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Effects of Temperature and Growing Seasons on Crop Water Requirement: Implications on Water Savings

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ABSTRACT: Water savings can be improved through reducing agricultural water consumption. The crop water requirement (CWR) depends on several factors including temperature and growing seasons. This study investigated the effects of temperature and growing seasons on CWR in Saudi Arabia. Increase in temperature by 1°C increased the CWR by 1.9 - 2.9%, 1.9 – 3.0% and 2.2 – 3.8% for dates, alfalfa and wheat respectively. Total CWR was estimated to be 8713 million cubic meters in 2011, which showed an increase of 1.8 – 2.9% for 1°C increase in temperature. CWR for wheat was more sensitive to growing seasons than dates and alfalfa. Empirical relationship was developed to predict the effects of growing seasons on CWR for wheat while changes in CWR for dates and alfalfa were not significant. Through shifting growing seasons and minimizing the effects of temperature for the major crops, significant amount of groundwater may be saved, which can reduce the production of costly desalinated water. © JASEM

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Keywords: Water resources; conservation; crop water requirement; temperature; growing seasons; policy;

Introduction

Increase in demands for food and energy crops have resulted in an increase in the demand for water around the globe (Rosegrant and Ringler, 2000; Liu *et al.*, 2008). Crop production consumes over 80% of global freshwater supplies (Shiklomanov, 2000). The global water footprint (WFP) for crop production was 7404 billion cubic meters (BCM) per year during 1996–2005, in which wheat, rice and maize consumed 1087, 992 and 770 Gm^3/yr of water respectively (Mekonnen and Hoekstra, 2010). The WFP for wheat, rice and maize were in the ranges 1805-1868, 1519-2102 and 1101-1229 m^3/ton respectively (Mekonnen and Hoekstra, 2010). The agricultural water demand is affected by the types and amounts of crops, efficiency of cultivation, length and timing of growing seasons and climatic conditions (Hoekstra and Chapagain, 2007). Higher temperature can have higher evaporative demand, leading to additional water requirement for crop production (Allen *et al.*, 1998; Chowdhury and Al-Zahrani, 2013a).

Saudi Arabia produces several crops, including wheat, alfalfa, dates, maize, vegetables, grapes and citrus (SSYB, 2012; MOA, 2012). Recent studies have indicated that the usual practices of cultivation might have detrimental effects on groundwater reserves (Al-Sheikh, 1998; FAO, 2009). The country has adopted a policy to reduce water withdrawals from the non-renewable sources by reducing agricultural activities and introducing modern irrigation practices (SSYB, 2012). Past studies have projected the increase of temperature in the ranges of 1.8° - 4.1°C and 2.5° - 5.1°C by 2050 and 2070–2100 respectively, which can increase reference evapotranspiration (ET_o) by 10.3 - 27.4% (Al-Zawad, 2008; Chowdhury and Al-Zahrani, 2013a). In addition, crop growing seasons and type of crop can affect water demands (Allen *et al.*, 1998; Al-Sheikh, 1998). For example, water demands for wheat, vegetables and fodder crops in Saudi Arabia were 13173, 18000 and 39000 m^3 per hectare respectively (Al-Sheikh. 1998). Al-Omran and Shalaby, (1992) estimated CWR for wheat, maize, tomato, citrus and dates in the Eastern and Central regions of Saudi Arabia as 883, 751, 1703, 2259 and 4021 mm/yr respectively. In the Wadi Sirhan, Al-Jouf (Saudi Arabia), Saifuddin *et al.*, (2004) reported CWR for alfalfa, potato and wheat as 34864, 6522 and 6473 m^3/ha/season respectively. CWR for millet, wheat, maize and alfalfa in Makkah were 728, 519, 453 and 1923 mm/yr respectively (Hashim *et al.*, 2012).

Understanding of the effects of temperature and growing seasons on CWR is important to manage water resources. This paper aims to analyze the effects of temperature and growing seasons on CWR for crops in different regions of Saudi Arabia. The growing seasons of the main crops were differed and CWR were predicted. Effects of such shifts were estimated. Empirical relationship was developed for water savings in producing wheat.

MATERIALS AND METHODS

Data Collection: Data on cultivated area and crops were obtained from the Saudi Statistical Yearbook (SSYB, 2012). Data on temperature, wind speed, sunshine periods, humidity and rainfall were obtained from the Ministry of Water and Electricity (MOWE, 2011, 2012). The crop growing seasons were obtained from literature (Alsadon, 2002; Alamoud *et al.*, 2012;

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JADCO, 2013; Abbas, 2013). The historical data on rainfall and temperature were obtained from the CLIMWAT database of Food and Agriculture Organization (FAO, 2012). The soil type in different regions was obtained from the Saudi Geological Survey (SGS, 2012). Further details on the data can be accessed from literature (Abbas, 2013).

Predicting CWR: CROPWAT 8.0 software predicts CWR and irrigation requirements using the Penman-Monteith method (Allen *et al*., 1998; FAO, 2013). It can be used to evaluate farmers' irrigation practices and to estimate crop performance under rain fed and irrigated conditions. It includes standard crop and soil data in the CLIMWAT database from more than 5000 stations worldwide, which is editable using the local data (FAO, 2013). The Penman-Monteith method has been recommended by the Food and Agriculture Organization (FAO) for its reasonable prediction of ET_o (Allen *et al*., 1998; Smith and Kivumbi, 2006; Mhashu, 2007). The actual evapotranspiration (ET_c) is predicted on 10-day basis following:

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

where, ET_c = actual evapotranspiration (mm/day), ET_o = reference evapotranspiration (mm/day); K_c = crop coefficient at a specific growth stage, which varies with growth stages (Allen *et al*., 1998; Smith and Kivumbi, 2006). The growing period is divided into four stages: initial, development, mid-season and late season. The initial stage spans from planting date to approximately 10% of ground cover and the development stage extends from 10% ground cover to effective full cover (e.g., initiation of flowering). The mid-season stage runs from effective full cover to the start of maturity (e.g., beginning of the ageing, yellowing, leaf drop or browning of fruit) while the late season spans from the start of maturity to harvest (Allen *et al*., 1998). The Penman-Monteith method can be presented as:

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

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); u_2 = wind speed at 2 m height (m/s); e_s = saturation vapor pressure (kPa); e_a = actual vapor pressure (kPa); Δ = slope of vapor pressure curve (kPa/°C); and γ = psychrometric constant (kPa/°C). In this method, ET_o is calculated for a reference surface, which is a hypothetical grass reference crop having crop height of 0.12 m, shading the ground and not short of water. The weather is measured at 2 m (or converted to that height) above the reference surface and a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23 are assumed. Further details on this method can be found in literature (Allen *et al*., 1998; Abbas, 2013). The effective rainfall, defined as the rainfall in excess of deep percolation and runoff, plays an important role in quantifying CWR. This water is stored in the root zone and can be used by the plants. The effective rainfall can be estimated following literature (e.g., Sheng-Feng *et al*., (2006); Molua and Lambi, (2006)) as:

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

where, P_{eff} = effective rainfall (mm) and P_{tot} = total rainfall (mm). Equation 3 is valid for a rainfall of P_{tot} < 250 mm/year. In Saudi Arabia, major parts of the country have yearly average rainfall lower than this (SSYB, 2012). The agricultural water demand is predicted as:

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

where, Q = CWR for all crops within the irrigation scheme (m^3/day); *i* = crop index; A_i = crop area (hectare: ha); ET_{ci} = crop evapotranspiration (mm/day); P_{eff} = effective rainfall (mm/day); and 10 = conversion factor from ha-mm/day to m^3/day. Further details on the Penman-Monteith method can be found in Allen *et al*., (1998).

RESULTS AND DISCUSSIONS

Input Data: The average temperature in 2011 varied between 11.8° - 34.5°C and the range was 3° - 42.8°C. Annual rainfall varied in the range of 49.1 - 264 mm/yr with an average of 123 mm/yr. Data on cultivated areas were available in literature (SSYB, 2012; Abbas, 2013). 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 K_c were obtained from literature (JADCO, 2013; Elnesr *et al*., 2013; Kader and Hussein, 2009; Al-Saif, 1999; Alsadon, 2002). Average wind speeds were 5.4 - 18 km/hr while the relative humidity was 26 - 65% (FAO, 2012). The net solar radiation was 18.2 - 19.8 MJ/m²/day, with higher in summer and lower in winter (FAO, 2012).

Crop Water Requirement (CWR): The ET_o in all regions were in the range of 2.2 – 10.9 mm/day with the average of 5.0 - 6.9 mm/day. The highest ET_o was in Riyadh and Al-Jouf in Jun-Jul (10.4 – 10.9 mm/day). In Riyadh, ET_o in different months varied in the range of 3.2 – 10.9 mm/day with an average of 6.9 mm/day. During May-Aug, ET_o were 8.5 – 10.9 mm/day while in Dec-Mar, ET_o were in the range of 3.2 – 5.4 mm/day. The total CWR in 2011 was estimated to be 8713 MCM (Figure 1). Riyadh had the highest CWR (2802 MCM), followed by Qaseem (1426 MCM), Al-Jouf (873 MCM) and Hail (867 MCM) respectively (Figure 1).

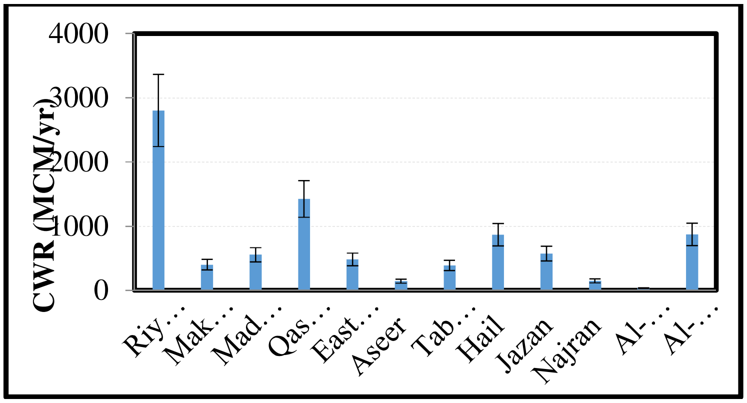

Fig 1. Predicted average CWR for each region in Saudi Arabia in 2011

The lowest CWR was estimated for Al-Baha (39 MCM). The crop and region wise distribution of CWR is shown in Table 1. Dates, alfalfa and wheat had about 75% of total CWR (dates: 40%; alfalfa: 21%; and wheat: 14%). Vegetables, fruits, sorghum and maize had CWR of 10.6, 4.5, 6.7 and 2.9% respectively. CWR for dates were 1032, 837 and 429 MCM in Riyadh, Qaseem and Madinah respectively. CWR for alfalfa in Riyadh, Qaseem and Al-Jouf were 989, 252 and 188 MCM respectively. For wheat, Al-Jouf had the highest CWR (476 MCM) followed by Riyadh (200 MCM). In Jazan, sorghum had CWR of 525 MCM while maize was mainly produced in Hail with CWR of 144 MCM. CWR for tomato was highest in Riyadh (60 MCM) while CWR for potato was highest in Hail (48 MCM).

Table 1. CWR for crops produced in Saudi Arabia in 2011 (MCM/year)

	wheat	Millet	Sorghum	Maize	Barley	Tomato	Potato	Other Vegetables	Alfalfa	Dates	Citrus	Grapes
Riyadh	199.8	-	8.3	23.9	2.1	59.5	34.5	371	988.9	1032	61.2	21.6
Makkah	2.6	5.3	35.6	4.8	1.4	20.3	1.4	58.9	10.4	225.7	26.2	9.7
Madinah	1.4	0.01	-	0.01	0.04	12.5	0.02	7.8	46.8	428.8	12.6	48
Qaseem	131.6	-	-	57.7	0.1	11.1	34	54.7	252.3	837.2	32.2	14.9
Eastern Region	135.1	-	-	2.4	0.4	17.2	1	35.2	38.8	242.4	10.4	2.1
Aseer	13.5	0.2	10.2	1.1	2.2	11.3	0.4	5.3	16.3	77.6	3.5	4
Tabouk	117.1	-	-	0.2	0.8	1.1	20.5	7.7	150.3	46.1	27.8	15.9
Hail	125.5	-	-	143.7	0.9	6.8	48.1	28.7	112.7	367.2	18.8	14.9
Jazan	0	9.8	525.4	4.3	0.1	11.3	-	15.2	-	5.7	2.6	-
Najran	4.7	-	-	-	0.1	5.8	0.3	6.5	32.1	72	28.3	0.6
Al-Baha	2.6	0.01	0.5	0.7	0.3	1	0.04	1.6	0.8	28.2	0.6	2.4
Al-Jouf	476.2	-	-	13.4	2.5	9.2	14.1	10.7	187.7	128.9	12.6	17.4
Total	1210	15.3	580	252.2	10.9	167.3	154.3	603.3	1837	3492	236.9	151.5

The percentile distribution of CWR are shown in Figure 2. CWR for dates had the highest percentage in Riyadh, Makkah, Madinah, Qaseem, Eastern Province, Aseer, Hail, Najran and Al-Baha. The regions of Riyadh, Qaseem, Hail and Madinah were the main contributors of dates. Riyadh was also the highest contributor of alfalfa, vegetables and fruits. In Al-Jouf, CWR for wheat was highest (54.6%), while in Jazan, CWR for sorghum, millet and maize was 93.5%, in which CWR for sorghum was 91.5% (Figure 2). Al-Jouf and Riyadh were the main contributors of wheat while significant amounts of wheat were also produced in Qaseem, Eastern Province, Tabouk and Hail. Makkah, Madinah, Qaseem Tabouk, Hail, Najran and Al-Jouf produced significant quantities of fruits (citrus and grapes).

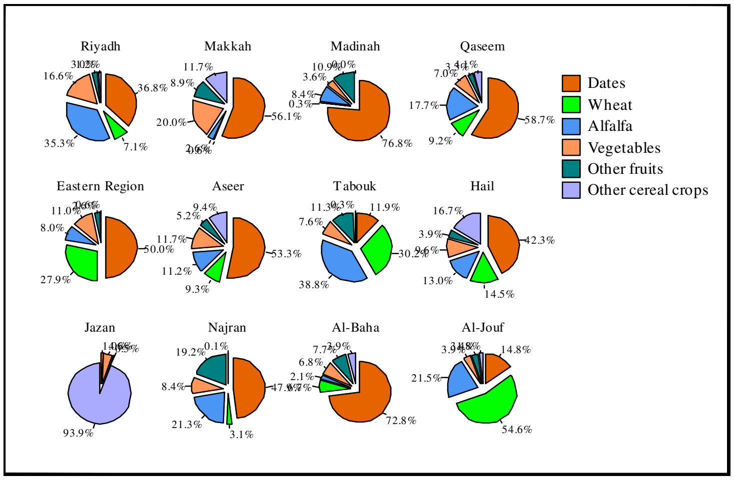

Fig 2. Distribution of CWR (%) in different regions of Saudi Arabia; Other cereal crops are millet, sorghum, maize and barley; other fruits: citrus, grapes (excludes dates); Vegetables include all types of vegetables including tomato and potatoes

Wheat, alfalfa and dates were the major crops consuming approximately 75% of CWR. CWR for these crops were further assessed for unit production. The yields of wheat, alfalfa and dates per hectare of lands varied in the ranges of 3.0 - 7.2, 16.2 - 23.1 and 4.7 – 10.4 tons respectively (SSYB, 2012). The average CWR for producing one ton of wheat, alfalfa and dates in different regions were predicted to be 1321, 862 and 3232 m^3/ton respectively while their ranges were (740 – 2017, 669 – 1097 and 1713 – 4316 m^3/ton respectively. The results demonstrate wide ranges of crop yields and CWR per ton of wheat, alfalfa and dates, indicating that appropriate allocations for crops in different regions may save groundwater resources. However, better understanding is needed on water availability, cost of water transport and crop yields.

Seasonal Variability of CWR : The CWR showed seasonal and regional variability (Figure 3). Monthly average CWR was 726 MCM with the range of 168 – 1364 MCM. CWR was highest in May-Jul (1310 – 1364 MCM/month) and lowest in Nov-Jan (168 – 231 MCM/month). Monthly average CWR was highest in Riyadh (234 MCM) followed by Qassim (119 MCM), Al-Jouf (73 MCM) and Hail (72 MCM) while the lowest CWR was in Al-Baha (3.0 MCM). In Riyadh, CWR was highest in Jun-Jul (489 - 494 MCM/month) while the lowest CWR was in Jazan during Oct-Jan (1.3 – 2.1 MCM/month). In Qaseem, CWR was highest in May-Jul (217 – 223 MCM/month) and lowest in Dec-Jan (24-33 MCM/month). In Al-Jouf, wheat was the main crop and it was grown in Jan-May, leading to higher CWR in Mar-Apr (164 – 205 MCM/yr).

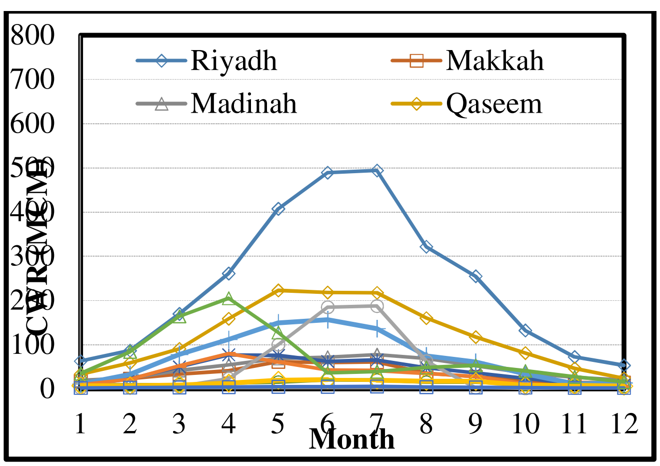

Fig 3. Seasonal variability of CWR in different regions of Saudi Arabia [1: Jan – 12: Dec]

Overall, CWR in summer (e.g., May-Jul) were much higher than in winter (e.g., Nov-Feb). Higher CWR in summer was possibly due to large amounts of crops produced in summer, low rainfall, growing stage with higher K_c and higher temperature. Production of dates and alfalfa in Riyadh can be the examples. The growing periods of these crops were Dec-Nov and Oct-Sep respectively while the mid-season of growing stage (e.g., higher values of K_c) was in summer. Interaction of ET_o at higher temperature and higher K_c increased CWR (Eq. 1). Shifting of the mid-season growing stage from summer to a lower ET_o season may reduce CWR and reduce water extraction from the non-renewable sources. However, interaction effects of ET_o at higher temperature and higher K_c needs better understanding to avoid any negative effect (e.g., crop yields, crop quality, etc.).

Effects of Temperature: Effects of temperature were investigated by increasing temperature in the range of 1° - 5°C and keeping the other factors constant. The total CWR was increased from 8713 MCM to 9716 MCM for 5°C increase in temperature, which showed an increase in CWR by 2.3%/°C. In different regions, rate of increase in CWR was estimated to be in the range of 1.8 – 2.9% for 1°C increase in temperature. The increase in CWR for temperature increase in different regions are shown in Figure 4. For 1°C, 3°C and 5°C increase in temperature, CWR increase were estimated to be 199, 606 and 1002 MCM respectively (Figure 4). Among different regions, Riyadh showed the highest increase in CWR (57.7 MCM), followed by Qaseem (31.4 MCM), Al-Jouf (24.9 MCM) and Hail (20.3 MCM) respectively (Figure 4).

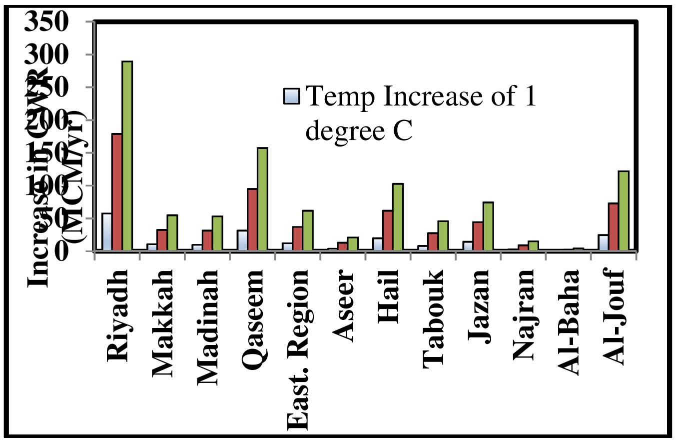

Fig 4. Effects of temperature increase on crop water requirements in different regions

Some past studies have reported possible increase in temperature in the range of 1.8 – 5.1°C by the end of this century. The Intergovernmental Panel on Climate Change (IPCC) have also reported similar increase in temperature in the Arabian Peninsula (IPCC, 2007). Such an increase may increase the total CWR by 4.1 – 12% for the same level of agricultural production. With respect to crops, wheat, dates and alfalfa were the main crops. Effects of temperature change on CWR for these crops were investigated further. Average increase of CWR for dates, alfalfa and wheat were 2.3, 2.3 and 2.8% for 1°C respectively while their ranges were 1.9 - 2.9%, 1.9 – 3.0% and 2.2 – 3.8% respectively. In this study, CWR for 1 hectare (ha) of dates, alfalfa and wheat producing lands were 23896, 19742 and 6467 m^3 respectively, which were consistent to past studies (Al-Sheikh, 1998; Al-Omran and Shalaby, 1992; Saifuddin *et al*., 2004). Increase in temperature can further increase CWR. In addition, temperature increase may also affect the crop yields, which may change CWR per unit production. Better understanding of the effects of temperature on crop yields may provide further insights.

Effects of Growing Period: The main three crops were wheat, dates and alfalfa, which were produced in 196, 162 and 102 thousand ha of cultivated lands respectively. The 4^{th} largest land area is for sorghum (84 thousand ha) (SSYB, 2012). The growing season of wheat is Nov-May (Mustafa *et al*., 1989) while few regions start wheat planting during January (Saifuddin *et al*., 2004; Almisnid, 2005). Wheat needs approximately 130 days from planting to harvesting, meaning that wheat planted in Jan is harvested in Apr – May, while ET_o in Apr-May is relatively higher than Nov-Mar. Five scenarios of wheat growing periods: S_1 (Jan 01 – May 10); S_2 (Dec 15 – Apr 23); S_3 (Dec 01 – Apr 09); S_4 (Nov 15 – Mar 24); and S_5 (Nov 01–Mar 10) were investigated. Table 2 shows the CWR for wheat in different growing seasons (S_1-S_5). The current practice had CWR for wheat of 1209 MCM while the S_1, S_2, S_3, S_4 and S_5 scenarios had CWR of 1046, 870, 757, 672 and 638 MCM respectively. The data showed an exponential relationship between CWR and planting dates, which were represented as:

$$Y = 1192.9e^{-0.00934X} \quad (5)$$

Where, Y = Overall CWR for wheat (MCM/yr); X = Shift of planting date (day) from Jan 15 to an earlier date. This is to be noted that equation 5 was obtained through considering Jan 15 as the current planting date and maximum shifting period of 75 days earlier (e.g., Nov 01). The regional analyses also showed exponential relationships.

Table 2. CWR for wheat in different regions at different growing periods

Regions	Current	S_1	S_2	S_3	S_4	S_5
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; S_1: (Jan 01 – May 10); S_2: (Dec 15 – Apr 23); S_3: (Dec 01 –Apr 09); S_4: (Nov 15 – Mar 24); S_5: (Nov 01 – Mar 10)

Dates is the main crop in nine regions (Figure 2). Riyadh, Madinah, Makkah and Najran have the growing cycle of Jan-Dec (Alamoud *et al*., 2012). For Dec 01-Nov 30 cycle, CWR in Riyadh was 1032 MCM. Four additional scenarios of growing cycles: S_1: (Nov 15 - Nov 14); S_2: (Nov 01 - Oct 31); S_3: (Dec 15 –Dec 14); and S_4: (Jan 01 – Dec 31) had CWR of 1037, 1044, 1022 and 1010 MCM respectively. In Qaseem, growing season was Oct-Sep. Four additional scenarios: S_1 (Sep 15 – Sep 14); S_2 (Sep 01 – Aug 31); S_3 (Oct 15 –Oct 14); and S_4 (Nov 01 – Oct 31) were also assessed. CWR for the current cycle and S_1-S_4 were 837, 832, 832, 834 and 835 MCM respectively. In the other regions, shifts in growing cycles were also investigated. However, changes in CWR were insignificant in these scenarios.

Alfalfa is primarily produced in Riyadh, Qaseem, Al-Jouf and Tabouk. In Riyadh, current growing period (Oct 01–Sep 30) had CWR of 989 MCM. Four additional scenarios with growing cycles of S_1: (Sep 15 - Sep 14); S_2: (Sep 01 - Aug 31); S_3: (Oct 15 –Oct 14); and S_4: (Nov 01 – Oct 31) had CWR of 978, 952, 996 and 986 MCM respectively. However, Qaseem region did not show significant change in CWR in these scenarios. Sorghum is the main crop in Jazan, which had a growing cycle of Apr-Aug. For growing period of Apr 15 – Aug 17 (125 days), CWR was 525 MCM. For the shifted growing periods of S_1: (Apr 01 – Aug 03); S_2: (Feb 01 – June 05); S_3: (Jan 15 –May 19); S_4: (Jul 01 – Nov 02); and S_5: (Jul 15 – Nov 16), CWR were 518, 457, 430, 490 and 468 MCM respectively. In context to total CWR in the country, shift of growing seasons was performed for the main crops in each region (Table 3). Total CWR for shifted growing seasons was estimated to be 7982 MCM, which was 731 MCM less than the current practice (Table 3). Water savings was estimated to be the highest in Al-Jouf, followed by Riyadh, Qaseem and Hail. Shifting of the planting date of wheat to Nov 01 might save 572 MCM of water, which was 78% of the total water savings (Table 2). For the shifted growing periods of dates, alfalfa, sorghum and grapes, 37, 61, 61 and 1 MCM of water could be saved. Future study should look into the implications of a shift on crop yields.

Policy Implications on Water Savings: The Ministry of Economy and Planning (MOEP), Saudi Arabia reported that agricultural water use in 2009 was 15464 MCM, which was projected to be 12794 MCM in 2014, indicating a decrease of 3.7%/yr (MOEP, 2010). At this rate, water supply for agriculture in 2011 was 14300 MCM, which was 5587 MCM more than the estimated CWR. It can be noted that few seasonal crops might have been produced in different regions (e.g., greenhouse cultivation), which were not included in this study, mainly due to data unavailability (SSYB, 2012). These crops need to be included to better estimate water loss. In Saudi Arabia, the type of soil is sandy and sandy loam (SGS, 2012) with high conductivity. Higher temperature in summer might also be responsible for increased water consumption in summer. In addition, the months of mid-season growing stages could have played significant role on CWR. Higher K_c for dates, alfalfa and wheat were noted for May-Oct, May-Sep and Apr-May respectively. In these months, ET_o were much higher and K_c were 0.95, 0.95 and 1.15 respectively, which have resulted in higher levels of CWR. Shifting the mid-season growing stages to the months with lower ET_o could save groundwater. With few hypothetical scenarios, possible water savings was estimated. To save groundwater, Saudi Arabia has taken few initiatives. Agricultural activity is being reduced (MOEP, 2010; SSYB, 2012; CSIS, 2011). It is to be noted that wheat is the main crop for food security in Saudi Arabia and the 3rd largest water consuming crop while the 1st and 2nd crops were dates and alfalfa respectively (SSYB, 2012). This study recommends using food security as a criterion under current regional political situation for future decision analysis on controlling agricultural activities.

Table 3. CWR before and after shifting growing seasons for the major crops and water savings

Region	Shifted Crops	Growing Periods		CWR (MCM)		
		Before shifting	After shifting	Before shifting	After shifting	Water savings
Riyadh	Wheat	Jan 15	Nov 01	2802.5	2661.4	141.1
	Alfalfa	Oct 01	Sep 01			
	Dates	Dec 01	Jan 01			
Makkah	Dates	Aug 01	Sep 01	402.3	400.3	2
	Wheat	Jan 15	Nov 01			
Madinah	Dates	Oct 01	Nov 01	558	552.8	5.2
	Grapes	Mar 01	Apr 01			
	Alfalfa	Oct 01	Nov 01			
Qaseem	Wheat	Jan 15	Nov 01	1425.9	1351.5	74.4
	Alfalfa	Oct 01	Sep 01			
	Dates	Oct 01	Sep 01			
Eastern Region	Wheat	Jan 15	Nov 01	485	415.7	69.3
	Dates	Aug 01	Sep 01			
Aseer	Wheat	Jan 15	Nov 01	145.6	139.9	5.7
	Dates	Aug 01	Sep 01			
	Alfalfa	Oct 01	Sep 01			
	Sorghum	Apr 15	Jan 15			
Tabouk	Wheat	Jan 15	Nov 01	390.6	327.4	63.2
	Alfalfa	Oct 01	Nov 01			
	Dates	Oct 01	Nov 01			
Hail	Wheat,	Jan 15	Nov 01	867.3	793	74.3
	Alfalfa	Oct 01	Sep 01			
	Dates	Oct 01	Nov 01			
Jazan	sorghum	Apr 15	Jan 15	574.3	516.8	57.5
Najran	Wheat,	Jan 15	Nov 01	150.4	147.9	2.5
	Alfalfa	Oct 01	Sep 01			
	Dates	Oct 01	Nov 01			
	Citrus	Mar 01	Mar 15			
Al-Baha	Wheat	Jan 15	Nov 01	38.8	38	0.8
	Dates	Aug 01	Sep 01			
Al-Jouf	Wheat	Jan 15	Nov 01	872.7	637.2	235.5
	Dates	Apr 01	Mar 01			
	Alfalfa	Mar 01	Feb 01			
		Total		8713.4	7981.9	731.5

In Saudi Arabia, most of the agricultural farms practice open irrigation, which could have led to higher evaporative and conductive losses. The advanced irrigation practices (e.g., sprinkler irrigation, green house, etc.) might reduce the overall losses. In many countries, greenhouse cultivation is becoming popular, which can reduce the evaporative losses. Although Saudi Arabia has started greenhouse cultivation for few vegetables and fruits, these are still at limited scale (SSYB, 2012).

Another option is relocating crops from higher CWR regions to lower CWR regions. Using crop yields (FAO, 2012), CWR for dates, alfalfa and wheat were estimated to be in the ranges of 1713 – 4316, 669 – 1097 and 740 - 2017 m^3/ton respectively. The Eastern Province, Aseer and Hail were the most water efficient regions for dates (1713 m^3/ton), alfalfa (669 m^3/ton) and wheat (740 m^3/ton) respectively. Although Riyadh was not on top of the water efficient regions (CWR for dates, alfalfa and wheat were 3975, 982 and 1265 m^3/ton respectively), Riyadh produced the highest fractions of dates and alfalfa and the 2nd highest fraction of wheat (SSYB, 2012). Shifting the production of dates, alfalfa and wheat from Riyadh to Eastern Province, Aseer and Hail may conserve 2262, 313 and 525 m^3/ton of water respectively. Strategic planning on relocation of agricultural activities might save groundwater for future. However, relocation of agricultural activities is not straightforward. Such a strategic move needs comprehensive study on crop yields, technical feasibility, water availability, financial burdens, and most importantly, the social aspects.

Many countries are using treated wastewater (TWW) for agriculture. While reuse of TWW augments water supplies for agriculture, contribution of TWW to agricultural water demands in Saudi Arabia needs further attention. In 2011, wastewater generation was little more than 2000 MCM while 1260 MCM was treated and approximately 325 MCM was recycled for reuse (MOEP, 2010; MOWE, 2011, 2012). The low reuse of TWW might be due to the lack of infrastructure for collection, treatment and recycling of wastewater (MOEP, 2010; Chowdhury and Zahrani, 2013b). If the total TWW could be collected and recycled, that would satisfy less than 11% of total agricultural water supplies in 2011 (MOEP, 2010). The agricultural fields are generally far away from treatment plants. Cost of TWW transportation to the agricultural fields might be significant. It is essential to explore other options for the best use of TWW and to identify the strategy for the maximum benefit of reusing TWW in Saudi Arabia. As an example, approximately 2650 MCM of water was needed in the domestic sector in which approximately 1600 MCM was supplied by the desalination plants. Significant fractions of the domestic water supplies were used for washing machine and toilet flushing. On average, one toilet flush needs 5–13 liters of water while a load of washing machine consumes 57-151 liters of water (Waterwise, 2015). Approximately 15% and 30% of total domestic water is used for washing machine and toilet flushing respectively (Waterwise, 2015). There is an opportunity to explore the option of reusing TWW for washing machine and toilet flushing. The domestic wastewater can be collected and treated in the community/satellite treatment plants, which can be transported back to the community. This is likely to avoid the collection of large amounts of wastewater and long transportation, which can keep the cost minimal. The total cost (e.g., capital, treatment, transportation and maintenance cost) of reusing tertiary TWW were in the range of US$ 0.83 – 2.03/m^3 with an average of US$ 1.43/m^3. The overall cost for using desalinated water (including transportation cost) were in the range of US$ 1.31 – 2.37/m^3 with an average of US$ 1.84/m^3 (Kajenthira *et al.*, 2011; Chowdhury and Al-Zahrani, 2013b). Reuse of TWW can save about US$ 0.41/m^3 of water and approximately 45% of domestic water demands can be supplemented (≅ 1200 MCM/year). At this rate, reuse of TWW may save approximately US$ 492 million (=$1200\times10^6\times0.41$) per year. This system can save the environment from pollution related to wastewater discharges into the wadies, sand dunes and the Arabian Gulf and Red Sea. There is a need to perform pilot scale feasibility study in this direction. The remaining TWW can also be reused for local agricultural fields and/or landscaping activities. Future study may look into this option.

*Conclusions***:** This study demonstrated implications of temperature and growing seasons on CWR. CWR for wheat showed exponential decay pattern when planting date were shifted from Jan to an earlier date, with the maximum shifting period of 75 days (e.g., Nov). Further investigation is needed on the effects of shifting of growing seasons for the main crops, relocation of crops from higher CWR to lower CWR areas, effects of relocation on crop yields, technical feasibility, water availability and cost of water transportation to the agricultural areas. Several factors (e.g., historical trends, labor availability, rainfall, crop yields, market demand and price, groundwater availability and/or permits) can be the major barriers for such shift. Future study is needed to better understand the effects of the noted factors.

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