Augmentation of surface water sources from spatially distributed rainfall in Saudi Arabia

Muhammad Al-Zahrani, Shakhawat Chowdhury and Amin Abo-Monasar

ABSTRACT

This study investigated the rainfall patterns, spatial variability, surface runoff generation and dam requirements in the southwestern region of Saudi Arabia. The region was divided into four areas Asir, Jazan, Al-Baha and the Red Sea Coast. Surface runoff was estimated for eight scenarios considering the runoff coefficients of 0.05–0.70, resulting in 203–2,835 million cubic meters (MCM) of runoff per year in this region. The runoff in the Asir, Jazan, Al-Baha and the Red Sea Coast were estimated to be in the ranges of 88–1,230, 53–738, 32–443 and 30–425 MCM per year, respectively. The capacities of the existing dams in Asir, Jazan and Al-Baha are approximately 373, 194 and 31 MCM, respectively, while the coast does not have any dam. A significant fraction of runoff is likely to be lost in each scenario of assessment. Water resources may be augmented through construction of new dams and/or wells in appropriate locations. However, better understanding is advisable on locations, water availability, surface evaporation in wadies and reservoirs, accumulation of solids in dam/reservoirs, hydraulic conductivity, economic burdens and national policy.

Key words | rainfall characterization, runoff loss spatial variability, surface runoff collection, water resources management

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INTRODUCTION

The Kingdom of Saudi Arabia is located in an arid region, which has low average annual rainfall (FAO 2009; Chowdhury & Al-Zahrani 2013a). The population has increased several fold since 1972, resulting in a significant increase of water use (CIA 2011). The total water consumption in 2000, 2004 and 2009 was 20,740, 20,270 and 18,507 million cubic meters (MCM), respectively. The agricultural water demand in these years was 18,540, 17,530 and 15,464 MCM, respectively. The domestic water demand was 1,750, 2,100 and 2,330 MCM, respectively, while the industrial water demand was 450, 640 and 713 MCM in these years, respectively (MOEP 2010). Water demands in the kingdom are satisfied by non-renewable groundwater sources (NGW), renewable surface and groundwater sources (RGSW), desalinated water (DW) and treated wastewater (TWW), in which the NGW supplies the most followed by the RGSW, DW and TWW (MOEP 2010). Approximately 13,490 and 11,551 MCM of water was supplied from the NGW in 2004 and 2009, respectively (MOEP 2010). Water supplies from RGSW were 5,410 and 5,541 MCM in 2004 and 2009, respectively. The desalination plants supplied 1,070 and 1,048 MCM of DW in 2004 and 2009, respectively, while TWW reuse was increased from 260 to 325 MCM during this period (MOEP 2010). However, the data from the Ministry of Water and Electricity (MOWE) showed considerable differences. The MOWE reported that the GW extraction in 2009, 2010, 2011 and 2012 was 16,842, 16,110, 15,408 and 14,999 MCM, respectively (MOWE 2013). The variability was also noted for wastewater generation and reuse, supplies of DW, and dams and surface water supplies (MOWE 2013).

In an earlier study, the Ministry of Water (MAW) of Saudi Arabia [currently, MOWE] reported that the proven, probable and possible groundwater reserves in the non-renewable aquifers were approximately 259, 416 and 761 billion cubic meters (BCM), respectively (MAW 1984;

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Water Atlas 1995; FAO 1998). FAO (1998) reported that approximately 42% of the reserves might have been consumed by 1996. The total surface runoff was estimated to be 2.2 BCM/year (FAO 2009), most of which infiltrates to recharge the shallow aquifers. In 2012, a total of 449 dams in the country stored and recharged approximately 2.02 BCM of runoff (MOWE 2013), which is significantly higher than the MOEP data, which reported 302 dams collecting approximately 1.4 BCM of runoff in 2009 (MOEP 2010). The water reserves and withdrawal rates indicate that the available resources may not be enough to provide support on a long-term basis (MAW 1984; Water Atlas 1995; FAO 1998; Chowdhury & Al-Zahrani 2013a). It is advisable to find new resources of water and conserve NGW (MOEP 2010).

Harvesting of rainwater from the regions with higher rainfall may provide significant support for water resources management. Rainwater harvesting has been practised since 4500 BC. Different approaches were adopted to collect and use surface runoff in the Arabian region. In Yemen, rainwater was collected and stored through channels and dams in 1700 BC. In the Negev desert to the north of the Arabian Peninsula, rainwater was collected for domestic and agricultural uses about 4000 years ago (Evenari 1961; Sivanappan 2006). It is economically feasible and known as a potential alternative to water resources in the arid regions (Yuan *et al.* 2002). In Saudi Arabia, the source of surface water is the seasonal precipitation. The country has an overall average annual rainfall of approximately 125 mm (Chowdhury & Al-Zahrani 2013a). In the north, annual rainfall varies between <100 and 200 mm (long-term average = 70.1 mm/year), while in the south, 500 mm/year of rainfall (long-term average = 265 mm/year) is not unlikely (FAO 2009). The largest runoff occurs in the western region, which represents approximately 60% of the total runoff although it covers only 10% of the land area (FAO 2009). The remaining 40% of the runoff occurs in the far south of the western coast (Tahama), which covers 2% of the land area (FAO 2009). The MOWE data revealed that 89 dams in the southwestern (SW) region collected approximately 600 MCM/year of water (MOWE 2011). Some of the major dams are King Fahd dam in the Asir region (capacity: 325 MCM), Wadi Abha in the Asir region (capacity: 213 MCM) and Bish dam in Jizan (capacity: 193.6 MCM). However, the yearly rainfall data indicate that the possible surface runoff might be significantly higher than the currently collected runoff. The floods in the SW regions in 2009, 2011 and 2013 were responsible for 100, 10 and seven deaths, respectively (BBC News 2009; CNN World 2011; Arab News 2013), which indicated that the runoff might be higher than the capacities of the dams, and/or the drainage systems are vulnerable.

In this study, rainfall patterns and spatial variability in the SW region (e.g., Asir, Jazan, Al-Baha and the Red Sea Coast) were investigated. The surface runoff was quantified at various scenarios of runoff coefficients. The current capacities of the dams were compared with the runoff. The additional capacities of the dams needed to store the excess runoff were estimated. Finally, the policy-related issues and benefits of collecting the excess runoff were highlighted.

METHODOLOGY

Study area

The SW region of Saudi Arabia is mountainous with elevations exceeding 2,000 m above the mean sea level. The region lies within the subtropical climate zone and receives the highest rainfall in the country (Al-Subyani 2004; FAO 2009). The location of the study region is shown in Figure 1. It includes Al-Baha (north part), Asir (center), Jazan (south) and the Red Sea Coast (west). It covers approximately 57,394 km^2 of land area. The study region was divided into four areas Asir, Jazan, Al-Baha and the Red Sea Coast (Figure 1). The Asir region falls under the influence of a relatively moist south-easterly stream of monsoon air (Al-Subyani 2004). The periods of March–May and July–August are the main rainy seasons, possibly due to an increase in rainfall along the leeward side of the mountains and the Red Sea Coast. In Al-Baha, the rainy periods are the spring months (March–May), while rainfall is low for the rest of the year. In Jazan and the Red Sea Coast, the rainy periods are July–November and April–May.

Selecting method of analysis

Rainfall is generally measured by rain gauges and radar-based remote sensing (Maliva & Missimer 2012). Rain

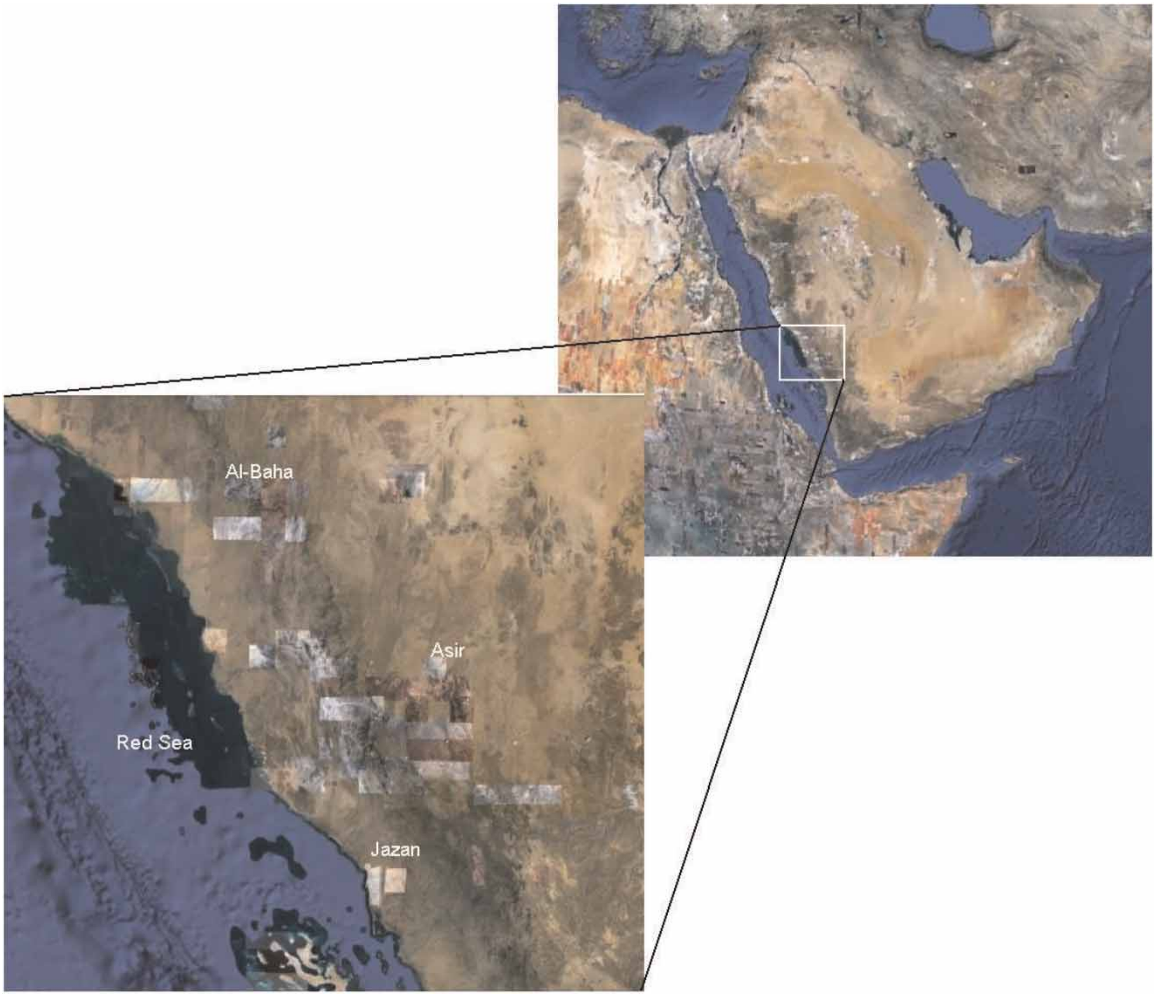

Figure 1 | Area of study in the south-western region of Saudi Arabia.

gauges provide point measurements of rainfall, which have several limitations, while the long-term records may provide satisfactory levels of accuracy. In contrast, the radar measurement of rainfall can provide data over large areas, which is more useful for evaluation of catchment or basin-wide water budgets (Maliva & Missimer 2012). In this study, long-term rain gauge data (1965–2010) were available for the SW region. The SW region is a highly complex area in terms of terrain and rainfall distribution. The region contains mountains, valleys, gullies, wadies, plains, lowlands and the Red Sea Coast. To estimate the rainfall distribution, monthly average data were collected from the monitoring stations for 45 years (1965–2010). Several techniques are used to predict rainfall distributions (Al-Subyani 2004). The Thiessen polygon method is one of the classical techniques for characterizing spatial distribution of rainfall. This method divides the study area into polygons of influence. Each polygon contains a rainfall station in its centroid and the rainfall records of that station are assigned to the polygon. The polygon boundaries are determined based on the distances between the rainfall monitoring stations (Isaaks & Srivastava 1989). This method is still used in estimating average distribution of precipitation (e.g., Li *et al.* 2009). The polynomial interpolation is another classical technique used for estimating the spatial distribution of rainfall. This technique develops a linear or non-linear polynomial relationship for estimating rainfall based on the locations of rainfall stations (Hwang *et al.* 2012). The inverse distance weighted (IDW) method is widely used in hydrological and climate change studies (Chen *et al.* 2010; Hwang *et al.* 2012).

This technique depends on the distance between rainfall stations to develop a relationship for predicting rainfall in the un-gagged locations. The nearest un-gagged locations from the existing stations are given the highest weight, while the farthest has the lowest weight (Isaaks & Srivastava 1989; Chen *et al.* 2010).

The classical estimation and interpolation methods simplify the rainfall estimates. Such simplifications often encounter disadvantages, which may be misleading and/or reduce the accuracy of rainfall distribution, particularly in arid regions where spatial variation is extreme. Averaging methods, such as arithmetic, harmonic and geometric methods, are simple techniques to deal with the highly complex terrain and hydrological aspects. Polygon techniques, such as Thiessen and triangulation, produce a discontinuous rainfall distribution between the sub-areas. This discontinuity depends on several factors, such as the size of the sub-areas, rainfall variations and the averaging process. Conventional polynomial techniques build their estimations based on the locations in space of known rainfall stations without considering the topography. This is an important drawback, especially when strong orographic and elevation effect are anticipated (Hwang *et al.* 2012). The IDW method estimates rainfall at a specific location as a block. The estimation is based on the distance between the centroids of stations. As such, the size of the block does not show any difference to the estimations.

The geostatistical techniques incorporate spatial distribution of rainfall stations, which increases the accuracy of rainfall distributions. The drawbacks of conventional techniques can be greatly reduced in these techniques (Isaaks & Srivastava 1989). These techniques are frequently used in estimating rainfall distributions (Haberlandt 2007; Murthy & Abbaiah 2007; Cheng *et al.* 2008). Kriging and Co-Kriging have been widely used by hydrologists and climatologists to show spatial distribution of rainfall. The Kriging results in unbiased estimations with reduced variance (Webster & Oliver 2000). It uses the weighted linear combinations of data, minimizes the mean errors and tries to reduce the variance errors (Isaaks & Srivastava 1989).

Kriging and Co-Kriging methods

In the Kriging method, the rainfall at any un-gauged location can be estimated by adding a random error parameter to the mean rainfall in that region (Al-Subyani 2004). This can be expressed as

$$Z(x) = \mu + \varepsilon(x) \tag{1}$$

where Z = rainfall in the un-gauged location; x = coordinate of the location; μ = overall mean rainfall; and ε = random error with spatial dependence. Kriging calculates the rainfall at unknown locations by using the available data. It incorporates the spatial distribution of gauged and un-gauged locations and assigns weight to each location to control its effect on the un-gauged locations (Isaaks & Srivastava 1989). It can be shown as

$$Z(x_o) = \sum_{i=1}^{n} \lambda_i Z(x_i) \tag{2}$$

where $Z(x_i)$ = the measured rainfall for the ith point; $Z(x_o)$ = the estimated rainfall at a specific location; and λ_i = the linear weight for the measured rainfall at the ith point. The values of the weights (λ_i) are spatially dependent on the locations of the measured rainfall data. These are the functions of the semivariogram and mean. These weights can be determined through simultaneous solution of linear equations as

$$\sum_{j=1}^{n} \lambda_i \gamma_{x_i x_j} + \mu = \gamma_{x_i} \tag{3}$$

$$\sum_{i=1}^{n} \lambda_i = 1 \tag{4}$$

where λ_i = weight at point i; λ_j = weight at point j; μ = overall mean; $\gamma_{x_i x_j}$ = semivariogram between points x_i and x_j; and γ_{x_i} = semivariogram between points i and its location. Semivariogram is a function that shows the degree of spatial dependence of $Z(x)$. It is defined as the variance of the difference of field values at two locations across realizations of the field (Cressie 1993). Semivariogram is defined as:

$$\gamma(h) = \frac{1}{2n} \sum_{i=1}^{n} [Z(x_i + h) - Z(x_i)]^2 \tag{5}$$

where n = number of pairs; x and $x+h$ = sampling locations at direction x separated by distance h; and Z = measured values for rainfall at the corresponding locations. Co-Kriging is a modified form of Kriging with similar concepts. The main difference is the use of two variables (e.g., rainfall and altitude) in the estimation process in Co-Kriging compared to one variable used in Kriging (rainfall). Rainfall is considered as the primary variable and the secondary variable must be spatially correlated with the primary variable (Isaaks & Srivastava 1989). Unlike Kriging, Co-Kriging has three semivariograms, one for each of the primary and secondary variables and a cross semivariogram for both variables as

$$\gamma_m = \frac{1}{2n}\sum_{i=1}^{n}[m(x_i+h)-m(x_i)]^2 \tag{6}$$

$$\gamma_c = \frac{1}{2n}\sum_{i=1}^{n}[c(x_i+h)-c(x_i)]^2 \tag{7}$$

$$\gamma_{mc} = \frac{1}{2n}\sum_{i=1}^{n}[m(x_i+h)-m(x_i)][c(x_i+h)-c(x_i)] \tag{8}$$

$$m(x_o) = \sum_{i=1}^{n}\lambda_i m(x_i)+\sum_{j=1}^{n}v_j c(y_j) \tag{9}$$

where M = primary variable; c = secondary variable; x_i = ith point location for the primary variable; x_o = estimated value at specific location for the primary variable; y_j = jth point location for the secondary variable; λ_i = weight for the measured value at the ith point location for the primary variable; and v_j = weight for the measured value at the ith point location for the secondary variable. Co-Kriging was reported to have shown a better estimation of rainfall distribution compared to other geostatistical techniques (Hevesi *et al.* 1992). In this paper, Co-Kriging was used to estimate the distribution of the rainfall over the SW region using rainfall records as the main variable and the elevation of the rainfall stations as an auxiliary variable. Based on the rainfall contour maps, it is possible to estimate the monthly and annual rainfall volume in these regions. Further details on Kriging and Co-Kriging can be found elsewhere (Isaaks & Srivastava 1989; Hevesi *et al.* 1992; Cressie 1993).

RESULTS

Statistical distributions for rainfall

The rainfall distributions over the SW region showed tempospatial variability. The monthly rainfall data for the period of 45 years (1965–2010) in the Asir, Jazan, Al-Baha and the Red Sea Coast mainly followed the Gamma, LogNormal (LN) and Weibull distributions. Tables 1–4 show the statistical distributions of monthly rainfall for different areas. In Asir, average rainfall in July followed Normal distribution, while the monthly rainfall for all other months in each area followed the LN, Weibull, Gamma or largest extreme value distributions, indicating that the rainfall mostly followed the skewed patterns (Tables 1–4). The coefficient of variation (CV = std dev/mean) of the rainfall showed high values (Asir: 0.50–2.54; Al-Baha: 1.1–4.48; Jazan: 0.72–1.83; and Red Sea Coast: 0.56–1.42), meaning that these data had very wide ranges (Tables 1–4). The skewness coefficients for the rainfall in Asir, Al-Baha, Jazan and

Table 1 | Monthly rainfall distributions for Asir (mm)

Month	Distribution	Average	CV (%)	Skewness
January	Gamma (0.62, 15.47)	9.81	125.7	2.71
February	Gamma (0.48, 18.75, 0.086)	8.98	145.4	3.19
March	Gamma (0.68, 29.29)	20.22	120.0	2.47
April	W (1.09, 31.93, 4.3)	35.26	81.03	1.91
May	LEV (17.81, 16.1)	27.0	76.3	1.10
June	W (1.0, 5.07, 0.07)	5.1	99.24	1.97
July	N (8.93, 5.16)	8.9	58.55	-0.03
August	LN (2.79, 0.47, 0)	18.19	49.37	1.65
September	Gamma (0.77, 4.31, 0.04)	3.45	113.4	2.21
October	W (0.64, 3.48)	4.85	161.6	3.76
November	LN (1.05, 1.57)	9.43	253.7	9.11
December	W (0.73, 4.62)	5.69	132.5	2.67

W: Weibull; LN, LogNormal; LEV: largest extreme value; N: normal (for W, LN, LEV and Gamma distributions: 1st parameter = shape factor; 2nd parameter = location; 3rd parameter: threshold value). For the normal distribution [1st parameter: mean; and 2nd parameter: standard deviation]; CV: coefficient of variation.

Table 2 | Monthly rainfall distributions for Al-Baha (mm)

Month	Distribution	Average	CV (%)	Skewness
January	Gamma (0.70, 11.69)	8.36	119.8	2.38
February	Gamma (0.70, 8.96)	6.29	120.1	2.56
March	Gamma (0.72, 17.2, 0.29)	12.78	115.1	2.59
April	LN (2.71, 0.93, 0)	23.22	117.4	5.0
May	Gamma (0.82, 12.47)	10.11	110.0	2.12
June	Gamma (0.85, 3.13)	2.67	108.0	2.23
July	W (0.76, 1.71, 0.002)	2.04	135.7	3.27
August	LN (0.26, 1.65, 0.02)	5.48	386.8	23.0
September	LN (-1.36, 1.21, 0.01)	0.54	181.2	7.22
October	LN (-0.016, 1.79)	5.04	448.1	24.7
November	Gamma (0.71, 5.77)	4.1	119.1	2.38
December	Gamma (0.80,6.06)	4.85	113.2	2.23

W: Weibull; LN: LogNormal; Gamma [1st parameter = shape factor, 2nd parameter = location; 3rd parameter: threshold value].

Table 4 | Monthly rainfall distributions for the Red Sea Coast (mm)

Month	Distribution	Average	CV (%)	Skewness
January	Gamma (0.79, 13.06)	10.0	114.9	2.42
February	Gamma (0.48, 11.5, 0.06)	5.7	141.5	2.87
March	W (0.83, 7.85, 0.11)	8.7	118.2	2.47
April	LN (2.04, 1.0, 0.11)	12.9	125.8	4.69
May	W (1.12, 12.75, 0.36)	12.8	86.3	1.65
June	LN (2.40, 0.56, 0)	12.8	58.3	1.82
July	Gamma (1.55, 6.94)	10.7	79.4	1.59
August	LN (2.89, 0.57, 0)	20.7	60.4	1.66
September	LN (2.98, 0.53, 0)	22.6	56.0	1.79
October	LN (2.67, 0.85, 0)	21.2	107.4	4.37
November	Gamma (1.33, 8.0)	10.7	87.4	1.72
December	W (0.96, 8.27, 0.28)	8.9	97.8	1.98

W: Weibull; LN: LogNormal; Gamma [1st parameter = shape factor; 2nd parameter = location; 3rd parameter: threshold value].

Table 3 | Monthly rainfall distributions for Jazan (mm)

Month	Distribution	Average	CV (%)	Skewness
January	Gamma (0.99, 18.12)	17.6	103.3	2.13
February	Gamma (1.0, 10.22)	10.2	98.8	1.93
March	Gamma (0.69, 18.27, 0.44)	12.9	116.5	2.29
April	W (0.98, 28.11)	28.5	101.5	1.95
May	W (1.11, 21.96,0)	21.3	92.6	1.81
June	LN (2.67, 0.7, 0)	18.7	79.0	2.71
July	LN (2.90, 1.26)	39.2	183.1	7.79
August	LN (3.71, 0.68,0)	51.7	77.7	2.86
September	LN (3.23, 0.65,0)	31.2	72.2	2.34
October	W (1.25, 21.17)	19.7	79.8	1.32
November	W (1.21, 25.11, 0)	23.4	82.1	1.45
December	LN (2.78, 0.96)	25.6	117.9	3.73

W: Weibull; LN: LogNormal; Gamma [1st parameter = shape factor, 2nd parameter = location; 3rd parameter: threshold value].

the Red Sea Coast had the ranges of −0.03–9.11, 2.12–24.7, 1.81–7.79 and 1.59–4.69, respectively. The skewness coefficient of zero indicates that the data are symmetric, the negative value indicates that the tail on the left side of the curve is longer than the right side, while the positive value indicates that the tail on the right side is longer than the left side, and the bulk of the values lie to the left of the mean value (Montgomery & Runger 2007). The higher values of CV, high positive skewness coefficients and skewed distributions in Tables 1–4 demonstrate that the rainfall in some months was much higher than the averages of monthly rainfall in these areas.

The yearly average rainfall in these areas was investigated for calculating the exceedance probabilities. The cumulative distribution functions (CDFs) for the yearly average rainfall in Asir, Al-Baha, Jazan, the Red Sea Coast and the entire region (Asir, Al-Baha, Jazan and the Red Sea Coast in combination) are presented in Figure 2. The 50-percentile rainfall for Asir, Al-Baha, Jazan, the Red Sea Coast and the entire region were 151.8, 74.6, 266, 143 and 162.2 mm, respectively (Figure 2). The 50-percentile rainfall in Asir, Jazan and the Red Sea Coast were much higher than the average yearly rainfall of the country. Figure 2 shows that the probabilities of exceeding the rainfall of 250 mm/year were 0.063, 0.004, 0.575, 0.133 and 0.011 for Asir, Al-Baha, Jazan, the Red Sea Coast and the entire region, respectively. The annual average rainfall in Asir, Al-Baha, Jazan, Red Sea Coast and the entire region exceeded 400 mm/year by the exceedance probabilities of 0.001, 0.00, 0.108, 0.02 and 0.00, respectively. Among these four areas, the rainfall exceeded the value of 500 mm/year in Jazan and the Red Sea Coast by the probabilities of 0.028 and 0.006, respectively. Figure 2 demonstrates that the highest annual rainfall were recorded for Jazan followed by the

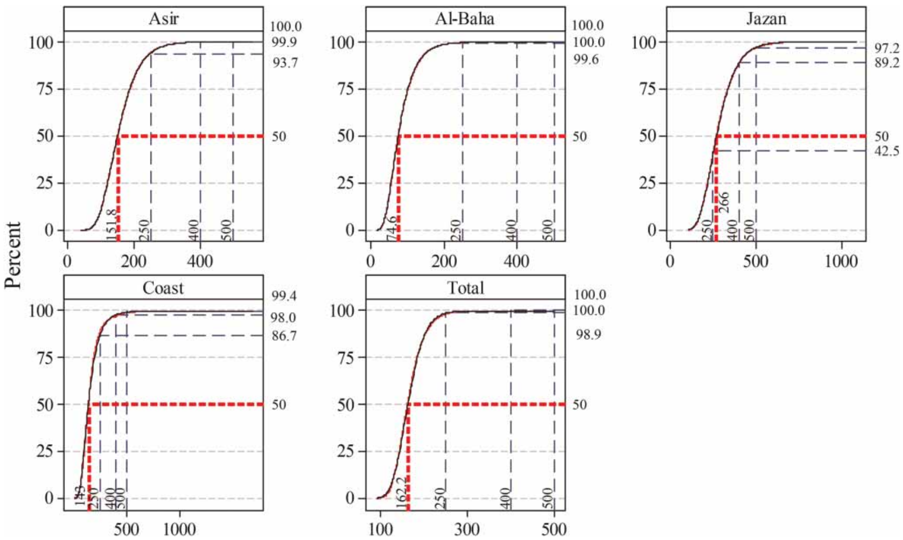

Figure 2 | Determination of probabilities of exceedance of yearly average rainfall in the south-western region (*Y* axis represents cumulative probability; *X* axis represents rainfall: mm/yr).

Red Sea Coast and Asir, while the lowest average rainfall was recorded for Al-Baha. Further details on the exceedance probabilities for different cutoff values are presented in Table 5. The data in Table 5 and Figure 2 indicate that there might be high potential of harvesting surface runoff from Asir, Al-Baha, Jazan and the Red Sea Coast.

Correlations between rainfall and elevation

In the Co-Kriging technique, the coefficient of determination (R^2) and correlation coefficients (r) for the cross-validation plots of rainfall data and elevations of stations were in the range of 0.77–0.99 and 0.877–0.995, respectively. The high values of correlation coefficients (r) demonstrate strong relationships between the rainfall records (main parameter) and the elevations of stations (auxiliary or secondary parameter). However, when other estimation techniques, such as Kriging and IDW were used, R^2 for the cross-validation plots was in the ranges of 0.13–0.63 and 0.11–0.63, respectively. Figure 3 shows the comparison of R^2 for the cross-validation plots in the Kriging, Co-Kriging and IDW methods. The Co-Kriging method presented better estimations for rainfall distributions at varying elevations of rain gauge stations. This method appears to be better than the Kriging and IDW methods (Figure 3). Between the Kriging and IDW methods, Kriging showed higher R^2 from December to May, while the IDW method showed higher R^2 from June to November. The strong correlations between rainfall and elevation demonstrate that the areas with higher elevations in the SW region may experience higher rainfall.

Rainfall quantity

The region under study covers an area of $157.59 \times 364.2\ \text{km} = 57{,}394\ \text{km}^2$, with the latitude/longitude

Table 5 | Regional rainfall exceedance probability (rainfall per year)

Area	100 mm	200 mm	250 mm	300 mm	350 mm	400 mm	450 mm
Asir	0.9	0.199	0.063	0.018	0.005	0.001	0.00
Baha	0.258	0.014	0.004	0.001	0.00	0.00	0.00
Jazan	0.999	0.807	0.575	0.358	0.207	0.108	0.055
Coast	0.764	0.252	0.133	0.07	0.037	0.02	0.0011
Total	0.995	0.133	0.011	0.005	0.001	0.00	0.00

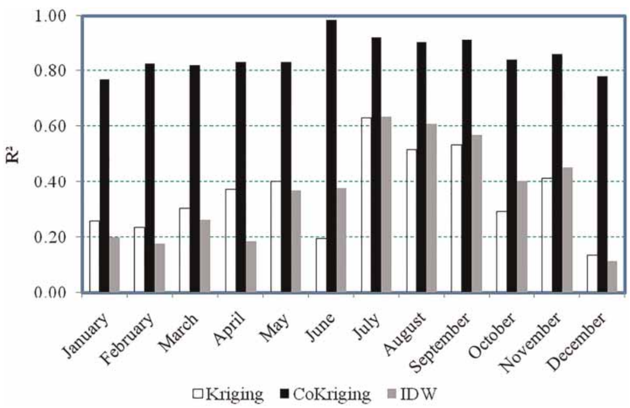

Figure 3 | R^2 for Kriging, Co-Kriging and IDW methods.

combinations of (186,773 m E, 1,877,164 m N) and (344,363 m E, 2,241,392 m N), respectively (Figures 4–6). The details of the region are shown in Figure 1. The rainfall contour maps (Figures 4–6) show that the entire region had significant amounts of rainfall. Figures 4–6 show that the rainfall in Jazan (bottom), Coast (left) and Asir (central) were much higher than Al-Baha (north), which is consistent with the CDF of the rainfall in these areas. Using the rainfall intensities from the contour maps (Figures 4–6) and their corresponding areas, total rainfall in these areas was calculated. April, May and August had the highest averages of rainfall all over the year, amounting to about 873, 566 and 488 MCM, respectively, of rainfall for the SW region. The total rainfall for the entire region was estimated to be 4.05 BCM per year. The monthly distributions of rainfall in different areas are presented in Figure 7. Asir had the largest amount of rainfall totaling approximately 1.76 BCM/year. The rainfall in Jazan, Al-Baha and Red Sea Coast were 1.05, 0.63 and 0.61 BCM per year, respectively. The cumulative rainfall in Asir was higher than the other areas in most months except September and October (Figure 7). Approximately 43.5% of the cumulative rainfall was from Asir. Jazan, Al-Baha and the Red Sea Coast contributed approximately 25.9%, 15.5% and 15.1%, respectively, of the cumulative rainfall. The rainfall intensities in Jazan were higher than Asir in most cases. However, for the cumulative rainfall, predicted using the contour maps in Figures 4–6 and the corresponding areas, it is shown that the Asir area had the largest amount of cumulative rainfall, due mainly to a larger land area than Jazan.

Surface runoff and storage capacities

The MOWE reported that 89 dams are available to capture surface runoff in the SW region (MOWE 2011). Among these, 56 dams are used for storage, 14 for flood control, 13 for drinking water and six for irrigation purposes (Table 6). Most of the dams are located in Asir (60), followed by Al-Baha (26 dams) and Jazan (three dams), while no dam is available in the Red Sea Coast (MOWE 2011). The total capacity of the dams is about 600 MCM, in which 562, 1.9, 30.1 and 3.9 MCM are used for storage, irrigation, drinking and flood control, respectively (Table 6). The dams in Asir have the highest capacity (373 MCM), while Jazan and Al-Baha have the capacities of 194 MCM and 31 MCM, respectively (Table 6).

To estimate the runoff, it was essential to understand the intensity–duration–frequency (IDF) curve and/or rainfall–runoff curve for each area. However, no established IDF curve was available for these areas. The study areas are mostly mountainous, consisting primarily of sedimentary rock, limestone, sandstone and shale, which have made these mountains impervious. The Asir Mountains are approximately 103,684 km^2, running parallel to the Red Sea and extending from the Yemen border to Taif, Saudi Arabia. This study focused on the area of 57,394 km^2 comprising mainly the mountains and valleys. It is likely that the surface runoff is generated within a few minutes of rainfall. The recent photograph of Arab News on 'Flash flood' (Arab News 2013) shared a similar view. There have been few examples of intense flow immediately after heavy rainfall. The intense flows in 2009, 2011 and 2013 were responsible for the death of 100, 10 and seven people, respectively, in the SW region (BBC News 2009; CNN World 2011; Arab News 2013). In the areas with similar geological structure, past studies used the runoff coefficients in the range of 0.05–0.65. For an area in the SW region, Nouh (1987) reported a runoff coefficient in the range of 0.133–0.185. Şen & Al-Suba (2002) estimated the runoff coefficients at Tihama, Asir in the range of 0.05–0.22. In the mountainous areas, some studies showed that runoff coefficient might reach 0.65 (Holko & Kostka 2008). In this study, a wide range of runoff coefficients, ranging from 0.05 to 0.70, was assumed for each area to have an understanding of the

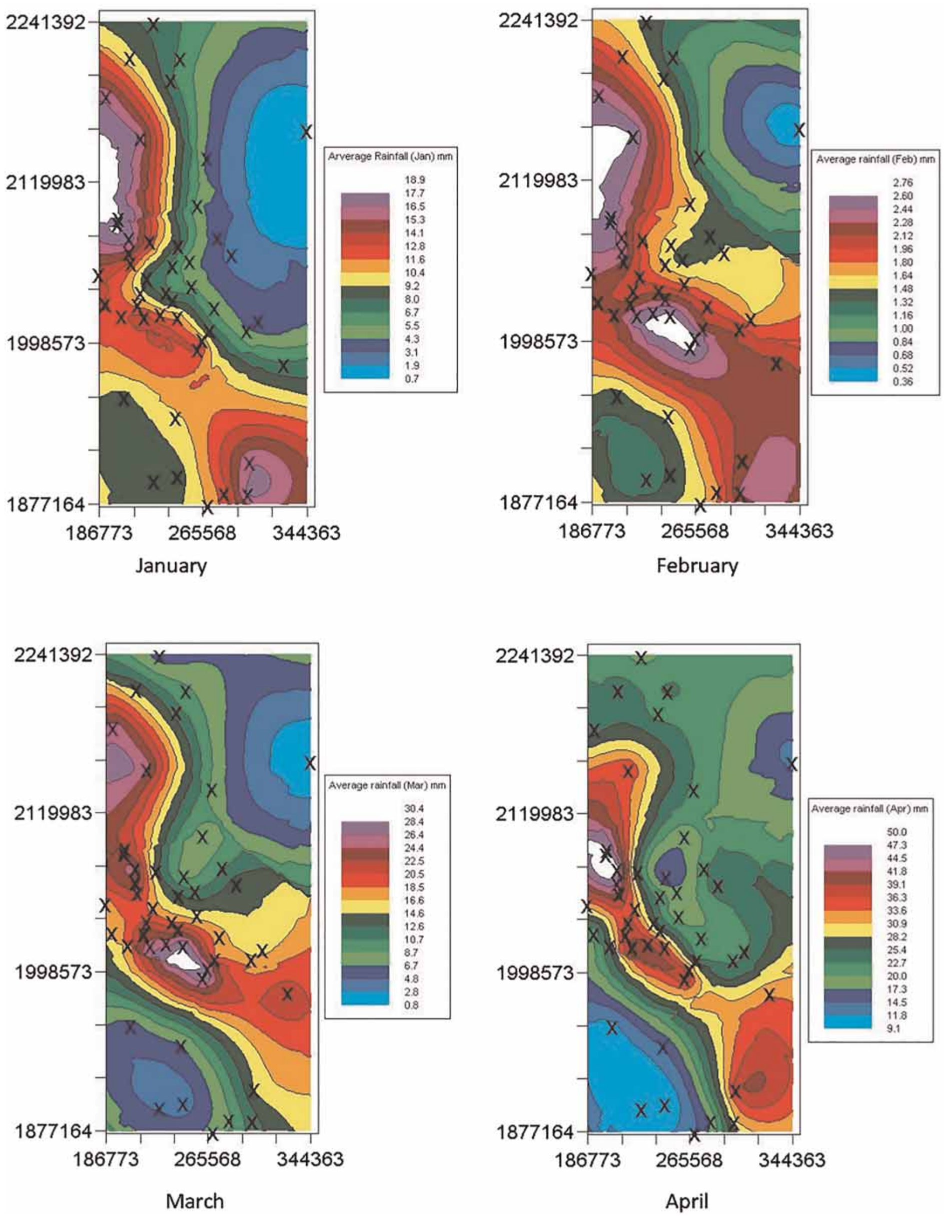

Figure 4 | Monthly average rainfall distributions from January to April using Co-Kriging.

possible ranges of runoff generations. Eight runoff coefficients covering the lowest and highest reported values of runoff coefficients were assumed in this paper (Table 7). The runoff at different scenarios are presented in Table 7. It should be noted that the runoff coefficients reported in the earlier studies were for some specific areas, which may not be representative of the entire region. Further, the mountains may have much higher runoff coefficients than the wadies, valleys, empty lands and green fields. In addition, the travel time is highly dependent on the topography, and evaporation and infiltration can play an important role on the values of runoff coefficients. As such, values of runoff coefficients are likely to vary tempospatially. To incorporate such a wide range of uncertainty, this study considers eight discrete values of runoff coefficients. Upon

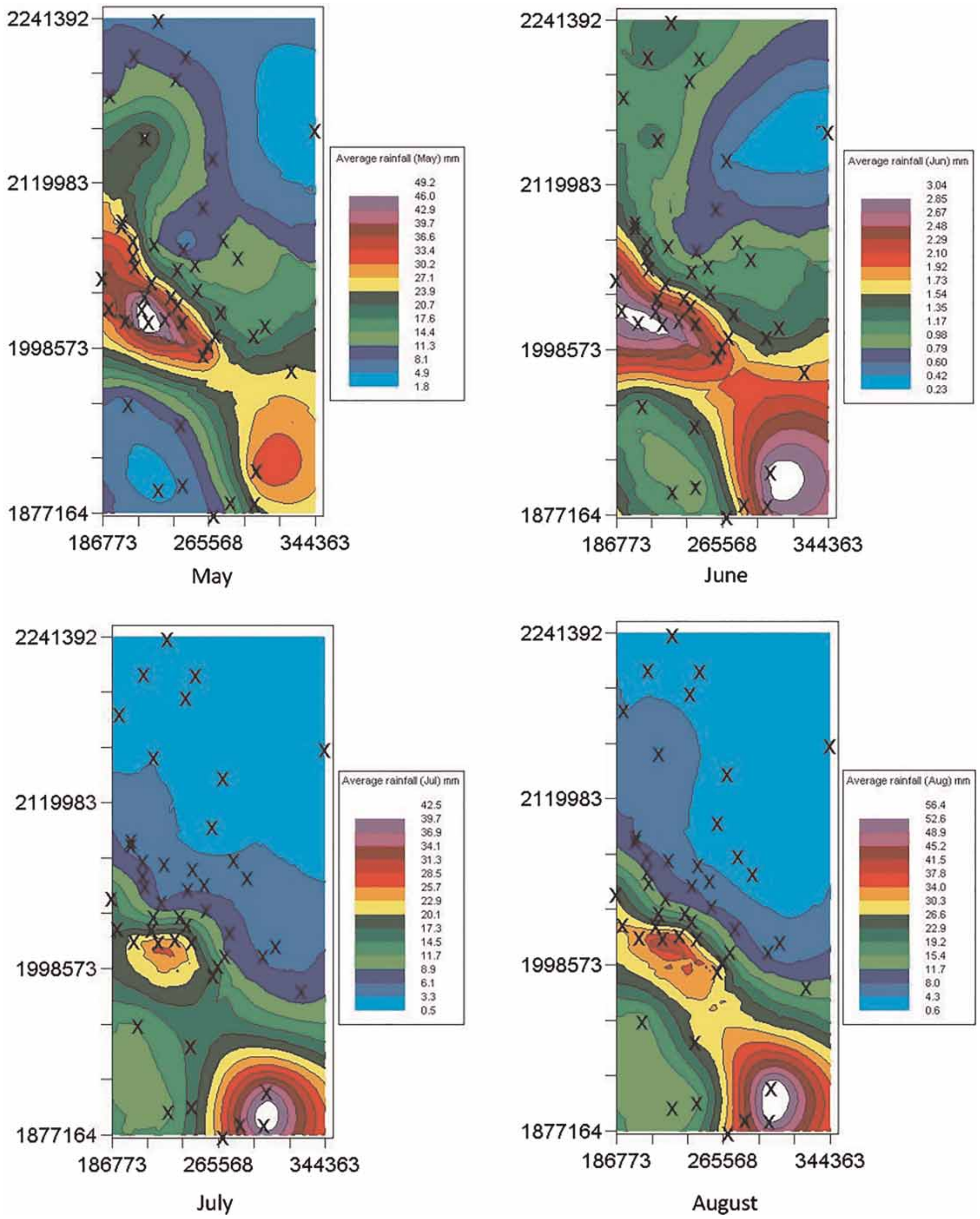

Figure 5 | Monthly average rainfall distributions from May to August using Co-Kriging.

availability of more reliable data, the results can be updated in future.

The total runoff was estimated using the rainfall intensities in different months, their corresponding areas and runoff coefficients (0.05–0.70). Generation of runoff in the SW region was estimated to be in the range of 203–2,835 MCM per year. In Case I, annual runoff was estimated to be 88, 53, 32 and 30 MCM in Asir, Jazan, Al-Baha and Red Sea Coast, respectively. For an intermediate scenario, for example, Case IV, runoff was estimated to be 527, 316, 190 and 182 MCM in these areas, respectively. For Case VIII (maximum), the runoff was predicted as 1,230, 738, 443 and 425 MCM, respectively. However, the storage capacities of the existing dams in Asir, Jazan and Al-Baha are 373, 194 and 31 MCM, respectively. No storage dam was reported in the Red Sea Coast. The data indicate that

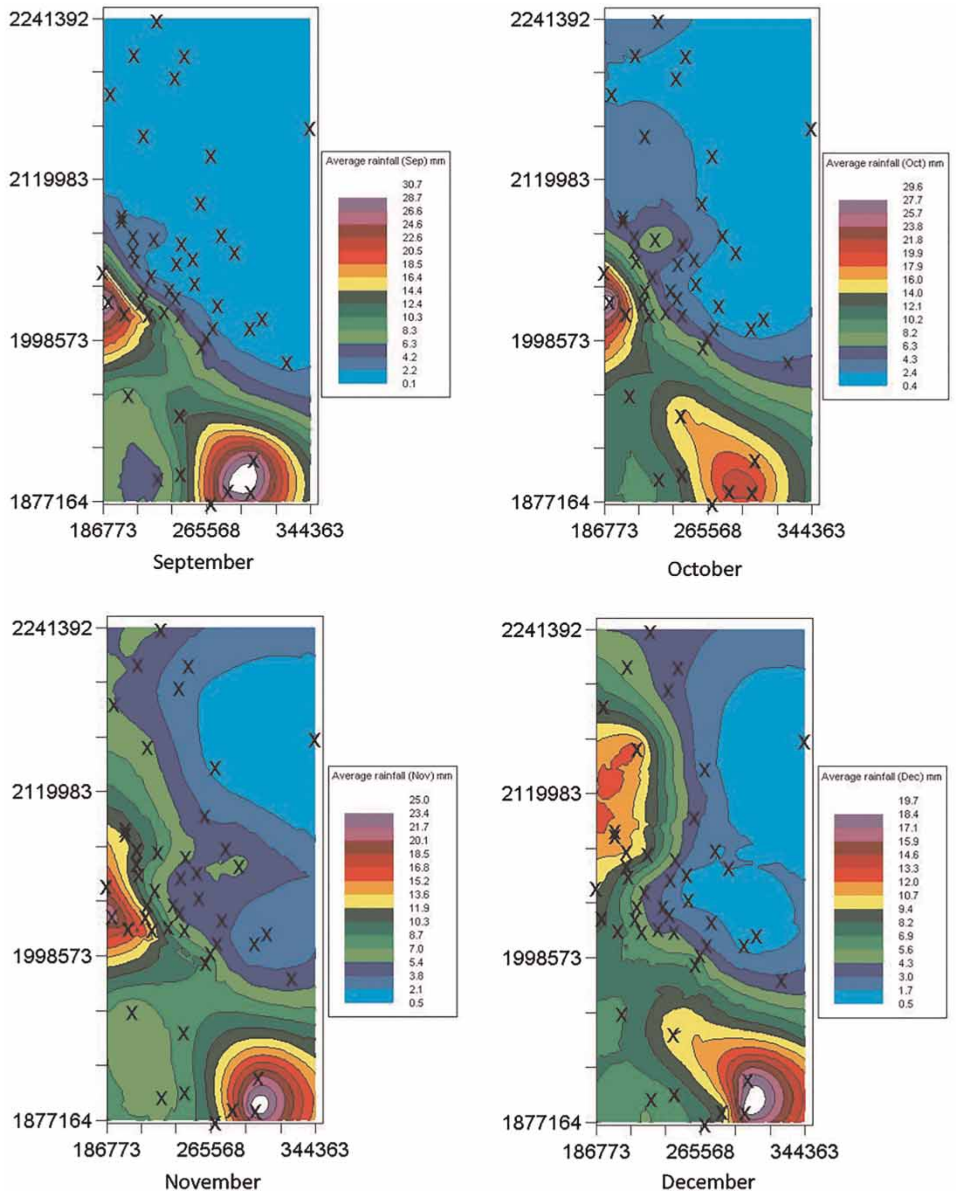

Figure 6 | Monthly average rainfall distributions from September to December using Co-Kriging.

in Case I, 0.4 and 30 MCM per year of runoff are not collected in Al-Baha and the Red Sea Coast, respectively. In Case IV, approximately 154, 122, 159 and 182 MCM per year of runoff are not collected in Asir, Jazan, Al-Baha and the Red Sea Coast, respectively, while in Case VIII, 857, 544, 411 and 425 MCM per year of runoff are not collected in these areas, respectively. While comparing with Case I, approximately 85% of the annual runoff in the SW region is collected, in which the runoff in the Red Sea Coast is not collected at all. In Case IV, 49.2% of runoff in the SW region is collected. Asir, Jazan and Al-Baha collect approximately 70.8, 61.3 and 16.3% of the annual runoff, respectively. In Case VIII, approximately 30.3, 26.3, 7.0% of runoff is collected in Asir, Jazan and Al-Baha, respectively. Further details on the runoff loss can be found in Table 8.

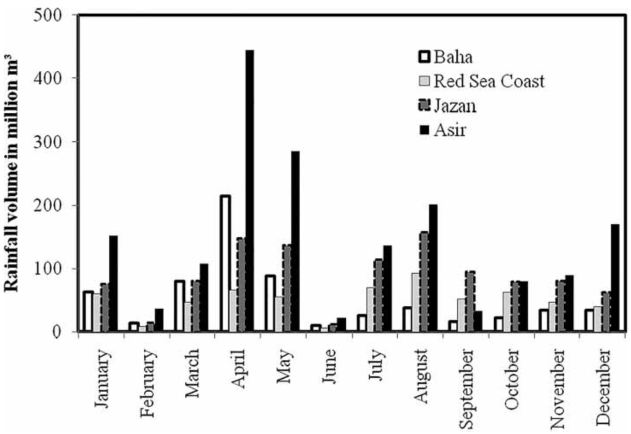

Figure 7 | Monthly rainfall for the Baha, Red Sea Coast, Jazan and Asir areas.

The eight scenarios of runoff show that the uncollected runoff was in the range of 30.4–2,237 MCM/year (Tables 7 and 8), representing 15.0–78.9% of the total runoff. Figure 8 presents the dam capacities and predicted surface runoff for each area separately and in combination. The results show that the value of runoff coefficients need to be approximately 0.2 or more to exceed the current levels of storage capacities in Asir and Jazan (Table 8; Figure 8), while for Al-Baha and Red Sea Coast, even lower coefficients might lead to the loss of runoff. It should be noted that Şen & Al-Suba (2002) reported the runoff coefficients of 0.05, 0.07 and 0.07 for Baysh, Damad and Jazan wadies (SW region), respectively. However, it is likely that the runoff coefficients for the mountains will be higher than the runoff coefficients in the wadies (Holko & Kostka 2008). In Case I (Table 7), total runoff generations were estimated to be 203 MCM/year, which is much lower than the current storage of surface runoff (e.g., 598 MCM/year). However, runoff will still be lost, as there is no dam in the Red Sea Coast. Further, the floods in 2009, 2011 and 2013 indicated that the generations of surface runoff in these regions could be much higher than the dam capacities, meaning that the average runoff coefficients in these areas might be higher than Case I. Future study on runoff coefficients might better estimate the runoff in these areas.

Table 6 | Dams, their locations, type and capacities

	Asir		**Jazan**		**Baha**		**Coast**		**Total**	
	No.	**Capacity**	**No.**	**Capacity**	**No.**	**Capacity**	**No.**	**Capacity**	**No.**	**Capacity**
Storage	34	360.27	1	193.64	21	8.08	–	–	56	561.99
Irrigation	3	0.99	2	0.43	1	0.50	–	–	6	1.91
Drinking	12	7.59	0	0	1	22.5	–	–	13	30.09
Control	11	3.79	0	0	3	0.14	–	–	14	3.93
Total	60	372.64	3	194.07	26	31.23	–	–	89	597.92

Table 7 | Runoff generations and collections in the south-western regions under different scenarios (MCM/year)

		Predicted runoff							
Area	**Current storage**	**Case I (C = 0.05)**	**Case II (C = 0.1)**	**Case III (C = 0.2)**	**Case IV (C = 0.3)**	**Case V (C = 0.4)**	**Case VI (C = 0.5)**	**Case VII (C = 0.6)**	**Case VIII (C = 0.7)**
Asir	373	88	176	351	527	703	878	1,054	1,230
Jazan	194	53	105	211	316	422	527	633	738
Baha	31	32	63	126	190	253	316	379	443
Red Sea Coast	0	30	61	121	182	243	303	364	425
Total	598	203	405	810	1,215	1,620	2,025	2,430	2,835

Table 8 | Runoff wastage in the south-western region of Saudi Arabia (MCM/year)

Area	Runoff wastage[a]							
	Case I	Case II	Case III	Case IV	Case V	Case VI	Case VII	Case VIII
Asir	–	–	–	154	330	505	681	857
Jazan	–	–	17	122	228	333	439	544
Baha	0.4	32	95	159	222	285	348	411
Red Sea Coast	30	61	121	182	243	303	364	425
Total	31	93	233	617	1,023	1,426	1,832	2,237

[a]Cases I–VIII: C = 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, respectively.

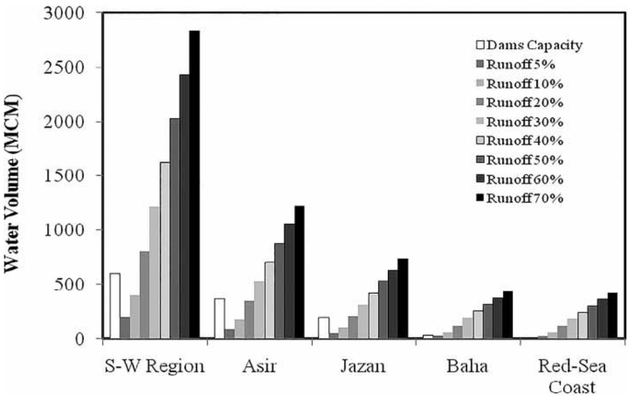

Figure 8 | Comparison of dams' capacity and runoff.

DISCUSSION

Technical issues

The above assessment approximated the possible scenarios of runoff from the long-term rainfall patterns in the SW region of the country through considering a wide range of runoff coefficients. Several other limiting factors need to be considered to obtain better assessments, such as evaporation and permeability of water throughout the flow routes (e.g., wadies), distance from the rainfall stations to the dam locations, loads of solids with runoff, etc. Past studies have reported that the free surface evaporation from the wadies can be in the range of 5–80% of the water on an annual basis (Al-Turbak 1989; Al Maktoumi 2013; Lopez et al. 2014). Missimer et al. (2014) reported that up to 80% of the water in the old wadies could be lost through free surface evaporation. For a dam reservoir in the SW region of the country, the potential loss through surface evaporation was estimated to be in the range of 4.7–6 m per year (Lopez et al. 2014). The distance of the wadies that needs to be traveled by the runoff to reach the dam/reservoir can be another important factor. Significant amount of runoff can be lost through evaporation and infiltration while traveling to the dam/reservoirs. In addition, large amounts of solids can be accumulated in the dam/reservoirs during the flood events, which might reduce sub-surface water recharge significantly. Consequently, reduced recharge of water is expected in the aquifer (Missimer et al. 2014). The feasibility of dam construction and maintenance costs are the other factors to be taken into consideration. Construction of Wadi dams is quite expensive with costs ranging from $250 million to over $1 billion USD depending on the size and complexity of the dam (Missimer et al. 2014). In addition, water transportation from these sources and maintenance costs for the pipelines can also be significant. The complexity indicates that actions will be needed to minimize the effects of evaporation in the dam. In addition, the effects of solid deposits on water recharge need to be minimized. One of the possibilities may include water recharge through considering several small zones for water ponding and constructions of shallow wells in these zones. However, well construction, maintenance, porosity of the mediums under the wells, cost of pressurized recharge and solid depositions can be limiting factors for this option. It is advisable to perform optimization studies through incorporating the related factors for maximizing the benefits from rainfall in the SW region.

Policy implications

Studies have demonstrated that Saudi Arabia needs water conservation, TWW reuse for agriculture, and to find new sources of water (MOEP 2010; Chowdhury & Al-Zahrani 2013a, b). The desalination plants supplied approximately 1,050 MCM of DW in 2009 (MOEP 2010; SWCC 2011), which increased to 1,595 MCM in 2013 (MOWE 2013). The MOEP had a plan to increase the desalination plants from 30 to 44 by 2014, which were projected to produce 2,070 MCM of DW in 2014 (MOEP 2010). In 2014, the predicted domestic water demand was 2,583 MCM, indicating the needs of additional water from other sources (MOEP 2010; Chowdhury & Al-Zahrani 2013a). The MOEP indicated that agricultural water demand would be decreased from 15,464 to 12,794 MCM from 2009 to 2014 (MOEP 2010). During this period, the industrial water demand was predicted to increase from 713 to 930 MCM. The MOWE reported that 15,408 and 14,999 MCM of GW was supplied to different regions in 2011 and 2012, respectively (MOWE 2013). In addition, 449 dams with a capacity of 2.02 BCM were used for recharge, flood control, and to supply water for domestic and irrigation purposes in 2012 (MOWE 2013). In 2012, a total of 81 wastewater treatment plants treated approximately 1,261 MCM of domestic wastewater while only 181 MCM of TWW was reused (MOWE 2013). However, the MOEP data showed that the reuse of TWW was 325 MCM in 2009 (MOEP 2010). The MOWE and MOEP data indicate that a significant amount of wastewater and TWW was not reused.

Past studies have reported that construction of infrastructure to collect and treat domestic wastewater and to recycle TWW for agriculture might provide significant support toward conserving NGW (Chowdhury & Al-Zahrani 2013b, c). These studies have demonstrated that comprehensive reuse of TWW might produce approximately 654 thousand tons of wheat, which was about 20% of the national wheat demand in 2011. The country had a plan to increase TWW reuse from 325 to 570 MCM by 2014 (MOEP 2010), which is still much less than the generated domestic wastewater (Chowdhury & Al-Zahrani 2013b, c). An aggressive policy to increase TWW reuse may be beneficial to the country, while comprehensive reuse of TWW requires significant costs and maintenance, which deserves the attention of the policy-makers.

In addition to the support from TWW reuse, new sources of water are required. The option of importing water from neighboring countries requires long-term political stability, cost and bi-lateral relationships. Although transferring water from one region to another region has been practised in some countries (e.g., Libya and China), Saudi Arabia lacks such sources (Mays 2011). Finding new sources within the country might be a better option (Chowdhury & Al-Zahrani 2013a). Harvesting runoff might be an emerging option in Saudi Arabia. Although the countrywide average annual rainfall is low, this study shows that significant fractions of runoff are being wasted from the SW region. By varying the runoff coefficients from 0.05 to 0.7, this study estimated much higher runoff generations than the capacities of the existing dams (Tables 7 and 8). The flash floods from the torrential rain in the SW region indicated higher runoff from rainfall events and/or poor drainage facilities (BBC News 2009; CNN World 2011; Arab News 2013). Through constructing new dams in the appropriate locations of the SW region, the country may increase runoff collection by 30.4–2,237 MCM/year. Such collection can lower NGW extraction, which is a strategic priority of the country. A policy to look into the possibility of increasing runoff collection from the SW region can help in water resources management, while such policy can also reduce dependency on the NGW sources. However, construction of large dams requires comprehensive study on the locations, elevations, IDF curves, rainfall–runoff relationship, flow directions, runoff coefficients and economic viability. In addition, higher rates of surface evaporation and accumulation of solids at the bottom of the dam reservoirs need careful attention. This indicates that faster rates of recharge may be an option, while the faster rates can be obtained through constructing shallow wells at the appropriate locations. Alternatively, storing water in underground tank/reservoirs might be another option. Future study is warranted to address these points.

SUMMARY AND CONCLUSIONS

In Saudi Arabia, fossil water is limited and non-renewable in terms of real-time recharge at a particular hotspot. There might be an opportunity to increase runoff collection by constructing new dams/wells in the SW region. By analysing the rainfall, this study shows the potentials for additional runoff collection in the SW region. The total runoff generations in eight scenarios can be in the range of 203–2,835 MCM per year. In any scenario, loss of runoff is likely (Table 8). Availability of infrastructure (dam, well, etc.) may provide significant support for water resources management. For example, at runoff coefficient of 0.05, Asir, Jazan, Al-Baha and the Coast have the potential to collect approximately 0.0, 0.0, 0.4 and 30 MCM/year of additional runoff, which can be increased to 154, 122, 159 and 182 MCM/year at runoff coefficient of 0.3 (Case IV). At higher runoff coefficients, these values are likely to be higher. In the context of agriculture, 30.4 MCM/year of water (e.g., additional runoff for Case I) may produce approximately 12.2 thousand tons of wheat annually (at the rate of 2,492 m^3/ton). For Case IV, this can be 249 thousand tons, which is approximately 7.5% of the national wheat demand in 2011.

The contour maps assist in identifying the approximate locations of new dams and/or wells for water storage and/or recharge. However, to identify the exact locations for new dams or wells, further details are needed on the locations, IDF curves, evaporation, water flow directions, water seepage and structural and geological feasibility. Future study should focus in these directions. In addition, runoff estimates can be improved by using the IDF. Future study should try to develop the IDF curves for these areas. This paper represents the first phase of the study to shed light on the importance and potentials for collecting surface runoff from the SW region of Saudi Arabia.

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