Arab Gulf Journal of Scientific Research, 25 (1/2): 39 - 49 (2007)

Research Paper Ref. No 2426

Hydrogeological and Quantitative Groundwater Assessment of the Basaltic Aquifer, Northern Harrat Rahat, Saudi Arabia

التقييم الهيدروجيولوجي والكمي لحاملة مياه البازلت، حرة رهاط الشمالية، المملكة العربية السعودية

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ABSTRACT: The Northern Harrat Rahat consists of 300m of basalt lavas covering some 2,000 km^2 to the south-east of Al-Madinah in western Saudi Arabia. Like many basalt sequences, the Rahat basalts form an important aquifer and groundwater resource. The aquifer has a saturated thickness of up to 60m and is made up of the weathered upper part of underlying basement, pre-basalt sands and gravels, and the fractured basalts. Since 1992, groundwater has been abstracted from the aquifer as part of the Al-Madinah water supply. To assess the potential of the aquifer, an assessment has been made based on pumping tests of about 70 wells. The hydraulic parameters have been shown to be highly variable, typical of the fractured domain. The aquifer contains good-quality water in storage, but receives limited recharge. Groundwater temperature anomalies indicate remnant volcanic activity locally. A numerical groundwater model has been constructed, which has been calibrated using limited groundwater head measurements, but with good abstraction records. Predictions of groundwater heads and the examination of several abstraction scenarios indicate that the aquifer can continue to support part of the Al-Madinah demand for the next several years, if certain well distributions are adopted. The predictions also show that the aquifer can only support the total demand of the city for a few days as a contingency resource.

Keywords: *Basaltic aquifers, groundwater resources, mathematical modeling, Saudi Arabia.*

المستخلص: يتكون الجزء الشمالي من حرة رهاط الواقعة الى الجنوب من المدينة المنورة من تدفقات بازلتية بسمك 300 م تقريبا و تغطي مساحة في حدود 2000 كم^2. كما هو الحال في كثير من الطبقات البازلتية يمثل هذا التتابع البازلتي خزانا مهما للمياه الجوفية و يصل السمك المشبع بالمياه الى حوالي 60 م. و يتألف الخزان من: الجزء الاعلى المكون من صخور القاعدة، الرمل و الحصى الواقع تحت او خلال طبقات البازلت، و صخور البازلت المتصدعة. تم الاعتماد على اختبارات الضخ لحوالي 70 بئرا و التي اظهرت اختلافا كبيرا في قيم المعاملات الهيدروليكية كما هو متوقع في مثل هذا النوع من الصخور. و تعتبر نوعية المياه الجوفية ملائمة لاغراض الشرب والري حسب المواصفات العالمية و المحلية. تم تقييم الخزان كمصدر للمياه باستخدام نموذج حسابي لمحاكاة حركة المياه الجوفية. وتم معايرة النموذج باستخدام المعلومات المحدودة عن مستوى المياه الجوفية وتم بعد ذلك استخدام النموذج للتنبؤ بمستوى المياه الجوفية في المستقبل. و باختبار عدة سيناريوات للسحب من الخزان اظهرت النتائج ان الخزان قادرا على الوفاء بجزء من حاجة المدينة المنورة للمياه لعدة سنوات قادمة.

كلمات مدخلية : *حاملة مياه بازلتية، موارد مياه جوفية، نمذجة رياضية، المملكة العربية السعودية.*

INTRODUCTION

The study area is the northern part of Harrat Rahat, to the immediate southeast of Al-Madinah Al-Munawwarah, and covers an area of approximately 2,000 km^2 (Figure 1). Groundwater occurs in an aquifer composed of basalt lavas and underlying alluvium and weathered basement. Within the area are three wellfields providing part of theAl-Madinah water supply. A number of geological and hydrogeological investigations have been carried for in the Al- Madinah region, some of which relate to the study area. Detailed geologic mapping of the area includes work by Pellaton (1981), Moufti (1985), and Camp & Roobol (1991). A number of regional hydrogeological studies have been carried out and have been summarized by Bayumi (1992), who investigated the hydrogeology of the Northern Harrat Rahat.

The geology of the basalts is reasonably well detailed as is the composition of the aquifer. The extent of the aquifer to the east and the south of the study area, however, is not fully understood due to the absence of hydrogeological information.

Abstraction from the aquifer started in the early 1970's, but between 1990 and 2000, three wellfields were constructed to supply Al-Madinah with water. Significant head declines have occurred in the northern part of the area as a result of over-abstraction and many of the wells in the northern fields have dried up. The study described below has been carried out to examine the extent of the over-abstraction, to improve the understanding of the aquifer and to test alternative abstraction scenarios.

Basalts form some of the most difficult aquifers to evaluate because of the inherent variability in their hydraulic properties. Available data were used to form a conceptual model of the aquifer by defining the hydrogeologic framework and evaluating the hydraulic characteristics. The data were also used to determine the water budget and evaluate the hydrochemistry. Finally, a regional groundwater flow model, focused upon the existing wellfields, was constructed and used to test management alternatives based on water requirement data.

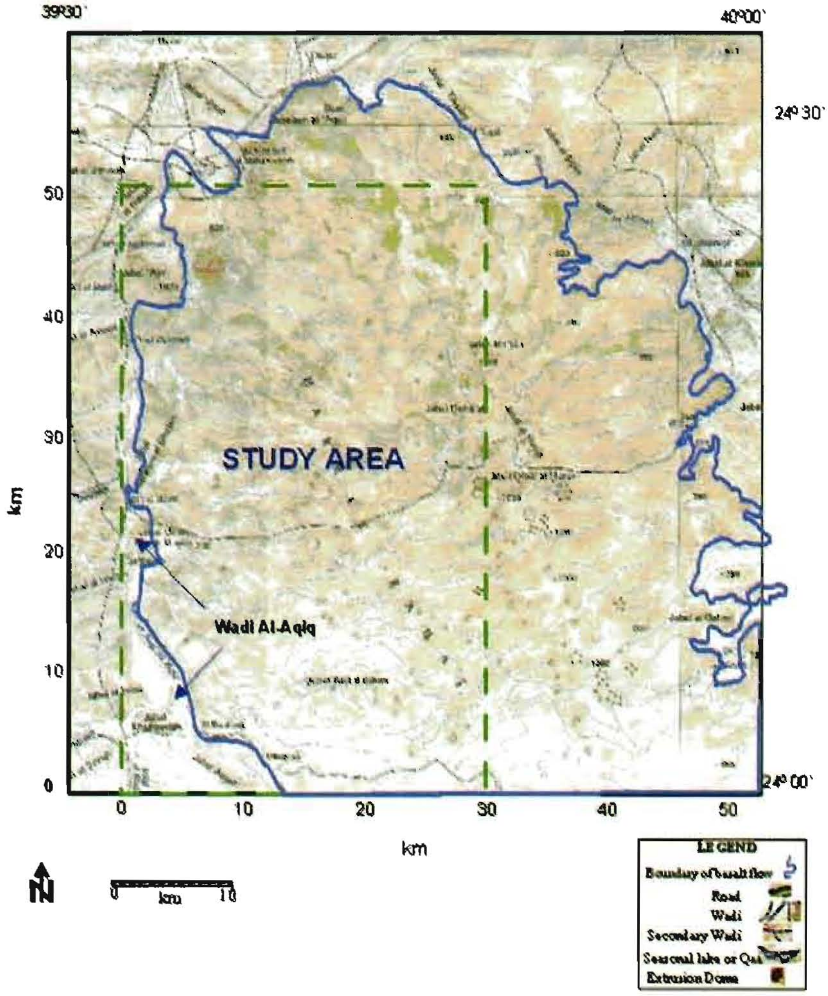

Fig. 5. Location and limits of the study area. Zero reference for the study is 24°00′ N, and 39°32′ E.

GEOLOGICAL SETTING

Physiography and Drainage

The lava fields of the western part of the Arabian Peninsula comprise one of the world's largest alkali volcanic provinces with an approximate area of 180,000 km^2. They were produced by the continental intra-plate volcanism accompanying the opening of the Red Sea (Camp and Roobol, 1991). The Harrat Rahat lava field is one of the largest components of this continental basalt province and forms a major topographic feature extending from Al Madinah Al Munawwarah in the north to the northern outskirts of Jeddah and Makkah in the south. It measures about 310 km north-south and 75 km east-west; a total area of 19,830 km^2.

The harrat has an irregular sub-basaltic topography consisting of basins that are elongated along the length of the harrat. Two main wadis existed before the volcanic eruptions as inferred from geophysical investigation (Daessle and Durozoy, 1972). Both wadis flowed northwards towards what is now the Al-Madinah city area. New drainage evolved after the initial extrusion and was modified as eruptions took place until the present-day system developed. Currently, there are two major wadis draining a combined watershed area of about 4500 km^2 and collecting about 260x10^6 m^3 of rainfall annually.

Local Subsurface Geology

Harrat Rahat has evolved over the past 10 million years and is composed of three stratigraphical units separated by two disconformities: the Shawahit (10 - 2.5 Ma), Hammah (2.5 to 1.7 Ma), and Madinah (1.7 to Recent) basalts (Camp and Roobol, 1991).

Two main basaltic layers 150-200m thick have been identified, overlying the basement. They are distinguished by their color – a light gray upper layer and dark gray to black lower layer. The upper layer is consistently within the top 70 – 100 m section. The two layers correspond to Madinah (upper layer) and Hammah basalts. Sand and gravel is present locally immediately above the bedrock with some very fine sand and clay layering in basalt inter-flow zones.

HYDROGEOLOGY

While the general geology of the area is reasonably well understood, the hydrogeological data are limited in distribution. Some groundwater table elevation data, abstraction, and well test information are available for three wellfield areas that are about 10 km apart, but away from these areas only limited data are available, principally at the margins of the aquifer system. To extend the limited and localized database, four exploratory wells were drilled as part of the present study. The data from those wells helped in completing the contour maps of bedrock elevation and alluvial deposits and basalt thicknesses.

Aquifer System Definition

The geological sequence and aquifer are shown conceptually on the left of Figure 2. The aquifer definition is based upon an interpretation of the well records. The main producing zone consists of: (1) the topmost weathered part of the 'basement', generally less than 5 m thick, (2) the sub-basaltic gravels and sands deposited on the pre-lava ground surface, and (3) densely fractured, jointed, and vesicular basalts that characterize the lower part of the lava sequence. The base of the aquifer is the bottom of the 'basement' weathered zone.

The top of the aquifer is regionally a free water surface. Minor semi-confined zones occur caused by the presence of thin layers of low permeability material and variations in lava and inter-lava hydraulic characteristics.

For undisturbed conditions (i.e. non-abstraction conditions), the saturated thickness of the system ranges from 50 to 60 m. The sub-lava and inter-lava flow alluvium varies in lithology from clay to sands and gravels, and is of variable extent and thickness. The presence of fine- grained inter-beds in places may impede groundwater flow locally, and may be a possible explanation of the low productivity of some wells.

Groundwater Head Distribution and Lateral Boundaries

Pre-development (steady state) water levels

It is considered that prior to abstraction, the aquifer system was in a state of dynamic equilibrium. The drilling of deep wells started in about 1967 with exploratory wells. 1970 probably marks the year when the aquifer started to be developed. Few groundwater head data exist for the pre-1970 period; consequently, the pre-development head distribution has been based initially on a combination of scattered well data compiled by Bayumi (1992) and data interpolated from later wellfields. The distribution is shown in Figure 3, and has been derived finally, iteratively from the groundwater model discussed below.

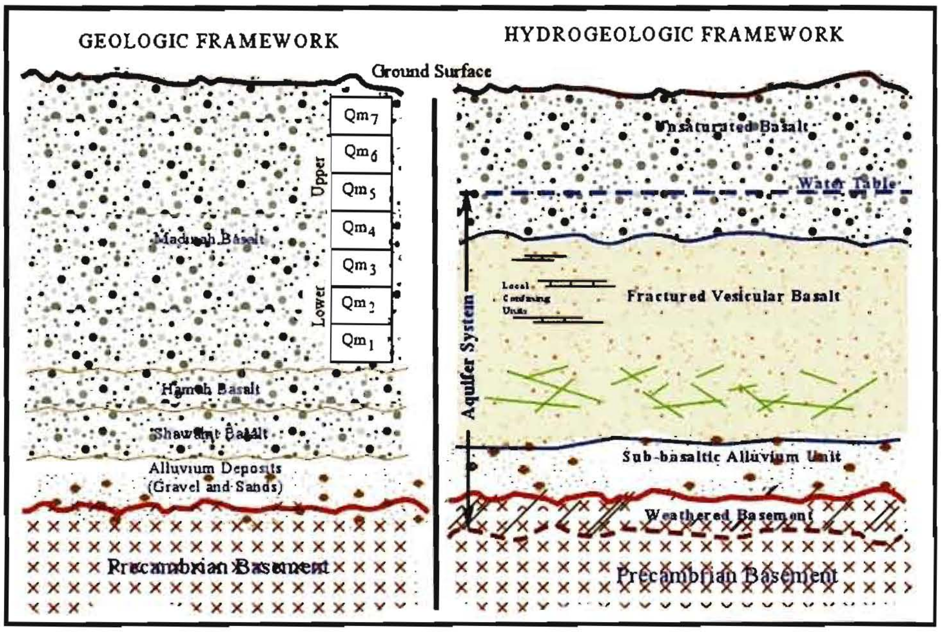

Fig. 2. Correlation between geologic and hydrogeologic frameworks in northern Harrat Rahat.

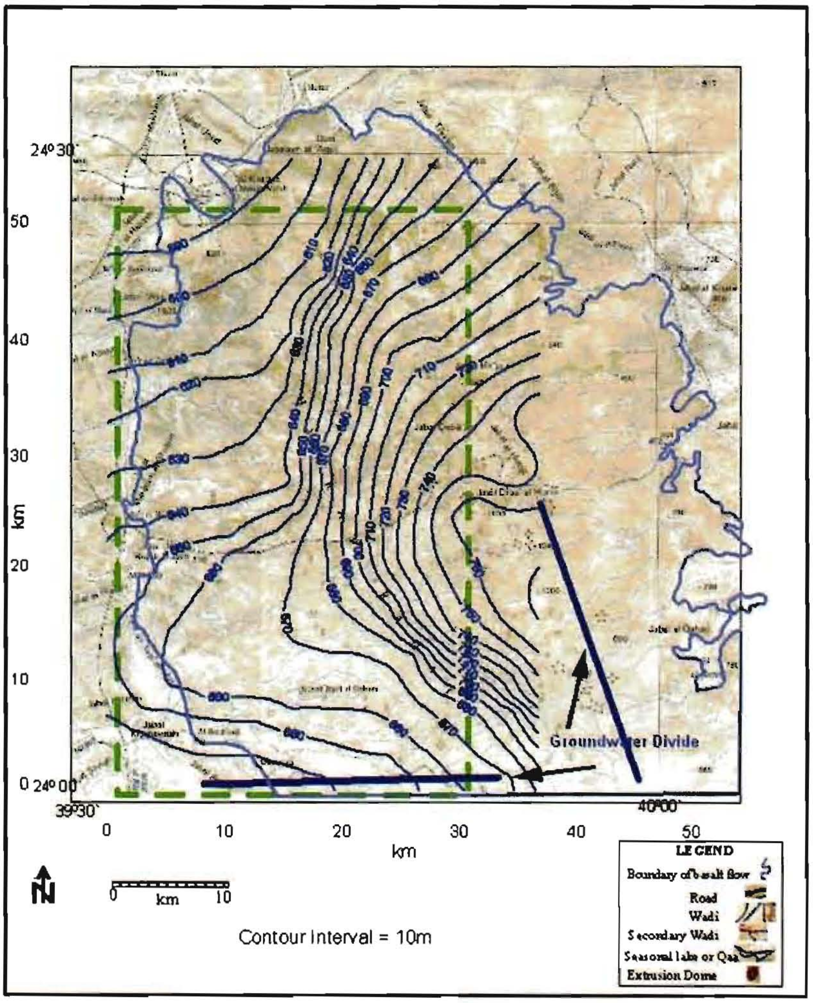

Fig. 3. Predevelopment (pre 1970) water levels.

From the head distribution in Figure 3, certain hydrogeological features are apparent. A groundwater divide occurs coincident with the topographical divide in the east demarcating a no-flow flow boundary to the system. A broad groundwater divide is present in the south trending generally east-west. In the extreme south of the study area, under undisturbed conditions (i.e. non-pumping), groundwater head indicates south-westerly flows. The control for these flows is the wadis and sebkhas of the Wadi Al-Yatimah to the south of the study area. In the west, in the Wadi Al-Aqiq, the heads accord with flow to the north in the direction of the down-gradient of the wadi, demonstrating that the system along this boundary is drained by the wadi alluvium. Heads in the north indicate a westerly groundwater flow consistent with the presence of the Al-Madinah springs that have been the historical northerly drainage point for the aquifer system in that area. The two groundwater divides define the principal part of the aquifer system in which heads decline variably from the south-east to the north and north-west.

Transient Groundwater Heads

Heavy abstraction has occurred since about 1975. Declines of up to 10 m in the groundwater levels were observed in the north over a period of about 20 years (Bayumi, 1992). The rate of abstraction probably exceeded 12 $\times 10^6$ m^3/year by 1990 and was concentrated in the northern parts of the aquifer.

As a result of declining heads and yields in the northern wellfields, a further wellfield was drilled in the Abar Al-Mashi area, consisting of three well groups. Pumping of the wellfield commenced in 1992 and, where feasible, the wellfield has been operated since that date. Figure 4 shows a south-to-north cross section of elevations of ground surface, water levels, and bedrock.

AQUIFER CHARACTERISTICS

Pumping Tests Results

The complex, fracture dominated character of the aquifer has led to difficulties in performing and interpreting pumping tests. The parameter range deduced from testing is considerable, with transmissivity ranging between 13,300 and 1 m^2/d, and storage between 0.3 - 0.00031.

In considering the parameters, various hydrogeolgical factors need to be stressed. Most of the data relate to pumping well data that cannot strictly be analyzed for transmissivity and certainly cannot be analyzed for storage. Where transmissivity interpretations are applied to pumping well data, the results tend to significantly under-estimate transmissivity. Further, radial theory used in pumping test interpretation is of doubtful applicability in secondary permeability systems. Some pumping tests resulted in no drawdown for significant pumping discharges, providing strong evidence of localized very highly transmissive zones. Some wells with similar designs, in close proximity, gave markedly differing well yields during production testing, further demonstrating flow path complexities and the typical difficulties of obtaining definitive aquifer characteristics for lava aquifers.

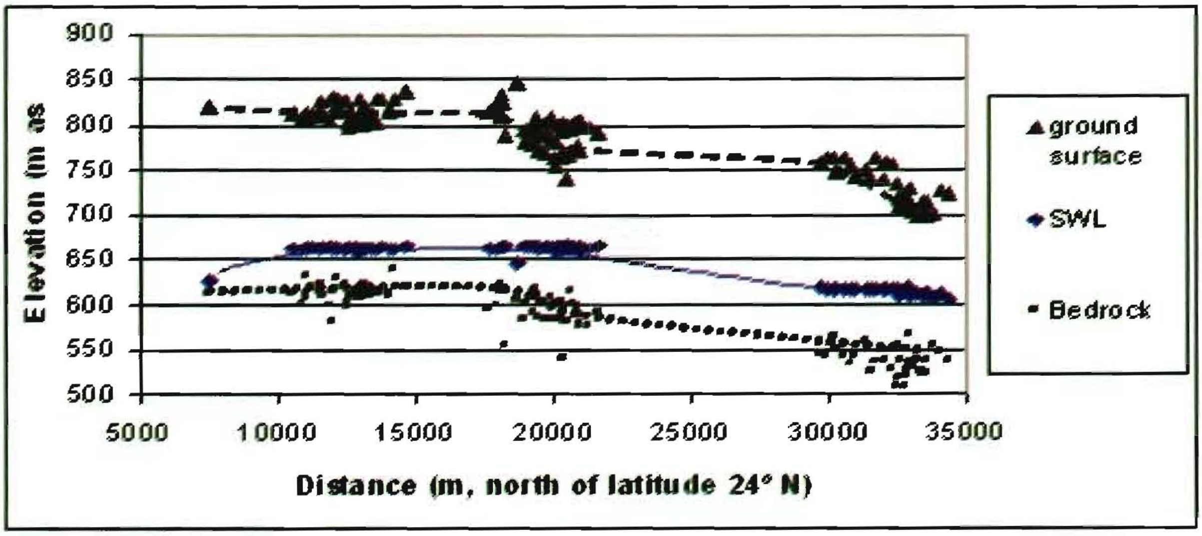

Fig. 4. S-N cross section of ground surface elevation, static water level, and bedrock elevation across the study area as obtained from well completion reports.

The data provide no clear pattern in spatial transmissivity distribution. Conceptually, the highest hydraulic conductivities would be expected in the lowermost lavas, which are the oldest, the most widespread, and which have been subjected to weathering conditions more than later lavas. These lavas were the most viscous of the lava pile and therefore most prone to fracture. Additionally, they will have been the most affected of the lavas in terms of minor seismic activity. The younger lavas, mainly present in the east, were less viscous on extrusion and therefore less prone to fracture, inferring a lower potential for porosity. In the eastern high elevation, volcanic cone area, the older fractured lavas exhibit veining associated with later volcanic activity. In this area, therefore, it is considered that any initial porosity would have been radically reduced. It is concluded that the regional transmissivity distribution is therefore likely to be low values in the east with higher values in the west.

In view of the absence of any reliable data of specific yield from well testing, reliance for storage understanding was placed upon the interrogatory modeling of regional drawdowns, which in fact provides far better insight than individual well complex testing. The storage values are discussed below in the numerical modeling.

Groundwater Flow

The general groundwater flow direction in the system is to the north and northwest with the discharge historically to the Ayn er Zerqa springs at Al-Madinah, and alluvium in the Wadi Al-Aqiq (west) and the Wadi Al-Hamdh (north). Groundwater has accumulated in time through recharge from rainfall, runoff, and from subsurface groundwater flow from the south, outside of the study area. Natural discharges from the system occur through alluvium in fringing wadis and the system has been stressed by abstractions.

The area is arid with the current aridity cycle probably having been a feature for the past 8000-6000 years. Highly variable rainfall frequency and small amounts are typical. When combined with an extremely high evaporation potential, effective direct recharge through the soil profile from rainfall, is precluded. Potential evaporation is in excess of 2m annually, which compares with an annual rainfall mean of 63mm.

The broken surface of the lavas allows indirect recharge to occur; however, data are unavailable to allow a direct assessment, as the measure of such recharge poses immense hydrological difficulties. An estimate of recharge of about 10% of annual mean rainfall has been used as an initial guide and has been tested in the model described below. The concept of natural discharges to alluvium in the fringing wadis is rational but not quantifiable from the field data. As with most other flows in the system, these discharges have been examined through the groundwater modeling. Abstraction data prior to 1970 is fragmentary. Annual discharge in the Al-Madinah general area is estimated at about 70 million m^3/year in 1970 and 34.10^6 m^3/year (net of irrigation return) from about 1145 wells for 1979 (Italconsult, 1979). Both the number of wells and the annual abstraction has increased since. Three wellfields have been operated for the city supply since 1992, producing a combined average of 43,000 m^3/day. 60 private wells were surveyed for the present study with an estimated production of 21×10^6 m^3/year.

Groundwater Quality

The groundwater quality is currently suitable for both drinking and agriculture. Higher temperatures and slightly higher chloride concentrations encountered at depth in some eastern wells indicate ongoing volcanic influences.

GROUNDWATER RESOURCES APPRAISAL

The resources potential for the aquifer has been assessed using the United States Geological Survey finite difference groundwater flow model MODFLOW (Macdonald and Harbaugh, 1988, USGS, 2000). The concepts described above have been incorporated as relevant using an iterative approach. Information from the wellfield has been the dominant factor. The hydrogeological database, as demonstrated above, is limited in distribution. The model representation achieved, and discussed below, cannot be considered to be truly definitive; however, it does provide a means of understanding bulk performance of the aquifer with respect to future water demands. The lack of definition (detailed description of the different parameters) is typical for a groundwater system in an arid area that has been developed progressively from a practical resources point of view.

Modelling Assessment

Model Framework and Boundaries

For modeling a single layer representation was adopted using a north-south, east-west grid of 50 x 55 cells of 1km x 1km cells (Figure 5). The cell sizing was modified so that a highest density covers the wellfield areas.

The major eastern groundwater divide was assigned as a 'no-flow' boundary. For the southern boundary of the model the current study area boundary has been used for convenience. No hydrogeological data exist within any reasonable distance to the south of this boundary, although the lavas extend for some distance. A 'general head 'boundary condition has been used, permitting two-way flow. Accepting the premise that the aquifer system drains naturally to the alluvium in the fringing wadis (Figure 1), 'drain' boundaries have been applied as shown in Figure 5 in the west and in the north of the model. In the extreme south-west and extreme north-west, 'no-flow' boundaries have been applied, where the aquifer system abuts directly against basement rocks.

The lower boundary has been defined as a 'no flow' boundary. The system is unconfined, so that a free water surface is calculated within the model, defining the upper boundary.

Any groundwater modeling analysis is an iterative examination of the various parameters controlling groundwater flow. The procedure is dependent upon field data and an interpretation of the hydrogeological conditions. Assumptions are inherent in the procedure and require testing on a trial basis. Flows are the most important element in understanding the system which can pose problems in arid areas, because base flows rarely occur and recharge is not understood in any definitive sense. The groundwater heads that reflect flows are therefore used as a guide to understanding of the system and its modeled representation.

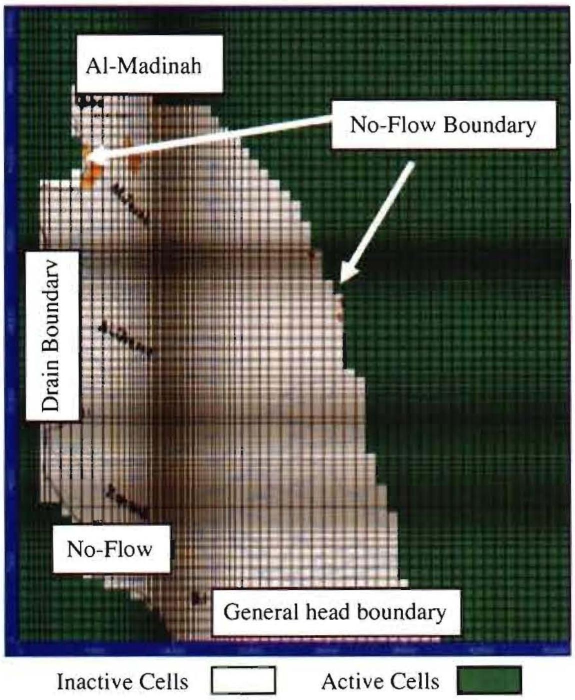

Fig. 5. Model grid and boundaries.

Calibration

The procedure used in the study was to model an approximate 'steady state' condition reflecting the conceptualized pre-development groundwater head distribution. This was used to obtain an approximate understanding of the main flow inputs and outputs for the system and to produce a head distribution that could be assigned as the initial values for the 'transient state' modeling. The head distribution shown on Figure 3 reflects this phase of the modeling.

For the transient calibration, the period 1970 to 2001 was adopted, with the assumption that no meaningful abstraction occurred prior to that period and that the specified heads approximated in the 'steady state' analysis could be used as initial heads.

In MODFLOW, specifications are required for the time interval flow calculations that include 'stress period' and 'time step' values. These values were arranged so that the model outputs could be judged for specified years from a daily output, maintaining, however, numerical stability in the solution. The 'transient state' was examined in the conventional manner by inputting parameter matrices and modifying these on a 'trial and error' basis. The principal calibration control used was individual representative heads for the three wellfield groups. Dependable data from observation wells that does not reflect very localized pumping is only available for 1992 and 2001-2002. These data are shown on the head calibration in Figure 6.

Parameter Inputs

The hydraulic parameters were eventually determined iteratively. Low hydraulic conductivities (K) have been assigned in the east (0.01 to 6 m/d) and high values in the west (7 to 40 m/d)

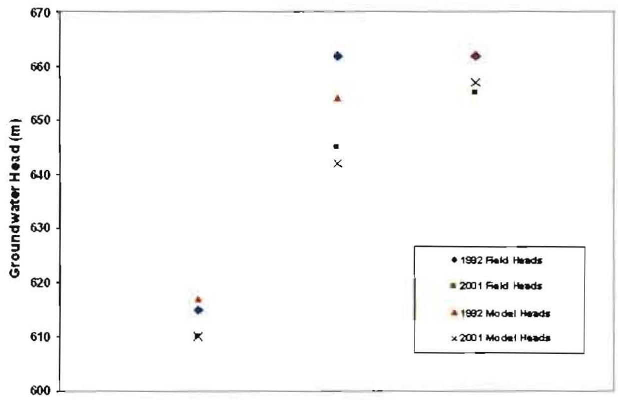

Fig. 6. Comparison of field and model heads (m asl) at the three well group locations for 1992, and 2002.

in keeping with the concept discussed above. A similar approach was adopted for the specific yield (S_y); 0.05 to 0.08. Because of the problems noted above for determining hydraulic characteristics in lavas, it is difficult to assess the veracity of the values derived. However, the characteristics portray regionally a moderately high transmissive aquifer with a low specific yield, consistent with what would be expected in a fractured basalt medium. At the 'drain' boundaries a simple rule was applied setting drain base to about 50m below wadi ground elevation. For realization, the boundary uses a conductance term, reflecting drain permeability and flow convergence. The flow of groundwater to the drain is controlled mainly by the conductance. A conductance is also required for the 'general head' boundary. Conductance values for both drain and general head boundaries were derived iteratively.

Refined recharge input ranged between 4 and 10 mm/year. The values are small as would be expected, with the highest recharge assigned to the highest topography.

As applicable, a pumping schedule was applied to the wellfield based upon a very good record of abstractions. Most of the abstraction data were recorded daily for each well and assigned to the appropriate wells in the model.

Groundwater Head Distributions Derived

As a result of the transient state data testing, a sequence of groundwater head distributions were obtained for the 1970-2002 period. The system distribution for 2002 is shown in Figure 5. In Figure 6 the relationship between the representative field heads for the well groups in the 3rd wellfield are compared with the model generated heads.

Comments on the Calibration Results

For the calibration, it is essential that it be borne in mind that the aquifer has been operated for the practical purposes of water supply. The aquifer has not been researched historically with a view to an aquifer system analysis so that the database for a definitive analysis is not available. It is further stressed that the type of aquifer, which is dominated by lava flows, is one of the most difficult to evaluate. Nevertheless, good bulk abstraction data are available, together with some limited relatively undisturbed head data. The influence of the abstraction has been adequately represented in the calibration and gives confidence that the regional aquifer characteristics are of the right order. It therefore follows that the flow balances derived are reasonable and that, despite the assumptions inherent in the type of modeling carried out, the calibrated model provides a tool for examining future abstraction potential.

Sensitivity Analysis

Sensitivity of the model heads was tested by individually and simultaneously changing K and S_y by ±20%, ±40% over the calibrated values. An example is shown in Figure 7. The model is reasonably sensitive to changes in K but the solution becomes unstable when S is increased or decreased by more than 20%, and the solver parameters had to be changed for the solution to converge. The best agreement between simulated and measured heads was obtained with the original (calibrated) values of K and S_y. These sensitivity results are important in showing that the model is sensitive to S_y in that the aquifer supply is dependent upon storage.

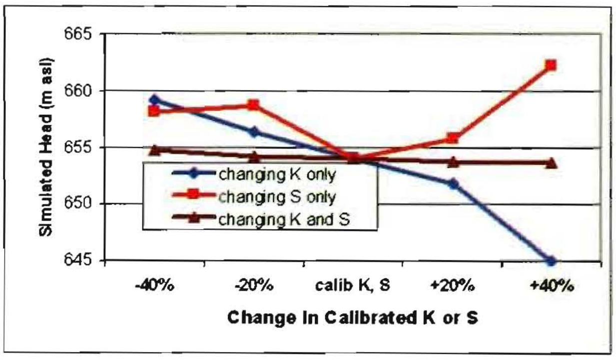

Fig. 7. Sensitivity analyses where changes in simulated 1992 head are plotted versus changes in calibrated K and S.

Management Alternatives

Water supply demand for Al-Madinah is

expected to reach 375,000 m³/day by 2010, and 460,000 m³/day by 2015. The bulk will be met by desalinized water but there will be a shortfall which, if feasible, will be taken from the aquifer. Further, it is important to understand the extent to which the aquifer can support demand in the event of temporary failure of the desalinized water supply.

To examine whether the aquifer could support the expected demand shortfall, several abstraction scenarios have been tested. The scenarios are: (a) abstract the shortfall entirely from the current operational wells in the field, (b) abstract the shortfall from a well configuration embracing the wellfield and adjacent areas, and (c) abstract all of the city's water demand from the current wells in case the desalinated water is partially or completely discontinued. The first scenario was selected from an operational standpoint, while the second scenario was examined with consideration to distributing the abstraction and the consequent drawdown impact on the aquifer. The third scenario is a short-term contingency plan.

Future Scenario Results

In the simulation modeling for the first two scenarios, the abstraction demands have been introduced for the period 2002-2032, following the calibration period 1970-2001.

For Scenario 1, abstractions were assigned to the producing wells of the wellfield and the total abstraction amount is divided equally among the wells. The simulation results for the scenario show that the aquifer sustainability will become critical in about 2010. The demand, however, should be met at least to this date even if no alternative scenario is adopted, and it may be concluded that sufficient aquifer potential exists to allow time for decisions related to alternative supply sources to be made.

For Scenario 2, the distribution of abstraction has been changed from Scenario 1 in order to examine the potential of the aquifer with a less concentrated drawdown impact. A different configuration of abstraction wells and a different abstraction schedule were used for Scenario 2. All wells are located in the general area hosting the wellfield. The impact of pumping on the aquifer is less in Scenario 2 compared to Scenario 1, because abstraction is more distributed (Figure 8). The simulation results for Scenario 2 show that the aquifer sustainability will become critical in about 2014. The demand, however, should be met that year, even if no alternative scenario is adopted.

Scenario 3 examined the hypothesis where part or all of the desalinized supply becomes temporarily unavailable and the total supply has to be abstracted from the aquifer system. Three cases were tested and are summarized in Table 1. In the scenario, the total abstraction (amount lost from desalinated supply + current well field supply) in each case is distributed equally among the wells used in Scenario 2. In Case 1, where only part of the desalinated water supply discontinues, the amount assigned

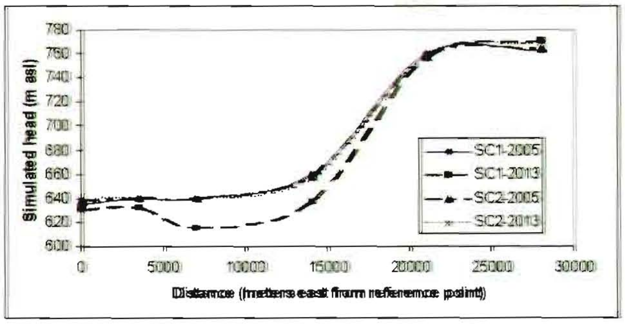

Fig. 8. Water table across the wellfield (W-E) as simulated in scenarios 1 and 2, for 2005, and 2013.

Table 1. Emergency abstraction plans during a temporary halt in the desalinized water supply.

Case	Incident	Amount lost (m^3)	Total Abstraction (m^3)	Duration	Can aquifer support demand?
I	First Line discontinued	80,000	130,000	• 3 days • 15 days • 30 days	Yes Yes Yes
II	Second Line discontinued	200,000	250,000	• 3 days • 15 days • 30 days	Yes No No
III	First and second Lines discontinued	280,000	330,000	• 3 days • 15 days • 30 days	No No No

to each well is 2,300 m^3/day, assuming it is practically possible. Reserve wells may have to be drilled. It appears that the aquifer can support this demand for the three periods.

In Case 2 where 200,000 m^3 are required, aquifer support for only 3 days would appear likely. For more than 3 days, there will be significant declines in the water level, many wells will dry up, and the aquifer could be depleted in the wellfield area. Again, the current wells with the current production of about 1000 m^3 each cannot provide the required volume for the case. Some 100 more reserve wells would be needed, if the contingency were to be feasible. Case 3 was not tested for the reasons noted for Case 2.

Aquifer Potential as a Water Storage Facility

Both field observations and groundwater model show that the aquifer is being over-exploited and if current operations continue will become virtually redundant. Further, a poorer quality groundwater is being drawn to the system from the east. However, the aquifer does provide a proven groundwater storage facility that could play an important role in an integrated water resources management scheme whereby excess desalinated water and/or treated wastewater could be recharged into the aquifer and recovered when demand dictates.

The location of the aquifer close to Al-Madinah, with the infrastructure of wells and pipe network, provide an overall facility that would be worth testing for storage and retrieval purposes in order to prolong the aquifer life and provide a strategic reserve for Al-Madinah.

CONCLUSION

A basalt aquifer system covering 2000 km^2 has been defined in the northern part of Harrat Rahat close to Al-Madinah Al-Munawwarah. The main producing zones consist of: (1) the topmost weathered part of the basement, (2) the sub-basaltic gravels and sands of the pre-lava surface, and (3) the fractured, jointed, and vesicular lower part of the lava sequence.

Under undisturbed conditions, the saturated thickness in the study area ranges from 50-60 m. The aquifer system has been described in regional terms because of the complexity of the lava hydraulics and the lack of detailed data. However, the regional interpretation is considered suitable for groundwater resources purposes.

Prior to the mid-1970's when abstraction commenced, the aquifer was in a state of equilibrium. Random well drilling occurred and three major wellfields were constructed for the Al-Madianh water supply. The rate of abstraction has exceeded the amount of recharge.
Groundwater quality is suitable for both drinking and agricultural purposes. Higher water temperatures and relatively higher chloride concentrations exist in the east indicating ongoing volcanic influence.

The groundwater resources potential of the aquifer system has been assessed using a numerical groundwater model. Three possible abstraction scenarios for future management have been tested which indicate that the aquifer can support the Al-Madinah demand up to about 2010 using the current well configuration. The aquifer can support the demand, however, for more several years, if more wells are drilled. A contingency scenario tested to determine the ability of the aquifer to support the Al-Madinah in the event of problems with the desalinated water supply found that with the current well distribution, the aquifer can support the total demand for only a few days.

ACKNOWLEDGEMENT

The authors would like to thank the King Fahd University of Petroleum and Minerals for its support. The Al-Madinah Water Directorate supported this study and provided most of the data. The help of Jowaher Raza, Mohammad Fargali, and Mamdouh Raddadi is appreciated.

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Ref. (2426)

(Paper selected and revised from the seventh Gulf Water Conference: Water in the GCC... Towards an Integrated Management. Water Science and Technology Association (WSTA), State of Kuwait, November 19-23, 2005)