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Recharge Estimation in Karst Aquifers by Applying Water Level Fluctuation Approach

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Abstract

In arid and semi-arid areas, quantifying groundwater recharge is an essential issue for groundwater resources management. Since recharge is a function of many parameters such as level of karst development and climatic conditions, then selecting the best technique of recharge estimation that takes these parameters into consideration is still an issue. This paper presents an alternative technique for estimating annual groundwater recharge using the fluctuation of water level within an aquifer during a specific time interval as a result of the water balance of inflows and outflows. The Western Aquifer Basin (WAB), West Bank and Israel, was depicted for a case study. The estimated amount of annual recharge was also correlated with monthly rainfall rates to study the effect of rainfall variation on the generated recharge. The results confirm that the high variations of annual recharge volumes are directly linked to monthly rainfall variation. For the WAB, the annual recharge is mainly dominated by the amounts of rainfall accumulated during the four wet months i.e. November, December, January and February. On the basis of these results a multi-regression equation has been developed to consider monthly distribution of rainfall as a chief factor in forecasting annual recharge within the aquifer. This equation can be applied in the future to generate any synthetic rainfall scenarios. The average annual recharge for WAB for the period 1970-2006 was estimated at 385 million cubic meters per year (Mm^3/yr).

Introduction

Groundwater recharge may be defined as 'the downward flow of water reaching the water table, forming an addition to the groundwater reservoir' [1]. Unfortunately, direct measurement of recharge at catchment scale is not possible; therefore it is commonly estimated using indirect methods such as: soil moisture budgets, empirical infiltration coefficients, soil moisture flux, lysimeters, tracers, direct observations, fluctuation of water level, etc.

Generally, the Western Aquifer Basin (WAB) recharge processes are dominated by the seasonal rainfall (quantity, distribution, and intensity), evapotranspiration, outcropping geological formations, infiltration through the unsaturated zones, soil and land use types. The annual recharge for the WAB has been studied by different Palestinian and Israeli researchers. Up to date, the most accepted technique for estimating annual recharge is the empirical equation which correlates the annual recharge with the annual rainfall [2]. However, this equation does not take into account the temporal distribution of the rainfall over the replenishment areas of the aquifer, which shows a high variation in rainfall from year to year in terms of rain intensity and amounts. Meaning that, the rainfall temporal distribution will have a major influence on the generated recharge. This makes the estimated recharge according to the annual amount is not accurate and may lead to over or under estimates of the accurate amounts.

Study Area

The transboundary Western Aquifer Basin (WAB) or "Yarkon Tananim" in the Israeli literature is one of

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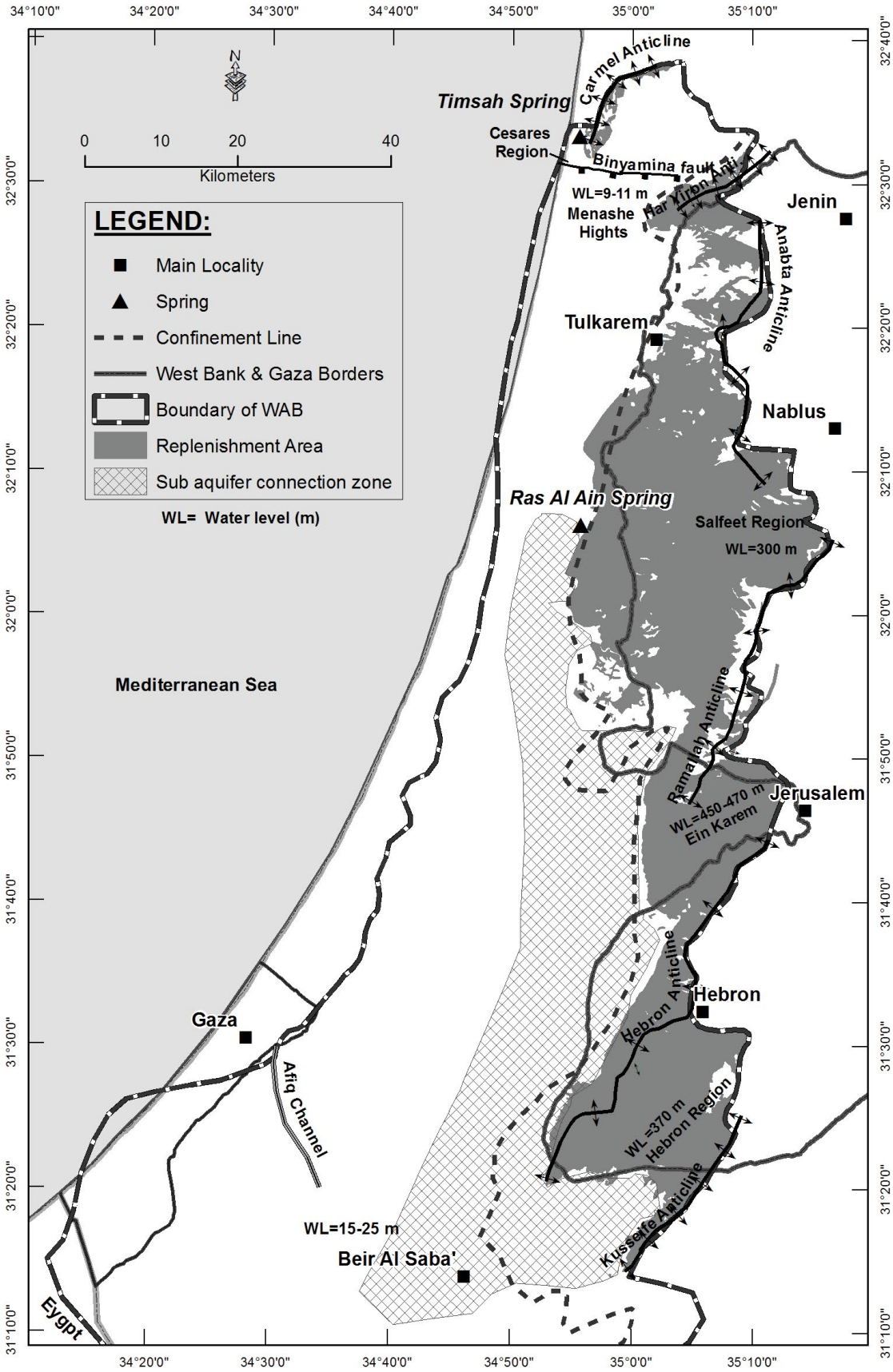

Figure 1: Map of the study area.

the most important sources of freshwater for Palestinian Authority and Israel, Figure 1. The WAB stretches northward from the area south of the Egyptian border all the way up to the foothills of Mountain Carmel and from

West Bank mountains in the east heading westward towards the Coastal Plain of the Mediterranean Sea. The WAB is naturally replenished by rainfall on exposures covering an area of 1932 km^2. The natural outlets of this aquifer are Ras Al Ain (Yarkon) and Timsah (Tananim) springs. The mean annual volume of undisturbed flow from these springs is estimated at 350 Mm^3/yr [3]. In 1951/1952, the pumping was significantly started with 10 Mm^3 and then dramatically increased to 300 to 342 Mm^3 by the late of 1960s and early 1970. The pumping outflow was then become more dominant than the natural outflow starting from year 1972/73, when the pumping rate was increased to 385 Mm^3 and then kept up to date in the range of 340-450 Mm^3/yr depending on rainy season, Abusaada, 2011) [4].

The formations of the WAB are classified as a karstic aquifer; with a general thickness ranging between 600 and 1000 meters. The aquifer is predominantly composed of permeable limestones and dolomitic limestones interbedded with argillaceous rock [3,5,6]. The water level of the WAB demonstrates large variations across the basin. In replenishment areas (i.e. the unconfined part of the aquifer), water table above sea level is located within the range of 450-470 m in Ein Karem area, 370 m in the mountains of Hebron and 300 m in the Salfeet area, [6]. In the confined part of the WAB, the piezometric head is ranging between 9-11 m in Menashe Heights to 15-25 m near Beir Al Saba' area, Figure 1.

The basin is located in a Mediterranean climate zone, characterized with moderate temperatures and intermediate precipitation that mostly falls during the coldest half of the year (October-April). Generally, the mean annual precipitation over replenishment areas of the aquifer is estimated at around 559 mm.

Problem Statement

Estimating recharge is still considered as a main parameter for managing groundwater resources. However, there are many techniques are used; the best estimation technique for karst aquifer systems is still an issue which required a specific attention to include all factors that control the recharge mechanism.

This paper presents the estimation of annual aquifer recharge based on the water level fluctuations technique for a karstic aquifer system (i.e. WAB). Consequently, the historical records (i.e. rainfall, water level, outflow, etc.) over a certain period are used to estimate the annual recharge. As a result, the relation between the temporal rainfall distribution and generated recharge will be understood and then used to develop a new empirical equa-

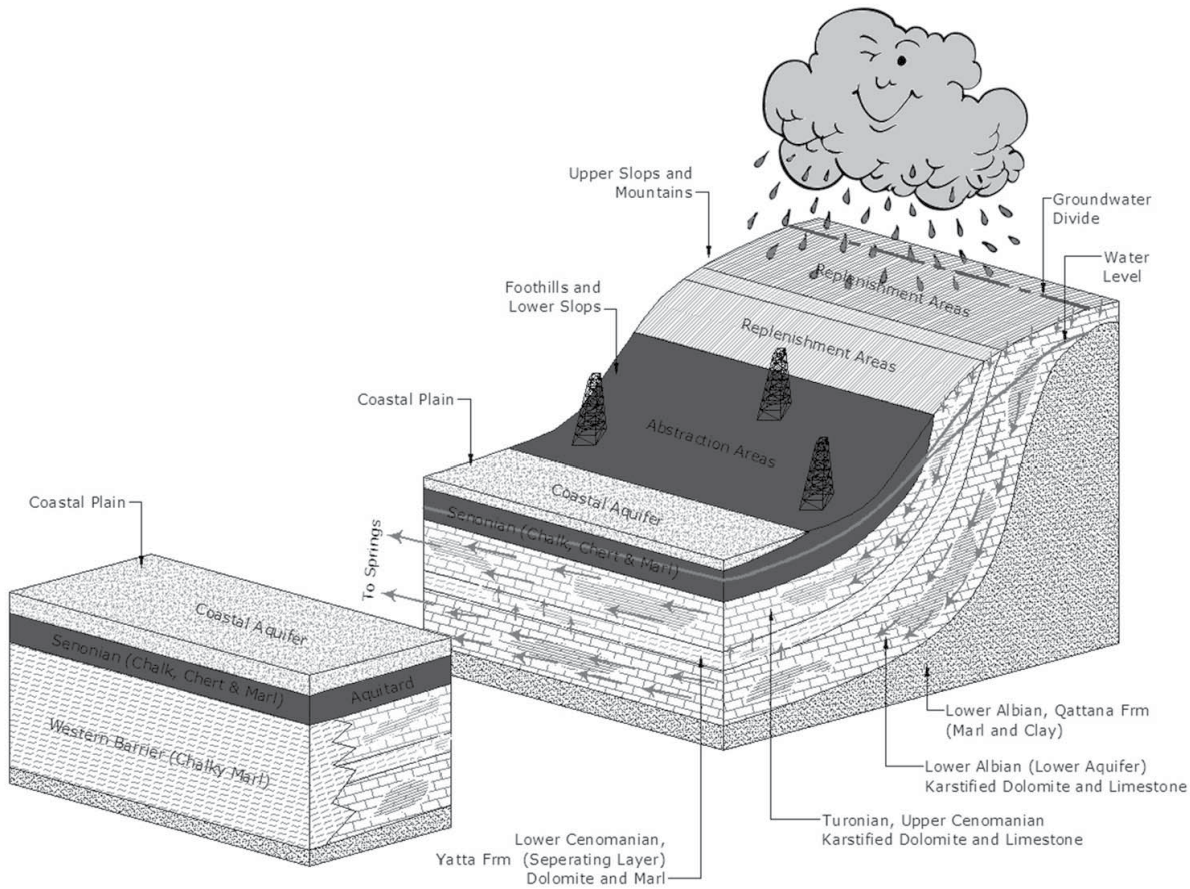

Figure 2: Hydrogeological setting of the WAB [19].

tion that takes into account the temporal variation of rainfall. It is hoped that the technique developed herein would also be applicable to similar karstic aquifers.

Geology and Hydrogeology of the WAB

The WAB is composed of the middle-to-late-Cretaceous Judea Group [2]. It is divided into two main sub-aquifers (i.e. upper and lower) separated by a lower permeability layer (i.e. Yatta formation). The upper and lower sub-aquifers' rocks are mainly composed of a sequence of hard, karstic and permeable limestone and dolomite with a thickness of 600-1000 m, [7]. However, the impermeable layer (i.e. Yatta formation) does not totally prevent water from being transported between the two main sub-aquifers. In some locations, hydrogeological evidence prove that Yatta formation is not uniform and due to severe fracturing affects it behaves as a permeable layer [2,8], accordingly flow could be exchanged between the two sub-aquifers. Based on the groundwater balance, distribution of salinities, and transfer of solutes, an intra-connection map has been developed, Figure 1, showing the area where the two sub-aquifers may be connected, Guttman, et al. 1988 [6]. Figure 2 shows the hydrogeological setting of the WAB.

The northern boundary of the aquifer is defined by the anticline in the Carmel Mountain where Jerusalem and Bethlehem formations are exposed and also, using the flow directions in the Carmel Mountain [6]. The eastern boundary was outlined along the groundwater divide and along hydrological barriers assumed from structural and lithological considerations. This boundary is traced from the core of the Har Yiron anticline in the north through the Anabta anticline, the Ramallah structural divide, the Hebron structural barrier and the Kusseifa anticlinorium [6,9]. In Jerusalem and Hebron areas the boundary is shifted to the east in order to include all areas where generated flow can move towards the south-west direction. The southern boundary of WAB extends to the south-west crossing the Egyptian border [6,9] where the inflow and outflow are very limited due to limited rainfall.

In the west, the impermeable chalky marls of the Daliya formation and Talme Yafe Groups, Figures 2, act as impervious barriers along the western boundary of the WAB except in Cesarea region (west of Timsah spring), Figure 1, where there is a possible direct connection or a connection along the buried Binyamina fault with the Mediterranean Sea [10].

The amount of sea water intrusion was estimated by [11] using concentration of Chloride Mass-Balance taking into consideration the historical discharge rates, the water quality of Al Timsah spring which represents the mixture of fresh groundwater and sea water, salinities of both sea water and fresh groundwater. Accordingly, the amount of sea water intrusion was estimated at 3.5-3.9 Mm^3/yr.

Recharge Estimation

Background

The annual precipitation over the replenishment areas is the dominant natural source of recharge for the WAB [6,12-14]. Generally the up to date known approach for estimating the annual recharge for the WAB is the empirical equation (Guttman's equation) which correlates the annual recharge with annual rainfall, Eq.(1). This equation was developed by using an inverse calibration technique, whereby recharge is estimated by following the calibration of heads and groundwater flow rates [2].

$$Rc = \begin{cases} 0.45(Rf-180) & when \quad Rf < 600mm \\ 0.88(Rf-410) & when \quad 600 < Rf < 1000mm \\ 0.97(Rf-463) & when \quad Rf > 1000mm \end{cases} \quad (1)$$

Where:

Rc: Annual recharge (mm)

Rf: Annual rainfall (mm)

Accordingly, since the annual precipitation ranges between 250 and 1350 mm, ground water recharge in the WAB will range between 6% and approximately 65% of the rainfall, [2]. The recharge to rainfall ratios are considered high compared to other aquifers due to the high karstification of the aquifer. The average recharge to rainfall coefficient is estimated in the range of 30-33% [10].

Eq. (1), relates the annual recharge to the annual rainfall. This means that the temporal rainfall distribution is neglected. In this paper, an alternative technique for estimating the annual recharge in the WAB is presented,

Table 1: Monthly rainfall characteristics over recharge areas of the WAB.

Parameter	Unit	Monthly rainfall characteristics*								
		Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Mean	mm	0.2	17.5	62	119.1	138.2	116.2	77.7	24.5	3.6
Annual average	%	0.00%	3.10%	11.10%	21.30%	24.70%	20.80%	13.90%	4.40%	0.60%
Standard deviation	mm	0.6	17.4	56	77.2	69.2	69	41.6	32.9	6.8
Maximum	mm	3	66	235	350	387	325	168	180	33
Minimum	mm	0	0	3	12	36	28	7	0	0

*No rainfall has been recorded during June, July and August.

whereby the temporal distribution is taken into consideration. This is a prerequisite if transient groundwater modeling is attempted.

Monthly Rainfall in the WAB

There are more than 25 rainfall gauges are uniformly distributed over the replenishment area of the WAB, PMD 2010 [15]. The monthly rainfall records from all were used to calculate the average monthly rainfall for the period identified in this study (that from September 1970 to August 2006). The mean monthly rainfall in the recharge area of the WAB and its characteristics are shown in Table 1 and described as follows:

1. The hydrological water year starts in September and ends in May. Records show that rainfall during summer months is almost non-existent (June, July and August).
2. The mean annual rainfall mean was calculated at 559 mm/yr. The distribution shows a high variability of annual rainfall with a high standard deviation of 155.2 mm. This is best elaborated by a comparison between the maximum and minimum annual rainfall values as well as its monthly distribution; the years of 1991/92 recorded the maximum rainfall amounts of 1123 mm, while the minimum recorded rainfall was 293 mm in the year 1998/99. Figure 3, shows the monthly distribution of rainfall over the period of 1970 to 2006 which presents the high variation of monthly rainfall from season to season.
3. The shape of the annual distribution of rain is analogous to a log-normal distribution skewing to the right (towards March and April), Figure 4.
4. January shows the highest average amount of rainfall of 138.2 mm representing 24.7% of the annual average. Additionally, in January, the highest monthly rainfall rates were found for January 1974 reaching a total of 387 mm.
5. Most of the annual rainfall occurs during December, January and February with an average of 65% from

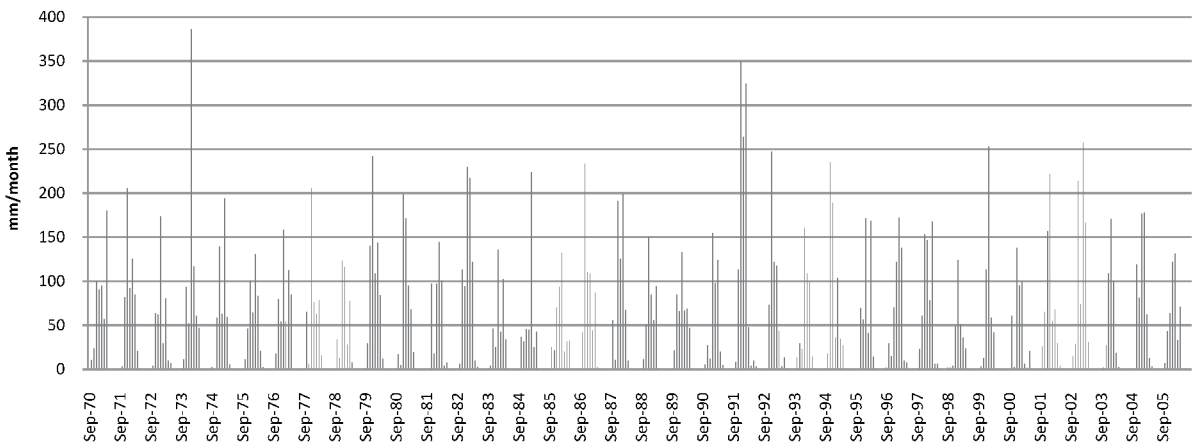

Figure 3: Monthly rainfall records over the recharge areas of the WAB.

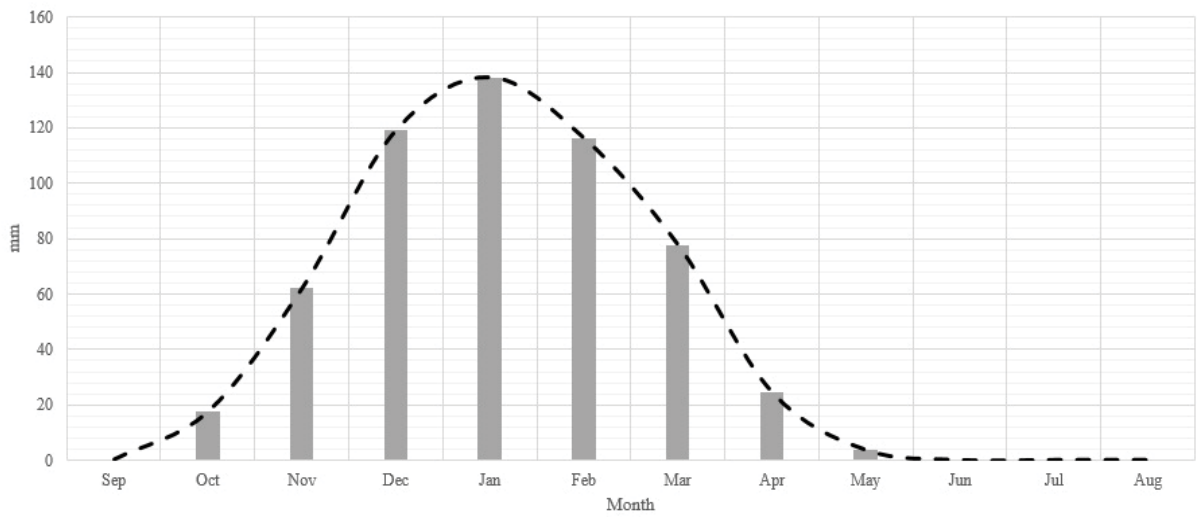

Figure 4: Mean of monthly rainfall over the recharge areas of the WAB.

the mean annual rainfall.

6. The rainfall during September and May presented the lowest values during the year standing for less than 1% of the annual average.
7. Rainfall in April is generally very low (4.4% of the annual average), with few exceptions of high intensity storms such that of 1971, which generated approximately 180 mm.
8. November and March have moderate average rainfall depths (11.1% and 13.9% respectively).

Recharge estimation technique

The Water Level Fluctuation (WLF) technique is considered as one of the traditional approaches for estimating groundwater recharge [16,17], accordingly, recharge can be determined by examining water level fluctuations shown in well hydrographs, where it is assumed that if no recharge occurred, then the hydrograph recession would continue until a base level is reached. By extending the hydrograph recessions, the difference between the extrapolated recession curve and the actual groundwater level, multiplied by the specific yield, corresponds to the amount of recharge for that time period, taking into account any abstractions or infiltrations/injections and the net balance of inflows and outflows [18].

However, the WLF technique is commonly used in unconfined aquifers, it can be also used for the WAB as a special case due to many reasons; firstly, it is composed of two layers and both layers have confined and unconfined conditions, [19]. Secondly, the two sub-aquifers are connected in many places due to severe fracturing affects as well as due to the composition of Yatta formation which is not uniform, therefore, in many places, it behaves as a permeable layer, [2,8] accordingly flow could exchange between the two sub-aquifers and also water levels in both layers in the confined part are almost the same [20].

Thirdly, the water levels in the confined part of the two sub-aquifers were distributed systematically from north to south. Figure 5, shows a sample of water levels at some observed wells which proved that water levels within these wells are highly correlated (i.e. Pearson correlation is ranging between 0.918 and 0.996 and correlation is significant at less than 0.005 level for all wells), meaning that water levels in the entire aquifer will be systematically affected as a result of any abstraction, injection or natural recharge. Accordingly, the WLF technique could be applied where the average drop/rise of the water level in the confined part of the aquifer could be used as an indicator for the amount of inflow or outflow and could be mathematically described based on [18] approach as a special case using the following equation, Eq. (2):

$$R = \alpha \times \Delta h + Q_o - Q_{Other\ inflows} \quad (2)$$

Where:

R = Recharge (m^3) during period T

Δh: Average change in water table elevation (m) during period T

A: Storage coefficient (m^3/m)

$Q_{Other\ inflows}$: Sea water intrusion, artificial recharge, lateral flows (m^3) during period T

Q_o: Outflow (m^3) during period T

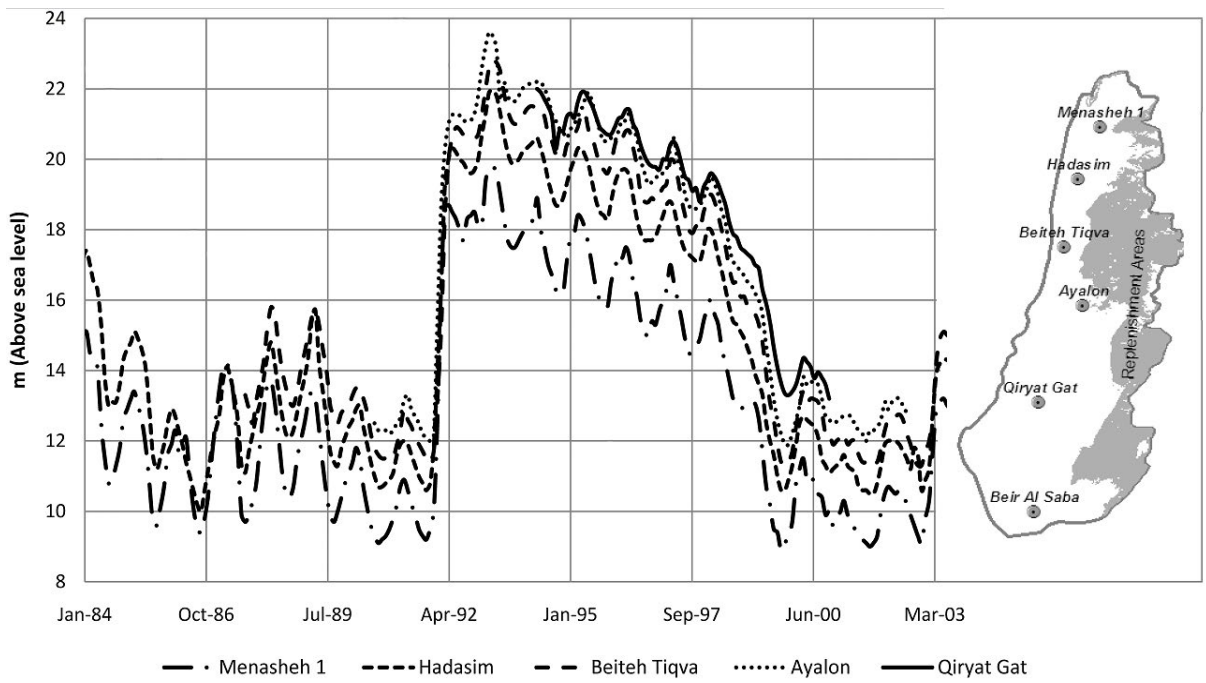

Figure 5: Water level time series for different observed well within the confined part of the WAB.

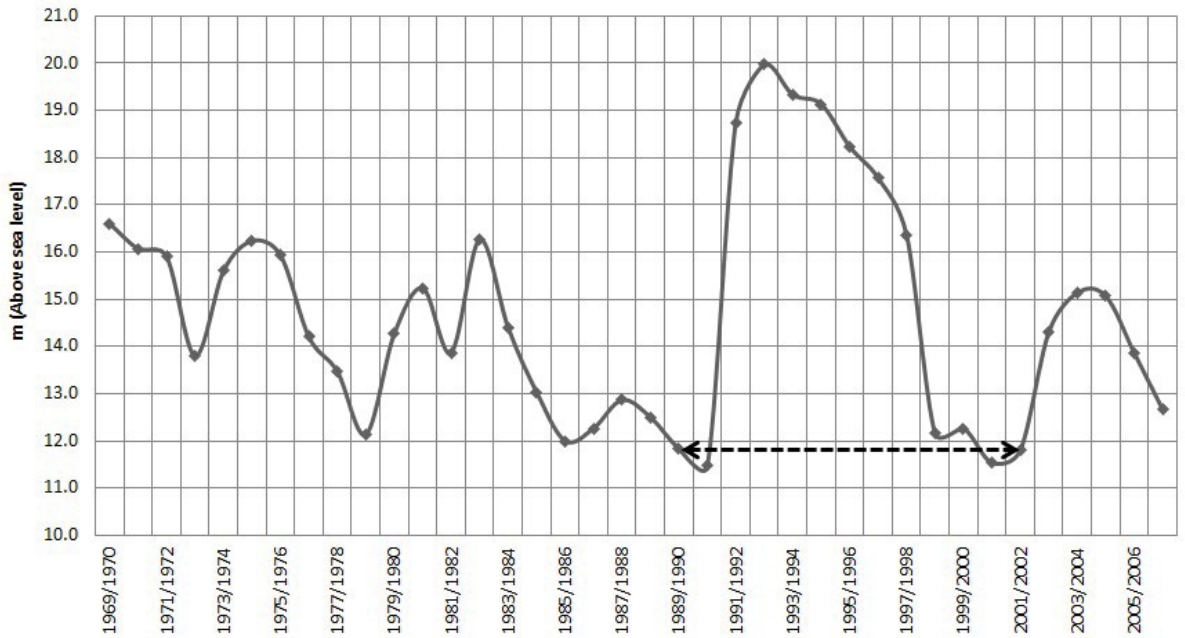

Figure 6: Average water level in the confined part of WAB (generated from wells time series and HSI, 2007).

Since α is not defined yet, Eq. (2) has two unknowns. As a result, quantifying recharge for any time interval is still not possible. This problem can be solved by looking for a period within the historical records of the average water level where the start and the end of the selected period have the same water level (complete cycle), Figure 6. During this period, the net storage of the aquifer should be equal to zero. Accordingly, the term (α x Δh) becomes zero, R will then equal the net outflow during the same period.

The average water level in the confined part of the WAB was generated from the water level time series of the observed wells within the confined part of the aquifer, Figure 6, and validated by the mean annual water level which was calculated by the Hydrological Service of Israel [21] using the same monitoring wells. The Figure shows different water level cycles. For the purpose of this paper, the second cycle between years 1989/90 and 2001/02 was selected and water balance analyses have been conducted.

Results

Inflow/outflow: The total outflow from the WAB is equal to the wells' abstraction and springs' discharge, while, the sum inflow of the WAB is equal to the natural recharge, sea water intrusion and injected water. Consequently, subtracting the total amounts of water flowing into the aquifer through both artificial recharge and sea water intrusion from the sum of annual outflow, for the past 13 years, yields a value equal to the sum of recharge over that same period, Eq. (3). This means that for any specific year, the recharge is equal to outflow plus the change in aquifer storage. Table 2 shows the total amounts of annual outflow (Qnet) with all their components during the analysed period.

$$\sum_{1989/90}^{2001/02} R_i = \sum_{1989/90}^{2001/02} \left(Q_i^w + Q_i^s\right) - \sum_{1989/90}^{2001/02} \left(Q_i^{ar} + Q_i^{se}\right) \quad (3)$$

Where

i: Year

R: Annual recharge (Mm^3)

Q^w: Annual pumping (Mm^3)

Q^s: Annual discharge (Mm^3)

Q^{ar}: Annual pumping (Mm^3)

Q^{se}: Annual sea water intrusion (Mm^3)

As a result, the sum of recharge over the past 13 years amounts is equal to the sum of net outflow (i.e. 5395.5 Mm^3 = 415 Mm 3/yr). For the same period, the average estimated recharge using Guttman's equation was equal to 341 Mm^3/yr, which is 74 Mm^3 less than the recharge estimated by Water Level Fluctuation (WLF) technique.

Calculating the storage coefficient of the WAB: The storage coefficient of the WAB (α) is defined as the total water that could be abstracted from or injected into the WAB per one meter drop/rise in the confined part of the WAB. Based on this definition and taking the water level during year 1989/1990 as a reference, the amount of water stored in the aquifer at time (t) is calculated through the following equation Eq. (4):

$$S(t) = \alpha \times h(t) \quad (4)$$

Where:

S(t): Storage after exceeding the reference water level (m^3)

Table 2: Net outflow during the period 1989/90 to 2001/02.

Year	Pumping from WAB	Total spring discharge	Sea water intrusion*	Total injection	Net outflow
	Mm³				
1989/90	400.8	26.2	3.9	1.1	422
1990/91	342.3	18.8	3.9	0	357.2
1991/92	245.1	59.5	3.9	36.6	264.1
1992/93	313.6	97.2	3.9	1.5	405.4
1993/94	321.5	75	3.9	0.1	392.5
1994/95	374.4	70.7	3.9	0.6	440.6
1995/96	354.7	59	3.9	2.6	407.2
1996/97	375.2	57.8	3.9	3.7	425.4
1997/98	412.7	51.6	3.9	0.2	460.2
1998/99	576.1	35	3.9	0.1	607.1
1999/00	400.8	27.1	3.9	0	424
2000/01	395.3	19.2	3.9	0.2	410.4
2001/02	364.7	20.3	3.9	1.7	379.4
Sum	4877.2	617.4	50.7	48.4	5395.5

*Sea water is estimated by Paster, et al. [11] with range 3.5-3.9 Mm³/yr (i.e minor inflow compared with other inflows), therefore, the upper limit is used.

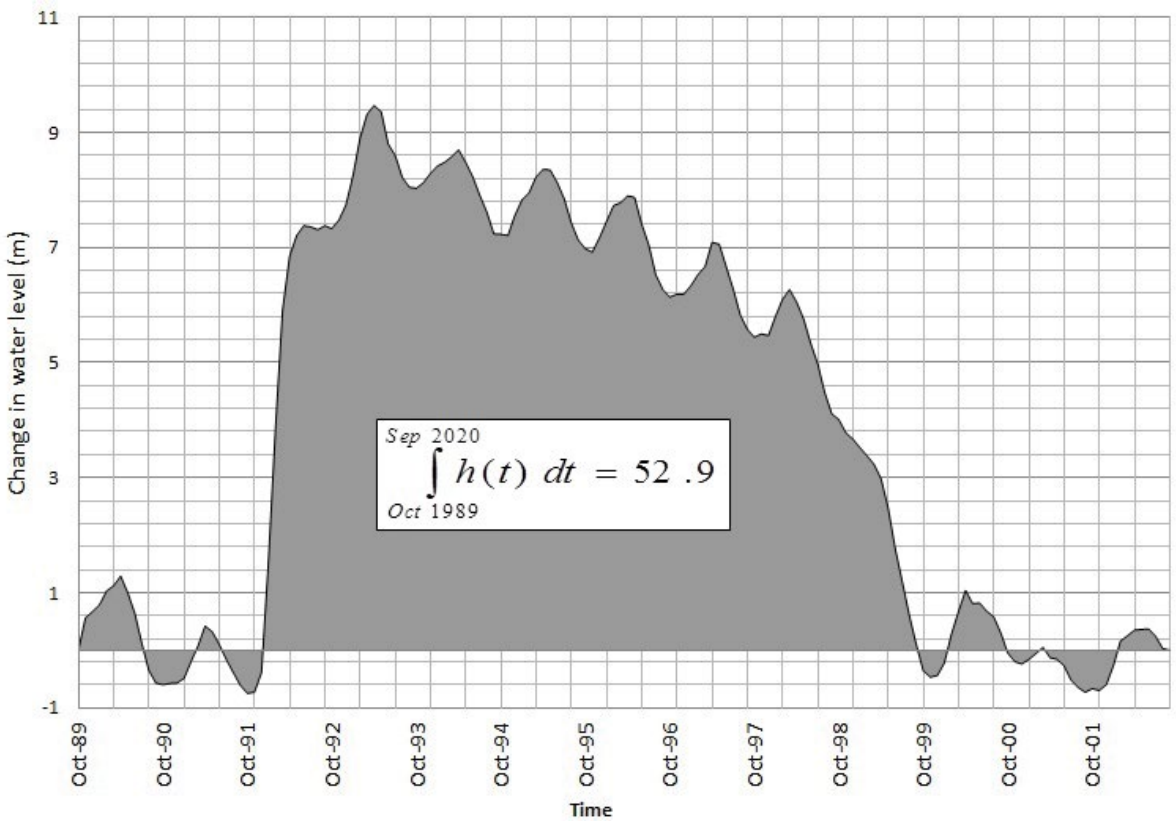

Figure 7: Average monthly water level in the confined part of the WAB during the selected period.

h(t): Average water level in the confined zone (m) at time t (reference year 1989/90)

α: Storage coefficient of the WAB (m³/m)

During the period 1989/90 and 2001/02, the net sum of inflow was equal to the outflow (i.e. the net storage is equal to zero). Therefore, the integral of S(t) over the same period is equal to the net outflow or net inflow. Then Eq. (4) becomes as follows, Eq. (5):

$$\int_{Oct\,89}^{Sep02} S(t)\,dt = \alpha \int_{Oct\,89}^{Sep02} h(t)\,dt = \sum_{Oct\,89}^{Sep02} inflow = \sum_{Oct\,89}^{Sep02} outflow \quad (5)$$

The integral of water level (h) over the same period is equal to the area under the water level curve. For an ac-

curate calculation of storage coefficient; monthly records of water level were used, Figure 7. As a result, the storage coefficient of the WAB could be calculated by the following equation, Eq. (6):

$$\alpha = \frac{Q}{\int_{Oct89}^{Sep02} h(t)\,dt} = \frac{5395.5}{52.9} = 102\ Mm^3/m \qquad (6)$$

Where:

Q: Sum of outflow over the considered period (m^3)

h(t): Average water level (m)

α: Storage coefficient of the WAB (m^3/m)

Once this equation was applied, it was concluded that for every meter drop or rise in the confined area within

Table 3: Annual recharge estimates by WLF technique and its comparison with other estimate techniques.

Year	Avg. water level	Change in water level	Change in storage	Net outflow	Estimated recharge		
					WLF	Guttman, 2000	HSI, 2007
	m		Mm^3				
1970/71	16.1	-0.5	-47.9	347.8	299.9	329.6	392
1971/72	15.9	-0.2	-16	334.3	318.4	351.5	408
1972/73	13.8	-2.1	-201.2	418.8	217.7	218.9	305
1973/74	15.6	1.8	172.4	362.5	534.9	612.5	528
1974/75	16.2	0.6	60.7	351.8	412.5	299.5	366
1975/76	15.9	-0.3	-28.7	445.9	417.1	245.4	310
1976/77	14.2	-1.7	-166	373	207	334.2	400
1977/78	13.5	-0.7	-70.2	387.1	316.9	288.3	343
1978/79	12.1	-1.3	-127.7	412.9	285.2	191.7	229
1979/80	14.3	2.1	204.4	319.7	524	596.9	436
1980/81	15.2	1	92.6	344.3	436.9	343.8	378
1981/82	13.9	-1.4	-130.9	381.1	250.2	254	303
1982/83	16.3	2.4	229.9	326.2	556.1	656.9	473
1983/84	14.4	-1.9	-178.8	471.1	292.3	183.4	239
1984/85	13	-1.4	-130.9	444.7	313.8	236.9	247
1985/86	12	-1	-99	408.1	309.1	215.8	254
1986/87	12.3	0.3	25.5	350.8	376.3	373.2	416
1987/88	12.9	0.6	57.5	376.5	434	425.9	426
1988/89	12.5	-0.4	-35.1	382.3	347.2	233.8	306
1989/90	11.7	-0.8	-73.4	422	348.6	268.6	340
1990/91	11.5	-0.3	-25.5	357.2	331.7	232.3	295
1991/92	18.7	7.3	696.1	264.1	960.2	1243.2	780
1992/93	20	1.2	118.1	405.4	523.5	357.9	425
1993/94	19.3	-0.6	-60.7	392.5	331.8	234.8	244
1994/95	19.1	-0.2	-19.2	440.6	421.4	399.4	424
1995/96	18.2	-0.9	-86.2	407.2	321	298.4	337
1996/97	17.6	-0.7	-63.9	425.4	361.5	336.9	399
1997/98	16.4	-1.2	-114.9	460.2	345.3	396.5	326
1998/99	12.2	-4.2	-402.3	607.1	204.8	97.9	146
1999/00	12.3	0.1	9.6	424	433.6	264.2	352
2000/01	11.5	-0.7	-70.2	410.4	340.2	214.1	258
2001/02	11.8	0.3	25.5	379.4	404.9	370.5	419
2002/03	14.3	2.5	239.5	378.8	618.3	643	512
2003/04	15.1	0.8	79.8	357.8	437.6	218.1	262
2004/05	15.1	-0.1	-6.4	358.4	352	383	346
2005/06	13.9	-1.2	-114.9	411.9	297	254.5	325
Avg./Total	12.7	-0.08	-7.18	392.8	385.6	329.6	359.7

the WAB, the aquifer storage will lose or gain 102 Mm^3. This quantity appears to almost match the result obtained from [6] where he concludes that between 1977 and 1987 the cumulative groundwater deficit was in the order of 300 Mm^3, a volume equivalent to a 3 m drop in water level for the confined part of the WAB.

This step was followed by the calculation of the annual recharge by incorporating the storage capacity coefficient, the annual change in water level in the confined part and the net outflow from WAB as shown in the following equation, Eq. (7).

$$R_i = Q_o^i + \alpha \times \Delta h_i \quad (7)$$

Where:

R: Recharge in year i (m^3)

Q_o^i: Net outflow in year i (m^3)

α: Storage coefficient of the WAB = 102 Mm^3/m

Δh: Annual change in water level in year i (m)

Table 3 displays the results obtained for the annual recharge of the WAB over the period from 1970/71 to 2005/06 through the application of Eq. (7) as well as a comparison with the values attained by the Guttman's empirical equation. The average recharge during this period yielded 385.2 Mm^3/yr which is a value higher than the values obtained by Guttman's equation (i.e. 329.6 Mm^3/yr).

Figure 8 illustrates recharge values estimated by the two different methods (Water level fluctuation and Guttman's equation) drawn out in the same graph with the annual rainfall over the period 1970-2006. The estimates obtained from the WLF technique have similar trends to the Guttman method, due to the fact that the generated recharge is directly proportional to rainfall amounts. However, it was obvious that in many years the generated recharge was more influenced by the intensity and temporal distribution of rainfall. For example, the year 2003/04 had a much higher recharge rate than was estimated by Guttman equation. Similarly, the year 1976/77 had a much lower rate than other estimate owing to the factors mentioned above.

The ratio between recharge and rainfall (Rc/Rf) were obtained by dividing the annual recharge estimates by the annual rainfall. Table 3 shows large differences in the ratios between the coefficients Rc to Rf in the two used methods. This variation is a direct consequence of the dissimilarity between the two methods in the level of consideration of the temporal distribution of the monthly rainfall and quantity for each year. The average Rc/Rf ratios estimated by the two techniques during the analyzed period are as follows: 35.7% and 30.5% by applying WLF and Guttman's equation respectively. The recharge coefficient obtained by WTF is more close to other recharge coefficients for other similar karst aquifers, [17,22].

Recharge equation: As discussed before, to consider the temporal distribution of rainfall, the monthly rainfall amounts from 1970/71 to 2005/2006 were used to simulate the annual recharge quantities. The data set was divided into two parts; the first (1970/71 - 1996/97) was used to develop an empirical equation which relates the annual recharge with monthly rainfall. The second part of data was used to validate the developed equation. A correlation test between monthly rainfall and the annual estimated recharge (i.e. WLF estimates) has been carried out. The rainy year 1991/1992 was removed from the correlation test since it is an exceptional year where rainfall is twice the mean annual rainfall. Table 4 shows the correlation values as well as the significance levels of the correlated parameters. The result proved that the rainfall during December, January and February are highly correlated with high significance to annual recharge; November is also correlated but with less significance.

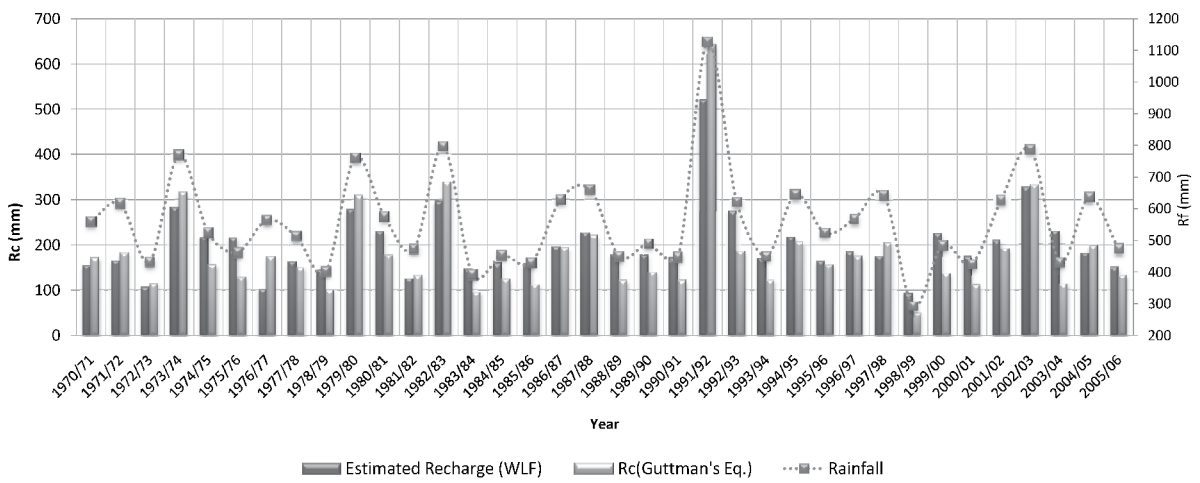

Figure 8: Annual recharge estimates with rainfall distribution for the analyzed period.

Table 4: Correlation test between monthly rainfall and annual recharge (1970/71 - 1996/97).

		Monthly rainfall								
		Sep	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**
Recharge	Pearson correlation	0.072	0.002	0.25	0.7	0.38	0.68	-0.164	-0.243	-0.089
	Sig. (2-tailed)	0.363	0.495	0.082	0.006	0.046	0.007	0.211	0.115	0.332

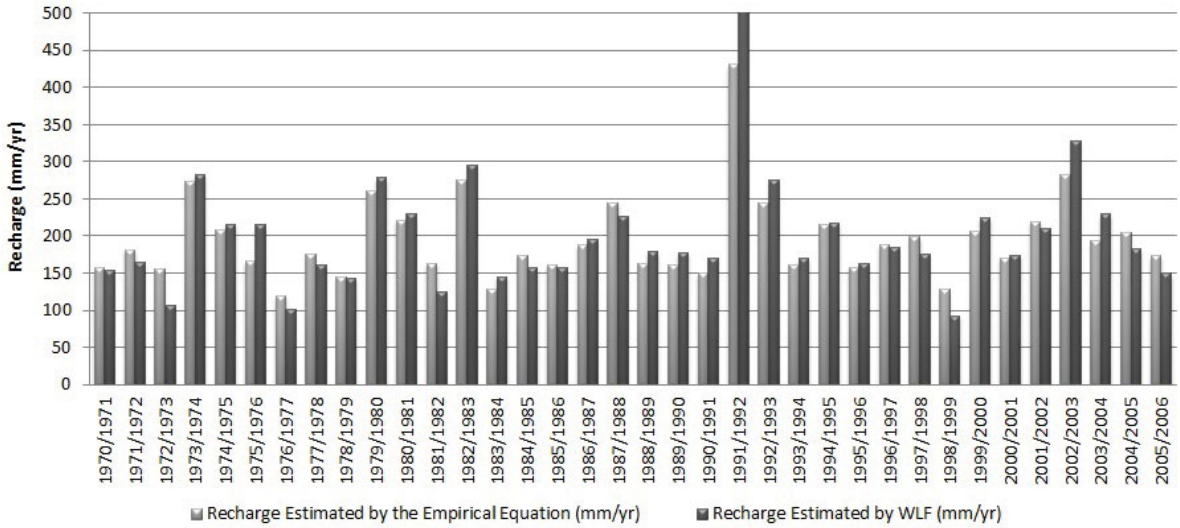

Figure 9: Recharge versus rainfall relations obtained by WLF technique and multi-regression.

All other rainy months were totally not correlated. Accordingly, the annual recharge is considered as a function of four rainy months within the year; November to February.

Based on the correlation results, the empirical equation of annual recharge and monthly rainfall was developed using a multi-regression technique. The result of multi-regression provided the equation coefficients with high significant level (less than 5%). The recharge equation has been noted below Eq. (8), through which 39.7 Mm^3/yr has been assumed the value representing all recharge reaching the WAB during the months of March to October as well as from other minor sources of recharge (i.e. leakage from agricultural and domestic networks and return flow from irrigation). This value represents around 19.8% of the average recharge reaching the WAB.

$$Rc = 0.197 \times R_{Nov} + 0.382 \times R_{Dec} + 0.381 \times R_{Jan} + 0.413 \times R_{Feb} + 39.7 \quad (8)$$

Where:

Rc: Annual recharge (mm)

R: Monthly rainfall (mm)

The equation above was used to generate annual recharge estimates for the complete data set (1970/71-2005/06).

The result, Figure 9, shows an excellent match for both simulation and validation periods. As a result, this equation is applicable to be used for estimating the annual recharge for any synthetic rainfall scenario taking into consideration the monthly rainfall variations.

Discussion and Conclusion

It was shown that annual recharge of the WAB could be estimated using the Water Level Fluctuation Technique by using its historical records of inflows, outflows and water level records. As a prerequisite condition for applying this technique, finding a water level cycle within the records is required. Within this water level cycle, the net aquifer storage will equal to zero. This period also formed the basis for the estimation of the storage coefficient of the WAB (α), i.e. the amount of water that could be abstracted from or recharged into the aquifer per one meter drop/rise. This factor provides a good tool to estimate the annual recharge by using the annual change in water level within the aquifer and the net outflow from the aquifer.

The estimated annual recharge of the WAB proves that the amount of annual recharge is affected by the monthly rainfall distribution more than it is by the annual amount of rainfall. Therefore, simply estimating annual recharge from total annual rainfall amounts is an inaccurate approach and will probably lead to either over or under estimating the annual recharge amounts. The annual recharge was estimated by the WLF technique for the last 37 years (1971-2007) and then the time series of annual recharge and monthly rainfall were used to develop an empirical equation relating annual recharge with monthly rainfall. This developed recharge equation will improve the future estimate of annual recharge by taking into account the monthly distribution of rainfall. The equation shows that recharge is highly dependent

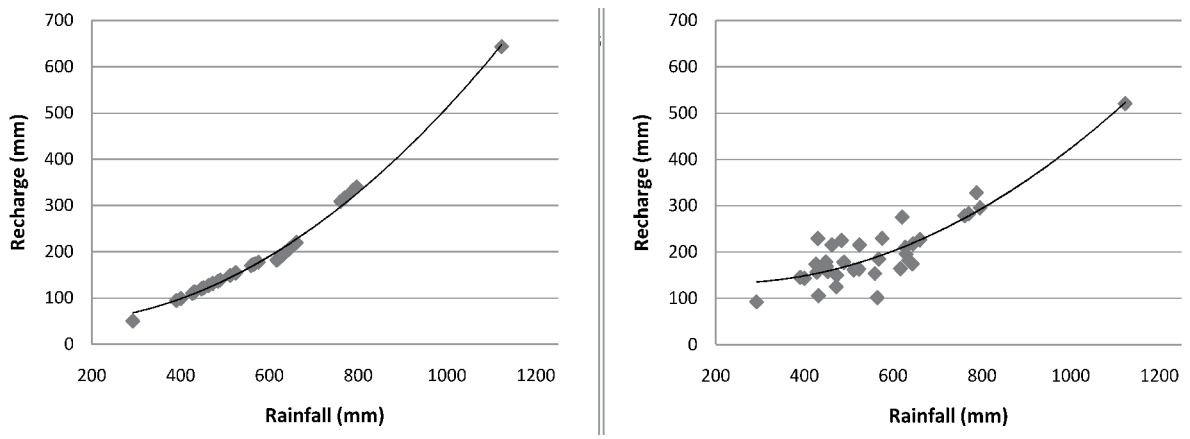

Figure 10: Recharge versus rainfall relation (a) By Guttman's Eq (b) by WLF technique.

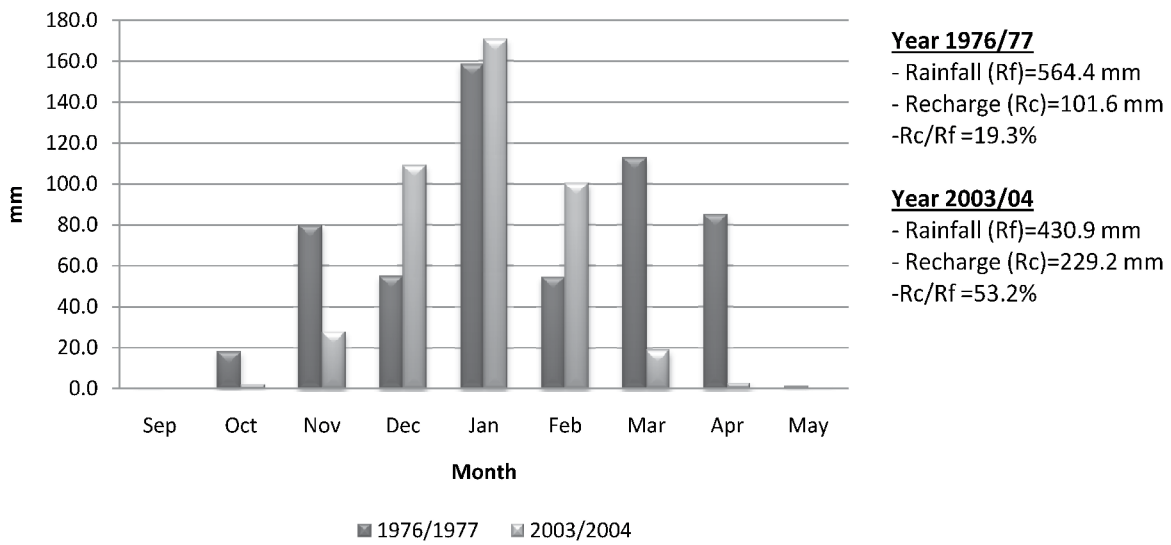

Figure 11: Rainfall for years 1976/77 and 2003/04.

on rainfall amounts during four main rainy months: November, December, January and February. Also, the equation concludes that the monthly rainfall in the months March to October is not effective for generating recharge; where the generated recharge from rainfall from these months and other minor recharge components was estimated at 39.7 Mm^3/yr during the analyzed period (1970/1971-2005/2006).

The rainfall/recharge relation in the two WAB recharge estimation techniques can be summarized as follows:

1. Recharge estimates by Guttman's equation: recharge estimates are strictly proportional to the annual amount of rainfall, yet estimates intensify with higher rainfall amounts due to the polynomial nature of the graph that was generated via a second-order polynomial equation. Furthermore, this technique does not take into account the rainfall intensity nor its temporal monthly distribution, (Figure 10A).
2. Recharge Estimation with the Water Level Fluctuation Technique (WLF): In this technique, the estimated annual recharge values show less correlation with the annual amount of rainfall (Figure 10B). The examination of historical records proves that the relation between annual recharge and rainfall is not that well developed, thus the monthly distribution was considered as supporting factor. This factor constitutes the underpinning elements of the WLF technique and was thus deployed in the development of the consequent computational equation.

As an example of high influence of monthly rainfall distribution, Figure 11 illustrates two years when the generated recharge has been fundamentally influenced by the temporal monthly distribution of rainfall rather than the total annual amounts. These two years have the highest and lowest Rc/Rf ratios (52.4% in year 2003/04 and 19.3% in year 1976/77). The Figure reflects the characteristics of the seasonal rainfall for the two years that led to high and low recharge to rainfall ratios:

1. The characteristics of seasonal rainfall that have high Rc/Rf ratio (e.g. year 2003/04):

a. The graph representing the monthly temporal distribution throughout the year takes the shape of a normal distribution.

b. About 80% of the annual rainfall accumulates during four consecutive months (November, December, January and February). It is worth mentioning that these four months have the lowest potential evapotranspiration rates, [23].

1. The characteristics of seasonal rainfall that have low Rc/Rf ratio (Year 1976/77):

a. The graph representing the monthly temporal distribution throughout the year takes a shape far from a normal distribution.

b. Generally, this case pointed out relatively low rainfall amounts during the main rainy months (November, December, January and February).

c. High percentages of rainfall occurred during October, March and April, a period characterized for having elevated potential evapotranspiration rates especially compared to November, December, January and February, [23].

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