Historical trends in crop water demand over semiarid region of Syria

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Abstract
Climate change has caused a shift in aridity, particularly in the world’s dry regions, affecting several sectors, predominantly the agricultural and water resources. This research examined the climate change effects on crop water demand (CWD) in Syria during 1951–2010. Given the lack of observed data, this analysis relied on Global Precipitation Climatology Center (GPCC) precipitation and Climatic Research Unit (CRU) temperature. Potential evapotranspiration (PET) at each grid was estimated using the Penman–Monteith model and the CWD using the FAO-56 method. The analysis revealed that CWD in Syria increased during 1981–2010 compared to that during 1951–1980. The increase in CWD was found for grapes, tobacco, barley, and cotton, whereas the maximum changes were during April and May. The most remarkable changes in CWD were for barley, between −20 and 40 mm. It showed a decreased CWD in the south and a rise in the north (0−40 mm). The CWD for wheat showed a decline in most parts of the country, except in the north. The increase in CWD for barley and wheat caused an increase in agricultural water stress in the region. Agriculture planning needs to be developed according to the expected future climate changes to maintain the agricultural production in the region.

1 Introduction
Rapid environmental changes due to unsustainable human activities have created numerous global challenges (Liu and Raven 2010; Shahid et al. 2017). The rise in temperature due to anthropogenic activities causing the increase in greenhouse gasses (GHG) altered the rainfall distribution and intensity (Scherer and Diffenbaugh 2014; Wang and Chen 2014; Iqbal et al. 2019, 2021; Swain et al. 2016; Shiru et al. 2019). Changes in precipitation rate, frequency, and distribution caused a rise in hydrological hazards worldwide (Mayowa et al. 2015; Mohsenipour et al. 2018; Noor et al. 2019). Because of their fragile ecosystems, arid and semiarid zones are more responsive to minor shifts in climatic conditions (Mehrotra and Mehrotra, 1995; Samadi et al. 2012; Qutbudin et al. 2019). Arid areas often experience extremely dynamic hydrological processes causing unusual events, for example, flash flooding caused by substantial precipitation and water stress induced by a lengthy dry spell (Buytaert and Bièvre 2012; Pour et al. 2020). Climate would become more uncertain in the arid region in the future, creating a drastic impact on agriculture in the region (Nam et al. 2015, Boretti and Rosa 2019).

Global warming-induced surface temperatures have modified evapotranspiration, air moisture retention potential, and, as a result, the seasonal and spatial distribution of rainfall has changed (Wang et al. 2016b). The Intergovernmental Panel on Climate Change (IPCC) estimated an intensification of water scarcity during dry periods in many regions, especially in Asian countries. Several studies also projected a reduction in crop production due to water stress (Bates et al. 2008). The situation may be adverse in the west of Asia and the Middle East region due to a higher increase in temperature (Houmsi et al. 2019). Studies showed a rise in temperature at a much higher rate in the Middle East than in many other regions (Salman et al. 2018). Unlike many other areas, the Middle Eastern region is experiencing a decrease in precipitation when the temperature rises (Lelieveld et al. 2012). These changes can cause a shift in aridity, atmospheric water balance, and crop water demand (CWD) (Acreman et al. 2009; Wheeler et al. 2004; Houmsi et al. 2019). Water balance changes can also disrupt soil heterogeneity and agricultural operation (Houmsi et al. 2019). It may have a
detrimental effect on the region’s livelihood and economic activities if unattended (Ahmed et al. 2019a; Khan et al. 2018b; Iqbal et al. 2020).

Aridity showed an expansion in major parts of the world, particularly in Middle Eastern countries. Houmsi et al. (2019) evaluated the aridity expansion in Syria during 1951–2010. The study reported that a total of 6.21% of the semiarid area has turned to arid because of rainfall reduction. El Kenawy and McCabe (2016) applied Pinna index and De Martonne index to analyze the changes in the aridity of the Middle East and Northern African region and showed a higher increase in aridity over the humid regions. Asadi Zarch et al. (2017) projected arid and semiarid land expansions globally. Sahour et al. (2020) reported a notable rise in aridity in a major part of the Middle East.

Agriculture is the most vulnerable field to climate change as it relies heavily on water resources (Zhang et al. 2012). In most arid regions, rural economies are highly dependent on agricultural land use. Cultivation is highly productive but restricted to the limited land area due to the unavailability of water (Nautiyal et al. 2015). The CWD is the water required to offset evapotranspiration losses from cropland (Liu et al. 2013b). Sun et al. (2018) evaluated the CWD in the Loess Plateau of northern Shaanxi and showed a downward trend for major crops in the range of 0.3 to 0.9% per year in the future. Liu et al. (2013a) investigated the water demand of spring barley in China’s Tibet region and reported increased CWD. Azad et al. (2018) studied the implications of global warming on wheat yield in Myandoab, Iran. They showed that a rise in temperature and potential evapotranspiration (PET) would decrease crop growing season and CWD. The negative effect of rising temperatures outweighs the positive effect of rising CO2 levels on crop production (Van Ittersum et al. 2003). Brouzynie et al. (2018) used a hydrological model and downscaled GCMs to quantify climate change impact on CWD of winter wheat and sunflower in northwestern Morocco. They reported evaporation as the major driver of CWD in the region.

The lack of water affects the livelihood of the vast agriculture-dependent population when it occurs in an arid region (Al-Furaiji et al. 2016). Climate-induced variations in the frequency and severity of agricultural water scarcity can cause severe and long-lasting effects on agriculture, livelihood, and natural systems if adequate adaptation plans are not realized (Nam et al. 2015). Understanding recent developments are vital for successfully implementing climate change adaptation plans (Wang et al. 2016a). Therefore, the present study proposes a framework for assessing the changes in crop water demand in a data scarce region like Syria. The extensive literature review revealed no research had been done using gridded datasets to examine historical shifts in CWD in Syria.

2 Study area and data
2.1 Study area
Syria is situated in the Middle East and covers an area of 185,180 km². Its latitude ranges from 32 to 38°N, and its longitude ranges from 35 to 43°E. The Mediterranean Sea, Turkey, Jordan, and Iraq border the country in the west, north, south, and east. The country’s topography mainly characterized as the western mountainous region and the vast eastern desert (Fig. 1).

Figure 2 shows Syria’s seasonal temperature and precipitation variability. The country has two distinct seasons: a warm summer (May–Oct) and a cool, rainy winter (Nov–Apr). The average daily maximum temperature varies from about 40 °C in summer to 12 °C in winter. The average daily minimum temperature goes down to 2 °C in winter. The summer minimum temperature is around 20 °C.

The Mediterranean winds carry moist air during winter. Therefore, Syria receives much of the precipitation in winter. The precipitation happens as snow and ice in the north. Most parts of the country virtually receive no rainfall in summer. The country’s rainfall varies between 75 and 1000 mm each year.

2.2 Data and sources
2.2.1 Gridded datasets
Various gridded data were applied in the present study, as described in Table 1, including precipitation data of GPCC (V.7) (Becker et al. 2013), temperature data from the CRU TS3.10 (Harris et al. 2014), and Princeton University Global Meteorological Forcing Dataset (PGF) (Sheffield et al. 2006). The selection of these three products was because of their broad applicability in various climate researches globally (Sarmadi and Shokoohi 2015; Shiru and Park 2020; Zhang et al. 2021; Liu et al. 2020). Besides, Houmsi et al. (2019) found those datasets most suitable for the Syrian region. The greater density of observed stations and the smart interpolation technique has made GPCC more suitable for many regions (Ahmed et al. 2017). CRU temperature data consider the manual and automatic procedures to maintain data quality. Rahman et al. (2018) and Pu and Ginoux (2016) found CRU temperature most suitable for the Middle East.

PET calculation using the PM method needs maximum temperature (Tmx) and minimum temperatures (Tmn), relative humidity (RH), solar radiation (SR), and wind speed (WS). The present study used Tmx, Tmn, RH, and
WS data of PGF. All the data are available for 1948–2010 at a resolution of 0.5°. The SR at a resolution of 0.5° was estimated using the model developed by Bojanowski et al. (2013).

Syria has two major crop growing seasons, winter and summer. About 73% of the total agricultural land of Syria is cultivated during winter (Houmsi et al. 2019). The major crops of Syria include wheat, barley, cotton, tobacco, and...
grapes. Wheat and barley are grown during winter, and cotton, tobacco, and grapes are grown during summer. Figure 3 shows the calendar of the chosen crops.

Cropping seasons in Syria differ only by a few days between irrigated and rain-fed areas. The cultivation time slightly varies with the time of rainfall in the rain-fed region. As a result, the winter crop season is more regular in irrigated areas than in rain-fed areas. Table 2 shows the periods used for the estimation of CWD for different crops.

### Table 1 Details of gridded data employed in the present study

| Products | Source and abbreviation | Temporal resolution | Spatial resolution | Geographical coverage | Climate variable |
|----------|-------------------------|---------------------|--------------------|----------------------|------------------|
| GPCC (Becker et al. 2013) | Global Precipitation Climatology Center, GPCC v.7 (http://www.esrl.noaa.gov/psd/data/gridded/data.gpcc.html) | Monthly (1901–2010) | 0.5°×0.5° | Global, land only | Precipitation |
| CRU (Harris et al. 2014) | The University of East Anglia Climatic Research Unit, CRU TS 3.22. (https://crudata.uea.ac.uk/cru/data) | Monthly (1901–2013) | 0.5°×0.5° | Global, land only | Temperature |
| Princeton (Sheffield et al 2006) | Global Meteorological Forcing Dataset for land surface modeling (http://hydrology.princeton.edu/data.pgf.php) | Daily (1948–2010) | 0.25°×0.25° | Global, land only | Vapor pressure, relative humidity, wind speed |

### Fig. 3 Calendar for selected main crops of Syria (FAO 2017)

![Calendar for selected main crops of Syria (FAO 2017)](image)

### Table 2 The periods used for the estimation of CWD for different crop growing (FAO 2017)

| Crops | Period (day) | Season (months) |
|-------|--------------|-----------------|
| Wheat | 240          | October to April|
| Cotton | 195         | April to July   |
| Barley | 195         | October to June |
| Tobacco | 150        | April to July   |
| Grapes | 210        | April to September|

### 3 Methodology

In this study, the CWD for various crops (barley, cotton, tobacco, grapes and wheat) were analyzed for two periods, 1951 – 1980 and 1981 – 2010, using gridded climate data. The procedure adopted in this study is as follows:

1. The PET was calculated using Penman–Monteith (PM) method at each grid for two periods, 1951–1980 and 1981–2010.
2. The CWD was calculated for each grid using the FAO-56 model.
3. The spatial distribution of changes in CWD for Syria for various crops was calculated and plotted using ArcGIS.

A detailed description of the methods used is stated below.

#### 3.1 Penman–Monteith potential evapotranspiration calculation method

PET can be estimated using a variety of techniques. The model used to estimate PET has a major effect on the CWD value. The model’s accuracy varies depending on
data availability, temporal scale, application, and climate condition (Berg et al. 2017). The FAO PM model (Allen et al. 1998) showed greater precision globally (Berg et al. 2017). As a result, it is extensively employed for PET estimation (Muhammad et al. 2019). The FAO PM empirical method for estimating PET (mm/day) can be expressed as:

$$PET = \frac{\Delta R_n + 0.4244(1 + 0.536u_2)(e_s - e_a)}{(\Delta + 0.067)(2.501 - 0.00236T)}$$  \hspace{1cm} (1)$$

where $u_2$ represents WS in m/h, $T$ is the temperature ($^\circ$C), $e_s$ indicates saturation vapor pressure (kPa), $e_a$ is the real vapor pressure (kPa), $\Delta$ represents gradient of the saturation pressure curve (kPa/$^\circ$C), and $R_n$ means surface net radiation (MJ/m$^2$/day). Here, $e_s$ was estimated from $T$, while $e_a$ from RH.

### 3.2 Estimation methods of crop water demand

Precipitation ($P$) and PET essentially define water balance (Thornthwaite 1948; Tsakiris and Vangelis 2005). The water balance equation estimates water demand for various crops (Kar and Verma 2005).

The FAO-56 model (Brouziyne et al. 2018) was used to calculate irrigation water requirement or CWD. The CWA for the $i$th month is the difference between the monthly precipitation, $P_i$, and PET$_i$.

$$CWA_i = P_i - PET_i$$  \hspace{1cm} (2)$$

The CWD can be calculated as:

$$W_{irr} = ET_{crop} - P_e$$  \hspace{1cm} (3)$$

where $W_{irr}$ irrigation water requirements; $ET_{crop}$ evapotranspiration; and $P_e$ effective precipitation.

The formula for calculating crop evapotranspiration is:

$$ET_{crop} = EC \times ET_{ref}$$  \hspace{1cm} (4)$$

where $EC$ denotes crop coefficient, and $ET_{ref}$ indicates reference evapotranspiration.

The term “effective precipitation” refers to the portion of rainfall used to fulfill the evapotranspiration needs of growing crops. Using the USDA equation, effective precipitation ($P_e$) is calculated (USDA 1983) as given below:

$$P_e = SF \times (0.70917P_0.82416P - 0.11556) \times 100.02426ET$$  \hspace{1cm} (5)$$

where $P_0$ represents monthly average precipitation (in inch); $SF$ denotes the soil water storage factor; and $ET$ is the average monthly crop evapotranspiration (in inch). The $SF$ is described as follows:

$$SF = (0.531747 + 0.295164D - 0.057697D^2 + 0.003804D^3)$$  \hspace{1cm} (6)$$

where $D$ denotes the amount of available $SF$ (in inch). $D$ is normally estimated between 40 and 60% of the usable soil water capacity, subjected to the irrigation management methods employed in the crop root area (USDA 1970). In this study, $D$ was considered 50%.

### 4 Results

#### 4.1 Validation of meteorological variables

Gridded climate data are always prone to biases in different forms. Therefore, such data are generally validated for a region before any climate studies (Ahmed et al. 2019b). However, validation depends on the availability of in situ data. Observed precipitation and daily mean temperature data at few locations are available in Syria. Those data were used in this study to validate the gridded data. The time series plot of GPCC precipitation and CRU temperature against the in situ data at a location in the northwest of Syria (Aleppo) is presented in Fig. 4. The figure also shows the residuals or the difference between observed and gridded datasets. The plots indicate the capability of gridded datasets in accurately reconstructing the seasonal and year to year variation of observed precipitation and temperature data. The residuals in precipitation were less than ±5 mm and the temperature less than ±1.5 °C in most cases. It established the suitability of the gridded data for CWD estimation in Syria.

Other data like RH, SR, and WS could not be verified for Syria due to the unavailability of in situ measurements. However, those data have been extensive employed for various climatological studies in Syria, other Middle Eastern countries, and the nearby region (Khan et al. 2018a; Pour et al. 2019; Nashwan et al. 2019; Wu et al. 2017; Houmsi et al. 2019).

#### 4.2 Areal average trends in meteorological variables

Figure 5 shows the meteorological variable maps used in the PM method for PET estimation. In Syria, the annual mean of daily RH and WS varied from the west coast to inland. The RH declines from above 70% in the tropical northwest to less than 50% in the southeast desert. The WS decreases from 4.3 km/h in the northwest to less than 2.8 km/h in the northeast. The SR showed a decrease with latitude. The country’s southeast received the most SR (7.3 W/m$^2$).

Figure 6 shows the variation in Tmx, Tmn, PET, rainfall, relative humidity, and aridity index (AI) for 1951–2010. The anomaly series was generated by subtracting the mean from the average areal values of the variables. The anomaly series represented the shifts in aridity
and other meteorological factors over time. In recent years, the mean temperature has hardly changed while the Tmn has risen. The PET showed a rise in recent years, while rainfall revealed a declination. The overall RH throughout the country remained almost unchanged. The AI in the region declined due to a rise in PET and a reduction in precipitation.

4.3 Geographical variability of potential evapotranspiration

The PET estimated using the PM method is shown in Fig. 7. The PET in Syria ranges from less than 1800 to

Fig. 4 a Time series of observed and GPCC precipitation; b residual series of GPCC precipitation; c observed and CRU daily mean temperature; d residual series of CRU mean temperature

Fig. 5 Annual average of a maximum temperature, b minimum temperature, c solar radiation, d vapor pressure, e relative humidity, and f wind speed
more than 2600 mm from the northwest to the southeast. Because of the higher PET than precipitation, the majority of the country is mostly arid.

4.4 Geographical distribution of the trends

The spatial distributions of precipitation, temperature, and PET trends were compared to better comprehend the CWD changes. Figure 8 presents the obtained results. Sen’s slope (Sen 1968) estimated the variations in rainfall, temperature, and PET, and the modified Mann-Kendal (MMK) test (Hamed 2008) evaluated the significance of the variations at $p < 0.05$. The results showed rainfall change in the country in the range from 4 to $-32.0$ mm/decade (Fig. 8a). The highest declination was in the north and northeast ($-32$ mm/decade), where the average annual precipitation is around 800 mm (Homsi et al. 2020). Rainfall declination in the northern semiarid zone was between $-12$ and $-16$ mm/decade, where the average annual precipitation is 300–400 mm. It means a large steady precipitation declination in the country’s north and northeast.

The temperature showed a dramatic increase across the country (Fig. 8b). The increase was larger in high-temperature regions than the low-temperature regions. The largest increases occurred in the east, especially in the northeast (0.28 °C/decade). Furthermore, it was steadily rising in the northwest (0.17 °C/decade). On the other hand, the increase in PET was not substantial at any place except one point in the south-eastern desert (Fig. 8c). The spatial pattern in the PET trend revealed temperature influences the country’s PET. Rising temperatures contributed to a rise in PET in most regions, but the rises were not statistically significant.
yet. However, the rising temperature pattern may trigger a rise in PET in the future.

### 4.5 Historical changes in irrigation demand for major crops

The Wilcoxon rank test (Woolson 2007) was used to evaluate shifts in CWD over two periods: 1951–1980 and 1981–2010. Figure 9 illustrates the findings for different crops. The + and − symbols signify increases and decreases, respectively. The results indicate a significant rise ($p < 0.05$) in CWD during 1981–2010 relative to that during 1951–1980 for all crops. Except for barley and wheat, all other crops showed higher water scarcity during 1981–2010 than during 1951–1980. The CWD for wheat showed a decrease in April and barley in February. Reduced rainfall and increased temperatures have resulted in higher CWD for most Syrian crops. The greatest rise in CWD was in April and May for all crops. It indicates increased water tension in recent years, mostly for summer crops.

### 4.6 Geographical variability of CWD change

Variations in CWD at different grid locations over Syria between 1951–1980 and 1981–2010 are shown in Fig. 10 to depict the spatial trend in CWD transition. The map’s color ramp defines the shift over two periods.

The CWD for barley showed a change in the range of −20 to 40 mm between 1951–1980 and 1981–2010. The negative value of CWD indicates a decrease in CWD, while a positive value indicates an increase. A decrease in CWD observed in the south of the country. However, there was a rise in CWD in the range of 0 to 20 mm in the north. As the country’s north covers most agricultural activities, the CWD of most crops increased. The remarked increase in CWD was for barley. There were no major changes in the CWD for cotton, grapes, and tobacco in any region. The CWD for wheat showed a decrease in most of Syria. However, it was rising in the northern and north-eastern major wheat cultivated regions. Overall, the findings suggest a rise in CWD for Syria’s two main crops, wheat and barley. The increase in CWD for barley and wheat has increased agricultural water stress in the region.

### 5 Discussion

An increase in aridity during 1951–1980 compared to 1981–2010 has been discussed in previous studies (Houmsi et al. 2019). More than 6% of semiarid land in Syria changed to arid between the two periods, while more than 5% of the dry sub-humid area shifted to semiarid. According to the findings, the main cause of Syria’s rising aridity is precipitation decline. More than 28% of the northern and north-western agricultural land transitioned from tropical to dry sub-humid or semiarid. The increased aridity has altered CWD in Syria. The rising temperature played a major role in the changes in CWD. The aridity shift would have the greatest impact on forested and agricultural lands in the future. The growing aridity would significantly impact land fertility and irrigation requirements. It may cause an increase in CWD, which can affect agricultural productivity and the agro-based industries due to the decrease in crop production, leading to economic instability in the future.

The increasing CWD was mainly in the intensive agricultural region of the country during 1951–2010. The increase was more for winter crops compared to summer crops. The increase in CWD was more in the southeast and
the least in the northwest. The declination of precipitation is the major cause of increasing CWD during winter. The increase in aridity has been reported in many previous studies with a rise in irrigation requirements. The present study validates this hypothesis also for Syria. However, the increase in CWD was much higher in Syria, which indicates a significant impact of climate change on agriculture and water stress in Syria. The temperature increased in most locations, with hotter regions getting more hot compared to the colder regions. The most significant temperature rise was in the northeast (0.17 °C/decade). The $PET$ at most grid points followed the same trend of temperature rise. The increased $PET$ is the major driver of rising CWD during 1981 – 2010 compared to 1951 – 1980. Therefore, most of the crops experienced higher water scarcity in recent years than during 1951–1980.

The present study analyzed CWD in all the regions of Syria from 1981 to 2010. The changes in crop water availability showed that the available water reduced up to 20 mm/decade for most of the crops. The highest decrease was for barley and the lowest for tobacco and grapes. The reduction in water availability affected crop production and, ultimately, the agricultural sector of Syria.
6 Conclusion

This paper analyzes the historical trends in CWD and the changes in water availability for five different crops in Syria. The gridded datasets were used for the first time to analyze the changes in PET and CWD in the region. The PM method was used to measure the PET using gridded data, and the FAO-56 model was used to calculate crop water demand in this article. The study reported the increase in CWD in all the parts of Syria. Except for wheat, the largest rise in CWD was in April and May for all crops. The water availability for all five main crops declined in Syria. The maximum decrease was for barley and wheat, followed by tobacco, cotton, and grapes. Climate change caused precipitation reduction and temperature rise, affecting the PET and CWD in the country. The study’s finding is very useful for the agriculture development planning and irrigation designing purpose, keeping in view the region’s expected changes due to the variation in climate. Further studies can be performed following the framework developed in this study to calculate the potential changes in future CWD under various climate change scenarios using different GCM simulations.

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Data availability The datasets presented in the article are available from the corresponding author on reasonable request.

Code availability The codes used in the current study are available from the corresponding author on reasonable request.

Declarations The authors declare that this paper is the result of our analysis and compilation. The paper is solely based on freely available data. All the authors contributed to the work.

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