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ORIGINAL ARTICLE

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Using CRD method for quantification of groundwater recharge in the Gaza Strip, Palestine

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Abstract Rainfall is the main source of groundwater recharge in the Gaza Strip area in Palestine. The area is located in the semi-arid zone and there is no source of recharge other than rainfall. Estimation of groundwater recharge from rainfall is not an easy task since it depends on many uncertain parameters. The cumulative rainfall departure (CRD) method, which depends on the water balance principle, was used in this study to estimate the net groundwater recharge from rainfall. This method does not require much data as is the case with other classical recharge estimation methods. The CRD method was carried out using optimisation approach to minimise the root mean square error (RMSE) between the measured and the simulated groundwater head. The results of this method were compared with the results of other recharge estimation methods from literature. It was found that the results of the CRD method are very close to the results of the other methods, but with less data requirements and greater ease of application. Based on the CRD method, the annual amount of groundwater recharge from rainfall in the Gaza Strip is about 43 million m^3.

Keywords Groundwater recharge/water budget · Rainfall/runoff · Arid regions · Gaza Strip

Introduction

Groundwater recharge from rainfall is the main source of recharge of the aquifer in the Gaza Strip area. Because of its geographical location in the semi-arid zone, there are almost no other sources of groundwater recharge in the Gaza Strip. The average rainfall in the area based on 20 years' records amounts to 321 mm/a (PWA 2001). Since the total area of the Gaza Strip is about 365 km^2, the annual volume of rainfall is about 111 million m^3. Only part of this amount percolates to the aquifer and the rest is evapotranspiration.

Identification of the net groundwater recharge is essential for groundwater modelling and water resources management. The calculation of the net groundwater recharge is a big challenge for the hydrologist since there is no specific method to find out the net recharge reliably. There are so many methods for quantification of groundwater recharge from rainfall. Each method has its limitations and difficulty in application. All the methods which have been used in this regard result in an estimation of the actual value.

Many stochastic parameters such as soil properties, topography, rainfall amount, evapotranspiration, and depth to the water table affect the amount of percolated water. Because of uncertainty associated with estimation of these parameters, each method of estimation of groundwater recharge usually ends with different result. Although many empirical formulas were developed to find out the net groundwater recharge, none of them have been shown to be efficient and accurate. Each method of recharge estimation has its limitations in terms of applicability and accuracy.

Review of recharge estimation methods

Regarding the Gaza Strip area, many studies have been carried out to estimate the groundwater recharge from rainfall. Melloul and Bachmat (1975) have estimated the groundwater recharge for the Gaza Strip using recharge coefficients. They subdivided the area into three sub-zones and computed the coefficients for each sub-zone based on the soil type, and the average rainfall. The coefficients were estimated based on regression analysis between groundwater recharge and soil type. According to their study, Melloul and Bachmat found that the annual groundwater recharge in the area equaled to 41 million m^3.

Another study was carried out in the area by IWACO and WRAP (IWACO and WRAP 1995) to estimate the net groundwater recharge based on chloride mass balance. The chloride mass balance method is based on the assumption of conservation of mass between the input of atmospheric chloride and the chloride flux in the subsurface. This study was applied to the northern part of the Gaza Strip, where the top soil is composed mainly of sand dunes. In other words, that particular area has a high infiltration rate. Results of this study have showed that the amount of groundwater recharge is about 46 million m^3 per year (IWACO and WRAP 1995). Table 1 summarises the results of recharge estimation according to the different methods as discussed before.

The problem with the previously-mentioned methods is that their accuracy is poor. Since the calculation of recharge requires many uncertain parameters such soil type, land use, and hydrogeological properties, the results have a high degree of uncertainty.

In this study, another method was used to estimate the net groundwater recharge from rainfall. This method is called cumulative rainfall departure (CRD) and it depends on less uncertain data than other methods. The data required by the CRD method are: monthly rainfall records, measurements of groundwater levels, aquifer storativity, abstraction records, and lateral inflow and outflow.

Table 1 Some results of groundwater recharge in the literature

Source	Method	Value (million m^3/year)
Fink 1970	Change in aquifer storage	33–67
Melloul and Bachmat 1975	Recharge coefficients	41
IWACO and WRAP 1995	Chloride mass balance	46
CAMP 2000	Land use and recharge coefficients	37
CAMP 2000	Groundwater modelling	40–45

Methodology

The cumulative rainfall departure method (CRD)

The CRD method was proposed first by Bredenkamp et al. (1995). The theory behind cumulative rainfall departure depends on the water balance in the aquifer. This balance can be expressed as follows:

$$R = Q_p + Q_{out} - Q_{in} + \Delta h_i A \times S, \tag{1}$$

where:

R: the total recharge to the aquifer [L^3/T],
Q_p: the discharge from pumping [L^3/T],
Q_{out}: the lateral outflow [L^3/T],
Q_{in}: the lateral inflow [L^3/T],
Dh_i: the change in groundwater level in a time period i [L],
A: the area of study [L^2] and,
S: the aquifer storativity.

When the pumping rate in the above equation is known, the change in aquifer storage accounts for the net balance between the inflow and outflow to the aquifer. Hence, the cumulative rainfall departure can be expressed by the relation between rainfall and groundwater level fluctuations. It is assumed that there is a linear relationship between the monthly change in water level and the cumulative rainfall departure. Bredenkamp et al. (1995) has expressed this relation between rainfall and CRD in the following form:

$$\mathrm{CRD}_i = \mathrm{CRD}_{i-1} + (P_i - C), \tag{2}$$

where:

CRD_i: the cumulative rainfall departure (mm) for month i [L];
CRD_{i-1}: the cumulative rainfall departure (mm) for month i-1 [L];
P_i: precipitation (mm/month) [L/T];
C: a cut off value (below which no recharge occurred) (mm) [L].

This equation illustrates the relation between two CRD amounts in two successive time periods. The general equation, which is used to compute the net recharge from the CRD method can be written in the following form (Bredenkamp et al. 1995):

$$h_i = h_{i-1} + \frac{R}{S} + \frac{Q_{in} - O_{out}}{S \times A} - \frac{Q_p}{S \times A}, \tag{3}$$

where:

R: effective recharge = fraction of precipitation (m) [L];
Q_{in}: inflow into aquifer (m^3/month) [L/T];
Q_{out}: outflow from aquifer (m^3/month) [L/T];

Q_p: withdrawal from aquifer (m^3/month) [L/T];
h_i: head (m) in month I [L];
h_{i-1}: head previous month [L];
S: storativity;
A: area of study [L^2].

The pumping rate and precipitation records are usually known with good accuracy. Thus, if the lateral inflow and storativity are known, the only unknown in the above equation is R, which is the net recharge. Application of the CRD method can be done by plotting of the monthly measured groundwater level versus the computed level. The latter term, as it appears in Eq. 3, can be computed as a summation of the groundwater recharge, pumping, and the groundwater lateral inflow and outflow. Given the value of the storativity, the fit between the computed and observed groundwater level can be assessed. The best estimate of recharge can be obtained when the best fit between the computed and measured groundwater head is achieved.

The best fit can be obtained by minimisation of the root mean square error (RMSE) between the measured and calculated groundwater heads. An optimisation procedure is used with the help of Excel to minimise the error and to get the best fit between the two curves.

In the following sections, application of the CRD method to a case study is presented. To see the effec-

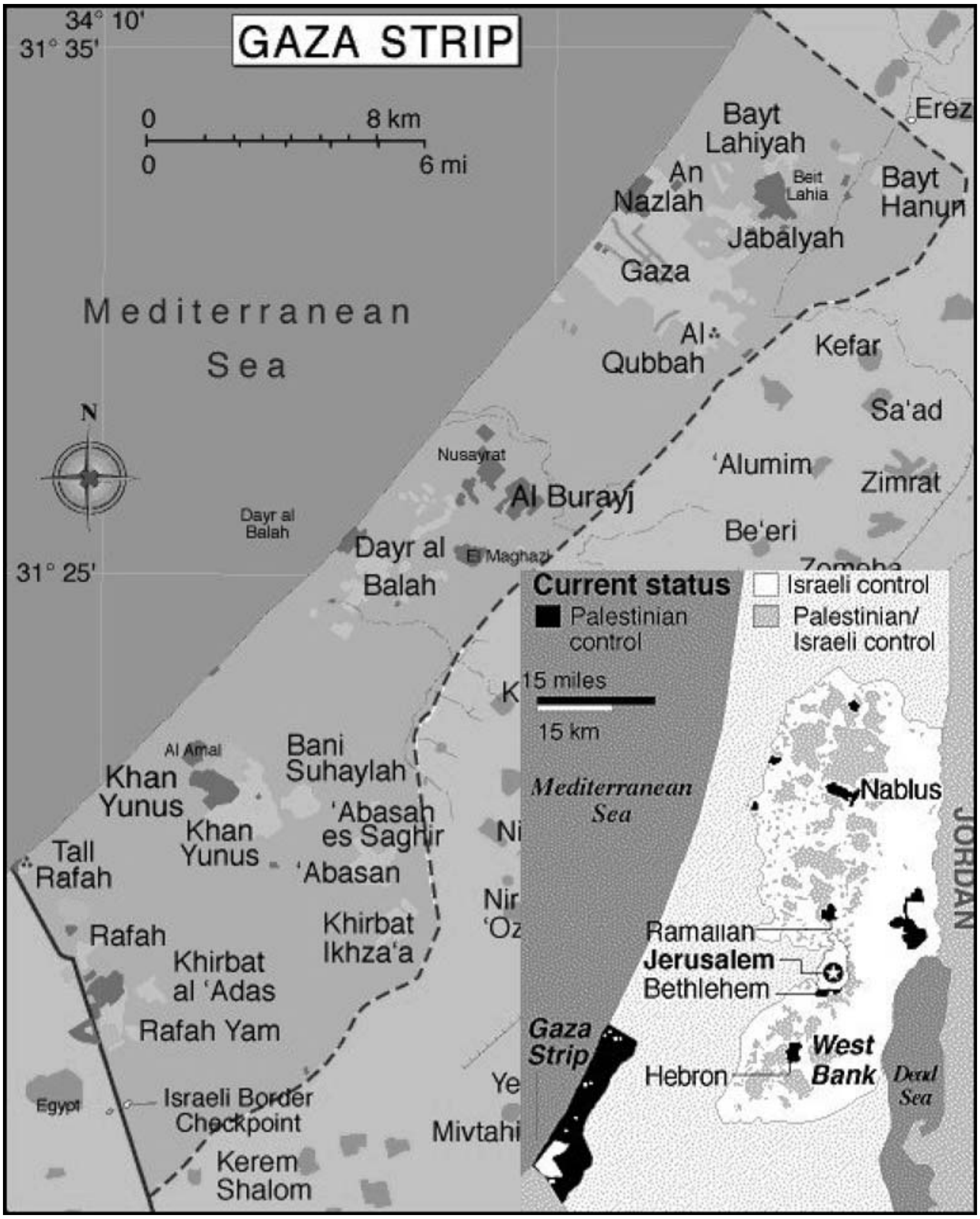

Fig. 1 Location map of the Gaza Strip

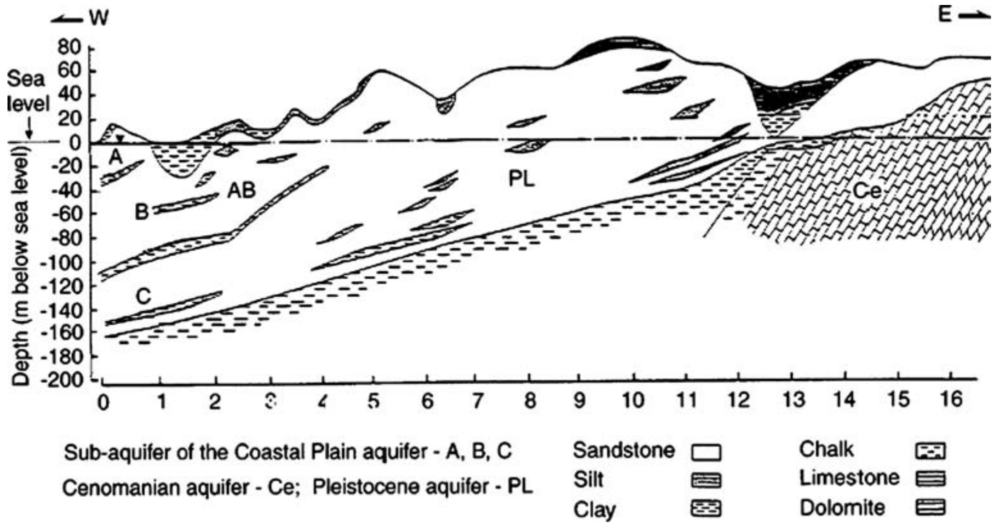

Fig. 2 Typical hydrogeological cross-section

tiveness of the CRD method, its results were compared with the results of other methods of recharge estimation.

Case study

The study area

The Gaza Strip area is part of the Palestinian occupied territories, located between longitudes 31 and 25 N, and latitudes between 34 and 20 E. It is a coastal area located along the eastern Mediterranean Sea (see Fig. 1). The length of the Gaza Strip is about 40 km, while the width varies from 6 to 12 Km. Thus, the total area of the Gaza Strip is about 365 km^2 . Because of its geographical location, the Gaza Strip forms a transitional zone between the semi-humid coastal zone in the north, the semi-arid loess plains in the east, and the arid Sinai desert in Egypt. The area consists of a littoral zone, a strip of younger dunes situated on top of a system of older Pleistocene beach ridge, and more to the east, gently sloping alluvial and loessial plains. The Gaza Strip is densely populated since about 1 million inhabitants (PCBS 2000) live in this small area. Therefore the population density in the area is the highest in the world.

Geology of the area

The aquifer system in the area of study is part of the coastal plain, which extends from Haifa city in the north to Sinai desert in the south and covers an area of about 2,000 km^2 (Metcaf and Eddy 2000). The coastal plain is characterised by flat relief, and is bounded to the east by the foothills of the mountain belt. This plain is narrow in the north and gets wider in the south with an average width of about 13 km. Calcareous sandstone and gravel from the Pleistocene age and recent Holocene sand dunes are the main water bearing layers in the aquifer. Some silts, clay, and conglomerate do exist in the aquifer formation. As shown in Fig. 2, the aquifer is mainly phreatic and its thickness varies from a few meters at the east of the Gaza Strip to some 170 m at the shoreline. The aquifer overlies thick impermeable marine clay of the Neogene age called the Saqiyia Formation.

Rainfall

The rainfall is an important component of groundwater recharge in the area since runoff is almost negligible. Although there is a wadi (seasonal stream) running from Israel across the Gaza Strip and draining into the Mediterranean sea, dams were built just behind the border of the Gaza Strip (United Nations 2003; ARIJ 1995). As a result, no flow takes place in this wadi anymore. There are eight meteorological stations in the area at which the rainfall amount is recorded on daily basis. According to the records of the Ministry of Transportation for the period from 1980 to 2000, the annual average rainfall varies from 433 mm/a in the north to 236 mm/a in the south. The absolute maximum annual rainfall in the entire area of the Gaza Strip was recorded in the hydrological year 1994/1995. At that year, the annual average rainfall was 567 mm. On the other hand, the absolute minimum annual rainfall amounts to 114 mm.

Different methods have been developed for the estimation of areal rainfall from raingauge measurements. It was found that the Thiessen method gives consistently better and more accurate results than other methods (Melesse et al. 2003). Therefore, the Thiessen method was used to obtain the weighting coefficients for the spatial distribution of rainfall in this study. With the help

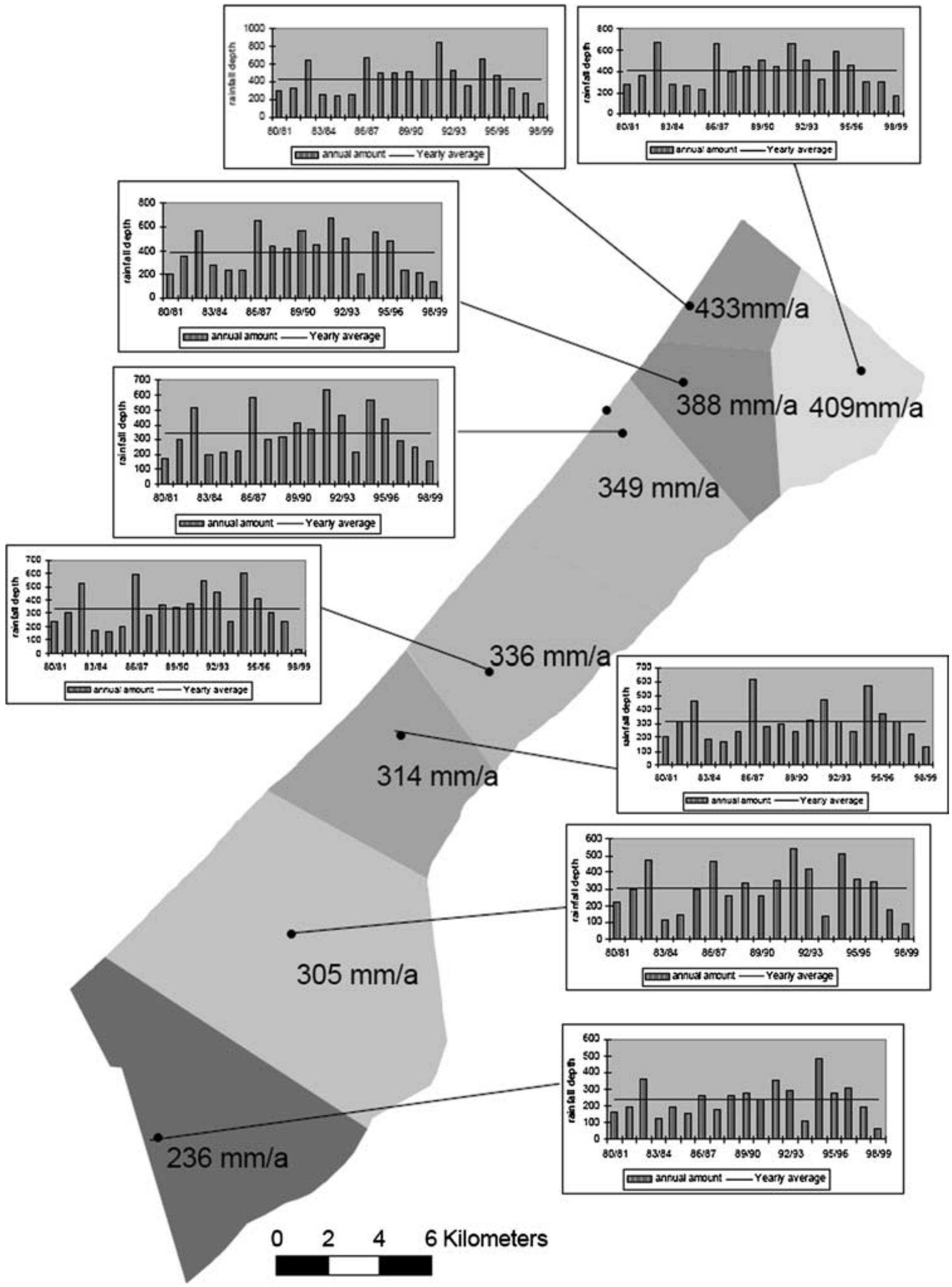

Fig. 3 Rainfall, meteorological stations, and Thiessen polygons

of GIS, Thiessen polygons were constructed to find out the spatial distribution of rainfall. Figure 3 illustrates the locations of the meteorological stations and average rainfall in each polygon based on the Thiessen method.

Water table fluctuations

The groundwater level monitoring network in the Gaza Strip has some 200 piezometers distributed in the entire area of the Strip. Distribution and allocation of these piezometers was done in such a way that they are away from any operating pumping well in order to ensure that the static water level can be monitored. This network was constructed a long time ago and maintained by the Palestinian Water Authority (PWA). Historical records of water levels are available for the past 30 years on monthly basis. Therefore, groundwater level records in the period from 1980 to 2000 were used with those rainfall records for the same period to carry out the CRD method. It should be noticed that the heads used in the CRD method are the water table since the aquifer

Table 2 Hydrogeological parameters based on analysis of pumping tests data

Well Id.	Lithology	T[a]	K[b]	Storativiy
L/159A	Calcareous sandstone and sand	2,640–3,290	30–70	5×10^{-3}
P/124	Calcareous sandstone and sand	845–1,330	15	8×10^{-3}
C/128	Calcareous sandstone and sand	868–2,000	27	5×10^{-4}
A/180	Sand dunes	3,460–7,960	140	0.03
R/162L	Coarse sand and gravel	3,300–4,600	70	6×10^{-3}
Information from Israeli resources (16 wells)				
	Calcareous sandstone and sand	2,900–9,000	29–90	10^{-2}–10^{-3}
	Calcareous sandstone and sand	–	10–100	10^{-3}

is phreatic. Following the construction of Thiessen polygons, the monthly records of water levels at each polygon were averaged to be used with the CRD method. In general, the aquifer in the Gaza Strip is shallow with depths to the water table varying from a few meters to 30 m at some particular locations.

Lateral inflow and outflow

Lateral inflow is an important parameter to the overall water balance in the Gaza Strip. The amounts of lateral inflow and outflow are subject to change from one year to another due to different hydrogeological parameters (rainfall, pumping, etc). However, the groundwater lateral inflow and outflow can be estimated based on different approaches. Since the groundwater level for the area of study is monitored monthly, a groundwater level contour map can be created. Therefore, the lateral inflow can be computed based on the difference between contours. Another approach for estimation of lateral inflow is the use of groundwater models. Coupling of results from different sources in the literature was done in order to get the best estimate of this amount. The Coastal Aquifer Management Program (CAMP) for the Gaza Strip has built an integrated groundwater numer-

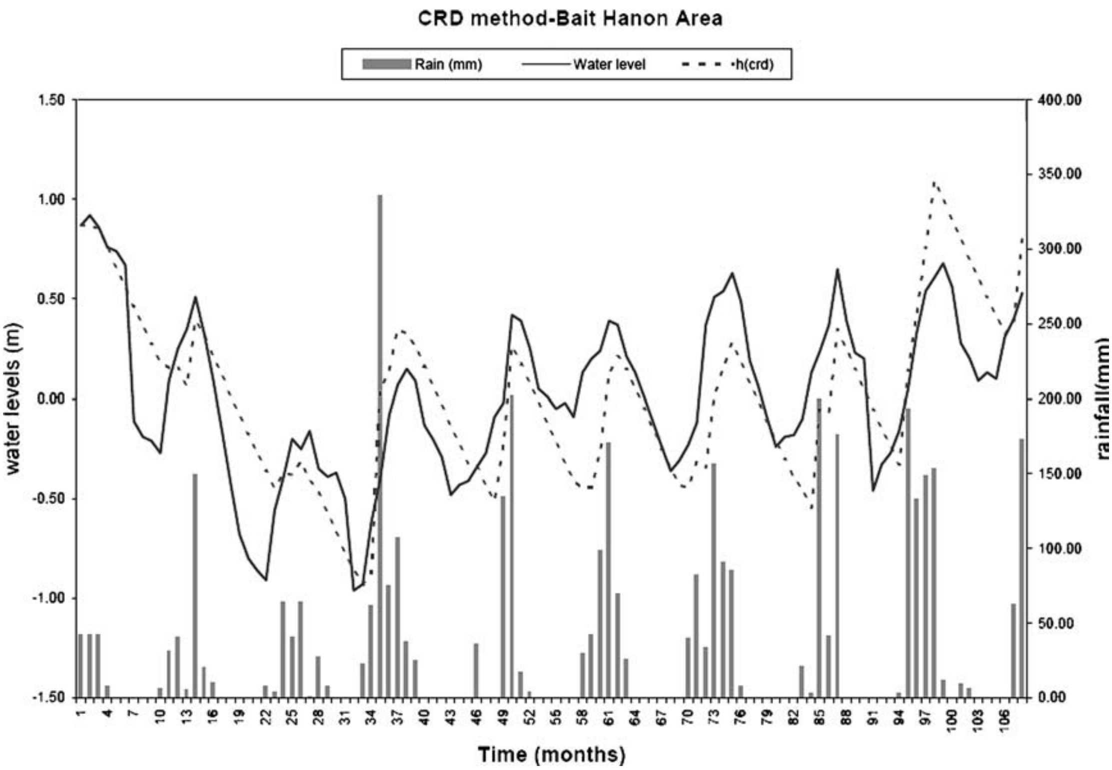

Fig. 4 CRD fitting diagram for Bait Hanon

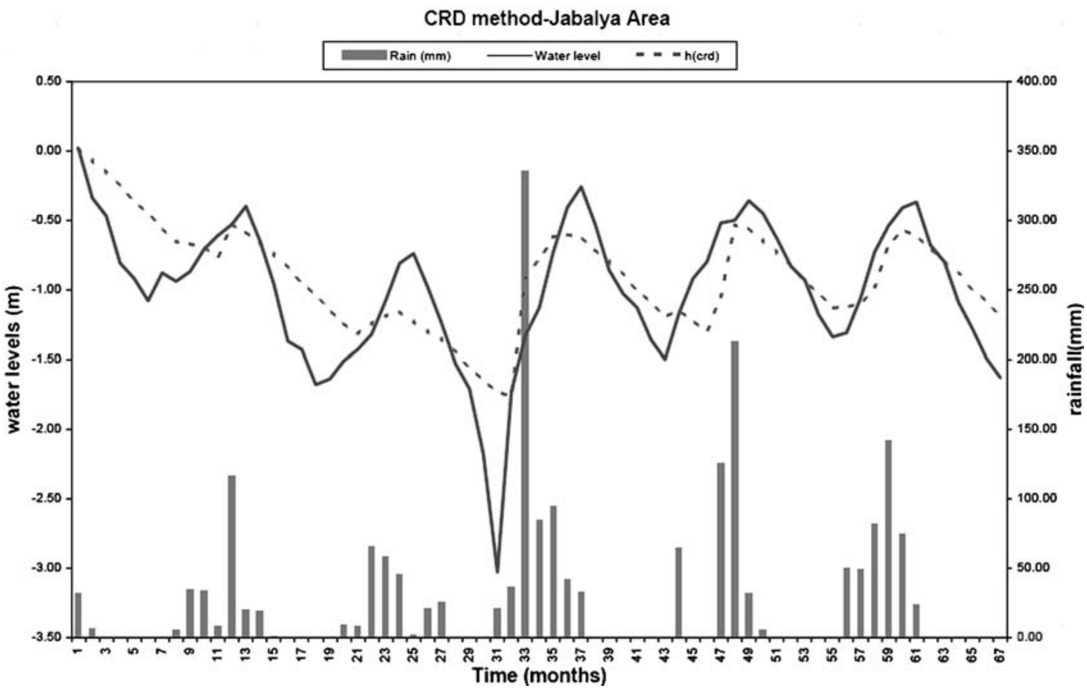

Fig. 5 CRD fitting diagram for Bait Lahia area

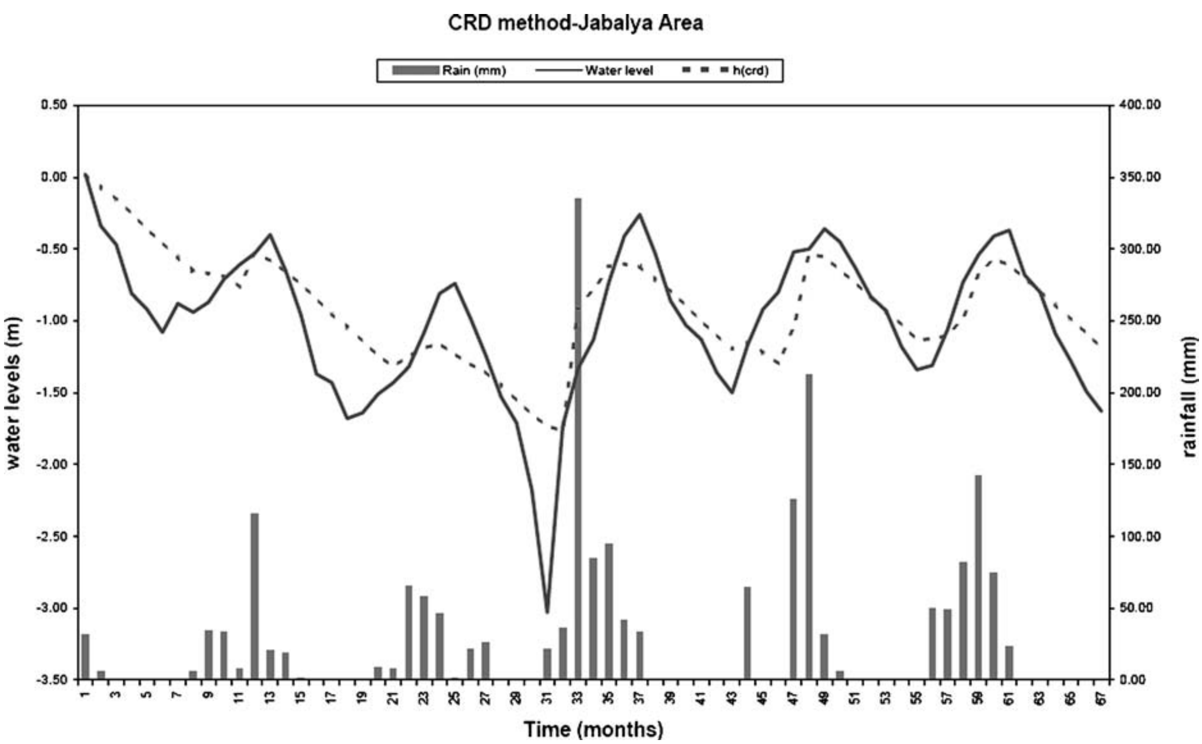

Fig. 6 CRD fitting diagram for Jabalya area

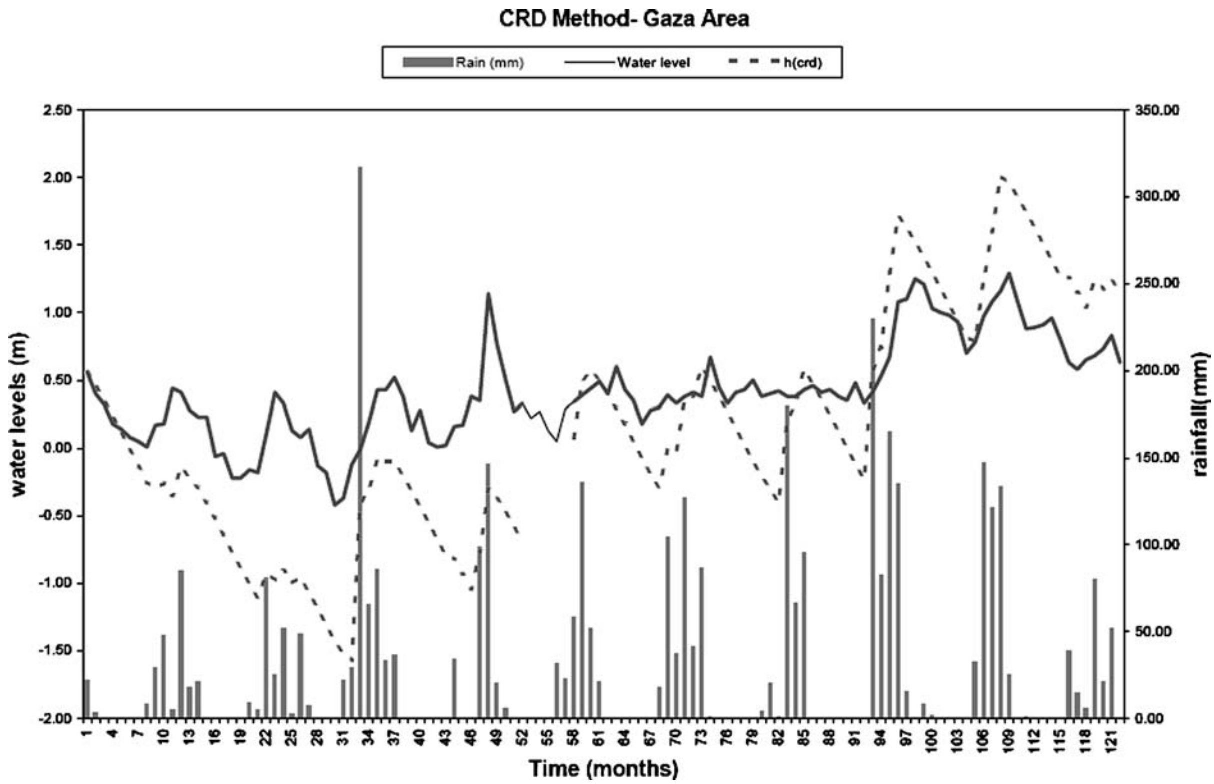

Fig. 7 CRD fitting diagram for Gaza area

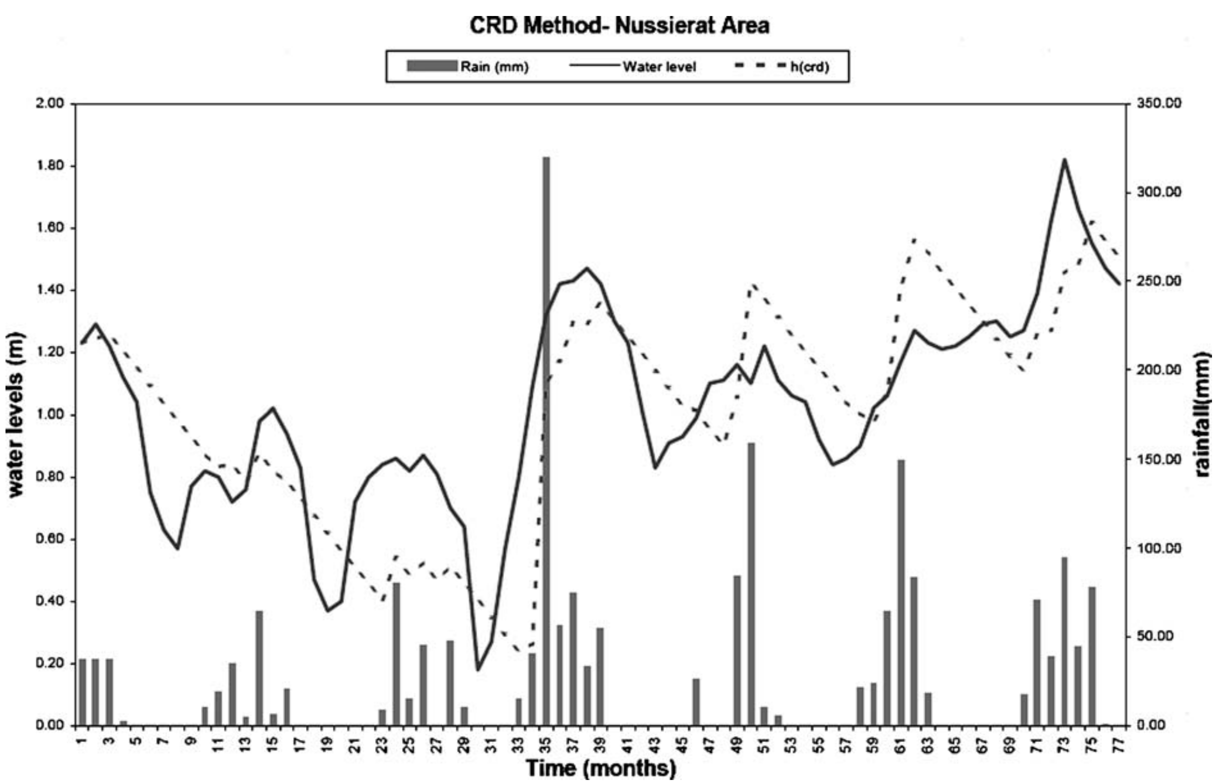

Fig. 8 CRD fitting diagram for Nussierat area

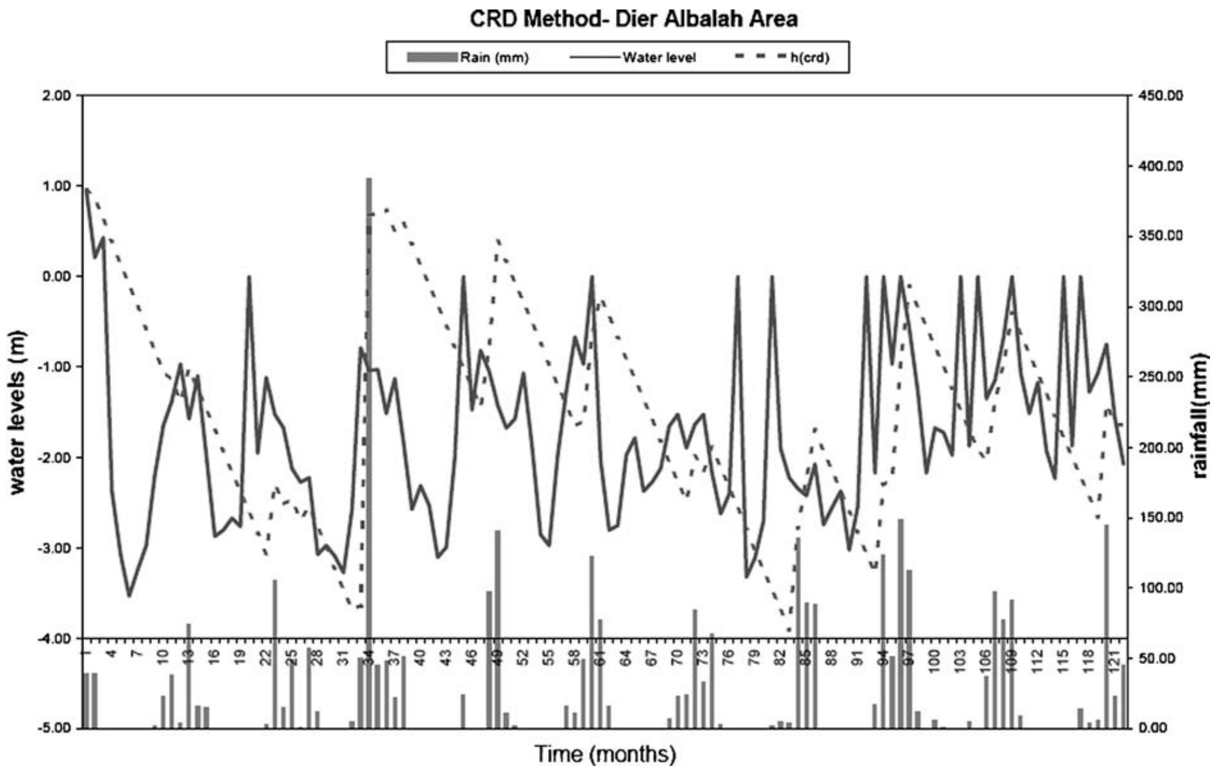

Fig. 9 CRD fitting diagram for Dier Albalah area

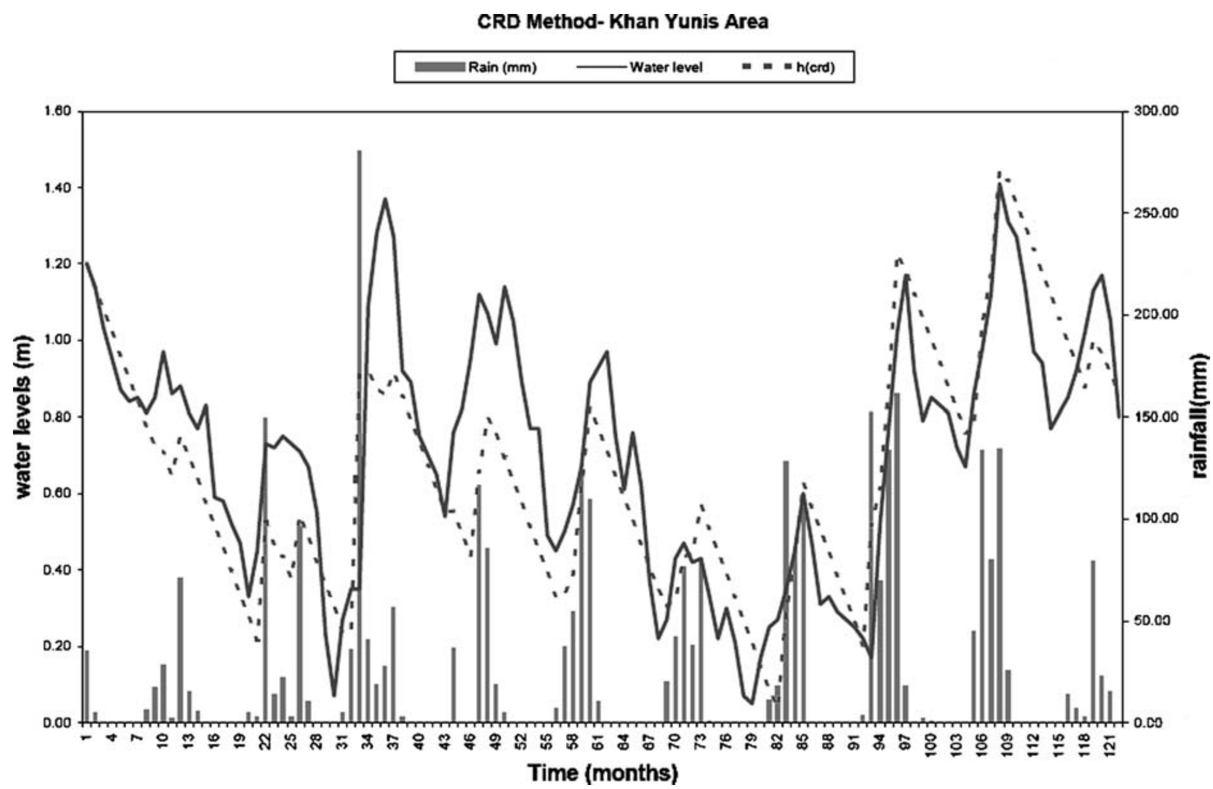

Fig. 10 CRD fitting diagram for Khan Yunis area

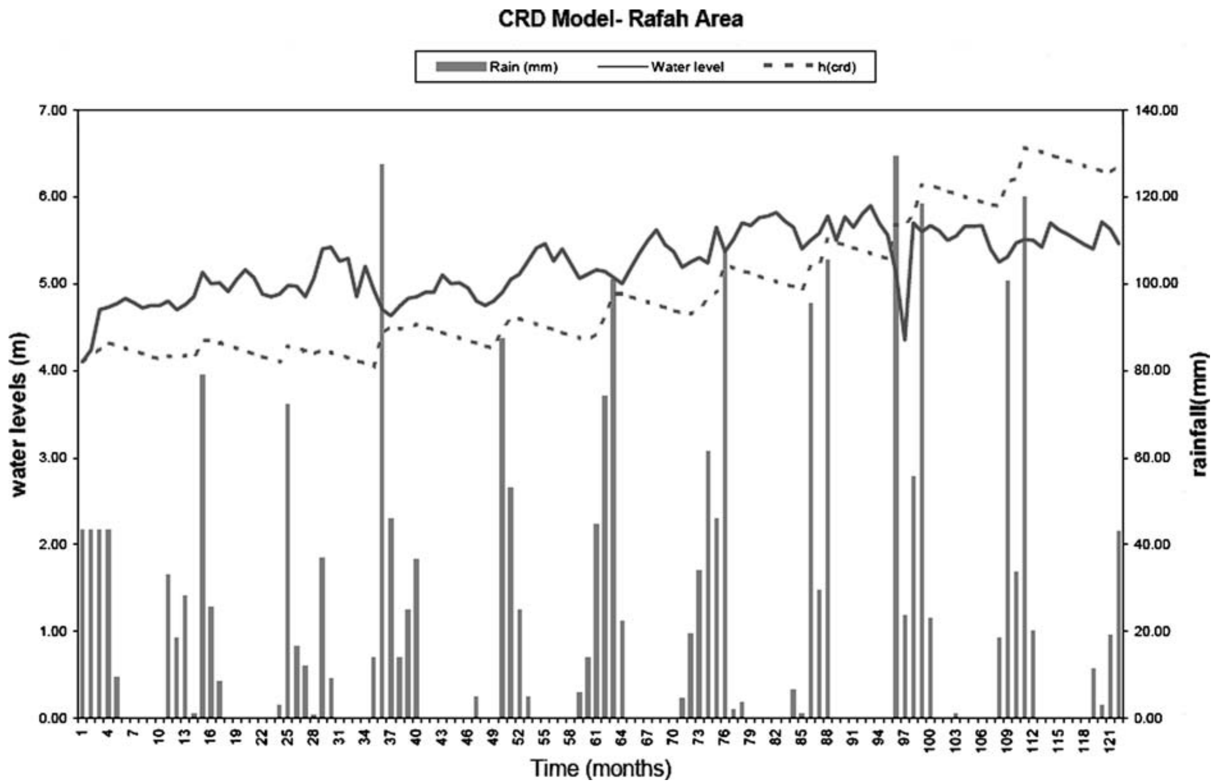

Fig. 11 CRD fitting diagram for Rafah area

ical model for the area of study (Metcalf and Eddy 2000). The results of this model, in addition to all other data in the literature (PWA 2001) were manipulated and used to obtain the values of lateral inflow to the aquifer.

Hydraulic parameters

Hydraulic properties are usually obtained by carrying out pumping tests. Many of these tests have been carried out in the Gaza Strip. In addition to the old pumping test data, the Palestinian Water Authority (PWA) has carried out different new pumping tests as a part of the CAMP project (Metcaf and Eddy 2000). Moreover, there are some old data from Israeli sources regarding the hydraulic properties in the Gaza Strip (Fink 1970; Melloul and Bachmat 1975; Yakirevich et. al. 1998) besides the data from the literature.

Table 2 summarises the results of the pumping tests that were carried out in the area. Values of transmissivity range between 700 and 5,000 m^2/day. The corresponding values of hydraulic conductivity range between 20 and 80 m/day. Storativity values range between 0.0005 and 0.03 as shown in the table. Complete statistical analysis for hydraulic parameters of the Gaza Strip area and rainfall analysis can be found in the literature (Baalousha 2004).

Application of the CRD method

Based on the polygons created by the Thiessen method according to meteorological stations shown in Fig. 3, the CRD model was applied on 8 sub-zones. The abstraction data and rainfall records were obtained from the Palestinian Water Authority and Ministry of Agriculture (PWA 2001) for the period from 1980 to 2000 on monthly basis. In an Excel spreadsheet, the monthly rainfall data were listed against the corresponding groundwater level data for each sub-zone, and plotted against time (Figs. 4, 5, 6, 7, 8, 9, 10, 11). The groundwater level has then been simulated based on Eq. 3, after identification of storativity, total inflow and outflow for the simulated period. The resulting groundwater level data from simulation has been plotted on the same axes as the rainfall and the measured groundwater data.

The relation between groundwater level and rainfall, which was described before in Eq. 3, is assumed to be linear. Thus far, the figure for each sub-zone represents the measured and simulated groundwater head. The last step is the optimization procedure to get the best fit between the measured and the simulated groundwater level. The optimization process is controlled by calculation of the root mean square error between the measured and simulated values. The best fit was achieved at the minimum RMSE. Once the minimum value of the

Table 3 Results of recharge modelling

Sub-Zone	CRD	RMSE
Bait Hanon	38.1%	0.0291
Bait Lahia	37.7%	0.0291
Jabalia	36.3%	0.0406
Gaza	34.8%	0.0374
Nussierat	31.64%	0.0266
Dier Balah	35.3%	0.1559
Khan Yonis	33.6%	0.0177
Rafah	41.1%	0.0601
Average	36.74	0.05045

RMSE has been achieved, the best estimate of recharge can be read from the model based on Eq. 3. The values of the RMSE for each sub-zone are given in Table 3. The whole process of optimization does not take more than one minute for each sub zone.

Results

Table 3 summarises the results of the CRD model. Figures 4, 5, 6, 7, 8, 9, 10, 11 show the fitting of the observed and modelled groundwater levels based on the recharge cumulative rainfall departure model.

The CRD method depends on different parameters as they appear in Eq. 3: rainfall, measured groundwater level, storativity, lateral flow, and pumping. It was found from sensitivity analysis that the estimated value of recharge is dependent on storativity more than other parameters such as lateral flow. Hence, reliable values of storativity should be input into the model. If the storativity value is far from the real value, assuming that other parameters are correct, no fitting of the model can be achieved. Thus, fitting of curves along with RMSE calculation can eliminate the uncertainty in storativity. It was found from sensitivity analysis that the change in the lateral flow has negligible effects on the estimated recharge value. This is obvious because the computed recharge based on Eq. 3 is dependent on lateral flow and pumping divided by the area, which is the sub-zone area.

The average groundwater recharge as a percentage of rainfall in the entire area of the Gaza Strip is calculated as 36.74%. Since the average annual rainfall is 321 mm/a, and the area of Gaza Strip equals 365 km^2, the calculated recharge value from rainfall amounts to 43.29 million m^3 per year. Comparing this result with the results in the literature (Table 1), it is clear that the results obtained using the CRD method are reasonable and close to the results obtained by other methods from the literature.

Conclusion

The cumulative rainfall departure method (CRD) is a good, cheap, and efficient tool to estimate the net groundwater recharge. From the results obtained in this study, it is clear that the CRD method can be applied easily with a minimum amount of data in comparison to other recharge estimation methods. The advantages of this method are that the only needed data are the rainfall, abstraction data, storativity of the aquifer, and the lateral inflow and outflow.

Moreover, the CRD method is independent of the coefficients which are needed for other methods of recharge estimation, and consequently, has less sources of uncertainty. The optimisation procedure followed in this method promotes and facilitates the fitting of the actual field measurements of groundwater head with the computed data. From sensitivity analysis, it is found that the estimated recharge based on the CRD method is dependent on the storativity value more than other parameters. The value of groundwater recharge obtained by the CRD method is comparable to the results of the coefficient method and seems very reasonable when applied to the groundwater model for the Gaza Strip.

Limitations

The CRD method can be used only for unconfined aquifers since it depends on fluctuations of the water table. To obtain accurate results using the CRD method, values of storativity, monthly records of water table and rainfall should be known with reliable accuracy. This method is best suited for aquifers with high storativity. Uncertainty of the estimated recharge based on the CRD method increases as the depth to the water table increases and vice versa.

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