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Study of Recharge Outcrop Relation of the Wasia Aquifer in Central Saudi Arabia

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ABSTRACT. The Wasia formation is the most prolific Cretaceous aquifer in central Saudi Arabia. The Recharge Outcrop Relation (ROR) is developed for calculating the amount of water that percolates into this aquifer. The relation provides an effective way of estimating recharge to aquifers in extremely arid regions where there is no vegetation cover at all. The result shows that the recharge amount is about 4 mm/year in the central part of Saudi Arabia. Furthermore, investigations by means of the Kriging method lead to Darcy velocity estimations within the aquifer in the study area. In addition, comparison of estimates based on groundwater velocity and those based on isotope information showed that they are in good agreement.

Introduction

In extremely arid regions of the world such as central Saudi Arabia, the recharge from surface flow to aquifers is very small, if it exists at all. Therefore, every single drop of water is very precious for groundwater storage. Consequently, the recharge calculations in those regions pose special problems which should be solved by refined techniques suitable for the prevailing conditions in the environment. Among those condition are sporadic areal distribution of rainfall event, its rare temporal occurrence, high intensity, barren earth surface with virtually no plant cover, ... etc. The central Saudi Arabia is located in an extremely arid zone belt of the world with characteristics of very little and unpredictable amounts as as well as irregular occurrences of rainfall, (Şen 1983). Rainfall occurs usually during a period from November to May. In addition, spatial haphazard variations of infiltration and porosity properties, in extremely arid regions, make the estimation of the total recharge to deep aquifer system rather difficult. Besides, the evaporation rates are high which lead to excess loss of water if it is available at the surface, (Salih and Şendil 1984).

From hydrogeologic standpoint, the Wasia formation is the most prolific Cretaceous aquifer in central Saudi Arabia. In fact, the Wasia is of significant potential as a source of water supply for domestic uses and agricultural purposes, especially in the northern part of the study area, (Fig. 1). This aquifer supplies the capital city,

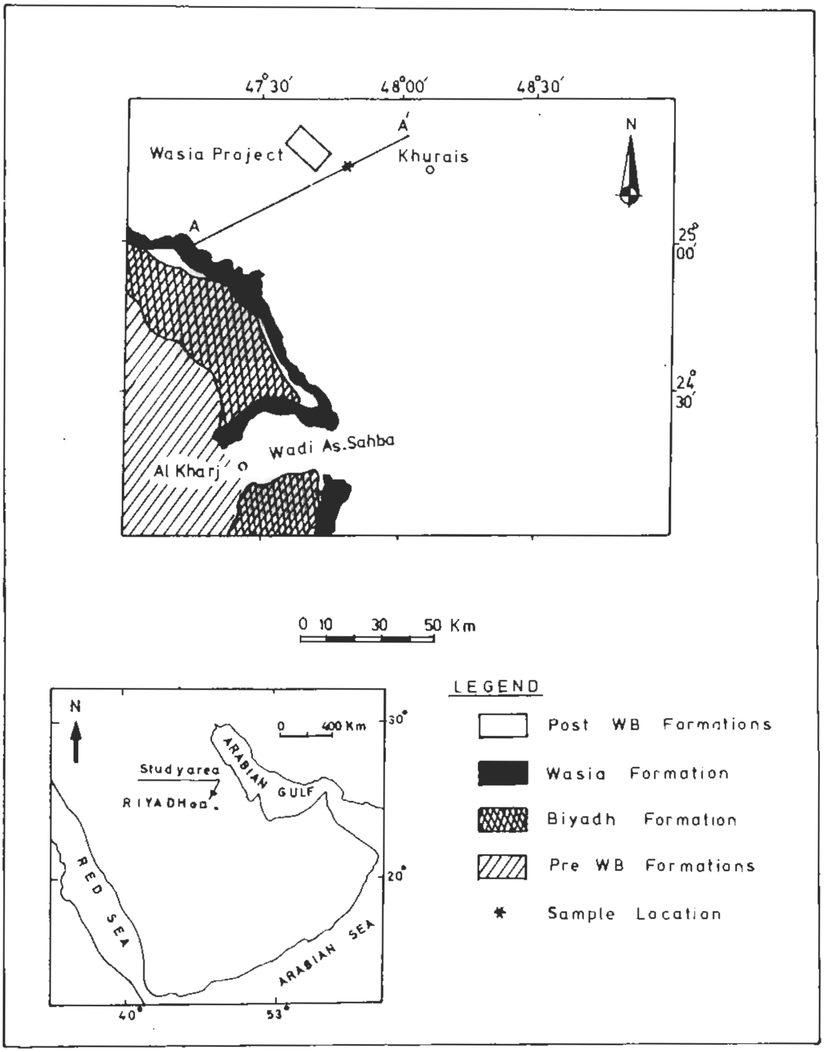

FIG. 1. Geologic and location map of the study area.

Riyadh, with about 100,000 m^3/day, (Noory 1983). The unprecedented demand on water from the Wasia aquifer makes it an indispensably valuable source of groundwater. On the other hand, in the south, Al-Kharj area has extensive irrigation projects. Some amount of rainfall directly, or indirectly runoff infiltrate to this aquifer as recharge which does not equalized the withdrawal amount from the same aquifer.

However, still such a recharge is extremely significant and due to be the paucity of rainfall data in the past its estimation has been rather unreliable, leading to overestimations. Although there have been many previous studies for estimating the recharge in the central Saudi Arabia by different authors, they are quite similar to the techniques which are valid for humid regions only. Some of them depend on costly isotope analysis and provide indirect answer, (Dinçer *et al.* 1974); some are based on exhaustive mathematical models which depend on water balance equation considering aquifer parameters, (Sir M. MacDonald and Partners, i.e., S.M.M.P. 1975); still others rely on simple assessment of hydrogeological data, (B.R.G.M. 1976); and finally, there are approaches which use complicated probabilistic techniques, (Caro and Eagleson 1981). None of these studies do consider the rock types within the ıdy area but depend on either digital computers for calculations or on sample analysis for trace elements.

It is among the main purposes of this paper to develop and to apply a new method for estimating the amount of the recharge, that percolates through outcrops. To this end, a simple and effective way of recharge calculation is presented on the basis of regional lithology and their combinations through monthly water balance approaches by considering daily rainfall events. It is shown that although this approach is simple, it still gives comparatively consistent results for arid regions than other techniques. Its adaptation does not present any difficulty for other arid regions of the world.

In addition, the Darcy velocity distribution within the study area is mapped by the Kriging estimation (Subyani 1988). The velocity interpolations are then confirmed by either the isotope studies or from the recharge calculations due to the previous workers such as Caro and Eagleson (1981). The comparison of results shows that the Kriging values are reliable in estimating the groundwater velocity.

Hydrogeology of the Study Area

The Wasia formation is a member of thick sedimentary sequence ranging from Cambrian to Recent. It consists mainly of sandstone, coarse in places but predominantly medium to fine grained and interbedded siltstone, clay and shale (Powers *et al.* 1966; Moshrif and Kelling 1984 and Subyani and Şen 1989). The Wasia sandstone is exposed as a discontinuous arch in the study area from the northwest to the south (see Fig. 1). The depositional environment of the Wasia formation is a part of Cretaceous depositional cycle (Sharief *et al.* 1989). During the Middle Cretaceous time, the fluvial deposition was mainly at the edge of the progressively older unit (Biyadh Formatoin). In subsurface, within the study area, the depositional environment changes from marine shelf carbonate (Shu'aiba Formation) below, to mainly shelf marine calstic and carbonate (Wasia Formation) above. During the upper Cretaceous time, a major marine transgression occurred and reached to the extent when the Aruma carbonate rocks were deposited unconformably (Fig. 2). From hydrogeological point of view, the Wasia and Biyadh (WB) sandstone aquifers in outcrop become as one hydrogeological unit. Therefore, it is very difficult to estimate the subsurface recharge contribution for the Wasia only. Structurally, the sedimentary sequence in central Arabia has a homocline structure, the beds dip gently on uniformally about

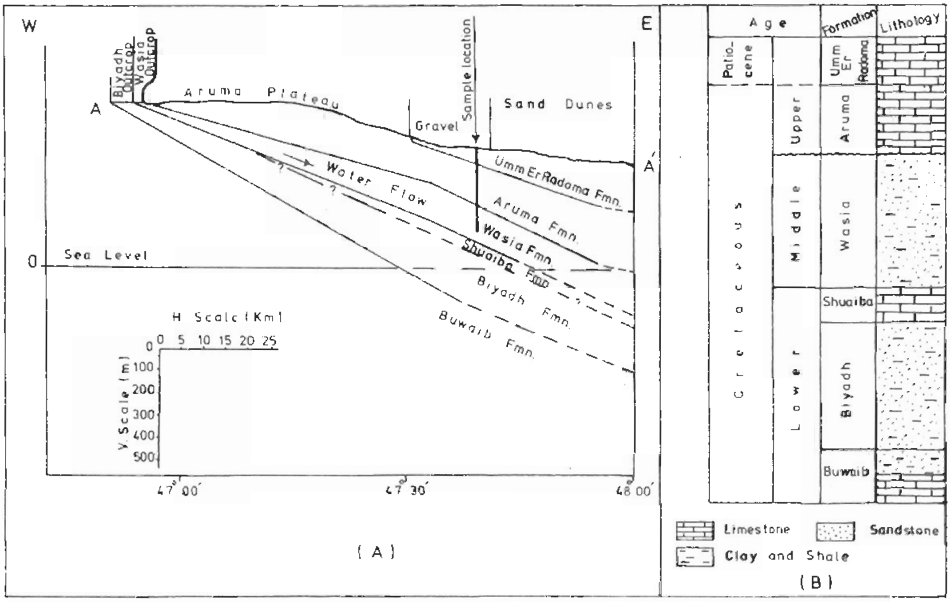

FIG. 2(A). Geological cross-section (A-A'). (Modified from B.R.G.M. 1976).
(B). Generalized rock units in the study area.

one degree to the east, the groundwater flow follows the dip direction to the east. For instance, in the south of the study area, there is As-Sahba structure depression. The (WB) sandstone crops out along the sides of the valley and beneath the wadi fill deposits. All three facies, namely Wasia, Biyadh and alluvium may be considered as one hydrogeological unit. Among the several major wadi systems is As-Sahba where water percolates into the alluvium and then into the deeper aquifers, (El-Khatib 1980).

Critical Discussion of Recharge Calculations

In Saudi Arabia there are neither rivers nor lakes except the seasonal runoff that goes through wadis. Therefore, domestic, agricultural and industrial activities are all dependent heavily on groundwater resources. In turn these resources are primarily dependent of natural recharges. In the study area, there have been studies estimating the recharge contribution to the Wasia and Biyadh aquifers. A brief summary of these studies are presented in Table 1. Sogreah (1968) estimated very roughly the recharge from the available hydroclimatological data. The average amount of rainfall likely to percolate deep enough contributing to groundwater storage is found as about 3-5 mm/year on the average. Sogreah (1968) has studied to some extent piezometric gradient, aquifer thickness and permeabilities which suggest that some 11×10^6 cubic meters per year of recharge takes place within Wadi As-Sahba only.

TABLE 1. Recharge rates from different studies.

Study	Method	Recharge Rate (mm/year)
Sogreah (1968)	Hydroclimatological Data	3-5
Dinçer *et al.* (1974)	Isotope	20.0
S.M.M.P. (1975)	Piezometry and Transmissivity	5.2
B.R.G.M. (1976)	Hydroclimatological Data	6.5
Caro and Eagleson (1981)	Dynamic Model	6.0
This Study	ROR	4.0

On the other hand, two distinctive methods are proposed by Dinçer *et al.* (1974) in calculating the recharge amount that goes through sand dunes around Khurais area. One of these method depends on temperature, grain size and the sand moisture measurements and shows that infiltration from the precipitation in the sand dunes is a complex phenomenon. Other method is based on thermonuclear tritium content of the sand moisture which neglects all of the previous physical properties. On the basis of these methods the authors concluded that the recharge is about 20 mm/year. Furthermore, S.M.M.P. (1975) estimated the recharge through the WB formations based on piezometry as well as transmissivity which very areally and accordingly calculated the average recharge value as 5.2 mm/year. B.R.G.M. (1976) concluded that their study of recharge depends on the hydroclimatological data which were reprocessed for the purpose of numerical model simulations leading to the annual recharge amount of about 6.5 mm/year. However, Caro and Eagleson (1981) estimated median annual recharge by using a dynamic model of annual water balance with the maximum depth of about 6 mm/year. At the end they reached to the conclusion that the Wasia aquifer is being mined due to the excessive pumping.

All of the aforementioned previous studies have missed some common points, in that the information itself in the form of data is not enough to give a clear picture of the recharge phenomenon. For example, Sogreah (1968) study depends on very short records of hydroclimatological data (about 5 years). Dinçer *et al.* (1974) measured the recharge rate from isotope technique, which yield reliable answers about the groundwater mixture, age and recharge possibilities only. However, it fails to provide reliable numerical answers for groundwater recharge amounts. On the other hand, S.M.M.P. (1975) study is more precise, especially around unconfined portion. B.R.G.M. (1976) concluded from long period data and model simulation leading to an optimized value which did not consider the outcrop of geological formations. Besides, it requires digital computer usage for calculations which might not be practical.

ROR Model

Recharge Outcrop Relation (ROR) is a new method for estimating the amount of recharge that goes through outcrops. It is a technique which combines the geological lithology with water budget. It provides a simple way of calculating mean monthly recharge amount from daily rainfall amounts. In the study area, there are 5 climatological stations for rainfall measurements and they are located at Riyadh, Al-Kharj, Dirab, Khurais and Harad as shown in Fig. 3. In order to apply the ROR method, the study area is divided by using the Theissen polygon technique into representative subareas for each station. Hence, each subarea will be referred to by the name of sta-

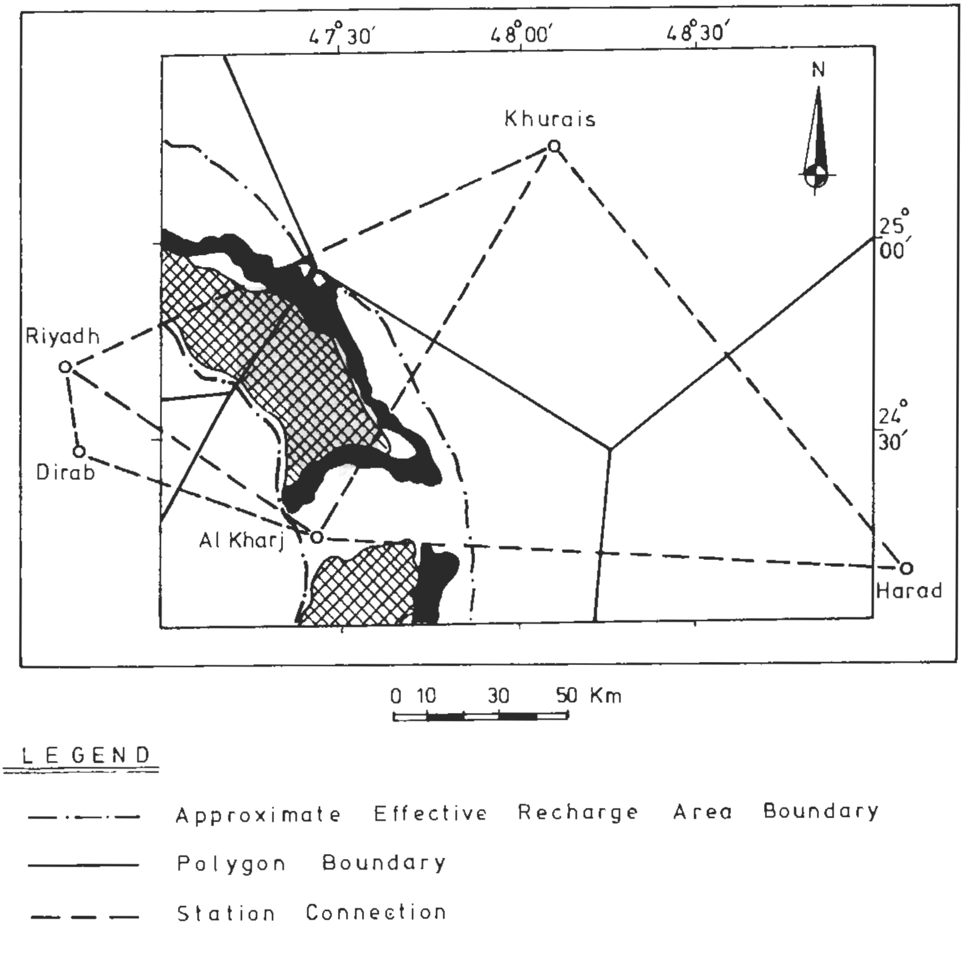

FIG. 3. Theissen polygon on subareas in the study area.

tion whithin the subarea. It is obvious from such subdivision of the area that outcrop of WB falls under Riyadh and Al-Kharj subareas only. This means that the recharge to these aquifers is direct, whereas the recharge from Dirab subarea is indirect i.e., prior to recharge there appears runoff in this subarea. Table 2 and 3 show the mean monthly recharge rates (7 months) in Riyadh and Al-Kharj stations for period 1964-1984 and 1970-1983, respectively. In these tables the second column shows the mean monthly rainfall which is calculated from daily rainfall records. In the third column is the mean monthly values of actual evapotranspiration for the same daily rainfall

TABLE 2. Monthly recharge rates for Riyadh area (1964-1984).

Months with Rainy Days (1)	Mean Rainfall (mm) (2)	Mean Actual ETR (mm) (3)	Lake ETR = ETR × 0.7 (mm) (4)	Runoff = Rain. × 0.1 (mm) (5)	Recharge Rate (mm) (6)
J	10.2	5.6	3.6	1.0	5.6
F	10.3	5.0	3.5	1.0	5.7
M	12.6	19.7	22.5	15.0	0.0
A	11.5	17.3	12.1	1.1	0.0
M	4.7	10.0	7.0	0.5	0.0
N	2.3	2.3	1.6	0.23	0.5
D	5.0	3.7	2.6	0.5	0.8
Total					12.7

TABLE 3. Monthly recharge rates for Al-Kharj area (1970-1983).

Months with Rainy Days (1)	Mean Rainfall (mm) (2)	Mean Actual ETR (mm) (3)	Lake ETR = ETR × 0.7 (mm) (4)	Runoff Rain × 0.1 (mm) (5)	Recharge Rate (mm) (6)
J	5.0	4.1	2.9	0.5	1.6
F	5.0	4.0	2.8	0.5	1.7
M	17.0	23.0	16.1	1.7	0.0
A	10.0	12.0	8.4	1.0	0.0
M	1.8	7.6	5.3	0.2	0.0
N	1.7	2.3	1.6	0.2	0.0
D	3.4	3.8	2.6	0.3	0.5
Total					3.8

period depending on the equation for estimating the actual evapotranspiration $(ETR)_{act.}$ as:

$$(ETR)_{act.} = 1.16\ (ETR)_{J\text{-}H} - 0.37 \tag{1}$$

where $(ETR)_{J\text{-}H}$ is the evapotranspiration according to Jensen-Haise method which was recommended by Salih and Şendil (1984) for central Saudi Arabia conditions. To calculate the lake ETR, the observed ETR records are multiplied by pan coefficient which is equal to about 0.7 for arid zones, (Linsley *et al.* 1975). The result are presented in Tables 2 and 3 column 4. The study area is devoid of runoff measurements and therefore the runoff percentages are calculated empirically from rainfall for arid zones as 10 percent, (Chow 1964) which are shown in column 5. Finally, the mean monthly recharge is calculated by applying the following water balance equation :

$$\text{Recharge Rate} = \text{Rainfall} - (\text{Runoff} + \text{Lake ETR}) \tag{2}$$

which leads to the results presented in the column 6 of Tables 2 and 3. In order to calculate the recharge rates by ROR method first of all, estimates of particular outcrop formation – percentages within each subarea are calculated from respective polygons by using planimeter. Subsequently, the multiplication of these percentages with the respective amount of recharge gives the amount of water received by WB outcrop as recharge. Details of the calculations are presented in Table 4. The recharge con-

TABLE 4. ROR calculations.

Sub Area	Total Area (km^2)	Effective WB Area (km^2)	Percentage of WB Area %	Recharge (mm/y)	Recharge to WB Area (mm/y)
Riyadh	2710	1924	71	12.6	9.0
Al-Kharj	9250	4530	49	3.8	1.8
Weighted Average (mm/y)					4.0

tributing area of WB in Riyadh and Al-Kharj subareas has an area of 1924 km^2 and 4530 km^2, respectively. The weighted average recharge in Table 4 is calculated as :

$$r_w = \frac{r_R \times A_R + r_K \times A_K}{A_R + A_K} \tag{3}$$

where:

r_R is the recharge rate to Riyadh subarea
A_R is the area of Riyadh subarea
r_K is the recharge rate of Al-Kharj subarea
A_K is the area of Al-Kharj subarea

Substitution of the necessary quantities from Table 4 into equation (3) leads to

$$r_w = \frac{9 \times 1920 + 1.8 \times 4530}{1920 + 4530} = 4.0 \text{ mm/year}$$

This weighted average value represents the recharge with use of ROR method. Comparison of this value with the results of previous studies as presented in Table 1 indicates the obvious overestimation of other techniques which are valid for humid regions only.

Groundwater Velocity

Caro and Eagleson (1981) after their estimation of aquifer recharge in central Saudi Arabia, concluded that the Wasia aquifer is being mined. However, according to Subyani and Şen (1989) the groundwater velocity distribution is obtained after geostatistical modelling of the Wasia aquifer parameters namely hydraulic conductivity, (k) and hydraulic gradient, (i). Hence, the result of regional groundwater velocity in the form of map is shown in Figure 4 which indicates that the groundwater velocity through the aquifer is rather low, (2.1 m/year). As mentioned earlier, Figure 2 illustrates the recharge location and flow direction through the geologic cross-section including isotope sample location. Low groundwater velocity means that the

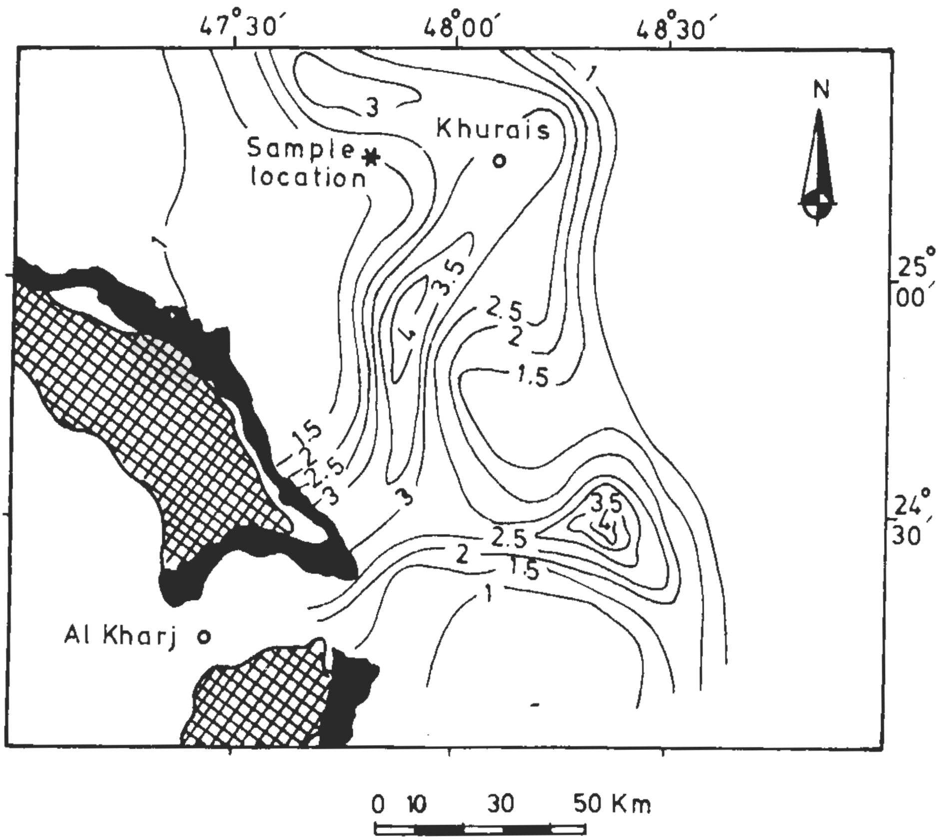

FIG. 4. Kriged map of groundwater velocity.

recharge takes very long time to move through aquifer materials. Supporting the Kriged velocity, Figures 1 and 2 illustrate the isotope sample location from which S.M.M.P. (1975) determined the age, as more than 35,000 years by Carbon 14 dating.

Furthermore, the distance between recharge area and the sample location is about 80 km, and the average Kriged velocity is 2.1 m / year. Hence, from the basic physical relationship as Time = Distance / Velocity one can calculate, the time as $80 \times 10^3 / 2.1 = 38{,}000$ years. It means that the water reaches from the recharge area to that location after more than 35,000 years according to isotope dating and around 38,000 years by Kriged groundwater velocity.

Conclusion

The ROR technique is developed for calculation of the recharge amount that contributes to the Wasia and Biyadh aquifers. The necessary hydrogeological data are available at Riyadh and Al-Kharj stations for a period of 21 and 14 years, respectively in forms of daily rainfall amounts. The Theissen polygon method and subsequently the percentages of the effective Wasia and Biyadh outcrop areas are used to estimate the recharge rates. The results show that the amount of recharge is about 4 mm / year with ROR, and 5.8 mm / year without ROR consideration. The latter value corresponds to the average of all the previously available results for the same area in the literature but from different studies available. It is obvious that the ROR result is the smallest among the results of the different studies which are mainly applicable in humid regions. Hence, they provide overestimations of groundwater storage availabilities in the arid regions of the world such as central Saudi Arabia. This might be due to the fact that they do not take into consideration the lithological extends of the different rocks which are not covered by any vegetation at all. The elegency of ROR is that it gives an emphasis on the lithological coverage of the rocks within the arid regions in addition to hydroclimatological data that are also used in other techniques.

From Kriged map of velocity distribution within the area, the regional groundwater velocity is obtained, as 2.1 mm / year which compares well with the isotope study.

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دراسـة التغـذيـة وعلاقـتها بمنكشف متـكون الوسيـع في وسـط المملكة العربيـة السعوديـة

علي صبياني و زكاي شن

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المستخلص . يعتبر متكون الوسيع من أهم الخزانات المائية التابعة للعصر الطباشري في وسط المملكة . وهذه الورقة تتعلق بدراسة العلاقة بين التغذية المَطرية ومنكشف المتكون بنـوع من الـدقة وخاصة أن المنطقة تقع ضمن نطاق المناطق الشديدة الجفاف ، ودلت النتائج على أن مقدار التغذية لداخل المتكون لا تتجاوز ٤ ملمتر/سنة . وبتطبيق طريقة التنبوء الإقليمي Kriging Method لحساب سرعة المياه الجوفية داخل المتكون مقارنة بعمر المياه عن طريق النظائر المشعة أثبتت أن المياه الجوفية عبارة عن مخزون غير متجدد على المدى القريب .