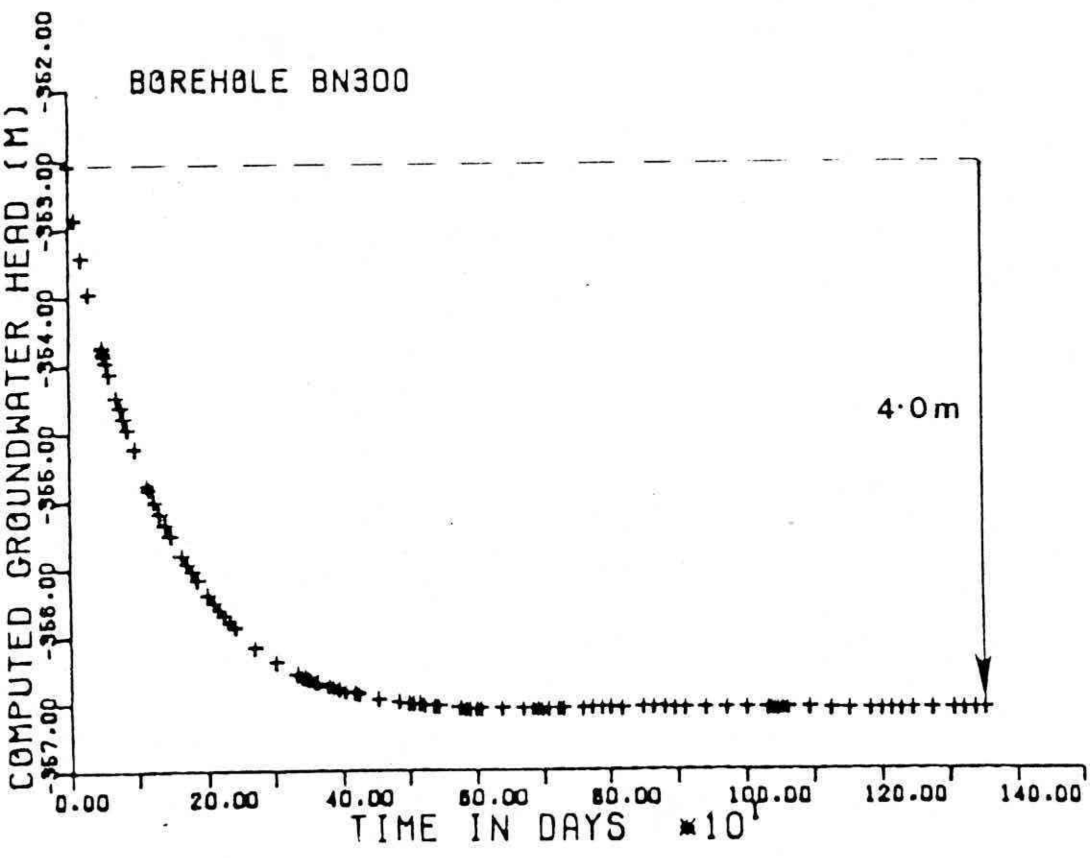


Computed Decline in Groundwater Heads After 4 Years

with Altered Recharge Conditions and No Pumping [Schedule B1]

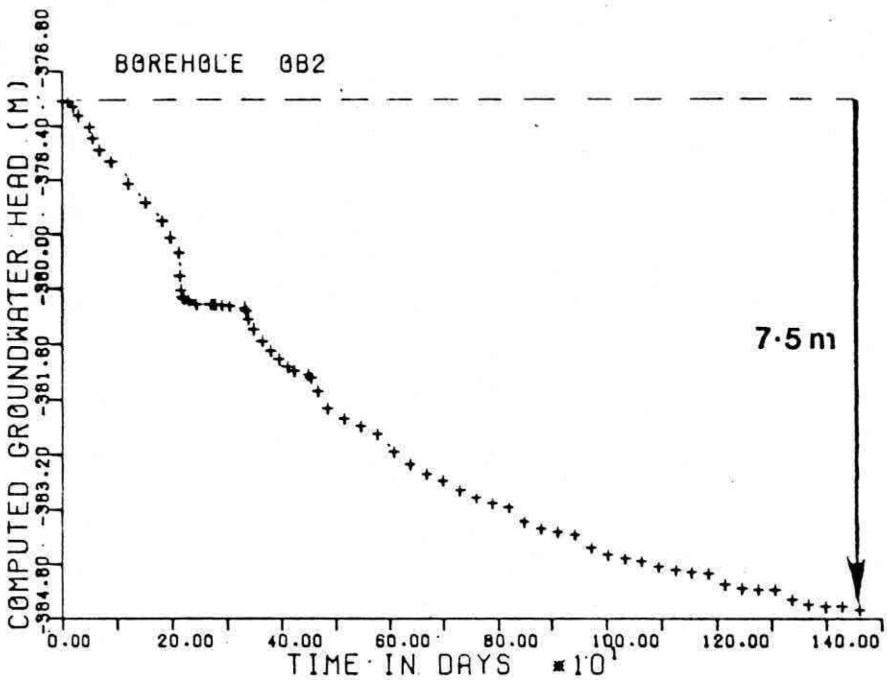
Figure 20

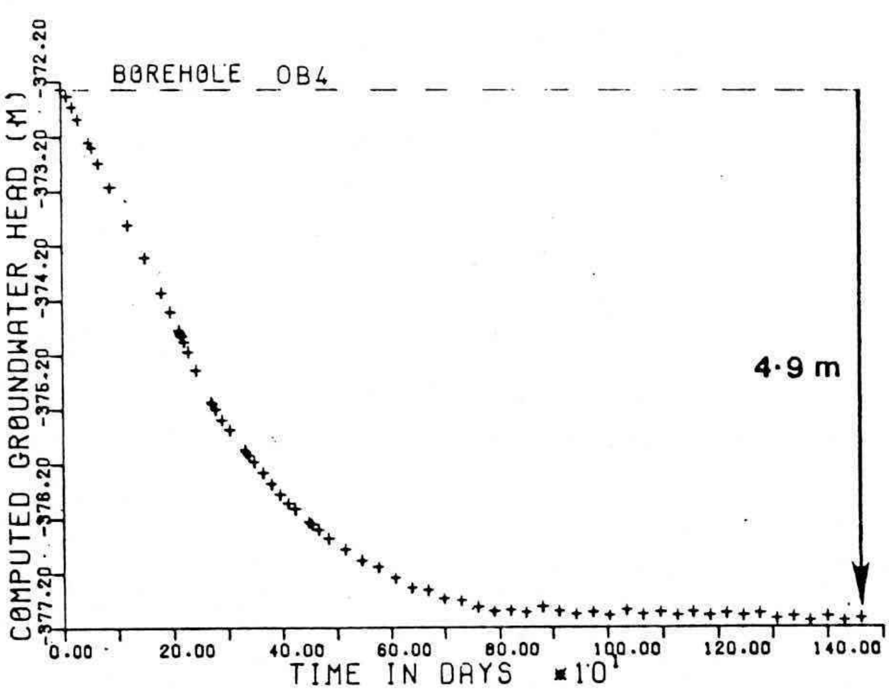




Predicted Decline in Water Levels at OB2 and BN300 with Planned Abstraction and Altered Recharge Conditions [Schedule B2]

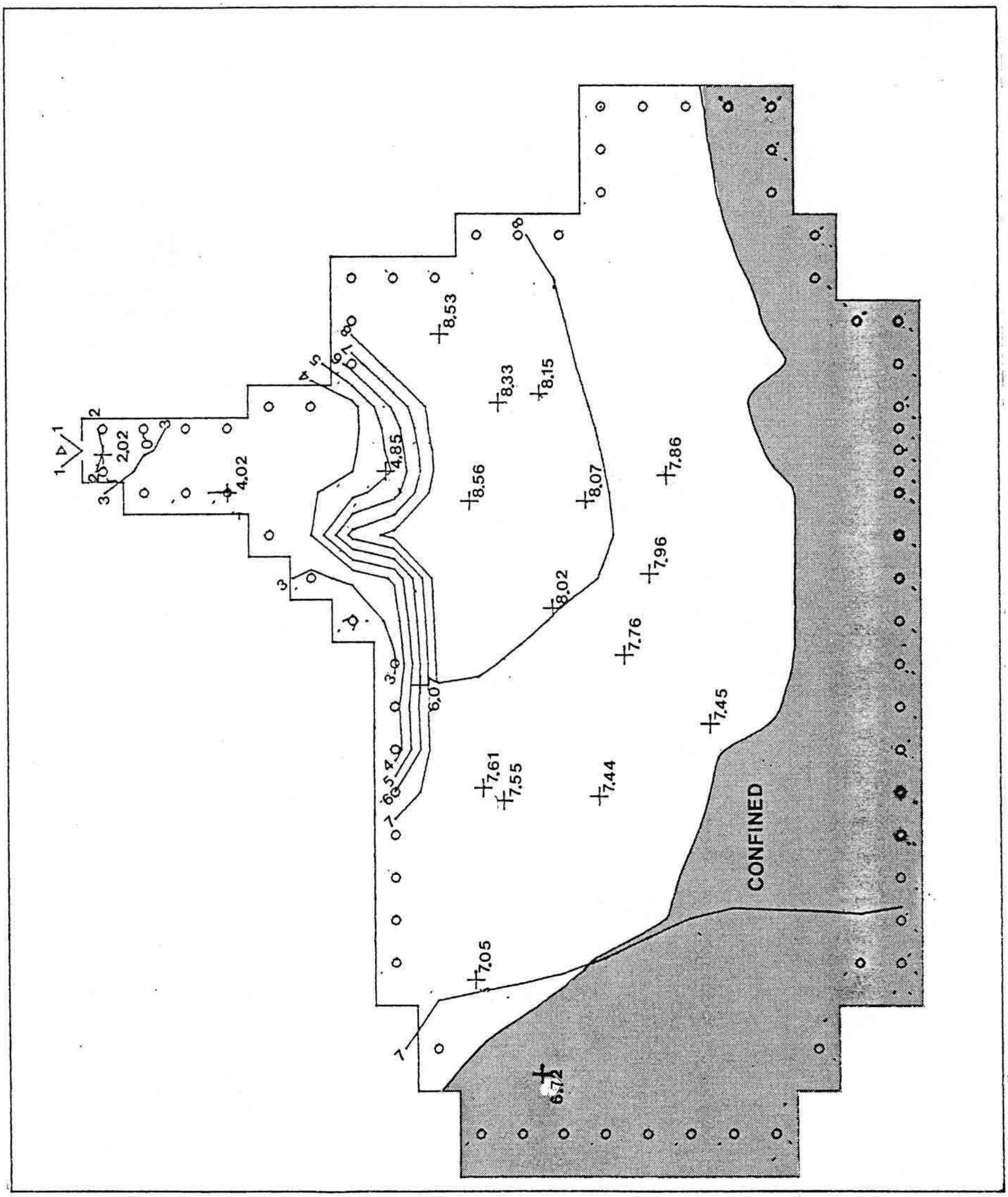
Figure 21





Predicted Decline in Water Levels at OB2 and OB4 with Modified Abstraction and Altered Recharge (Schedule C)

Figure 22



Computed Drawdown After 4 Years Pumping at Modified Abstraction Rate and Altered Recharge Conditions [Schedule C]

Figure 23

APPENDIX I

SELECTED WELL HYDROGRAPHS

Figures I.1 to I.8 are selected water level hydrographs relating to water level changes in the main aquifer, over the period 1977 to 1980 inclusive.

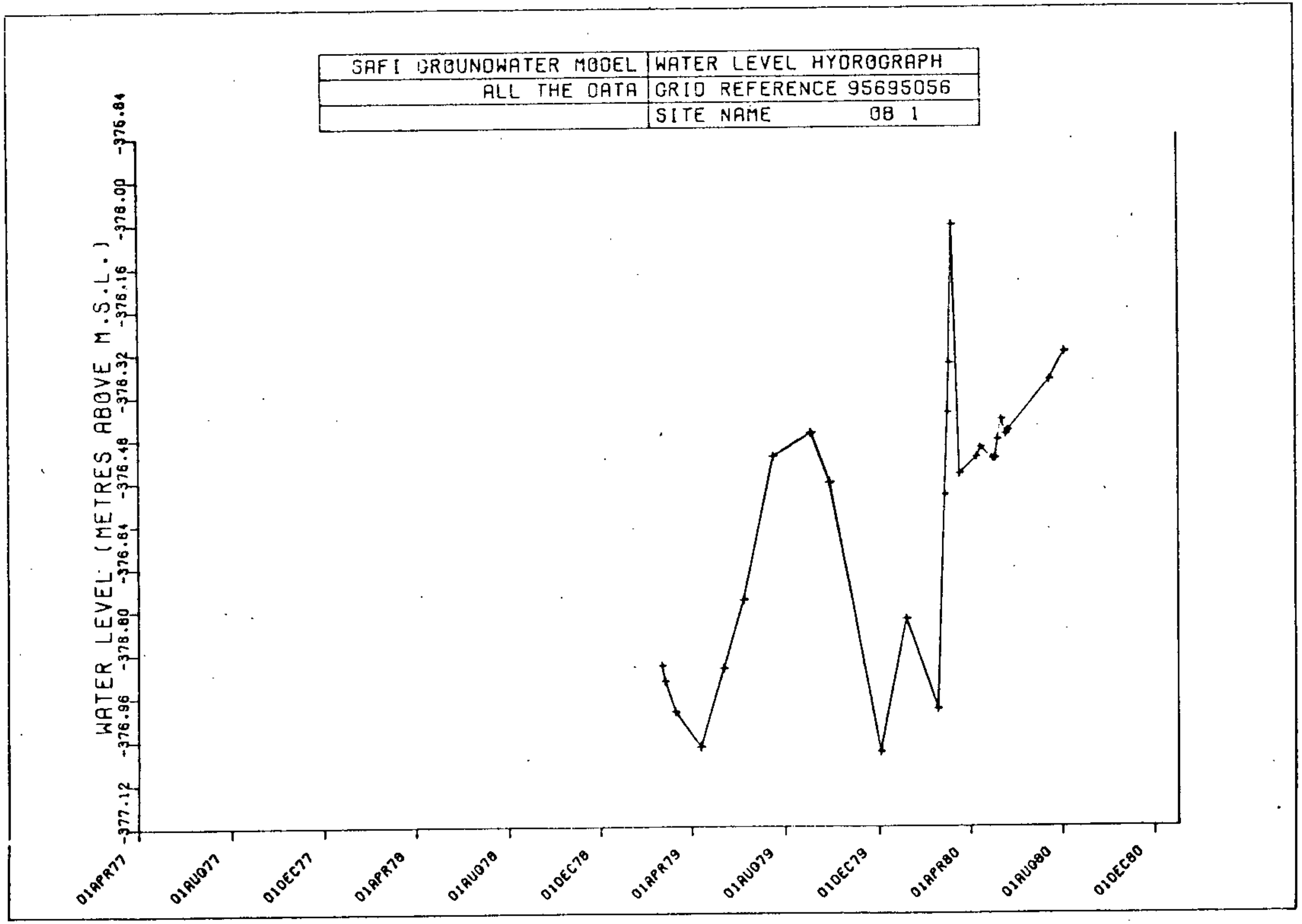

SAFI GROUNDWATER MODEL
ALL THE DATA
WATER LEVEL HYDROGRAPH
GRID REFERENCE 95695056
SITE NAME OB 1
WATER LEVEL (METRES ABOVE M.S.L.)
-377.12
-376.96
-376.80
-376.64
-376.48
-376.32
-376.16
-376.00
-376.84
01APR77
01AUG77
01DEC77
01APR78
01AUG78
01DEC78
01APR79
01AUG79
01DEC79
01APR80
01AUG80
01DEC80

Figure 1·1

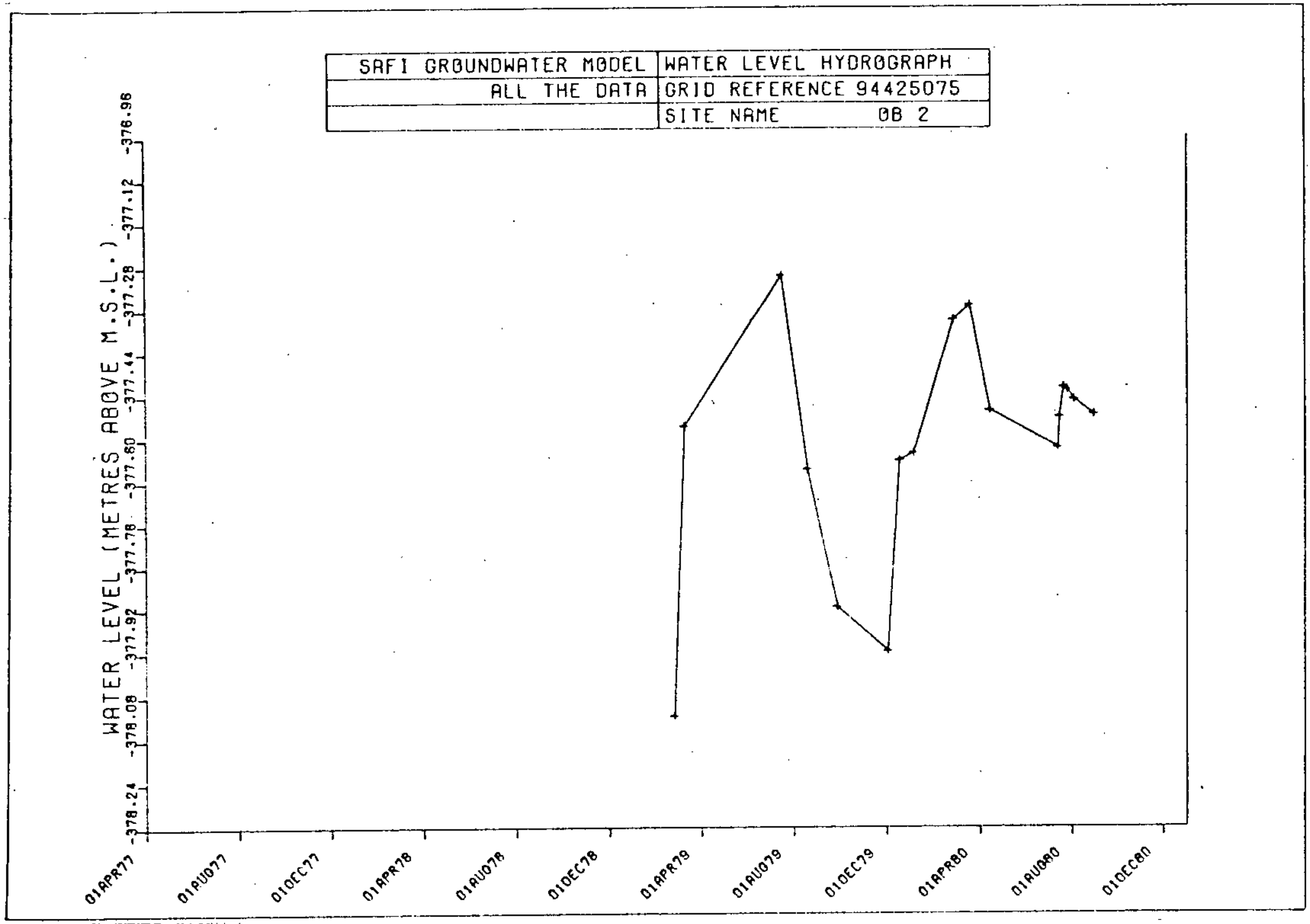

SAFI GROUNDWATER MODEL
ALL THE DATA
WATER LEVEL HYDROGRAPH
GRID REFERENCE 94425075
SITE NAME OB 2
WATER LEVEL (METRES ABOVE M.S.L.)
-376.96
-377.12
-377.28
-377.44
-377.60
-377.78
-377.92
-378.08
-378.24
01APR77
01AUG77
01DEC77
01APR78
01AUG78
01DEC78
01APR79
01AUG79
01DEC79
01APR80
01AUG80
01DEC80

Figure 1·2

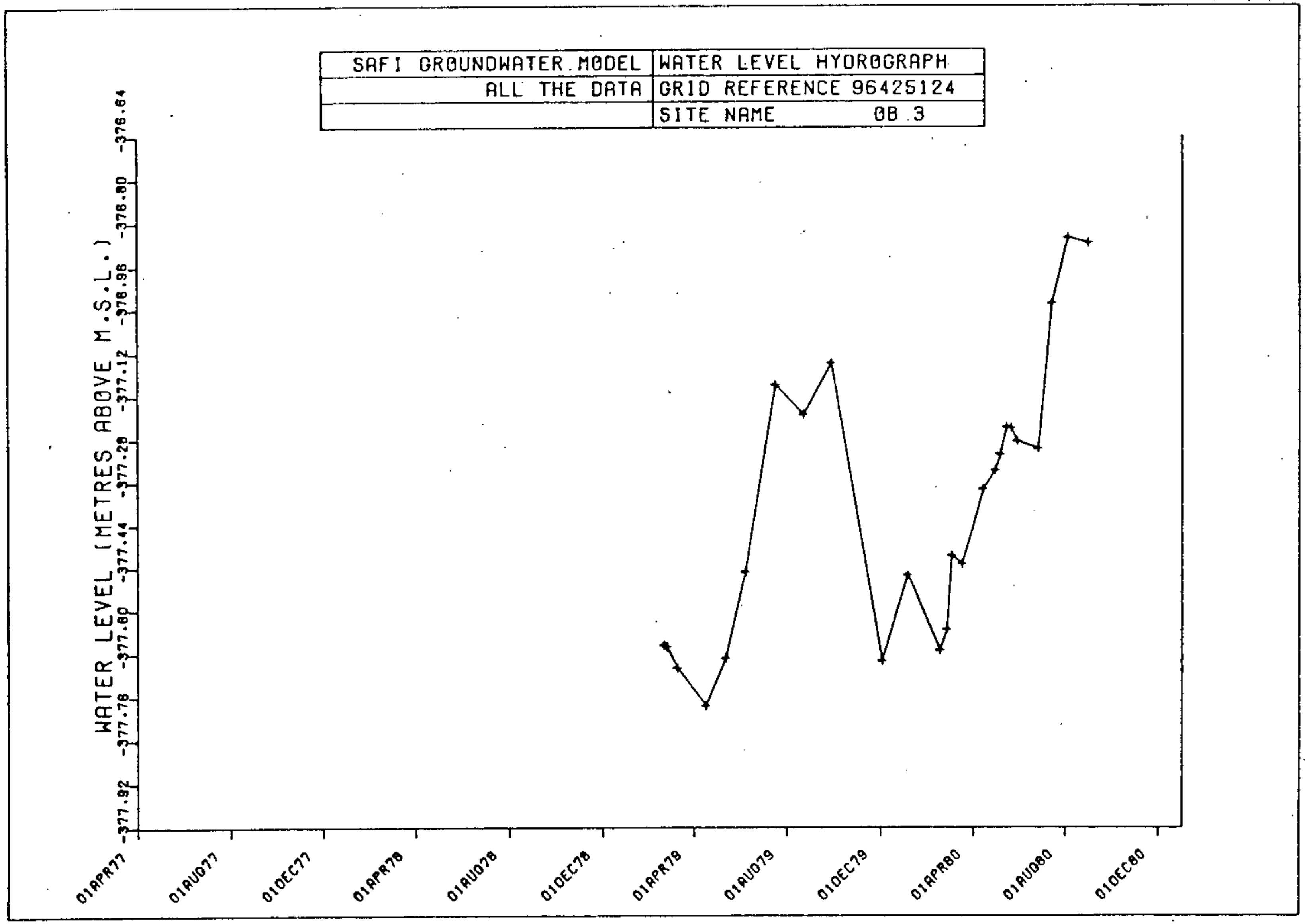

SAFI GROUNDWATER MODEL
ALL THE DATA
WATER LEVEL HYDROGRAPH
GRID REFERENCE 96425124
SITE NAME OB 3
WATER LEVEL (METRES ABOVE M.S.L.)
-377.92
-377.76
-377.60
-377.44
-377.28
-377.12
-376.96
-376.80
-376.64
01APR77
01AUG77
01DEC77
01APR78
01AUG78
01DEC78
01APR79
01AUG79
01DEC79
01APR80
01AUG80
01DEC80

Figure 1·3

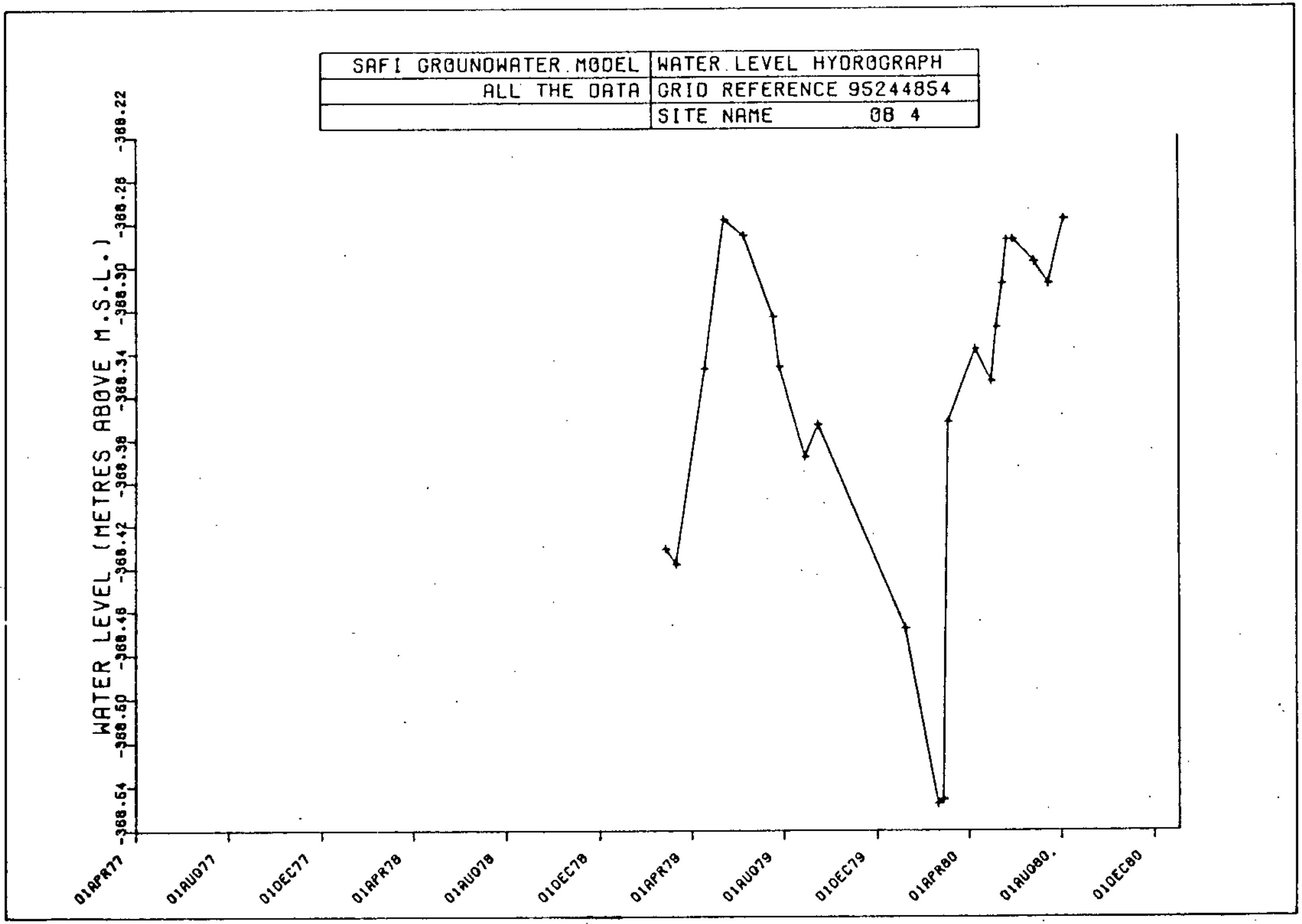
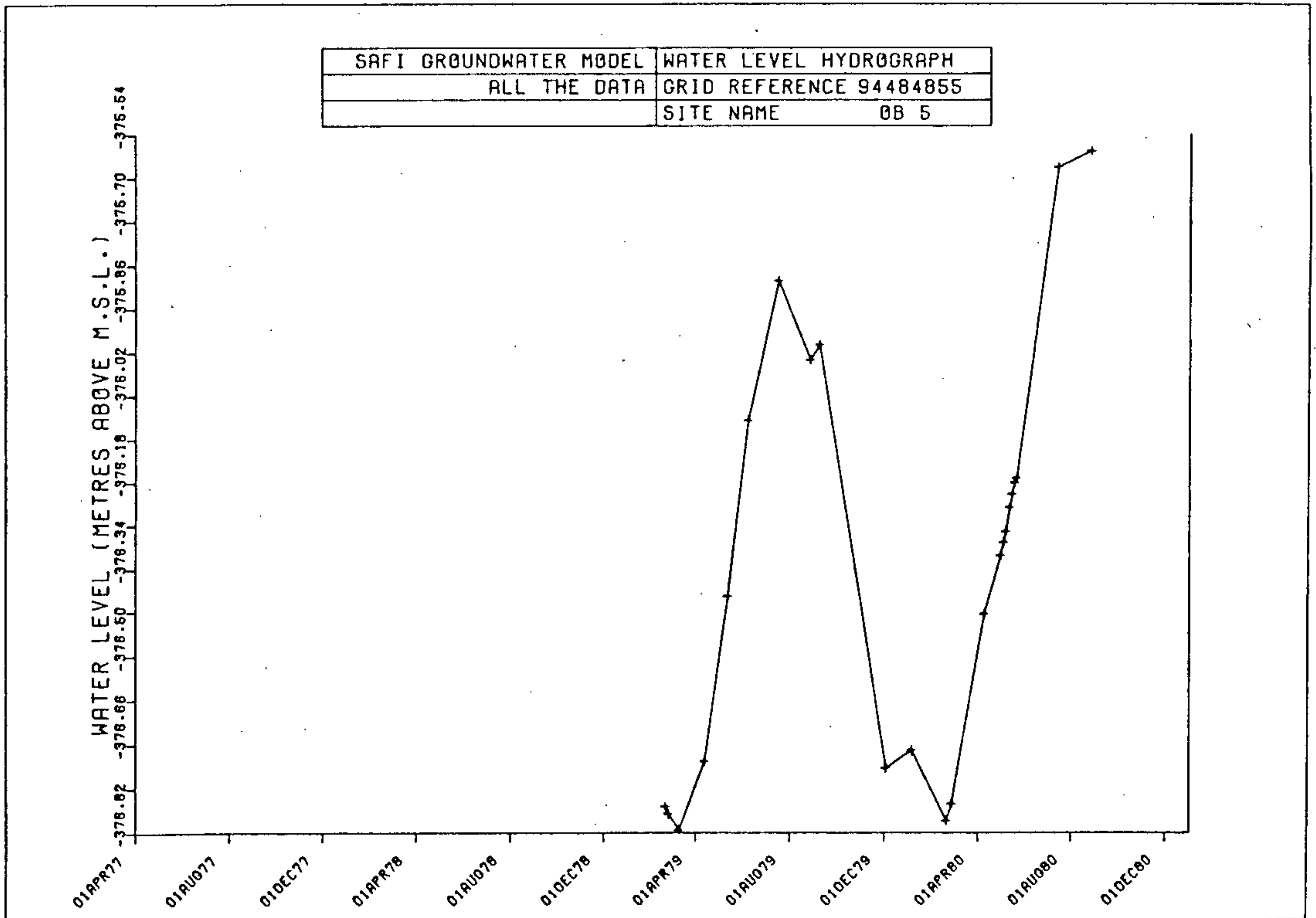

SAFI GROUNDWATER MODEL
ALL THE DATA
WATER LEVEL HYDROGRAPH
GRID REFERENCE 95244854
SITE NAME OB 4
WATER LEVEL (METRES ABOVE M.S.L.)
-388.22
-388.26
-388.30
-388.34
-388.38
-388.42
-388.46
-388.50
-388.54
-388.58
01APR77
01AUG77
01DEC77
01APR78
01AUG78
01DEC78
01APR79
01AUG79
01DEC79
01APR80
01AUG80
01DEC80

Figure 1·4


SAFI GROUNDWATER MODEL
ALL THE DATA
WATER LEVEL HYDROGRAPH
GRID REFERENCE 94484855
SITE NAME OB 5
WATER LEVEL (METRES ABOVE M.S.L.)
-376.82
-376.66
-376.50
-376.34
-376.18
-376.02
-375.86
-375.70
-375.54
01APR77
01AUG77
01DEC77
01APR78
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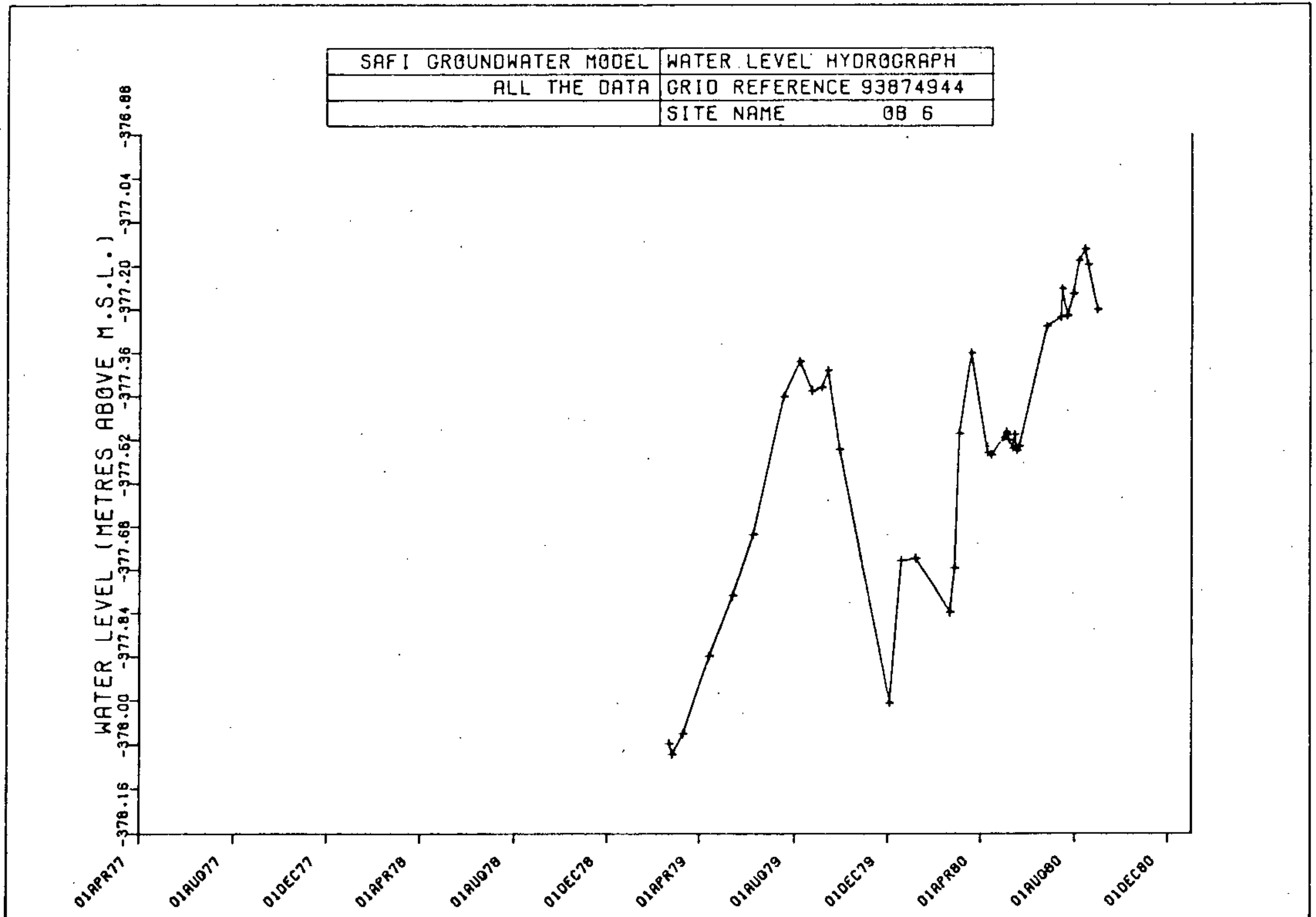
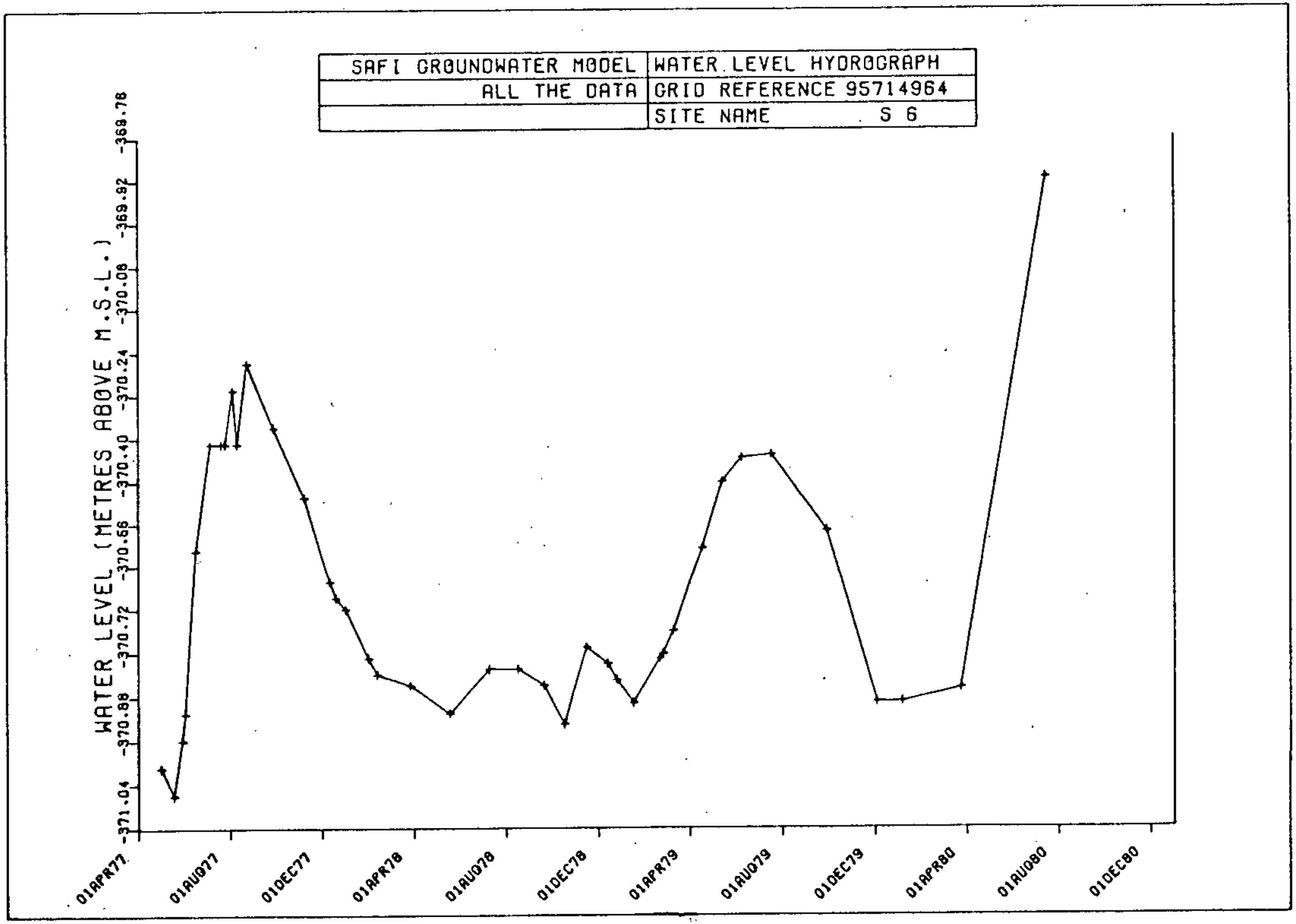
01AUG80
01DEC80

Figure 1·5



SAFI GROUNDWATER MODEL
WATER LEVEL HYDROGRAPH
ALL THE DATA
GRID REFERENCE 93874944
SITE NAME OB 6
WATER LEVEL (METRES ABOVE M.S.L.)
-376.88
-377.04
-377.20
-377.36
-377.52
-377.68
-377.84
-378.00
-378.16
01APR77
01AUG77
01DEC77
01APR78
01AUG78
01DEC78
01APR79
01AUG79
01DEC79
01APR80
01AUG80
01DEC80

Figure 1·6


SAFI GROUNDWATER MODEL
ALL THE DATA
WATER LEVEL HYDROGRAPH
GRID REFERENCE 95714964
SITE NAME S 6
WATER LEVEL (METRES ABOVE M.S.L.)
-371.04
-370.88
-370.72
-370.56
-370.40
-370.24
-370.08
-369.92
-369.76
01APR77
01AUG77
01DEC77
01APR78
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01DEC78
01APR79
01AUG79
01DEC79
01APR80
01AUG80
01DEC80

Figure 1·7

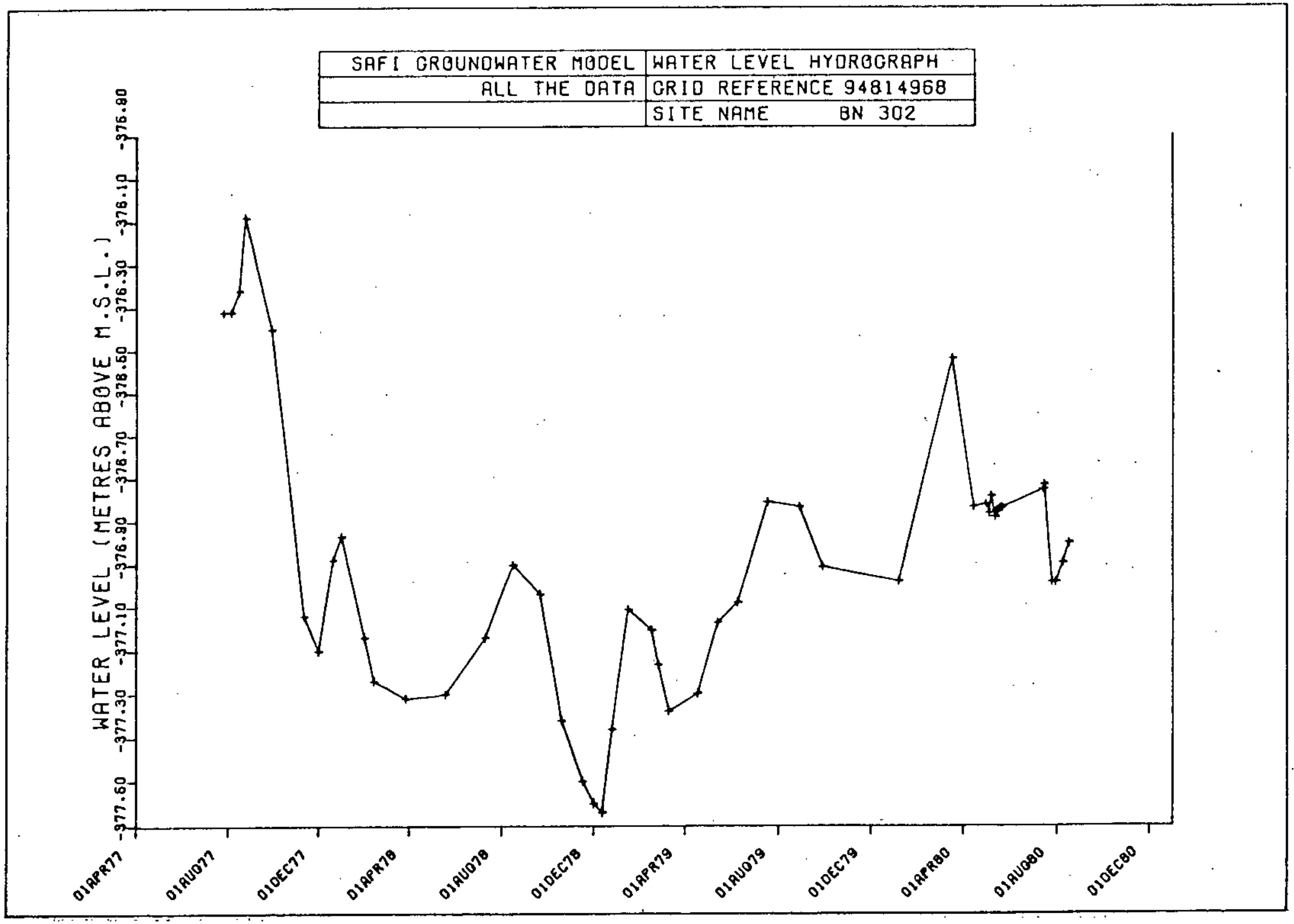

SAFI GROUNDWATER MODEL
WATER LEVEL HYDROGRAPH
ALL THE DATA
GRID REFERENCE 94814968
SITE NAME BN 302
WATER LEVEL (METRES ABOVE M.S.L.)
01APR77
01AUG77
01DEC77
01APR78
01AUG78
01DEC78
01APR79
01AUG79
01DEC79
01APR80
01AUG80
01DEC80

Figure 1·8

APPENDIX II

GROUNDWATER AS A SUPPLEMENTARY SOURCE OF SUPPLY

The Mujib and Southern Ghors Irrigation Scheme proposes to utilize fully the surface water flow of the Wadi Hasa to develop existing agriculture and to expand the area of agriculture by reclaiming new land. The likely effects of this scheme on APC industrial water supplies have been assessed previously[1], in regard to the reclamation of poor quality land in particular. If the Arab Potash Company (APC) is given priority use of the Wadi Hasa, the area of agricultural development will need to be modified accordingly. The area of agriculture is largely governed by the availability of water during the period of peak crop water demand whereas the industrial water requirement is relatively constant through the year. Groundwater supplies could be used by APC during the peak crop water demand period which could then allow a greater area of cultivation and more effective use of the total water resources.

This Appendix presents an assessment of the surplus Wadi Hasa baseflow availability for two alternative areas of agricultural development; firstly, development of the existing agricultural area of 11900 dunums (du) and, secondly, expansion of the existing area to that capable of being developed potentially at Ghor Safi, about 25000 du. From this assessment we have derived the need for groundwater to supplement the direct diversion of APC supplies from the Wadi Hasa during the periods of peak crop water demand and a wellfield operation to supply the groundwater requirement. This abstraction has then been examined with the model as Schedule C.

Data from the Mujib Scheme study have been used to estimate the source water duty demand for periods of 10 days for the drip irrigation of a 30 du Type-A vegetable farm and an area of 1000 du of mature citrus cultivation. This type of farm is similar to the present agricultural practice and is likely therefore to be more widely adopted. It also has a water demand which is near the mean demand of the five different types of farm which

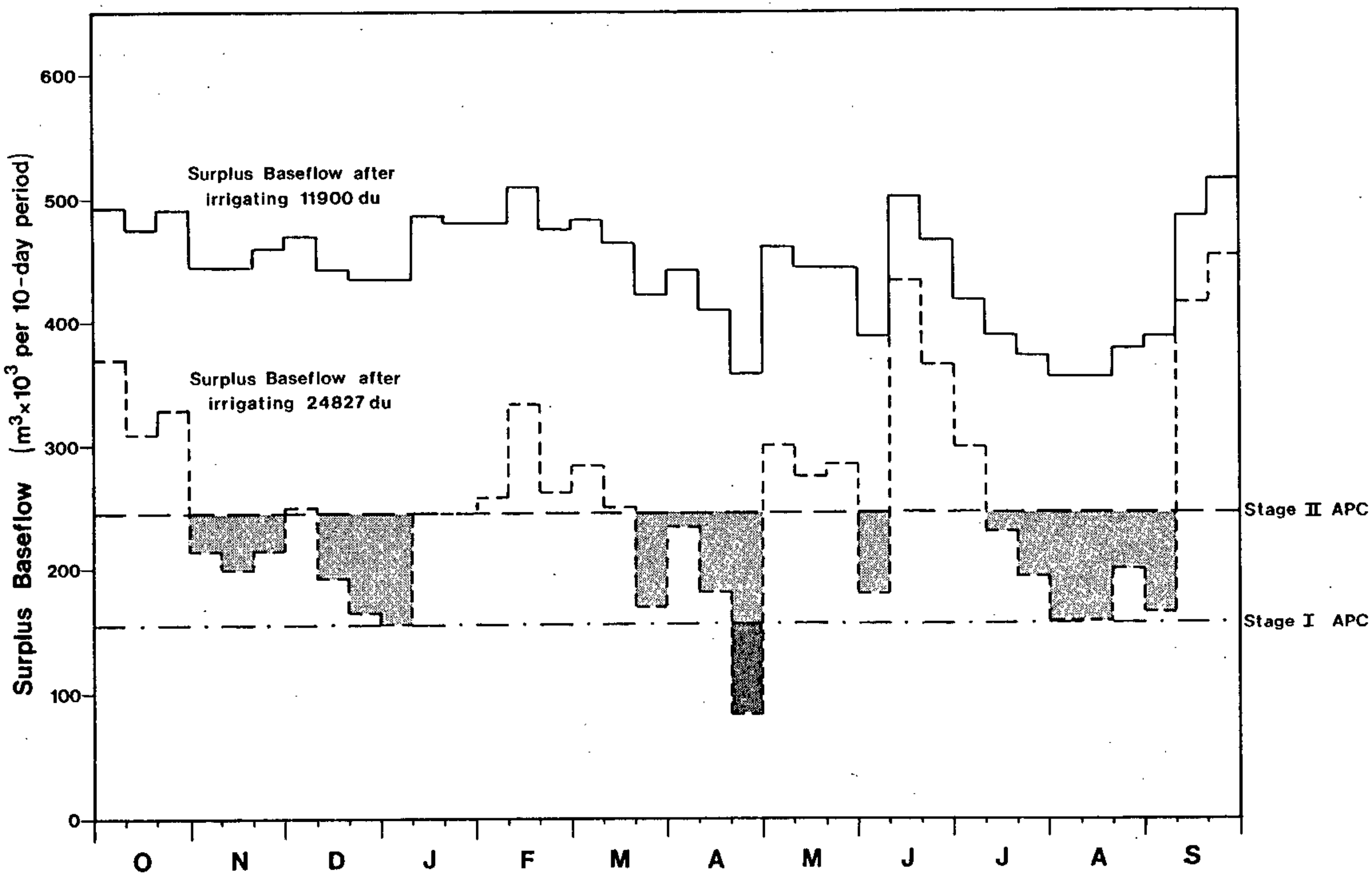
[1] *A Review of the Water Supply to the Arab Potash Project with respect of the Mujib and Southern Ghors Irrigation Project Feasibility Study. Apr. 1980*

were considered by the Mujib Scheme study. For each area of development the total source water duty demands were compared with the 80% reliable Wadi Hasa baseflow to obtain the surplus flow that could be available to meet the industrial water demands. The supplementary groundwater requirement is then the difference between the industrial demand and the surplus baseflow. The surplus baseflow and groundwater requirements are shown in Figure 2.1 for a typical year after development.

By restricting agricultural development to the existing area, the Wadi Hasa can supply both the agricultural and industrial water demands, including the Stage II APC demand of 9 million m^3/year. However, even after supplying the Stage II demand there would be a net surplus of 6 million m^3/year, which would not be an efficient utilisation of the Wadi Hasa flow availability. Groundwater abstraction would not be required for this restricted agricultural development area except during days of flood (about 12 days/year). At the peak crop water demand, with APC given priority use, the residual flow could be used to irrigate an additional 13300 du (total 25200 du) or 9125 du (total 21025 du) at the Stage I and Stage II demands respectively. If the future Stage II APC demands are to be met from the Wadi Hasa, the area of agricultural development would need to be restricted to the smaller total area of 21025 du.

Expansion of the agricultural area to nearly 25000 du would require groundwater supplies to supplement direct diversion of the Wadi Hasa by APC during peak crop water demand periods as well as during days of flood. The groundwater requirement to offset crop water demands is small, only 0.07 million m^3/year, during Stage I but about 1.1 million m^3/year in Stage II. The time-varying model has been used to examine the capability of the aquifer to an intermittent groundwater abstraction of 1.05 million m^3/year, representing a conjunctive use scheme with an expanded agricultural area of 25000 du. The results are given in Schedule-C. A minimum recharge of 2940 m^3/d will be required to sustain this groundwater requirement.

The existing volume of recharge will be reduced by a conjunctive use scheme involving the Wadi Hasa to that entering the aquifer as underflow at the weir, about 5000 m^3/d. This should support the above groundwater requirement without a further significant depletion in storage.



Surplus Wadi Hasa baseflow and groundwater demands with alternative agricultural developments

Shortfall in surplus baseflow during Stage I APC

Shortfall in surplus baseflow during Stage II APC

NOTES:
Shown for typical year following agricultural developments

Not including annual pre-planting leaching water requirements of 0·6 and 1·24 million m^3/year for each development respectively

Figure 2·1

To support demand during days of flood when diversion is not possible, would require a groundwater abstraction of about 0.19 million m^3/year during the period from November to April. The wellfield would need to be capable of supplying the daily water requirement. However, it is not possible to use the model to examine abstraction in this detail. The available drawdowns of the wellfield boreholes would be reduced by 5 m due to the depletion in storage caused by the reduction in recharge following agricultural development. As a consequence, boreholes SPB1 and BN 309 would be taken out of commission or pumped at a much reduced rate. The five remaining boreholes could supply about 15000 m^3/d, at the present fitted peak pumping capacity, approximately that needed to meet the daily Stage I water demand. However, the present wellfield would have a shortfall in capacity of about 9000 m^3/d at the daily Stage II demand, which would require additional boreholes to maintain supplies during days of flood. The minimum recharge to support abstraction during days of flood is 510 and 810 m^3/d for Stage I and Stage II respectively.

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