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GHOR SAFI GROUNDWATER MODEL

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SUMMARY

Hydrological information has been collated to develop a PC-based groundwater flow model of the main alluvial fan aquifer at Ghor Safi, from which APC currently obtains most of its water supply. Water level data for the pre-development situation prior to APC abstraction together with seasonal and annual water level data from the APC observation well network have been used to calibrate and test the model.

Difficulties in developing the model were experienced as only limited information is available on the sources of recharge, the storage coefficient of the main aquifer and the permeability of the clay layer that covers a large part of the main aquifer. The hydrogeological information available for the lower parts of the fan is also still rather limited. As a result of these limitations in the data, it was found that similar contour patterns to those observed could be produced by different combinations of recharge and aquifer conditions. However, a recharge of 10.5 Mm^3/y combined with upward leakage produced an acceptable calibration of the model consistent with the present knowledge of the aquifer system.

The model was verified using APC abstraction data. It was demonstrated that the steady decline in water levels observed between 1982 and 1992 is associated with the annual changes in APC abstraction, which have not allowed water levels in the aquifer to stabilise. This suggests that the irrigation improvements at Ghor Safi have not resulted in a significant reduction in the amount of recharge to the main aquifer. Consequently, it should be possible to sustain a constant supply without a further significant decline in water levels if an appropriate constant annual rate of abstraction is selected, based preferably on a water resources management strategy for the area.

The model has been used to show the likely aquifer response by the year 2000 to abstraction rates of 6.18 Mm^3/y and 4.5 Mm^3/y by APC together with an abstraction of 0.25 Mm^3/y to meet municipal water demands. These abstraction rates are similar to the highest and lowest rates of APC abstraction in 1985/6 and 1989/90, respectively. The rate of 6.18 Mm^3/y, taken together with the normal Hassa surplus flow used by APC, represents the current capacity of the Safi pumping station/pipeline system which supplies APC. The rate of 4.5 Mm^3/y has been proposed as a 'safe yield' based on the commonly adopted practice of setting safe yield as approximately 50% of estimated annual recharge. In both the above cases regional water levels stabilise at elevations about 6 to 7 m above the fan-edge elevation, which suggests that water quality should not be seriously affected at these abstraction rates provided the amount of recharge is not reduced in future.

The model was also used to indicate the effects on the Safi aquifer of a proposed dam on the Wadi Hassa at Tannour. Although the amount of recharge from floods is variable and uncertain, a reduction in 'average' flood recharge (tentatively estimated as 1.5 Mm^3/y) results in an average fall in water levels of about 1 m. However, the dam may allow more of the present surplus baseflow to be used for irrigation which would have more serious consequences for future recharge and APC abstraction.

The model can be used to examine almost any combination of abstraction, well distributions and changes in recharge to assist APC in planning and managing their future water supplies. It is recommended that abstraction/recharge scenarios are now selected to be studied with the model.

1. BACKGROUND

1.1 Introduction and Objectives

The APC wellfield at Ghor Safi was commissioned in 1982 and by December 1992 a total of 52.2 Mm^3 had been abstracted. During this period the wellfield was expanded and a supplementary supply obtained from the surplus baseflow of the Wadi Hassa to meet the rise in APC water demands. By 1992 water levels had declined by about 5 to 10 m at Safi, which may have been partly due to changes in the irrigation system at Ghor Safi during the 1980's and partly due to a period of dry years when there was limited flood runoff.

It is anticipated that the water sources at Ghor Safi will still be needed to supplement the future supplies from the Dhira wellfield [1], which is presently under construction some 35 km north of Safi. The future role of the Safi wellfield will depend on the availability of the floodflow and surplus baseflow, abstraction from the Dhira wellfield, whether conjunctive-use schemes are implemented and additional demands for water supplies at Safi.

The changes in the hydrological regime due to the irrigation scheme may affect the future abstraction from the Safi wellfield. Other considerations affecting the output from the wellfield include the following:

* the 'safe yield' of the aquifer must take into account groundwater management constraints, such as the need to maintain sufficient groundwater flow into the fan-edge area to prevent a deterioration in water quality.
* greater use of the surplus baseflow or floodflows will reduce recharge to the main aquifer.
* the output from each well is sensitive to the available drawdown, which is limited by the relatively shallow depth to the base of the main aquifer.
* the present capacity of the Safi pumping station and pipeline limits the total output to a maximum of about 950 m^3/h and the wellfield output is reduced when the combined supply from surplus baseflow and the wellfield reaches this capacity.
* the availability of suitable sites for new wells is becoming more difficult.

Numerical groundwater modelling techniques provide a practical means of examining alternative water supply strategies. A groundwater flow model of the Safi aquifer was first developed in 1980 [2]. This was based on a mainframe computer and a computer code was written specifically for the study. At that time data were insufficient to verify the model and the model was used in a steady-state mode to estimate recharge and to examine the main factors governing groundwater flow through the aquifer system. It was used in 1985 to examine the first few years of APC abstraction [6].

The objectives of the present model study were to:

* incorporate new groundwater data and other information
* examine the longer term sustainable yield of the aquifer
* predict the aquifer response to continued APC abstraction.

In addition, APC requested that the potential effect of a proposed dam on the Wadi Hassa at Tannour should also be considered since this could reduce the amount of recharge.

The Mujib and Southern Ghors Irrigation Scheme (MSGIS) had just begun to be implemented at the time of the previous study. More information has since become available on the use of baseflow for irrigation as well as on the aquifer characteristics and the water level response to abstraction. In addition, it was considered appropriate to use a PC-based groundwater flow model as suitable commercial codes are now more widely available.

1.2 Model Description

The model code AQUA (version 3.1) was selected for the model study. This is a finite element, time-varying 3-D flow and contaminant transport model employing the Galerkin method with triangular elements. Areal values of most parameters (transmissivity, anisotropy etc) can be changed element by element and time-varying information at nodes (eg. abstraction patterns or infiltration rate) can be easily represented. The package contains pre- and postprocessors to facilitate the input and output of data. A zoom facility and sub-grids allow any part of the model to be examined in more detail.

All groundwater flow models suffer some limitations in representing complex aquifer conditions, such as those that occur at Ghor Safi. The present version of AQUA uses transmissivity (T) rather than aquifer thickness (D) and permeability (K) in the 3-D mode and consequently does not fully represent unconfined conditions when there is a significant change in the saturated aquifer thickness. In common with most groundwater models, some time varying aspects are not fully represented, such as changes in storativity with a change from confined to unconfined conditions or constant heads in the upper aquifer with leaky aquifer conditions.

However, since data are still lacking on certain parameters (eg. storativity and recharge) and certain areas of the Safi aquifer (eg, fan-edge area), the ease and speed of use of AQUA compared to many other model codes to test alternative concepts was felt to be an advantage.

Saline water occurs at a depth of about 100 m in the upper part of the fan and is present in the fine-grained deposits of the Wadi Araba-Dead Sea. As yet the wellfield supplies have shown no adverse changes in water quality. Nonetheless, a significant decline in water level would alter the position of the interface between the fresh and saline groundwater, especially with the high density of the Dead Sea.

Although the model has not been used to examine changes in groundwater quality that could result from overabstraction, the water level response predicted by the model can provide a qualitative indication of the risk of such changes. For example, if water level elevations fall to less than the elevation of the fan-edge (about -390 metres below Aqaba datum) there would be a serious risk of saline intrusion, which would be preceded by the upconing of poor quality water at the production wells.

1.3 Modelling Procedure

Developing and testing a groundwater flow model requires reliable data on the physical geometry and characteristics of the aquifer system and on the hydrological stresses imposed on that system. A successful calibration usually requires that at least one parameter should be known with reasonable accuracy, otherwise equally valid results may be possible from different sets of values for the various parameters. Despite the information on the Safi aquifer that is now available, the aquifer system is complex and suitable data are still lacking for certain parameters and in the more peripheral parts of the fan.

The hydrological regime at Ghor Safi has also undergone considerable changes, especially since 1982/3. The various stages of development can be summarised as follows:

I Natural (historical) situation prior to irrigation.
II Pre-development situation with traditional irrigation methods but with no significant groundwater abstraction (prior to 1982).
III Transitional period when groundwater heads were adjusting to significant abstraction and widespread improvements in irrigation and drainage (1980's).
IV Post-development situation.

The baseflow of the Wadi Hassa has been used for irrigation at Ghor Safi for hundreds of years, and hence the aquifer system was in a steady-state before APC began to abstract groundwater in 1982. Data from this pre-development phase forms the basis of the calibrated model.

Besides groundwater abstraction by APC, some of the more important developments that have altered the hydrological regime at Safi since 1982 include:

- a change from traditional furrow irrigation to modern efficient drip-irrigation methods, expansion of the area under cultivation, drainage of the fan-edge area, flood-relief channels and the temporary diversion of surplus flows from the Wadi Hassa to reclaim new agricultural land.

- a new pipeline to supply APC with surplus irrigation water from the Wadi Hassa.

- new wells to provide municipal water supplies to Ramleh (New Safi) and also to provide water supplies to a new tomato processing factory.

Unsteady-state aquifer conditions developed during the 1980's as the aquifer responded to APC abstraction and to changes in the amount and distribution of recharge and discharge.

Information provided by APC, the Water Authority of Jordan (WAJ) and the Jordan Valley Authority (JVA) has been used to update the description of the aquifer system, its characteristics, and the historical pattern of abstraction and undiverted wadi flow as background to the model. More detailed information can be found in the list of references.

Those parameters for which information is available include:

- APC abstraction (other abstraction is limited)
- transmissivity distribution (except in the fan-edge area)
- base of aquifer (except in the fan-edge area)
- top of main aquifer
- piezometric surface of main aquifer (pre-development)
- water table in upper aquifer (pre-development)
- water level fluctuations prior to abstraction
- water level changes in response to abstraction
- present use of Wadi Hassa by JVA
- spring discharge (pre-development).

However, limited or no information is available on the following parameters:

- storage coefficients (S)
- permeability of the confining clay layer
- changes in recharge and discharge resulting from the MSGIS
- contribution from flood recharge
- underflow at the exits of the Wadi Hassa and Wadi Abyad
- groundwater transfer across the Dead Sea fault
- characteristics of the Samra deposits
- groundwater evaporation in the fan-edge area.

Hence, the geometry of the aquifer, its transmissivity and pre-development water level configuration, and abstraction history are reasonably well known but information on the storativity and components of the water balance is still rather limited.

The following general procedure was adopted to calibrate and verify the model:

(i) - steady-state comparison of modelled water level contours with those observed prior to development using various recharge estimates and alternative concepts of the aquifer conditions.

(ii) - time-varying runs to calibrate the model against pre-development water level fluctuations using various estimates of aquifer storativity.

(iii) - time-varying runs to verify the model against the water level changes observed between December 1982 and December 1992 in response to APC abstraction.

Sensitivity tests on the transmissivity values, leakage co-efficient, head in the upper aquifer, recharge and storativity were also carried out. The model was then used to examine the aquifer response to two abstraction scenarios:

Schedule A: abstraction at the Safi pipeline/pumping station capacity after allowing for the continued use of the Hassa surplus flows by APC at their present level.

Schedule B: abstraction at the suggested safe yield of the aquifer, also with the continued use of Hassa surplus flows by APC.

In addition, the model was used to indicate the change in water levels resulting from a reduction in flood recharge, which may result from the development of the Tannour dam.

2. MODEL REPRESENTATION OF THE AQUIFER SYSTEM

As data are seldom sufficient to fully describe an aquifer system and its characteristics, a first step in modelling is to prepare a conceptual 'model' which incorporates a simplified representation of those features of the system considered to have the most influence on recharge, flow and discharge. This interpretation is then represented and tested by the numerical model and adjusted if necessary during calibration.

The important features of the aquifer system indicated by the earlier model can be summarised as follows [2]:

- the sequence of most interest consists of sands and gravels overlain by silty clay layers (or lenses)
- the main aquifer has unconfined (water table) conditions in the upper part of the fan but is increasingly confined by clay layers towards the fan edge
- in the middle part of the fan the main aquifer is semi-confined with upward leakage into a shallow water table aquifer (upper aquifer)
- the base of the main aquifer is a thick grey clay which is present in at least the middle and lower part of the fan
- prior to the MSGIS recharge took place through the bed of the wadi channel from undiverted baseflow and occasional floods, and from unlined canals and field seepage
- water levels in the upper part of the fan close to the exit of the Wadi Hassa appear to be supported by underflow entering the fan deposits through the wadi gravels of the Hassa channel beneath the diversion weir
- natural discharge from the main aquifer is controlled by upward leakage through the overlying clays into the overlying water table aquifer.

Hence the aquifer system can be described as comprising a shallow water table within a clayey or silty sequence overlying a semi-confined to confined gravel aquifer (main aquifer), except in the upper part of the fan where the surface clay sequence is absent and the main aquifer is unconfined. Assuming that saline water and clays in the fan-edge area restrict subsurface outflow from the main aquifer, then the discharge from the whole aquifer system would take place mainly from the upper aquifer as springflow and by shallow groundwater evaporation.

2.1 Aquifer Geometry

Figure 2.1 shows the main topographic features of Ghor Safi, which is the largest of the alluvial fans along the southeastern ghors, covering an area of about 25 km^2. It has a broadly semi-circular shape with a radius of about 5 km and is bordered on the east by an escarpment whilst at the fan-edge it merges with the deposits of the Wadi Araba and the mud flats of the Dead Sea.

The alluvial sediments forming Ghor Safi were derived mainly from the Wadi Hassa, which drains the mountainous area east of the escarpment. The Wadi Abyad also has a small alluvial fan which extends over some 1.5 km^2. This merges with the Hassa alluvial fan deposits near the new town of Ramleh (New Safi). The Hassa has been incised into an older sequence of alluvial deposits (Samra deposits of Lisan age) close to the escarpment that are still preserved as ridges adjacent to the exit of the Hassa.

The rift valley deposits underlying Ghor Safi are extremely thick (>2000 m). However, the main (freshwater) aquifer is limited to a sequence of alluvial gravels and sands within the top 50 to 100 m. Geophysical surveys and well logs indicate that the main gravel aquifer underlies about 50% of the present area of the fan, as the sequence in the northern and southern parts of the fan consists of a thinner sequence of mainly finer-grained deposits. As lithological information is lacking in the fan-edge area, the western boundary of the main aquifer is not known but is assumed to occur at the present edge of the fan. Sections across the fan are shown in Figures 2.2 and 2.3.

The zone of most active groundwater movement occurs above a depth of about 100 m in the upper part of the fan. Elsewhere, the base of the main aquifer is defined generally by a grey clay layer (Lisan Marl?) at least 30 m thick in the wellfield area at a depth of about 50 m. Figure 2.4 shows an interpretation of the clay layers reported in well logs, which may occur as lenses rather than as continuous layers. There appears to be two relatively thick (> 10 m) clay layers at different depths in the upper part of the fan. The elevation of the main clay layer rises steeply to the east and south of OB4-OB7 and it may have been partly eroded by an earlier channel of the Hassa/Abyad in the area around S6. In addition, a thick clay layer recorded in wells S7-SPB7-BN300-S8 may separate the main aquifer from the Samra sequence just south of the Wadi Hassa and restrict flow to the south.

The information provided by geophysical surveys, well drilling, and pumping tests was used to divide the fan into four zones as shown in Figure 2.5, the hydrogeological conditions and characteristics within each zone being broadly similar. Zone 1 refers to the unconfined upper part of the fan, Zone 2 is the semi-confined area of the main aquifer in which the wellfield is located, Zone 3 is the confined fan-edge area and Zone 4 is the Wadi Araba-Dead Sea region.

2.2 Model Area, Boundaries and Grid

The previous model was limited to the area of Ghor Safi. However, it was decided to also include the Wadi Araba channel in the new model. A rectangular area was chosen for the model extending 8.5 km from east to west (190E to 198.5E) and 9 km from north to south (45N to 54N), a total area of 76.5 km^2.

The model grid was orientated north-south to facilitate the input of spatial data. A 250 m nodal spacing was used over the fan and 500 m grid applied elsewhere. The model consists of 905 nodes and 1737 elements. The basic features of the model are shown in Figure 2.6.

The northern and southern boundaries of the model were selected to coincide with the mud-flats separating Ghor Safi from small alluvial fans to the north and south. Groundwater flow in these areas is from east to west parallel to these boundaries, except in the extreme southwestern part of the model where inflow from the south occurs along the Wadi Araba channel. Although these boundaries would be considered as no-flow boundaries (being parallel to the direction of groundwater flow), fixed head values reflecting the topography were applied.

The east and west boundaries of the model were defined as no-flow boundaries. The western boundary coincides with the line of the Wadi Araba channel where flow occurs from south to north roughly parallel to the boundary. The eastern boundary was placed east of the Dead Sea Fault rather than at the fault itself because of the rectangular shape of the model domain compared to the SSW trend of the faultline. Very low transmissivities [a zero T cannot be applied in the model] were assigned to the bedrock area between the Dead Sea Fault and the eastern edge of the model. Whilst this results in an artificial contour pattern in this area, the amount of flow involved is extremely small.

As Ghor Safi lies below normal sea level (Aqaba datum), all water levels were converted to a base level of -500 mbAD (the bottom of the deepest well is -505 mbAD) to enable positive values to be used in the model, eg. the fan-edge elevation of -390 mbAD would be +110 m in the model.

Selected landscape features were digitised: the main highway, fan-edge zone, wadi channel, Dead Sea fault, the 100 and 25 ohm-m resistivity contours (taken as the edge of the upper fan and the boundary between main gravel and predominantly clayey sequences, respectively). These features are shown in Figure 2.5.

2.3 Aquifer Characteristics

The recovery test results from 16 wells (see Annex A), most of which are located in the central part of the fan, were used to provide an initial distribution of transmissivity (T) within each zone.

Some areas where the sequence consists almost entirely of clays have low T values, such as at well S1. However, the presence of a few thin gravel layers within an otherwise mainly clay sequence can produce high T values, such as at SPB5.

Recent pumping tests at sites S2 and SPB10 gave lower T values than earlier tests carried out when water levels were shallower, which suggests that the top part of the main aquifer may be more permeable. However, the model cannot represent a change in T caused by significant changes in the saturated thickness since AQUA is not based on values of permeability and saturated aquifer thickness.

The average T values were 2000 m^2/d for Zone 1 and 6000 m^2/d for Zone 2, the corresponding average permeabilities (K) being 75 and 200 m/d, respectively. The lower values in the upper part of the fan are due to the deeper water levels and also because the sequence appears to consist partly of less permeable Samra deposits. No test data are available for the fan-edge area (Zone 3) or the Wadi Araba (Zone 4), which were allocated initial T values of 500 and 50 m^2/d, respectively.

The Samra deposits around the exit of the Wadi Hassa are older alluvial fan deposits of unknown thickness. Their hydraulic characteristics are unknown, but as they appear to be more consolidated and more finer grained than the more recent alluvial deposits forming Ghor Safi they are likely to have a lower permeability.

The hydraulic characteristics of the upper aquifer are not represented in the model. Upward leakage into this aquifer from the main aquifer is controlled by the difference in head between the two aquifers and the permeability of the separating clay layer. A uniform value of 10^{-2} m/d for the permeability (k') of the clay layer was selected from published values for silty clay (1 to 10^{-4} m/d). The hydraulic resistance (or leakage co-efficient, Lc) was calculated from k'/m, where m is the average saturated thickness of the clay layer (10 m).

Prior to abstraction the characteristics of the clays and the head difference between the two aquifers would have more influence on hydraulic gradients than the transmissivity of the main aquifer, whereas with large-scale abstraction the transmissivity of the main aquifer would become a more important control on groundwater flow.

The increasing proportion of clays in the sequence towards the fan-edge produces increasingly confined conditions in both the shallow and deeper parts of the aquifer system. However, there is only limited information on either the storage coefficients (S) or specific yields (Sy). Two pumping tests indicated Sy values of 17% (well BN 302/OW304) and 15% (well S2/OW2) near the boundary between Zone 1 and Zone 2 [4]. Sand or gravel sequences commonly show a wide range of Sy values ranging from 10 to 30%, although mixed sands and gravels have values usually in the range of 15 to 25%. Values of S usually range from $5x10^{-3}$ to $5x10^{-5}$.

An initial distribution for S and Sy was selected as follows for each zone: Z1 20%, Z2 10-12.5% and Z3 $1x10^{-4}$ (typical semi-confined value). The Wadi Araba, Samra deposits and the bedrock area were given a very low S value of $1x10^{-5}$.

Under natural conditions the seasonal fluctuations in Zones 2 and 3 would reflect the low confined to semi-confined values of S. However, if large-scale abstraction from the main aquifer lowered the piezometric surface below the base of the overlying clays then the main aquifer would become unconfined and the S value would approach the Sy values.

2.4 Recharge and Discharge

In the previous model an input of 3.5 Mm^3/y was required in the region of the Hassa weir to reproduce the heads observed in the upper part of the fan. It was suggested that this may be underflow passing through the wadi channel deposits beneath the weir. If so, this would be relatively constant and unaffected by the irrigation works.

The wadi channel is deeply incised into the bedrock. Well S9, which was drilled just downstream of the weir, recorded 59 m of gravels on sandstone bedrock and a water level of only 1.4 mbgl. A similar thickness of 40 m also occurs in the Wadi Hammad channel at Ain Maghara some 35 km north of Ghor Safi. On this basis underflow could occur through the bed of the Wadi Abyad.

However, whilst the model requires an input at the wadi exits, it is by no means certain whether this is derived from underflow, from flood or from a higher proportion of baseflow recharge immediately downstream of the weir.

Furthermore, it is not known whether significant groundwater inflow occurs across the Dead Sea Fault from the eastern highlands. This seems unlikely north of Wadi Abyad where the escarpment comprises Saramuj Conglomerate. However, permeable Dissi Sandstone form the escarpment at and to the south of Wadi Hassa, and, although partly overlain by Samra deposits of relatively low permeability, there would be a possibility for groundwater inflow along this part of the escarpment. Interestingly, there are major E-W trending faults at the boundary between the Dissi Sandstone and Saramuj Conglomerates in the Abyad-Hassa area through which preferential inflow might take place.

Direct recharge to the alluvial fan deposits from rainfall is considered to be insignificant as the annual rainfall is only about 50 mm/y. Indirect recharge from flood runoff on the Hassa and Abyad, whilst important during wet years, is infrequent and variable and consequently difficult to represent in the model. The 'average' winter floodflow takes place as short runoff events occurring on average for a total of 8 days per year between November and May [3], of which a significant proportion may be lost to the Wadi Araba. The potential recharge from floods has been estimated to be 1.5 Mm^3/y from water level fluctuation data [6], but this must be considered very tentative.

The most important recharge component is the perennial baseflow of the Wadi Hassa. The Wadi Hassa has a drainage area of 2520 km^2, although most of the baseflow is derived from the lower part of the catchment from bedrock springs in the Wadi Afra tributary. The annual total baseflow is about 23.5 Mm^3/y and there is relatively little seasonal variation in flow (80% reliable minimum flows range from 675 l/s in the summer to about 790 l/s during the winter [3]).

Before the MSGIS was implemented, a significant proportion of the flow diverted from the Wadi Hassa for irrigation could infiltrate along the unlined distribution canals and in the fields from the traditional furrow irrigation technique, although the main canals in the upper part of the fan were lined to reduce seepage losses in this area of more sandy soils. As the main area of irrigation (about 15 km^2) was limited to the central area of the fan, the recharge from diverted baseflow would contribute mainly to the upper aquifer rather than the main aquifer.

A field survey of water losses in the distribution system in 1979 [5] indicated that the total recharge from diverted and undiverted baseflow prior to the MSGIS could be as high as 13 Mm^3/y, comprising: undiverted baseflow, 2.25 Mm^3/y; canal seepage, 9.24 Mm^3/y; and field seepage, 1.5 Mm^3/y. This suggests that 55% of the total baseflow contributed to recharge, predominantly from unlined canals, with 83% of the recharge contributing to the upper aquifer. However, the previous model study suggested that recharge to the main aquifer taking place in the upper part of the fan was more likely to be about 7 Mm^3/y, comprising: 3.5 Mm^3/y from underflow at the Hassa weir, 1.7 Mm^3/y from canal seepage and 1.8 Mm^3/y from floods and undiverted baseflow.

In 1983, shortly after the APC wellfield began production, a modern irrigation system was introduced by the MSGIS. Details of the timing of the changeover are not available to us, but it is understood that the main engineering works were introduced during 1983/4 (Jan 1983-May 1984, improvements to the diversion headworks; May 1983-March 1984, piped distribution system; April 1983-July 1984, new drainage network). The system was commissioned in June 1986, although it was not until about 1989 that the full scheme was fully operational. During the conversion to drip irrigation, it is also understood that surplus baseflows were used to reclaim land in the fan edge area. The scheme has enabled the area of irrigation to be expanded from about 14000 ha to about 21000 ha.

The rate of baseflow at the time of the peak crop water requirement determines the area that can be irrigated from the Wadi Hassa, but as the baseflow is essentially constant there remains a varying amount of baseflow surplus to the crop water requirements that can infiltrate along the wadi channel throughout most months of the year. The average diversion for irrigation is about 75%, even after the MSGIS improvements. The surplus flow in 1990 and 1992 reported by JVA was 5.1 and 9.0 Mm^3/y, respectively. The amount of surplus flow used by APC over the period 1988 to 1992 was 1.42 Mm^3/y.

The change to drip irrigation would have reduced recharge to the upper aquifer from diverted flows (canal and field seepage). However, it may not have had the same impact on recharge to the main aquifer from undiverted flows because of the relationship between cultivated area and irrigation efficiency and the essentially constant baseflow, ie. the new irrigation system enables a larger area to be cultivated for the same amount of baseflow by improving the water use efficiency. Similarly, the monthly distribution of surplus flows may not have been affected significantly by the irrigation scheme.

Prior to development, the water table in the upper aquifer intercepted the ground surface at elevations of between -375 and -385 mbAD. Springs, direct groundwater evaporation and evapotranspiration occurred in the fan-edge zone (Zone 3) between these elevations and the fan-edge (about -390 mbAD). The amount lost by shallow groundwater evapotranspiration in the fan-edge area and from any subsurface groundwater flow from the main aquifer into the Wadi Araba deposits is not known. The total spring discharge at the fan-edge has been estimated to be about 150 l/s, or 4.73 Mm^3/y [4], which is perhaps an indication of the minimum long-term recharge. About 3.15 Mm^3/y of this outflow is collected from drainage channels into a sump at Samar in the south-western part of the fan where groundwater appears to be forced towards the surface by a rapid reduction in aquifer thickness south of SPB1.

To expand the area of cultivation in the fan-edge area, the MSGIS installed a drainage network and cleared much of the natural vegetation. These changes would lower water levels in the upper aquifer and reduce groundwater evapotranspiration. Abstraction from the main aquifer would also intercept the natural upward leakage into the upper aquifer and thus reduce the amount of water entering the fan-edge area. In addition, it was also suggested in the previous model that part of the recharge leaving the upper fan (Zone 1) may pass over the upstream edge of the clay layer and into the upper aquifer. If so, more of this recharge would enter the main aquifer when water levels dropped beneath the clay edge in response to abstraction.

Hence, the combined effects of the MSGIS and APC abstraction are likely to have affected the upper aquifer rather than the main aquifer. Following these various developments the main components of the present water balance of the main aquifer would be as follows:

Inputs	**Losses**
Undiverted baseflow	APC diversion of surplus flow
Underflow	Drainage channels
Floodflow	Abstraction

In the pre-development situation, almost all of the recharge to the main aquifer would have passed upwards into the upper aquifer to be lost in the fan-edge area. Hence, the alluvial fan can be considered as a discrete hydrological system and an internal fixed head placed around the fan-edge. Similarly, in representing the main aquifer, it would not be necessary to include springs and groundwater evapotranspiration from the upper aquifer and consequently these losses were excluded from the model.

2.5 Water Level Configuration

Figure 2.7 shows the water level elevations of the main aquifer and the upper aquifer for the predevelopment situation based on water level data for 1977-1980. This was used as a basis for calibrating the steady-state model. At that time flowing artesian conditions were still encountered towards the fan-edge in both shallow and deeper wells (eg PS4, OB2). The head gradient decreases down the slope of the fan as the area of leakage increases and as the width of aquifer through which flow occurs increases.

The water table elevation for the upper aquifer was taken to be the depth at which water was first encountered in each well. The water level (piezometric surface) for the main aquifer was usually reported to be about 2-3 m (range 0-5 m) above the water table indicating a potential for upward leakage from the main aquifer. The small difference in head makes it difficult to distinguish the water levels relating to each aquifer, especially as the degree of confinement of both aquifers increases towards the fan-edge and with depth of penetration. Therefore, the heads in the upper aquifer in Zones 2 and 3 were represented in general terms only.

3. MODEL CALIBRATION (PRE-DEVELOPMENT CONDITIONS)

3.1 Steady-state Calibration

The pre-development water level configuration for the main aquifer (see Figure 2.7) was used as a guide for the calibration of the steady-state model. Some trial runs were first undertaken with the following simple representation of the aquifer system before the more complex features of the system were introduced into the model:

- a single, unconfined aquifer with no overlying clay layer
- no fixed head at the fan-edge
- a fixed head of -326.4 mbAD at the Hassa diversion weir (well S9)
- T values of 50 m^2/d for the Samra deposits and the Wadi Araba area.

A model run was first made with no baseflow recharge (ie. underflow input only, the amount being controlled by the fixed head at the weir) to establish whether the observed radial flow pattern was controlled simply by the T values and by subsurface losses at the fan-edge into the Wadi Araba deposits. However, this produced a very low gradient across the fan (a 10 m drop in head compared to the observed 40 m), a dominantly southeasterly direction of flow and a steep gradient in the fan-edge area.

For the next trial run, the fixed head at the Hassa weir was removed and a maximum recharge for the whole system (in this simplified version the whole aquifer would be unconfined and therefore would receive recharge from all the different sources) of 14.67 Mm^3/y was introduced comprising:

- a fixed inflow of 0.7 Mm^3/y at the Hassa weir
- an average recharge along the wadi channel upstream of the Safi roadbridge (channel area 1.5 km^2) totalling 6.167 Mm^3/y (based on the assumption that the ratio of diverted to undiverted flow prior to the irrigation scheme was similar to that after the scheme, using data for 1990 and 1992) distributed equally along the wadi channel nodes
- an irrigated area of 15 km^2 with a 60% irrigation efficiency, or a recharge of 7.8 Mm^3/y from canal and field seepage.

This distribution produced a markedly asymmetric flow pattern dominated by the wadi channel and still with steep gradients in the fan-edge area.

Neither the observed head values or head configuration were produced by these trial runs suggesting that:

- a larger inflow was required at the wadi exit to sustain the heads in this area or that the T values in the upper part of the fan were low.
- the head gradient across the fan could not be supported simply by decreasing the T values or increasing the amount of recharge.
- the Samra deposits must have a low T or limited connection with the alluvial fan deposits.

The slope, permeability and head difference across the clay layer in the central part of the fan together with clays at the fan-edge restrict the natural outflow from the main aquifer. The subsequent runs were carried out with a clay layer over the confined part of the main aquifer (Zones 2 and 3) together with a simplified head distribution for the upper aquifer. T values in the upper part of the fan were reduced to reflect the basal clay layer at about -395 mbAD and the T value assigned to the Samra deposits reduced to a very low nominal value of 1 m^2/d. An internal fixed head of -390 mbAD was added along the fan-edge.

A series of calibration runs were then made with different amounts of annual recharge, varying from 6 to 11 Mm^3/y, together with a range of Lc values and heads in the upper aquifer. A reasonable fit to the predevelopment water level configuration was achieved with the distribution of transmissivity, leakage and heads in the upper aquifer shown in Figures 3.1, 3.2 and 3.3, respectively, and a total recharge to the main aquifer of 10.5 Mm^3/y, comprising 9 Mm^3/y distributed along the Hassa channel and an inflow of 1.5 Mm^3/y at the Wadi Abyad.

The steady-state model head distribution is shown in Figure 3.4. Heads for the observation well network and other wells are listed in Annex B. This configuration was used as the starting condition for all subsequent time-varying runs.

3.2 Time-varying Calibration

For the time-varying calibration, the annual recharge of 10.5 Mm^3/y was distributed monthly at the 10 nodes involved according to the present variation in surplus flow diversion and the winter flood season, with the underflow inputs at the Hassa weir and Wadi Abyad held constant throughout the year. Figure 3.5 shows the monthly pattern of recharge based on the nodal values listed in Annex A.

Calibration was based on a comparison of the model predicted seasonal head change at selected observation wells with the corresponding water level hydrographs for 1979. The seasonal water level fluctuations in 1979 were taken to represent the pre-development conditions when the aquifer responded only to seasonal variations in irrigation demands. The peak seasonal water level occurs in July/August, the months of lowest irrigation demand and therefore maximum recharge from surplus baseflow. The average annual fluctuation was about 0.7 m in the wellfield area.

The initial distribution of S produced seasonal variations of only 0.07 to 0.15 m, suggesting that the aquifer was acting more as a semi-confined system. Reducing the S values to 35% of their initial values, as shown in Figure 3.6, produced seasonal variations of 0.52 m at OB3 and 0.81 m at OB5, very close to those observed of 0.6 m and 0.88 m, respectively. The recharge pattern produced a maximum water level in July consistent with that observed. The model and observed hydrographs for OB3 and OB5 are shown in Figure 3.7a and for OB1 and OB6 in Figure 3.7.b.

4. MODEL VERIFICATION (TRANSITIONAL CONDITIONS, 1982-1992).

To verify the model representation, the head changes predicted by the calibrated model were compared to those observed in response to the historical APC abstraction over the 10-year period from December 1982 to December 1992.

4.1 APC Abstraction

The annual supply from the APC sources at Ghor Safi is given in Table 4.1. The annual wellfield abstraction together with the annual change in abstraction are shown in Figure 4.1. The total wellfield abstraction over the period 1982-1992 was 52.2 Mm^3 and the average supply obtained from the Wadi Hassa over the period 1988-1992 was 1.42 Mm^3/y (range 1.08 to 1.71 Mm^3/y). The abstraction from non-APC wells is not recorded, although this has been estimated to be about 0.25 Mm^3/y [6].

Only 1.22 Mm^3 was abstracted from the wellfield in the first year of operation. This was increased each year to a peak of 6.49 Mm^3/y in 1985 and then held at a similar level (6.39 Mm^3/y) in 1986 before being reduced to 4.22 Mm^3/y in 1988 after a supply was obtained in mid-1987 from the Wadi Hassa. Since 1989, abstraction has risen steadily each year, reaching 5.77 Mm^3/y in 1992, or only 11% less than the previous peak abstraction in 1985.

To provide a representative pattern of the average abstraction from each APC production well for each year for use in the model verification, the abstraction rate of each well in each particular year was expressed as a percentage of the total abstraction rate of all those wells operating in that year. This percentage was then applied to the annual abstraction. The resulting values are listed in Annex A, Table 3a-c.

4.2 Water Level Changes at APC Observation Wells, 1982-1992

The annual minimum water levels in December for the period 1977-1992 at each APC observation well are given in Table 4.2 and plotted for 1982-1992 in Figure 4.2. Table 4.3 shows the annual change in water levels.

The original APC observation well network of seven wells (OB1 to OB7) constructed in 1979 had been reduced to only three by 1987, although a new observation well (OB8) was drilled in 1993 at the edge of the wadi channel near S11. As the limited water level changes at OB4 suggests that this well is not functioning properly, a complete record for the full period is available for only two wells, OB3 and OB5, and these were used for the model verification.

The water levels at OB2, OB3, OB5 and OB6 for the period from the start of abstraction in mid-1982 until 1987 show a total decline averaging 6.125 m, or 1.225 m/y. There was a slight recovery in 1987/8 when abstraction was reduced. Levels declined once more as abstraction began to increase, but at a much slower rate of 0.2 m/y such that the average decline over the period 1987-1992 was only 1.1 m. The diversion of some 25% of surplus flows by APC after 1987 seems to have had little effect on water levels, although this amount represents only about 14% of the estimated total recharge.

The total decline shown by OB3 and OB5 over the 10-year period was 6.2 and 9.0 m, respectively. Both wells show a similar pattern of annual water level change (correlation coefficient about 90%). The rate and pattern of water level decline was generally similar throughout the aquifer, although the overall decline was larger in the south (about 7.5 m) than in the north of the fan (about 5 m). This reflects the distribution of abstraction, with 70% of the APC abstraction taking place south of the wadi channel compared to 30% north of the channel.

The water level response at OB3 and OB5 corresponds closely to the cumulative wellfield abstraction, as illustrated by Figures 4.3 and 4.4. This suggests that recharge to the main aquifer has remained relatively constant and that the aquifer was not able to reach a steady-state due to the annual increase in APC abstraction. The slower rate of water level decline after 1989 could be due not only to an overall reduction in the total amount abstracted by APC after a supply from the Hassa was obtained in 1987 but also to the steady but smaller additional amount abstracted each year to meet a gradual rise in water demands, which allowed the aquifer to adjust more readily to abstraction.

4.3 Time-Varying Verification

The time-varying verification runs were undertaken with a constant recharge at each recharge node totalling 10.5 Mm^3/y together with the pattern of annual abstraction for the APC production wells (see Annex A) and the S values derived from the time-varying calibration. The model was run for 10 years with annual time steps.

The water level change at each observation well is given in Annex B.2. The model water level elevations at OB3 and OB5 are plotted in Figure 4.6. The pattern is reasonably similar to that observed, more so at OB3 than OB5, although the initial rate of drawdown is rather steeper and the 'recovery' in 1987 is not so pronounced. The decline after 4 years (1460 days, end of 1986) at OB3 of 5.6 m was the same as observed, whilst that at OB5 of 6.9 m was slightly less than that observed (7.6 m), perhaps due to local variations not represented by the model.

Since the amount of recharge for the model runs was kept constant at its pre-development level, these results confirm that the observed water level decline must be due to the APC abstraction and not to a significant reduction in the amount of recharge. Hence it should be possible to avoid a further decline in water levels (quasi steady-state) by selecting a constant rate of abstraction appropriate to the amount of recharge that can be intercepted without causing adverse effects on water quality or the pumping rates of individual wells.

These results largely verified the overall model representation. Figure 4.6 shows the model predicted water level configuration in 1992 at the end of the 10-year abstraction period, which should be compared to Figure 3.4. Water levels decline by about 5-10m in the wellfield area but by 15-20m in the upper part of the fan.

5. MODEL PREDICTIONS

The future contribution from the Safi wellfield has yet to be defined. This depends partly on the output from the Dhira wellfield, which is expected to be commissioned in 1995. However, two abstraction schedules were selected for some trial predictive runs with the new model. Firstly, it was assumed that the contribution from the Safi wellfield continues at the capacity of the Safi pipeline/pumping station (Schedule A) and secondly at the suggested 'safe yield' of the aquifer (Schedule B). In both cases, it was also assumed that APC would continue to use surplus Hassa baseflows to supplement the Safi wellfield and allowance has been made for municipal water demands. The predictions are given up to December 1999.

In addition, a steady-state run was made to indicate the possible impact of the proposed Tannour Dam. If constructed, the controlled release of floodflows will enable more of the surplus baseflows to be used for irrigation. The dam is therefore likely to reduce the amount of recharge from both floods and surplus baseflow in the long term.

5.1 Abstraction at Safi Pipeline/Pumping Station Capacity (Schedule A)

The present capacity of the Safi pipeline/pumping station is 950 m^3/h, which is equivalent to an annual supply of 7.6 Mm^3 (8000 operating hours). If APC continue to divert an average of 1.42 Mm^3/y from the Hassa surplus baseflow, then the wellfield output would be restricted to 6.18 Mm^3/y. However, the capacity of the pumping station could be increased to remove this constraint on supplies.

There has been an upward trend in the amount of water abstracted from the wellfield since 1988. This is shown in the following table (in Mm^3), which includes estimates of the abstraction in 1993 and 1994 assuming that the same trend has continued:

	1988	1989	1990	1991	1992	1993	1994
Total	4.22	4.34	4.64	5.11	5.77	[6.61]	[7.63]
Increase		0.12	0.30	0.47	0.66	[0.84]	[1.02]

However, as abstraction after 1993 would exceed the present capacity of the pipeline/pumping station if used in conjunction with the surplus flows of the Hassa, it was assumed for the model that APC abstraction would be constrained to a maximum constant rate of 6.18 Mm^3/y.

Changes are presently being made to the wellfield with the construction of new and replacement wells, some of which are expected to provide a standby capacity. For the model simulation, the abstraction rates of those wells operating in 1992 were maintained at the same level and the additional abstraction met by wells SPB10 and SPB12 thereafter. The distribution of these wells is shown in Annex A.

For the model simulation an abstraction rate of 6.18 Mm^3/y was maintained from 1993 to 1999, inclusive. A constant additional abstraction of 0.25 Mm^3/y for supplies to Ramleh (obtained equally from WAJ wells S2W and S11) was included from 1983 through to 1999 inclusive, giving a total constant abstraction of 6.43 Mm^3/y from 1993 onwards. This is also similar to the previous peak wellfield abstraction of 6.49 Mm^3 in 1985.

The predicted water levels at each observation well are given in Annex B, Table B1.2. The data for OB3 and OB5 are plotted in Figure 5.1. Water levels stabilise at about -384 mbAD

(116 m model elevation), which is some 6 m above the fan-edge elevation and equivalent to an average drawdown over the wellfield of about 7.5 m.

The water level contour pattern at the end of 1999 is shown in Figure 5.2. This indicates a rather low gradient across most of the fan and continued groundwater flow into the fan-edge area.

5.2 Abstraction at Safe Yield (Schedule B)

The 'safe yield' concept of aquifer management is intended to ensure that the long-term average annual abstraction does not result in adverse effects. The safe yield can be more closely defined when water resources management criteria are identified and applied, but it is common practice for the safe yield to be taken as 50% the annual recharge. As development proceeds the concept of an 'optimal yield' may become more applicable, which allows for some short term depletion of the groundwater held in aquifer storage.

The model calibration suggested that the annual recharge is about 10.5 Mm^3/y, although this is still rather uncertain. An abstraction rate of 4.5 Mm^3/y was adopted as a conservative estimate of the present 'safe yield' of the main aquifer for the following reasons:

- it is similar to the annual discharge of the fan-edge springs, which is considered to represent the long-term minimum annual recharge;
- water levels began to stabilise when APC abstracted 4.22 Mm^3/y in 1988;
- the surplus baseflow, after APC diversion, is about 4.75 Mm^3/y and the actual contribution from 'underflow' at the Wadi Abyad and Wadi Hassa and from floods is still uncertain.

For the predictive runs, it was assumed that abstraction takes place from the same wells as for Schedule A, increasing to 6.18 Mm^3/y in 1993 and 1994 due to the pipeline/pumping station constraint but then reducing to 4.5 Mm^3/y in 1995 until the end of 1999. Municipal abstraction was also continued at the same rate of 0.25 Mm^3/y, giving a total abstraction of 4.75 Mm^3/y from the aquifer from 1995 through to 1999, or a reduction of 1.68 Mm^3/y compared to Schedule A over the same period. This level of abstraction would be similar to APC maintaining abstraction at the low levels of 1984 or 1988-1990.

The predicted water level elevations at each observation well are given in Annex B Table B.1.2. The data for OB3 and OB5 are plotted in Figure 5.3. Water levels recover slightly in 1995 when abstraction is reduced and stabilise at an average of about -383 mbAD (117 m model elevation), which is only 1 m less than at the higher rate of abstraction used in Schedule A. This water level would be about 7 m above the elevation of the fan-edge and hence maintains a positive gradient towards the fan-edge. The water level configuration, shown in Figure 5.4, is little different to that for Schedule A.

5.3 Impact of Reduced Floodflows

Major floods are an important source of occasional recharge to alluvial fan aquifers in semi-arid regions. However, the recharge from floods in such areas is extremely difficult to quantify because of their variability.

Some estimates of floodflows at Tannour and Ghor Safi were made during the MSGIS study in 1979 [3]. The drainage area above Tannour is 2200 km^2 (compared to 2520 km^2 above

Ghor Safi), but the area with rainfall exceeding 200 mm is only 63 km^2 above Tannour compared to 480 km^2 above Ghor Safi. The mean annual peak discharge is approximately 200 m^3/s at Ghor Safi compared to 79 m^3/s at Tannour, where the mean total runoff is about 7.21 Mm^3/y (range 0 to 55 Mm^3/y).

At Ghor Safi, the standard flood is about 28 hours in duration with floods typically occurring about 8 times per year. A large proportion of each flood is likely to be lost to the Wadi Araba channel/Dead Sea. Also baseflow diversion by JVA is not possible during floods, which represents an unused baseflow of about 0.65 Mm^3/y.

Studies are being undertaken by others to assess the availability of water from Tannour Dam for additional irrigation supplies in the Safi-Feifa area. Earlier estimates suggest that the Tannour dam will have an average annual release of about 3.3 Mm^3/y and a reservoir capacity of about 12 Mm^3 [3]. It is understood that the availability of these controlled flows may allow more of the present surplus baseflow to be utilised therefore reducing the amount of recharge from both floodflows and surplus baseflow and the diversion of baseflow by APC. However, the effect on the availability of surplus baseflow is not known as yet and for the model predictions only a direct reduction in flood recharge was examined.

The model was run in the steady-state mode without flood recharge (estimated as 1.5 Mm^3/y, or about 15% of the total recharge). This produced a fall in water levels of about 2 m at the top of the fan and 0.8 to 0.9 m at OB3 and OB5. Hence, a reduction in floodflow recharge in itself may have a limited impact on water levels, although the recharge contribution from occasional large floods is not known.

6. DISCUSSION

a. The amount of information on the aquifer system has increased in recent years. Even so, certain parameters, such as flood recharge, are still difficult to quantify. As a result it was possible to produce similar results from alternative, but still acceptable, combinations of aquifer characteristics and recharge. The dominant control appears to be the leakage coefficient of the clay layer. A reasonable and consistent calibration was achieved with a total recharge of 10.5 Mm^3/y, although the relative contribution from each of the recharge components could be different to that used. However, it was also possible to produce the steady-state water level configuration and the seasonal water level fluctuation without the clay layer using a lower recharge of 6.5 Mm^3/y (mainly undiverted baseflow) and the same values of S, although S had to be increased to the initial (Sy) values to produce the observed water level decline (this could represent an increase in S with dewatering of the sequence).

b. Heads in the upper part of the fan can only be reproduced by significant recharge in this area rather than by a low T. The pattern of groundwater contours in the Wadi Abyad fan required an additional input of 1.5 Mm^3/y, probably through the wadi channel deposits, although this could be floodflow recharge or even an input through the bedrock faults that occur in this area. None of these possibilities would be affected by the MSGIS. The minimum recharge is therefore likely to be about 4.5 Mm^3/y (excluding floods) if surplus flows were to become unavailable.

c. The observed changes in water level could be reproduced with the historical APC abstraction without a reduction in recharge. This suggests that the decline in water level is due to the continued increase in APC abstraction each year which prevented the aquifer from reaching equilibrium and that recharge to the main aquifer has not been significantly altered by the MSGIS. The irrigation scheme is more likely to have affected the upper aquifer water balance components (canal and field seepage, springflow and groundwater evapotranspiration).

d. The optimum yield of the aquifer cannot be defined properly until a set of water resources management criteria are established (eg. water quality, available drawdowns). However, for practical purposes it is suggested that abstraction should not exceed 4.5 Mm^3/y, equivalent to about 50% of the annual recharge, after allowing for municipal demands.

e. Continuous abstraction at the maximum capacity of the pipeline, after allowing for supplies from the Hassa, produces a steady-state condition in the wellfield area with an average water level of about -384 mbAD. This head should not pose a serious risk of saline intrusion. Continuous abstraction at the proposed safe yield of 4.5 Mm^3/y also produces a steady-state condition with water levels only about 1 m higher than those at the higher rate of abstraction.

f. The yield of each production well is governed partly by the relatively shallow depth of the top of each screen. The average elevation of the top of the lowest screen in each production well is -399 mbAD (range -384 to -416 mbAD), or about 10 m below the fan-edge elevation. This available drawdown, however, cannot be fully utilised because the pumping water level in each well should not be allowed to decline below an elevation of -390 mbAD to avoid the risk of saline intrusion. The average pumping water level in the wellfield boreholes is estimated to be about -386 mbAD at present, which suggests that there is limited scope for a higher rate of abstraction. These well design, water level and water quality constraints need to be assessed in more detail and combined with better estimates of recharge to prepare a sound aquifer management strategy.

g. As floods in any one year are estimated to contribute about 15% of the average annual recharge, the interception of floods by the proposed Tannour Dam would result in a regional fall in water levels of only about 1 to 2 m. However, flood recharge especially from large floods, is not known with any reliability. If surplus baseflow recharge is also reduced by the controlled use of floods then the impact of the Tannour Dam could be significantly greater.

h. As yet the future role of the Safi wellfield after the development of the Dhira wellfield cannot be fully defined and consequently only three simplified scenarios were examined with the model. The model is now available to study other spatial and time-varying combinations of recharge and abstraction to assist the development and management of the main aquifer at Ghor Safi. This could be undertaken in conjunction with the Dhira model presently under development to assist the planning and management of future water supplies for APC. It is recommended that several 'what-if' scenarios are selected to be examined with these models.

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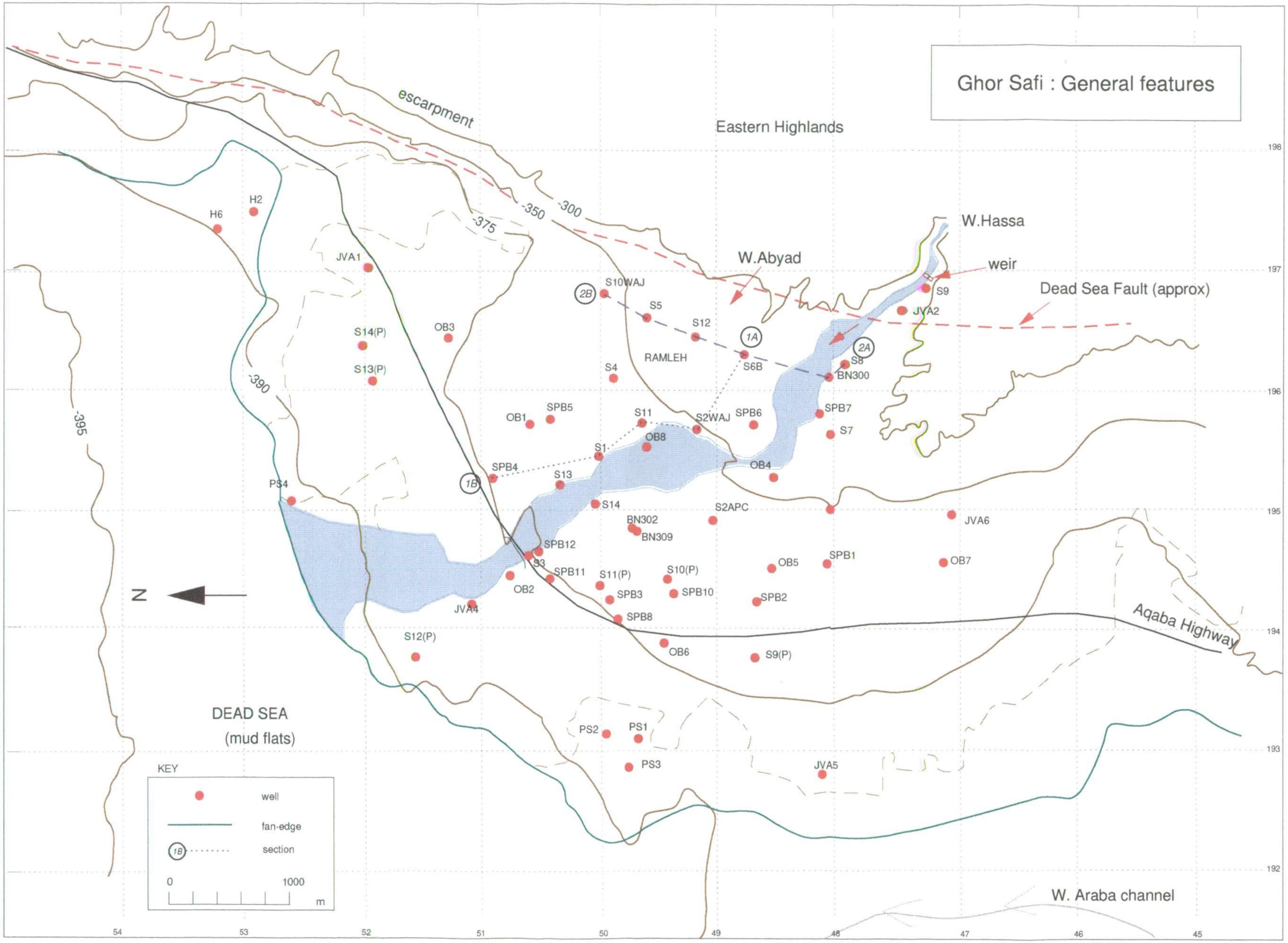
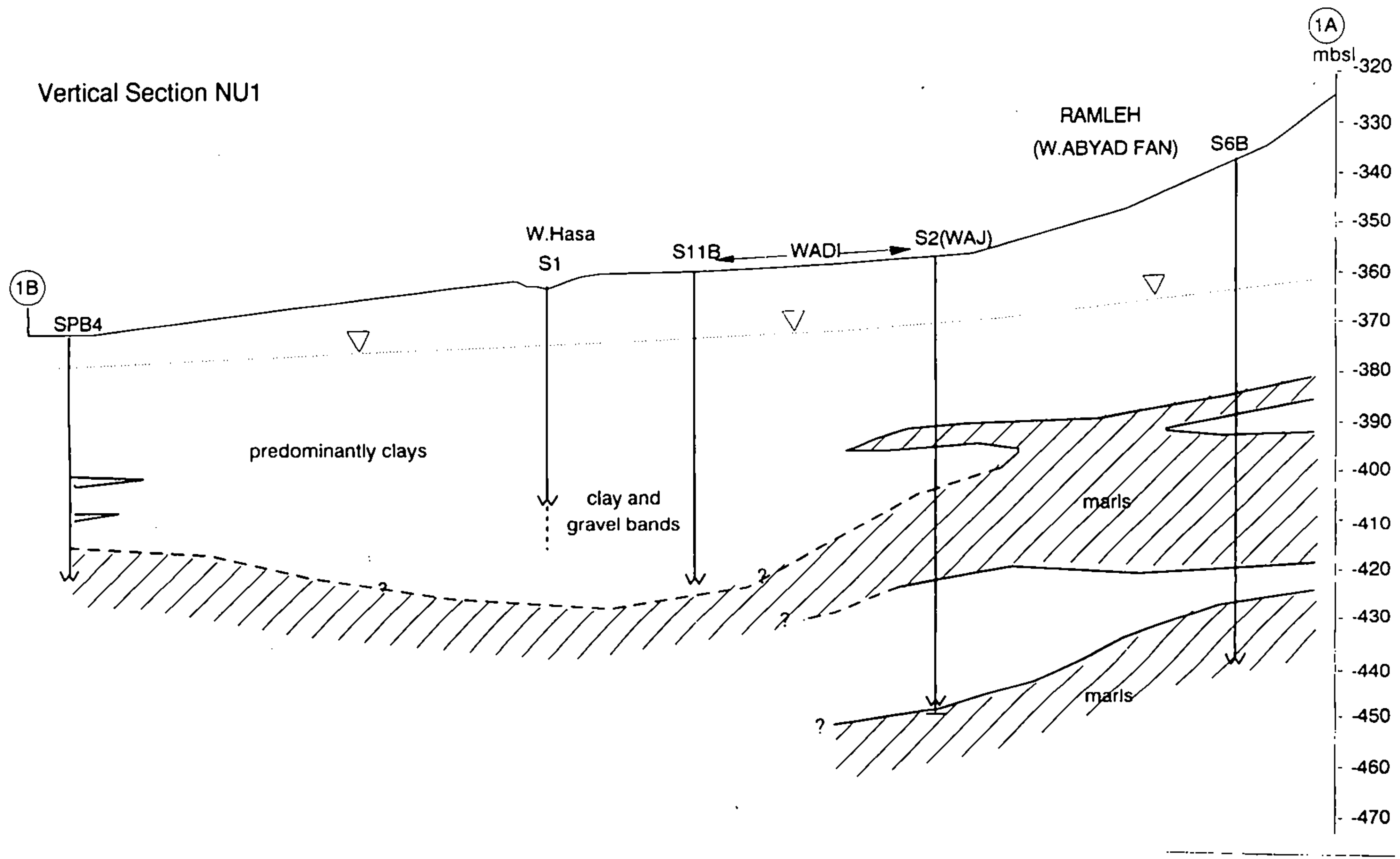
7. Sir Alexander Gibb and Partners/Institute of Hydrology UK. April 1989. Future Water Supply Options.



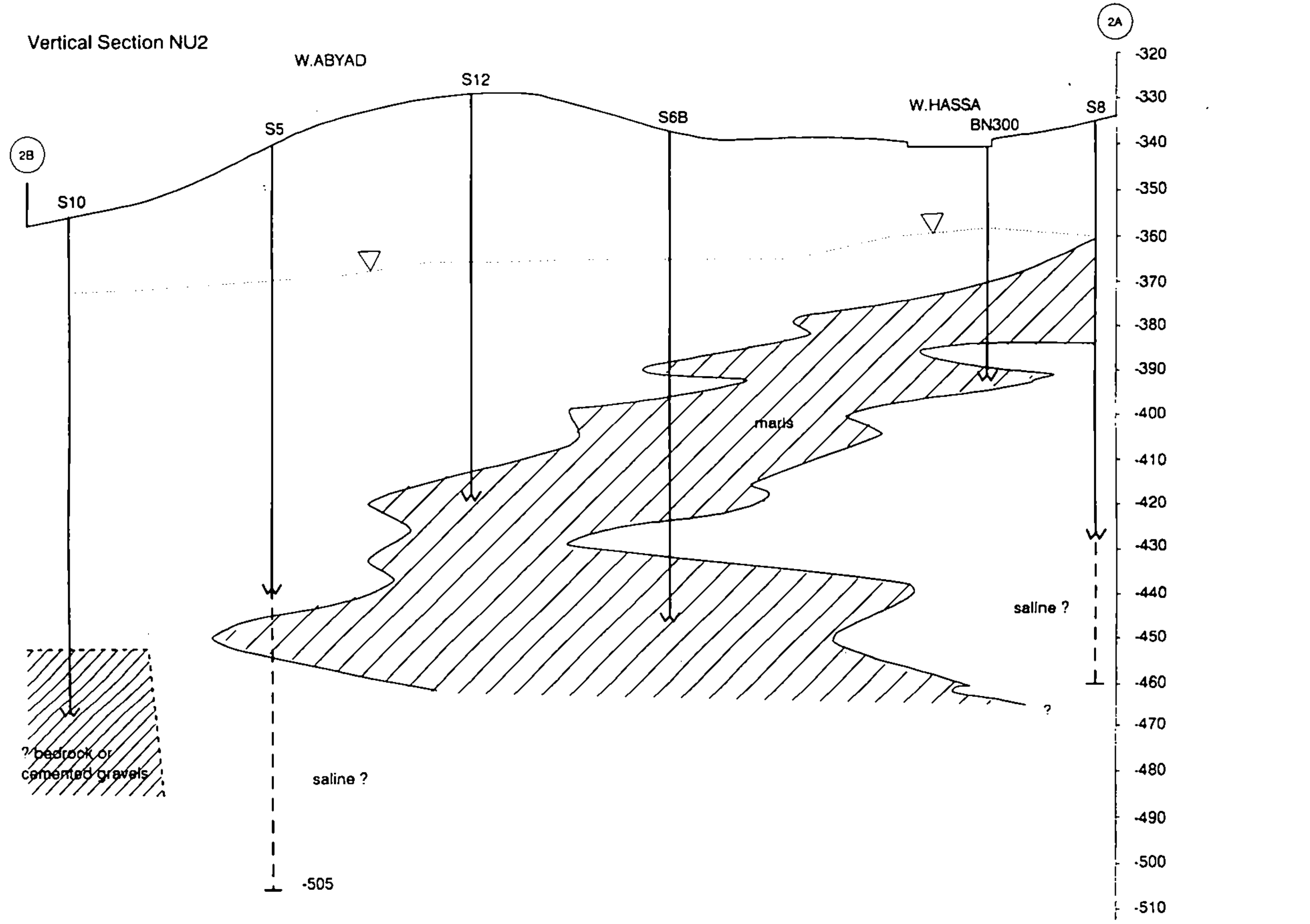
Ghor Safi : General features
Eastern Highlands
escarpment
-300
-350
-375
-390
-395
W.Hassa
weir
W.Abyad
Dead Sea Fault (approx)
RAMLEH
H6
H2
JVA1
JVA2
JVA4
JVA5
JVA6
OB1
OB2
OB3
OB4
OB5
OB6
OB7
OB8
S1
S3
S4
S5
S6B
S7
S8
S9
S10WAJ
S11
S12
S13
S14
S2WAJ
S2APC
S14(P)
S13(P)
S12(P)
S11(P)
S10(P)
S9(P)
SPB1
SPB2
SPB3
SPB4
SPB5
SPB6
SPB7
SPB8
SPB10
SPB11
SPB12
BN300
BN302
BN309
PS1
PS2
PS3
PS4
1A
1B
2A
2B
N
DEAD SEA
(mud flats)
Aqaba Highway
W. Araba channel
KEY
well
fan-edge
section
0
1000
m
198
197
196
195
194
193
192
54
53
52
51
50
49
48
47
46
45

Figure 2.1



Vertical Section NU1
1A
mbsl
-320
-330
-340
-350
-360
-370
-380
-390
-400
-410
-420
-430
-440
-450
-460
-470
RAMLEH
(W.ABYAD FAN)
S6B
S2(WAJ)
WADI
S11B
W.Hasa
S1
1B
SPB4
predominantly clays
clay and
gravel bands
marls
marls

Figure 2.2



Vertical Section NU2
W.ABYAD
S12
S6B
W.HASSA
BN300
S8
S5
S10
2A
2B
-320
-330
-340
-350
-360
-370
-380
-390
-400
-410
-420
-430
-440
-450
-460
-470
-480
-490
-500
-510
marls
saline ?
saline ?
?
-505
? bedrock or
cemented gravels

Figure 2.3

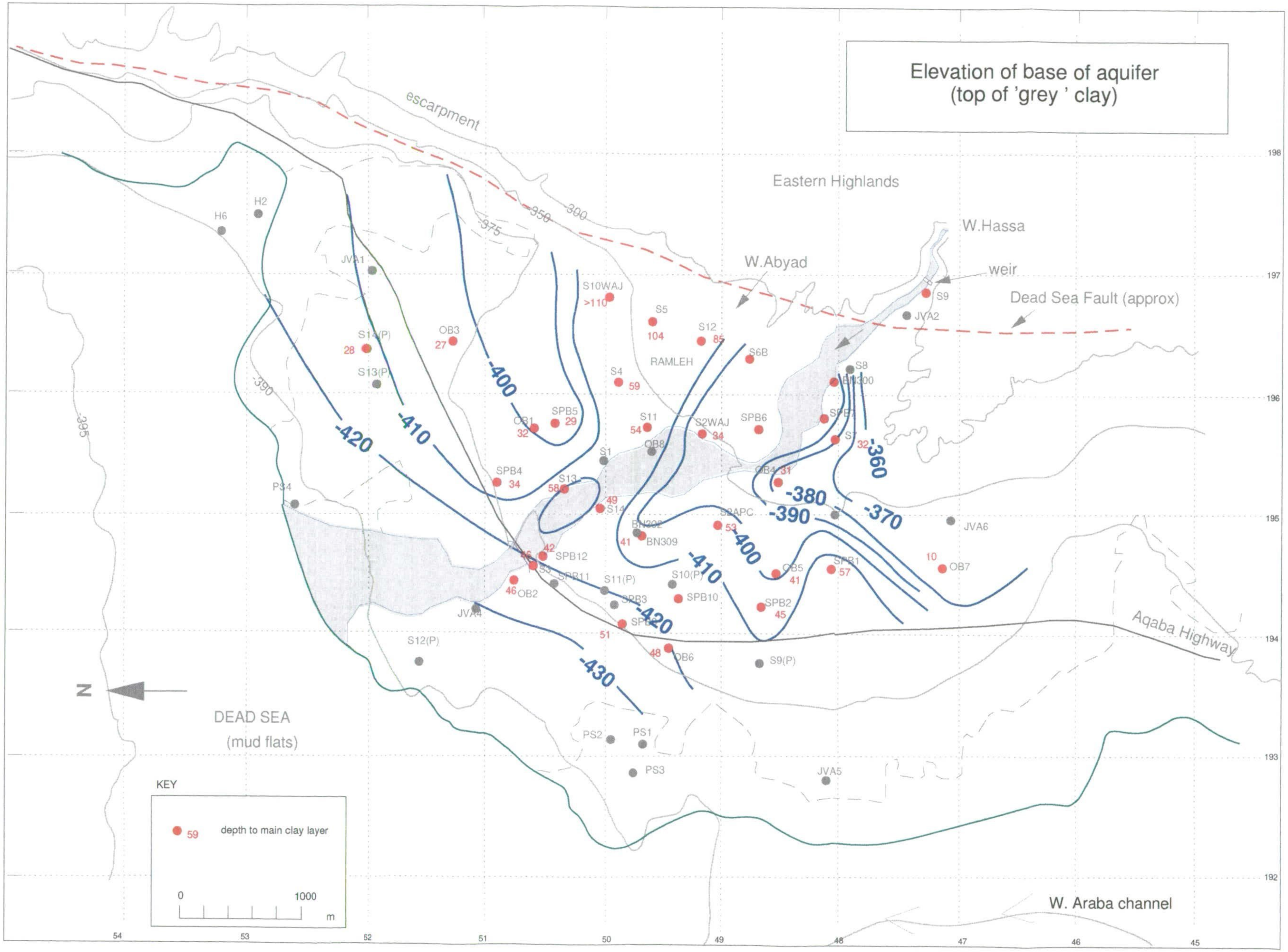

Elevation of base of aquifer
(top of 'grey ' clay)
Eastern Highlands
W.Hassa
weir
W.Abyad
Dead Sea Fault (approx)
escarpment
RAMLEH
DEAD SEA
(mud flats)
Aqaba Highway
W. Araba channel
KEY
59 depth to main clay layer
0 1000
m
-360
-370
-380
-390
-400
-410
-420
-430

Figure 2.4

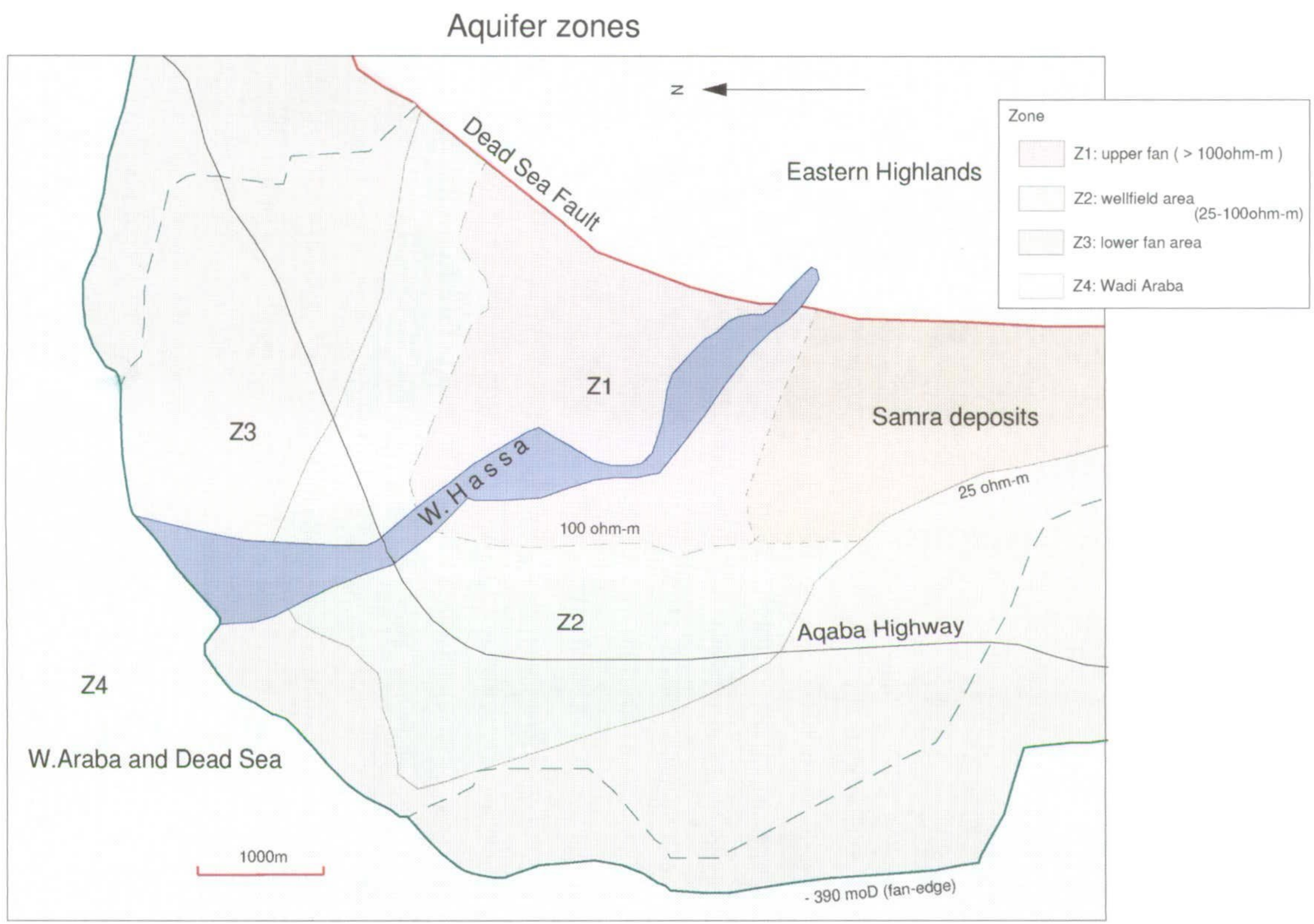
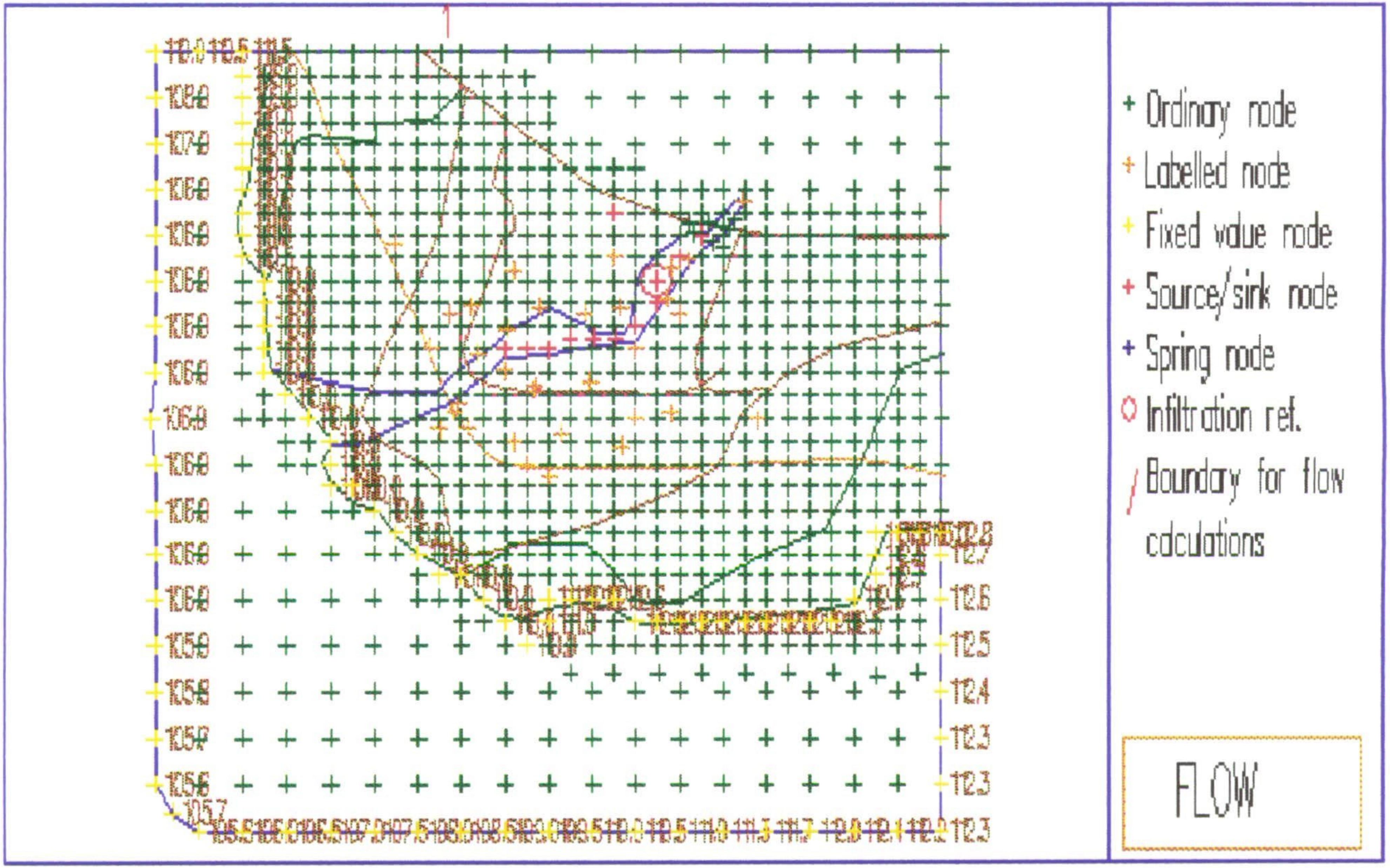

Aquifer zones
N
Dead Sea Fault
Eastern Highlands
Zone
Z1: upper fan (> 100ohm-m)
Z2: wellfield area (25-100ohm-m)
Z3: lower fan area
Z4: Wadi Araba
Z1
Samra deposits
Z3
W. Hassa
25 ohm-m
100 ohm-m
Z2
Aqaba Highway
Z4
W.Araba and Dead Sea
1000m
- 390 moD (fan-edge)

Figure 2.5

Figure 2.6 Boundaries, nodes and labelled wells



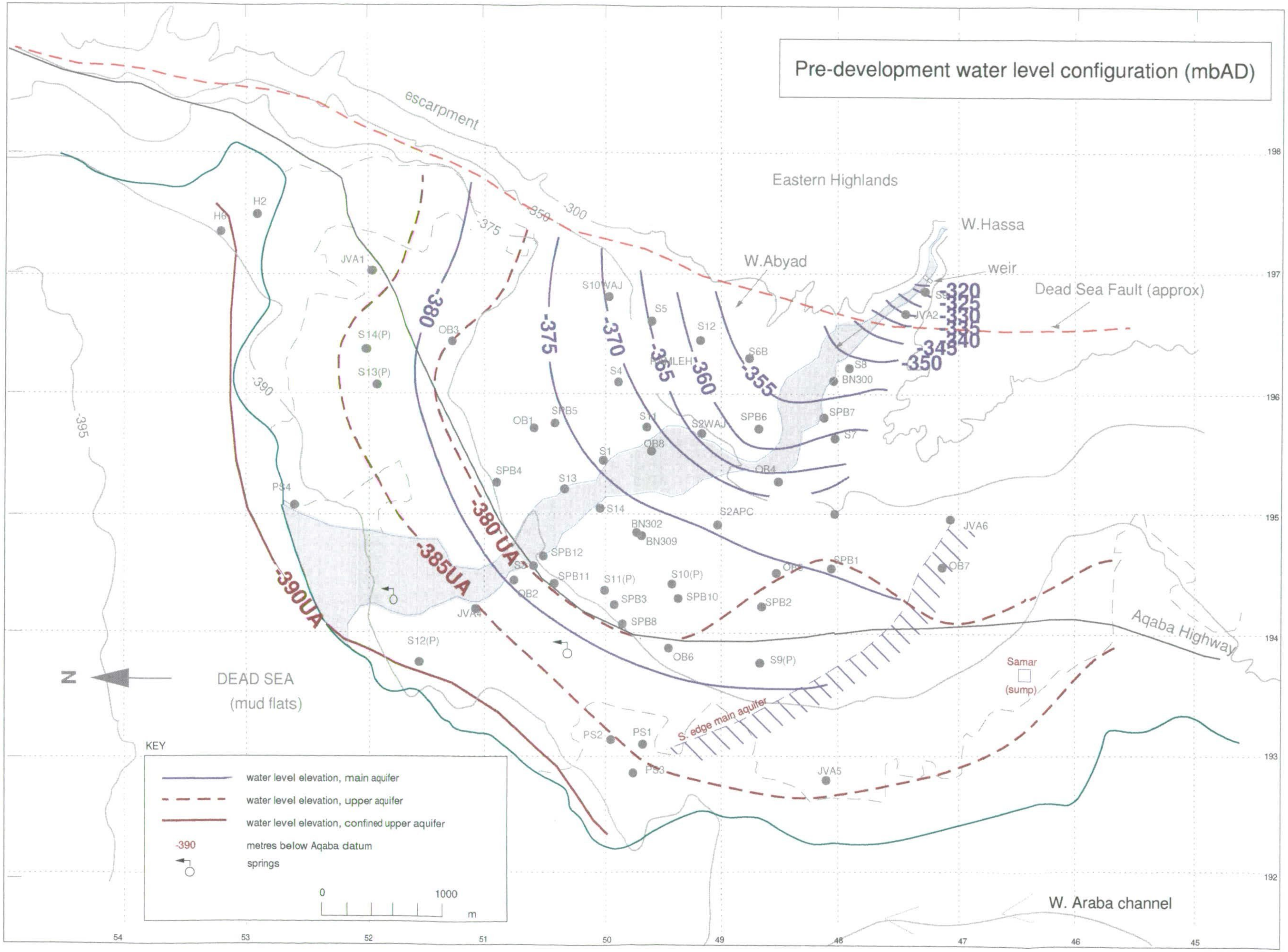

Pre-development water level configuration (mbAD)
escarpment
Eastern Highlands
W.Hassa
weir
W.Abyad
Dead Sea Fault (approx)
DEAD SEA
(mud flats)
N
Aqaba Highway
Samar
(sump)
S. edge main aquifer
W. Araba channel
KEY
water level elevation, main aquifer
water level elevation, upper aquifer
water level elevation, confined upper aquifer
-390
metres below Aqaba datum
springs
0
1000
m

Figure 2.7

Figure 3.1 Model Transmissivity (m2/s)

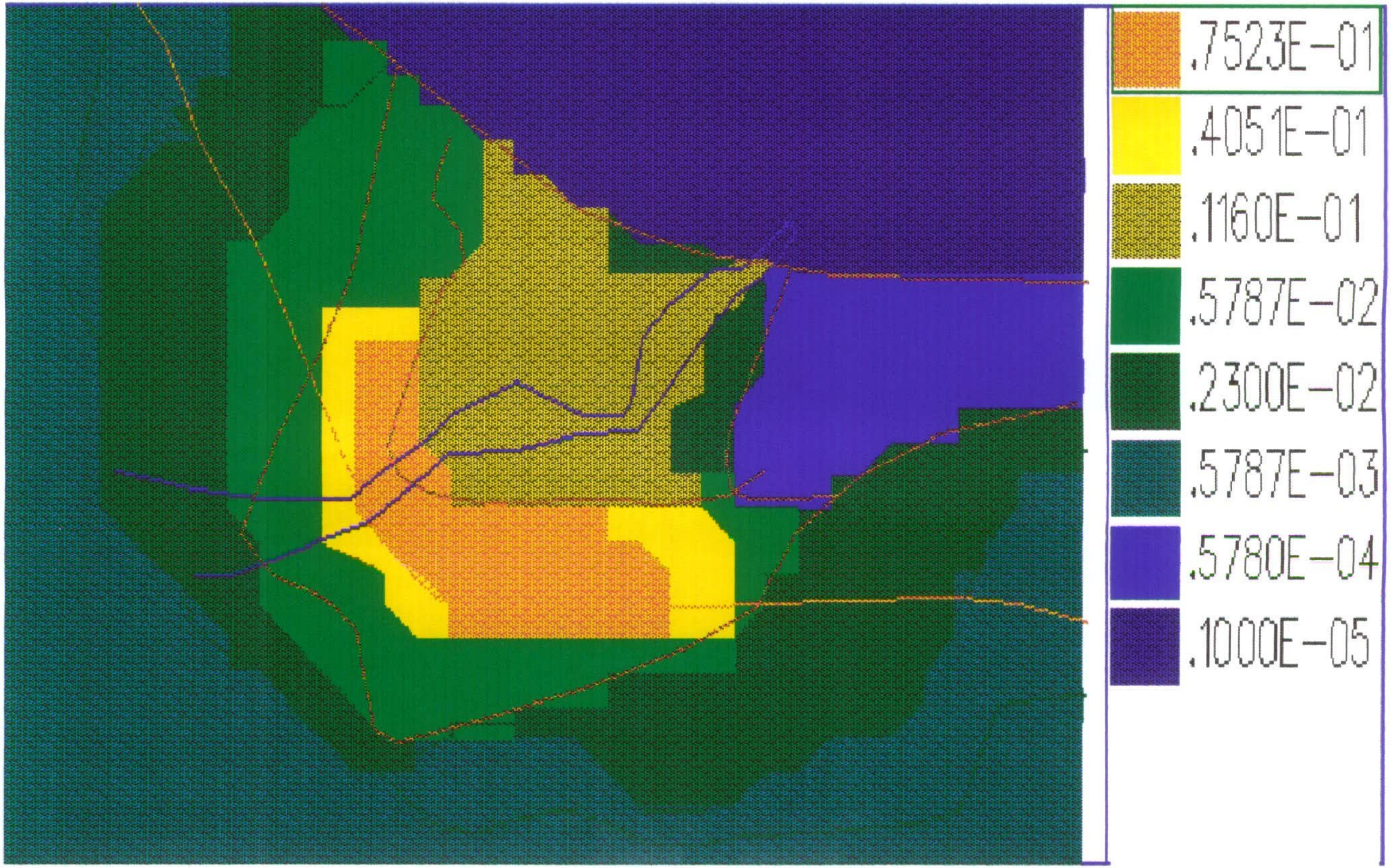


Figure 3.2 Model leakage coefficient distribution (m/s/m)

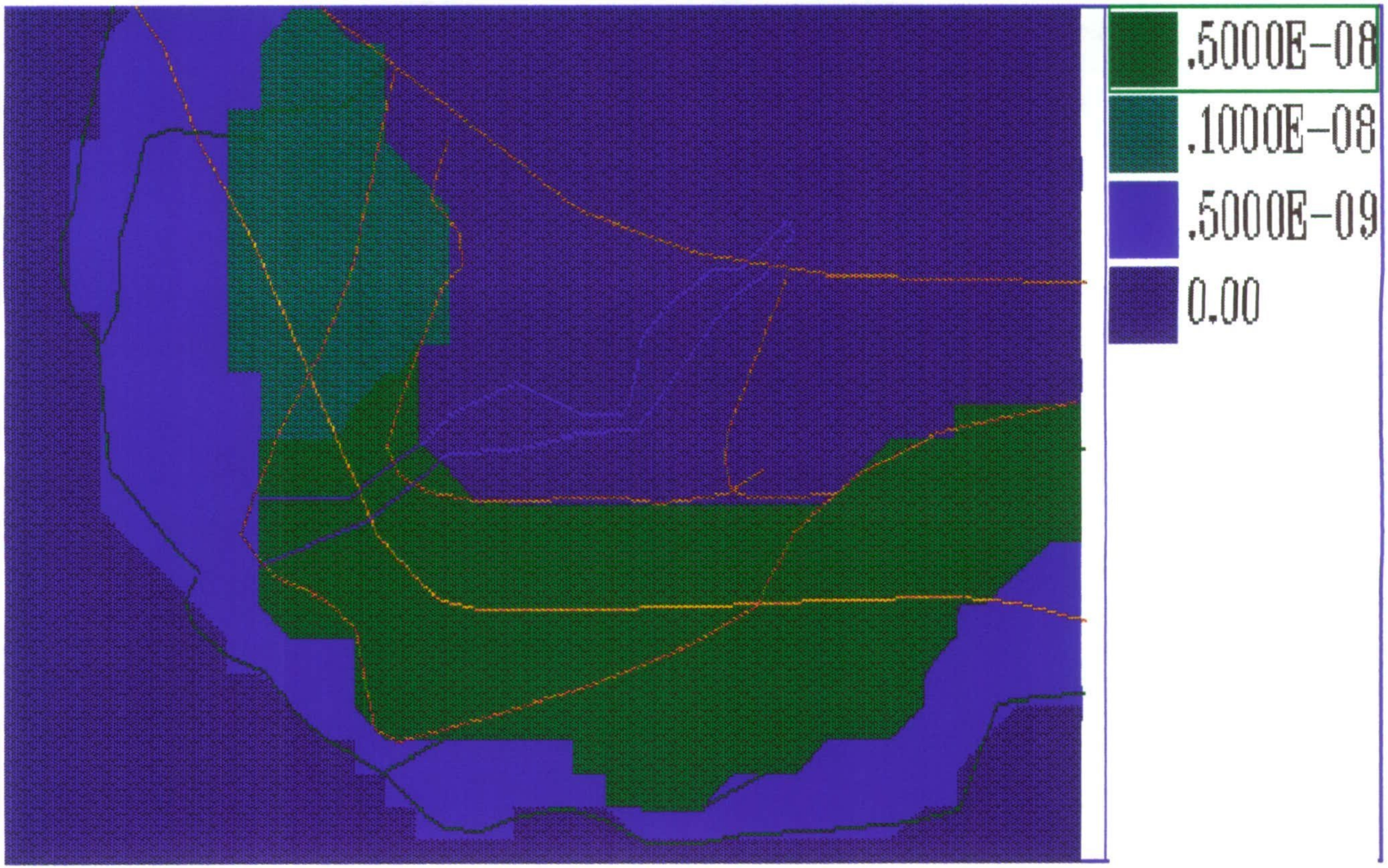
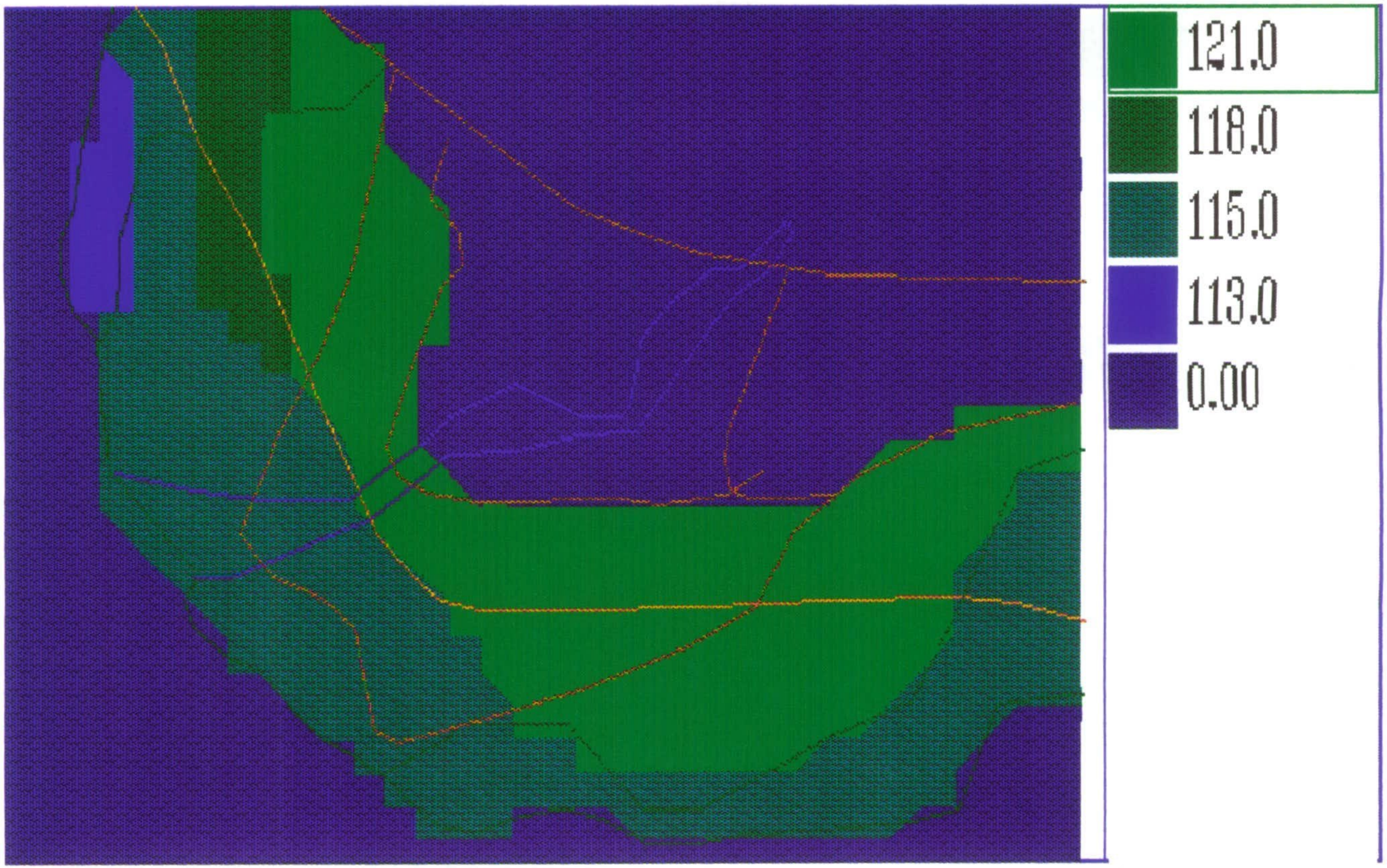


Figure 3.3 Head in upper aquifer (m, model)



Steady-state head elevations

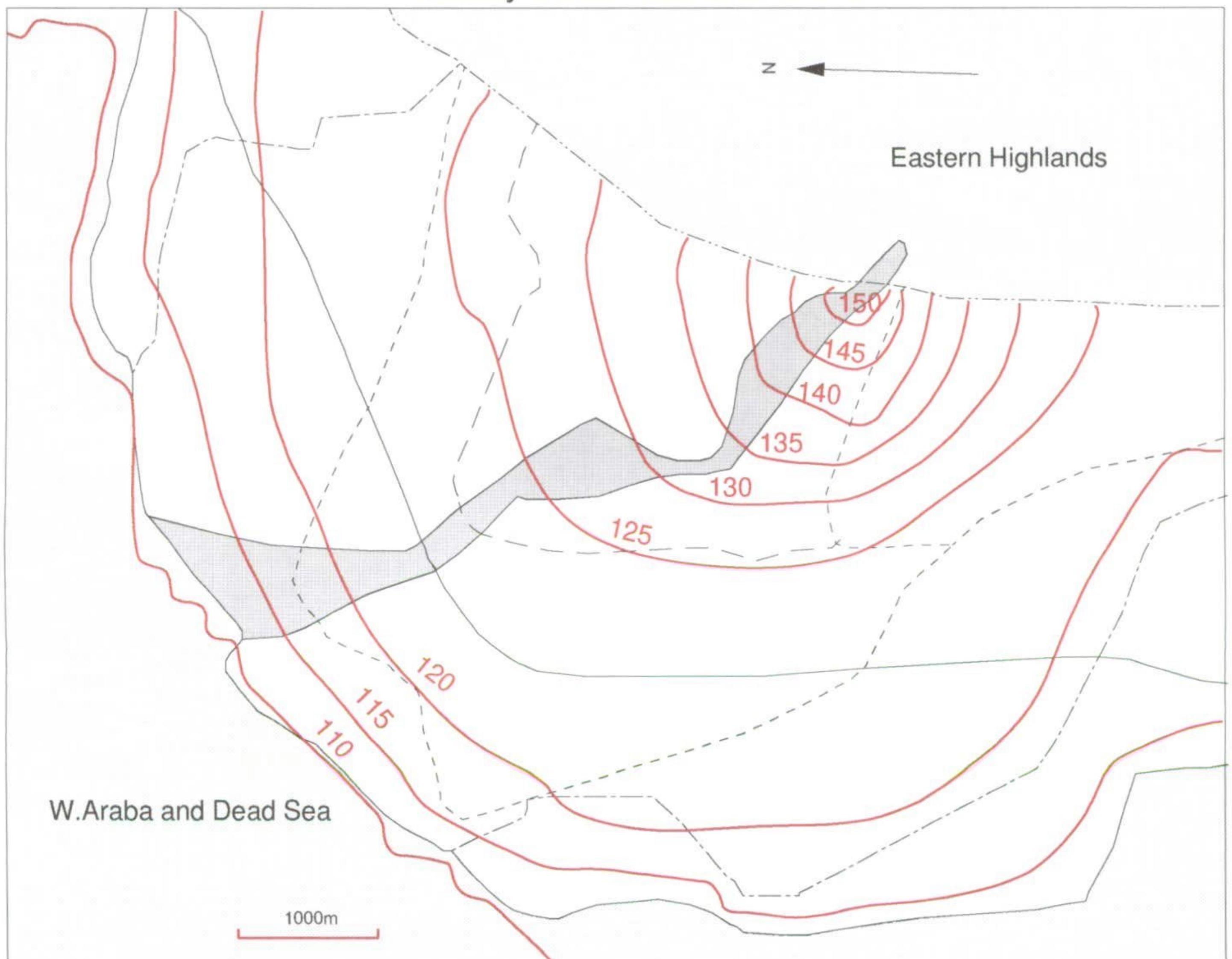


Figure 3.4

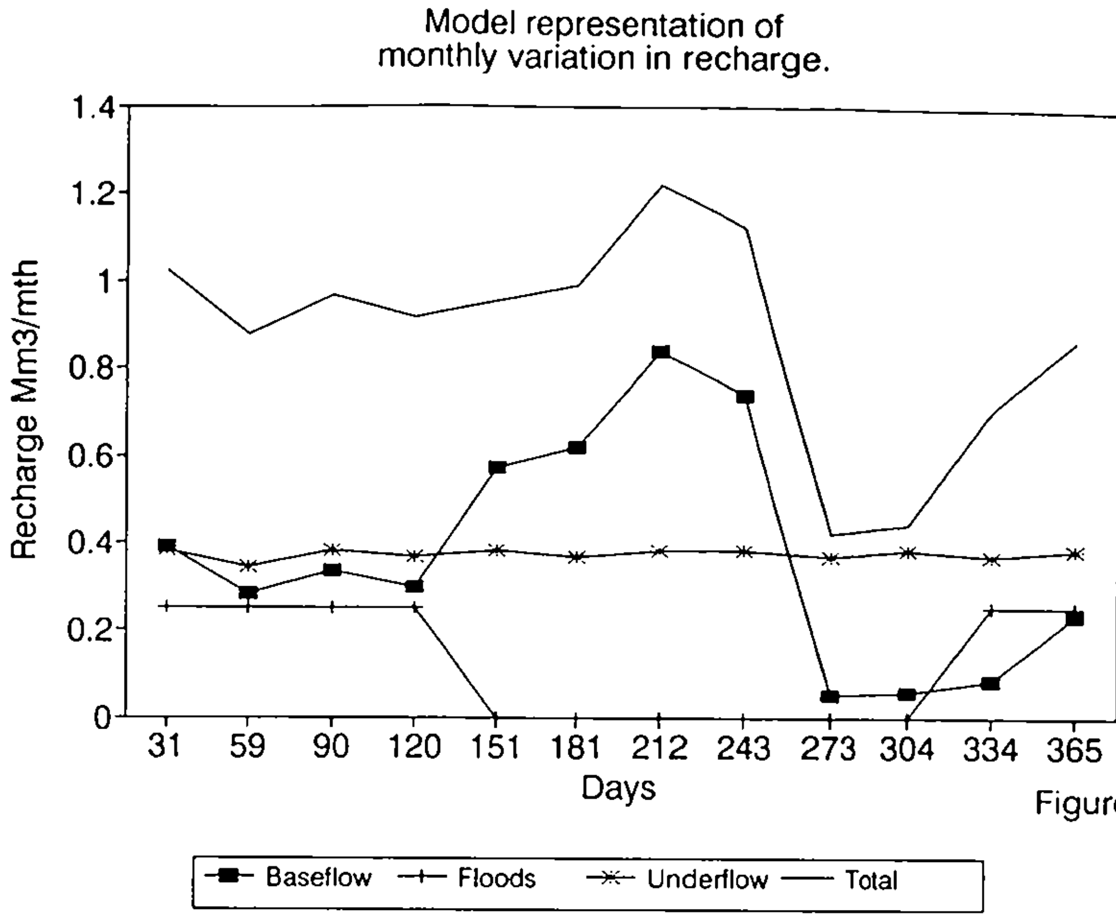
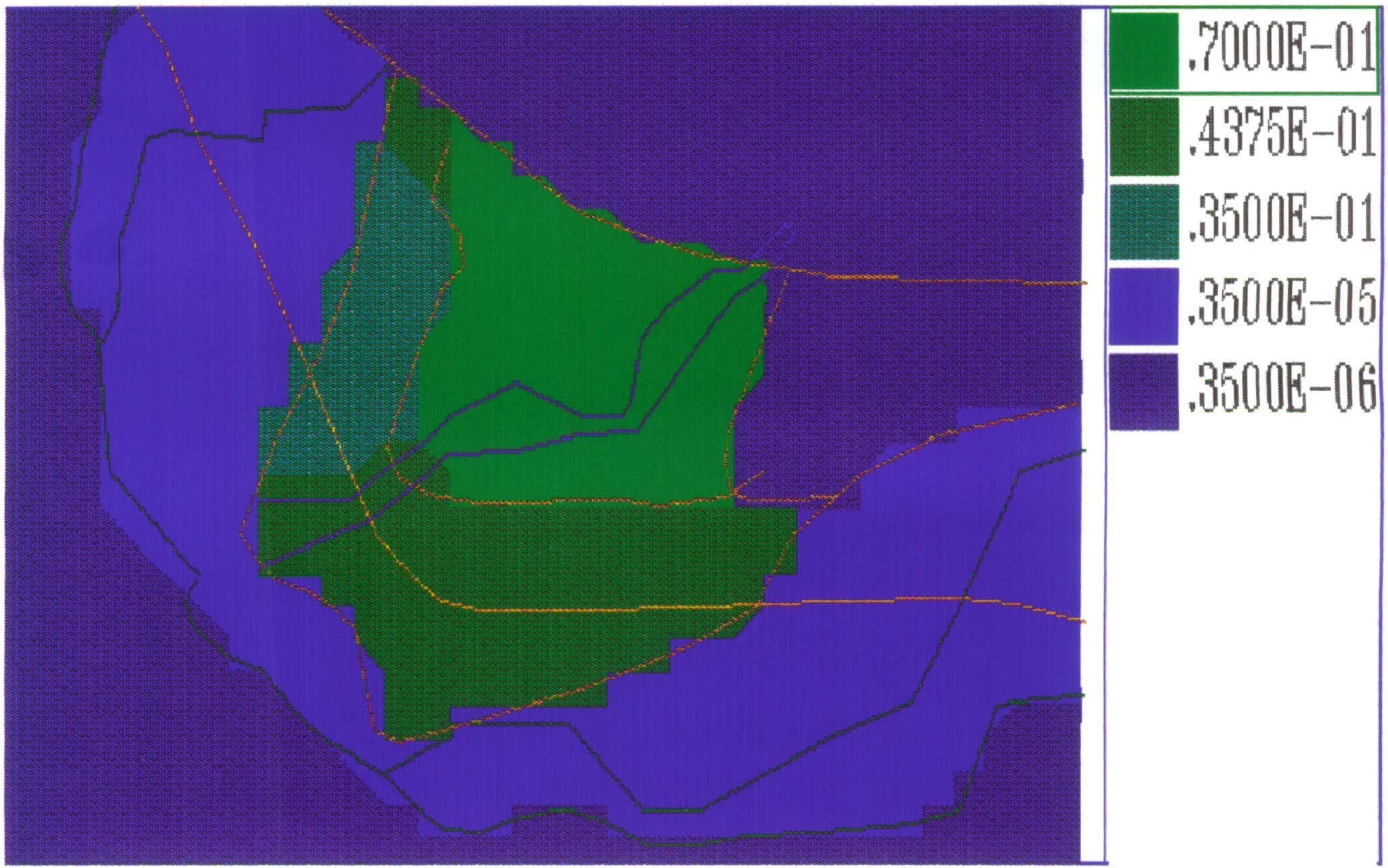

Model representation of
monthly variation in recharge.
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Recharge Mm3/mth
31
59
90
120
151
181
212
243
273
304
334
365
Days
Baseflow
Floods
Underflow
Total

Figure 3.5

Figure 3.6 Model storativity (S) distribution.



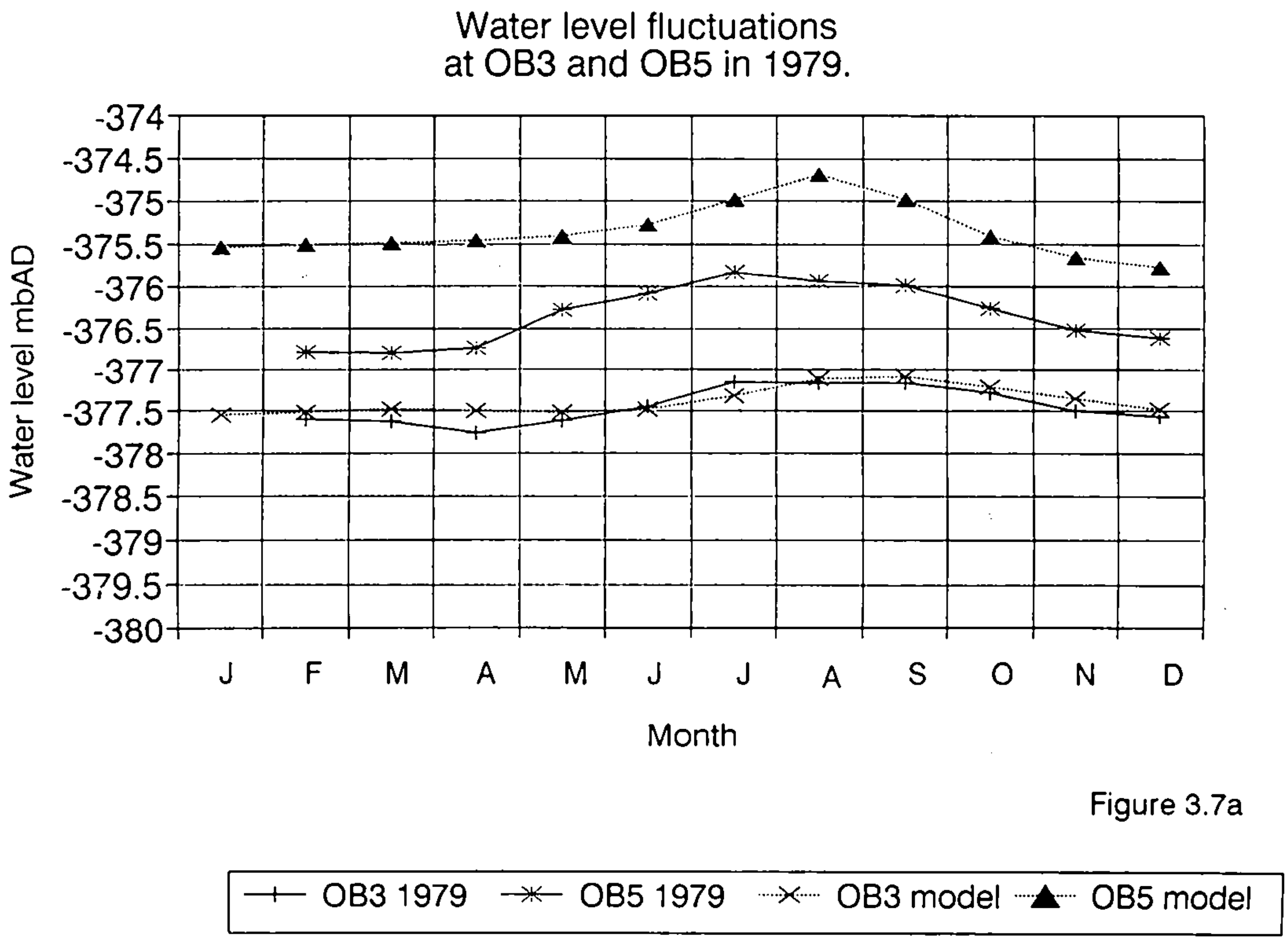

Water level fluctuations
at OB3 and OB5 in 1979.
Water level mbAD
-374
-374.5
-375
-375.5
-376
-376.5
-377
-377.5
-378
-378.5
-379
-379.5
-380
J F M A M J J A S O N D
Month
OB3 1979
OB5 1979
OB3 model
OB5 model

Figure 3.7a

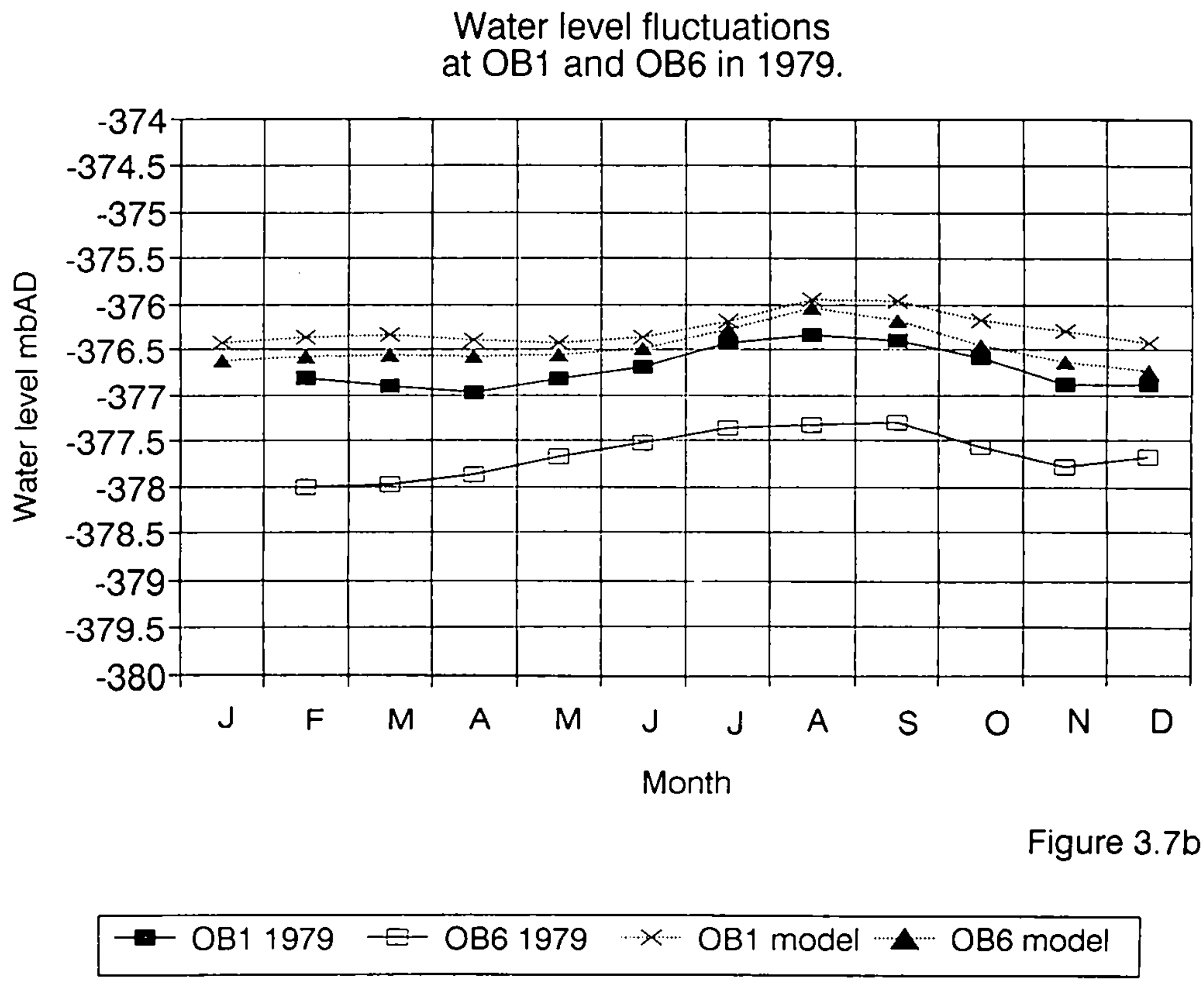

Water level fluctuations
at OB1 and OB6 in 1979.
Water level mbAD
-374
-374.5
-375
-375.5
-376
-376.5
-377
-377.5
-378
-378.5
-379
-379.5
-380
J F M A M J J A S O N D
Month
OB1 1979
OB6 1979
OB1 model
OB6 model

Figure 3.7b

Table 4.1

APC water supply from Ghor Safi, 1982-1992 (Mm3).

	Wellfield	Hassa	Total
1982	1.22	0	1.22
1983	4.01	0	4.01
1984	4.65	0	4.65
1985	6.49	0	6.49
1986	6.39	0	6.39
1987	5.36	0.66	6.02
1988	4.22	1.71	5.93
1989	4.34	1.48	5.82
1990	4.64	1.45	6.09
1991	5.11	1.60	6.71
1992	5.77	1.09	6.86
Total	52.2	7.99	60.19

Table 4.2

Annual Minimum Water Level at APC Observation Wells (m bgl)

Year	OB1	OB2	OB3	OB4	OB5	OB6	OB7	BN 302	S6
1977								14 15	13 40
1978								14.45	13 50
1979	9.25	0.00	0.45	20.35	16.97	6.15	7.88	14.00	13.60
1980									
1981									
1982		0.40	0.70	20.20	17 10	6.10		14.00	
1983		1 30	0 80	20.20	18 30	7.50		15 70	
1984		2.00	1.60	20.80	18 90	7 90		16.40	
1985		2.60	2 80	20.00	20 40	8 90		17.10	
1986		3 80	4.00	20 40	22.60	10.20			
1987		5 80	5.70	20.70	24.70	12.60			
1988									
1989			5.56	20.35	23 30				
1990			6.15	20.45	24.00				
1991			6.35		24.96				
1992			6.65	21.20	26.00				

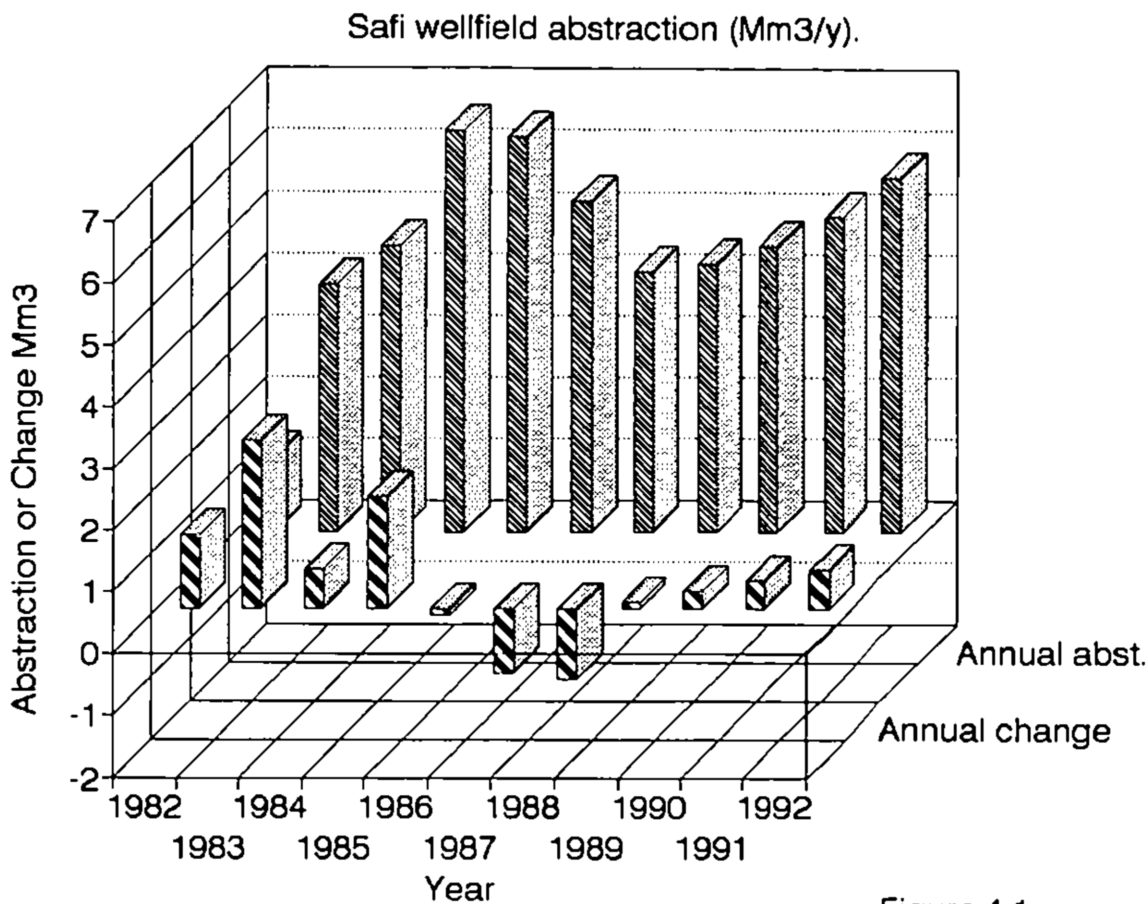
Notes: Min water level in December of each year.

Table 4 3

Annual Change in Minimum Water Level (m)

Year	OB1	OB2	OB3	OB4	OB5	OB6	OB7	BN 302	S6
1977									
1978									
1979									
1980									
1981									
1982									
1983		0.90	0.10	0.00	1.20	1.40		1.70	
1984		0.70	0 80	0.60	0.60	0.40		0.70	
1985		0 60	1.20	-0.80	1.50	1.00		0.70	
1986		1.20	1.20	0 40	2.20	1 30			
1987		2.00	1.70	0.30	2.10	2.40			
1988									
1989									
1990			0.59	0 10	0.70				
1991			0.20		0 96				
1992			0 30		1 04				
Total 1982-92			5 95	1.00	8 90				
Change 1982-87		5 40	5 00	0.50	7 60	6 50			
Change 1987-92			0 95	0.50	1 30				

Note: Negative value is a rise in water level.



Safi wellfield abstraction (Mm3/y).
Abstraction or Change Mm3
7
6
5
4
3
2
1
0
-1
-2
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
Year
Annual abst.
Annual change

Figure 4.1

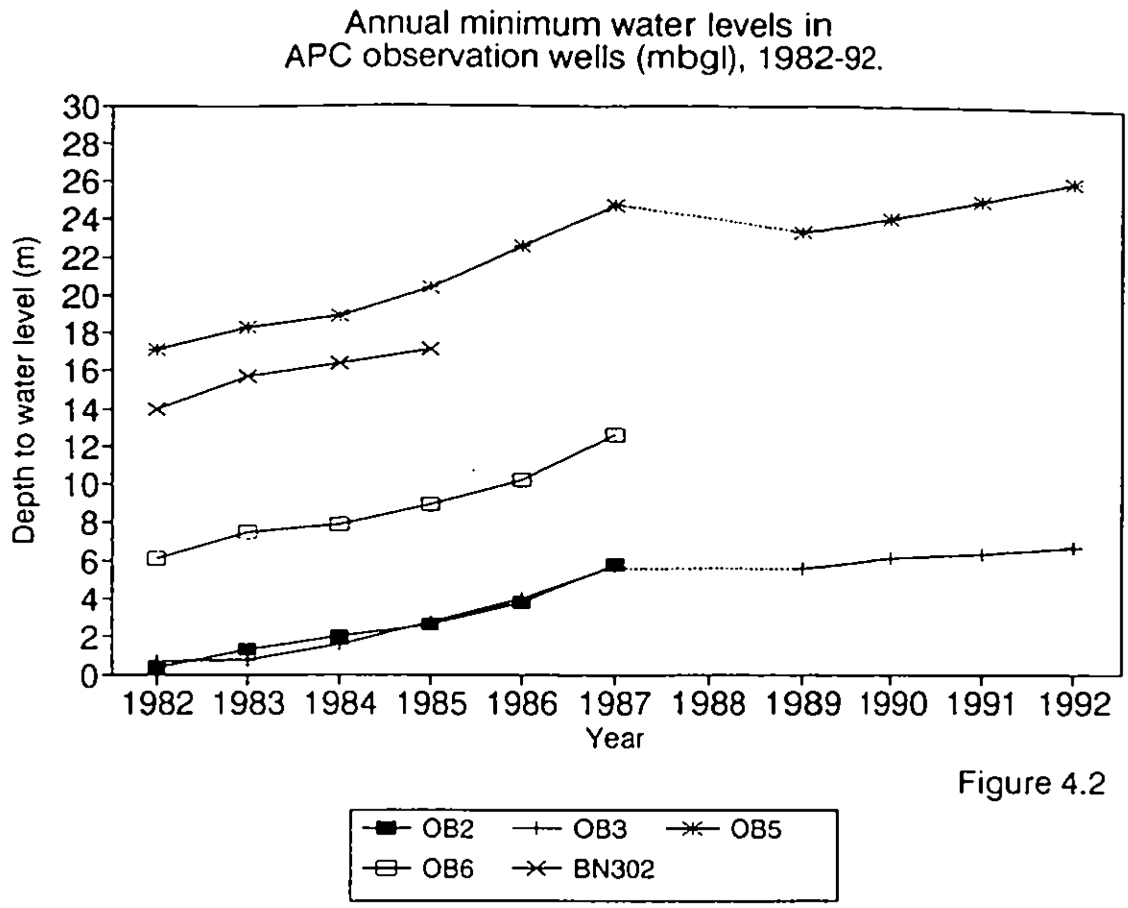

Annual minimum water levels in
APC observation wells (mbgl), 1982-92.
Depth to water level (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
Year
OB2
OB3
OB5
OB6
BN302

Figure 4.2

Annual Abstraction and Water Levels at
OB3 and OB5

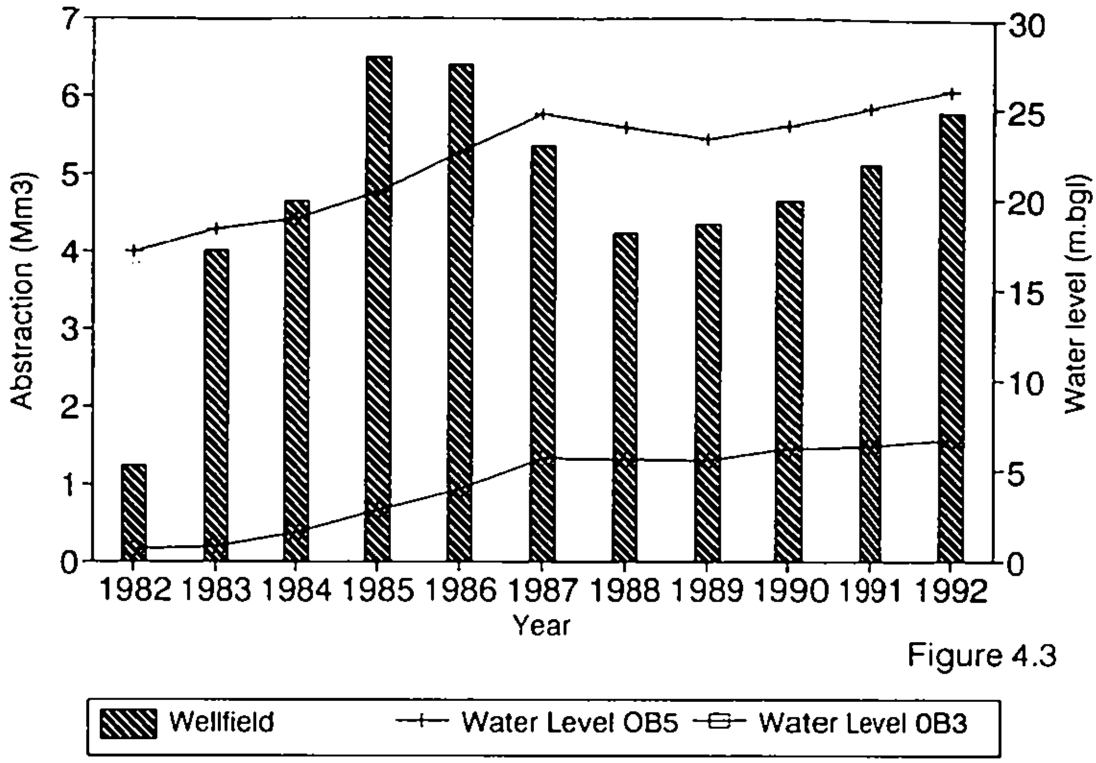
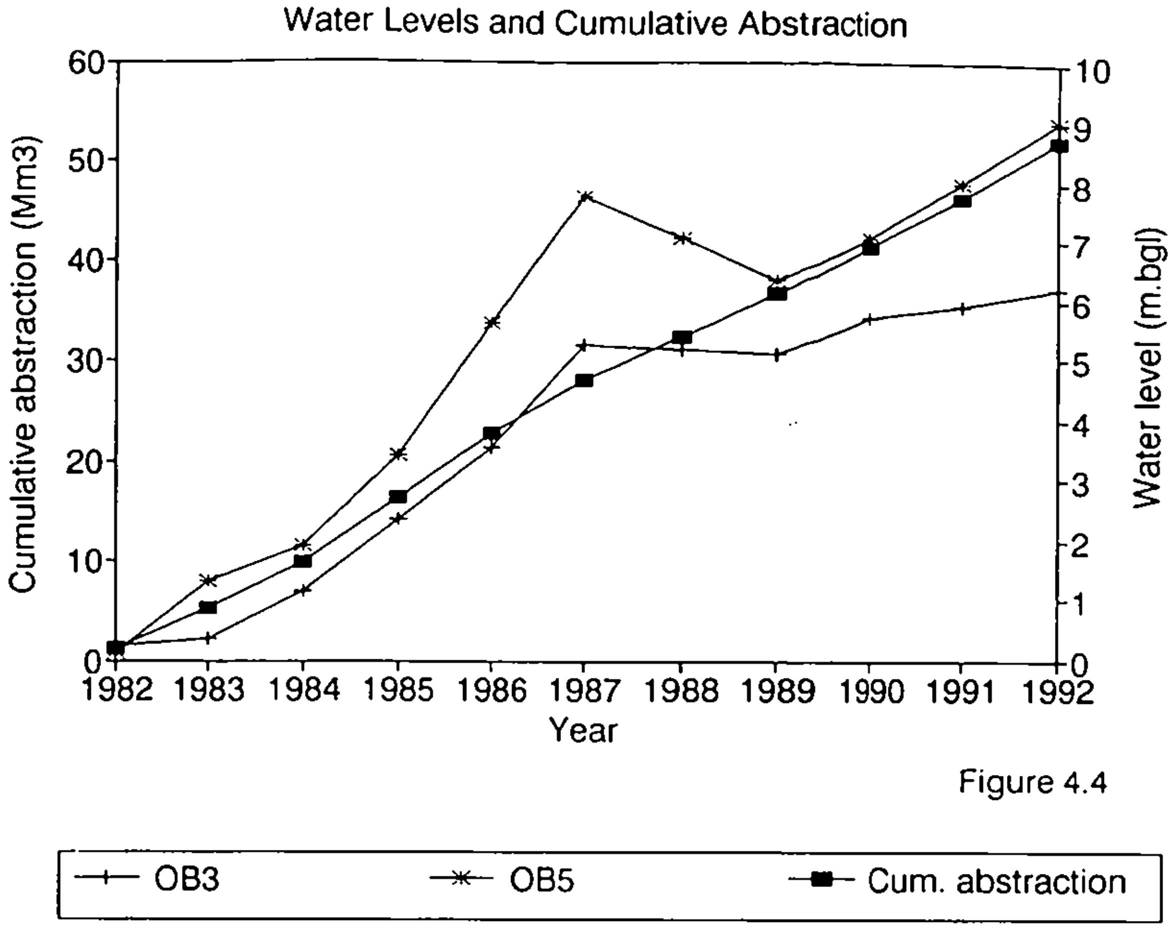


Figure 4.3



Water Levels and Cumulative Abstraction
Cumulative abstraction (Mm3)
Water level (m.bgl)
Year
60
50
40
30
20
10
0
10
9
8
7
6
5
4
3
2
1
0
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
OB3
OB5
Cum. abstraction

Figure 4.4

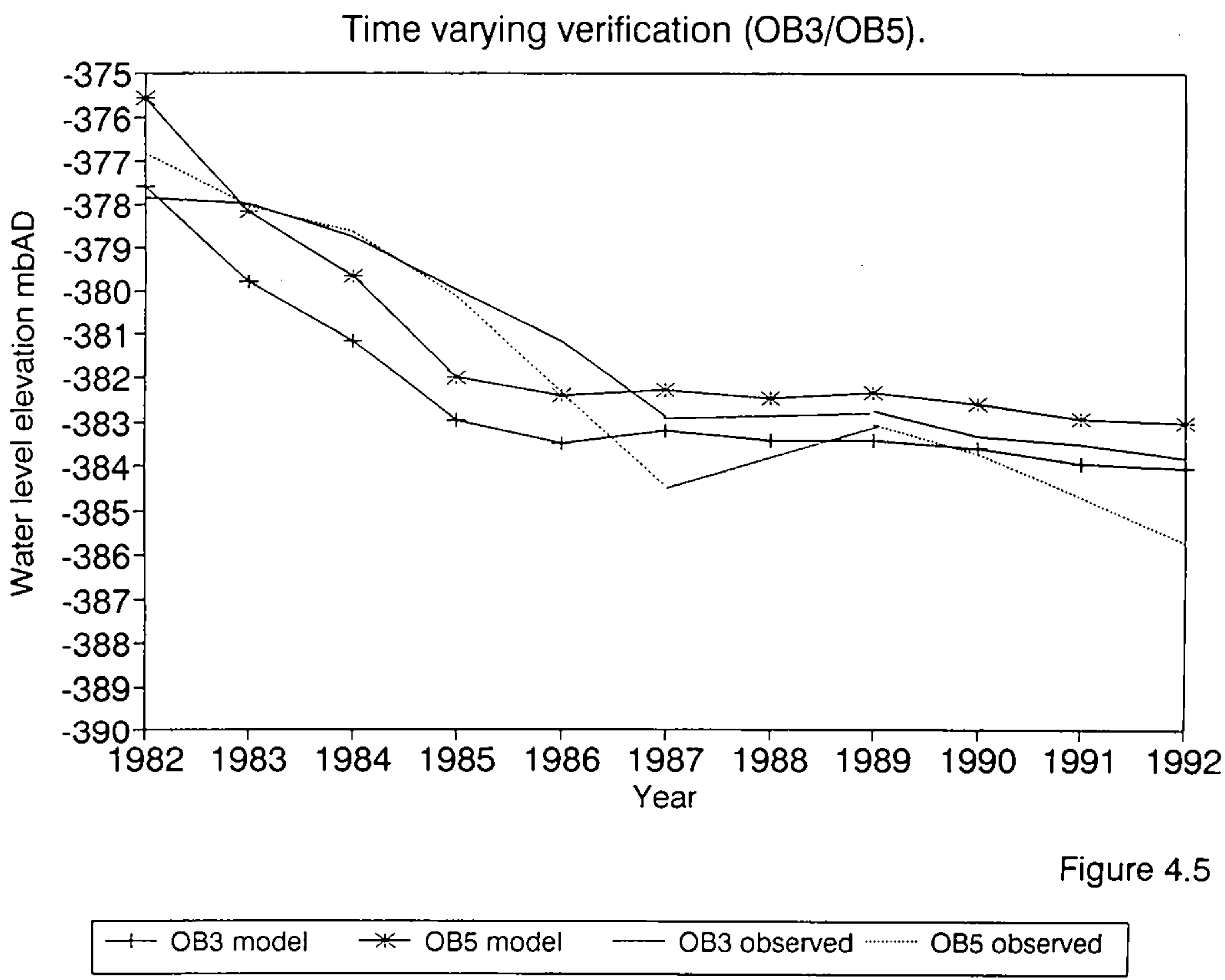

Time varying verification (OB3/OB5).
Water level elevation mbAD
-375
-376
-377
-378
-379
-380
-381
-382
-383
-384
-385
-386
-387
-388
-389
-390
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
Year
OB3 model
OB5 model
OB3 observed
OB5 observed

Figure 4.5

Model heads 1992

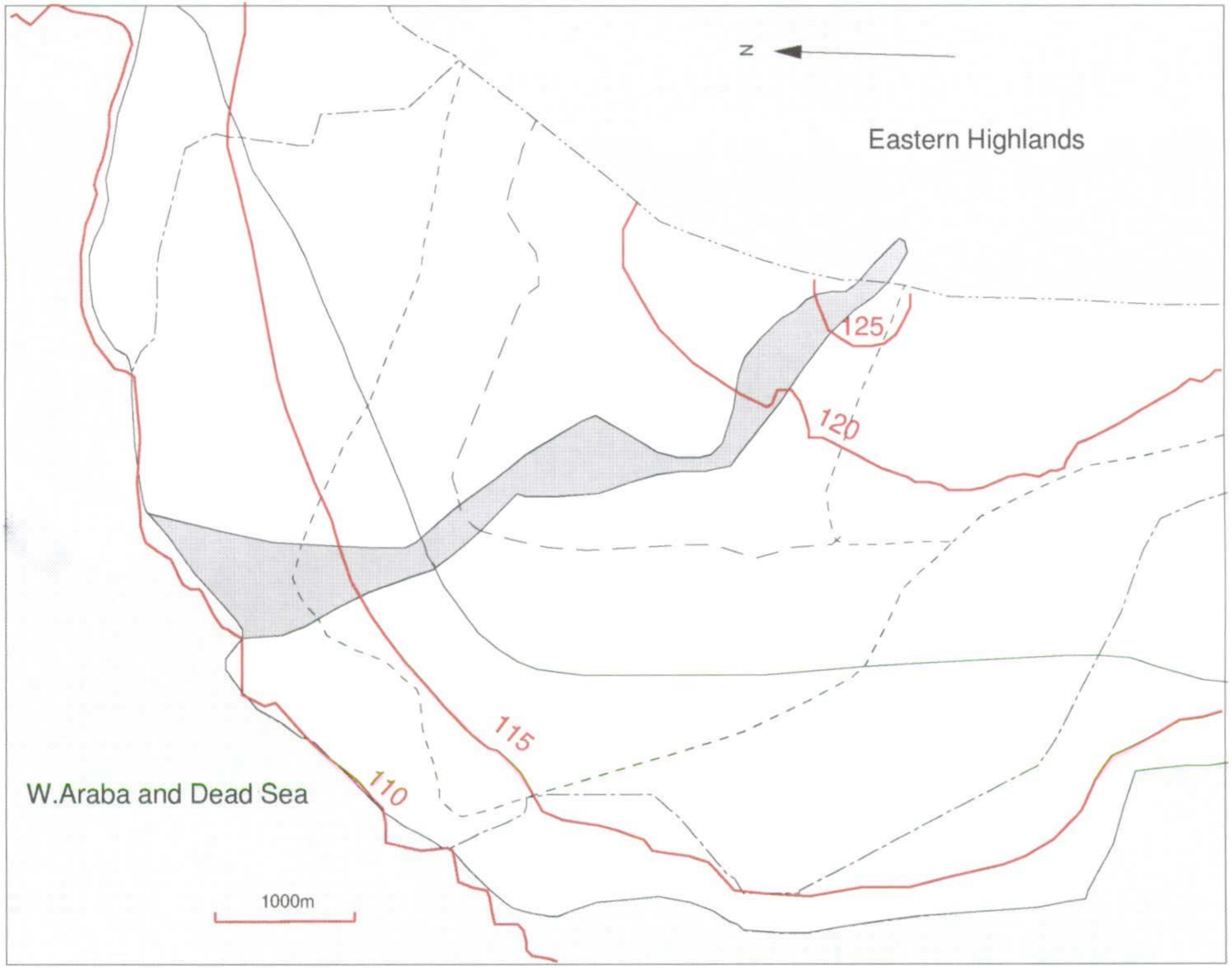
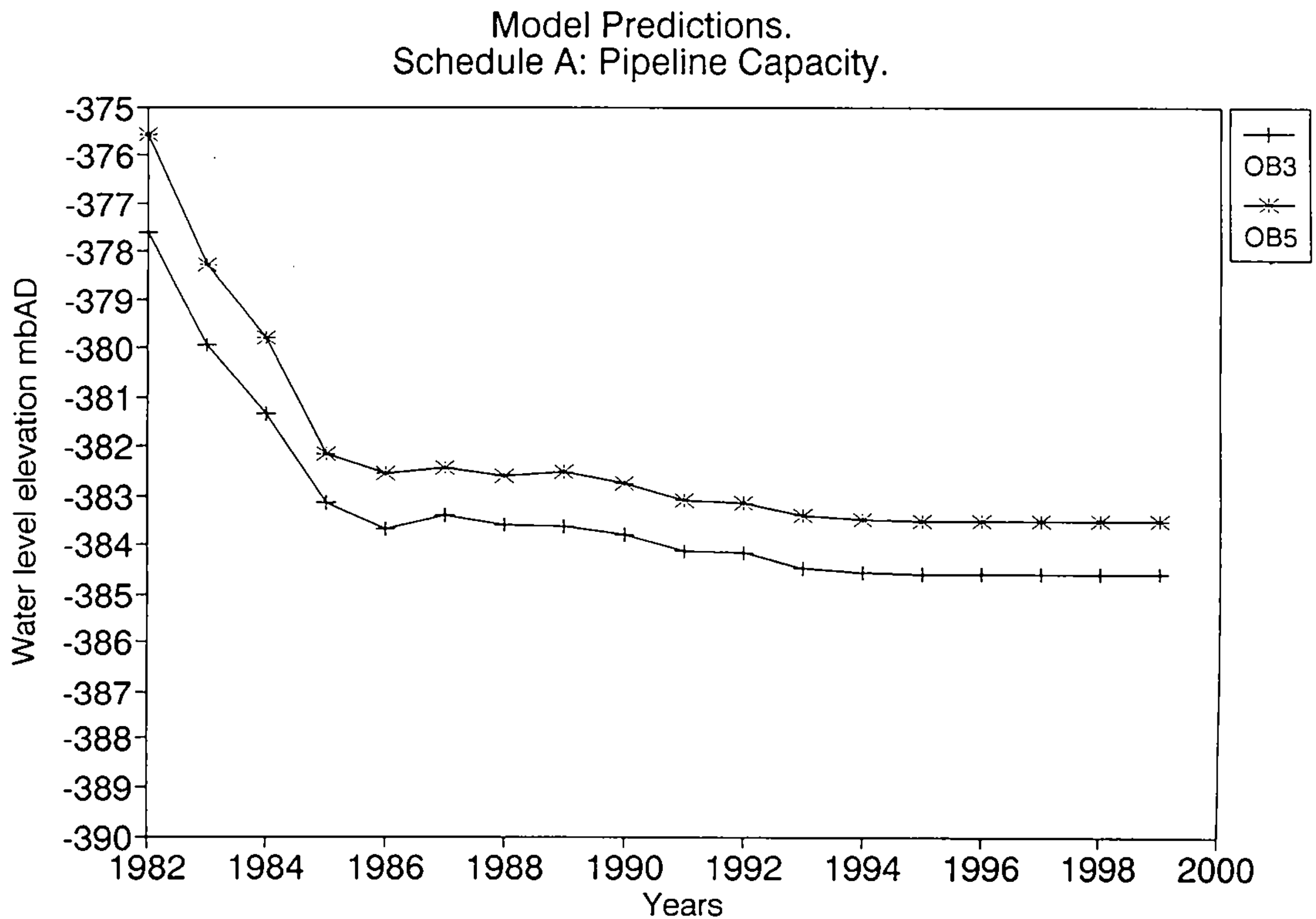


Figure 4.6



Model Predictions.
Schedule A: Pipeline Capacity.
Water level elevation mbAD
-375
-376
-377
-378
-379
-380
-381
-382
-383
-384
-385
-386
-387
-388
-389
-390
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
Years
OB3
OB5

Figure 5.1

Schedule A: Predicted head configuration

Figure 5.2

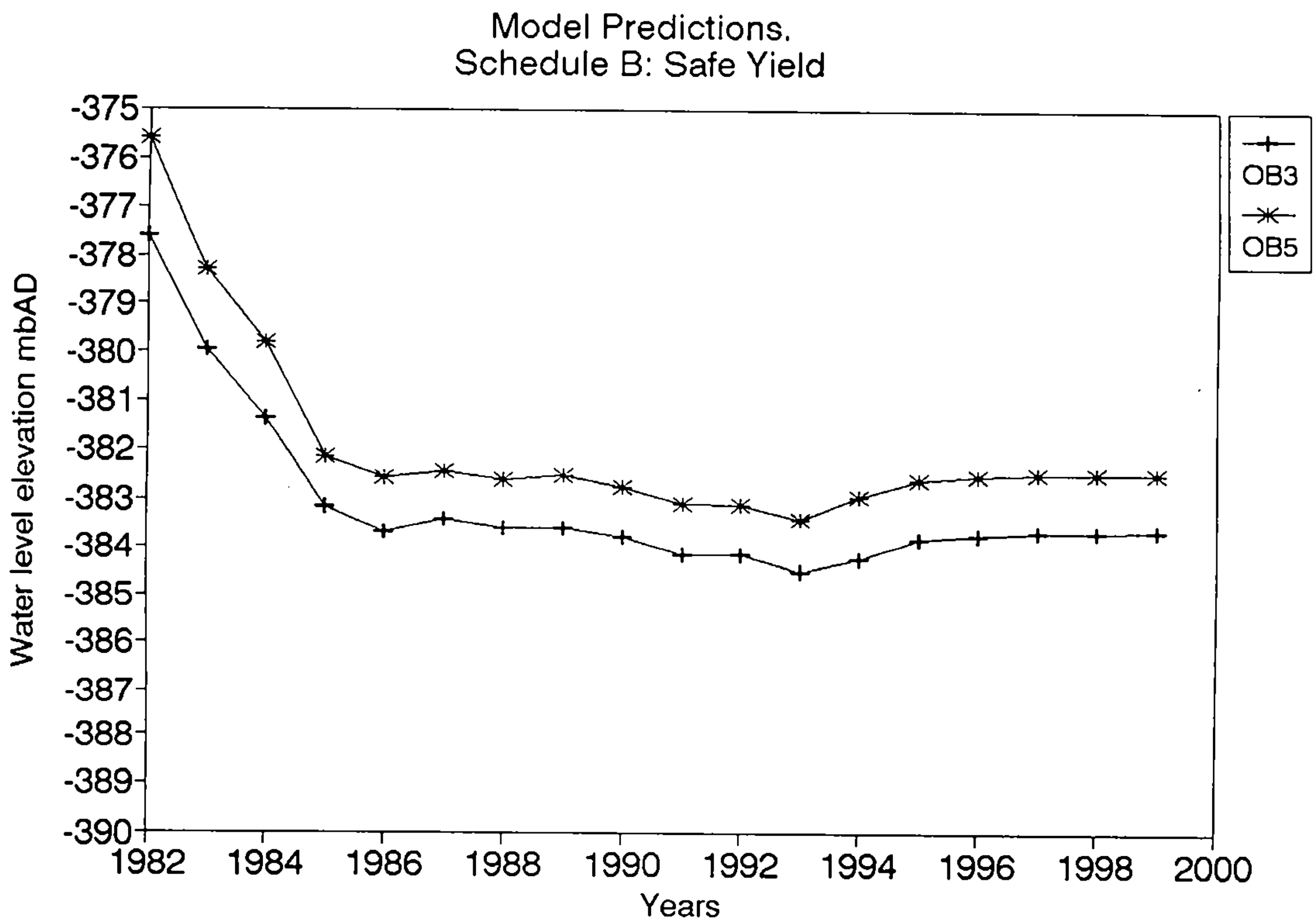

Model Predictions.
Schedule B: Safe Yield
Water level elevation mbAD
-375
-376
-377
-378
-379
-380
-381
-382
-383
-384
-385
-386
-387
-388
-389
-390
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
Years
OB3
OB5

Figure 5.3

Schedule B: Predicted head configuration

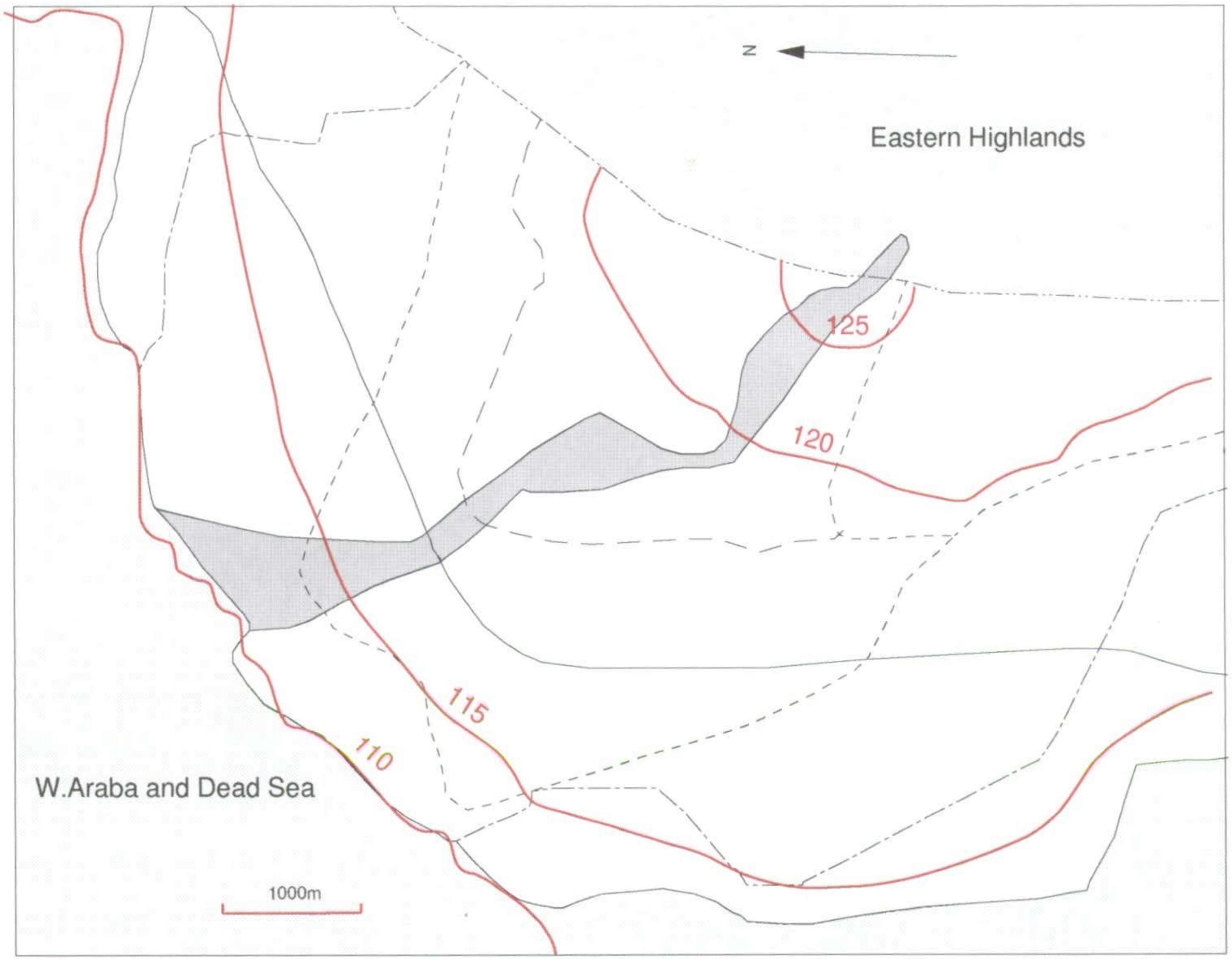


Figure 5.4

Annex A.

Table A.1	Transmissivity values from recovery tests
Table A.2	Simulation of monthly historical recharge.
Table A.3 a-c	Simulation of historical abstraction.

Table A.1

Transmissivity estimates based on Recovery Tests.

Well	Rate m3/d	Date	T m2/d	Zone
SPB1	3000	Oct.1980	3660	2
SPB2	3000	Oct.1980	4775	2
SPB3	3000	Oct.1980	6310	2
SPB4	3000	Oct.1980	5490	2
SPB5	3000	Oct.1980	18300	2
SPB6	3000	Oct.1989	1280	1
SPB7	2800	Sep.1989	1735	1
SPB8	2808	May 1990	6425	2
SPB10	1486	May 1993	1815	2
SPB11	2304	Jun.1993	7030	2
SPB12	1920	Jun.1993	6165	2
S1B	558	May 1993	365	2
S2	3300	1977	11000	1
S2B/C	2640	May 1990	2790	1
BN309	873	1977	2500	1
S10P	2880	Sep.1977	7530	2

Notes:

BN 309 no recovery data. T from observation well data.

Table A.2

Simulated Monthly Variation In Recharge (by node).

Nodes 850 816 817,783,1331,1330 Surplus irrigation and floods

			Surplus		Flood	Total	
Month	Day	% ann	Mm3/mth	m3/s	Mm3/mth	Mm3/mth	m3/s
Jan	31	8.70	0.3915	0.1462	0.15	0.542	0.2022
Feb	28	6.25	0.2813	0.1163	0.15	0.431	0.1783
Mar	31	7.44	0.3348	0.1250	0.15	0.485	0.1810
Apr	30	6.60	0.2970	0.1146	0.15	0.447	0.1725
May	31	12.75	0.5738	0.2142	0	0.574	0.2142
Jun	30	13.75	0.6188	0.2387	0	0.619	0.2387
Jul	31	18.64	0.8388	0.3132	0	0.839	0.3132
Aug	31	16.43	0.7394	0.2760	0	0.739	0.2760
Sep	30	1.14	0.0513	0.0198	0	0.051	0.0198
Oct	31	1.31	0.0590	0.0220	0	0.059	0.0220
Nov	30	1.88	0.0837	0.0323	0.15	0.234	0.0902
Dec	31	5.15	0.2318	0.0865	0.15	0.382	0.1425
Annual Mm3			4.50		0.9	5.40	

Node 884 Hassa underflow — Node 743 Abyad underflow

Month	Day				m3/s
Jan	31	0.2548	0.0951	0.1274	0.0476
Feb	28	0.2301	0.0951	0.1151	0.0476
Mar	31	0.2548	0.0951	0.1274	0.0476
Apr	30	0.2466	0.0951	0.1233	0.0476
May	31	0.2548	0.0951	0.1274	0.0476
Jun	30	0.2466	0.0951	0.1233	0.0476
Jul	31	0.2548	0.0951	0.1274	0.0476
Aug	31	0.2548	0.0951	0.1274	0.0476
Sep	30	0.2466	0.0951	0.1233	0.0476
Oct	31	0.2548	0.0951	0.1274	0.0476
Nov	30	0.2466	0.0951	0.1233	0.0476
Dec	31	0.2548	0.0951	0.1274	0.0476
Annual Mm3		3.00		1.5	

Nodes 1329,644,609,574 Floods only

Month	Day		
Jan	31	0.1000	0.0373
Feb	28	0.1000	0.0413
Mar	31	0.1000	0.0373
Apr	30	0.1000	0.0386
May	31	0	0
Jun	30	0	0
Jul	31	0	0
Aug	31	0	0
Sep	30	0	0
Oct	31	0	0
Nov	30	0.1000	0.0386
Dec	31	0.1000	0.0373
Annual Mm3		0.6	

Total recharge

Jan	31	0.8963	0.3346	1.0237	0.3822
Feb	28	0.7614	0.3147	0.8765	0.3623
Mar	31	0.8396	0.3135	0.9670	0.3610
Apr	30	0.7935	0.3062	0.9169	0.3537
May	31	0.8285	0.3093	0.9559	0.3569
Jun	30	0.8653	0.3338	0.9886	0.3814
Jul	31	1.0938	0.4083	1.2210	0.4559
Aug	31	0.9941	0.3712	1.1215	0.4187
Sep	30	0.2979	0.1149	0.4212	0.1625
Oct	31	0.3137	0.1171	0.4411	0.1647
Nov	30	0.5803	0.2239	0.7038	0.2714
Dec	31	0.7365	0.2750	0.8639	0.3226
		9.00 (no floods)		10.50 (with floods)	

Table A.3a

Safi2: Percent of Annual APC Abstraction from each well, 1982-1992.

Year	Annual total m3	Percent/well of pumping rate each year SPB1	SPB2	SPB3	SPB4	SPB5	SPB6	SPB7	BN309	S2	S1	S11	SPB8	Pumping Rate m3/h	
1982	1216783	15	15	15	14	15	0	0	7	19	0	0	0	850	
1983	4006883	15	15	15	14	15	0	0	7	19	0	0	0	850	
1984	4653181	15	15	15	14	15	0	0	7	19	0	0	0	850	
1985	6489051	11.5	16.3	15.2	12.5	13.6	0	0	2.5	18	5	5.4	0	918	
1986	6391613	14.3	17.1	18.8	11.5	14.4	0	0	0	18.9	4.9	0	0	818	
1987	5363600	7.5	16.4	23.9	13.4	13.1	0	0	0	19.7	6	0	0	670	
1988	4218233	18.8	14	21	11.1	9.4	0	0	0	20.5	5.1	0		585	
1989	4338651	11.9	13.6	23	11.1	10.2	0	0	0	24.2	6	0		587	Feb
1990	4637414	8.2	8.8	14.3	7.9	8.8	7.1	11.1	8.8	9.9	4.4	0	10.6	911	Oct
1991	5110728	7.4	9.7	12.6	8	8	6.8	10.3	8	12	4.6	0	12.6	875	
1992	5773829	7.4	9.2	12.3	8.6	9.9	7.4	11.1	8.6	11.1	3.1	0	11.1	810	Oct
Total	52199966														

Table A.3b

Safi2: Simplified Monthly APC Abstraction, 1982-1992.

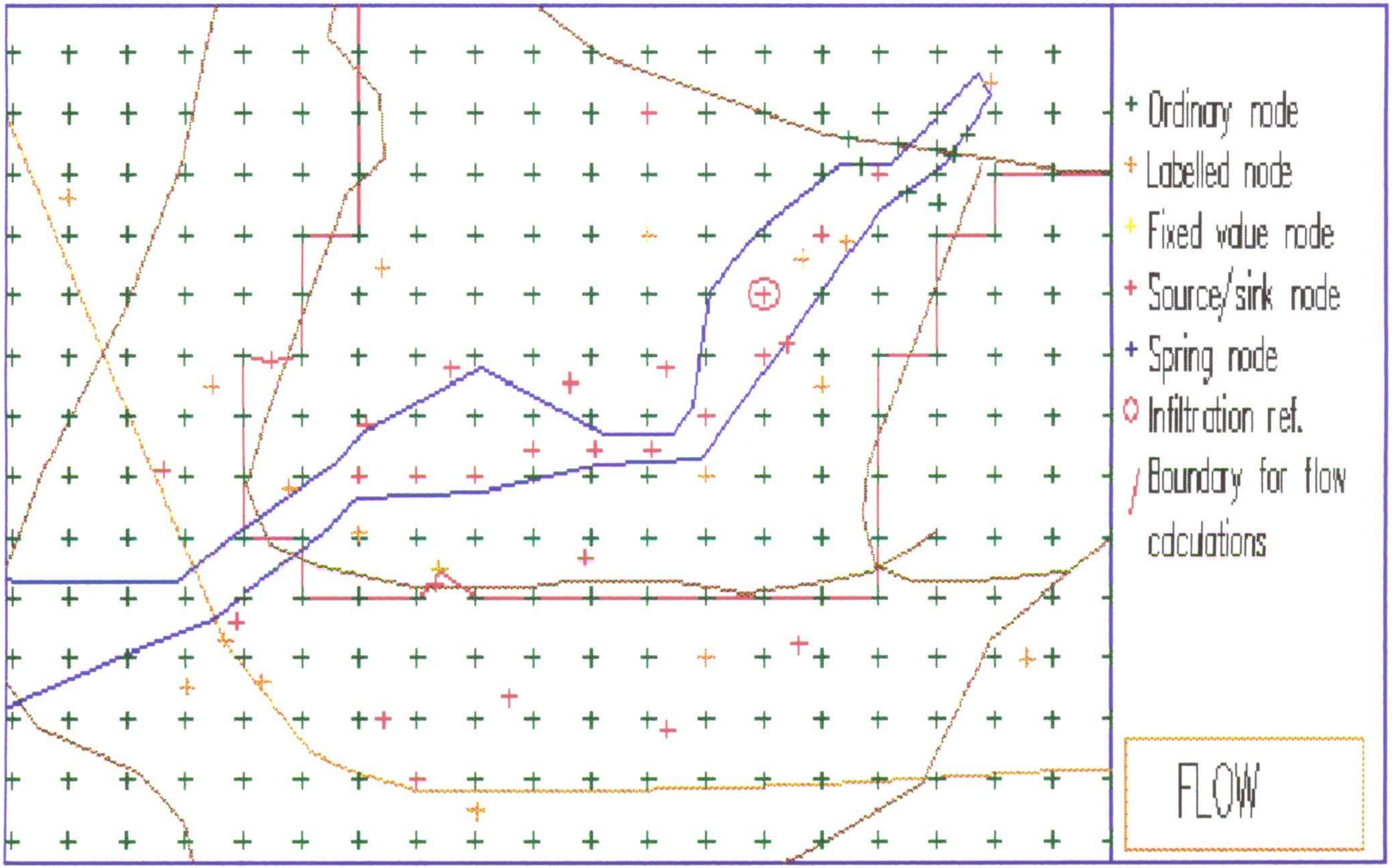
		Monthly abstraction m3										
Month	Percent of annual	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
Jan	8	40112	320552	372256	519126	511331	429090	337460	347093	370994	408860	461908
Feb	8	40112	320552	372256	519126	511331	429090	337460	347093	370994	408860	461908
Mar	8	40112	320552	372256	519126	511331	429090	337460	347093	370994	408860	461908
Apr	8	40112	320552	372256	519126	511331	429090	337460	347093	370994	408860	461908
May	8	40112	320552	372256	519126	511331	429090	337460	347093	370994	408860	461908
Jun	8	40112	320552	372256	519126	511331	429090	337460	347093	370994	408860	461908
Jul	8	40112	320552	372256	519126	511331	429090	337460	347093	370994	408860	461908
Aug	8	86875	320552	372256	519126	511331	429090	337460	347093	370994	408860	461908
Sep	10	164750	400687	465317	648903	639160	536359	421822	433864	463740	511071	577381
Oct	10	243250	400687	465317	648903	639160	536359	421822	433864	463740	511071	577381
Nov	8	230000	320552	372256	519126	511331	429090	337460	347093	370994	408860	461908
Dec	8	211125	320552	372256	519126	511331	429090	337460	347093	370994	408860	461908
		1216784	4006894	4653194	6489066	6391630	5363618	4218244	4338658	4637420	5110742	5773842
	Av m3/h	139	457	531	741	730	612	482	495	529	583	659
	Av m2/s	0.0386	0.1271	0.1476	0.2058	0.2027	0.1701	0.1338	0.1376	0.1471	0.1621	0.1831

Table A.3c

Safi2: Model Simulation of Average Annual Abstraction at APC Wells, 1982-1992 (m3/s).

	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	Average
SPB1	0.005788	0.019059	0.022133	0.023663	0.028983	0.012756	0.025147	0.016372	0.012058	0.011992	0.013548	0.017409
SPB2	0.005788	0.019059	0.022133	0.03354	0.034658	0.027893	0.018726	0.018711	0.012941	0.01572	0.016844	0.020546
SPB3	0.005788	0.019059	0.022133	0.031277	0.038103	0.040649	0.02809	0.031643	0.021028	0.02042	0.02252	0.025519
SPB4	0.005402	0.017788	0.020657	0.025721	0.023308	0.022791	0.014847	0.015271	0.011617	0.012965	0.015746	0.016919
SPB5	0.005788	0.019059	0.022133	0.027984	0.029186	0.02228	0.012573	0.014033	0.012941	0.012965	0.018126	0.017915
SPB6	0	0	0	0	0	0	0	0	0.010441	0.01102	0.013548	
SPB7	0	0	0	0	0	0	0	0	0.015587	0.016692	0.020323	
BN309	0.002701	0.008894	0.010329	0.005144	0	0	0	0	0.012941	0.012965	0.015746	
S2	0.007331	0.024141	0.028035	0.037038	0.038306	0.033506	0.027421	0.033294	0.014558	0.019447	0.020323	0.025764
S1	0	0	0	0.010288	0.009931	0.010205	0.006822	0.008255	0.00647	0.006482	0.005676	
S11	0	0	0	0.011111	0	0	0	0	0	0	0	
SPB8	0	0	0	0	0	0	0	0	0.015587	0.02042	0.020323	

Annex A. Recharge and Abstraction nodes.



Annex B.

Table B.1 Head output values at labelled nodes.

Table B.1

Model head elevations at labelled nodes.

1. Steady-state runs.

Node	Name	Water level mbAD	Steady-state calibration Model	Steady-state calibration mbAD	No flood recharge Model	No flood recharge mbAD
614	SPB8		123.02	-376.98	122.16	-377.84
743	Abyad		136.53	-363.47	134.80	-365.20
745	S6B		135.32	-364.68	133.39	-366.61
784	OB4	-368.4	130.73	-369.27	129.03	-370.97
787	OB5	-376.3	124.29	-375.71	123.36	-376.64
1316	OB1	-376.7	123.42	-376.58	122.46	-377.54
1317	OB2	-377.5	122.26	-377.74	121.43	-378.57
1318	OB3	-377.45	122.21	-377.79	121.40	-378.60
1319	OB6	-377.7	123.19	-376.81	122.34	-377.66
1320	OB7	-373.3	122.23	-377.77	121.81	-378.19
1321	BN302	-377.2	123.98	-376.02	122.95	-377.05
1323	BN300	-357.5	142.48	-357.52	140.02	-359.98
1324	S3		122.65	-377.35	121.78	-378.22
1325	S4	-372.6	126.69	-373.31	125.43	-374.57
1326	S7	-359.5	137.63	-362.37	135.39	-364.61
1327	S8	-367	145.70	-354.30	143.17	-356.83
1354	SPB1	-375.3	124.41	-375.59	123.51	-376.49
1355	SPB2	-376.9	123.93	-376.07	123.04	-376.96
1356	SPB3	-375.3	123.04	-376.96	122.17	-377.83
1357	SPB4	-377.5	122.95	-377.05	122.04	-377.96
1358	SPB5	-376.25	123.70	-376.30	122.71	-377.29
1359	SPB6	-360	134.09	-365.91	132.07	-367.93
1360	SPB7	-366.6	138.76	-361.24	136.41	-363.59
1362	SPB10		123.61	-376.39	122.71	-377.29
1363	SPB11		122.70	-377.30	121.84	-378.16
1364	SPB12		122.74	-377.26	121.86	-378.14
1365	BN309	-377.2	123.64	-376.36	122.68	-377.32
1366	S2	-375.9	125.84	-374.16	124.64	-375.36
1367	S1		124.95	-375.05	123.72	-376.28
1368	S11		127.57	-372.43	126.11	-373.89
1369	S13		123.27	-376.73	122.32	-377.68
1370	S14		123.39	-376.61	122.41	-377.59
1371	S2W	-365	130.78	-369.22	129.00	-371.00

2. Time-varying runs.

a) Model verification.

Days	OB1	OB2	OB3	OB4	OB5	OB6	BN302	
0	123.51	122.41	122.41	130.88	124.43	123.34	123.91	1982
365	121.08	120.23	120.54	127.96	121.84	120.96	121.18	1983
730	119.54	118.85	119.28	126.24	120.38	119.52	119.61	1984
1095	117.48	117.04	117.46	121.07	118.02	117.54	117.66	1985
1460	116.86	116.51	116.83	119.86	117.61	117.06	117.10	1986
1825	117.21	116.80	117.03	119.81	117.74	117.31	117.37	1987
2190	116.96	116.59	116.82	119.26	117.56	117.10	117.13	1988
2555	116.97	116.58	116.80	119.15	117.66	117.07	117.01	1989
2920	116.78	116.39	116.65	118.90	117.43	116.85	116.79	1990
3285	116.38	116.06	116.33	118.42	117.08	116.51	116.40	1991
3650	116.26	115.95	116.22	118.25	116.98	116.41	116.29	1992

b) Schedule A: Pipeline capacity constraint.

	OB1	OB2	OB3	OB4	OB5	OB6	BN302	
0	123.51	122.41	122.41	130.88	124.43	123.34	123.91	1982
365	120.97	120.07	120.38	127.79	121.72	120.83	121.08	1983
730	119.37	118.65	119.07	126.01	120.21	119.36	119.46	1984
1095	117.30	116.84	117.25	120.82	117.85	117.37	117.49	1985
1460	116.66	116.31	116.61	119.60	117.44	116.88	116.92	1986
1825	117.02	116.60	116.82	119.54	117.58	117.13	117.19	1987
2190	116.77	116.39	116.61	119.00	117.38	116.92	116.95	1988
2555	116.77	116.38	116.58	118.89	117.48	116.90	116.83	1989
2920	116.58	116.20	116.44	118.63	117.25	116.67	116.61	1990
3285	116.18	115.88	116.12	118.15	116.91	116.34	116.23	1991
3650	117.17	115.84	116.10	118.05	116.66	116.30	116.19	1992
4015	115.89	115.52	115.89	117.80	116.59	116.00	115.88	1993
4380	115.82	115.45	115.82	117.71	116.52	115.93	115.81	1994
4745	115.80	115.43	115.80	117.68	116.50	115.91	115.79	1995
5110	115.79	115.42	115.79	117.66	116.49	115.90	115.78	1996
5475	115.78	115.42	115.79	117.66	116.49	115.90	115.78	1997
5840	115.78	115.42	115.79	117.66	116.49	115.90	115.77	1998
6205	115.78	115.42	115.79	117.66	116.49	115.90	115.77	1999

c) Schedule B: Safe yield.

	OB1	OB2	OB3	OB4	OB5	OB6	BN302	
0	123.51	122.41	122.41	130.88	124.43	123.34	123.91	1982
365	120.97	120.07	120.36	127.79	121.72	120.83	121.08	1983
730	119.37	118.65	119.07	126.01	120.21	119.36	119.46	1984
1095	117.30	116.84	117.25	120.82	117.86	117.37	117.49	1985
1460	116.66	116.31	116.62	119.60	117.44	116.88	116.92	1986
1825	117.02	116.60	116.82	119.54	117.56	117.13	117.19	1987
2190	116.77	116.39	116.61	119.00	117.38	116.92	116.95	1988
2555	116.77	116.38	116.58	118.89	117.48	116.90	116.83	1989
2920	116.58	116.20	116.44	118.63	117.25	116.67	116.61	1990
3285	116.18	115.86	116.12	118.15	116.91	116.34	116.23	1991
3650	116.17	115.84	116.10	118.05	116.88	116.30	116.19	1992
4015	115.90	115.52	115.89	117.80	116.59	116.00	115.88	1993
4380	116.13	115.75	116.08	118.40	117.04	116.37	116.29	1994
4745	116.63	116.16	116.46	118.81	117.38	116.75	116.70	1995
5110	116.75	116.26	116.57	118.95	117.46	116.85	116.81	1996
5475	116.79	116.30	116.60	119.00	117.52	116.89	116.84	1997
5840	116.81	116.31	116.62	119.00	117.53	116.90	116.86	1998
6205	116.81	116.32	116.62	119.00	117.54	116.90	116.86	1999