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ORIGINAL ARTICLE

Aridity and Risk Calculations in Saudi Arabian Wadis: Wadi Fatimah Case

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Abstract

Background Infrequent rainfall and rare flash floods are the primary sources of water in semi-arid and arid regions and are the key aspects in the management of water supply. In these regions, rainfall varies temporally and spatially with infrequent high intensities and sporadic occurrences, making it impossible to systematically record measurements as a proper time series.
Purpose The main purpose of this paper is to present temporal (risk assessment) and spatial (isohyet maps) methods for the evaluation of monthly rainfall water volumes and infiltration rates. Additionally, an aridity index based on rainfall and temperature measurements is proposed for use in semi-arid and arid regions.
Method The limited data available for semi-arid and arid regions are treated using effective probabilistic and statistical methods. Calculation of the volume of rainfall is achieved through a simple hydrological procedure which involves examining monthly isohyet maps based on a set of rainfall measurements from weather stations in scattered locations. Calculation of rainfall and infiltration risks are performed according to the logarithmic normal probability distribution function. Furthermore, the potential monthly rainfall and infiltration rates are calculated using a set of pre-selected risk percentages.
Results Aridity index, rainfall volume, and risk values are presented for Wadi Fatimah, which is located in the western Saudi Arabia. Potential rainfall and infiltration rates are calculated on a monthly scale using a set of pre-selected risk percentages. These simple calculations provide a sound basis for future studies on groundwater resource storage strategy, operation, and management.
Conclusions Water management studies can be best advanced through simple but effective assessment methods, as presented in this paper with specific applications to the Wadi Fatimah drainage basin that joins the Red Sea.

Keywords Climatology · Hydrology · Aridity · Recharge · Risk · Rainfall · Volume · Wadi · Groundwater

1 Introduction

Atmospheric general circulation, the location and distribution of mountain ranges, high altitude plateaus, and water bodies on the Earth's surface are among the most significant causative factors playing an important role in the occurrence of rainfall. Rainfall is most abundant where the air rises (equatorial area), and limited where it sinks (sub-tropical areas), a variable which is difficult to estimate. Arid regions experience high temperature and evapotranspiration and in general have less than 100 mm of annual rainfall, which weakly recharges the groundwater resources due to low percolation rates. Global climates are classified by their two most important elements: temperature and precipitation (IPCC 2007). A similar classification method is presented by Abdullah and Al-Mazroui (1998) for the rainfall climatology of Saudi Arabia. The geographical distribution of the climate patterns shows warm and moist characteristics in the low latitudes, while warm and much drier climates prevail in the subtropics such as the Arabian Peninsula (Al-Sefry et al. 2004). Recently, Almazroui et al. (2015) classified the five climate zones of the Arabian Peninsula, in particular over Saudi Arabia which accounts for about 80% of the Peninsula (Almazroui et al. 2012a, b).

Annual evapotranspiration and runoff rates have been studied in detail by various researchers (e.g., Schreiber

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1904; Turc 1954; Pike 1964; Arora 2002). They have succeeded in expressing the annual evaporation rates in the context of the aridity index. Their work has concentrated mainly on drainage basins in the humid regions. In the arid regions, the main drainage basins are wadis which differ in some important ways from the basins in humid areas. The term wadi is used for drainage basins in arid regions, where there is little vegetation at high elevations, but quaternary alluvial depositions at lower levels in the valleys and depressions (Şen 2008). Wadis differ from humid region watersheds, as in that they experience limited rainfall and have high evaporative fluxes. The annual mean evapotranspiration and surface runoff are the functions of temperature (solar irradiation) and rainfall, and determine the renewal of surface and groundwater resources. In humid regions, the solar irradiation and evapotranspiration rates are much lower than in arid and semi-arid areas. High solar irradiation leads to high evaporation rates, thus surface drying occurs. This process increases the duration and intensity of drought and produces low runoff. On the other hand, high solar irradiation warms the atmosphere and increases the water holding capacity, which in turn increases the rainfall occurrence. Potter (1992) defined arid and semi-arid regions based on the value of the precipitation to evaporation ratio, P/E. A region is deemed arid, if the value of this ratio is less than 0.5, for values between 0.5 and 1.0, the region is considered semi-arid, whereas in humid regions, the ratio is greater than 1.0. In arid zones, the rain gauge density is low, and therefore, lumped-input modeling techniques are not appropriate due to the large sampling errors. Pilgrim et al. (1988) stated that if the drainage area is less than 10 km^2, it is not uncommon for a flood event to occur at the outlet as a result of an intensive storm rainfall over a limited area that is not adequately represented by the gauge readings.

Reduction of disaster risk is a very significant research topic for sustainable development promoted by a joint workshop and report by the United Nations International Strategy for Disaster Reduction, the Islamic Development Bank and the Presidency of Meteorology and Environment, Saudi Arabia (Regional Workshop 2009). Isohyet maps, kinematic waves, and rational methods are used for synthetic flash flood hydrograph estimations in arid regions (Sevinç and Şen 2007). It is almost impossible to achieve reliable real-time prediction of extreme events through numerical models, although estimates are possible for a set of recurrence intervals (risks), 5-year (0.20), 10-year (0.10), 25-year (0.04), 50-year (0.02), and 100-year (0.01), which are necessary for any strategic planning to mitigate against the destructive water effects in a region.

The main purpose of this paper is to present simple temporal (risk assessment) and spatial (isohyet maps) methods to evaluate the monthly rainfall water volumes and infiltration rates. In addition, an aridity index based on rainfall and temperature measurements is used for arid regions, particularly for Saudi Arabia.

2 Study Area and Climatology

Wadi Fatimah is the closest drainage basin to the three important cities, Jeddah, Makkah and Taif, in the central western part of Saudi Arabia. Jeddah is located on the coast of the Red Sea, downstream from Wadi Fatimah, the holy city of Makkah lies in the middle-stream belt at 260 m above the mean sea level (MSL), and Taif is located at 2400 m above the MSL near the upstream portion of the same wadi. Although this region has a desert climate, its proximity to the Red Sea has a slight modifying effect on this pattern and this is reinforced by the high Sarawat Mountains (Hijaz Escarpment) in the east (Fig. 1). The Sarawat Mountains act as an orographic cooling barrier, and hence more rainfall episodes are expected around Taif city, which is situated in the upstream highlands of this wadi.

The infiltration rate is low due to the carbonate and quartz–feldspar epiclastic rocks in the Fatimah group (Moore and Al-Rehaili, 1989). There are some studies on the climate variability in the region (e.g., Italconsult 1973; Al-Qurashi 1981 and Al-Jerash 1985; Almazroui et al. 2012a, b). Regional studies have been undertaken by Al-Jerash (1983, 1988), Şen (1983), Nouh (1987, 1988) and Abdulla and Al-Badranih (2000).

Convective storms are coupled with orographic effects in summer, and in winter months, Mediterranean-born frontal rainfall events may lead to occasional flash floods with considerable damage to human life and property in Saudi Arabia. Several devastating flash floods like the ones on 25th November 2009, 26th January 2011 and 17th December 2015 at Jeddah alerted the administrators to the need for in-depth research on predictions of extreme events with a specific risk dimension (Almazroui et al. 2012a, b). Winter rainfall is caused by disturbances in the Mediterranean Sea, the Sudanese depression, and by westerly waves in the upper atmosphere. As for summer rainfall, this is caused by a combination of the northward advance of the southwesterly monsoon and the intertropical convergence zone (Al-Yamani and Şen 1993). In spring, the low-level convergence lines at the Red Sea are responsible for the large amount of rainfall. These rains are favored by the presence of an upper level trough of 700 mb. They also enhance the Sudanese depression and extend across the Red Sea (Al-Qurashi 1981). For these rainfall events, the main sources of moisture are the Indian Ocean, the Arabian Sea, and the Red Sea with some contributions from the Mediterranean Sea during the winter and spring seasons (Şen 1983).

Scanty, irregular and unreliable rainfall events occur over most parts of Saudi Arabia in the wet

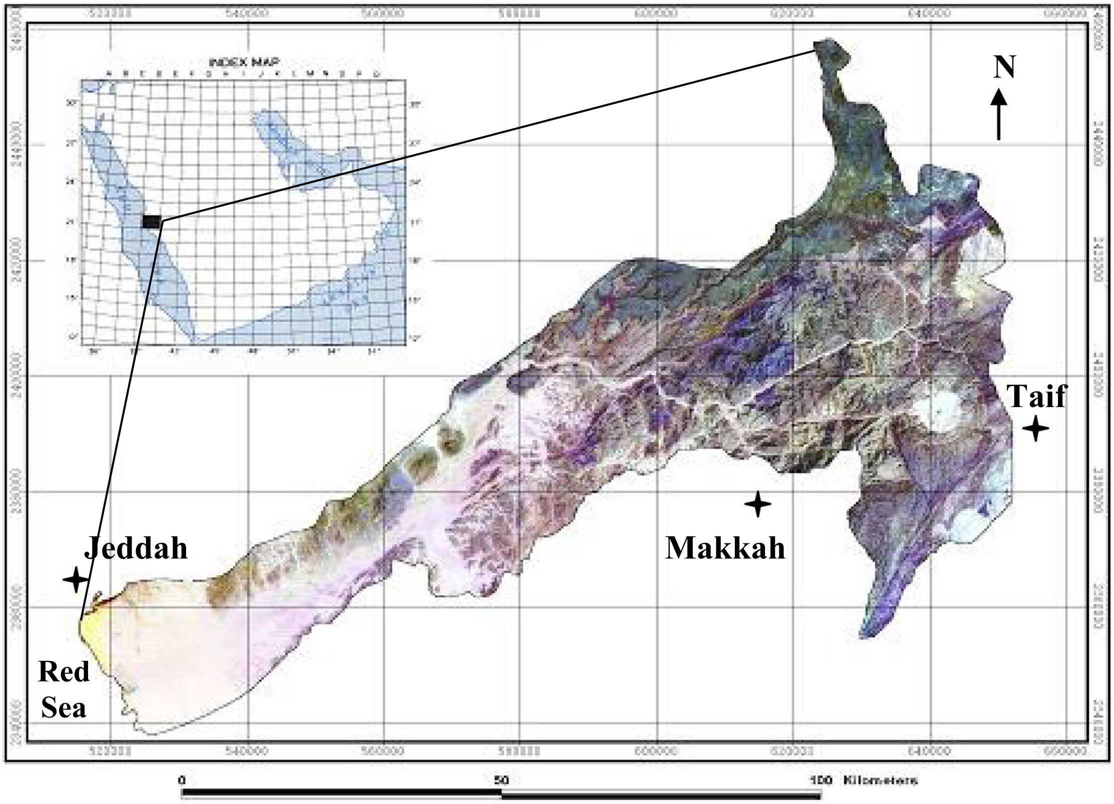

Fig. 1 Location map for Wadi Fatimah

(November–April) season (Almazroui et al. 2014). However, over the mountainous regions such as the Sarawat Mountains, the rainfall patterns are distinctly different from the rest of the country, due to topographically driven convective rainfall events (Abdullah and Al-Mazroui 1998). In Saudi Arabia, the average annual rainfall is 93 mm within a range of 25–229 mm (Almazroui et al. 2017). The annual rainfall varies from 50 to 100 mm along the Red Sea coast encompassing Jeddah city (52 mm), which is under the influence of cold-weather penetrations of Mediterranean origin during the winter season. The number of rainfall events is very low and some years may have no rainfall events at all, a typical characteristic of a semi-arid region. Recharging of the groundwater takes place upstream of the wadi after each rainfall event. Each rainfall event is provoked by convective and orographic mechanisms and, during winter, by the cyclonic frontal mechanism. However, orographic rainfall occurs more frequently than the other types. Evaporation from the Red Sea is driven towards the Hijaz Escarpment hills in the afternoon by the circulation of the westerly wind (Fig. 2). The hills upstream of Wadi Fatimah form a barrier to the air movements forcing the moist air upward, where it becomes cold and finally generates rainfall.

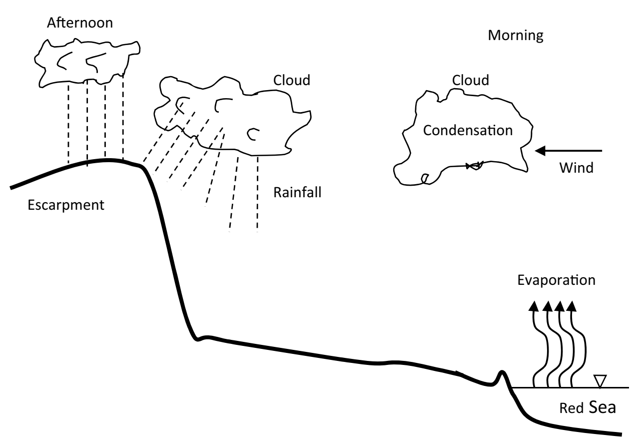

Fig. 2 Orographic rainfall mechanisms

The available meteorological data indicate that rainfall events occur most often in winter at low altitudes which include the cities of Jeddah and Makkah, but additional events have occurred over the escarpment at Taif city during pre-autumn and post-winter seasons. The number of rainfall occurrences (frequency) at the two meteorology stations near Jeddah (on the Red Sea coast) and Taif (on top of the

Sarawat Mountains) show the aforementioned pattern clearly (Fig. 3).

In Saudi Arabia, the conventional four rainfall seasons are dependent on the air mass movements and region (Al-Yamani and Şen 1993; Almazroui 2011). There are more regular rainfall events in the Taif region (above the Hijaz Escarpment at high altitudes) than in Jeddah (Hijaz Coastal area, low altitudes). In each month, there are more rainfall events at Taif than Jeddah, which imply that the upstream part of Wadi Fatimah is subject to more storm events than the downstream portion. Figure 4 presents the average monthly rainfall amount. Comparison of Fig. 4a, b shows that during the months December–February, the amount of rainfall in Jeddah is higher than in Taif. This indicates clearly that the Mediterranean climate descends from the northwest to the area under study, but due to the Red Sea trough, it has more effect on the low-lying Hijaz coastal area than on the downstream portion of Wadi Fatimah as a result of the penetration of air masses further south. During the other months, the effect of Indian monsoon climate pervades from the south and southeast over the area and becomes more pronounced at high elevation than in the Red Sea coastal area.

There are also distinct differences in the mean daily temperatures between the low-lying region of Tihamat Hijaz and Escarpment highlands. Minimum temperature averages in the two areas are about 23 and 15 °C in January with maximum temperatures in July at 32 and 28 °C, respectively. Monthly average temperatures are shown in Fig. 5. At both the high and low altitudes, there is a cyclical variation with high temperatures in June–August and low temperatures in December–February. During the summer months, the difference in monthly average temperature is smaller than in winter months. This indicates that in summer, the impact of the Hijaz Escarpment is not as significant as it is in winter.

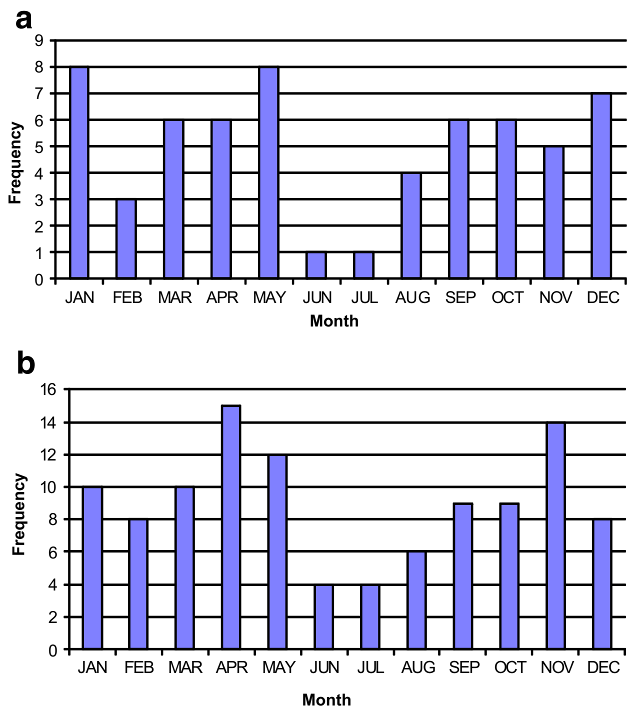

Fig. 3 Frequencies of monthly rainfall events **a** Jeddah, **b** Taif

3 Aridity Index

For arid and semi-arid regions in general, any practical simple aridity index is defined mainly by the precipitation deficiency leading to water supply shortages and dry spells (drought). Strategic surface and groundwater resource management require this scarcity to be scientifically determined in terms of deficit amounts and drought duration and intensity (Al-Sefry et al. 2004). Various definitions for

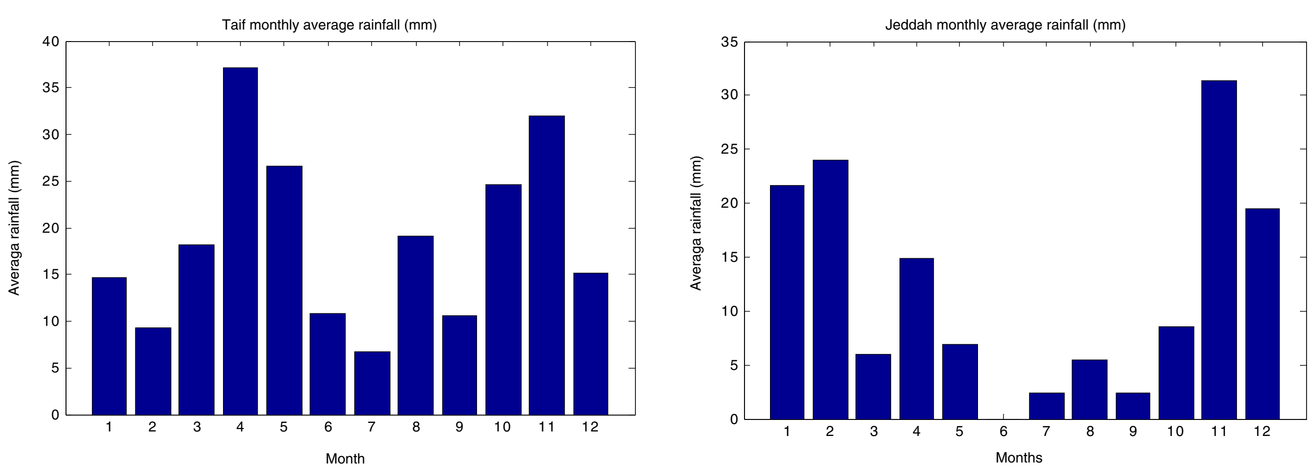

Fig. 4 Monthly average rainfall amounts, **a** Jeddah, **b** Taif

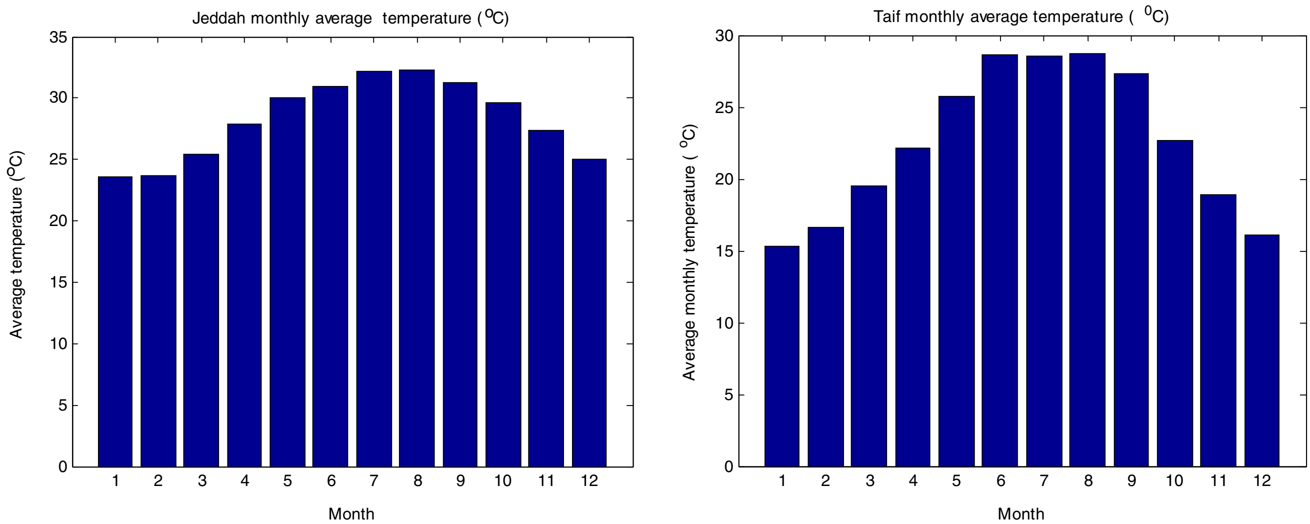

Fig. 5 Monthly average temperatures, **a** Jeddah, **b** Taif

precipitation amount and duration may be applied such as "drought is a period of more than some particular number of days with precipitation less than some specified small amount" (Great Britain Meteorological Office 1951). The chosen specified small amount (threshold) is site and/or region-specific and depends on the problem being studied. The qualitative measurements for drought duration will vary depending on the meteorological features of each country. In England, for instance, 15 consecutive rainless days are considered to be the start of a drought period. A more severe drought duration is considered to be the one lasting more than 30 days. However, in arid regions such as Saudi Arabia, a duration of more than 2 years without rainfall is considered to be the start of a drought period. For instance, in Bali, a 6-day rainless period signals drought. In some areas, drought duration is thought to have started, if the amount of rainfall falls below 2.5 mm. Another approach is to consider rainfall amount as a measure of aridity, so that if 21 consecutive days have only one-third of the historical normal rainfall, then this is considered a sign of aridity. There are also other definitions that are based on the percentage of rainfall amount. For instance, if the annual rainfall is less than 60 or 70% of the average measured amount of normal rainfall, then this year is considered to be a precursor to a possible drought spell. In some other locations, 85% of the annual rainfall may be taken as a threshold, and such thresholds may be proposed depending on the hydro-meteorological condition of the area (Şen 2015).

In the literature, many aridity indices exist, including the De Martonne (1926) aridity index, the Thornthwaite (1948) indices of humidity and aridity and the UNESCO (1979) aridity index. A detailed description of each aridity index is presented by Şen (2015). In this article, a new aridity index, A_{index}, is defined as average monthly rainfall, $\bar{R}$ per degree centigrade of average monthly temperature, $\bar{T}$ as follows:

$$A_{\text{index}} = \frac{\bar{R}}{\bar{T}} \tag{1}$$

The unit of measurement is mm/°C and its application using monthly temperature and rainfall records from Jeddah and Taif locations results in the graphs in Fig. 6.

Its value is zero for non-rainfall occurrence, but in general, it usually has a value of close to 1 for the rainfall–temperature relationship. As can be seen from this figure for the two stations in Saudi Arabia, a maximum value of around 2 may be assumed, because the temperature in the area under study is high. Potential groundwater recharges take place at high aridity index values with low evaporation and short drought durations. Figure 6 indicates that aridity indices in Jeddah (low-lying lands) are less than 1 except in November. In Taif (high altitude more than 2000 m above mean sea level), April and November have high aridity indices. The Indian monsoonal effect occurs in April, whereas the Mediterranean type of weather pattern takes place in November. In arid regions, calculation of groundwater recharging helps to plan better and more sustainable water management activities. Therefore, groundwater harvesting possibilities are enhanced after each rainfall storm and subsequent runoff and flash flood (Şen et al. 2011). Furthermore, the possible effects of climate change on arid regions must be taken into consideration (Şen et al. 2012).

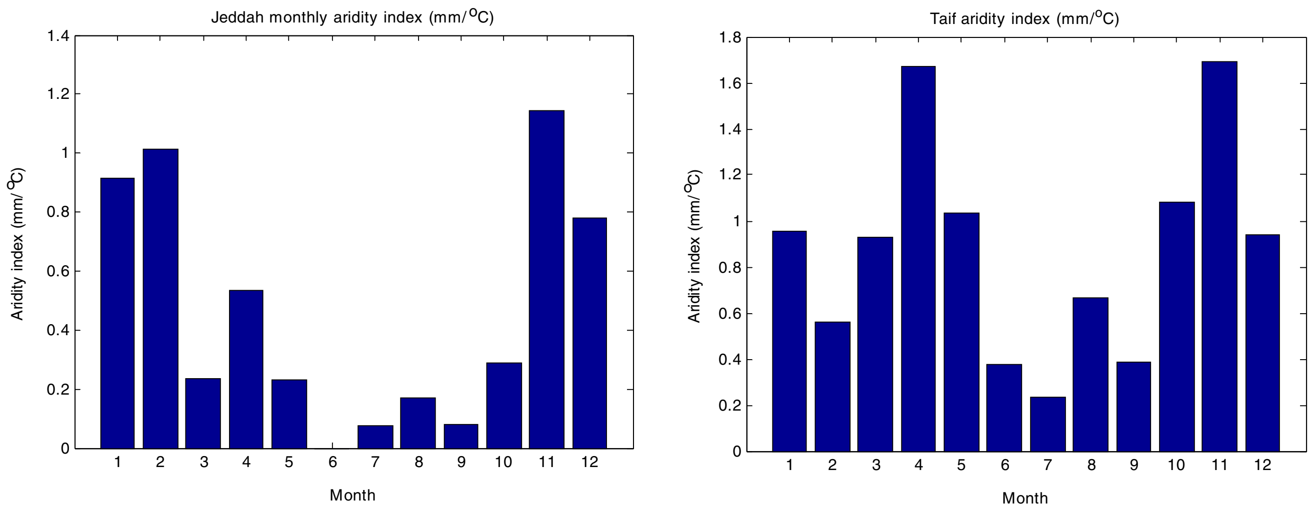

Fig. 6 Aridity index, **a** Jeddah, **b** Taif

4 Rainfall Water Volume

To calculate the potential average monthly recharge of aquifer groundwater storage, it is necessary to draw monthly mean areal precipitation patterns for the region. For this purpose, monthly isohyet maps are prepared for the Wadi Fatimah catchment area, but for the sake of brevity, only the January isohyet map is presented in Fig. 7. In January, peak areal precipitation is in the southern part of the Fatimah basin with a 35 mm contour line. From this peak, regional rainfall decreases steadily in the direction of the east, north and west, with only 15 and 20 mm in the Fatimah catchment. In the mid-south, 25 mm contours show a level of precipitation that is useful for water resource planning, including groundwater recharge.

Accordingly, the groundwater calculations should take into consideration the part of the catchment area that lies between the 15 and 25 mm contours. Annually, the upper catchment receives an average rainfall of almost 300 mm, and this level steadily decreases towards the Red Sea, where it is 70 mm per year at Jeddah. Rich, productive rainfall events are due to frontal weather movements during the winter season, which starts vaguely from December until the end of April. A high percentage of annual rainfall occurs within the first few months of this period. In the hotter months, there are sporadic rainfall occurrences of a mainly orographic type along the Hijaz Escarpment upstream of Wadi Fatimah. Convective rainfall occurrences are somewhat rare, and they take place in the middle or lower portions of the wadi. The combination of orographic and frontal weather systems during the winter season leads to the most intensive rainfall occurring over the upstream region.

Both temporal and spatial rainfall patterns over Wadi Fatimah are used to calculate the water volume available from the monthly rainfall, R_V. These calculations are achieved by multiplying the drainage area, A_i, confined between the two successive contours P_i and P_{i-1} and the average rainfall value of the two contours.

$$R_V = \sum_{i=2}^{n} A_i(P_i - P_{i-1}) \tag{2}$$

where n is the number of consecutive contour intervals. Finally, the water volume available from monthly rainfall, between the successive contours in different months and their cumulated values are presented in Table 1.

This table estimates the water volume available from monthly rainfall for the whole of the Fatimah catchment area at roughly 85×10^6 m^3. The total annual rainfall volume that falls on the Wadi Fatimah drainage basin area is about 1.0×10^9 m^3. The monthly distribution of the volumes is given in Fig. 8.

Cumulative rainfall water volume assessments are presented in Fig. 9 for the whole year. It is evident from this figure that there is an almost constant volume of total monthly rainfall of about 85×10^6 m^3/month, which is equal to the slope of this graph. The standard deviation of rainfall water volume is almost 1/3 of the mean value, 28×10^6 m^3. All of the rainfall water volume cannot be retained as natural recharge of the wadi quaternary deposit aquifers because of evaporation, depression and runoff losses.

5 Rainfall Volume and Risks

Figure 7 indicates the scattered locations over the study area of 24 meteorology stations with 20 years of rainfall records. It is possible to calculate potential rainfall

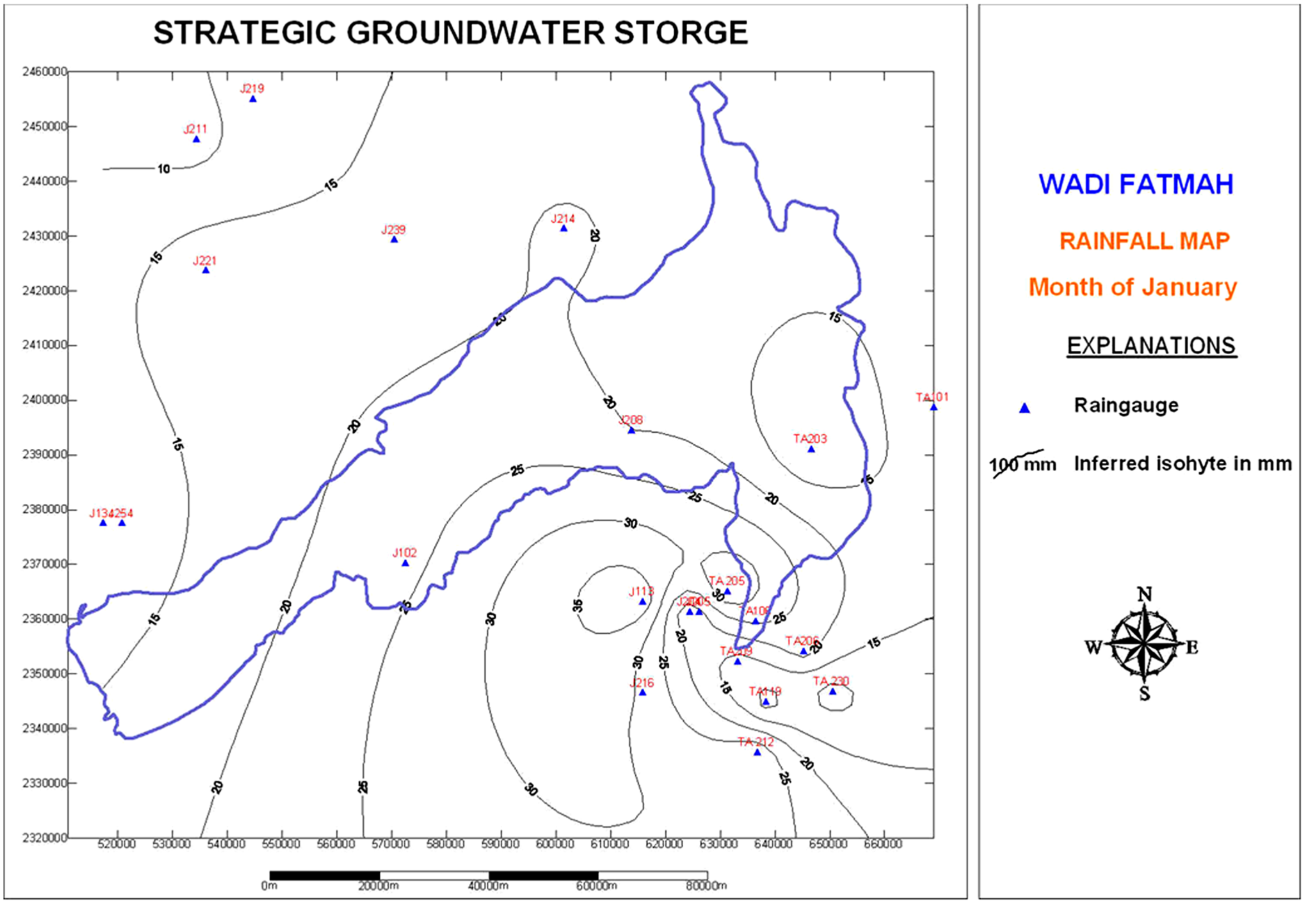

Fig. 7 January isohyet map

Table 1 Monthly and annual average rainfall water volumes

Contour lines (mm)	Monthly rainfall volumes (× 10^6 m^3)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0–5		0.997	1.275			9.2656	7.08			1.42		
5–10		10.367	8.278	10.69	1.36	9.391125	24.31	0.36		7.82		
10–15	8.64	28.165	32.38	6.24	5.02	11.31	8.77	6.32	31.17	34.59	10.94	6.66
15–20	42.66	23.412	14.809	9.5	12.06	22.19	0.14	34.6	30.82	15.9	20.08	32.2
20–25	41.24	1.875	5.472	16.16	61.5	0.46		11.08	18.33	2.3	20.94	36.08
25–30	9.13		1.6	14.41	24.5			22.53	4.63	1.83	46.22	36.04
30–35			0.564	14.12	8.28					0.91	20	
35–40			0.788	16.89	2.06					1.36		
40–45			0.47	17.04	1.13							
45–50				8.68	1.7							
50–55				2.46								
Total	101.67	64.816	65.636	116.19	117.61	52.616725	40.3	74.89	84.95	66.13	118.18	110.98

amount at a given set of risk levels. Before calculating the risk levels, the probability distribution function (pdf) is determined for each month for Saudi Arabia, as this is applied for rainfall harvesting in Wadi Al-Lith (Almazroui et al. 2017). It has been already determined by various researchers working in the field of hydrology that the monthly rainfall data adheres to the logarithmic normal pdf model (Aitcheson and Brown 1957; Benjamin and

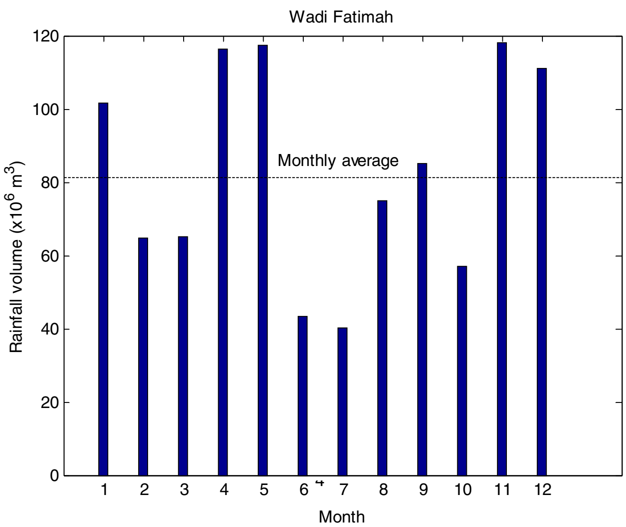

Fig. 8 Monthly rainfall volume distributions over the whole Wadi Fatimah drainage area

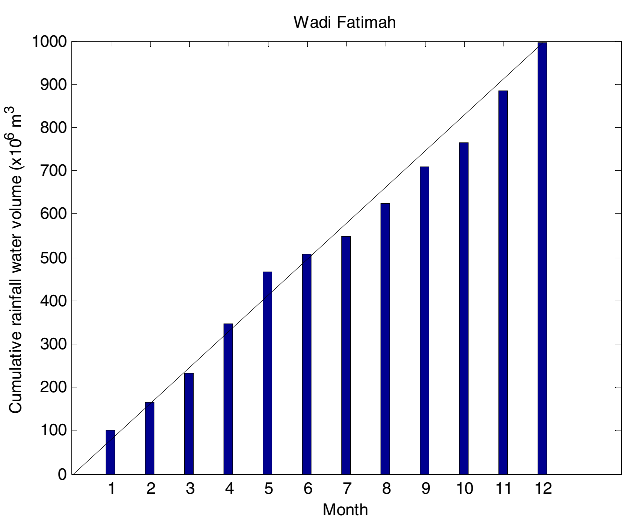

Fig. 9 Cumulative rainfall water volumes ($\times 10^6$ m^3)

Cornell 1970). The following steps are taken to produce the risk calculation.

(1) After determination of the theoretical pdf, calculate the logarithmic mean α, of the variable concerned
(2) Calculate the logarithmic standard deviation β, of the same variable,
(3) Identify the minimum data value
(4) Identify the maximum data value
(5) The range is the difference between the maximum and minimum values; let the variable that represents this range be labeled x. Divide the range into sub-intervals of length 0.01
(6) Calculate the theoretical logarithmic probability values according to the logarithmic normal pdf expression (Benjamin and Cornell 1970):

$$f(x) = \frac{1}{x\beta\sqrt{2\pi}} \exp\left[-\frac{1}{2}\frac{(\mathrm{Ln}x - \alpha)^2}{\beta^2}\right] \tag{3}$$

The corresponding cumulative pdf (cdf) can be obtained after an integration operation:

$$z = \int_0^{\infty} f(x)\mathrm{d}x \tag{4}$$

Plotting x against z yields the graphical representation of the logarithmic normal cdf
(7) Finally, plotting x against $1 - z$ provides the necessary risk graphs for the variable concerned

The mean and standard deviation of the logarithmic normal pdf of the rainfall of each month is calculated and presented in Table 2.

One can observe that April and October have the maximum averages. This implies that there are two rainfall regimes over the study area in one year. However, high standard deviations are coupled with low mean values. This shows that variability is greater in areas where the rainfall is low. The risk level of disaster increases with the standard deviation and this point is very significant in strategic planning studies.

The coefficient of variation, C_V, is defined as the division of the mean value, m, by the standard deviation, S, which gives the average rainfall amount per unit of standard deviation as,

$$C_V = \frac{m}{S} \tag{5}$$

The higher the coefficient of the variation the more sporadic the rainfall, and so Table 2 suggests that there

Table 2 Monthly rainfall logarithmic parameters

Months	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Logarithmic mean	2.83	2.25	2.64	3.08	2.74	1.98	1.93	2.54	2.78	3.04	3.04	2.81
Logarithmic standard deviation	0.46	0.7	0.79	0.65	1.16	1.42	1.22	0.9	0.88	0.49	0.4	0.52
Coefficient of variation	0.16	0.31	0.30	0.21	0.42	0.72	0.63	0.35	0.32	0.16	0.13	0.18

are no persistent rainfall events in the summer months. In general, the risk, r, is the probability, P, that the rainfall amount, R, will be higher than a given threshold value, R_T given as:

$$r = P(R > R_T) \tag{6}$$

There is a risk graph for each month, but in Fig. 10 for the sake of brevity, only the January rainfall–risk relationship is given.

The open circles represent the average monthly rainfall values, and the best fit theoretical logarithmic normal cdf is shown as a solid line. It is now possible to calculate the probability of average monthly rainfall occurrence for January, for example, the probability of 10 mm or more of rainfall is 88% (dashed horizontal and vertical lines). The same figure shows a 10% risk of an average rainfall amount of 30 mm or more. In practical applications, the selected return period (risk) sets are 5-year (20%), 10-year (10%), 25-year (4%), 50-year (2%) and 100-year (1%).

Table 3 presents the monthly average rainfall amount for these return periods (risk). The advantage of the risk values shown in Table 3 is that they may be used for planning purposes. For instance, for strategic planning for, say a 25-year return period (4% risk), the corresponding rainfall amounts for each month are available in the third row of Table 3.

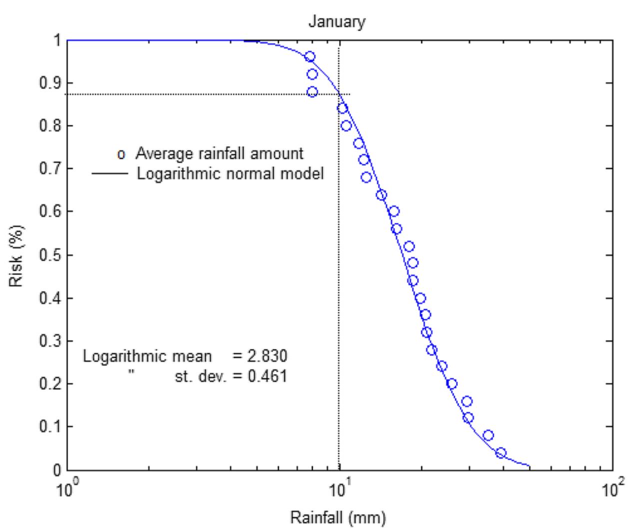

Fig. 10 Rainfall-risk graphs for January monthly averages

6 Infiltration Volume and Risk

Infiltration process is the percolation of water through the soil surface into the subsurface, and is the most important contributor to groundwater recharge. In arid regions, recharge of unconfined aquifers occurs through infiltration from ephemeral streams following substantial flooding (Dein 1985).

Infiltration rates through soils vary greatly depending on the place and time. Spatial variation is affected by the geology and topography of the land surface. For example, on steep slopes, a significant fraction of the rainfall becomes runoff. Different textures and structures in the sub-soil layers can affect the downward movement of water. Despite the highly complex nature of the infiltration process, several methods have been developed to estimate it (Green and Ampt 1911; Horton 1940; Philip 1957). The importance of the infiltration process is obvious, because it controls the recharging of the groundwater, regulates floods, prevents soil erosion, and provides water to plants. In this paper, infiltration estimates are made from field infiltration data collection according to the three rainfall storm durations using the Horton model, and the results are given in Table 4.

Complete infiltration tests are carried out in wadi beds, and infiltration volumes are obtained for the storm durations indicated in Table 4, although they turned out to be high compared to the maximum possible infiltration

Table 4 Wadi Fatimah calculation of volume of infiltration through the alluvium

Storm duration (h)	Soil infiltration constant (k)	Area exposed to infiltration (km^2)	Calculated infiltration volume ($\times 10^6$ m^3)
3.0	37.9	187.5	433.0
6.7	37.9	187.5	965.0
2.9	37.9	187.5	418.0

Table 3 Monthly average rainfall amounts (mm) for different risk levels

Return period (year)	Risk (%)	Months											
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
5	0.50	36	33	48	61	98	95	50	50	85	45	45	40
10	0.10	30	28	40	50	75	50	33	40	50	40	35	32
25	0.04	22	15	22	35	38	20	15	22	28	28	28	26
50	0.02	17	9	13	20	17	8	7	17	17	20	20	18
100	0.01	12	5	7	13	8	3	2	9	8	14	15	14

Table 5 Maximum rainfall volume allowing infiltration

Rainfall amount (× 10^6 m^3)	Runoff magnitude (× 10^6 m^3)	Maximum infiltration volume (× 10^6 m^3)
58.8	15.7	43.1
125.4	18.8	106.6
56.5	11.1	45.4

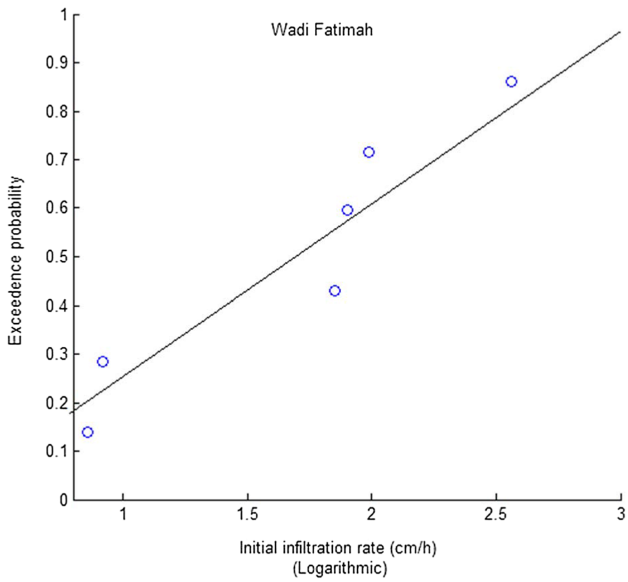

Fig. 11 Cumulative probability of initial average infiltration rate

Table 6 Infiltration rate risk levels

Risk (%)	Infiltration rate (cm/h)
5	2.9
10	2.6
25	2.4
50	1.67
75	0.90

volume shown in Table 5. Table 4 is for the entire Wadi Fatimah, while in Table 5 the infiltrations are calculated corresponding to a particular rainfall amount.

It is possible to plot hourly infiltration rates versus extreme probability values, which provide a basis for the infiltration threshold probability as in Fig. 11. The vertical axis in the figure does not show risk directly, but has to be converted to risk values by subtracting all the threshold probabilities from 1.

The plot in Fig. 11 implies that risk = (1 − exceedence probability), and accordingly, Table 6 provides the infiltration rates corresponding to the given set of risk levels.

7 Conclusions

Arid regions suffer from the scarcity of hydrological data, among which rainfall and temperature records, measured at a number of meteorology stations, are relatively better than others. In general, the aridity index is based on rainfall and temperature records, and in this paper, a new definition for an aridity index is proposed for water resource assessment. Simple probabilistic methods for temporal models and isohyet maps for spatial evaluations are presented and applied to the Wadi Fatimah drainage basin in the central western part of Saudi Arabia. The volumes of monthly rainfall are calculated as risk attachments for pre-selected design durations such as 5-, 10-, 25-, 50-, and 100-year. The infiltration capacity of the region is based on actual field infiltration measurements combined with a probability distribution model for risk calculations. In this paper, the rainfall and infiltration risk calculations are achieved according to logarithmic normal probability distribution function. Furthermore, the potential monthly rainfall and infiltration amounts are calculated under the set of pre-selected risk percentages. These simple calculations provide a sound basis for future studies on groundwater resource storage strategy, operation, and management. Climate model data may be useful to calculate risk and infiltration for the future climate and this is suggested for further study.

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