



Groundwater Recharge Level Estimation from Rainfall Record Probability Match Methodology

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Abstract

Groundwater reservoirs' assessment and management studies present more difficulties compared to surface water resources, because their storage media are geological formations, which have spatial heterogeneities that cannot be expressed by empirical or deterministic methodologies easily. Especially, their recharge possibilities are dependent not only on the precipitation features, but also on uncertainties including heterogeneous porosity, specific yield, storage, hydraulic conductivity, permeability and transmissivity quantities. The best way to treat such uncertainties is through the probability distribution function (PDF) methods, which reflect the spatial and temporal randomness in the meteorological and hydrogeological variabilities. In general, this paper presents temporal PDF behaviors of the rainfall variation and groundwater level fluctuation in addition to the probabilistic correlation between them. For this purpose, the cumulative distribution functions (CDF) of rainfall and groundwater level rise departures are considered from respective mean values. The two CDFs are related to each other on the valid assumption that the more the rainfall cumulative departure from the mean the more is the groundwater fluctuation. The application of this probabilistic methodology is presented to available data from the south eastern part of Turkey.

Keywords Estimation · Groundwater level · Match · Probability · Rainfall · Recharge

1 Introduction

Groundwater resources play key role in irrigation, drainage and water supply problems in every region and they are also reliable water resources in cases of emergency such as during dry spells, water stress periods, droughts, earthquake aftermath, etc. Groundwater recharge depends on the capability of geological formations and precipitation events. Sustainable groundwater development and management are gaining unprecedented significance in arid and semi-arid regions and even in rather humid regions due to recent climate change impacts (IPCC 2001, 2007).

There are various methodologies for groundwater recharge stimulations in the open literature and each one has specific conditions and features for the application. One of

the common approaches is the water balance studies where rainfall, infiltration, evaporation and surface runoff are taken into consideration. Schicht and Walton (1961) estimated groundwater recharge by water balance method including infiltrating water that reaches the saturation zone. Among the physical techniques, channel water-budget approach considers surface-water gains and transmission losses based on stream-gauging data (Lerner et al. 1990; Lerner 1997; Rushton 1997). Meyboom (1961), Rorabough (1964), Mau and Winter (1997), Rutledge (1997) and Halford and Mayer (2000) tried to estimate groundwater recharge in watersheds through stream hydrograph separation. At high elevations of river upstream catchments stable, oxygen and hydrogen isotopes are used for identifying groundwater recharge from rivers and lakes (Taylor et al. 1989, 1992; Stuyfzand 1989). Singh (1995) reviewed many watershed models, which generally provide recharge estimates as a residual term in the water-budget equation (Arnold et al. 2000; Leavesley and Stannard 1995; Hatton 1998a, b). The minimum recharge rate can be controlled by $\pm 10\%$ accuracy with various parameter measurements in the water-budget equation. Natural environmental tracers in the Earth's atmosphere like chloride (Cl) are used to estimate recharge rates (Allison and

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Hughes 1978; Scanlon 2000; Phillips 1994; Subyani and Sen 2006; Şen et al. 2017).

One of the most practical groundwater recharge estimation procedure is by comparison of rainfall record heights with groundwater level fluctuations and detailed account about the origin of this approach can be found in works by Wenzel (1936), Sophocleous (1991), Wu et al. (1996), Xu and van Tonder (2001) and Al-Amri and Subyani (2017). It has been clearly showed that fluctuation of natural groundwater level is related to the rainfall departure from the mean rainfall of the preceding time period. If the departure is positive, the water level will rise or vice versa.

The purpose of this paper is to suggest a probabilistic approach for assessing the relationship between the cumulative rainfall departures (CRD) that give rise to groundwater recharge and the groundwater level fluctuations in the study area. In the previous researches, a linear relationship has been assumed between the CRD and the groundwater flow. In this paper, a nonlinear relationship has been obtained through the probabilistic equivalence of rainfall and groundwater level fluctuations. These are modeled by the most convenient probability distribution functions (PDFs) and their cumulative distribution functions (CDFs). The core of this paper is to match the CDFs to each other and then to estimate the groundwater levels from the rainfall records. This probabilistic model application is presented for a transboundary aquifer in the southeastern province of Turkey.

2 Probabilistic Methodology

Groundwater recharge is a process of infiltration through which an addition of water takes place to groundwater reservoir either naturally after rainfall occurrence or artificially after irrigation and artificial water impoundments. The unconfined aquifers are replenished through natural recharges due to each rainfall residual remnants after the losses (evapotranspiration, depression, interception and runoff). The cumulative rainfall deviations are the main reasons for effective groundwater recharge. As a result of loss off-sets, there is always a time lag between the rainfall incidence and rise in the groundwater levels.

Depending on the geological material between the existing water table and earth surface, the time lag can be short, medium or large. Short time lags are coupled with highly permeable layers within hours after intensive rainfalls. Medium time lags imply intermediate permeability of the unsaturation material, which may take days. The time lag between the rainfall occurrence and the groundwater level rise depends on the duration, frequency and intensity of the rainfall, unsaturation thickness, the soil texture, the type and size of vegetation and the geology of the aquifer material.

The basis of probabilistic approach includes the following steps to estimate groundwater levels from the rainfall data.

1. The best theoretical CDF, $(CDF)_{GL}$, of the groundwater level measurements, G_{LM} , and simultaneous actual rainfall, R_A , measurements, $(CDF)_{AR}$, are determined separately.
2. The probabilities, P_{GL} , of each groundwater level records are calculated from the $(CDF)_{GL}$.
3. These probabilities are entered the theoretical $(CDF)_{AR}$, and hence, groundwater level corresponding to rainfall amounts, R_G , are obtained.
4. The groundwater level, R_G , theoretical CDF, $(CDF)_{GR}$, is obtained, which implies groundwater level conversion from rainfall amounts.
5. The $(CDF)_{AR}$, and $(CDF)_{GR}$, are shown on the same graph to visualize their match to each other.
6. The R_A amounts are scattered against the R_G , so as to determine the simple and valid model between the two sequence.
7. The R_G amounts are entered into the $(CDF)_{GR}$, and their corresponding probabilities, P_{GR} , are calculated.
8. These probabilities are entered into the $(CDF)_{GL}$, so as to estimate the groundwater levels, G_{LE} .
9. Finally, for the calibration and validation of the presented methodology, the groundwater level measurements, G_{LM} , are compared with the G_{LE} through a scatter diagram.

It is very convenient to have rainfall station and well locations close to each other, if not on the same point location. To assess groundwater recharge, it is then possible to relate the rainfall records and groundwater level measurements at the point. The possible relationship of rainfall amounts' to groundwater levels can be searched through various techniques including probabilistic, statistical, and stochastic or any other convenient approach. It is well known that groundwater level response to rainfall will be after a time lag, which will depend on the unsaturation zone geological properties. The more is the unsaturation zone hydraulic transmissivity and infiltration capability, the shorter will be the time lag.

In hydrogeological studies, there are several PDFs that are in common use, but for the purpose of this paper herein only the Gamma and Weibull PDFs are considered; whereas in case of any other PDF, the same procedure can be applied for the match between the groundwater level and rainfall simultaneous records.

Two-parameter Gamma PDF has a shape parameter, α , and scale parameter β , which is also called as a rate parameter. The general mathematical expression of this PDF is given as follows (Feller 1967):

$$f(x) = \frac{1}{\beta^\alpha \Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \quad \text{for } x > 0, \alpha > 0, \beta > 0, \quad (1)$$

where $\Gamma(\alpha)$ denotes the Gamma function as,

$$\Gamma(\alpha) = \int_0^{\infty} x^{\alpha-1} e^{-x} dx.$$

The arithmetic average and the variance of this PDF are given as $\alpha\beta$ and $\alpha\beta^2$, respectively. It is well known that if $\alpha < 1.0$ ($\alpha > 1.0$), then the Gamma PDF has J-shaped (mound-shaped) appearance. As α gets large, the Gamma PDF approaches the normal (Gaussian) PDF.

On the other hand, the Weibull PDF has either three or two parameters as γ is the shape parameter, μ , is the location parameter and α is the scale parameter. Its mathematical form is as follows:

$$f(x) = \frac{\gamma}{\alpha} \left(\frac{x - \mu}{\alpha} \right)^{\gamma-1} e^{-\left(\frac{x - \mu}{\alpha} \right)^{\gamma}} \quad \text{for } f(x) \geq 0, x \geq \mu,$$

$$\gamma > 0, \alpha > 0 \quad \text{and} \quad -\infty < \mu < +\infty. \quad (2)$$

If $\alpha = 0$, then it turns down to a two-parameter Weibull PDF.

3 Study Area and Data

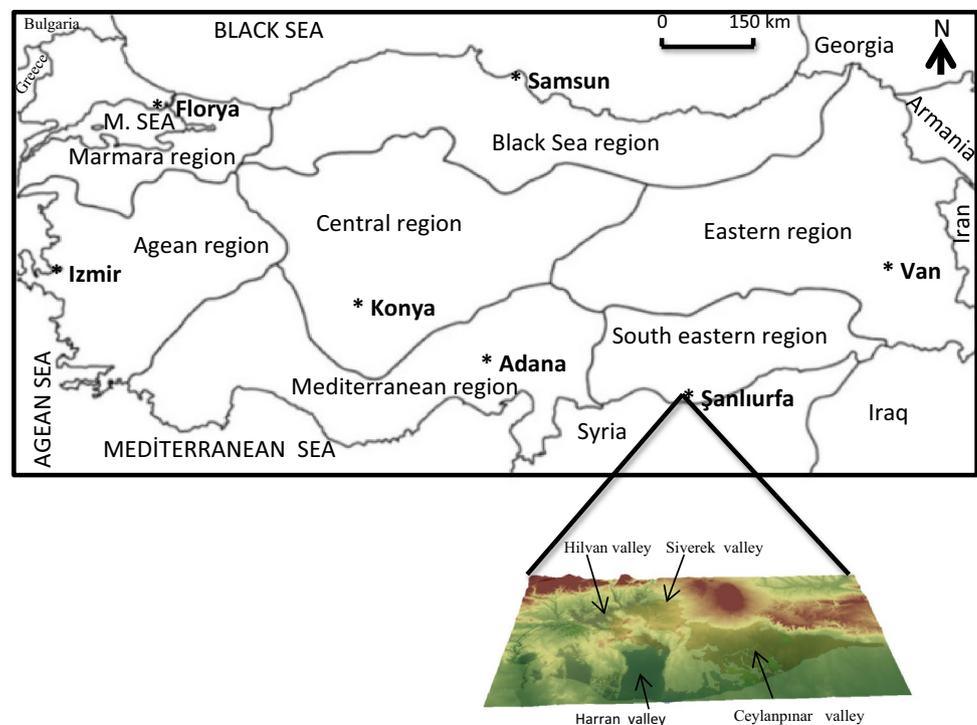
The study area lies within the Ceylanpınar drainage basin in the southeastern province of Turkey, where a transboundary aquifer exists between Turkey and Syria and this unconfined

aquifer is almost completely recharged from Turkish part of the drainage basin with its 95% areal share (Fig. 1). The southeastern province of Turkey has border with Syria and Iraq in the semi-arid region. The groundwater storage in the unconfined aquifer in the Ceylanpınar drainage basin is recharged by rainfall occurrences in the northern humid regions of Turkey, and at about 30 km toward the south from Turkey–Syria political boundary, on the Syrian side, there are springs, which indicate that the groundwater resources have transboundary significance. This sub-basin is in the Euphrates River drainage basin. The sub-drainage has 80 km width from east to west and 40 km from north to south. Its position is between the 36°00'–37°20' latitude and 39°30'–40°10' latitudes. The elevation from the mean sea level varies from 370 to 527 m with an average of 397 m (DSİ 2011).

This region has continental climate type with cold winter rainfalls, short and humid spring, dry, semi-arid, long summer, and comparatively more rainfall and cool autumn than spring season. Average annual temperature is about 22 °C. The upper 350-m layer is composed of gravel, basalt and silt, which provides an unconfined aquifer type to which groundwater recharge is possible after rainfall events. The annual average rainfall is about 300 mm with reduction from the north to south direction.

In the region, dominant geological formations are sedimentary rocks in the form of limestone and from the magmatic formations there are basaltic covers scattered all over the region. The limestones are from Eocene and Miocene

Fig. 1 Study area location map



eras and they have outcrops in the south and west areas. The limestone has fractures, fissures and solution cavities and therefore, deep aquifers are in the form of karstic formations. The well discharges vary between 20 and 80 l/s.

The study area is covered with 2.1-m thickness of soil. The main geological units in the region are sedimentary rocks, limestones and magmatic basalts. Limestones are of Miocene and Eocene ages and they have outcrops at the south and west. Limestones form the regional aquifer, because of karstification due to fractures and solution cavities. The stream channels extend in the north–south direction and they are on the Eocene limestone bases. Limestones include at a set of places marl and conglomeratic intercalations.

Basalts are abundant in the north and northwestern parts of the study area and they are from Paleo-Quaternary era covering old Eocene limestone. They have aquifer properties depending on fractures. In the northeastern part of the region, volcanic rocks cover about 7200 km² and they are spread at the northern boundary of the study area. The stratigraphic section from the location is shown in Fig. 2.

For the application of the methodology proposed in the previous section, records of monthly precipitation are chosen with groundwater level fluctuation near the border. The well is located in the Ceylanpınar drainage basin close to the Turkey–Syria border in the southeastern province of Turkey. Monthly groundwater level measurements in an observation well are given in Table 1 from 1996 to 2002 with the nearby meteorology station records. The data are obtained from two governmental departments, which area State Water Works (Devlet Su İşleri, DSI)

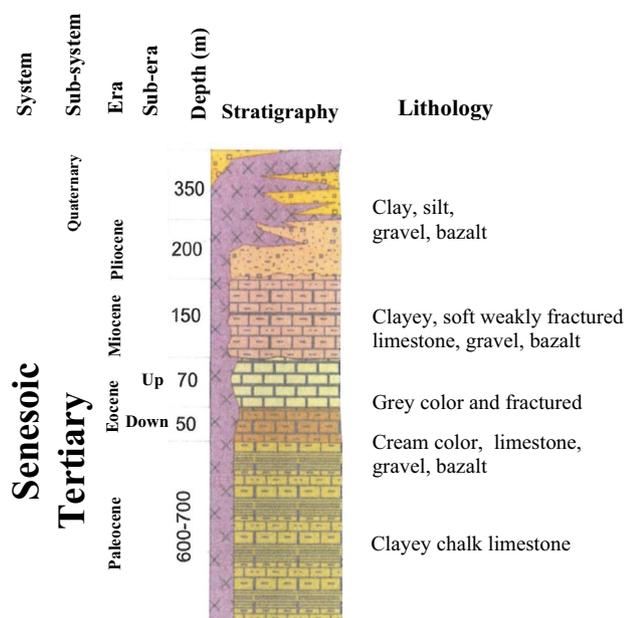


Fig. 2 Stratigraphic cross section

for the groundwater level measurements and Meteorology General Directorate for rainfall records. The groundwater level and rainfall data are available on monthly basis from 1995 to 2002, inclusive. The statistical features of the data are presented in Table 2. In Fig. 3 the internal structure of each record is reflected through the sample serial correlation function for 24-month lag time duration, which implies that due to monthly records, there are periodicities and the first-order correlation coefficients for the groundwater level and the rainfall records are 0.87 and 0.27, respectively. These two numbers indicate comparatively that the rainfall records are more random than the groundwater level fluctuations.

The monthly arithmetic averages of the rainfall and groundwater level measurements are about 43 mm and 6.54 m, respectively, with standard deviations 40.90 mm and 2.02 m. Practically, the arithmetic average and the standard deviation of the rainfall amounts are close to each other and this is a very characteristic feature of arid or semi-arid region.

4 Methodology and Application

The application of probabilistic groundwater recharge methodological approach is achieved for 8 years' monthly simultaneous records in the southeastern part of Turkey (Fig. 1). The execution of the nine methodological steps mentioned in Sect. 2 to data in Table 1 leads to Fig. 4, where the theoretical CDF of the rainfall records is shown.

The scatter of monthly rainfall values and the entire scatters in this and all subsequent figures are obtained by empirical probability calculations after the execution of the following steps.

1. Sort the monthly rainfall (groundwater level) data in ascending order and each value is attached with a rank, m , which changes from 1 to n , where n is the number of available data.
2. Each sorted data are attached with an empirical probability value in terms of its order, m , and the number of data as follows,

$$P_m = \frac{m}{n + 1}. \quad (3)$$
3. Ordered data values versus these probabilities yield the scatter diagram in each figure.

In Fig. 4, monthly rainfall records abide with the theoretical Gamma PDF. In all figures, the rainfall return periods (2-year, 5-year, 10-year, 25-year, 50-year, 100-year, 250-year and 500-year) correspond to risk levels (0.50, 0.20,

Table 1 Groundwater and rainfall measurements

Month.year	Groundwater level (m)	Rainfall (mm)	Month.year	Groundwater level (m)	Rainfall (mm)
Jan.95	6.87	121.7	Jan.00	6.07	71.4
Feb.95	6.26	17.9	Feb.00	5.75	156.7
Mar.95	4.75	109.4	Mar.00	4.8	62
Apr.95	4.09	69.9	Apr.00	3.97	3.6
May.95	3.24	24.6	May.00	3.09	8.3
Jun.95	3.8	2	Jun.00	2.96	5.3
Jul.95	5.6	3	Jul.00	4.56	21.2
Aug.95	7.09	6.5	Aug.00	5.95	2.1
Sep.95	7.74	22.1	Sep.00	6.12	1.4
Oct.95	7.74	20.9	Oct.00	6.59	18.8
Nov.95	7.51	61.9	Nov.00	6.27	55.1
Dec.95	7.27	46.2	Dec.00	6.25	39.1
Jan.96	6.91	12.1	Jan.01	5.85	55.8
Feb.96	6.63	105	Feb.01	5.76	93.9
Mar.96	5.27	43.8	Mar.01	5.52	101.2
Apr.96	4.4	77.9	Apr.01	4.9	91.8
May.96	3.69	8.9	May.01	4.05	5.6
Jun.96	3.46	10.8	Jun.01	3.91	12.87
Jul.96	5.37	8.4	Jul.01	6.58	1.4
Aug.96	7.8	1.1	Aug.01	8.53	0.2
Sep.96	8.07	53.5	Sep.01	8.32	1.7
Oct.96	8.01	13.7	Oct.01	8.7	14.5
Nov.96	7.66	47.4	Nov.01	8.26	17.6
Dec.96	7.45	80.3	Dec.01	8.15	42.2
Jan.97	6.62	43.1	Jan.02	7.9	10.7
Feb.97	6.08	18.9	Feb.02	7.59	77.7
Mar.97	5.92	85.2	Mar.02	7.59	2.7
Apr.97	5.24	114.2	Apr.02	7.92	97.2
May.97	4.72	21.4	May.02	7.32	43.1
Jun.97	4.34	12	Jun.02	8.85	0.3
Jul.97	5.82	1.95	Jul.02	10.75	22.2
Aug.97	6.23	23.2	Aug.02	11.27	9.1
Sep.97	8.15	3.6	Sep.02	11.14	1.9
Oct.97	8.76	83.8	Oct.02	11.68	0.3
Nov.97	7.85	28.4	Nov.02	11.22	113.5
Dec.97	7.06	80	Dec.02	10.67	160.2

Table 2 Groundwater level and rainfall data statistical features

Data type	Arithmetic average	Standard deviation	Skewness	Kurtosis
Groundwater level (m)	6.64	2.05	0.43	0.02

0.10, 0.04, 0.02, 0.01, 0.004 and 0.002). The most convenient theoretical CDFs are obtained through the Matlab program by consideration of the least squares method.

The execution of the same steps and procedures to groundwater level data results in Fig. 5, where the theoretical CDF appears as Weibull type different than the rainfall CDF.

The convenience of the Weibull CDF to groundwater level data can be visualized with confidence.

The applications of steps 2–4 in Sect. 2 lead to the groundwater level conversion data to rainfall amounts, R_G , which then yield to another Weibull CDF as $(CDF)_{GR}$ in Fig. 6 through the application of the theoretical CDF and the empirical probability attachment scatter diagram according to Eq. (3).

Fig. 3 Sample serial correlation function

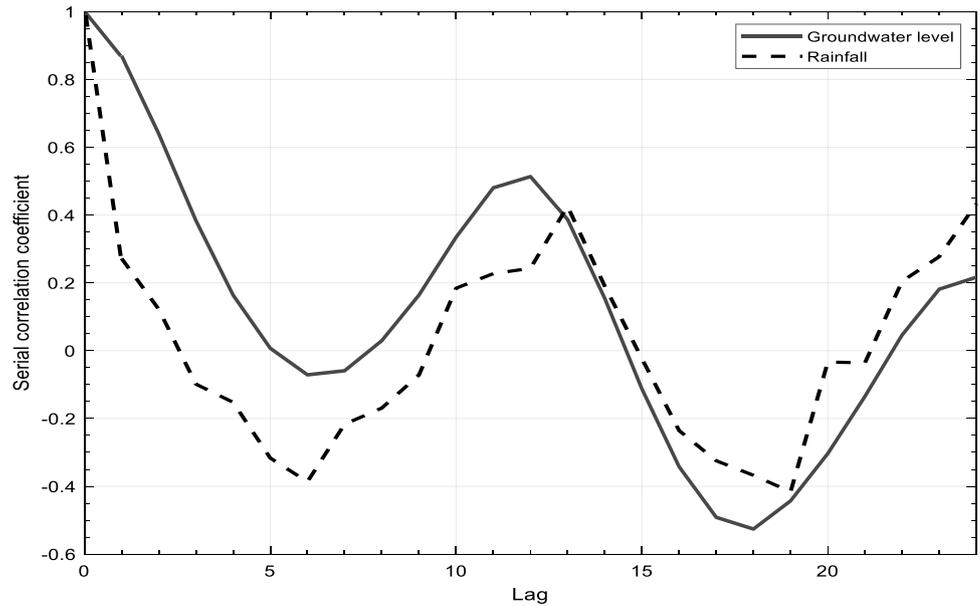
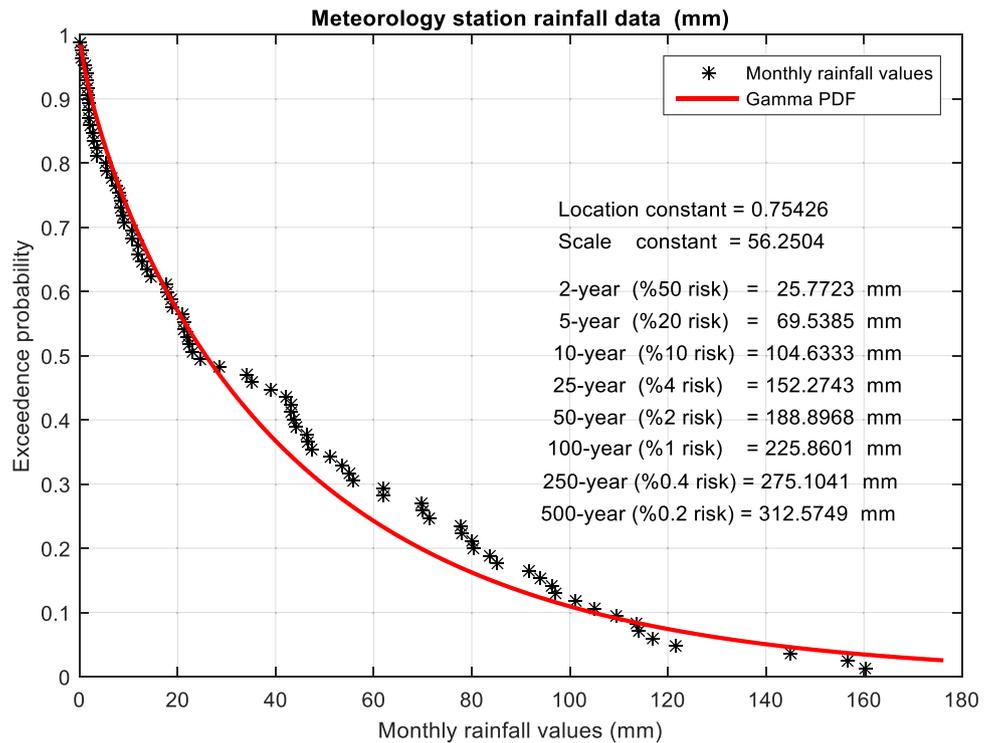


Fig. 4 Actual rainfall record (CDF)_{AR}



In Fig. 7, two rainfall CDFs, namely, (CDF)_{AR} and (CDF)_{GR}, are shown collectively one on the top of other and a complete matching of the theoretical CDFs, although with different distribution parameters (location and scale) fall on each other. There are some discrepancies between the empirical scatter values, but on the average, the two theoretical CDFs are almost identical within practically acceptable error limits of $\pm 10\%$.

One can observe that return period values are very close to each other and the maximum percentage relative error for 500-year return period is $100 \times (335.6759 - 312.5749) / 335.6759 = 6.7$, which is less than 10% acceptable level.

Up to this point, the suggested probability procedure provided a good match between the rainfall and groundwater levels conversion rainfall CDFs. Hence, any groundwater level value can be converted to rainfall CDF or vice versa.

Fig. 5 Groundwater level data (CDF)_{GL}

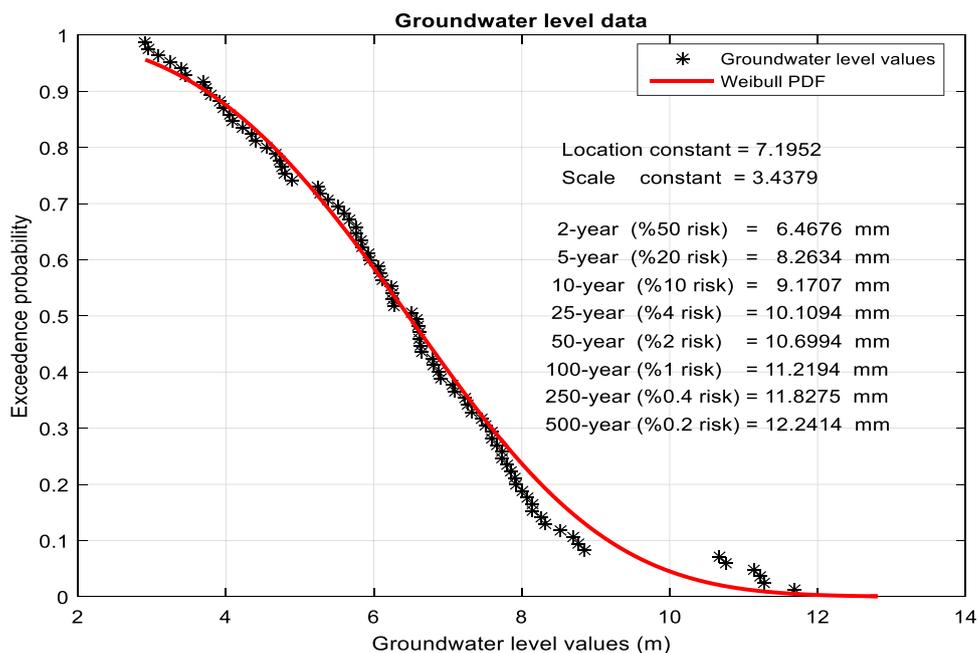


Fig. 6 Groundwater level data (CDF)_{GR}

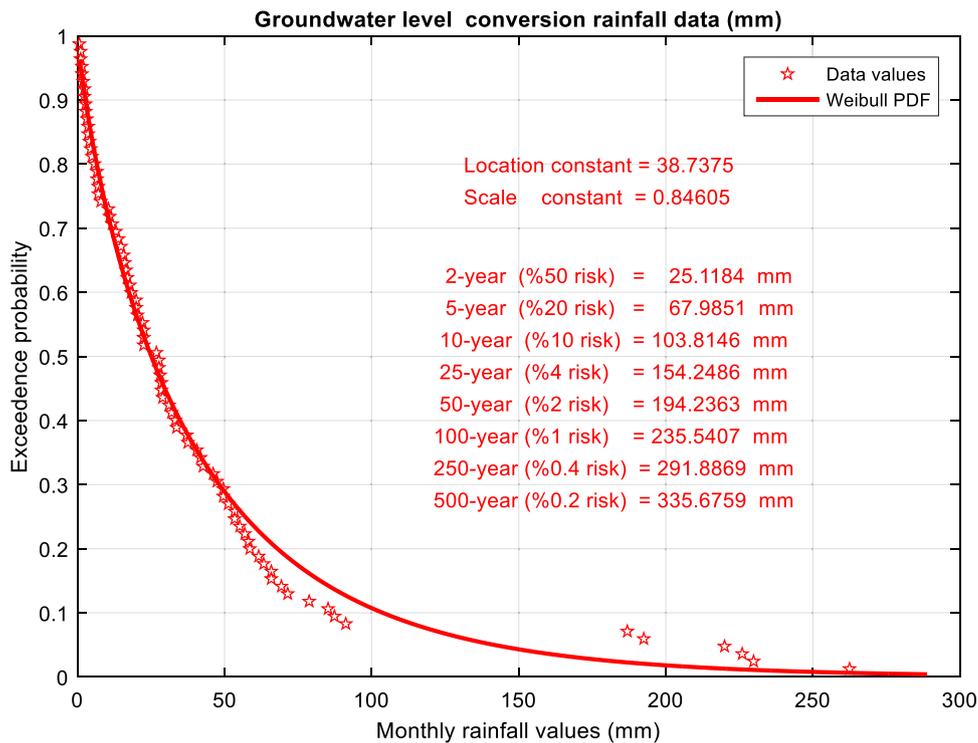


Figure 8 indicates the relationship between the sequences of monthly rainfall amounts with the groundwater level conversion rainfall values. In case of perfect relationship, all the scatter points are expected to fall on or within practically insignificant error bands around the 1:1 (45°) straight line. Although two theoretical CDFs in Fig. 6 merge completely corresponding to 1:1 (45°) straight line, this is not the case in consideration of the data scatter values as in Fig. 8.

As one can observe from this figure, there are two data groups, which may be classified as low and high values with the following simple mathematical formulations,

$$R_{GR} = 0.80R_{AR}, \tag{4}$$

and

$$R_{GR} = 85 + R_{AR}, \tag{5}$$

Fig. 7 $(CDF)_{AR}$ and $(CDF)_{GR}$ match

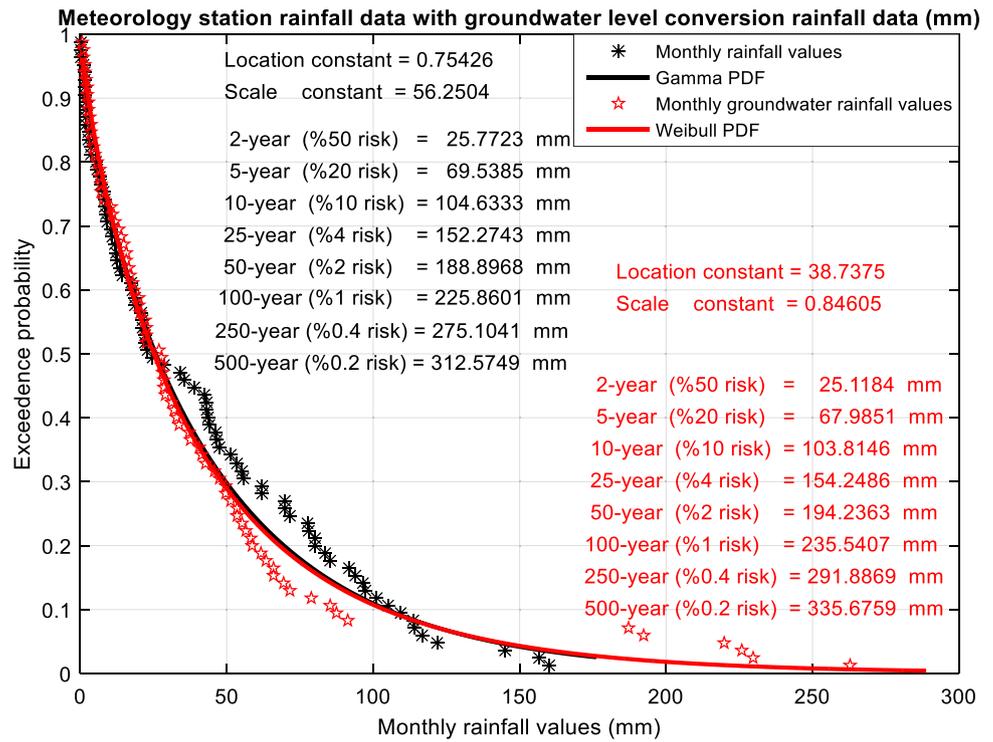
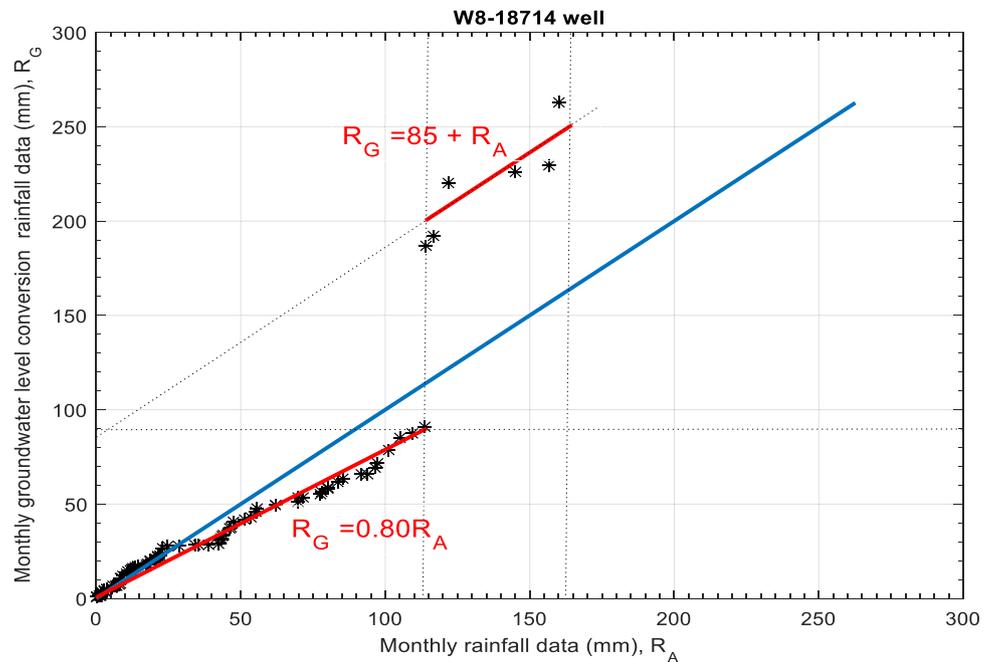


Fig. 8 Actual and groundwater level-based rainfall relationships

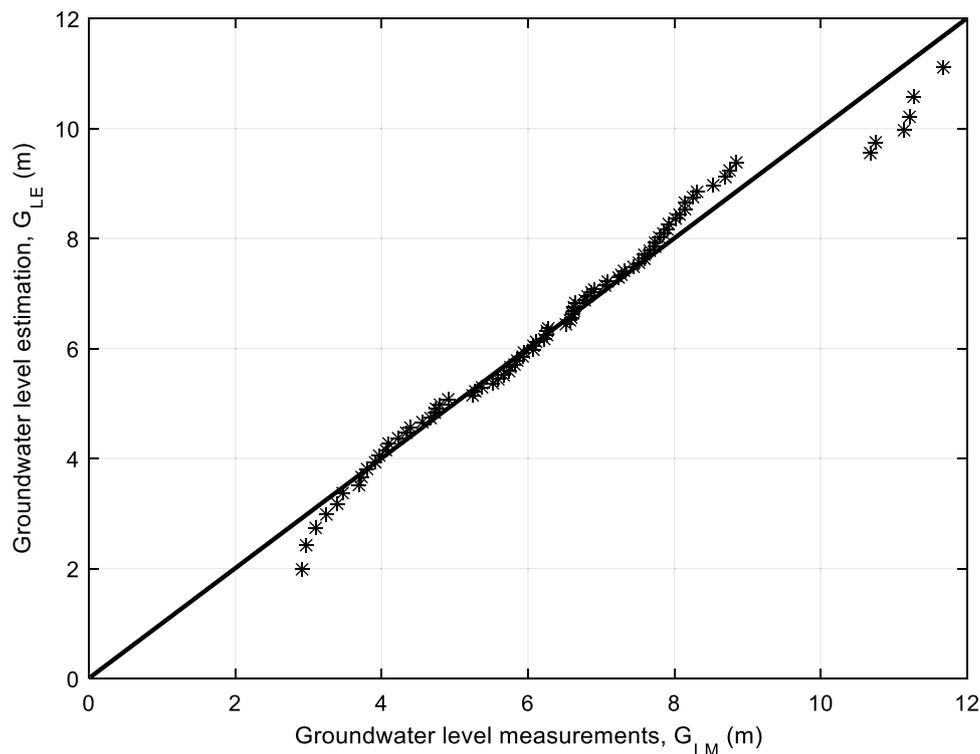


respectively.

The final part of the application is concerned with the validation and calibration of the suggested probabilistic method for groundwater level estimation from monthly rainfall records. For this purpose, the following procedural steps are needed.

1. Calculate groundwater level-related rainfall amounts, R_{GR} from monthly rainfall data, R_A through Eqs. (4) and (5).
2. Calculate the probability, P_{GR} , values corresponding to R_{GR} rainfall amounts.

Fig. 9 Groundwater level measurements versus estimations scatter diagram



3. Enter the $(CDF)_{GL}$ theoretical PDF for the groundwater level estimation, G_{LE} values.
4. Plot G_{LM} series versus G_{LE} , as a scatter diagram and compare the 1:1 (45°) straight line with the scatter points.

The application of these steps to available groundwater level data leads to the final result as in Fig. 9, where the measurement and groundwater level estimations appear along 1:1 (45°) straight line, which is an evidence for the calibration and validation of the suggested methodology.

As a discussion, the applicability of the proposed probabilistic method is straightforward provided that simultaneous monthly records are available for the groundwater level and rainfall records. It is necessary that the groundwater level measurements must be taken from an observation well that is not affected by pumping well influences. This is to say that the observation well should be outside of the pumping wells' radius of influence. This condition is necessary for direct relationship between the rainfall amounts and groundwater levels.

5 Conclusions

Groundwater recharge calculation after each rainfall event is very important for the management, operation, abstraction and water supply studies. Although it is preferable to have a

number of observation and pumping wells for such effective studies, it is also important to assess groundwater recharge calculations through simple preliminary methodologies to plan for future estimations. In this paper, rather simple probabilistic method is suggested to estimate the groundwater level fluctuations from monthly rainfall records. For this purpose, after the determination of the best theoretical probability distribution functions (PDFs) of the rainfall and simultaneous groundwater measurements, they are matched onto each other to convert the groundwater levels to rainfall amounts or vice versa, and hence, one can estimate the groundwater fluctuations from monthly rainfall amounts. The success of this methodology depends on the observation well measurements that are not affected from the pumping well influences. The application of the proposed probabilistic methodology is presented for monthly rainfall and groundwater level measurements in the southeastern province of Turkey.

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