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Groundwater Budgeting for A Multi-Aquifer System Using Numerical Techniques

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ABSTRACT. The use of numerical techniques to define the detailed water budget analysis for each individual aquifer in a multi-aquifer system under steady state and transient conditions has not been well established in the literature. In this work, numerical analysis has been used to define the water budget for each individual aquifer in a multi-aquifer system in Greater Dhahran Area. A quasi-three dimensional simulation model of groundwater flow in the multi-aquifer system was developed using USGS-MODFLOW. The MODCELL program of the USGS was used to calculate the cell-by-cell flow volumes in each aquifer. The output data files from MODCELL were converted from binary to ASCII formats using CONVML utility module of the USGS. A special program was developed to make the output data files of MODCELL compatible with CONVML utility module.

The groundwater budget shows the importance of Umm Er Radhuma (UER) aquifer as a major water supply source to Dhahran area, as well as a potential recharge source to the Khobar and the Alat aquifers. The findings of the water budgeting are recommended to be used in improving the present and future water management and conservation schemes for the area. Similar techniques can be used to improve the groundwater use and management in other parts of the country as well as other arid regions.

In countries located in arid and semi-arid regions such as Saudi Arabia, the groundwater resource is a major water supply source. Numerical techniques in groundwater modelling have been used extensively to investigate the behavior of groundwater flow under different water pumping policies (BRGM 1977, GDC 1980, Yazicigil *et al.* 1986, Yazicigil *et al.* 1987 and Rasheeduddin *et al.* 1989). However, the use of the same techniques to calculate a detailed groundwater budgeting for each individual aquifer in a multi-aquifer system under steady state and transient conditions has not been well established in the literature. Detailed groundwater budgeting is essential for the development of effective and long - term water pumping policies; and water management and conservation schemes especially in areas where groundwater is pumped heavily such as the Greater Dhahran Area. The budget defines the contribution of each individual aquifer to the pumped groundwater and the interrelation among aquifers under steady and transient conditions.

The Greater Dhahran area is located in the Eastern province of Saudi Arabia (Fig. 1). It includes the cities of Dhahran and Al-Khobar. The area is heavily populated (around 400,000 inhabitants) and intensively developed due to the presence of Saudi Arabian American Oil Company (Saudi ARAMCO), King Fahd University of Petroleum and Minerals (KFUPM) and the International Airport. The climate is severely arid with an average rainfall of 75 mm/year. The groundwater resources from the existing aquifer system supply more than 90% of the total water demand. The multi-aquifer system in the area consists of three main aquifers namely: the Umm Er Radhuma (UER), the Khobar and the Alat (Fig. 2). The quantities of groundwater withdrawal from the Umm Er Radhuma (UER) and the Khobar Aquifers have increased by 96 percent during the last decade due to extensive developments in social, industrial and construction sectors. The water demands are expected to increase in the future. Development of proper pumping policies are important to satisfy the growing demands and to conserve the finite water resources. This should be based on an understanding of a detailed groundwater budget of each aquifer in the vicinity of the Greater Dhahran area. Previous regional groundwater studies for Eastern province did not investigate the water budget of the aquifers. The previous hydrogeological studies by Italconsult (1969) and GDC (1980) defined the main aquifer system and its general characteristics over an area of 362,000 Sq. Km of the Eastern Province. Yazicigil *et al.* (1986) developed a numerical model for the Dammam Aquifer as a single hydraulic unit to asses the impact of water stresses on groundwater level in the Eastern Province. But, the most important regional aquifer underlying the Rus Formation *i.e.*, the Umm Er Radhuma Aquifer, was not included as a part of the aquifer system. Rasheeduddin *et al.*(1989) developed a quasi-three dimensional groundwater flow model to determine the hydraulic properties of the multi-aquifer system including the Alat, the Khobar and the Umm Er Radhuma Aquifers on a regional level.

In this work, the numerical analysis has been used to define the water budget for each individual aquifer in a multi-aquifer system in Greater Dhahran Area. Therefore, the present study used the United States Geological Survey's MODFLOW (McDonald and Harbaugh 1988) to simulate the groundwater flow conditions. MODCELL and CONVML programs were used to calculate the detailed groundwater budget in a multi-aquifer system in the Greater Dhahran Area of 224 Sq.Km.

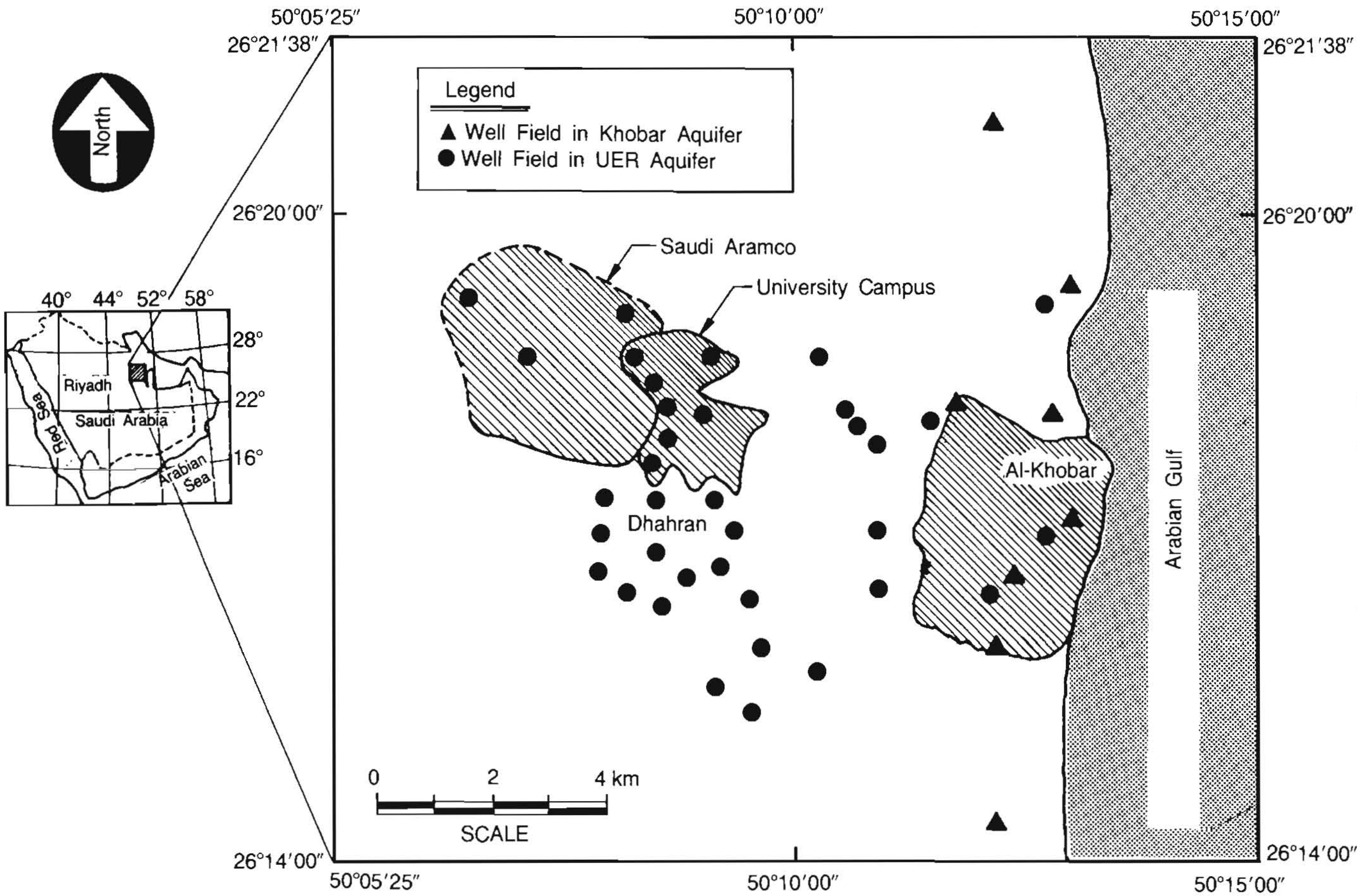

Fig. 1. Location Map of the study area showing the distribution of well fields.

Age			Formation	Member	Generalized Lithologic Description	Thickness (m)	Hydrogeologic Unit
Quarternary			Surficial deposits		Gravel, sand and silt		Variable productivity depending on recharge
Tertiary	Paleogene	Eocene	Dammam	Alat	Skeletal, detrital and dolomitic limestones	0 – 80	Aquifer
Tertiary	Paleogene	Eocene	Dammam	Alat	Dolomitic marls with limestone intercalations (orange color)	0 – 30	Aquitard
Tertiary	Paleogene	Eocene	Dammam	Khobar	Skeletal-detrital limestones, dolomitic limestones with argillaceous limestones near the bottom	0 – 70	Aquifer
Tertiary	Paleogene	Eocene	Dammam	Alveolina Limestone	Limestones interbedded with shales and marls	0 – 20	Aquitard
Tertiary	Paleogene	Eocene	Dammam	Midra and Saila Shales	Blue and dark gray fissile shales with gypsiferous lenses	0 – 10	Aquitard
Tertiary	Paleogene		Rus		Chalky limestones, anhydrites marls and shales	10 – 90	Aquitard
Tertiary	Paleogene	Paleocene	Umm Er Radhuma (UER)		Limestones, dolomitic limestones and dolomites	> 300	Aquifer
Cretaceous			Aruma		Limestones, subordinate dolomites and shales	—	Aquifer

Fig. 2. Generalized Lithostratigraphic succession of the study area (modified after Powers *et al.* 1966).

History of Groundwater Extraction

The major groundwater pumping activities in the Greater Dhahran Area are from the Umm Er Radhuma (UER) Aquifer. More than 70 production wells were drilled within the area. The major users of groundwater from this aquifer are: King Fahd University of Petroleum and Minerals (KFUPM), Saudi ARAMCO, the International Airport and other communities at Al-Khobar city in the vicinity of the Dammam Dome. The groundwater is mainly used for domestic and landscape irrigation purposes. The main water users of Khobar Aquifer are in the city of Al-Khobar. Fig. (1) shows the major well field locations in the UER and Khobar aquifers. The total groundwater withdrawals from UER Aquifer have significantly increased from 17.83 million m^3 (MCM) in 1967 to 37.29 and 68.56 MCM in 1980 and 1990 respectively. The extraction rates from Khobar aquifer have also increased from 7.84 MCM in 1967 to 20.9 and 45.46 MCM in 1980 and 1990 respectively. The overall increase from both aquifers during 1980 - 1990 was around 96%. Groundwater from the Alat Aquifer is not utilized in the area.

Conceptual Basis of Groundwater Budgeting

A detailed water budget analysis for each individual aquifer of a multi-aquifer system was established during steady state and transient conditions using the following steps:

- A groundwater flow simulation model was developed for the multi-aquifer system in Greater Dhahran area using the USGS groundwater flow model, MODFLOW, developed by McDonald and Harbaugh (1988). This step defines the total volumetric groundwater budget in terms of inflows and outflows for the whole multi-aquifer system during steady state and transient conditions.

- A special program MODCELL developed by USGS (Harbaugh 1990) was used to calculate the volumetric inflows and outflows of each cell of individual aquifer within the modeled area under steady and transient conditions.This program utilizes the output of MODFLOW to calculate the groundwater budget of each cell.

- A utility module CONVML developed by USGS (Harbaugh 1990) was used to convert the output data files of MODCELL which contain the detailed budget of each aquifer from binary to ASCII formats. A special program was developed in FORTRAN in order to make the output files of MODCELL compatible with CONVML format requirements.

Groundwater Budget

In the present study, each aquifer *i.e.*, the Alat, the Khobar and the Umm Er Radhuma were considered as an individual unit of a multi-aquifer system. Inflows and outflows of an individual cell of each aquifer were calculated to define the total volumetric budget of the aquifer. The volumetric budget during steady state conditions is given in Table (1). The final simulation run has indicated that most of the inflows to the system are from head dependent boundaries in the west. The UER Aquifer receives about 13,700 m^3/day (9% of its water) by recharge due to precipitation and the rest (134,928 m^3/day or 91%) is through lateral inflow across the western head dependent boundary. A significant amount of this water (67,417 m^3/day or 45%) flows upwards to the Khobar aquifer, about 48,861 m^3/day (33%) is discharged from pumping wells and about 32,118 m^3/day (22%) flows out of the area across the eastern boundary. The Khobar Aquifer receives about 67,417 m^3/day or 86% of its water by vertical flows from UER Aquifer and 11,300 m^3/day (14%) by lateral inflow across the western boundary. This indicates the importance of vertical recharge from the UER Aquifer into the Khobar Aquifer as a major source of water supply. About 21,476 m^3/day or 27% of Khobar water is discharged from wells and 52,511 m^3/day (67%) flows out of the area across the eastern boundary. In the Alat aquifer, about 4,954 m^3/day (90%) comes by upward flows from Khobar and 580 m^3/day (10%) from lateral inflows through the western boundary. Almost all this water flows out of the study area across the eastern boundary.

Table 1. Volumetric budget in m^3/day for the entire model during steady state conditions, 1967.

	Alat Aquifer	Khobar Aquifer	UER Aquifer	Total
Constant head	− 5,536	− 52,511	− 32,118	− 90,165
Discharge from wells	—	− 21,476	− 48,861	− 70,337
Recharge due to precipitation	—	—	13,700	13,700
Head dependent boundary flows	580	11,300	134,928	146,808
Vertical leakage into the aquifer	4,954	67,417	—	72,371
Vertical leakage out of the aquifer	—	−4,954	−67,417	−72,371
Balance	− 2	−224	232	6
Percent error	0.03	0.28	0.15	0.002

The same procedure was adopted to calculate the detailed water budget of an individual cell of each aquifer during transient conditions. The volumetric budget for the year 1990 (Table 2) shows that the inflows from the western head dependent boundary have increased to 219,723 m^3/day and 70,670 m^3/day in UER and Khobar Aquifers respectively. Discharges from wells in UER, and Khobar Aquifers were increased to 180,218 and 115,506 m^3/day respectively. Alat Aquifer receives 535 m^3/day through the head dependent boundary in the west. Recharge due to precipitation in UER Aquifer remained at the previous level of steady state conditions. Outward flows through the constant head boundaries from the UER and the Khobar aquifers have been reduced to 3,223 m^3/day and 3,945 m^3/day respectively. About 1,796 m^3/day is being discharged through the eastern boundary towards the Arabian Gulf from the Alat aquifer. Vertical flows from UER to Khobar and from Khobar to Alat were reduced to 50,022 m^3/day and 1,260 m^3/day respectively. Fig. (3) shows the hydrogeological cross section and groundwater budget during transient simulation. The overall percent discrepancy in water balance of all aquifers was very negligible *i.e.*, 0.17%.

The groundwater budget shows the importance of UER Aquifer as a major water supply source to Dhahran area, as well as a potential recharge source to the Khobar and the Alat Aquifers. These important findings should be taken into consideration when developing future water management and conservation schemes in Dhahran.

Table 2. Volumetric budget in m^3/day for the entire model -1990

	Alat Aquifer	Khobar Aquifer	UER Aquifer	Total
Constant head	− 1,796	− 3,945	− 3,223	− 8,945
Discharge from wells	—	− 115,506	− 180,218	− 295,724
Recharge due to precipitation	—	—	13,700	13,700
Head dependent boundary flows	535	70,670	219,723	290,928
Vertical leakage into the aquifer	1,260	50,022	—	51,282
Vertical leakage out of the aquifer	—	−1,260	−50,022	−51,282
Balance	1	19	−40	−41
Percent error	0.05	0.16	0.17	0.012

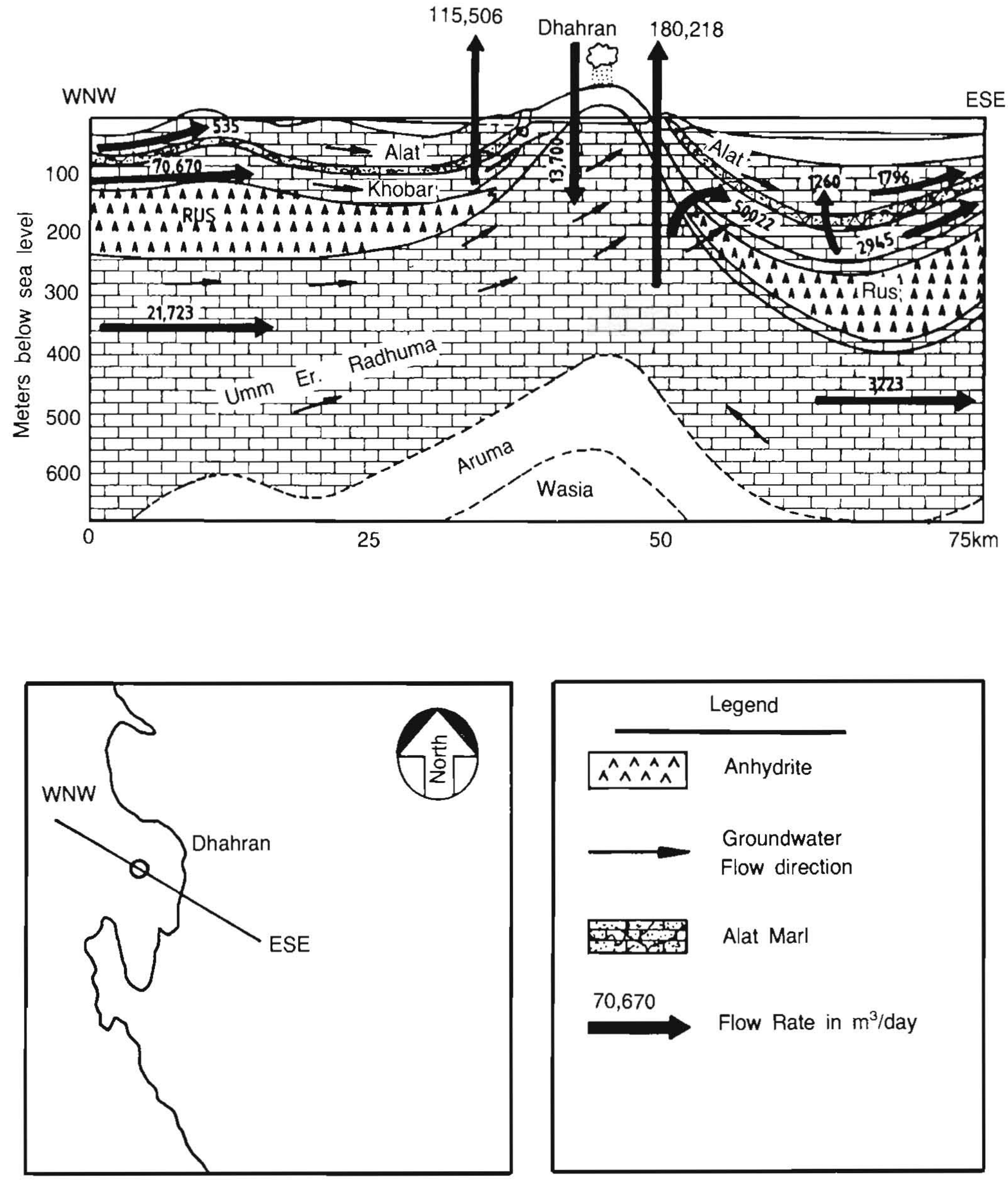

Fig. 3. Hydrogeological cross section showing groundwater budget during the year 1990.

The technique used in this study has proven to be an effective tool in defining a complicated water budget in a multi-aquifer system under steady and transient conditions. This technique can be used on regional as well as localized areas such as Dhahran.

Conclusion

Numerical techniques were utilized successfully to define a detailed groundwater budget for each individual aquifer in a multi-aquifer system in the Greater Dhahran Area under steady and transient conditions. The MODFLOW, MODCELL and CONVML programs were used to achieve this objective. A special program was also developed to make the output data files of MODCELL compatible with the CONVML utility module. The developed water budget suggests that UER Aquifer is highly productive and is the main potential groundwater source in the area followed by the Khobar Aquifer in satisfying the present and future water demands. It also shows that the Alat Aquifer is an insignificant groundwater source in the area. These findings are essential for developing present and future water pumping policies and management schemes for the area. Similar techniques can be used to other parts in Saudi Arabia, and in other countries in arid as well as semi-arid regions to improve the groundwater resources management and conservation.

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إعداد ميزانية المياه الجوفية للنظام متعدد التكوينات الحاملة للمياه بإستخدام التقنية الرقمية

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إن استخدام تقنية التحليل الرقمي لحساب الميزانية المائية التفصيلية لكل تكوين في مجموعة التكوينات الحاملة للمياه هو أمر غير مألوف. إستخدم التحليل الرقمي في هذه الدراسة للتعرف على الميزانية المائية لكل تكوين حامل للمياه بشكل فردي ضمن نظام مجموعة من التكوينات الحاملة للمياه في منطقة الظهران الكبرى. تم تطوير نموذج شبه ثلاثي الأبعاد لتمثيل جريان المياه الجوفية في نظام مجموعة التكوينات الحاملة للمياه وذلك باستخدام نموذج (USGS - MODFLOW). ثم استخدم برنامج (MODCELL) لحساب تدفق المياه في كل خلية من خلايا كل تكوين. وقد استخدم برنامج (CONVML) لتحويل البيانات المحسوبة من (MODCELL) من لغة الحاسب الآلي غير المقروءة الى بيانات حسابية مقروءة. وتم تطوير برنامج خاص لتحويل البيانات المحسوبة بواسطة (MODCELL) من أجل جعلها ملائمة للاستعمال من برنامج (CONVML).

ان نتائج ميزانية المياه الجوفية التي تم حسابها توضح أهمية تكوين أم الرضمة كأحد المصادر الرئيسية للمياه في منطقة الظهران وكمصدر هام لتغذية تكويني الخبر والعلاه.

يـوصي باستعمـال نتائـج ميزانيـة المياه الجـوفية لتحسـين خطط إدارة الميـاه الجوفية والمحافظة على الثروة المـائية حـاضراً ومستقبـلاً في منطقـة الدراسـة. كما ويمكن استعمال تقنيات مماثلة للتعرف على ميزانية المياه الجوفية في منـاطق اخرى من المملكة أو بلدان اخرى في المناطق الجافة من أجل تحسـين برامـج إدارة المياه الجوفية والمحافظة عليها.