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Water Resources Conservation in Agriculture: Sensitivity Analysis for Climate Change and Growing Seasons

Shakhawat Chowdhury and Muhammad Al-Zahrani

Department of Civil and Environmental Engineering, Water Resources Group,
King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia

Abstract: Conservation of groundwater resources is an issue in Saudi Arabia. Being the largest consumer of groundwater, agriculture sector is a concern in context to water conservation. The crop water requirements (CWR) can be affected by the crop growing seasons and climatic conditions. This study performed sensitivity analysis of climate change and growing seasons on CWR in Saudi Arabia. CWR was predicted to be 8713 and 9176 million cubic meters (MCM) in 2011 and 2050 respectively (for constant productions), representing an increase of 11.9 MCM per year, while such amount of water is needed to produce approximately 4900 tons of wheat per year. Increase of CWR was predicted to be in the ranges of 3.3 – 11.9%, 3.3 – 12.1% and 3.9 – 15.6% for dates, alfalfa and wheat respectively. Overall, 1°C increase in temperature increases CWR by 1.8 – 2.9%. The shift of growing seasons of the major crops may conserve 732 - 903 MCM water per year. CWR of wheat had an exponential decay relationship for a shift of up to 75 days earlier from the current growing period. The findings might be useful in developing strategies related to water conservation in agriculture.

Key words: Water conservation · Crop water requirements · Effects of temperature · Effects of growing seasons

INTRODUCTION

Crop production requires freshwater while this is a scarce resource in many arid countries [1]. The global water footprint related to crop production during 1996–2005 was estimated to be 7404 billion cubic meters (BCM) per year [2]. The demands for agricultural water can be greatly affected by the total volume of consumption, consumption pattern, efficiency of agricultural practices and climatic conditions [3]. Higher temperature can lead to higher evaporative demand, leading to the higher water requirement per unit of crop production [4, 5]. Saudi Arabia is an arid country with low annual rainfall, limited groundwater reserves and harsh climate [6, 7]. The country produces different types of crops, including wheat, alfalfa, dates, maize, vegetables, grapes and citrus [6, 8]. Wheat is the most important crop for food security of the country [9]. Agriculture in Saudi Arabia relies on the availability of seasonal water, surface water stored through dam reservoirs, valley basins, treated wastewater and shallow/deep aquifers, while most of the water comes from non-renewable groundwater sources [7, 9]. Recent studies have indicated that usual practices of cultivation might have detrimental effects on groundwater reserves in future [10, 11]. To avoid such implications, the country has adopted a policy to lower freshwater withdrawals from the non-renewable sources by reducing agricultural activities and introducing advanced irrigation practices. For example, in 2005-2009, approximately 2.65, 2.63, 2.56, 1.99 and 1.15 million tons (MT) of wheat, respectively, were produced in the country [6]. The policy on reducing freshwater withdrawals by reducing agricultural activities can have negative effects on future agriculture [6].

Further, harsh climate can intensify the stress on agricultural water demands. Past studies have predicted 1.8 - 4.1°C and 2.5 - 5.1°C increase in temperature in the country by 2050 and 2070–2100 respectively, which can increase reference evapotranspiration (ETo) by 10.3 - 27.4% [5, 12]. The evaporative demands of crops greatly depend on growing seasons, temperature and type of the crop [4, 10]. For example, water demands for wheat, vegetables and fodder crops in Saudi Arabia were reported to be 13173, 18000 and 39000 m^3 per hectare

Corresponding Author: Shakhawat Chowdhury, Department of Civil and Environmental Engineering,
Water Resources Group, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia.
Tel: +966-13-860-2560; E-mail: schowdhury@kfupm.edu.sa.

respectively [10]. Al-Omran and Shalaby [13] estimated CWR for wheat, maize, tomato, citrus and dates as 883, 751, 1703, 2259 and 4021 mm/yr, respectively, for the Eastern and Central regions of Saudi Arabia. Saif *et al*. [14] reported CWR for alfalfa, potato and wheat as 34864, 6522 and 6473 m^3/ha/season respectively, in Al-Jouf, Saudi Arabia. CWR in Makkah were predicted as 727.8, 518.5, 452.6 and 1922.5 mm/yr for millet, wheat, maize and alfalfa respectively [15]. The crops produced in summer are likely to have more CWR than that of winter [4], due mainly to higher temperature and lower rainfall.

Analysis of sensitivity on CWR for climate change and growing seasons is important to better manage water resources. In this study, CWR were predicted for the commonly grown crops in two cases of climatic scenarios: (i) climatic conditions at 2011 (Case I); and (ii) the forecasted climatic scenario in 2050 (Case II). Effects of temperature change on CWR were investigated. The growing periods of major crops were differed and CWR were predicted. Effects of such shifts on water conservation was predicted. Finally, strategies to conserve groundwater were outlined.

MATERIALS AND METHODS

Data Collection: CWR depends on climatic conditions, crop area and type, soil type and growing seasons [4, 16, 17]. Data on temperature, wind speed, sunshine periods, humidity, rainfall, soil type, cultivated area and growing period were obtained from literature [6, 8, 18, 19]. Changes of temperature and rainfalls between 2011 and 2050 were obtained from Chowdhury and Al- Zahrani [5]. The data were reported for different grids spaced at 2.5° Latitude by 3.75° Longitude, which were adjusted for different regions using linear interpolation [20]. Data on crops and cultivated areas were obtained from Saudi Statistical Yearbook [6].

Predicting CWR: CROPWAT software predicts CWR through estimating reference evapotranspiration (ETo) and crop evapotranspiration (ETc) using the Penman-Monteith method [4, 21]. It assists in developing irrigation water management strategy. The Penman-Monteith method has been recommended by the Food and Agriculture Organization (FAO) for its appropriate combinations of relevant climatic parameters to predict ETo [22, 23]. CWR was estimated for each crop and added through irrigation scheme planning to predict total water requirements. The ETc is predicted on decadal basis (e.g., 10 days) following:

$$ET_c = ET_o \times K_c \quad (1)$$

where, ETc = actual evapotranspiration of crop (mm/day), ETo = reference evapotranspiration (mm/day); Kc = crop coefficient at a specific growth stage. Kc depends on the type of crop (e.g., albedo, height, resistance of canopy), soil and climatic parameters, such as, soil surface, evaporation and wind speed and direction [4, 22]. Kc varies over the crop growing period resulting in variable CWR at different stages of growth [4, 22]. The Penman-Monteith method can be presented as:

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

where, R_n = net radiation at 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); u2 = wind speed at 2 m height (m/s); es = saturation vapor pressure (kPa); ea = actual vapor pressure (kPa); Δ = slope of vapor pressure curve (kPa/°C); and γ = psychrometric constant (kPa/°C). The effective rainfall plays an important role in quantifying CWR. The effective rainfall can be estimated following literature [24, 25] as:

$$P_{eff} = P_{tot} \frac{125 - 0.2P_{tot}}{125} \quad (3)$$

where, Peff = effective rainfall (mm) and Ptot = total rainfall (mm). Equation 3 is valid for a rainfall of Ptot < 250 mm, which satisfies the rainfall conditions in Saudi Arabia [6]. The monthly agricultural water requirement is predicted as:

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

where, Q = monthly agricultural water requirement of irrigation scheme (m^3/day); *i* = crop index; Ai = crop area (hectare); ETc*i* = crop evapotranspiration (mm/day); Peff = the effective rainfall (mm/day) and 10 conversion factor [24]. Further details on the Penman-Monteith method can be found in Allen *et al*. [4].

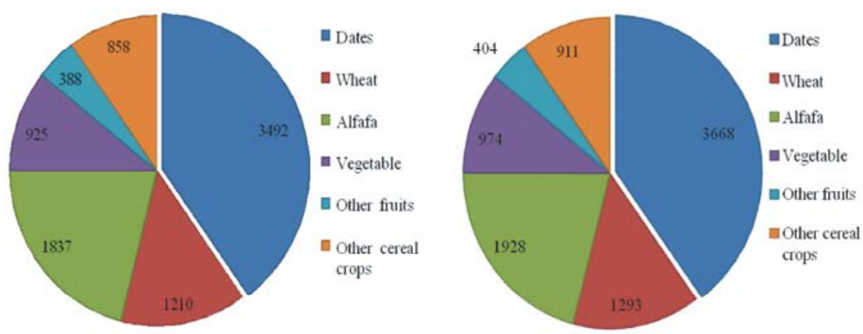
RESULTS AND DISCUSSIONS

Input Data: Annual average temperature in 2011 varied between 11.8 and 34.5°C in different regions. Overall range of temperature in 2011 was 3 - 42.8°C, while the range of predicted temperature in 2050 is 5.5 - 45.9°C. Increase in temperature from 2011 to 2050 was reported to be 1.8 – 4.1°C [5]. In 2011, total annual rainfall varied in the range of 49 - 264 mm/yr with an average of 123 mm/yr.

Table 1: ETo in 2011 and 2050 for each region in Saudi Arabia (mm/day)

Month	Riyadh		Makkah		Madinah		Qaseem		Eastern Region		Aseer		Tabouk		Hail		Jazan		Najran		Al-Baha		Al-Jouf	
	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II
Jan	3.3	3.5	4.6	5	3.5	3.7	2.8	3.1	2.2	2.4	3.5	3.8	2.8	3	2.6	2.8	4.3	4.6	4.4	4.7	3.8	4.1	3	3.2
Feb	4	4.3	5.3	5.7	4.5	4.7	3.8	4	3.2	3.4	4.1	4.4	3.6	3.9	3.7	4	4.8	5.1	5	5.3	4.9	5.2	4.1	4.5
Mar	5.4	5.7	5.6	6	6.4	6.7	5.3	5.6	4.3	4.5	4.7	5	5	5.4	5	5.3	6.1	6.5	6.4	6.7	6.2	6.6	5.8	6.2
Apr	7.5	7.9	6.5	6.9	8	8.4	7	7.4	5.4	5.7	5.5	5.8	7.3	7.7	6.4	6.8	6.5	6.9	6.6	6.9	6.9	7.3	7.8	8.3
May	9	9.3	7.1	7.5	8.9	9.2	8.8	9.2	7.1	7.5	5.9	6.3	7.4	7.8	7.7	8.1	6.8	7.1	8	8.3	7	7.3	8.7	9.1
Jun	10.9	11.4	7.5	8	9.1	9.5	9.5	9.9	8.7	9.1	6.2	6.2	8.2	8.5	8.8	9.2	7.3	7.8	8.6	8.9	7	7.3	10.4	10.9
Jul	10.7	11.2	7.6	8.1	9.6	10.1	9.6	10.1	8.7	9.2	6.1	6.5	8.6	9	9	9.5	7.3	7.9	7.7	8	7.5	7.9	10.9	11.5
Aug	9.7	10.2	7.5	8.1	8.9	9.3	8.6	9	8	8.5	5.6	5.9	8	8.4	8	8.5	7.2	7.8	7.4	7.7	7.7	8.1	9.8	10.4
Sep	8.5	9	6.8	7.4	7.4	7.8	7	7.4	6.7	7.1	6.3	6.8	7	7.5	7.3	7.7	7	7.6	8.1	8.6	7.3	7.8	9	9.5
Oct	6.3	6.8	5.1	5.6	6.2	6.6	6.3	6.8	5.2	5.6	5	5.4	5.6	6	5.6	6.1	5.8	6.4	5.1	5.4	6.3	6.8	6.4	6.9
Nov	3.9	4.2	4.7	5.1	4.9	5.3	4.4	4.7	3.5	3.8	3.7	4.1	3.5	3.8	3.7	4	5.1	5.6	5.2	5.5	4.6	5	4.2	4.6
Dec	3.2	3.4	4.5	4.8	3.5	3.7	3	3.2	2.5	2.8	3.2	3.5	2.5	2.7	2.6	2.8	4.4	4.8	4	4.3	3.6	3.8	2.6	2.8
Average	6.9	7.3	6.1	6.5	6.7	7.1	6.3	6.7	5.5	5.8	5	5.3	5.8	6.2	5.9	6.2	6.1	6.5	6.4	6.7	6.1	6.4	6.9	7.3

Case I: Current state (2011); Case II: (2050)



a. Case I (2011) b. Case II (2050)

Fig. 1: Distribution of CWR for different crops in Case I and Case II (MCM/yr) other cereal crops: (millet, sorghum, maize and barley); other fruits (e.g., citrus and grape).

The overall yearly rainfall have been predicted to increase in 2050 [5]. The distributions of cultivated lands and crops in different regions vary widely. The largest area was used for cultivating wheat, followed by dates and alfalfa, while the total cultivated area was highest in Riyadh, followed by Qaseem) and Al-Jouf. The growing periods and growth coefficients (Kc) for different crops are also variable. The planting dates and growing periods vary depending on the regions and type of crops. For example, the best planting dates of wheat starts from early Nov to the end of Jan and the growing period is approximately 130 days [18, 19, 26-29]. The growth stage with Kc$^{>}$ 1.0 indicates that the crop consumes more water than the corresponding ETo. The average monthly wind speeds vary in the range of 5.4 - 18 km/hr, while significant variability in wind speed was reported from region to region [16]. The annual average relative humidity ranged between 26 - 65% in all regions [16]. The net radiation was in the range of 18.2 - 19.8 MJ/m^2/day, with higher in summer than those in winter [16]. The Saudi Geological survey reported that the soil surface in most of the agricultural areas is sandy and sandy loam, which was characterized as light sand [32].

Reference Evapotranspiration: ET_o shows seasonal and regional variability (Table 1). In Riyadh, ET_o varies in the range of 3.2 – 10.9 mm/day (Case I). During May-Aug, it was 8.5 – 10.9 mm/day, while in the other months, this range was 3.2 – 7.5 mm/day (Table 1). Further, ET_o was much lower during Dec-Mar (3.2 – 5.4 mm/day). Higher ET_o in summer can be explained by higher temperature and lower rainfall in summer. It was higher in 2050 than that of the 2011 in all regions. Average ET_o in Riyadh was 6.9 mm/day in 2011 (Case I), which was predicted to be 7.3 mm/day in 2050 (Case II), representing an increase of 5.4%. Overall, ET_o was in the range of 2.2 – 10.9 mm/day in 2011, which was predicted to be 2.4 – 11.5 mm/day in 2050. On average, ET_o may be increased by approximately 6% from 2011 to 2050 in the country. The past results have also demonstrated higher levels of ET_o in future than the current levels of ET_o [5, 12].

Crop Water Requirements: Total CWR in the country were predicted to be 8713 and 9176 MCM/yr for Case I and Case II respectively (Fig. 1). CWR in Riyadh, Qaseem, Al-Jouf and Hail were higher with the values of 2803, 1426, 873 and 867 MCM/yr respectively (Case I). For Case II,

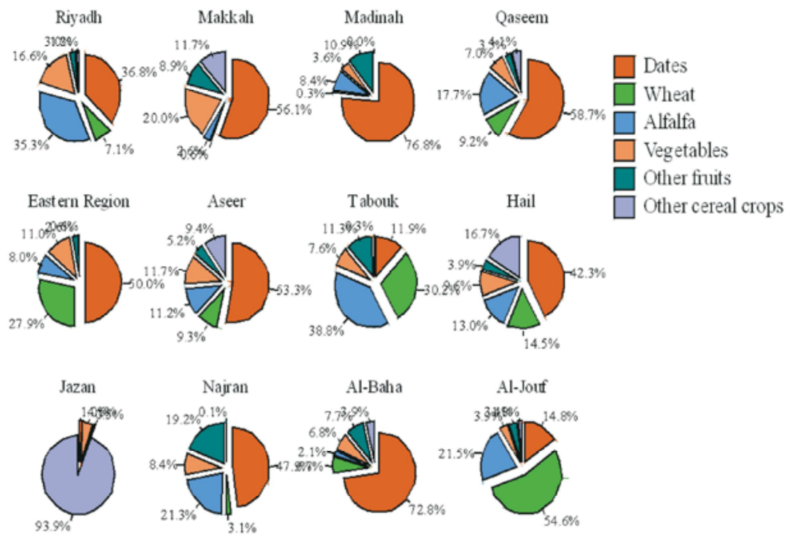


Fig. 2: Distribution of CWR (%) in different regions of Saudi Arabia for Case I; Other cereal crops are millet, sorghum, maize and barley; other fruits: citrus and grapes; Vegetables include all types of vegetables including tomato and potatoes.

Table 2: Total CWR for all crops produced in each region of Saudi Arabia in 2011-2050 (MCM/year)

Regions	Cereal Crops										Vegetables						Fodder and Fruits							
	wheat		Millet		Sorghum		Maize		Barley		Tomato		Potato		Other Vegetables		Alfalfa		Dates		Citrus		Grapes	
	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II	Case I	Case II
Riyadh	199.8	214.3	-	-	8.3	8.6	23.9	25	2.1	2.3	59.5	61.8	34.5	36.3	371	387.6	988.9	1038	1032	1085	61.2	64.3	21.6	22.7
Makkah	2.6	2.7	5.3	5.6	35.6	37.6	4.8	5.1	1.4	1.5	20.3	21.6	1.4	1.5	58.9	62.7	10.4	11	225.7	238.8	26.2	27.6	9.7	10.2
Madinah	1.4	1.5	0.01	0.01	-	-	0.01	0.01	0.04	0.05	12.5	12.9	0.02	0.02	7.8	8.2	46.8	48.7	428.8	447.9	12.6	13.2	48	49.9
Qaseem	131.6	139.6	-	-	-	-	57.7	60.5	0.1	0.1	11.1	11.6	34	35.9	54.7	57.2	252.3	263.6	837.2	877.6	32.2	31.8	14.9	15.6
Eastern Region	135.1	143.2	-	-	-	-	2.4	2.5	0.4	0.4	17.2	18.1	1	1.1	35.2	37.1	38.8	40.8	242.4	255.5	10.4	10.9	2.1	2.3
Aseer	13.5	14.6	0.2	0.2	10.2	10.6	1.1	1.1	2.2	2.3	11.3	11.5	0.4	0.4	5.3	5.6	16.3	16.7	77.6	80.2	3.5	3.6	4	4
Tabouk	117.1	121.3	-	-	-	-	0.2	0.2	0.8	0.8	1.1	4.5	20.5	21.6	7.7	8.2	150.3	156.5	46.1	48.2	27.8	28.9	15.9	16.5
Hail	125.5	137.4	-	-	-	-	143.7	150.8	0.9	1	6.8	7.1	48.1	51	28.7	30.1	112.7	119.6	367.2	390.1	18.8	20	14.9	15.8
Jazan	0	0	9.8	10.7	525.4	561.1	4.3	3.9	0.1	0.1	11.3	11.5	-	-	15.2	16.4	-	-	5.7	5.6	2.6	2.5	-	-
Najran	4.7	4.9	-	-	-	-	-	-	0.1	0.1	5.8	6	0.3	0.3	6.5	6.8	32.1	32.9	72	74.3	28.3	29.1	0.6	0.6
Al-Baha	2.6	2.8	0.01	0.01	0.5	0.5	0.7	0.7	0.3	0.3	1	1	0.04	0.05	1.6	1.6	0.8	0.8	28.2	28.3	0.6	0.6	2.4	2.4
Al-Jouf	476.2	510.3	-	-	-	-	13.4	14.2	2.5	2.7	9.2	9.7	14.1	15.1	10.7	11.3	187.7	199.5	128.9	136.6	12.6	13.3	17.4	18.5
Total	1210	1293	15.3	16.5	580	618.4	252.2	264.1	10.9	11.5	167.3	177.5	154.3	163.3	603.3	632.7	1837	1928	3492	3668	236.9	245.8	151.5	158.2

Case I: Current state (2011); Case II: (2050)

CWR in these regions were 2945, 1494, 931 and 923 MCM/yr respectively, indicating an increase of 4.8 – 6.6%. Similar increase was predicted for the other regions. The country wide CWR for dates, alfalfa and wheat were 3492, 1837 and 1210 MCM/yr respectively (Case I), representing 40, 21 and 14% of total CWR. CWR for other cereal crops, vegetables and fruits represent approximately 9.9, 10.6 and 4.5% of total CWR respectively. In case II, CWR for dates was 3668 MCM/yr, representing an increase of 5% from 2011, while CWR for alfalfa, wheat, other cereal crops, vegetables and fruits may be increased by 5, 6.9, 6.1, 5.2 and 4% respectively (Fig. 1ab).

The crop and region wise CWR are shown in Table 2. In case I, CWR for dates were 1032, 837 and 429 MCM/yr in Riyadh, Qaseem and Madinah respectively. The CWR for alfalfa were 989 and 252 MCM/yr in Riyadh and Qaseem respectively. In case of wheat, Al-Jouf had the highest CWR (476 MCM/yr), followed by Riyadh (200 MCM/yr). In addition, Qaseem, Tabouk, Hail and Eastern region had CWR for wheat in the range of 117 – 135 MCM/yr (Table 2). In Jazan, sorghum is the main crop (CWR: 525 MCM/yr), while maize is mainly produced in Hail (CWR: 144 MCM/yr). CWR for tomato is highest in Riyadh (60 MCM/yr), while CWR for potato is highest in Hail (48 MCM/yr).

The percentile distributions of CWR (Case I) are shown in Figure 2. CWR for dates had higher fractions in Riyadh, Makkah, Madinah, Qaseem, Eastern region, Aseer, Hail, Najran and Al-Baha. In Al-Jouf, CWR for wheat was highest (54.6%), while in Jazan, CWR for sorghum was highest 91.5% (Table 2). Riyadh is also the

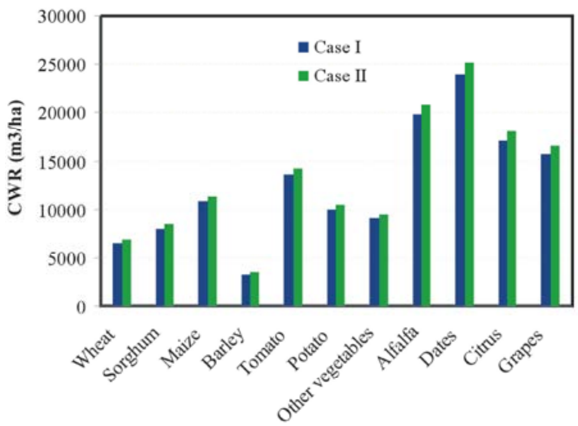


Fig. 3: CWR per 1 ha of cultivated land in Riyadh (Case I: 2011; Case II: 2050)

highest contributor of alfalfa, vegetables and some fruits. Al-Jouf and Riyadh are the main contributors of wheat, while significant amounts of wheat are also contributed from Qaseem, Eastern region, Tabouk and Hail (Table 2). Moderate supplies of some fruits (citrus and grapes) are obtained from Makkah, Madinah, Qaseem Tabouk, Hail, Najran and Al-Jouf.

Sensitivity Analysis for Temperature: Effects of temperature were investigated through sensitivity analysis by increasing temperature between 0.5 and 5°C, while the other factors were kept constant. CWR was increased from 8713 to 9716 MCM/yr for an increase of temperature of 5°C, which had a positive slope of 201 MCM CWR/°C. An increase of temperature by 1°C increases CWR by 2.3% (range: 1.8 - 2.9%) in the country. Averages of increase of CWR per 1°C are 2.3, 2.3 and 2.8% for dates, alfalfa and wheat respectively, while their ranges are 1.9 - 2.9%, 1.9 – 3.0% and 2.2 – 3.8% respectively.

Increase of temperature from 2011 to 2050 was predicted to be 1.8 - 4.1°C in Saudi Arabia [5], while such change might increase CWR of crops. To elucidate the effects of temperature increase in 2050, analysis was performed by considering the predicted temperature of 2050, while rainfall was kept constant to the level of 2011. Total CWR was estimated to be 9222 MCM/yr, indicating an overall increase of 5.8% (5.0 – 7.1%). CWR for wheat may be increased by 5.8 and 6.5% in Riyadh and Al-Jouf respectively. For dates, CWR may be increased by 5.5 and 5.8% in Riyadh and Qaseem respectively, while for alfalfa, increase in CWR is 5.5% for Riyadh. The effects were further analyzed in context to CWR per ha of cultivated lands in Riyadh (Fig. 3). In Case I, CWR for date, alfalfa and wheat were 23896, 19742 and 6467 m^3/ha respectively (Fig. 3), while for Case II, these values are 25203, 20803 and 6839 m^3/ha respectively. For the other crops, similar increase from Case I to Case II is anticipated (Fig. 3). The findings on CWR/ha of land were in moderate to strong agreement with some previous studies [10, 13-15]. It is to be noted that Al-Sheikh [10] reported the water demands for wheat, vegetables and fodder crops in Saudi Arabia as 13173, 18000 and 39000 m^3 per hectare respectively, where the authors have used the data of water supplies in the respective crop productions, while the water supplies might be significantly higher than the CWR [10].

An effort was also given to understand the values of water conservation in context to wheat production. Increase in CWR in Saudi Arabia was estimated to be 463 MCM/yr from Case I to Case II. Assuming linear increase, slope of increase in CWR was 11.9 MCM/yr from 2011. Approximately 2430 m^3 of water is needed to produce 1 ton of wheat, meaning that the increase in CWR is equivalent to water necessary for producing approximately 4900 tons of wheat per year. If water supply is maintained at the same level, wheat productions may need to be reduced by 4900 tons/year. In Saudi Arabia, yield of wheat is 5.4 - 5.7 tons/ha, meaning that 860 - 907 ha of wheat producing land has to be abandoned every year. It is to be noted that CWR were predicted assuming no change in the policy or current regulations on producing various crops in Saudi Arabia. Any change in policy can affect these predictions.

Sensitivity analysis for Growing Periods: This study performed sensitivity analysis by shifting growing periods of the main crops. The main crops are wheat, dates, alfalfa and sorghum, which are produced in 196, 162, 102 and 84 thousand ha of lands respectively. The growing season of wheat is Nov-May [33], while many regions plant wheat during Jan [14, 34]. Wheat needs approximately 130 days from planting to harvesting, meaning that wheat planted in Jan can be harvested during Apr - May, while ETo in Apr-May is relatively higher. Five scenarios of wheat growing periods: S1 (Jan 01 - May 10); S2 (Dec 15 - Apr 23); S3 (Dec 01 -Apr 09); S4 (Nov 15 - Mar 24); and S5 (Nov 01-Mar 10) were investigated to understand the effects of growing period. Table 3 presents the CWR for wheat in different growing periods. The current practice had CWR of approximately 1210 MCM/yr in the country, while the S1, S2, S3, S4 and S5 scenarios had CWR of 1046, 870, 757, 672 and 638 MCM/yr respectively. The data showed an

Table 3: CWR for wheat in different regions at various growing periods.

Regions	Current	S1	S2	S3	S4	S5
Riyadh	199.8	172.6	146.1	131.5	120.7	117.4
Makkah	2.6	2.4	2.3	2.1	2	1.9
Madinah	-	-	-	-	-	-
Qaseem	131.6	109.8	88	75.2	68.6	70
Eastern region	135.1	113.7	92.4	78.3	68.5	67.6
Aseer	13.5	12.8	12.2	11.8	11.8	12.1
Hail	125.5	108.3	90	77.8	65.2	56.5
Tabouk	117.1	102.8	85.7	73.3	63.2	58.2
Jazan	-	-	-	-	-	-
Najran	4.7	4.4	4	3.8	3.8	3.9
Al-Baha	2.6	2.4	2.2	2.1	2	2
Al-Jouf	476.2	417	347.5	301.1	265.7	248.7
Total	1208.7	1046.2	870.4	757	671.5	638.3

Current: Jan 15 - May 24; S1: (Jan 01 - May 10); S2: (Dec 15 - Apr 23); S3: (Dec 01 -Apr 09); S4: (Nov 15 - Mar 24); S5: (Nov 01 - Mar 10).

exponential relationship between CWR and planting periods. In Al-Jouf, Riyadh, Eastern region, Qaseem, Hail and Tabouk, the relationships can be presented through Equations (5-10) as:

$$Y_{AJF} = 467.8e^{-0.009X} \quad (5)$$

$$Y_{RYD} = 191.1e^{-0.007X} \quad (6)$$

$$Y_{ENR} = 129.3e^{-0.01X} \quad (7)$$

$$Y_{QSM} = 123.1e^{-0.009X} \quad (8)$$

$$Y_{HAL} = 125.8e^{-0.011X} \quad (9)$$

$$Y_{TBK} = 116.4e^{-0.01X} \quad (10)$$

where Y = CWR for wheat (MCM/yr); X = Shift of planting period (day) from Jan 15 (e.g., current practice) to an earlier date. This is to be noted that the above equations (5-10) was obtained through considering Jan 15 as the current planting date and maximum shifting period of 75 days earlier (e.g., Nov 01). However, any shift from the current planting date must be evaluated with respect to crop yields and technical feasibility.

Dates is a perennial crop with variable growing cycle. Past studies considered a growing cycle of Jan-Dec for Riyadh, Madinah, Makkah and Najran [30]. In Riyadh, CWR for dates was 1032 MCM/yr for the growing period of Dec 01-Nov 30. Four additional scenarios with growing cycles, S1: (Nov 15 - Nov 14); S2: (Nov 01 - Oct 31); S3: (Dec 15 - Dec 14); and S4: (Jan 01 - Dec 31) have CWR of 1037, 1044, 1022 and 1010 MCM/yr respectively. The change in CWR for a 30-day shift (backward or forward) was not significant. The growing cycles of Feb 01-Jan 31 and Mar 01-Feb 28 also found insignificant change in CWR for dates in Riyadh. In Qaseem, growing period for dates is Oct-Sep. Considering Oct 01-Sep 30 as the current growing cycle, four additional scenarios: S1 (Sep 15 - Sep 14); S2 (Sep 01 - Aug 31); S3 (Oct 15 -Oct 14); and S4 (Nov 01 - Oct 31) were assessed. CWR for the current practice and S1-S4 scenarios were predicted to be 837, 832, 832, 834 and 835 MCM/yr respectively. In the other regions, shifts in growing cycles were also investigated. However, changes in CWR were found to be insignificant. Future study may look into further details by varying planting date throughout the whole year.

Alfalfa is mostly produced in Riyadh, Qaseem, Al-Jouf and Tabouk with variable growing periods. In Riyadh, current growing period was Oct 01-Sep 30, which has the CWR of 989 MCM/yr. Four additional scenarios with growing cycles of S1: (Sep 15 - Sep 14); S2: (Sep 01 - Aug 31); S3: (Oct 15 -Oct 14); and S4: (Nov 01 - Oct 31) have CWR of 978, 952, 996 and 986 MCM/yr respectively. In Qaseem, CWR was 252 MCM/yr for the current practice, while in the S1-S4 scenarios, CWR were 251, 246, 255 and 252 MCM/yr respectively. In both regions, shifting planting periods by 15 and 30 days earlier has shown reduced CWR. Future study may look into further details by varying the planting date throughout the year. In Jazan, sorghum is the main crop, which has a growing cycle of Apr- Aug. For the growing period of Apr 15 - Aug 17 (125 days), CWR was 525 MCM/yr. For the shifted growing periods of S1: (Apr 01 - Aug 03); S2: (Feb 01 - June 05); S3: (Jan 15 -May 19); S4: (Jul 01 - Nov 02); and S5: (Jul 15 - Nov 16), CWR were 518, 457, 430, 490 and 468 MCM/yr respectively. The lowest CWR was predicted for S3: (Jan 15 -May 19), which might be due to the shift of mid-season growing stage from the summer months toward the winter months.

Table 4: Water supplies and CWR for different regions in 2011 (values in MCM)

Regions	Water Supply	CWR	Water loss	% Loss
Riyadh	3786.4	2802.5	983.9	26.0
Makkah	797.3	402.3	395.0	49.5
Madinah	896.4	558.0	338.4	37.7
Qaseem	2105.7	1425.9	679.8	32.3
Eastern Region	843.6	485.0	358.6	42.5
Aseer	324.1	145.6	178.5	55.1
Tabouk	678.8	390.6	288.2	42.5
Hail	1252.0	867.3	384.7	30.7
Jazan	1889.0	574.3	1314.7	69.6
Najran	233.4	150.4	83.0	35.5
Al-Baha	111.1	38.8	72.3	65.1
Al-Jouf	1398.3	872.7	525.6	37.6

Table 5: Water conservation through hypothetical scenarios of shifted growing seasons (MCM/yr)

		Growing Periods		CWR - Case I			CWR - Case II		
Regions	ShiftedCrops	Before shifting	After shifting	Before shifting	After shifting	Water conservation	Before shifting	After shifting	Water conservation
Riyadh	WheatAlfalfa Dates	Jan 15Oct 01Dec 01	Nov 01Sep 01Jan 01	2802.5	2661.4	141.1	2945.4	2797.6	147.8
Makkah	DatesWheat	Aug 01Jan 15	Sep 01Nov 01	402.3	400.3	2	425.8	423.6	2.2
Madinah	DatesGrapes Alfalfa	Oct 01Mar 01Oct 01	Nov 01Apr 01Nov 01	558	552.8	5.2	582.4	576.9	5.5
Qaseem	Wheat AlfalfaDates	Jan 15Oct 01Oct 01	Nov 01Sep 01Sep 01	1425.9	1351.5	74.4	1493.6	1413.2	80.4
Eastern Region	WheatDates	Jan 15Aug 01	Nov 01Sep 01	485	415.7	69.3	511.9	435.4	76.5
Aseer	WheatDatesAlfalfaSorghum	Jan 15Aug 01Oct 01Apr 15	Nov 01Sep 01Sep 01Jan 15	145.6	139.9	5.7	150.6	144.8	5.8
Tabouk	WheatAlfalfaDates	Jan 15Oct 01Oct 01	Nov 01Nov 01Nov 01	390.6	327.4	63.2	406.6	338.2	68.4
Hail	Wheat, AlfalfaDates	Jan 15Oct 01Oct 01	Nov 01Sep 01Nov 01	867.3	793	74.3	923	843.2	79.8
Jazan	sorghum	Apr 15	Jan 15	574.3	516.8	57.5	611.8	426.5	185.3
Najran	Wheat, AlfalfaDatesCitrus	Jan 15Oct 01 Oct 01Mar 01	Nov 01Sep 01Nov 01Mar 15	150.4	147.9	2.5	154.9	152.3	2.6
Al-Baha	WheatDates	Jan 15Aug 01	Nov 01Sep 01	38.8	38	0.8	39.1	38.2	0.9
Al-Jouf	WheatDatesAlfalfa	Jan 15Apr 01Mar 01	Nov 01Mar 01Feb 01	872.7	637.2	235.5	931.4	683	248.4
Total	8713.4	7981.9	731.5	9176.4	8272.8	903.6			

Case I: Current state (2011); Case II: (2050)

Strategy for Water Conservation: Total CWR in Saudi Arabia was predicted to be 8713 MCM/yr in 2011 (Case I). The Ministry of Economy and Planning (MOEP) reported that the agricultural water use in 2009 was 15464 MCM, which has been projected to be 12794 MCM in 2014, indicating a decrease of 3.7% per year [9]. At this rate, agricultural water use in 2011 was estimated to be 14,300 MCM, which is 5,587 MCM more than the predicted CWR (e.g., 39% water loss). The agricultural water supplies, predicted CWR in different regions and possible loss of water are shown in Table 4. Water loss in different regions was in the range of 26 - 69.6%, with the highest in Jazan (1315 MCM/yr), followed by Riyadh, Qaseem and Al-Jouf respectively (Table 4). The loss of water may be due to leakage in the water distribution systems, evaporation, water percolation through soil and inefficient irrigation practices. The data in the US Environmental Protection Agency (USEPA) showed that the loss through leakages in the water distribution systems might be significant and could negatively affect the yearly revenue [31]. Percolation of water through sandy soil might be significant, which could have a role on the higher agricultural water demands. Approach to minimize such percolation might assist in reducing water loss. Further, efficient irrigation practices could save water. Future study through incorporating water supplies, demands and water losses through multiple pathways may assist in conserving groundwater.

Table 5 summarizes water conservation based on the hypothetical periods of shifted growing seasons of the main crops in each region. Total CWR for shifted growing periods was estimated to be 7982 MCM/yr (Case I), which is 731 MCM less than the current practice (Table 5). Water conservation was estimated to be the highest in Al-Jouf, followed by Riyadh, Qaseem and Hail. In Case II, total water conservation is approximately 903 MCM/yr.

Water conservation was further investigated in context to the major crops. In Case I, shifting the planting date of wheat to Nov 01 can save 572 MCM/yr of water, which is 78% of the total water conservation (e.g., 731 MCM/yr). In Case II, this conservation was estimated as 612 MCM/yr out of 904 MCM/yr total (68%). The shifts for the other crops (planting time as of Table 5) may conserve some additional water. Another option might include relocating crops from the regions of higher CWR to the regions of lower CWR per unit production. For example, CWR for producing one ton of wheat might be different in Al-Jouf, Riyadh and Qaseem. Future study might investigate this strategy for water conservation. It is to be noted that the shift must be verified in context to yields, economic viability and technical feasibility.

In addition, reuse of treated wastewater (TWW) can enhance agricultural productions. Recent study reported that the production of domestic wastewater was more than 1500 MCM per year. Less than 50% of domestic wastewater is treated and a small fraction of TWW is reused. The untreated and the remaining TWW are discharged into wadies, sand dunes, Arabian Gulf and Red Sea. For example, the largest consumer of agricultural water is Riyadh, while Riyadh is also the producer of highest amount of domestic wastewater [9]. Future study may investigate cost and benefits of comprehensive reuse of TWW for agriculture in the major regions of Saudi Arabia.

CONCLUSIONS

This study performed sensitivity analyses on CWR for climate change and growing seasons. This research observed wide ranges of ETo with significant tempo-spatial variability among the regions. Effects of temperature on CWR were demonstrative, while such effects may be lowered by introducing greenhouse cultivation and/or shifting crop growing periods. 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.

Shift of growing periods for wheat may conserve significant amount of water. CWR for wheat were found to follow exponential decay pattern when planting dates were shifted from Jan to an earlier date, with the maximum shifting period of 75 days (e.g., Nov 01). Several strategies have been identified for further investigation, which might be useful in comprehensive management of water resources. For example, shifting growing periods of major crops, relocating the major crops from higher CWR/unit to lower CWR/unit regions, comprehensive reuse of treated wastewater for agriculture, minimizing water loss through efficient irrigation and conveyance systems, installation of leak detection devices, etc. Future research must investigate the related issues, such as, yields, product quality, technical feasibility and cost of productions prior to shifting. Despite limitations, this study sheds light on possible water conservation in agriculture sector through adopting appropriate irrigation technologies and growing periods.

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