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ORIGINAL ARTICLE

Implications of climate change on crop water requirements in arid region: An example of Al-Jouf, Saudi Arabia

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Abstract This study investigated possible implications of climate change on crop water requirements (CWRs) from 2011 to 2050 in Al-Jouf, Saudi Arabia. CWR were predicted for four scenarios: (i) current temperature and rainfall (S1); (ii) temperature in 2050 and current state of rainfall (S2); (iii) rainfall in 2050 and current state of temperature (S3) and (iv) temperature and rainfall in 2050 (S4). Assuming no change in the regulations relating to agriculture and irrigation in future, CWR were predicted to be 873 and 931 million cubic meters (MCM) per year for the S1 and S4 scenarios, respectively, indicating an increase of 58 MCM from 2011 to 2050. On an average, 1 °C increase in temperature may increase the overall CWR by 2.9% in this region. Following linear pattern of increase, slope of CWR was determined as 1.5 MCM/year from 2011, which is equivalent to the CWR of producing approximately 600 tons of wheat/year. The increase of CWR was due to the increase in temperature mainly, while the effect of rainfall changes was minimal. Sensitivity analysis on crop growing seasons showed that the shift of wheat growing season might conserve significant amount of groundwater. This study might be useful in explaining the negative effects of climate change on CWR in Al-Jouf and better planning for water resources management.

1. Introduction

Al-Jouf is one of the thirteen administrative regions in Saudi Arabia, located in the northwest of the country (Fig. 1). It has an area and population of approximately 85,000 km^2 and 440,000, equivalent to 4.3% and 1.6% of total area and population of the Kingdom, respectively (SGS, 2012). In Al-Jouf, approximately 112 thousand hectares of land was cultivated in 2009 to produce different crops (SSYB, 2010). It was the third largest agricultural region in Saudi Arabia (MOEP, 2010). Approximately 61%, 24%, 11.6% and 3.7% of the

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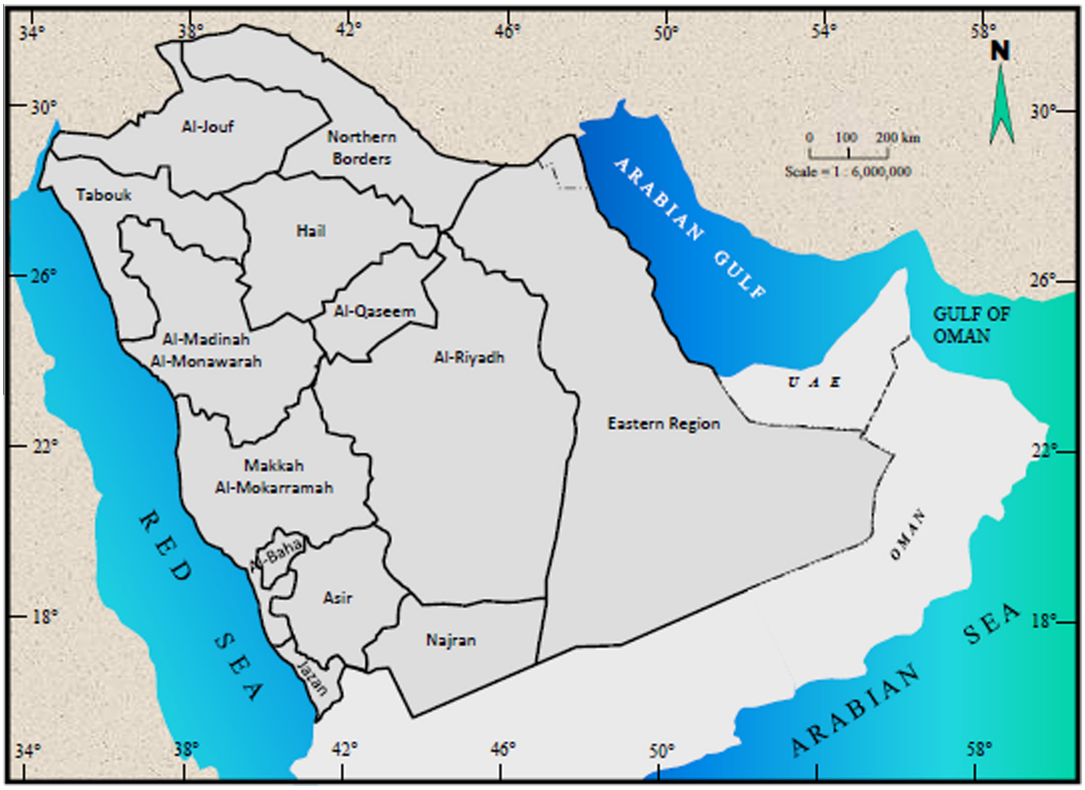

Figure 1 Location of different regions in Saudi Arabia.

cultivated lands were used for producing cereal crops, fruits, fodder crops and vegetables, respectively (SSYB, 2010; MOA, 2009). The important agricultural crops in Al-Jouf are wheat, maize, barley, vegetables, clover, dates, grapes and citrus fruits, while the production of wheat is the highest (e.g., approximately 58% of the cultivated lands). The Saudi Statistical Yearbook reported that Al-Jouf produced the highest fractions of wheat in the country (30.2–39.7%) during 2005–2009 (SSYB, 2010).

The climatic condition of Al-Jouf is arid with average monthly temperature varying in the range of 3.5 °C in winter to 39 °C in summer. The average annual rainfall is approximately 58 mm/year with an average evapotranspiration of approximately 7 mm/day (FAO, 2012). Average wind speed varies in the range of 6–10 km/hr, while the humidity is less than 20% in the dry months and up to 58% in winter (SSYB, 2010; FAO, 2012). The contribution of rainfalls to agriculture is minimal in this region (Al-Zawad, 2008; Alkolibi, 2002). Agriculture in Al-Jouf primarily depends on limited non-renewable groundwater sources, from which approximately 1510 million cubic meters (MCM) of water was supplied for agriculture in 2009 (MOEP, 2010). In some past years, agriculture in Al-Jouf consumed similar amounts of water (MOEP, 2010). At this rate, the groundwater reserves may not survive for a long time (MAW, 1984). In addition, climate change may impose further stress on the availability of water and agricultural productions. Past studies reported that the negative effects from climate change can affect Saudi agricultural sector (Al-Zawad, 2008; Alkolibi, 2002; Chowdhury and Al-Zahrani, 2013, 2015). Increase in temperature by 1 °C may change the thermal limits of the crop, which may lead to 5–25% decrease in crop productions (Parry and Swaminathan, 1993). The Hadley Centre Global model (HadCM3) reported reduced agricultural production in arid regions in future (Parry et al., 1999). Chowdhury and Al-Zahrani (2013, 2015) reported the increase in temperature by 2.1–4.1 °C in 2050 for the northern region of Saudi Arabia, while the maximum increase was reported to be 3.0–4.1 °C in the northwestern region. The increase of temperature was reported based on the Climate Change Scenarios B_2 and A_2, respectively. Al-Zawad (2008) predicted 5.1 °C increase in temperature in this region for the period of 2070–2100. Increase in temperature in such a range can increase evapotranspiration by 10.3–27.4% (Chowdhury and Al-Zahrani, 2013, 2015). Further, these studies also predicted decreased rainfalls for the northern region of Saudi Arabia (Al-Zawad, 2008; Chowdhury and Al-Zahrani, 2013, 2015). Increase in temperature, evapotranspiration, variable rainfall patterns and interactions of other meteorological parameters may have negative effects on crop water requirements (CWR). For better management of available resources and agricultural productions, it is important to understand CWR, current level of water supplies and possible effects of climate change in future.

The CWR can be predicted by several methods. The Food and Agriculture Organization (FAO) recommended using CROPWAT software to better estimate CWR under various scenarios of climatic changes (FAO, 2009). CROPWAT has been widely used in assessing CWR and scheduling agricultural crops (Smith, 1991; Smith and Kivumbi, 2006). George et al. (2000) developed an irrigation schedule model (ISM) for single and multiple fields using CROPWAT software, where the authors showed consistency between the field and predicted data. CROPWAT software has been widely used for predicting CWR, irrigation rescheduling, reference evapotranspiration, deficit irrigation scheduling and cropping patterns in Greece, Taiwan, Africa, USA, Morocco, Turkey, Zimbabwe and Pakistan (George et al., 2000; Anadranistakis et al., 2000; Sheng-Feng et al., 2006; Wahaj et al., 2007; Kang et al., 2009; Nazeer, 2009; Mimi and Jamous, 2010; Stancalie et al., 2010; Mhashu, 2007). Anadranistakis et al. (2000) estimated and validated CWR for cotton, wheat and maize in Greece. Sheng-Feng et al. (2006) showed that CWR, predicted by CROPWAT software, were efficient in managing irrigation water for different cropping patterns in Taiwan. A comparison among CROPWAT, MODWht and CERES-Wheat models showed that the CROPWAT software was better in predicting reference evapotranspiration (ET_o) (Kang et al., 2009). Past studies indicated that CROPWAT software could be a reliable tool to better understand CWR, irrigation planning and manage irrigation scheduling.

In context to Saudi Arabia, several studies have predicted water consumptions for different crops in various regions. For example, by using the FAO modified Penman–Monteith method, Mustafa et al. (1989) reported water requirements of wheat in the range of 3790–6740 m^3/ha/season. For the Central and Eastern regions, Al-Omran and Shalaby (1992) predicted water demands for wheat, maize, tomato, citrus and dates as 8830, 7510, 17,030, 22,590 and 40,210 m^3/ha/season, respectively. In the Al-Jouf region, Saifuddin et al. (2004) reported water requirements for wheat, potato and alfalfa as 6473, 6522 and 34,864 m^3/ha/season, respectively. However, studies focusing on overall water requirements for a wide array of crops produced in a region are limited. Further, studies on possible effects of climatic change on CWR for different crops in this region are also limited, while understanding of such effects is important to aid water resources management. This paper aims to understand the implications of climate change on CWR in Al-Jouf from 2011 to 2050. Four different scenarios: (i) CWR at current state of temperature and rainfall (S1); (ii) CWR at the changed temperature in 2050 and current state of rainfall (S2); (iii) CWR at changed rainfall in 2050 and current state of temperature (S3) and (iv) CWR at changed temperature and changed rainfall in 2050 (S4), will be investigated. Possible effect on CWR from climatic change will be identified. Sensitivity analysis will be performed by shifting the crop growing periods for the major crops and changing temperature increase rate.

2. Methodology

2.1. Model description

CWR depend on climatic conditions, crop area and type, soil type, growing seasons and crop production frequencies (FAO, 2009; George et al., 2000). CROPWAT is a collection of modules following the Penman–Monteith method that integrates several models necessary to predict CWR, irrigation water management and crop scheduling (Smith, 1991). It follows the FAO approved Penman–Monteith method to predict reference evapotranspiration (ET_o), crop evapotranspiration (ET_c) and irrigation water management (FAO, 1998; Smith, 1991). It is to be noted that ET_c represents the amount of water that crop losses due to evapotranspiration while CWR represent the amount of water to be supplied (Mhashu, 2007). CWR were estimated for each crop and then added through the irrigation scheme planning to predict the total water requirements. The first step in the CROPWAT software is to predict ET_c on a 10 day basis (e.g., time step = 10 days) as:

$$ET_c = ET_o \times K_c \tag{1}$$

where, ET_c = actual evapotranspiration by the crop (mm/day), ET_o = reference evapotranspiration (mm/day); K_c = crop coefficient at a specific growth stage. K_c depends on the type of crop (e.g., height of crop, resistance of canopy, albedo), soil and climatic parameters, such as, soil surface, evaporation and wind speed and direction (FAO, 1998; Smith and Kivumbi, 2006). Albedo is the fraction of solar radiation reflected by the surface of crop and soil, where as the canopy means the leaves and branches of crops that make a kind of roof. Resistance of canopy is the resistance of the crop against vapor transfer (FAO, 1998). The parameter K_c varies on the type of the crop and the growing stage of a crop (e.g., initial stage, crop development, mid-season and late season). On the other hand, ET_o depends on climatic data (e.g., temperature, wind speed, sunshine hours and humidity). The Penman–Monteith method has been recommended by the Food and Agriculture Organization (FAO) for its appropriate combinations of relevant climatic parameters for predicting ET_o (FAO 1998; Smith and Kivumbi, 2006; Mhashu, 2007). The basic features of the Penman–Monteith method includes: (i) height of the reference grass of 0.12 m; (ii) surface resistance of 70 s/m and (iii) albedo of 0.23. These assumptions represent evaporation from the surface of wide range of high standard green grass with enough water and active growth (FAO, 1998). The equation can be presented as:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2}$$

where, ET_o = reference evapotranspiration (mm/day); R_n = net radiation at the crop surface (MJ/m^2/day); G = soil heat flux density (MJ/m^2/day); T = mean daily air temperature at 2 m height (°C); u_2 = wind speed at 2 m height (m/s); e_s = saturation vapor pressure (kPa); e_a = actual vapor pressure (kPa); e_s–e_a = saturation vapor pressure deficit (kpa); Δ = slope of vapor pressure curve (kPa/°C) and γ = psychrometric constant (kPa/°C). In assessing CWR for a crop, it is essential to understand the effective rainfall over the cultivated area. The effective rainfall can be calculated following (Sheng-Feng et al., 2006) and (Molua and Lambi, 2006) as:

$$P_{eff} = P_{tot}\frac{125 - 0.2P_{tot}}{125} \tag{3}$$

where, P_{eff} = effective rainfall (mm) and P_{tot} = total rainfall (mm). Eq. (3) is valid for a rainfall of P_{tot} < 250 mm. In Saudi Arabia, major parts of the country have average rainfall less than this value (e.g. Al-Jouf region) (SSYB, 2010). Following the prediction of CWR for each crop, the monthly agricultural water requirements can be predicted as:

$$Q = \sum_{i=1}^{n} A_i(ET_{c_i} - P_{eff}) \times 10 \tag{4}$$

where, Q = monthly agricultural water requirement of irrigation scheme (m^3/day); i = crop index; A_i = crop planted area (hectare); ET_{ci} = crop evapotranspiration (mm/day);

P_{eff} = the effective rainfall (mm/day) and 10 represents the conversion factor (Sheng-Feng et al., 2006).

2.2. Data generation and application

CROPWAT requires climatic parameters (e.g., maximum and minimum temperature, wind speed, sunshine, humidity and rainfall), planting and harvesting dates of crops, soil type and cultivation area of crops for estimating CWR. The climatic data were collected from the weather station at Dawmat Al-Jandal representing the Al-Jouf region (FAO, 2012; PME, 2012; MOWE, 2013). These data were used to predict CWR for the current climatic conditions. To predict CWR for 2050, values of climatic parameters from past studies (Chowdhury and Al-Zahrani, 2013, 2015) were used. Information on different crops and cropping patterns (e.g., crop name, planting and harvesting date, cultivated area) in Al-Jouf were obtained from the Saudi Statistical Year Book (SSYB, 2010) and past studies (Alsadon, 2002; TVTC, 2004). The details of the crops, corresponding cultivated area and planting and harvesting dates are presented in Table 1. In Table 1, cultivated areas for wheat, maize and barley are approximately 65,162, 2179, and 801 hectares. Their growing seasons are: January-May, August–December and November–February, respectively. The cultivated areas for tomato, potato and other vegetables are: 693, 1837 and 1601 hectares while their growing seasons are April–August, January–May and March–June, respectively. The cultivated area for clover is about 11,908 hectares and the growing season is March–February. The cultivated areas for dates, citrus and grapes are approximately 5470, 727 and 1628 hectares, respectively. The crop growth stage coefficient (K_c) was obtained from FAO database for each crop. The growing stages for different crops and values of K_c at different growing stages for various crops are shown in Table 2. The K_c values for wheat are 0.55, 1.15 and 0.30 at the initial stage, mid-season and the late season, respectively. The value of 0.55 remains constant till the end of the 20 days of the initial stage. It increases gradually to 1.15 during the development stage of 30 days. Then it remains constant (1.15) during the mid-season of 50 days of growing period. It declines to 0.30 during the late season of 30 days. The K_c values for some crops increase to more than unity in the development stage and mid-season indicating that ET_c is higher than ET_o leading to an increased CWR in the development and mid-season stages. The soil surface in most of the agricultural areas in Al-Jouf is sandy, which can be characterized as light sand (SGS, 2012). Following the predictions of CWR for different crops, total water requirements were predicted. Further details on the input data for each scenario are presented below.

Table 1 Area, planting and harvesting dates for different crops in Al-Jouf region in 2009.

Crops	Area (hectare)	Planting date	Harvesting date
Wheat	65,162	15/01	24/05
Maize	2179	15/08	17/12
Barley	801	01/11	28/02
Tomato	693	01/04	23/08
Potato	1837	15/01	24/05
Other vegetables[a]	1601	01/03	03/06
Clover[b]	11,908	01/03	28/02
Dates	5470	01/04	31/03
Citrus	727	01/03	28/02
Grapes	1628	01/04	31/03

[a] [Marrow, eggplant, okra, carrot, dry onion, cucumber, melon, and watermelon].

[b] CWR for clover are estimated by using alfalfa as clover not available in the software database.

CWR were predicted using the current data (S1 scenario) for climatic conditions. Monthly averages of minimum and maximum temperature, humidity, wind speed, sunshine hours and rainfall data are shown in Table 3. The monthly average temperature was about 28.3 °C while the monthly average of maximum temperature was approximately 38.5 °C in August. The averages of humidity, wind speed and sunshine were 29%, 7 km/hr and 8.4 h, respectively (FAO, 2012; MOWE, 2013). The total annual rainfall was about 58 mm. The maximum rainfall in the current situation (e.g., 2011) was about 14 mm in April followed by 10, 9 and 8 mm in October, January and March, respectively. The changes in rainfall are expected to be slightly positive in some months (e.g. January–April, October–December and June), while it is almost zero in the other months (Table 3). The projected temperature in 2050 for Al-Jouf region was obtained from the data predicted by Chowdhury and Al-Zahrani (2013, 2015). An interpolation was done on these data to obtain the predicted temperature for the agricultural areas. For example, temperature in January of 2050 is expected to increase by 2.58 and 2.27 °C at A (lat. 27.50N; lon.33.75E) and B (lat. 30N; lon. 41.25E), respectively. Al-Jouf is located in these latitudes and longitudes (e.g., A and B). Using the following interpolation, increase in temperature for Al-Jouf was obtained as:

$$\text{Temp.} = 2.58 - \frac{(27.5 - 29.78) \times (2.58 - 2.27)}{(27.5 - 30)} = 2.29^{\circ}\text{C}$$

The temperature increase in 2050 is expected to be in the range of 2.1–3.6 °C in locations A and B in different months. These data were added to the current temperature (e.g., Table 3) and the predicted temperatures are shown in Table 4. The rainfall in 2050 was obtained from the same study following a similar procedure (Chowdhury and Al-Zahrani, 2013, 2015). The projected rainfall changes in 2050 are expected to be in the range of −3.02 to 8.04 mm in different months (Table 4). The rainfall during February, May and July was predicted to be zero, while it is expected to be within the range of 2–17 mm in the other months (Table 4). Table 4 indicates that there might be an increase in rainfall in some months, which can reduce CWR for those months. Data from Tables 3 and 4 have been incorporated to predict CWR for the S1–S4 scenarios.

3. Results

3.1. Reference evapotranspiration (ET_o)

The ET_o in 2011 and 2050 for the S1 scenario are presented in Fig. 2. Fig. 2 shows that ET_o in 2011 varies in the range of 2.6–10.9 mm/day. The ET_o increases gradually from approximately 3 mm/day in January to the peak value of about 10.9 mm/day in July. Then it decreases gradually to 2.6 mm/day in December (Fig. 2). The highest ET_o in July can be explained by the hot and dry summer and low rainfall in this

Table 2 Growing stages and crop growth stage coefficient (K_c).

Crops	Growing stages (days)				Total stage (days)	Crop growth stage coefficient (K_c)		
	Initial	Develop.	Mid-season	Late season		Initial	Mid-season	Late season
Wheat	20	30	50	30	130	0.55	1.15	0.30
Maize	20	35	40	30	125	0.30	1.20	0.35
Barley	15	25	50	30	120	0.30	1.15	0.25
Tomato	30	40	45	30	145	0.60	1.15	0.80
Potato	25	30	45	30	130	0.50	1.15	0.75
Other vegetables	20	30	30	15	95	0.70	1.05	0.95
Clover	150	30	150	35	365	0.40	0.95	0.90
Date	140	30	150	45	365	0.90	0.95	0.95
Citrus	60	90	120	95	365	0.70	0.65	0.70
Grapes	150	50	125	40	365	0.30	0.70	0.45

Table 3 Monthly values of climatic parameters in 2011.

Month	Temperature (°C)		Humidity (%)	Wind (km/hr)	Sun shine (hrs)	Net radiation (MJ/m^2/day)	Rainfall (mm)
	Min	Max.					
January	3.5	14.9	50	8	6.3	11.9	9
February	6.2	18.2	37	8	7.5	15.3	3
March	9.9	22.8	32	9	7.4	17.8	8
April	16.1	28.5	25	9	8.5	21.5	14
May	20.7	33.1	16	7	9.6	24.2	0
June	24	36.8	14	8	10.3	25.5	2
July	26.1	38.4	13	8	10.9	26.2	0
August	25.8	38.5	14	7	10.2	24.2	0
September	23.9	37.3	16	7	8.8	20.3	0
October	18.2	32	27	6	7.6	16.1	10
November	10.9	22.5	45	7	8	14.1	4
December	4.9	16.9	58	6	6.1	11	8
Average	15.8	28.3	29	7	8.4	19	4.8

Table 4 Monthly values of climatic parameters in 2050.

Month	Temperature (°C)		Humidity (%)	Wind (km/hr)	Sun shine (hrs)	Net radiation (MJ/m^2/day)	Rainfall (mm)
	Min.	Max.					
January	5.8	17.2	50	8	6.3	11.9	17
February	8.5	20.5	37	8	7.5	15.3	0
March	12	24.9	32	9	7.4	17.8	6
April	18.4	30.8	25	9	8.5	21.5	10.4
May	22.9	35.3	16	7	9.6	24.2	0
June	26.4	39.2	14	8	10.3	25.5	2
July	28.9	41.2	13	8	10.9	26.2	0
August	29.2	41.9	14	7	10.2	24.2	2.4
September	27.4	40.8	16	7	8.8	20.3	7.2
October	21.4	35.2	27	6	7.6	16.1	11.5
November	13.6	25.2	45	7	8	14.1	2.2
December	7.3	19.3	58	6	6.1	11	8.2
Average	18.5	30.9	29	7	8.4	19	5.6

month. The monthly variation of ET_o indicates that time of planting can affect CWR significantly for a particular type of crop. In S2 scenario, minimum and maximum ET_o was predicted to be in the range of 2.8–11.5 mm/day. In December, ET_o was minimal (2.8 mm/day), while in July, it was maximum (11.5 mm/day). It increases gradually from about 3.2 mm/day in January to the peak value of about 11.5 mm/day in July. Then it decreases gradually to 2.8 mm/day in December. Comparison between S1 and S2 shows that ET_o increases from 10.9 to 11.5 mm/day in July from 2011 to 2050. The yearly average of ET_o was 6.9 mm/day in 2011, which was predicted to be 7.3 mm/day in 2050 (6% increase). The S3 and S4 scenarios are essentially the same to the S1 and S2 scenarios, respectively (Fig. 2). The results indicate that CWR may be the highest during April–August. and lowest during December–February (Fig. 2). In Al-Jouf, few crops are grown during the summer months (Table 1), which might consume proportionately more water (Table 5(a–d)). In addition, some crops can have their

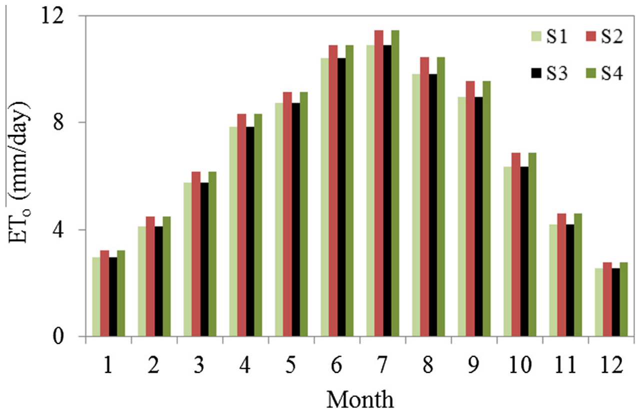

Figure 2 Change in evapotranspiration (ET_o) from 2011 to 2050) [1–12: January–December].

mid-season of growing stage during the summer months, which can have high values of K_c, leading to higher CWR. Shifting the mid-season of growing stage from the hot summer months may conserve water.

3.2. Effective rainfall

The effective rainfall was computed using the rainfall data in 2011 and the predicted data in 2050. The effective rainfall showed considerable monthly variation (Fig. 3). The maximum effective rainfall was 13.7 mm/month in April, whereas it was close to zero in May, July–September and between 2 and 10 mm/month in the other months. The total annual effective rainfall was estimated to be 57.1 mm, which is almost same as the total annual rainfall of 58 mm. The annual effective rainfall in 2050 has been predicted to be approximately 65.8 mm/year. In predicting CWR, the effective rainfall in 2011 was used for S1 and S2 scenarios, whereas the expected effective rainfall in 2050 was used for S3 and S4 scenarios.

3.3. Crop water requirements (CWR)

The highest water demands for S1–S4 scenarios were in May (1481.9–1540.6 mm), while the lowest water demands were in December (363.1–399.3 mm) (Table 5). Total CWR for producing dates had the highest rate (2356.3 mm/year), followed by citrus fruits (1734.7 mm/year) and clover (1576.2 mm/year). The rank of water consumption rate of wheat was 7th from the top, while the gross cultivated area for wheat was approximately 71%, leading to the highest consumer of water in this region (Table 5a–d). CWR were predicted to be 873, 930, 874 and 931 MCM/year for S1–S4 scenarios, respectively. The S4 scenario will require approximately 58 MCM/year of additional water than the S1 scenario. The increase in CWR in S2 and S4 scenarios was almost similar, possibly due to insignificant change in rainfall (e. g., S3 scenario). CWR for winter wheat were predicted to be 476, 507, 480 and 510 MCM/year for S1–S4 scenarios, respectively (Tables 5a–d). The findings indicate that CWR for wheat can be affected due to temperature increase in 2050. The difference between the S4 and S1 scenarios is approximately 34 MCM, indicating an increase of CWR for wheat by 34 MCM from 2011 to 2050. For vegetables, CWR for potato were more than the CWR for tomato and other vegetables (Fig. 4). CWR for all vegetables were approximately 34, 36, 34 and 36 MCM/year for S1–S4 scenarios, respectively. Increase in CWR for vegetables is approximately 2 MCM from 2011 to 2050. CWR for fodder crop were predicted to be 188, 201, 187 and 200 MCM/year for the S1-S4 scenarios, respectively. Increase in CWR for the fodder crop was approximately 13 MCM from 2011 to 2050. CWR for date were more than the CWR for grapes and citrus (Fig. 5). CWR for date were approximately 129, 137, 128 and 137 MCM/year for S1–S4 scenarios. The increase in CWR for date is 8 MCM from 2011 to 2050. In Al-Jouf, CWR for wheat, clover and date were estimated to be 54.6%, 21.5% and 14.8% of total CWR, respectively. The other crops (e.g., maize, barley, vegetables) also need 2–19 MCM/year of water, representing about 9.1% of the estimated CWR (Fig. 6).

3.4. Sensitivity analysis

The Al-Jouf region experiences temperature driven higher ET_o, ET_c and CWR rates in May–September, while in December–February, these values are likely to be the lowest. The crops, which are produced during May–September and/or have the mid-seasons of growing stages during these months, are likely to consume proportionately more water. For example, rates of CWR for dates, citrus fruits and clover were much higher during the summer months than the other months (Table 5). It is anticipated that there might be a scope to reduce CWR for these crops by shifting their growing periods fully or partially, to shift the mid-seasons of growing stages away from the summer months (e.g., May–September). In Al-Jouf, the highest amount of area is used for cultivating winter wheat followed by clover, dates, maize, potato and grapes (Table 1). Their growing seasons are: January–May, March–February, April–March, August–December, January–May and April–March, respectively (Table 1).

To better understand CWR, this study performed sensitivity analysis by shifting growing periods of the major crops. The growing periods for wheat was assumed to start from November till the end of January following past studies. A total of five additional scenarios were depicted as: Case I: (January 01–May 10); Case II: (December 15–April 23); Case III: (December 01–April 09); Case IV: (November 15–March 24) and Case V: (November 01–March 10). For the Cases I–V, CWR of wheat showed decreasing trends in the S1–S4 scenarios (Table 6). Case V showed the lowest levels of CWR in S1–S4 scenarios ranging from 249 to 272 MCM/year, indicating a possible conservation of 228–240 MCM/year of water (Table 6). Conservation of water for producing wheat in Case I through Case V was 59–63, 128–135, 175–185, 211–222 and 228–240 MCM/year, respectively. These conservations were corresponding to the shifts of wheat growing periods by 15, 30, 45, 60 and 75 days, respectively (Table 6). In S1 scenario, these conservations are 12%, 27%, 37%, 44% and 48% of CWR, respectively. The growing period for maize was shifted to October–February. Water conservation of maize was predicted to be 6–6.5 MCM/year. The growing seasons of potato were also shifted to November–March, indicating a conservation of 6.5–7.5 MCM/year of water. By shifting the growing

Table 5 Crop water requirements for different crops under various scenarios.

Crop	Monthly CWR (mm/month)												Total CWR	
	January	February	March	April	May	June	July	August	September	October	November	December	mm/year	MCM/year
S1 scenario (current temperature and rainfall)														
Wheat	25.8	92.5	211.5	266.1	134.9	–	–	–	–	–	–	–	730.8	476.2
Maize	–	–	–	–	–	–	–	49.1	168.0	231.0	145.0	22.8	615.9	13.4
Barley	104.0	72.7	–	–	–	–	–	–	–	–	50.3	84.6	311.6	2.5
Tomato	–	–	–	127.0	230.0	362.0	394.0	220.0	–	–	–	–	1333.0	9.2
Potato	23.1	77.1	205.0	267.0	197.0	–	–	–	–	–	–	–	769.2	14.1
Vegetables	–	–	124.0	223.0	291.0	28.9	–	–	–	–	–	–	666.9	10.7
Clover	83.9	109.0	64.3	79.8	109.0	122.0	135.0	231.0	263.0	185.0	122.0	72.2	1576.2	187.7
Dates	87.8	119.0	187.0	197.0	246.0	277.0	301.0	278.0	268.0	193.0	127.0	75.5	2356.3	128.9
Citrus	63.8	86.1	119.0	150.0	192.0	216.0	235.0	214.0	188.0	129.0	87.0	54.8	1734.7	12.6
Grapes	61.9	82.7	102.0	56.4	82.0	91.1	100.0	92.0	124.0	130.0	91.6	53.2	1066.9	17.4
Total	450.3	639.1	1012.8	1366.3	1481.9	1097.0	1165.0	1084.1	1011.0	868.0	622.9	363.1	11161.5	872.7
S2 scenario (changed temperature in 2050 and current rainfall)														
Wheat	28.5	100.8	226.1	282.5	140.3	–	–	–	–	–	–	–	778.2	507.1
Maize	–	–	–	–	–	–	–	52.2	178.0	248.0	158.0	25.3	661.5	14.4
Barley	114.0	79.3	–	–	–	–	–	–	–	–	55.2	92.9	341.4	2.7
Tomato	–	–	–	135.0	239.0	379.0	414.0	233.0	–	–	–	–	1400.0	9.7
Potato	25.6	84.0	220.0	283.0	205.0	–	–	–	–	–	–	–	817.6	15.0
Vegetables	–	–	133.0	237.0	302.0	30.3	–	–	–	–	–	–	702.3	11.2
Clover	92.1	118.0	69.2	85.4	114.0	128.0	142.0	245.0	279.0	199.0	133.0	79.4	1684.1	200.5
Dates	96.1	129.0	200.0	209.0	256.0	291.0	317.0	295.0	285.0	208.0	138.0	82.8	2506.9	137.1
Citrus	70.0	93.5	127.0	160.0	199.0	225.0	246.0	226.0	199.0	139.0	94.7	60.3	1839.5	13.4
Grapes	68.0	89.9	110.0	60.6	85.3	95.6	105.0	97.6	131.0	140.0	100.0	58.6	1141.6	18.6
Total	494.3	694.5	1085.3	1452.5	1540.6	1148.9	1224.0	1148.8	1072.0	934.0	678.9	399.3	11873.1	929.8
S3 scenario (changed rainfall in 2050 and current temperature)														
Wheat	22.2	95.6	213.6	269.5	134.9	–	–	–	–	–	–	–	735.8	479.5
Maize	–	–	–	–	–	–	–	47.5	161.0	229.0	146.0	23.2	606.7	13.2
Barley	95.9	75.7	–	–	–	–	–	–	–	–	52.0	84.3	307.9	2.5
Tomato	–	–	–	130.0	230.0	362.0	394.0	218.0	–	–	–	–	1334.0	9.2
Potato	19.5	80.1	207.0	270.0	197.0	–	–	–	–	–	–	–	773.6	14.2
Vegetables	–	–	126.0	226.0	291.0	28.9	–	–	–	–	–	–	671.9	10.8
Clover	76.3	112.0	66.4	83.3	109.0	122.0	135.0	229.0	256.0	183.0	123.0	71.9	1566.9	186.6
Dates	80.2	122.0	189.0	200.0	246.0	277.0	301.0	276.0	261.0	191.0	128.0	75.2	2346.4	128.3
Citrus	56.2	89.1	121.0	153.0	192.0	216.0	235.0	212.0	181.0	128.0	88.6	54.5	1726.4	12.6
Grapes	54.3	85.7	105.0	59.9	82.0	91.2	100.0	89.5	117.0	128.0	93.4	52.8	1058.8	17.2
Total	404.6	660.2	1028.0	1391.7	1481.9	1097.1	1165.0	1072.0	976.0	859.0	631.0	361.9	11128.4	874.1
S4 scenario (changed temperature and changed rainfall in 2050)														
Wheat	24.9	103.7	228.3	286.0	140.3	–	–	–	–	–	–	–	783.2	510.3
Maize	–	–	–	–	–	–	–	50.5	171.0	247.0	159.0	25.8	653.3	14.2
Barley	106.0	82.3	–	–	–	–	–	–	–	–	56.9	92.6	337.8	2.7

(*continued on next page*)

Table 5 (*continued*)

Crop	Monthly CWR (mm/month)												Total CWR	
	January	February	March	April	May	June	July	August	September	October	November	December	mm/year	MCM/year
Tomato	–	–	–	138.0	239.0	379.0	414.0	231.0	–	–	–	–	1401.0	9.7
Potato	21.9	87.0	222.0	287.0	205.0	–	–	–	–	–	–	–	822.9	15.1
Vegetables*	–	–	135.0	240.0	302.0	30.3	–	–	–	–	–	–	707.3	11.3
Clover	84.4	121.0	71.4	88.9	114.0	128.0	142.0	243.0	272.0	198.0	134.0	79.0	1675.7	199.5
Dates	88.5	132.0	202.0	213.0	256.0	291.0	317.0	292.0	278.0	206.0	140.0	82.5	2498.0	136.6
Citrus	62.4	96.5	129.0	163.0	199.0	225.0	246.0	223.0	192.0	138.0	96.4	60.0	1830.3	13.3
Grapes	60.4	92.8	112.0	64.1	85.3	95.6	105.0	95.0	124.0	139.0	102.0	58.2	1133.4	18.5
Total	448.5	715.3	1099.7	1480.0	1540.6	1148.9	1224.0	1134.5	1037.0	928.0	688.3	398.1	11842.9	931.4

* Vegetables: other vegetables.

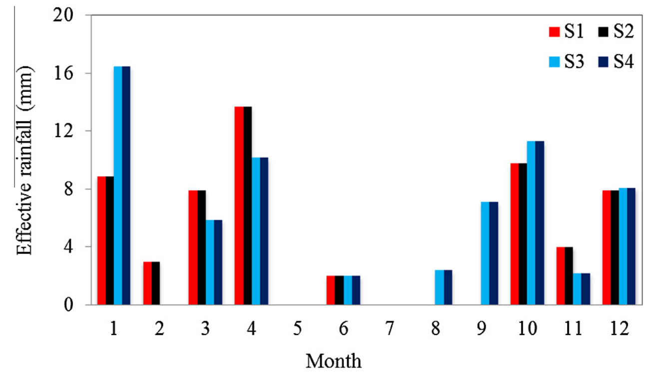

Figure 3 Change in effective rainfall from 2011 to 2050) [1–12: January–December].

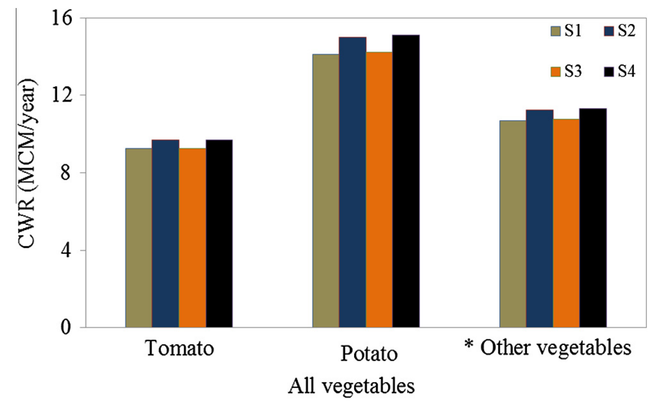

Figure 4 Crop water requirements (CWR) for all vegetables; *[marrow, eggplant, okra, carrot, dry onion, cucumber, melon, and watermelon].

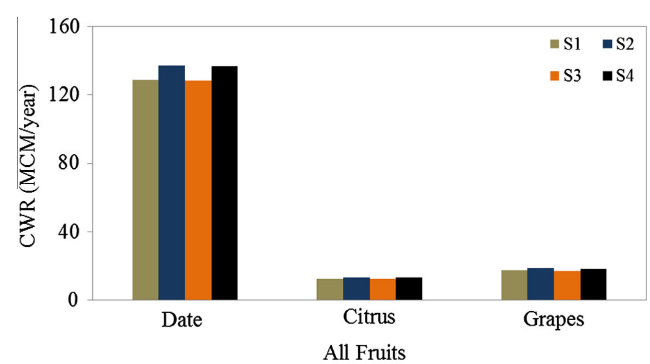

Figure 5 Crop water requirements (CWR) for all fruits.

seasons, these three crops may conserve approximately 240.5–254 MCM/year of water.

It is unlikely that shifting the growing season of each crop can conserve water. For example, the 2nd largest area in Al-Jouf is used for producing clover, which has the growing periods from January to December. Clover consumes much higher amount of water in summer than the other months (Table 5). A shift of growing period to November–October showed an increase of CWR by 50 MCM/year, meaning that this shift is not advisable. In addition, growing periods of

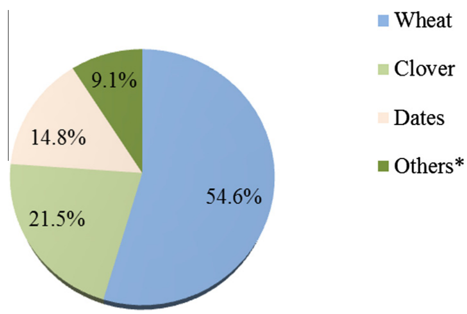

Figure 6 Percentage of crop water requirement for all crops in Al-Jouf region; *[maize: 1.5%; barley: 0.2%; vegetables: 3.9%; citrus: 1.5%; grapes: 2%].

clover of February 15–February 14 and February 01–January 31 may need additional water of 6.1–6.3 and 11.9–12.2 MCM/year. In contrast, growing period of March 15–March 14 and April 01–March 31 may save 3.1–3.2 and 7.6–7.9 MCM/year of water, respectively. Similar results were obtained for dates, showing insignificant change in CWR for the growing periods of April 01–March 31, March 15–March 14, March 01–February 28, April 15–April 14 and May 01–April 30.

The results showed demonstrative effects on CWR from temperature increase. To better explain the effects of temperature, sensitivity analysis was performed through increasing temperature by 0.5–5 °C. CWR of S1 scenario were increased from 873 to 995 MCM/year for an increase of temperature of 5 °C, which had a positive slope of 24.6 MCM CWR/°C. An increase in temperature by 1 °C increases the overall CWR by 2.9%. Further details on CWR changes due to temperature increase are shown in Table 7. CWR for winter wheat were increased by 3.0% per 1 °C increase in temperature, while CWR for clover were increased by 2.6% for 1 °C increase in temperature. For each type of crop, increase in temperature has shown increased level of CWR (Table 7). Minimizing the effects of temperature by alternative cultivation (e.g., greenhouse cultivation) may reduce overall CWR in Al-Jouf. It is to be noted that CWR were predicted assuming no change in the policy or current regulations on producing various crops in Al-Jouf. Any such change can affect these predictions. Further, shift of growing period for a crop must be verified with respect to crop yields, feasibility, fixed and operational costs, access to market and crop values. Future study must look into these factors prior to making any shift. In the absence of appropriate understanding on these factors, such shift may have detrimental effects on agricultural productions.

4. Summary and discussions

This study investigated possible implications of climate change on CWR in an arid agricultural region in Saudi Arabia. Changes in CWR from 2011 to 2050 in Al-Jouf were predicted. Al-Jouf is known to be an arid region with low annual rainfall and limited groundwater reserves, while a variety of crops are produced in this region. Four scenarios: (i) CWR at current state of temperature and rainfall (S1); (ii) CWR at the changed temperature in 2050 and current state of rainfall (S2); (iii) CWR at the changed rainfall in 2050 and current state of temperature (S3) and (iv) CWR at the changed temperature and changed rainfall in 2050 (S4) were investigated. The CROPWAT software was used in this study.

Table 6 Sensitivity analysis on CWR for variable growing periods of winter wheat.

Scenario	CWR (MCM/year)						Water conservation (MCM/year)				
	Current practice	Case I	Case II	Case III	Case IV	Case V	Case I	Case II	Case III	Case IV	Case V
S1	476.2	417.0	347.5	301.1	265.7	248.7	59.2	128.7	175.1	210.5	227.5
S2	507.1	447.1	375.2	326.6	289.7	272.1	59.9	131.9	180.5	217.4	235.0
S3	479.5	417.7	347.4	300.0	264.2	247.0	61.8	132.1	179.5	215.3	232.4
S4	510.3	447.8	375.1	325.5	288.1	270.4	62.6	135.3	184.9	222.2	240.0

Current practice: January 15–May 24; Case I: (January 01–May 10); Case II: (December 15–April 23); Case III: (December 01–April 09); Case IV: (November 15–March 24); Case V: (November 01–March 10).

Table 7 Sensitivity analysis on CWR for temperature variation.

Crop	Area (ha)	Current CWR	CWR (MCM/year) for temperature increase by 0.5 – 5°C									
			0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
Wheat	65,162	476	483	491	498	505	513	519	527	534	541	548
Maize	2179	13	14	14	14	14	14	14	15	15	15	15
Barley	801	3	3	3	3	3	3	3	3	3	3	3
Tomato	693	9	9	9	10	10	10	10	10	10	10	10
Potato	1837	14	14	15	15	15	15	15	16	16	16	16
Other vegetables	1601	11	11	11	11	11	11	12	12	12	12	12
Clover	11,908	188	190	193	195	198	200	202	205	207	209	212
Dates	5470	129	131	132	134	135	137	139	140	142	143	145
Citrus	727	13	13	13	13	13	13	14	14	14	14	14
Grapes	1628	17	18	18	18	18	19	19	19	19	20	20
Total	92,006	873	885	898	910	922	935	946	958	970	983	995

CWR were predicted for all listed crops produced in Al-Jouf. The major crops were wheat, maize, barley, tomato, potato, clover, dates, citrus and grapes, while these crops were produced in different growing seasons under variable climatic conditions. This study indicated that ET_o was in the range of 2.6–10.9 mm/day in 2011, which has been predicted to be in the range of 2.8–11.5 mm/day in 2050. Overall, 6% increase in ET_o from 2011 to 2050 was predicted. CWR were predicted to be 873–931 MCM/year for S1–S4 scenarios. CWR might be increased in the range of 5.3–9.6% from 2011 to 2050 for the same level of crop productions. The increase in CWR was mainly due to the increase in temperature. On an average, 1 °C increase in temperature may increase the CWR by 2.9% for this region. Increase in CWR for the same level of agricultural productions can pose an increased stress on the non-renewable groundwater resources in Al-Jouf. Assuming that the increase in temperature from 2011 to 2050 follows linear pattern, the rate of CWR increase was 1.5 MCM/year. In terms of wheat production, approximately 2430 m^3 of water is needed to produce 1 ton of wheat, meaning that approximately 600 tons of wheat can be produced by 1.5 MCM of water. If water supply is maintained at the same level, wheat productions may need to be reduced by approximately 600 tons per year. In Saudi Arabia, the yield of wheat production is approximately 5.4–5.7 tons/hectare, meaning that 105–111 hectares agricultural land has to be abandoned every year.

Sensitivity analysis by shifting crop planting dates demonstrates that a shift in crop producing periods might have implications on CWR. This study demonstrates that the shift in wheat production period by 15, 30, 45, 60 and 75 days might decrease the CWR by 12%, 27%, 37%, 44% and 48%, respectively. This is also applicable to some other crops. Such as, shift of maize and potato by 60 and 70 days might reduce CWR in the range of 46–49%. However, shift of crop producing periods cannot be performed in a straight forward way. The other factors, such as changes in the crop yields, feasibility, fixed cost and marketing have to be considered prior to make a shift of crop producing periods. Sensitivity analysis on temperature shows that CWR increase with the increase in temperature. Such increase might be better controlled through introducing greenhouse cultivation. Some regions in Saudi Arabia have started greenhouse cultivation. Future study should investigate feasibility of full and/or partial greenhouse cultivation for some major crops.

This study tries to explain some effects of climate change on CWR in an arid region in Saudi Arabia. However, different arid regions show different behavior with respect to seasonal variability of rainfall, temperature change, agricultural activities, soil types and crop types. As an example, Al-Jouf is well known for agriculture in Saudi Arabia, while the Empty Quarter does not have significant agricultural activities. Such differences must be considered to interpret the results of this study for other regions. Despite few limitations, this study sheds a light on the possible implications of climate change on crop water requirements and its direct and indirect effects on water resources management. Future study must understand the overall implications of climate change in Saudi Arabia and investigate the possibility of scheduling and/or shifting crop producing periods.

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