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Arab Potash Company, Jordan.

GROUNDWATER MODEL STUDY OF NORTH DHIRA

Phase 1

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Phase 1 of the Dhira Groundwater Model Study has used baseflow and springflow data in combination with geological and other information to develop a conceptual model of the hydrogeology and the likely recharge and discharge conditions within the region surrounding the new APC wellfield in north Dhira. This was used to design a numerical regional groundwater flow model [DHIRALCL] to investigate the significance of certain features of the regional hydrogeology in relation to the planned abstraction from the Dhira wellfield. Phase 2 of the study will use monitoring data on the actual aquifer response to abstraction to verify the model and undertake more detailed wellfield abstraction simulations.

It is estimated that a discharge of about 8.5 Mm^3/y (970 m^3/h) takes place from the outcrops of the Kurnub Sandstone along Wadi Ibn Hammad and Wadi Karak above the main escarpment. The amount of groundwater recharge entering north Dhira through the Kurnub Sandstone aquifer under natural conditions is estimated to be about 4.4 Mm^3/y (500 m^3/h), although the model suggests a smaller flow of 2.3 Mm^3/y (260 m^3/h) depending on the reliability of the transmissivity values. The Siwaqa Fault appears to act as a barrier to groundwater flow and about 20% of the flow of Ain Maghara could be derived from the deep aquifer in north Dhira.

Initial runs with the model at the planned abstraction rate of 700 m^3/h from the wellfield indicate large drawdowns at each new production well similar to those predicted independently from the results of the pumping test programme. About 50% of the planned abstraction is derived by increased recharge across the main escarpment due to an increase in hydraulic gradients. This implies that wadi baseflows may be reduced by the wellfield abstraction.

The study demonstrates the need for a survey of wadi baseflows supported by a programme of water sampling for chemical and isotope analyses to provide confirmation of the conceptual model and to resolve some of the water resource issues, such as the impact of abstraction on wadi baseflows and springflows.

1. BACKGROUND

1.1 Introduction and Objectives

The Kurnub-Um Ishrin aquifer system in the northern part of the Edh Dhira plateau, situated some 35 km north of the APC refinery, was identified as a potential source of groundwater [1]. Following a reconnaissance geological survey of the north Dhira area in 1991, three deep wells (TA1, TA2 and TA6) were drilled to penetrate the Kurnub-Um Ishrin aquifer system to depths of 600 to 1000 mbgl [2]. These, together with the artesian flow of an existing deep exploratory well (TS1D), will form the Dhira wellfield which will be used in conjunction with supplies from the Safi wellfield to meet the future water requirements of the APC refinery.

The new wells in north Dhira were constructed and tested during 1993/94. Construction details, lithological logs and pumping test reports were prepared for each individual well as the programme continued [3, 4]. On completion of the test programme, the results were integrated to prepare preliminary predictions of pumping water levels and flows and to discuss the test results and water chemistry in relation to certain water resource issues that may influence abstraction from the wellfield [5].

Due to the high cost of undertaking a groundwater resources exploration programme of the deep aquifer and the complexity of the aquifer system, it was originally proposed that groundwater development should proceed in stages, monitoring the aquifer response to a modest level of abstraction (400 m^3/h) before increasing the amount abstracted. In the event, a scheme was implemented to provide a pumping capacity of 700 m^3/h. The possibility of supplying levels of 700 and 1100 m^3/h from a combination of the Dhira wellfield and surplus flows from Ain Maghara and Wadi Karak has also been considered [6].

Perhaps the most important factor governing the level of abstraction is the degree of hydraulic connection throughout the whole sedimentary sequence as this determines the amount of groundwater inflow (recharge) from the eastern highlands area as well the location and way in which discharge takes place from the deep aquifer system. As the production tests carried out on the individual APC wells were too small in scale or duration to provide the necessary information on the regional aquifer response, a groundwater model study was proposed as a means of improving the understanding of the regional aquifer system and how this may influence long-term abstraction from the Dhira wellfield.

As information on the hydrogeology of the deep aquifer in the region is very limited, it was proposed that the modelling study would be undertaken in two phases. The first phase of the groundwater model study, which is described in this report, has used the data obtained from the deep well drilling programme in conjunction with a review of information on wadi baseflow and springflow data to develop and test a conceptual model of the regional aquifer system and to make some initial predictions of the aquifer response to abstraction. The second phase of the modelling study will use the data obtained from monitoring the aquifer response to actual abstraction from the wellfield to improve both the representation and calibration of the model from which predictions of the long-term yield of the aquifer can be made with greater confidence.

1.2 Model Code

A commercial, PC-based groundwater flow model code AQUA (version 3.1) was selected for the study. This model offers speed and flexibility in testing alternative concepts regarding flow through the aquifer system where data are limited. It is a 3-D groundwater flow and contaminant transport model employing the Galerkin finite element method with triangular elements and can be operated in both steady-state and time-varying mode. The package contains pre- and postprocessors to facilitate the input and output of data as well as zoom and sub-grid facilities to allow any part of the model to be represented or displayed in more detail. Output can be in the form of tables, graphs or maps.

The model is capable of representing most of those hydrogeological features of relevance to the Dhira area, including two-layered leaky aquifer systems, spatial variations in transmissivity (T) and storage coefficient (S), barrier boundaries, time-varying abstraction and head-controlled springflows. Flows at defined boundaries (such as the amount of recharge crossing the Dhira escarpment) can also be calculated by the model. Drawdown predictions at the individual production wells have to be adjusted to include well losses and partial penetration effects.

2. REPRESENTATION OF THE AQUIFER SYSTEM

2.1 Hydrogeological Features of the Region

The geology of the region has been mapped in some detail [7,8,9]. Figure 2.1 shows the main features of the region together with major faults and other geological structures, the outcrop areas of the Kurnub-Um Ishrin aquifer system (early Cretaceous) and the location of the APC production wells. A generalised east-west section is shown in Figure 2.2. The northern part of Edh Dhira in which the wellfield is located has an area of about 15 km^2 and extends from Wadi Ibn Hammad to Wadi Karak.

Edh Dhira comprises a low westwards sloping plateau some 15 km long by up to 5 km wide. It rises from about -350 mAD at the foot of the Haditha escarpment in the west, which marks the Dead Sea Fault, to about -150 mAD at the foot of the main (Dhira) escarpment in the east, which marks the Dhira Fault/Dhira monoclinal fold. East of the main escarpment, the eastern highlands rise steeply to nearly 1000 mAD. The main escarpment extends from Wadi Issal in the south to the Siwaqa Fault, which forms the northern boundary of Edh Dhira near Wadi Ibn Hammad.

Underlying Edh Dhira is a thick sequence of limestones, shales and sandstones that have been folded into an asymmetrical syncline plunging southeast at about 10°. The top of the Kurnub Sandstone Formation occurs at about 500 mbgl at the northern end of the Dhira syncline and at 1500 mbgl or more beneath a thick sequence of younger sediments in the southern part of Edh Dhira. An extremely thick sequence of Pleistocene Lisan marls and evaporites underlies the Lisan Peninsula to the west of the Dead Sea Fault.

An outline description of the hydrogeology of north Dhira area was prepared as part of a study to locate suitable sites for the new APC wells [2]. There are two main aquifer systems in the area: a shallow, limestone aquifer system of the Belqa-Ajlun groups and a deep sandstone aquifer of the Kurnub-Um Ishrin formations. These are separated by a thick sequence of shales (the Fuhays/Hummar/Shu'ayb formations) and the Burj Dolomite Shale Formation separates the deep aquifer from the underlying Salib Arkose aquifer.

The shallow aquifer is partly semi-karstified and has unconfined (water table) conditions. It is present beneath Edh Dhira and to the north of the Siwaqa Fault, but has been largely removed by erosion in the middle reaches of the Wadi Ibn Hammad and Wadi Karak above the main escarpment.

The deep aquifer forms a single, confined aquifer system some 450 m thick. The Um Ishrin Formation extends throughout the region, but the Kurnub Sandstone Formation has been removed by erosion along the coastline north of Haditha, along the Wadi Mujib and Wadi Wala some 15 km north of Edh Dhira, in the deeply incised middle reaches of the Wadi Ibn Hammad and Wadi Karak above the main escarpment, and to the south of the Dhira Fault. In the Wadi Issal just to the south of Edh Dhira, where erosion has exposed the Burj Dolomite, groundwater flow is restricted mainly to the underlying Salib Arkose.

The sequence is affected by numerous faults.The Dhira Fault, which extends along the main escarpment south of Wadi Karak, is considered to form a barrier to groundwater flow, but in any case both the Kurnub and Um Ishrin formations have been severely eroded along this part of the main escarpment. As the deep aquifer in the southern part of Edh Dhira is isolated by faulting and erosion from the sources of recharge in the eastern highlands, it is likely to have poor quality water and low hydraulic gradients, especially as groundwater movement will be restricted by the considerable depth of the Kurnub Sandstone. In contrast, the deep aquifer continues across the Dhira monoclinal fold between Wadi Karak and the Siwaqa Fault and enables groundwater in the deep aquifer to enter north Dhira area from the eastern highlands.

The NNE trending Dead Sea Fault along the western boundary of Edh Dhira comprises a series of faults. Geophysical evidence suggests that the main faultline is about two kilometres west of the Haditha escarpment. However, the geological sequence underlying Ghor Mazra-Ghor Haditha immediately west of the Haditha escarpment is uncertain since it is obscured by younger deposits. There is some geophysical evidence to suggest that both the shallow and deep aquifer systems are present at a relatively shallow depth beneath Ghor Mazra-Ghor Haditha. However, this fault is considered to form a barrier to groundwater flow at the Haditha escarpment, which has been taken as the western limit of the regional Kurnub-Um Ishrin aquifer system.

The Siwaqa Fault extends NE from the Dead Sea Fault at Ain Maghara as far as the Amman Highway where it forms a partial barrier to groundwater flow in the shallow limestone aquifer system represented by a drop in head across the fault of about 100 m [10]. The Siwaqa Fault is thought to have a similar throw in the north Dhira area bringing the Fuhays/Hummar/Shu'ayb shales against the Kurnub Sandstone to form a barrier to groundwater flow in the Kurnub aquifer. If so, then the Siawaqa Fault may form a boundary between the Mujib and Ibn Hammad-Karak groundwater systems and influence the direction of groundwater flow. Ain Maghara emerges from the Wadi Sir Limestone aquifer where the Siwaqa Fault intersects the Dead Sea Fault and several smaller NW-SE trending faults.

2.2 Water Levels

The four APC wells provide the only water level data available for the deep aquifer in the Dhira-Karak region, and even these may be influenced by the depth of penetration of each well and the well location in respect to local fault blocks. All of the Dhira wells have flowing artesian conditions with heads ranging from just above ground level at TA2 to about 133 magl at TS1D. The water level data from TA1 and TS1D indicate that groundwater contours approximately parallel the Siwaqa Fault and that the hydraulic gradient is about 1:30.

With such limited information, the regional water level configuration is rather conjectural making it difficult to assess the reliability of the steady-state model calibration. Nonetheless, an extrapolation of the contour trend and hydraulic gradient indicated by the water level data from the Dhira wells produced water level elevations consistent with the lowest point of the Kurnub Sandstone discharge area in the Wadi Ibn Hammad (c. -90 mAD) and the estimated water level elevation of Ain As Salkh (-320 mAD), although the lowest elevation of the Kurnub Sandstone outcrop in the Wadi Karak (about -80 to -120 mAD) is not consistent with this trend (it may well be that the main discharge point from the deep aquifer in both the Wadi Ibn Hammad and Wadi Karak occurs further upstream at the NE trending Sinan Fault which crosses both wadis). It would seem that the NW direction of groundwater flow is maintained over a wide area but is modified to a south-north direction at the Dead Sea Fault and to a more east-west direction in the Mujib catchment. The shoreline (taken to be the recent historical level of about -400 mAD) along the northern outcrop is considered to be the base level for the regional aquifer system.

The water level configuration of the shallow limestone aquifer system in the eastern highlands is fairly well known since this aquifer is widely exploited throughout Jordan [10]. However, water level data for this aquifer system in north Dhira are available from only two wells (IH1 and IH3) and from spring elevations (Ain Magahara, Ain Sikkin and Ain Merowhe), which indicate that water levels range from -300 to -350 mAD, or some 125 to 175 m lower in elevation than the artesian head of the deep aquifer in the western part of north Dhira.

2.3 Recharge and Discharge

The deep aquifer in north Dhira is recharged by lateral inflow from the east or south-east moving towards the Dead Sea, the ultimate base level of this aquifer system. The source of this recharge is still uncertain: it may be derived from the deep percolation of precipitation through fracture zones in the eastern highlands [11] and/or from much older water originating from wetter (pluvial) periods up to 35000 years ago moving from the outcrop area in Southern Jordan [15]. Neither source is likely to produce significant seasonal or annual variations in recharge, partly because of the large regional extent of the deep aquifer system.

The amount of recharge entering the deep aquifer in the northern part of Dhira as lateral inflow across the 6 km length of Dhira monocline will be governed mainly by the head gradient of the aquifer system and discharge losses along the wadi outcrop areas above the main escarpment. Previous estimates of the amount of recharge vary from 1.1 to 1.9 $Mm^3/y/km$ width of aquifer [12,15] which would indicate that recharge into north Dhira ranges from 6.6 to 12.2 Mm^3/y (750 to 1300 m^3/h) [2]. However, this does not allow for discharge losses from the outcrops of the deep aquifer along wadis Ibn Hammad and Karak upstream of the Dhira monocline.

Wadi baseflows, spring discharges and aquifer data are brought together in Annex A in order to estimate discharge losses from the deep aquifer and potential recharge into the north Dhira area. All of the major wadis have a perennial baseflow, although the proportion of this baseflow contributed by each aquifer system is uncertain. Available baseflow data suggests that perhaps 90% or more of the baseflow of Wadi Mujib and Wadi Ibn Hammad and about 25% of the flow of Wadi Karak is derived from the deep aquifer, although further surveys are required to confirm this. The Wadi Mujib is an important control on the regional groundwater flow pattern and discharge from the deep aquifer, but is considered to be separate from the Ibn Hammad-Karak system.

Whilst the baseflow of Wadi Mujib drains directly to the Dead Sea, the baseflows (and floodflows) of wadis Ibn Hammad and Karak infiltrate into the wadi gravels and the limestone aquifer underlying north Dhira. The estimated total baseflow of Wadi Ibn Hammad and Wadi Karak at the main escarpment is 12.35 Mm^3/y (1410 m^3/h), which is not dissimilar to the combined discharge of Ain Maghara and Ain Sikkin of about 10.64 Mm^3/y (1215 m^3/h) given that this takes no account of evaporation losses, possible lateral underflow across the Haditha escarpment in the wadi gravels and coarse Lisan deposits and uncertainties in the accuracy of the baseflow measurements. The shallow limestone aquifer in north Dhira is not connected to its main recharge area in the eastern highlands due to erosion in the middle reaches of Wadi Ibn Hammad and Wadi Karak.

The amount of groundwater flow in the deep aquifer over a 6 km width of aquifer updip of the wadi outcrops is estimated to be 12.88 Mm^3/y (1470 m^3/h). After subtracting the discharge from this aquifer in Wadi Ibn Hammad and Wadi Karak above the main escarpment of 8.5 Mm^3/y (970 m^3/h), the net recharge continuing into north Dhira across the Dhira monocline is 4.38 Mm^3/y (500 m^3/h). This amount is similar to a flow of 3.77 Mm^3/y (430 m^3/h) based on the Darcy flow equation using data obtained from the pumping test programme (see Annex A). These estimates of recharge contain uncertainties but are reasonably consistent with each other.

The location and manner in which discharge takes place from the deep aquifer system underlying north Dhira is unclear, but it seems unlikely that lateral outflow occurs across the Dead Sea Fault into the Mazra-Haditha area. Alternative possibilities include:

- discharge from the outcrop of the deep aquifer along the shoreline north of Haditha.
- upward movement through fractures or by more widespread upward leakage through the Fuheis/Hummar/Shu'ayb shales.

The outcrop of the Um Ishrin Formation along the shoreline north of Haditha would be considered to be a natural discharge point for the deep aquifer since water levels would be at sea level at the coast and therefore lower than those in the wellfield. However, except for a few minor springs, there is no evidence of significant discharge in this outcrop area (see Annex A), unless the discharge is more diffuse or occurs offshore. The Siwaqa Fault could also prevent significant groundwater flow from north Dhira from reaching the coastal outcrop.

The piezometric surface of the deep aquifer is about 125 to 175 m above that of the water table in the shallow aquifer, which indicates an upward potential for groundwater flow. Such a large difference close to the Dead Sea Fault would suggest that there is a very limited hydraulic connection between these aquifer systems. However, despite the generally low permeability of the Fuhays/Hummar/Shu'ayb shale formations, the large potential head difference over the area of north Dhira could still result in significant upward leakage. Indeed, studies of the deep aquifer on the western side of the Dead Sea indicate that upward leakage can take place through these shales [18]. In addition, more intensive fracturing associated with the Dead Sea Fault zone and/or NW-SE faults would increase the vertical permeability and enhance the degree of local hydraulic connection between the aquifer systems in north Dhira.

The flow of Ain Maghara appears to exceed the potential recharge from the baseflow of Wadi Ibn Hammad by 180 m^3/h (see Annex A). The difference could be derived by upward leakage from the deep aquifer in the area of the spring. If so, abstraction from the wellfield would have an effect on the flow of Ain Maghara, an important local source of irrigation. The similarity of the water chemistry of Ain Maghara to that of the new APC wells at Dhira [5] and the baseflow of Wadi Ibn Hammad [13] suggest a common origin. However, this does not necessarily suggest a direct hydraulic connection between the deep aquifer and Ain Maghara in north Dhira since the flow of Ain Maghara is linked to the baseflow of the Wadi Hammad which is derived mainly from the deep aquifer [5].

2.4 Aquifer Characteristics

Information on the aquifer characteristics of the Kurnub-Um Ishrin aquifer system is very limited. Short pumping tests of 1 to 2 days duration were carried out in 1985 at a rate of 110 m^3/h on three wells penetrating the Kurnub aquifer in Wadi Mujib and Wadi Hassa and gave specific capacities of 1.5 to 10 $m^3/h/m$ [16], whilst similar values of 0.7 to 3.6 $m^3/h/m$ were derived from the pumping tests carried out on the four APC production wells in north Dhira after 3 weeks abstraction at 125 to 240 m^3/h [5]. All of these specific capacity values are rather low and indicate correspondingly low transmissivities for the deep aquifer (high pumping rates of more than 100 m^3/h are only achieved because of the large available drawdowns).

The pumping tests carried out on the APC wells in north Dhira provide the only estimates of the transmissivity (T) of the Kurnub Sandstone aquifer within the model area [5]. T values of about 175 m^2/d were derived from an analysis of the early flow data from wells TA1 and TS1D. These indicate a permeability (K) of about 1 m/d similar to other wells penetrating the Kurnub aquifer elsewhere in Jordan [2], although the higher T values from TA1 and TS1D may be due to more intensive fracturing associated with the Dead Sea Fault. In contrast, low T values ranging from 25 to 50 m^2/d (K 0.17 to 0.33 m/d) were derived from the early time-drawdown data at TA6 and from the late flow data from TA1 and TS1D. Anisotropic aquifer conditions and/or barrier boundary effects were also shown by the test data. As the range in T values derived from the pumping tests may be due to local factors, such as fracturing or barrier boundaries, an intermediate value of 100 m^2/d was adopted as being representative of the regional system.

The Kurnub Sandstone aquifer constitutes only about one-third of the thickness of the deep aquifer system. Consequently, the transmissivity of the whole aquifer system will be greater than that indicated by the pumping tests, except in the areas of high relief where the Kurnub Sandstone is only partly saturated. Even so, the active zone of groundwater circulation in north Dhira may be restricted to the upper part of the aquifer system (ie. the Kurnub Sandstone aquifer).

A storage coefficient (S) value of 0.0004 was obtained from the pumping test on well TA2. This is a typical value for a confined aquifer. It was assumed that this value was representative of the confined areas of the Kurnub-Um Ishrin aquifer system, although the same S value was also adopted for the partly saturated sequence above the main escarpment. A higher value of 0.04 (4%), a fairly typical value for consolidated sandstones, was adopted for the unconfined outcrop areas in the north and along the major wadis east of the main escarpment. Figure 2.3 shows the distribution of storage coefficient used in the model.

The possibility of upward leakage from the deep aquifer to the shallow aquifer was examined during the steady-state calibration of the model. Potentially favourable conditions for such leakage occur adjacent to the Dead Sea Fault within a small area of about 2 km^2 between Ain Magahara and the NW trending fault at TS1D and eastwards as far as TA1 where the deep aquifer is more fractured and occurs at its shallowest depth. A typical value for the permeability of a shale sequence would be 0.01 m/d. This was divided by the total thickness of the Fuhays/Hummar/Shu'ayb formations and the Naur Limestone of about 300 m to obtain an initial value for the leakage coefficient of 0.3×10^{-9} m/s.

2.5 Conceptual Model

Seldom are there sufficient data to fully describe a particular hydrogeological setting. Consequently, preparatory work for a groundwater flow model includes the development of a 'conceptual model' that describes those hydrogeological features considered to have the most influence on the pattern of groundwater flow. This is then represented and tested by the computer model and adjusted if necessary.

Information on the hydrogeology of the region is very limited, partly because much of the area is inaccessible. As no abstraction yet takes place from the deep aquifer in the region, the system can be considered to be in a natural, steady-state (or equilibrium) condition.

Based on the outline description given in the preceding sections and the review of recharge given in Annex A, the following simplifying hydrogeological assumptions were used as a starting basis for the model design:

* recharge of the deep aquifer system takes place as lateral flow from the SE and E and is mainly head controlled;
* the low elevation of the northern outcrop area dictates the general NW direction of groundwater flow throughout the regional deep aquifer system, but more especially in the Mujib catchment;
* the major faults (Dead Sea, Dhira and Siwaqa faults) act as barriers to groundwater flow;
* hydraulic connection between north Dhira and the eastern highlands only occurs across the Dhira monocline between Wadi Karak and Wadi Ibn Hammad;
* the Wadi Mujib catchment is separated by the Siwaqa Fault from the Wadi Ibn Hammad-Wadi Karak catchments;
* leakage from the deep aquifer takes place in the area of Ain Maghara, although most of the flow of Ain Maghara and all of the flow of Ain Sikkin is linked to the recharge and aquifer characteristics of the shallow aquifer system (Ajlun and Belqa Groups);
* a zone of higher transmissivity borders the Dead Sea Fault north of Ain Sikkin;
* low transmissivities occur in the eastern part of north Dhira where the aquifer lies at greater depth than on the flanks of the Dhira syncline and these decrease southwards as the aquifer dips to even greater depths;
* intermediate transmissivities occur elsewhere in the region, except where the aquifer thickness is reduced in the outcrop areas;
* the aquifer is confined, except in the outcrop areas along the coastline to the north and in the wadis Ibn Hammad and Karak above the main escarpment.

The initial distribution of fixed boundary heads and transmissivity values used in the model were based mainly on information obtained from the Dhira wellfield.

2.6 Model Area, Boundary Conditions and Nodes

The multiple cone of depression resulting from the planned rate of abstraction from the Dhira wellfield (700 m^3/h) could influence water levels over a much larger area than north Dhira itself because of the confined nature of the deep aquifer in north Dhira. Fixed head boundary conditions also need to be placed sufficiently far from the wellfield so as not to unduly influence drawdown predictions. Hence, the model domain needed to include hydrogeological features of the region that might influence (or be influenced by) abstraction from the wellfield. For example, drawdowns could increase when the cone of depression intersects major geological boundaries and wadi baseflows could be reduced if water levels decline in the wadi outcrop areas.

The model described in this report is version 'DHIRALCL', which extends from grid lines 198E to 208E and from 73N to 85N. The area of the Kurnub aquifer represented by the model is about 70 km2 extending from the Dead Sea Fault to the lower part of the wadi outcrops in wadis Ibn Hammad and Karak and from the northern coastal outcrop to the Wadi Karak. The southern part of Dhira, where limited groundwater flow is thought to take place, and the area south of Wadi Dhira, where the Kurnub Sandstone has ben largely removed by erosion, were not included.

The model has a basic nodal separation of 500 m but additional nodes were placed in north

Dhira where greater accuracy was required and along faults where steeper gradients are likely to occur. Labelled nodes were placed at the APC wells and at the lowest elevation of the top of the Kurnub Sandstone in the wadi outcrop areas. The total number of nodes and elements were 382 and 715, respectively.

As most of Edh Dhira lies below normal sea level (Aqaba datum), heads in the model were expressed relative to the approximate level of the Dead Sea, ie. -400 mAD, which was taken as the baseline for the model heads. For example, an actual water level of -100 mAD becomes 300 m in the model.

Fixed head boundaries were placed along the north, east and southern edges of the model and fixed head nodes were also incorporated at Ain As Salkh and along the Dead Sea shoreline bordering the northern outcrop. These were based on the infered water level contours derived from the APC water level data. The maximum fixed head in the south-east was 410 m reducing to 200 m in the north-east, 300 m in the south-west and to 0 m along the shoreline of the northern outcrop.

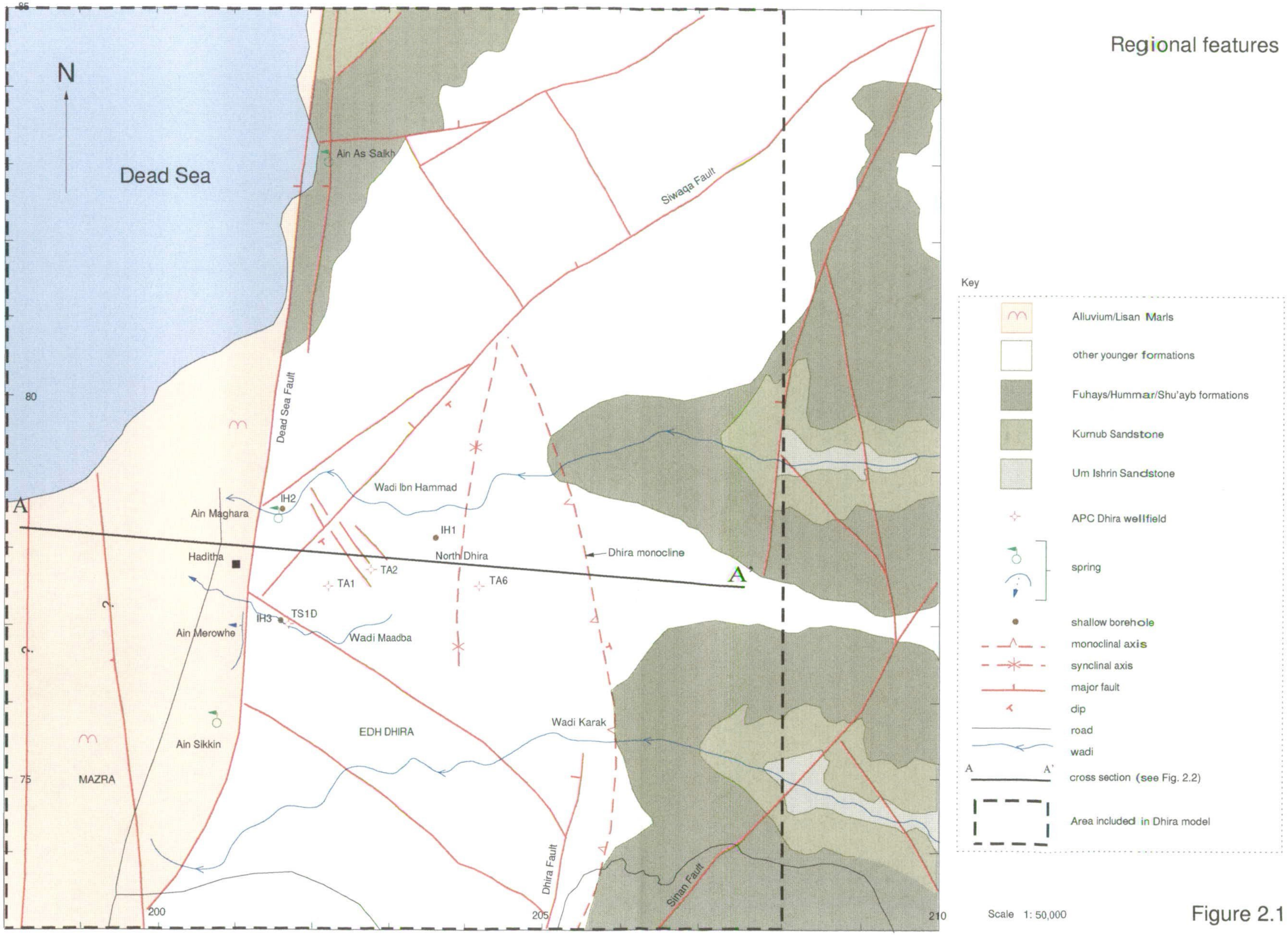
Three flow-calculation 'boundaries' were introduced into the model, as shown in Figure 2.4: along the Dhira monocline between the wadis Karak and Ibn Hammad to quantify the amount of flow passing from the eastern highlands into the north Dhira area (boundary B2); around the area of upward leakage (boundary B3); and also around the northern outcrop to show the amount of discharge leaving the aquifer system (boundary B1).

Figure 2.5 shows the transmissivity distribution used in the model. The regional average was assumed to be 100 m^2/d. A higher T value of 150 m^2/d was used to represent more intensive fracturing in a zone some 500 m wide adjacent to the Dead Sea Fault from Ain Sikkin to the northern outcrop where the Kurnub Sandstone occurs at relatively shallow depth in association with major faults. Low values ranging from 25 to 75 m^2/d were used in the deep parts of the aquifer and in the eroded outcrop areas. A zero transmissivity representing a no-flow boundary was placed along the line of the Dead Sea Fault forming the western boundary of the model. The Siwaqa and Dhira faults were also given a very low transmissivity (5 m^2/d) to create 'internal' partial boundaries.

The flow of Ain Maghara and Ain Sikkin were not included in the model as the characteristics of the shallow limestone aquifer (Belqa Group and upper part of the Ajlun Group) are not represented in the model. However, it is possible to represent the head distribution of the shallow aquifer to enable leakage to take place between the shallow and deep aquifer when combined with a leakage coefficient of the intervening aquiclude and the head distribution of the deep aquifer. It was assumed that significant upward leakage only takes place adjacent to the Dead Sea Fault in the area of greatest fracturing between TS1D and Ain Maghara. The elevation of the water table in the shallow aquifer within the area of leakage was taken to be a constant value of 85 m (model elevation), or 150 m below the average piezometric head of the deep aquifer in the same area, and a constant leakage coefficient was also applied.

Natural discharge from the aquifer system, such that from the deep aquifer along the wadi outcrops above the escarpment, can be represented as either 'abstraction' nodes or as a rate of flow related to the head ('spring' nodes). However this was not included in the model as neither the distribution of outflow along the wadis or how this flow is related to changes in head are known.

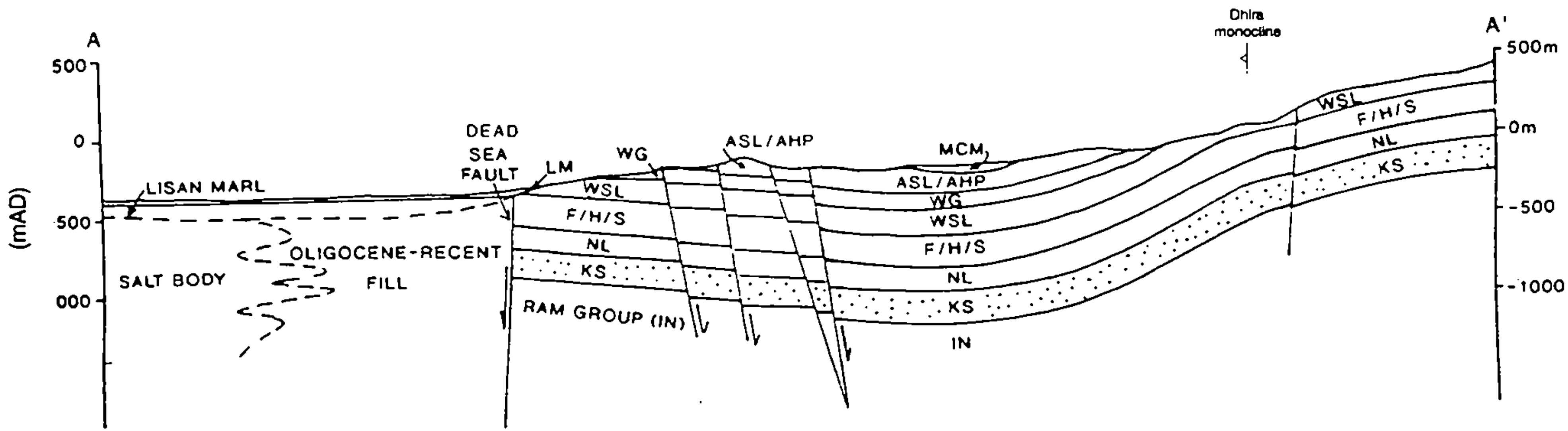
Regional features



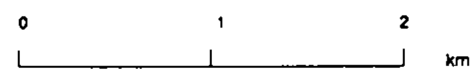
Scale 1: 50,000

Figure 2.1

Regional Section A - A'



DCu		Dana Conglomerate, upper	
DCl		Dana Conglomerate, lower	
URC		Um Rijam Chert-Limestone	BELQA GROUP (B) (mostly Upper Cretaceous)
MCM		Muwaqqar Chalk-Marl	
AHP		Al Hisa Phosphorite	
ASL		Amman Silicified Limestone	
WG		Wadi Ghudran Formation	
	DC	Dhiban Chalk	
	Tf	Tafilah Member	
	MC	Mujib Chalk	
WSL		Wadi Sir Limestone	AJLUN GROUP (AJ) (Upper Cretaceous)
F/H/S		Fuheis/Hummar/Shuayb, undifferentiated	
NL		Naur Limestone	
KS		Kurnub Sandstone Group	
IN		Um Ishrin Sandstone	RAM GROUP (R) (Cambrian)
BDS		Burj Dolomite-Shale	



SAGP/IH, 1991 [2]

For line of section see Figure 2.1

Figure 2.2

Model Storage and Leakage Co-efficient (m/s)

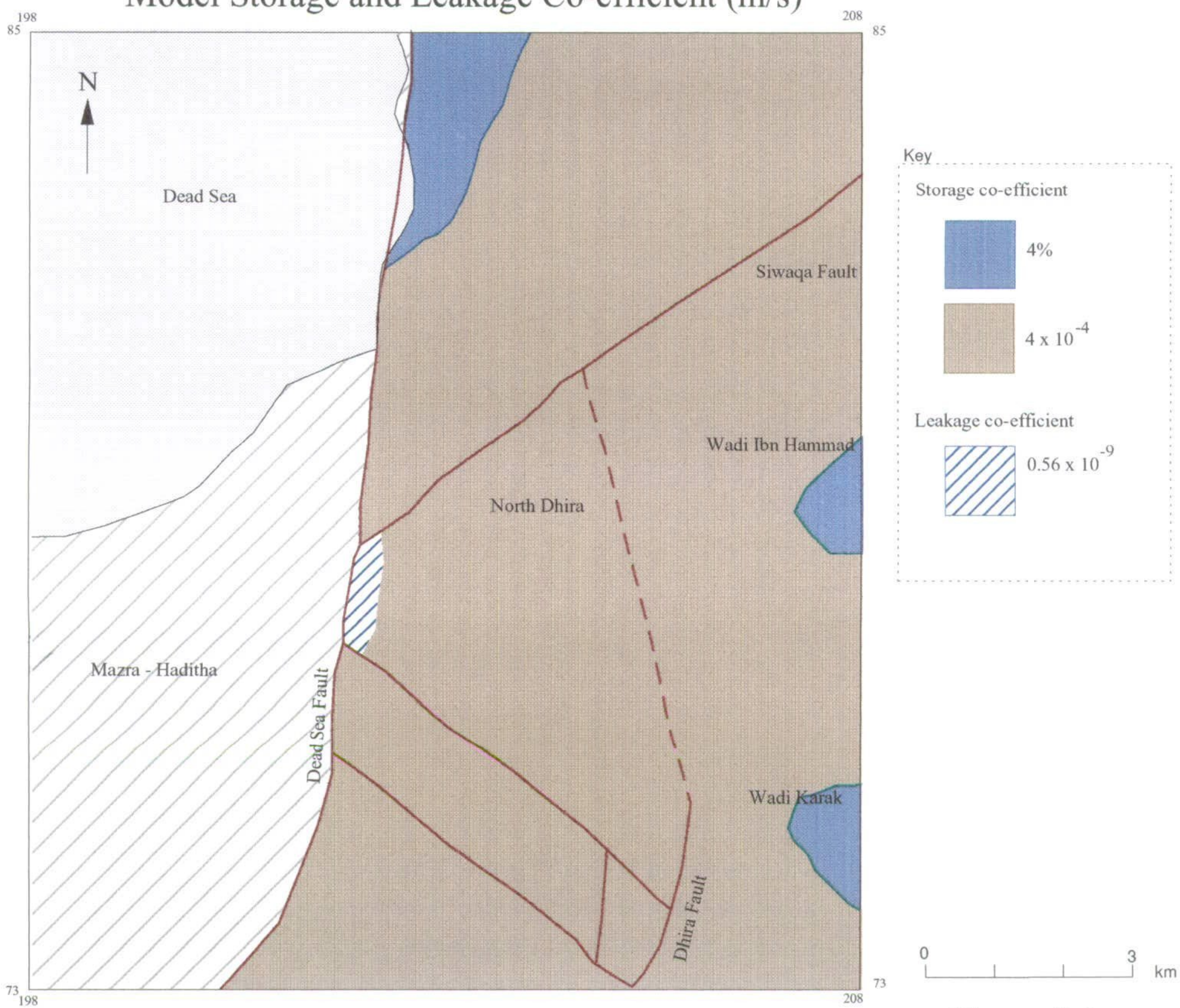


Figure 2.3

Model Flow Calculation Boundaries

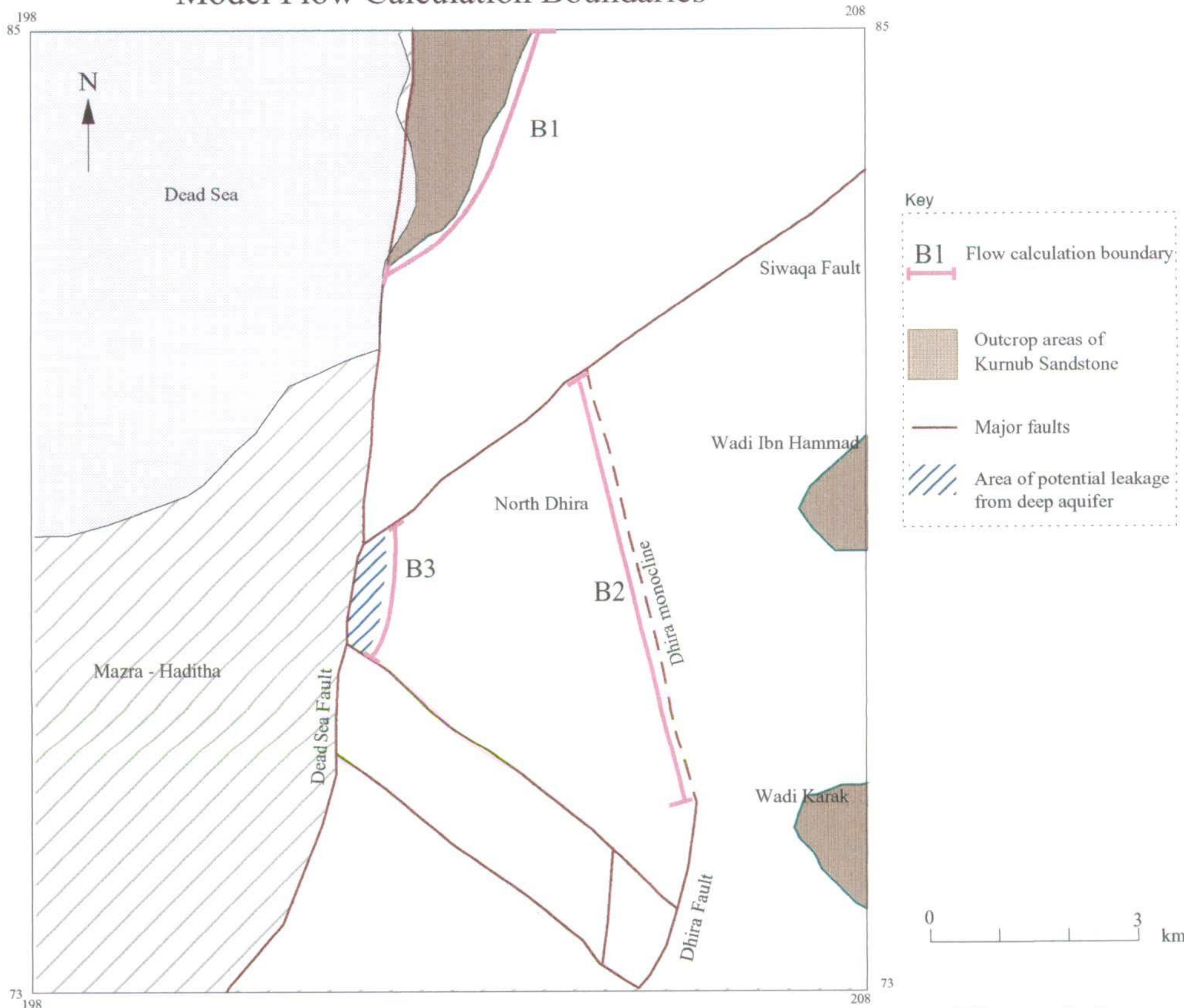


Figure 2.4

Model Transmissivity ($m^2 d$)

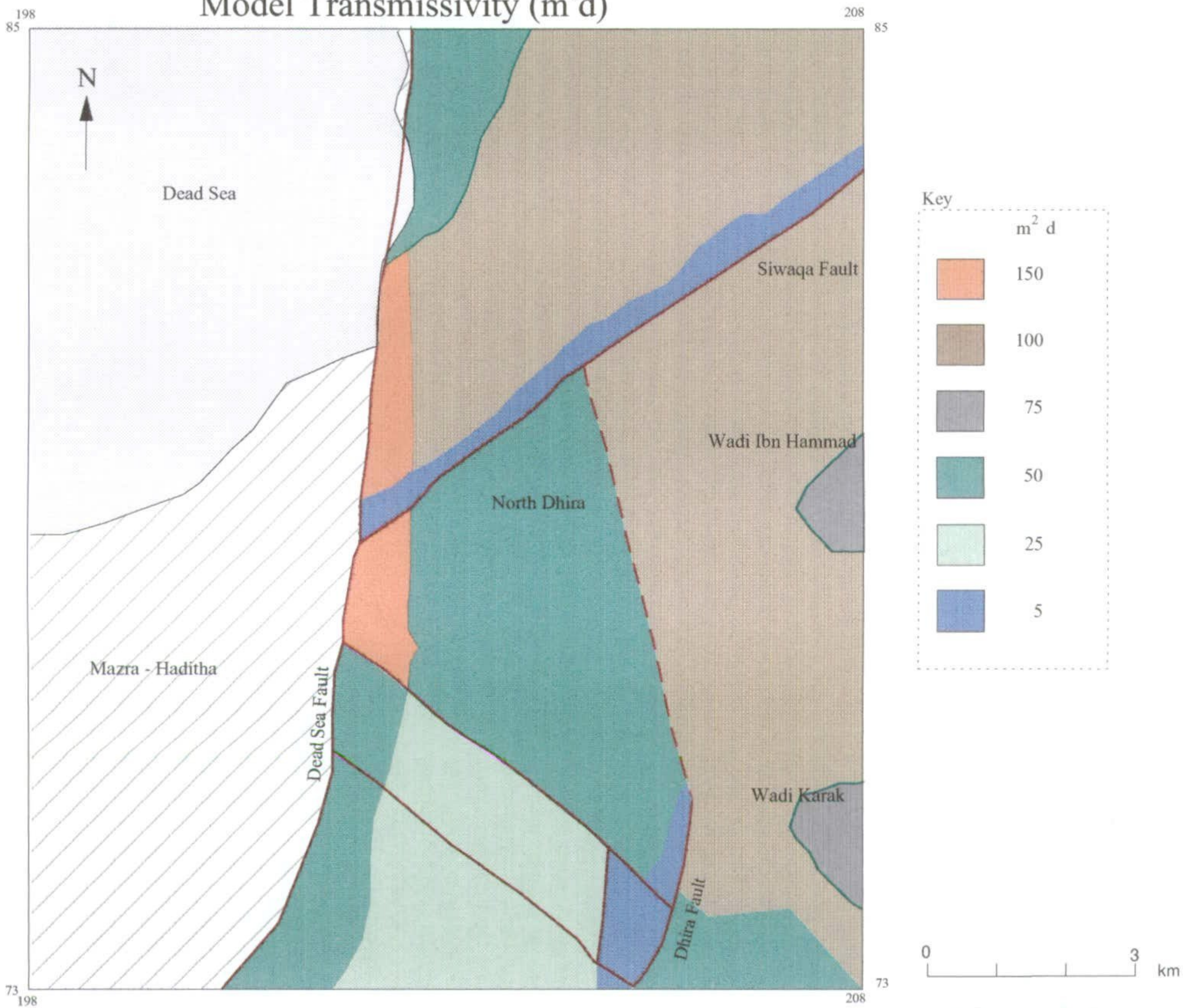


Figure 2.5

3. STEADY-STATE MODEL CALIBRATION AND VERIFICATION

3.1 Calibration of the Steady-state Model

To calibrate the steady-state model initial values for the boundary conditions and transmissivity were adjusted until an acceptable match was achieved between the model head contour pattern and that of the inferred water level map, with greater emphasis being placed on the wellfield area. Certain hydrogeological features of the aquifer system, such as the effect of the Siwaqa Fault, were also examined as part of the model calibration.

The rest water level elevations of the APC wells in north Dhira, as given below, with their model equivalent head values, were used as control points to guide the calibration of the steady-state model. The water level at TA2 is not consistent with those from the other wells. It is suspected that the true water level for TA2 may be higher than that recorded at the time of the pumping test when there was a small artesian flow, although a lower water level may occur at this site due to partial penetration or upward leakage. Consequently, less emphasis was placed on obtaining an accurate calibration at this well.

	TS1D	TA1	TA2	TA6
Ground level mAD	-298	-232	-183	-163
Rest water level mAD	-165	-165	-183	-122
Model equivalent m	235	235	217	278

Various trials were first carried out with a simplified T distribution to refine the initial values along the fixed head boundaries. These trial runs indicated that the magnitude of the regional T values has only a limited effect on heads in the wellfield area compared to the values of the boundary heads, especially those along the eastern boundary. However, the amount of flow through the aquifer (as calculated at the flow calculation boundaries) depends on the accuracy of the transmissivity values adopted since the flow is directly proportional to the transmissivity with fixed head boundary conditions.

A more detailed T distribution was then introduced. This included a higher T of 150 m^2/d along the Dead Sea Fault in the area of Ain Maghara to represent a zone of more intensive fracturing, and values of 50 and 25 m^2/d in the deeper part of the aquifer south of the NW trending faults in central Dhira. The steady-state model heads at the Dhira wells with this distribution are compared to the observed heads in Table 3.1a (non-leaky situation).

Upward leakage in the TS1D-Ain Maghara area was then introduced with a model head in the upper aquifer of 85 m and an initial leakage coefficient value of $0.3x10^{-9}$ m/s. This caused the water levels in the wellfield area to fall by an average of about 10 m compared to the previous simulations without upward leakage.

The transmissivity along the whole length of the Siwaqa fault was then reduced to a nominal value of 5 m^2/d to represent the suspected barrier effect of this fault. This raised heads in the wellfield area by 20 to 25 m compared to the previous run, but produced a head change across the fault of about 100 m (the same as that observed at its north-eastern extremity [10]) as well as a more pronounced east-west direction of groundwater flow in the area north of this fault.

Trials were then undertaken with higher leakage values in the area of upward leakage. A leakage value of $0.5x10^{-9}$ m/s produce a very close fit to the observed heads at TA1, TA6 and TS1D as given in Table 3.1b (leaky situation). None of the calibration runs produced an acceptable fit at TA2 or at the Wadi Karak, possibly because of underestimates in the 'observed' head at these locations.

The amount of groundwater flow crossing the flow calculation boundaries is also included in Table 3.1. The total groundwater flow through the system (B1) decreased from 6.72 to 5.15 Mm^3/y, a reduction of 175 m^3/h (1.57 Mm^3/y) when the leakage zone and a low T along the Siwaqa Fault were introduced, mainly due to the upward leakage. About 45% of the total flow, or 260 m^3/h (2.3 Mm^3/y), passes across the Dhira monocline into the wellfield area (B2), which is significantly less than that estimated from the water balance and Darcy equation of 500 m^3/h (4.38 Mm^3/y) and 430 m^3/h (3.77 Mm^3/y), respectively (see Annex A). About 175 m^3/h (1.54 Mm^3/y) enters the area of upward leakage (B3), which is almost exactly the same as the difference between the flow of Ain Maghara and the availability of potential recharge from the Wadi Ibn Hammad of 180 m^3/h (1.58 Mm^3/y).

It should be recognised that the calibration of a groundwater model requires that at least one parameter (transmissivity, fixed heads, recharge etc) needs to be reasonably well known otherwise more than one combination of values may produce an equally acceptable fit. The values of these parameters and their distribution have been largely inferred from only limited data. In addition, the model is more sensitive to the boundary head values than to the transmissivity values, which influences the reliability of the recharge estimates. Nonetheless, the steady-state groundwater contour and flow pattern shown in Figure 3.1 and flows through the aquifer are consistent with the information available and the conceptual interpretation of the aquifer system.

On this basis, the model in its present, unverified form would have the following implications regarding the development and management of the water resources in the Dhira area:

* discharge from the deep aquifer in the eastern highlands contributes to wadi baseflows;
* the Siwaqa Fault separates the Ibn Hammad-Karak groundwater catchment from the Mujib groundwater catchment;
* groundwater flow (recharge) enters the north Dhira area across the Dhira monocline;
* the Dead Sea, Siwaqa and Dhira faults form barriers to groundwater flow;
* upward leakage appears to occur in a localised area adjacent to the Dead Sea Fault between TS1D and Ain Magahara, such that part (20%) of the flow of Ain Maghara may be derived from the deep aquifer underlying north Dhira;
* transmissivities are generally low in the north Dhira area and reduce southwards;
* a zone of higher transmissivity is present along the Dead Sea Fault north of TS1D.

These suggest that abstraction from the wellfield will produce large drawdowns and have an adverse impact upon wadi baseflows and Ain Maghara, which are the main source of local irrigation supplies. However, these preliminary conclusions need to be verified by monitoring data once the Dhira wellfield comes on-line.

3.2. Simulation of Pumping Test Results

A simulation of the production tests carried out on TA1, TA2 and TS1D [4,5] was undertaken to provide an preliminary verification of the model. The model was used in a time-varying mode with the distribution of storage coefficient values given in Section 2.4. However, it should be stressed that exact agreement between the model simulation results and those observed during each of the pumping tests would not be expected since the model represents the more regional features rather than the local aquifer conditions. The model drawdowns also have to be adjusted for well losses and partial penetration effects in order to be comparable with the drawdown observed in each production well. Details of the tests carried out on each production well are given in earlier reports [4,5].

3.2.1 TA2 Pumping Test

A pumping test was carried out on TA2 in November 1993 at an average rate of 186 m^3/h for 22.75 days. This was followed by a recovery test of about five days. The head response at TA1 and TS1D was recorded during the test. Barrier boundary or anisotropic aquifer conditions influenced the water level data at both TA1 and TS1D after about 10 days. The drawdown observed at TA2 was 115 m after 7 days and 120 m after 23 days of abstraction. A time-step of 2 days was used for the simulation.

The model drawdowns at TA2, TA1 and TS1D are compared to the test data in Table 3.2a for a pumping duration of 7 and 22 days. Adjusting the model drawdown for partial penetration effects of 8% and a well efficiency of 47% [5] produces a drawdown of 94 m after 7 days compared to an observed drawdown of 115 m, an underestimate of 21 m or 18%.

A more reliable comparison with the observed drawdowns is provided by the data from TA1 and TS1D since the drawdowns at these sites are not influenced by well losses. It was found that the model drawdown at TA1 overestimates that observed by about 30 to 40% whilst that at TS1D is overestimated by between 60 and 120%. These results are not sensitive to leakage as almost exactly the same results are obtained if the simulation is undertaken without the leakage area and a low T on the Siwaqa Fault. A decrease in T from 130 m^2/d to between 35 and 50 m^2/d was noted during the test on TA2 due to barrier boundary effects and/or anistropic aquifer conditions and since the transmissivity around TA2 remains constant in the model at the lower T value of 50 m^2/d throughout the simulation run, the model would be expected to produce greater drawdowns than those observed.

The flow across the Dhira escarpment showed an increase of 32 m^3/h during the simulated test indicating that about 17% of the abstraction was supported by increased recharge across the escarpment.

3.2.2 TS1D Long-term Flow Test

A model run was undertaken to simulate the long-term flow test carried out for 225 days at TS1D in 1991. Unfortunately, no other deep wells were available at the time of the test to serve as observation wells. The model was run using 30 day time steps for a period of 210 days at the minimum artesian flow rate recorded at the end of the test of 242 m^3/h (flow response to an imposed drawdown of 133 m, ie. zero pressure head), which was kept constant throughout the model run.

The model drawdown after 210 days was 79.25 m. Expressed as specific drawdown, this is equivalent to 0.0136 d/m^2, or 36% less than the actual specific drawdown of 0.0214 d/m^2 after 210 days. The well losses at TS1D are not known since a step-test was not carried out at this well, although the model drawdown indicates a well efficiency of 60% which is similar to the new wells. However, the smaller drawdown shown by the model may be due to using the minimum rate of flow as a constant throughout the model simulation, ie. the total quantity of water 'abstracted' in the model simulation was less than that abstracted during the test.

TS1D is located within the area of upward leakage in the model. The drawdown with the leaky condition was 6 m less than the non-leaky representation due to the constant head in the shallow aquifer.

3.2.3 TA1 Flow Test

A model run was undertaken to simulate the main flow test on TA1, which was carried out for 22.75 days at zero pressure head (constant drawdown of 63 m) in May 1993. The flow at the end of the test was 240 m^3/h. The head change observed at TS1D at the end of this test was 8 m. A time-step of 2 days was used in the model run.

The model simulation of this test produced a drawdown of 53.6 m at TA1 after 22 days, or 15% less than that observed. However, when adjusted for partial penetration effects of 7% and a well efficiency of 62% [5] this represents a drawdown of about 92 m, indicating that the model overestimates the drawdown at TA1. This could be due to using the longer term 'effective' T value after the barrier boundary and/or anisotropic conditions began to affect the data (see Section 3.2.1). This may also be the reason for the large drawdown of 31.8 m predicted by the model at TS1D, which was four times that observed during the test.

The model drawdown at TA1 is not affected significantly by leakage during the duration of the test as the drawdown is only about 1 m less than that with non-leaky conditions.

Table 3.1 Steady-state Calibration

(a) Non-leaky and moderate T on Siwaqa Fault:

	Model	Observed	Difference
TA1	237.3	235	+2
TA2	237.9	217	+21
TA6	269.4	278	-9
TS1D	239.7	235	+5
WIH	297.2	310	-13

Dhira escarpment (B2)	310 m^3/h (2.70 Mm^3/y)
North-west outcrop (B1)	765 m^3/h (6.72 Mm^3/y)

(b) Leaky and low T on Siwaqa Fault:

	Model	Observed	Difference
TA1	234.3	235	-0.7
TA2	241.8	217	+24.8
TA6	277.3	278	-0.7
TS1D	234.2	235	-0.8
WIH	303.6	310	-6.4

Dhira escarpment (B2)	260 m^3/h (2.30 Mm^3/y)
Leakage zone (B3)	175 m^3/h (1.54 Mm^3/y)
North-west outcrop (B1)	590 m^3/h (5.15 Mm^3/y)

Notes: Observed heads are adjusted to the model datum of -400 mAD.

Table 3.2 Comparison with Pumping Test Results

(a) **TA2**

	Model	Observed
Drawdown (m)		
After 7 days:		
TA2	40.7	115.0
TA1	8.4	6.1
TS1D	4.7	2.2
After 22 days:		
TA2	50.8	120.0
TA1	17.9	14.0
TS1D	13.5	8.5

(b) **TS1D**

After 210 days at constant 242 m^3/h (min flow rate)

	Model	Observed
Drawdown (m)	79.2	[133][1]
Specific drawdown d/m^2	0.0136	0.0214

(c) **TA1**

After 22 days at constant 240 m^3/h (min flow rate)

	Model	Observed
TA1:		
Drawdown (m)	53.4	[63.3][1]
Specific drawdown d/m^2	0.0093	0.0110
TS1D drawdown (m):	33.0	8.0

Notes: - model drawdowns exclude well losses and partial penetration effects.

[1] zero pressure head (constant imposed drawdown at TA1 and TS1D)

Steady-state Contours and Flows

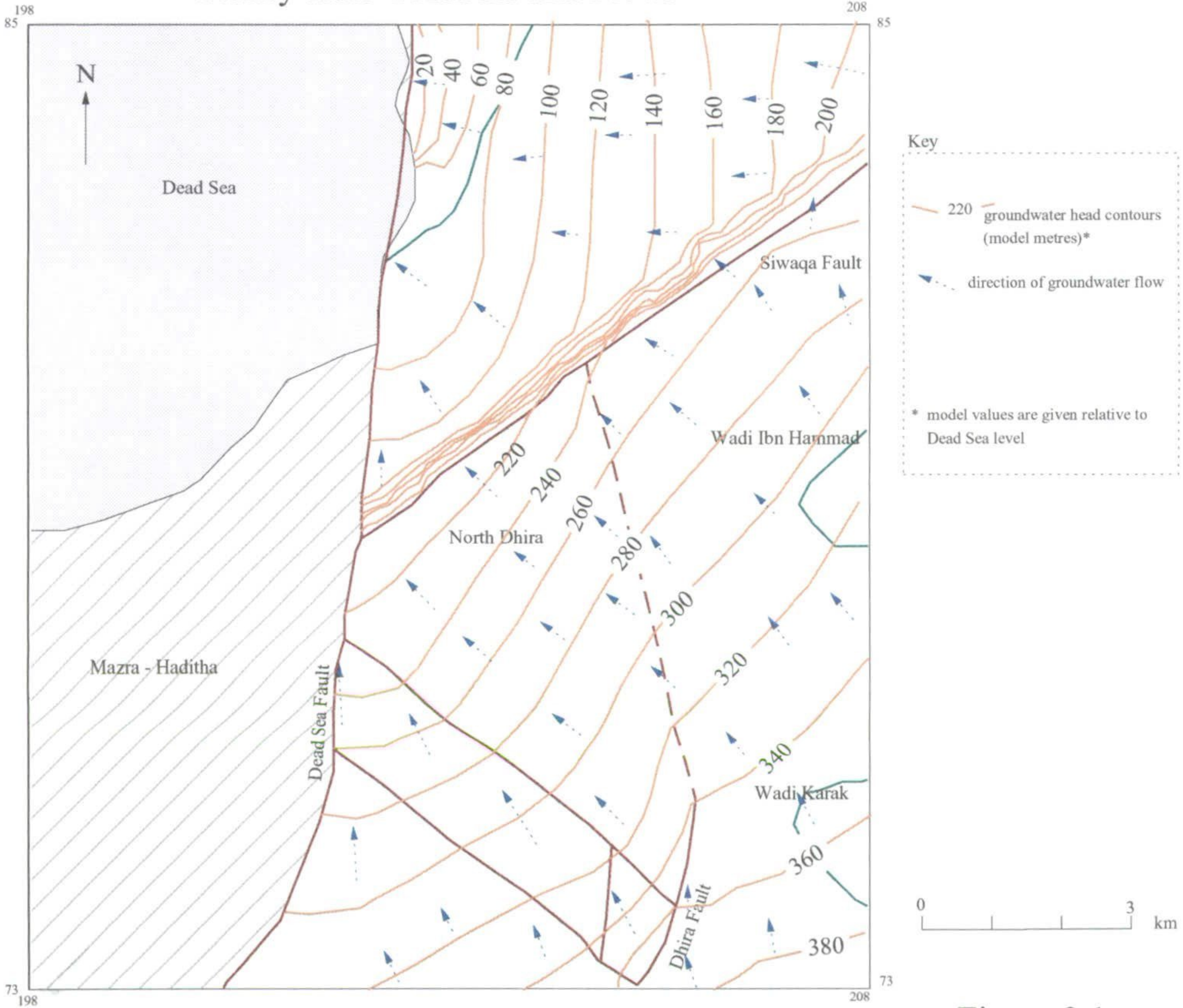


Figure 3.1

4. INITIAL MODEL PREDICTIONS

The model was used to simulate abstraction from the Dhira wellfield to provide an indication of the more regional effects of abstraction than would be otherwise be possible from the pumping test data alone. Only two scenarios were examined at this time since the model cannot be properly verified until monitoring data become available. The model was used in a time-varying mode to examine the aquifer response after 10 years of abstraction using time-steps of 180 days.

4.1 Abstraction Schedules

The planned rate of abstraction from the Dhira wellfield is 700 m^3/h, and this was assumed to comprise an average of 200 m^3/h from each of the three new wells and an average artesian flow of 100 m^3/h from TS1D. This was represented as **Schedule A**.

Long-term drawdown predictions based on the integrated results of the individual pumping tests indicated that the artesian flow of TS1D would drop below 100 m^3/h after about one year at the planned abstraction rate of 700 m^3/h [5]. As the diameter of TS1D is not sufficient to allow this well to be pumped at more than very low pumping rates, the average abstraction rates of the new wells would have to be increased to compensate for the loss of artesian flow from TS1D.

Additional abstraction from those wells furthest apart (ie., TA1 and TA6, or TA2 and TA6) would be preferable to minimise the drawdown interference effects between each well. However, TA6 is the least productive of the new wells and has larger drawdowns than TA1 or TA2 at a pumping rate of 200 m^3/h. Consequently, the shortfall in the planned abstraction rate of 100 m^3/h from TS1D was offset by increasing the pumping rate at both TA1 and TA2 to 250 m^3/h. This scenario, **Schedule B**, was represented as follows:

- Year 1: TA1, TA2 and TA6 at 200 m^3/h; TS1D at 100 m^3/h.
- Years 2 to 10: TA1 and TA2 at 250 m^3/h; TA6 at 200 m^3/h; TS1D no abstraction.

4.2 Schedule A - Planned Abstraction

The model drawdowns after 10 years at a constant abstraction rate of 700 m^3/h (6.13 Mm^3/y) from the wellfield are given in Table 4.1. The drawdown at each well during the first year is rapid, accounting for about 97% of the final drawdown, but stabilise thereafter. The greatest drawdowns, of about 145 to 150 m, occur at TA1 and TA2. The 'drawdown' at TS1D stabilises a few metres above ground level within about 1 to 2 years, which agrees with the earlier predictions based on the test data [5].

Groundwater inflow across the Dhira escarpment increases by 340 m^3/h (2.98 Mm^3/y), from 275 to 615 m^3/h (2.40 to 5.39 Mm^3/y), an increase of 125%. This indicates that about 50% of the planned abstraction rate of 700 m^3/h is supported by an increase in groundwater inflow across the Dhira monocline due to an increase in hydraulic gradient. The decline in model heads of 9 m at Wadi Ibn Hammad and 7.2 m at Wadi Karak indicates that the baseflow of these wadis could be reduced by abstraction from the Dhira wellfield.

The amount of leakage in the TS1D-Ain Maghara area reduces very rapidly from 175 m^3/h (1.54 Mm^3/y) to only 40 m^3/h (0.35 Mm^3/y), a decline of 77%, as the head in the deep aquifer declines and as abstraction intercepts groundwater that would otherwise move upwards into the shallow aquifer. This indicates that the flow of Ain Maghara would decline by about 135 m^3/h, or about 14%.

The amount of flow entering the northern discharge area declines by 65 m^3/h (0.54 Mm^3/y), from 590 m^3/h (5.15 Mm^3/y) to 525 m^3/h (4.61 Mm^3/y), a decrease of 11%. The overall net increase in flow of 143 m^3/h (1.25 Mm^3/y) or 14% compared to the natural steady state flow may be due to the fixed boundary heads or to the reduction in leakage. These changes in recharge and discharge also take place mainly within the first six months of abstraction.

Figure 4.1 shows the pattern of groundwater contours (as model heads) and flow after 10 years at the planned rate of abstraction. A deep cone of depression forms around TS1D-TA1-TA2 where heads decline to about -300 mAD (model head 100 m). This level is still some 50 m above the water level of the shallow aquifer such that if leakage is occurring between the two aquifers a positive upward hydraulic gradient is still maintained at this level of abstraction.

The drawdowns predicted by the model at each production well represent the combined effect of the drawdown due to aquifer losses, interference effects and barrier boundaries but do not allow for the additional drawdown due to well losses and partial penetration of the aquifer system. The model drawdowns adjusted for these effects using information from the pumping tests are compared to those predicted from the pumping test data [5] in Table 4.1. The results from the two approaches are in reasonable agreement, within 5 to 10% at TA6 and TA1 but overestimated by about 25% at TA2. Overall, the model predictions confirm that large drawdowns can be expected at each production well at the planned rate of abstraction.

4.3 Schedule B - Modified Abstraction

Table 4.3 shows the drawdowns resulting from a change in the abstraction pattern to compensate for the loss of artesian flow from TS1D. A drawdown of 126 m occurs at TS1D after one year, which is about 4 m less than with Schedule A. The drawdowns at TA1 and TA6 increase by about 2 m whilst that at TA2 increases by about 11 m. Drawdowns at the Wadi Ibn Hammad and Wadi Karak do not show any significant increase, and the recharge and discharge remain almost exactly the same as Schedule A. No significant change occurs in the contour or flow pattern, although the cone of depression centres more on TA2.

Table 4.1 Schedules A and B: Drawdowns after 10 years (m).

Schedule A: Four wells, total abstraction 700 m3/h.

	TS1D	TA1	TA2	TA6	WIH	WK
Rate m3/h	100	200	200	200		
Model drawdown (m)	130	144	149	111	9.0	7.2
pp (m)		10	13	59		
E (m)		94	183	164		
Total drawdown (m)		248	345	334		
Predicted drawdown (m)		269	272	325		

Schedule B: Three wells, total abstraction 700 m3/h.

	TS1D	TA1	TA2	TA6	WIH	WK
Rate (m3/h):						
- year 1	100	200	200	200		
- years 2 to 10	0	250	250	200		
Model drawdown (m)	126	146	160	113	9.1	7.3

Notes:

WIH Wadi Ibn Hammad; WK Wadi Karak.

pp = additional drawdown due to partial penetration
E = additional drawdown due to well losses

Predicted drawdowns are based on analysis of pumping test data.
Drawdowns for Schedule B uncorrected.

Schedule A: Groundwater Contours and Flow

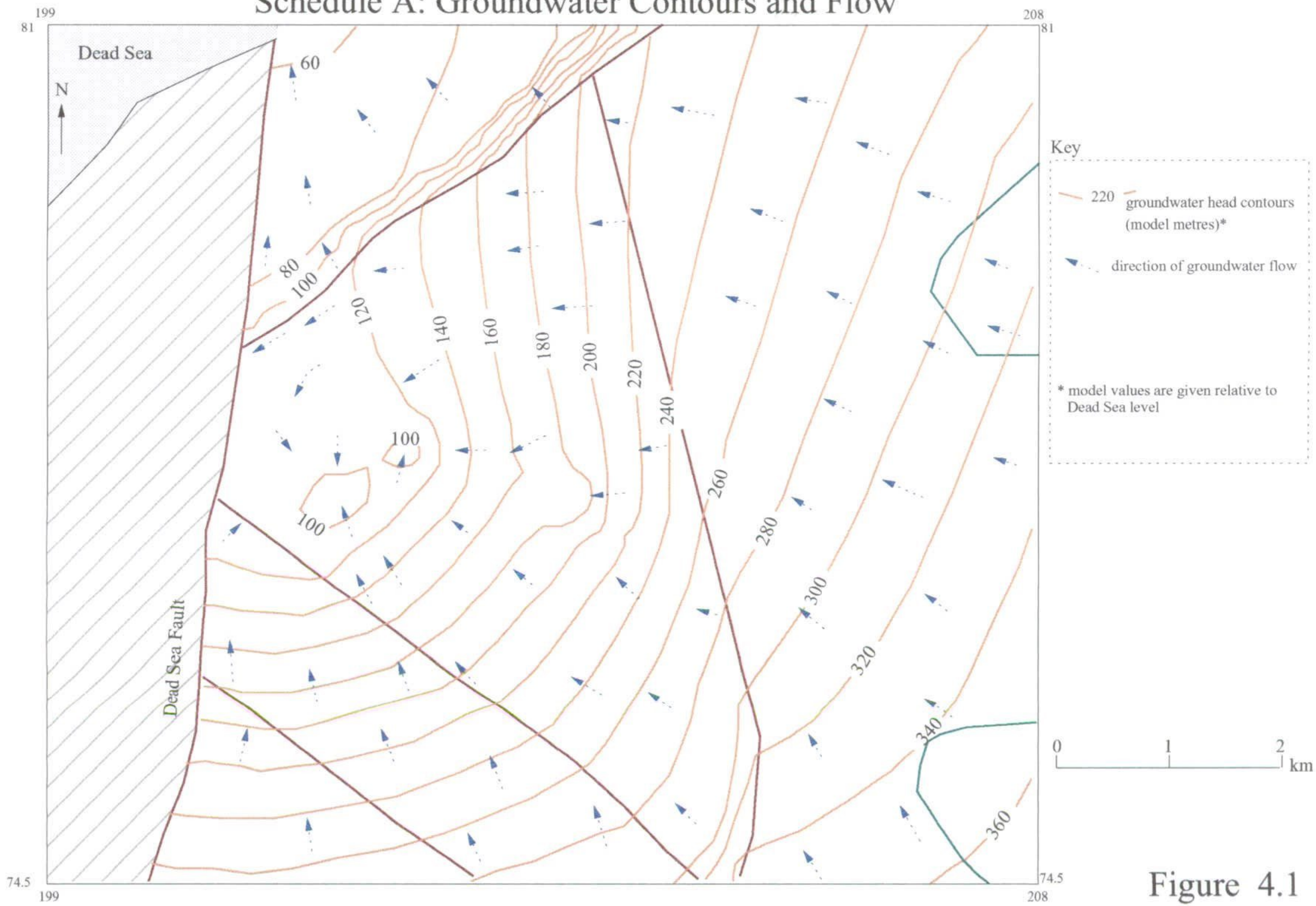


Figure 4.1

5. CONCLUSIONS AND RECOMMENDATIONS

A groundwater flow model of the region around the APC Dhira wellfield consistent with an interpretation of data obtained from the Dhira wellfield, geological information and wadi and springflow data has been developed. The calibration of the steady-state model was improved when the Siwaqa, Dead Sea and Dhira faults were represented as barrier boundaries and with upward leakage in the area between TS1D and Ain Maghara.

The fixed head boundary values tend to control the groundwater contour pattern in the model. As a result the values of transmissivity and hence the amount of groundwater recharge are uncertain. Even so, the amount of flow through the Kurnub aquifer is reasonably consistent with independent estimates based on a water balance approach and the Darcy flow equation.

The wadi flow data suggest that about 80% of the flow of Ain Maghara is derived from the baseflow of Wadi Ibn Hammad, which in turn originates from outcrops of the Kurnub-Um Ishrin aquifer system along the wadi bed upstream of the main escarpment. The model suggests that the remaining 20% the flow of Ain Maghara is probably derived by upward leakage from the deep aquifer in the vicinity of the spring.

Recharge to the wellfield takes place as lateral inflow across the Dhira monocline. The amount is governed by head gradients and discharge losses from the outcrops of the deep aquifer along the wadi beds upstream of the main escarpment. The amount of inflow entering the area of these outcrops was estimated to be about 1500 m^3/h, of which about 1000 m^3/h contributes to wadi baseflow and 500 m^3/h enters the wellfield area. However, the model indicates that the amount of recharge reaching the wellfield area could be as low as about 250 m^3/h, although this is subject to uncertainties in the values of transmissivity.

When adjusted for well losses and partial penetration effects, the model was found in general to overestimate the drawdowns observed during the pumping tests on the Dhira wells. This is mainly due to the lower T values (post-boundary and/or anisotropic conditions) being applied from the start of the simulation. Whilst the model should be more properly applied to the regional aquifer response, it was found that the adjusted drawdowns predicted by the model after 10 years data at a combined pumping rate of 700 m^3/h were within 5 to 10% of those estimated from the test data at TA6 and TA1 but overestimated by 25% at TA2.

Simulation of the planned abstraction of 700 m^3/h from the Dhira wellfield indicates:

* a rapid aquifer response to abstraction
* 50% of the abstraction is supported by increased flow across the Dhira monocline
* heads decline in the upstream wadi outcrops
* upward leakage is reduced
* large drawdowns occur at each production well.

These results imply that abstraction from the wellfield will have an impact on the availability of irrigation supplies by reducing wadi baseflows as well as the flow of Ain Maghara. This provides further support for the need to undertake surveys of the flow, chemistry and isotopic composition of wadis Ibn Hammad and Karak to demonstrate the interconnection within and between the shallow and deep aquifers, and to monitor baseflows and spring discharges as well as pumping water levels when abstraction begins.

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Annex A

Review of Recharge and Discharge in the Dhira-Karak Area.

Annex A. REVIEW OF RECHARGE AND DISCHARGE IN THE DHIRA-KARAK AREA

Wadi and springflow data were assembled during the Mujib and Southern Ghors Irrigation Project Feasibility Study in 1977 [13]. These were combined with more recent geological and hydrogeological studies of the region and the recent data from the new APC wells in north Dhira to assess the likely discharge from the deep aquifer upstream of the main escarpment and to prepare a water balance for the shallow and deep aquifer systems in the Dhira-Karak area. The conclusions were used to assist the design of the groundwater flow model.

A. Summary of Baseflows and Spring Discharges

1. Wadi Mujib System.

The Siwaqa Fault is considered to form a groundwater boundary between the Wadi Mujib and the Wadi Ibn Hammad-Wadi Karak. The northern end of the Dhira escarpment also terminates at this fault such that the wadis to the north of the fault drain to the Dead Sea without crossing an intervening limestone plateau (Edh Dhira).

The Wadi Mujib has a baseflow of about 12 Mm^3/y (1370 m^3/h), which begins at about the King's Highway [10]. The Kurnub Sandstone Formation is exposed below this point for some 15 km along the bed of the Wadi Mujib down to an elevation of about -300 mAD some 3 km upstream of the Dead Sea. The baseflow is reportedly derived from the Kurnub Sandstone and has a relatively high total dissolved solids.

2. Coastal Area between Wadi Mujib and Haditha.

The ultimate discharge level for the deep aquifer system is the outcrop area along the coastline north of Haditha, in particular for the area north of the Siwaqa Fault. Only the Um Ishrin Formation is exposed at the coast itself. The geological map records a spring (Ain As Salkh) of unknown flow and quality issuing from the Kurnub near the Dead Sea Fault close to the shoreline at an elevation of about -330 mAD. A sulphur spring is also shown issuing from the Kurnub Sandstone close to the shoreline slightly further north in Wadi al Ajawid.

The Kurnub Sandstone Formation outcrops along the beds of the wadis north of Wadi Shaqiq. No significant baseflows are reported in the Wadi Shaqiq, probably due to its small catchment area and because the outcrop of the Kurnub Sandstone Formation extends for only a few kilometres upstream of the Dead Sea.

3. Wadi Ibn Hammad-Ain Maghara

The Belqa and Ajlun group limestones outcrop in the upper reaches of the wadis in the eastern highlands and in north Dhira. They have been removed by erosion in the middle reaches of the wadi above the main escarpment exposing the Kurnub and Um Ishrin sandstone formations, which have a shallow westerly dip. The Um Ishrin is incised to an elevation of -50 mAD (about 150 m below the Kurnub-FHS junction) but the top of the Kurnub Sandstone, which is the lowest point of the Kurnub-Um Ishrin along this middle reach of the Wadi Ibn Hammad, occurs at about -90 mAD.

Springs issue from the limestone aquifer system at high elevations in the Wadi Ibn Hammad. The combined flow of these springs is reported to be about 80 m^3/h. However, the baseflow of Wadi Ibn Hammad increases to 900 m^3/h over a 5 km reach downstream of Wadi Fawwar, where the Kurnub and Um Ishrin formations are exposed along the wadi bed. Ain Hammam al Hamra (c. 140 mAD) issues from the Kurnub Sandstone along this reach where the wadi is crossed by the NE-trending Sinan Fault. Hence, the discharge from the main aquifer in this area is about 820 m^3/h, although this needs to be confirmed by further flow surveys.

The baseflow of the Wadi Ibn Hammad recorded at a waterfall about 1.5 km upstream of Ain Maghara is only about 90 m^3/h, and during the summer months the baseflow may not even reach Ain Maghara. As there are no reports of significant irrigation offtakes upstream (at least at the time of the wadi flow surveys in 1977), about 810 m^3/h of the baseflow is lost by infiltration along the wadi over a 5 km reach between the waterfall and the lowest point of the Kurnub Sandstone outcrop.

Infiltration of the baseflow would take place firstly into the wadi gravels, part of which may continue as subsurface flow in the alluvial gravel into Ghor Haditha (the alluvial fan of the Wadi Ibn Hammad) and/or through the coarse Lisan deposits that border the wadi channel in this area. Subsurface flow within the gravel sequence is shown by the shallow water level at well IH2, which was drilled through 40 m of gravel just upstream of Ain Maghara.

The water table at well IH1, which was drilled into the Belqa Group close to the southern edge of this wadi reach, has an eleavation only slightly less than the elevation of the adjacent wadi bed, which suggests that deeper infiltration takes place into the shallow limestone aquifer system. This infiltration would take place downstream of the Dhira monocline into the Belqa Group limestones of the shallow aquifer system that underlie north Dhira, as the Fuhays/Hummar/Shu'ayb shale formations outcrop along the wadi bed for the first 2 km downstream of the top of the Kurnub Sandstone. Severe drilling losses at TS1D and the new wells show that these limestones have a high permeability due to fractures and solutioning. Consequently, infiltration into these limestones from the Wadi Ibn Hammad baseflow is likely to be transmitted rapidly westwards towards Ain Maghara.

Ain Maghara (-345 mAD) emerges from the Wadi Sir limestones of the Ajlun Group at the bed level of the Wadi Ibn Hammad where it emerges onto Ghor Haditha and at the junction of the Siwaqa and Dead Sea faults. The flow of Ain Maghara (after allowing for the residual baseflow of Wadi Ibn Hammad at Ain Maghara) is about 990 m^3/h, or 180 m^3/h more than the baseflow recharge upstream (810 m^3/h). Although this difference could be due to inaccuracies in the baseflow and spring flow measurements, about 20% of the flow of Ain Maghara could be derived from other sources, such as groundwater flow along the Siwaqa fault, flood flows along the Wadi Ibn Hammad or upward leakage from the deep aquifer.

The baseflow of the Wadi Ibn Hammad has a similar chemistry to Ain Maghara. Since about 80% of the flow of Ain Maghara is derived from the recharge of baseflow along the Wadi Ibn Hammad which in turn originates mainly from the deep aquifer, the water chemistry of Ain Maghara would be expected to be similar to that of the deep aquifer, especially as there could be a short transit time of the baseflow recharge through the wadi gravels and the fractured limestones from only a few kilometres upstream of Ain Maghara. Groundwater in the Kurnub aquifer that does not contribute to the baseflow of the Wadi Ibn Hammad continues westwards into north Dhira as deep circulation within the Kurnub Sandstone aquifer which is tapped by the new APC wells. This could explain the close similarity of the chemistry of Ain Maghara to the new APC wells, whilst Ain Maghara could still be hydraulically separate from the deep aquifer system underlying north Dhira [5].

4. Wadi Karak and Ain Sikkin

The geology of the Wadi Karak catchment is similar to that of Wadi Ibn Hammad. The

Kurnub-Um Ishrin formations are exposed along the wadi bed for about 8 km from about one km upstream of the main escarpment. The lower part of the outcrop is obscured by gravel deposits but the top of the Kurnub at its lowest point in the wadi bed occurs at an elevation of about -120 mAD. The NE trending Sinan Fault also crosses the outcrop at an elevation of about -80 mAD.

Ain Sara, which supplies Karak, emerges from the Belqa-Ajlun aquifer system in the upper part of the catchment. This spring is thought to provide about 75% of the baseflow of the Wadi Karak [13]. The maximum baseflow of the Wadi Karak at the main escarpment is estimated to be about 900 m^3/h, similar to that of Wadi Ibn Hammad. In May-June 1977 the flow varied from about 430 m^3/h to about 680 m^3/h due to irrigation diversion along the wadi upstream and the average flow at the main escarpment is more likely to be about 610 m^3/h, although this needs to be confirmed by further flow surveys. This suggests that about 150 m^3/h (25%) of the baseflow is derived from the deep sandstone aquifer. Small hot springs are known to occur in the wadi bed near the main escarpment some 4 km upstream of the confluence of Wadi Karak and Wadi Dhira.

Ain Sikkin, which emerges from the coarse Lisan deposits at an elevation of about -305 mAD close to the Haditha escarpment on or close to the Dead Sea Fault, is generally considered to be derived from the recharge of Wadi Karak (and Wadi Dhira) as they cross Edh Dhira. The chemistry of Ain Sikkin is similar to that of Wadi Karak. The average flow of Ain Sikkin is about 225 m^3/h.

The baseflow of the Wadi Karak (about 600 m^3/h) and Wadi Dhira (about 150 m^3/h) does not reach Ghor Mazra, the alluvial fan of the Wadi Karak, some 5 km downstream of the main escarpment, as a result of irrigation diversion at the escarpment and infiltration into the wadi gravels. Part of this baseflow is likely to percolate into the underlying Umm Rijam Chert-Limestone and Dana Conglomerates as successful irrigation wells have been drilled close to the Wadi Karak along the Karak diversion pipeline some 1 to 2 km west of the main escarpment (although boreholes drilled into the Dana Conglomerates in the Wadi Dhira area show an increase in salinity with depth). However, about 70% of the baseflow of the Wadi Karak and almost all of the baseflow of Wadi Dhira are now diverted at the main escarpment for irrigation at Ghor Mazra and the Dhira area, respectively, which would have reduced the amount of recharge to the shallow aquifers in central Dhira.

The combined baseflow of Wadi Karak and Wadi Dhira at the main escarpment is about 750 m^3/h, which exceeds the flow of Ain Sikkin by 525 m^3/h (excluding any additional recharge from floodflows). However, based on data by irrigation command areas for 1992 provided by JVA, the surplus flow after irrigation diversion was estimated to average 220 m^3/h (Wadi Karak 165 m^3/h; Wadi Dhira 55 m^3/h) [17], which is almost exactly the same as the flow of Ain Sikkin.

B. Water Balance

1. Shallow Aquifers

The Belqa-Ajlun shallow aquifer system is recharged by precipitation and flood runoff in its outcrop area at high elevations in the upper part of the wadis. This recharge appears as numerous springs above an elevation of about 400 mAD (the approximate elevation of the top of the Fuhays/Hammar/Shuy'ab formations). However, the Belqa-Ajlun groups have been almost completely removed by erosion above the main escarpment in the middle reaches of the wadis Ibn Hammad and Karak above the main escarpment. Hence, the shallow limestone aquifer system in north Dhira will not be recharged by lateral flow from the area above the main escarpment. Direct recharge from precipitation is also insignificant in the Dhira area. Consequently, recharge of the shallow aquifer system in the north Dhira area depends on wadi baseflows and flood flows entering this area and possibly on upward leakage from the deep aquifer.

The Wadi Ibn Hammad, Wadi Karak and Wadi Dhira can be considered as a single unit in north Dhira from which discharge takes place at Ain Maghara and Ain Sikkin. After allowing for irrigation losses then the water balance of the shallow aquifer in north Dhira would be as follows in m^3/h:

Inputs:	Wadi Ibn Hammad	810
	Wadi Karak	165
	Wadi Dhira	55
	Total input	1030
Outputs:	Ain Maghara	990
	Ain Sikkin	225
	Total output	1215
	Input-output:	-185

In general, the discharge is likely to be a more accurate indication of the average recharge provided that there are no significant subsurface flows across the Haditha escarpment. The measurements of spring discharges are likely to be more accurate and the imbalance could be due to errors in the measurements of the baseflow of the Wadi Ibn Hammad.

The flow of Ain Sikkin can be accounted for by the recharge from Wadi Karak and Wadi Dhira, such that the overall imbalance is due to the flow of Ain Maghara exceeding the potential recharge from Wadi Ibn Hammad. This could suggest an additional, local contribution to Ain Maghara from the deep aquifer.

Ain Merowhe, which has a flow of 60 m^3/h, is not included in the above water balance. This spring emerges from the lower part of the Belqa group near the exit of Wadi Maadba between Ain Maghara and Ain Sikkin, has a brackish water composition similar to TS1D but with a low temperature and isotopic composition similar to Ain Maghara and Ain Sikkin. The origin of this spring is still uncertain, but if derived from the deep aquifer, then a total of 245 m^3/h (2.14 Mm^3/y) could be discharging from the deep aquifer at Ain Merowhe and Ain Maghara. However, until the accuracy of the water balance can be improved this must be considered as rather conjectural.

2. Deep Aquifer System

Groundwater recharge to the Kurnub-Um Ishrin aquifer system is derived by lateral flow from the east and south-east. NE trending faults seem to form partial barriers to groundwater flow [10] and the Siwaqa Fault is considered to separate the deep aquifer in the Wadi Mujib area north of this fault from that in the Ibn Hammad-Karak area south of the fault.

Part of the groundwater flow in the deep aquifer is discharged along the bed of the wadis Ibn Hammad and Karak upstream of the main escarpment. The remaining flow continues into north Dhira across the Dhira monoclinal fold, which extends for some 6 km along the main escarpment from Wadi Karak to the Siwaqa Fault at Wadi Ibn Hammad.

The modified Darcy equation has been used to estimate the amount of flow through the Kurnub Sandstone aquifer: Q = TIW, where Q is flow; T, transmissivity; I, hydraulic gradient; and W, width of aquifer through which flow takes place. Assuming an average transmissivity for the Kurnub aquifer above the escarpment is about 100 m^2/d and that the average hydraulic gradient is 1:17 (0.059) (approximately that of the wadi beds where the deep aquifer is exposed), then the amount of groundwater flow entering the area of these outcrops along the wadis Ibn Hamad and Karak across a 6 km width would be:

$$Q = 100 \times 0.059 \times 6000 \times 365 = 12.88\ Mm^3/y\ (1470\ m^3/h)$$

The discharge from the Kurnub Sandstone outcrops along these wadis above the main escarpment based on the available baseflow records is 8.5 Mm^3/y (970 m^3/h), comprising 7.2 Mm^3/y (820 m^3/h) along the Wadi Ibn Hammad and 1.3 Mm^3/y (150 m^3/h) along the Wadi Karak (see above). This would suggest that 4.38 Mm^3/y (500 m^3/h) continues as subsurface flow in the deep aquifer across the Dhira escarpment and into north Dhira.

The hydraulic gradient of the deep aquifer in north Dhira is estimated to be about 1:30 (0.0344) based on the water level data from the new APC wells. Assuming an average transmissivity of 50 m^2/d based on the late data from the pumping tests on these wells, then the amount of groundwater crossing north Dhira in the Kurnub Sandstone aquifer is:

$$Q = 50 \times 0.0344 \times 6000 \times 365 = 3.77\ Mm^3/y\ (430\ m^3/h)$$

This estimate agrees reasonably well with that estimated from the difference between the inflow at higher elevations and estimated baseflow, although all of the parameter values are subject to some uncertainty.

The manner or location in which groundwater leaves the deep aquifer system in north Dhira is still conjectural. Studies of the Kurnub on the western side of the Dead Sea suggest that upward movement occurs through the overlying shales and that groundwater flow is deflected northwards parallel to the Dead Sea Fault [18]. It seems likely that discharge from the deep aquifer occurs along its outcrop bordering the coast north of Haditha, where, however, the Kurnub Sandstone outcrop is narrow and largely obscured by Lisan deposits. Only the Um Ishrin Formation outcrop occurs along the shoreline from some 3 km north of Haditha. The Siwaqa Fault may also restrict the northward movement of groundwater, unless the area where it intersects the Dead Sea Fault is more fractured. Hence, unless the discharge is more diffuse and takes place offshore, there is the possibility that the deep groundwater may leak upwards into the shallow aquifer and/or continues westwards across the Dead Sea Fault.

The conclusions drawn from this review depend largely on the reliability of the baseflow estimates which need to be confirmed by flow surveys and monitoring, especially in Wadi Ibn Hammad.