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Climate change impact on the estimation of reference evapotranspiration, water requirement, and irrigation requirement in irrigated areas (a case study: Bardsir plain)

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ABSTRACT

Climate change impacts have been felt deeply by farmers of the Bardsir region, which is situated in the southeast of Iran. The current research focuses on the climate change impacts on the region's agricultural sector by the horizon of 2051. In the first step, by means of data generated by two micro lysimeters, the best-localized formula for estimating reference evapotranspiration was derived. Then the irrigation requirements of wheat, barley, rape, corn, alfalfa, potato, and onion crops were estimated by GFDL-ESM2M and Had GEM2-ES model outputs with two scenarios, RCP4.5 and RCP8.5. According to the findings, under both scenarios, the irrigation requirements of all plants will be increasing. Assuming that the current water consumption patterns remain unchanged, this will increase the total annual water demand of the plain from its present value of 331.9 to 369.66 million cubic meters (MCM) in the RCP4.5 scenario and 375.58 MCM in the RCP8.5 scenario based on GFDL-ESM2M model output. These values would be 345.11 and 349.85 MCM for RCP4.5 and RCP8.5, respectively, based on Had GEM2-ES model output by 2051. To conserve the current cultivation area, GCM models indicate, under a pessimistic scenario, even after modernizing the irrigation systems of the region the plain will encounter negative balance due to groundwater overdraft.

Key words: climate change, crop water requirement, irrigation requirement, RCP scenarios

HIGHLIGHTS

- Using real data of evapotranspiration derived by micro-lysimeters.
- Introducing the best evapotranspiration model for the region.
- Assessing different water resources management scenarios under climate change impacts.

INTRODUCTION

Any change in the internal components of the climate system or in the external forces that impact this system may result in climate variations. The climate variations that are caused by natural factors are called natural climate variability and those with anthropogenic causes are referred to as climate change. In the global climate zoning, Iran falls in the category of countries with arid and semi-arid climates (IPCC 2007[1]). Evidence from historical meteorological data and climate forecasts suggest that Iran, like many other countries, has been experiencing a change in climate in recent periods, and it is probable that this trend continues for the projectable future. Hydro-climatic hazards can be exacerbated by climate change by affecting the water cycle. This phenomenon can change the climatic patterns and therefore the volume of water resources available in a region. It is known to change the river discharge regimes, water and soil evaporation rates, and evapotranspiration (IPCC 2001). Climate change adaptation is one of the key components of infrastructure and development planning in the prescriptions of international institutions. One of the prerequisites of this adaptation is the accurate projection of forthcoming changes. Climate change is expected to overwhelmingly affect the water resources in Iran and other countries, including surface and underground water resources, water and sewage networks, urban water supply networks, and water-related structures (Shahvari *et al.* 2019). Hence, recent years have seen a growing number of research works on the hydrological

[1] Intergovernmental Panel on Climate Change.

outcomes of climate change inside and outside Iran using different methods and models. These studies are briefly reviewed in the following.

In a study by Ouyang *et al.*, they investigated the climate change effects on the Guangzhou Basin runoff in China using the output of six general circulation models (GCMs) in three representative concentration pathway (RCP) conditions. They used the Soil and Water Assessment Tool (SWAT) model. According to their findings, as a result of increased evapotranspiration, this basin is very likely to experience decreased streamflow in the future (Ouyang *et al.* 2015). The future hydrological effects of climate change in the Johor River Basin (Malaysia) were examined by Tan *et al.* using three RCP scenarios and six GCMs. Their findings indicated that annual precipitation and temperature increased, and, consequently, the streamflow of this basin was increased (Tan *et al.* 2017). Moreover, Kishiwa *et al.* assessed the climate change effects on surface water resources in the Pangani River Basin using SWAT and WEAP[2] models. This study projected that by the 2050s, runoff of this basin will increase by 10% (in comparison with the baseline period) and its temperature will rise by about 2 °C, and the basin will experience severe irrigation water deficiency, which necessitates a plan to control current and future water consumption (Kishiwa *et al.* 2018). Fraga *et al.* used the STICS[3] model for investigating the climate change impacts on agricultural water consumption in Portugal. This model showed a 60% reduction in crop production in the absence of management solutions for increasing crop yield (Fraga & Ataurib 2018). The climate change impacts on the evapotranspiration of the Kashfarud catchment area were examined by Alizadeh *et al.* by downscaling the outputs of the HadCM3[4] under the A2 scenario for the next 30 years. These researchers reported that because of the temperature rise, the evapotranspiration rate would increase in all months for all three periods studied (Alizadeh *et al.* 2010). Sobhani *et al.* and Goodarzi *et al.* conducted a series of research works to investigate the simulation performance of Statistical Downscaling Model (SDSM) and Long Ashton Research Station Weather Generator (LARS-WG) for different regions of the world and reported that both models have excellent accuracy in simulating climate change in future periods (Goodarzi *et al.* 2015; Sobhani *et al.* 2015). Sanikhani *et al.* examined the climate change effects on the runoff of Aji-Chay and Mahabad-Chay sub-basins in the Lake Urmia basin. After verifying the LARS-WG model's accuracy in the downscaling of statistics of the area, this model was used for temperature and precipitation projection with the A1B, B1, and A2 scenarios, which led to the projection of increasing precipitation and decreasing temperature in the coming periods. Finally, the Gene Expression Programming (GEP) model was used to model runoff for the years 2019, 2054, and 2089. This study projected a 50 and 55.9% decrease in the peak discharge of Mahabad-Chay and Aji-Chay basins by 2089 (Sanikhani *et al.* 2017). Akbarzadeh *et al.* investigated the climate change effects on groundwater resources of the Sufi Chay catchment area. For this purpose, they examined monthly mean rainfall data of six synoptic and rain gauge stations in the region. As shown by the research findings, withdrawal from groundwater reduced and water levels elevated during the months with higher rainfall. The trends of rainfall and temperature data in the Maragheh region showed decreasing rainfall and increasing temperature in recent decades, which have led to increased evapotranspiration and reduced snowfall, thereby leaving a significant impact on groundwater levels (Akbarzadeh *et al.* 2013). The climate change effects on irrigation water needs in the Baojixia region in Shaanxi Province, China, were studied by Wang *et al.* using the system dynamics method and under several different scenarios. This study projected that a 1 °C increase in temperature will increase the net irrigation water requirement by $12{,}050 \times 10^4$ m^3 and the gross water requirement by $20{,}080 \times 10^4$ m^3, but the irrigation water requirement would not rise at the same rate as temperature (Wang *et al.* 2016). Zhou *et al.* used the SDSM model for projecting the climate change impact on the crop water requirement in the Hetao irrigation district in China during 2041–2070 and 2071–2099. According to their findings, the climate would be wetter and warmer, ET_o would rise from 4 to 7%, and there will be similar increases in ETC and CWR (Zhou *et al.* 2017).

Goodarzi *et al.* investigated the climate change effects on the irrigation water requirement and related complications on groundwater levels in the 2017–2046 period using a combination of 20 different GCMs with RCP8.5 and RCP4.5 scenarios. According to their findings, there would be, respectively, a 4.1 and 2.5% increase in mean evapotranspiration of all months of the year under RCP8.5 and RCP4.5 scenarios, and an 18% rise in the mean irrigation water requirement of some plants, which mean climate change would significantly influence water consumption (Goodarzi *et al.* 2018). Gondim *et al.* examined the climate change effects on the water requirement in the Jaguaribe region in northeastern Brazil in the 2025–2055 period

[2] Water Evaluation and Planning.

[3] Simulateur Multi disciplinaire pourles Cultures Standard.

[4] Hadley Coupled Atmosphere–Ocean General Circulation Model.

using CMIP5[5] under two RCP scenarios. Their results showed that reference evapotranspiration in this region will increase by 2.3–6.3% and its irrigation water requirement will increase by 2.8–16.7% (Gondim *et al.* 2018). Rezazadeh *et al.* surveyed the climate change impact on the length of dry periods in Kerman province, Iran in the near future (2020–2050) by the use of GFDL-ESM2M[6] and four RCP scenarios. This study projected that in all scenarios, the mean annual temperature will increase; however, precipitation will only decrease in the central and southern regions of the province and will increase in other places (Rezazadeh *et al.* 2018). Alani *et al.* studied the climate change effects on irrigation requirements and water supply in the small catchment area of Nebhana Dam in the periods of 2021–2040, 2041–2060, and 2061–2080 by the LARS-WG model and two scenarios of RCP8.5 and RCP4.5. This work reported that the mean annual ET_o will increase by 6.1% and the mean annual rainfall will reduce by 11.4%, which will lead to a 24% decrease in the inflow to the basin (Allani *et al.* 2019).

Bardsir Plain in Iran's Kerman province is the region's hub of forage production and further renders the largest area under alfalfa cultivation within Kerman. As a result, forage production plays a crucial role in the employment and livelihood of the region's inhabitants. Given the potential impacts of climate change on forage cultivation, this study examined the potential outcomes of climate change on the region's temperature, precipitation, and crop water conditions. Accordingly, the actual evapotranspiration of alfalfa in two crop cycles was measured by two micro-lysimeters, and the best equation available within scientific literature for evapotranspiration estimation of the study area was identified. The GFDL-ESM2M and Had GEM2-ES models were used to simulate precipitation and temperature under two RCP scenarios with the help of the Climate Change Toolkit (CCT[7]). The CCT has been developed by Vaghefi *et al.* (2017) at Swiss Federal Institue of Aquatic Science and Technology (EAWAG). The simulations were employed to project the temperature trends and precipitation variations between 2021 and 2051. In addition, water and irrigation conditions of the Bardsir Plain were estimated at present and by 2051 under the two RCP scenarios, respectively. In a remarkable novelty in the case of this study, data collection was administered via micro-lysimeters based on real measurements in Bardsir Plain. Given that no measurment of evapotranspiration was conducted in Bardsir plain, all studies in this field have been carried out by the experimental equations so far. In this study for acheiving reliable results, the most compatible equation for evapotranspiration estimates was identified using collected data by two micro lysimeters.

MATERIALS AND METHODS

Study area

The study area is the Bardsir plain, located in Kerman province in southeastern Iran between 56 and 57° east longitudes and 29 and 30° north latitudes (Figure 1). This plain has a mean annual precipitation of about 90 mm, a mean altitude of 2,044 m, and a mean annual temperature of 15 °C. The minimum and maximum elevation of the plain are 2,010 and 2,078 meters from the sea level, and there is no significant variation in precipitation and temperature over the plain. This area has a monthly mean relative humidity of between 30 and 50% and an annual evaporation rate of about 2 m. According to the De Martonne climate classification, this plain has a dry climate (De Martonne 1920; Agricultural Statistics Report Crop Year 2017–2018).

Data collection

Field data were collected from an alfalfa farm under the supervision of the Bardsir Faculty of Agriculture over two growth cycles. Daily reference plant evapotranspiration was measured by two micro-lysimeters (Azar Khak Ab Urmia Co., Iran) with an accuracy of 0.08 mm. For this purpose, alfalfa was planted in the micro-lysimeters and irrigated at night. Before each irrigation, the drained water was collected and the lysimeters were weighted by a digital scale. The drained water was deducted from the irrigation water depth to estimate the soil's moisture content, and the moisture percentage that has been consumed by the evapotranspiration of the plant during the day was determined based on the weight difference obtained from the lysimeters. The reference plant evapotranspiration was also estimated by eight widely used equations listed in Table 1. Table 2 describes the variables/parameters of equations. Finally, the equations' results were compared with the data collected from the micro-lysimeters for identifying the best option to estimate evapotranspiration in the research area.

[5] Coupled Model Intercomparison Project Phase 5.

[6] Geophysical Fluid Dynamics Laboratory.

[7] https://www.2w2e.com/home/CCT.

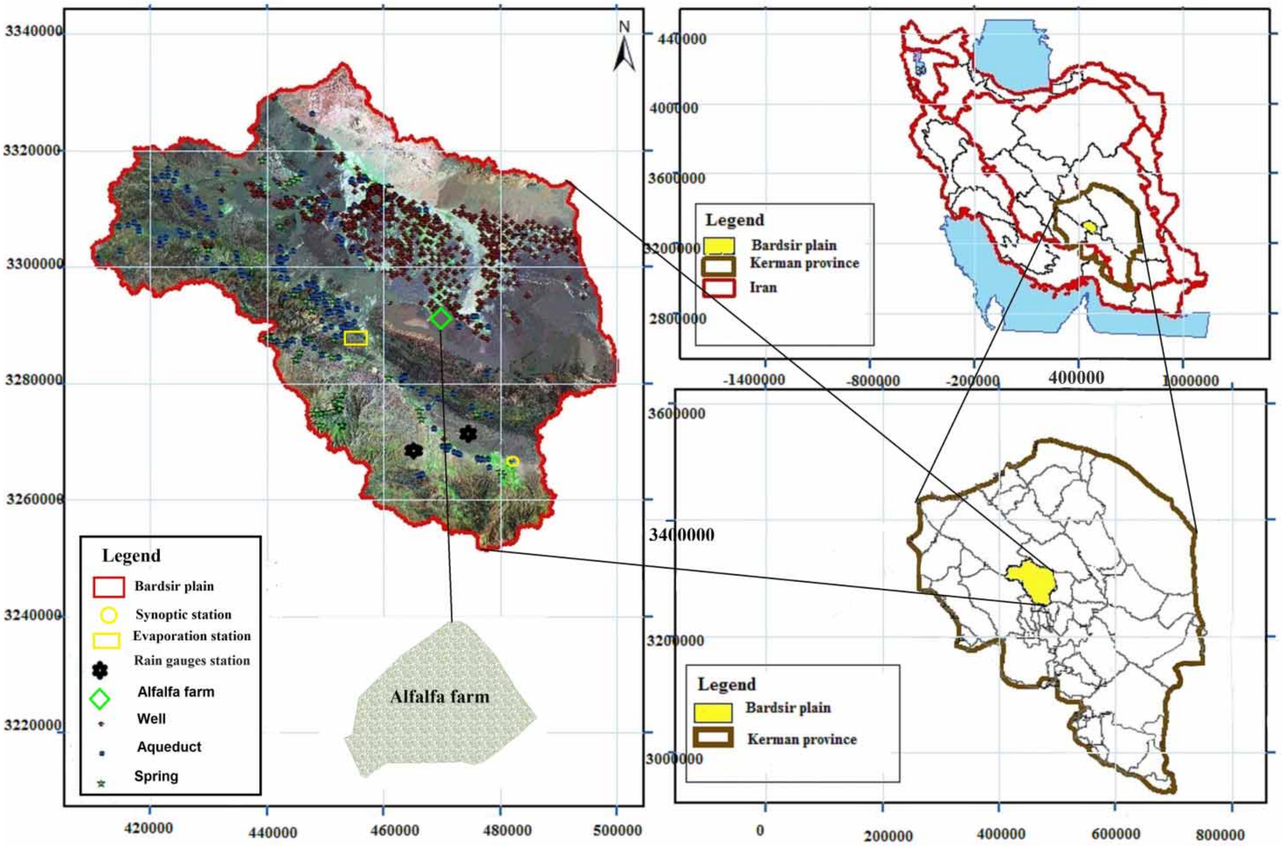

Figure 1 | Geographical location of Bardsir plain in Kerman province (Iran) and location of evaporation station, alfalfa demonstration farm (Water Resources Studies Report 2019).

The current research used the precipitation data and maximum and minimum temperatures recorded in Sangsayad and Jafarabad rain gauges and observed evapotranspiration data were collected using two micro lysimeters, which were installed in the Bardsir demonstration farm in the Bardsir plain. Considering the available statistical records, the base period was decided to be the 30-year period from 1987 to 2016. Simulations were performed for the near future period (2021–2051) under two RCP scenarios. After downscaling, the accuracy of the data projected by the model was checked using the coefficient of determination (R^2) and the root-mean-square error (RMSE). The projected data were then employed for estimating the irrigation and water requirement of the Bardsir plain by 2051 under the two RCP scenarios.

Goodness-of-fit measures

The performance of different approaches in the estimation of the reference plant evapotranspiration in the study area was compared using two statistical (goodness-of-fit) measures, i.e., the RMSE and R^2. The RMSE is given by the following equation:

$$\mathrm{RMSE} = \sqrt{\frac{1}{2}\sum_{i=1}^{n}[(\mathrm{ET_o}m)i - (\mathrm{ET_o}s)i]^2} \quad (1)$$

where $\mathrm{ET_o}m$ represents the evapotranspiration measured by the lysimeter, n denotes the number of observations, and $\mathrm{ET_o}s$ is the evapotranspiration estimated by the model. The R^2 is calculated by the following equation:

$$R^2 = \frac{\sum_{i=1}^{n}(P_i - P_{\mathrm{av})}(O_i - O_{\mathrm{av}})]^2]}{\sum_{i=1}^{n}(P_i - P_{\mathrm{av}})^2 \sum_{i=1}^{n}(O_i - O_{\mathrm{av}})^2} \quad (2)$$

Table 1 | Equations used for estimating reference plant evapotranspiration

Model	Equation	Reference
FAO B-C	$ET_o = a + b[p(0.46T + 8.13)]$ $a = 0.0043RH_{min} - \frac{n}{N} - 1.41$ $b = 0.82 - 0.0041RH_{min}1.07\frac{n}{N} + 0.066 \times u_d - 0.006RH_{min}\frac{n}{N} - 0.0006RH_{min} \times u_d$	Doorenbos & Pruitt (1977)
FAO P-M	$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}$	Allen *et al.* (1998)
H-S	$ET_o = 0.0023R_a(T_{mean} + 17.8)\sqrt{(T_{max} - T_{min})}$	Hargreaves & Samani (1985)
Irmak	$ET_o = 0.611 + 0.149R_s + 0.079T$	Irmak *et al.* (2003)
Priestley	$E_e = \left(\frac{\Delta}{\Delta + \gamma}\right)\frac{R_n}{\lambda}$ $ET_o = aE_e$	Priestley & Taylor (1972)
Turc	$ET_o = 0.31\frac{T}{T - 15}(R_s + 2.09)$ RH > 50%, $ET_o = 0.31\frac{T}{T + 15}\left(R_s + 2.09)(1 + \frac{50 - RH}{70}\right)$ RH < 50%,	Turc (1961)
Thornthwaite	$i_m = \left(\frac{T_m}{5}\right)^{1.5}$ $I_m = \sum i_m$ $ET_o = 16M\left(\frac{10T_m}{I}\right)^a$ $a = 6.75 \times 10^{-7}I^3 - 7.71 \times 10^{-5}I^2 + I.792 \times 10^{-2}I + 0.492$	Thornthwaite (1948)
Jensen-Hayes	$ET_o = C_T(T - T_x)R_s$ $C_T = 0.25$, $T_x = -3$	Jensen & Haise (1963)

Table 2 | Model variables/parameter descriptions

Model	Parameter	Reference
Blaney–Criddle	a, b: climatic coefficients P: mean daily percentage of total annual daytime hours T: daily mean air temperature (°C) n/N: mean ratio of actual to possible sunshine hours U_d: day time (7 A.M.–7 P.M.) wind speed at 2 m RH_{min}: minimum daily relative humidity ET_o: reference evapotranspiration (mm day^{-1})	Doorenbos & Pruitt (1977)
Penman–Monteith	Δ: slope of the vapor pressure curve (kPa °C^{-1}) R_n: net radiation (MJ m^{-2} day^{-1}) G: soil heat flux density (MJ m^{-2} day^{-1}) U_2: wind speed at 2 m height (m s^{-1}) e_s: saturation vapor pressure (kPa) e_a: actual vapor pressure (kPa) ($e_s - e_a$): saturation vapor pressure deficit (kPa) T: mean daily air temperature at 2 m height (°C) γ: psychrometric constant (kPa °C^{-1})	Allen *et al.* (1998)
Hargreaves–Samani	R_a: extraterrestrial radiation (MJ m^{-2} day^{-1}) T_{min}: minimum temperature (°C) T_{max}: maximum temperature (°C)	Hargreaves & Samani (1985)
Irmak	R_s: solar radiation (MJ m^{-2} day^{-1}) T: mean daily temperature (°C) RH: daily mean relative humidity (%)	Irmak *et al.* (2003)
Priestley	R_n: net radiation (MJ m^{-2} day^{-1}) λ: latent heat of vaporization (MJ kg^{-1}) Δ: slope of the vapor pressure curve (kPa °C^{-1}) $\alpha = 1.25$ γ: psychrometric constant (kPa °C^{-1})	Priestley & Taylor (1972)
Turc	R_s: solar radiation (MJ m^{-2} day^{-1}) T: daily mean air temperature (°C) RH: daily mean relative humidity (%)	Turc (1961)
Thornthwaite	i_m: thermal index T_m: mean air temperature (°C) α: coefficient M: correction factor	Thornthwaite (1948)
Jensen–Hayes	R_s: solar radiation (MJ m^{-2} day^{-1}) T: daily mean air temperature (°C) C_T: temperature constant $C_T = 0.25$, $T_x = -3$	Jensen & Haise (1963)

where O_i denotes the ET_o measured by the lysimeter, n represents the number of observations, P_i is the ET_o estimated in the considered scenarios, O_{av} is the mean of observations obtained from the lysimeter, and P_{av} is the mean of simulated data.

An introduction to the CCT

The CCT is a software tool that can be used for the extraction, downscaling, and bias correction of the data obtained from global climate models. The CCT is connected to five global ISI-MIP[8] databases and can be executed with four RCP scenarios. Table 3 shows the names of the global database and the emission scenarios available for the CCT.

The CCT uses the bias correction statistical downscaling method to correct biases (Vaghefi *et al.* 2017). Using multiple GCMs in order to reduce the uncertainty of future data projection has been mentioned as a standard practice in recent studies; however, Leiss *et al.* (2018) reported that this procedure necessarily does not lead to a good solution. In this study, two GCM models, GFDL-ESM2M and Had GEM2-ES, were employed to project near future climate data. These models have been checked and recognized to have satisfactory performance in the region by two independent studies (Rezazadeh *et al.* 2018; Jafary *et al.* 2020).

RESULTS AND DISCUSSION

Table 4 shows the values of goodness-of-fit measures for the outputs of commonly used evapotranspiration estimation methods relative to the data obtained from the lysimeters. This comparison was performed to determine the method that gives the best match with the experimental results of the study area. The measures used for this purpose are R^2 and RMSE.

As shown in Table 4, among the eight methods, the Blaney–Criddle model had the highest R^2 (0.892) and the lowest RMSE (0.103), which means it offers the most accurate results for the study area. Therefore, the Blaney–Criddle equation is the recommended formulation for estimating evapotranspiration in this area. This model also has the advantage of being simple and needing little climatic data.

Table 3 | Names of global databases and emission scenarios in the CCT

Name of databases in CCT	ISI-MIP model	Name of scenarios in CCT	Name of scenarios in ISI-MIP
GCM1	GFDL-ESM2M	scenario1	RCP 2.6
GCM2	HadGEM2-ES	scenario2	RCP 4.5
GCM3	IPSL-CM5A-LR	scenario3	RCP 6
GCM4	MIROC	scenario4	RCP 8.5
GCM5	NoerESM1-M		

Table 4 | Values of statistical measures for the classic evapotranspiration estimation methods

No.	Method	RMSE	R^2
1	Blaney–Criddle	0.103	0.892
2	Irmak	0.504	0.651
3	Jensen–Hayes	0.506	0.634
4	Turc	0.530	0.613
5	Torrent–White	0.394	0.554
6	Priestley–Taylor	0.406	0.551
7	Penman–Monteith	0.529	0.522
8	Hargreaves–Samani	0.398	0.489

[8] Inter-Sectoral Impact Model Inter-Comparison Project.

Although the Penman–Monteith is recommended by the FAO, as the reference model to simulate evapotranspiration (Allen *et al.* 1998), newly independent studies over Iran indicate that this model is not the best one in a number of regions. Moradi & Ziaeian (2019) checked 11 different models in Hormozgan province and recognized the Blaney–Criddle model as the best. In another study in Isfahan province, the Blaney–Criddle model was recommended among five different tested models (Salarian *et al.* 2014). The achievement of the current study confirms the two mentioned ones.

The most effective climate variables on evapotranspiration are air temperature, humidity, wind speed and sun radiation (Khoshravesh *et al.* 2017). In this study, only air temperature changes are considered for corresponding changes in future evapotranspiration and no significant changes are assumed on other climate variables, as GCM models do not provide any projection for them.

The aforementioned results regarding the effect of temperature on evapotranspiration using the CCT were used to examine the trends of changes in evapotranspiration of reference crops and then to estimate the irrigation water requirements and crop water requirements in the near future. Figures 2 and 3 show the observed mean monthly temperature for the base time period (1987–2016) and projected for the near future (2021–2051) ones under RCP4.5 and RCP8.5, using GFDL-ESM2M and Had GEM2-ES models.

As shown in Figure 2, under both scenarios and models, the temperature curves have shifted upward, which demonstrates a rise in temperature in the near future. These results suggest that the mean temperature will be increasing in two models/scenarios. The mean monthly temperature increase based on GFDL-ESM2M and Had GEM2-ES GCM models is 1.4 and 0.9 °C for the RCP4.5 scenario and 1.8 and 1.2 °C for the RCP8.5 scenario, respectively. However, as shown in Figure 3, there will be not much change in the precipitation of the region. This will result in increased evapotranspiration compared to the base period.

In a study, Jafary *et al.* (2020) projected precipitation and temperature in Kerman city using GCM models available in LARS-WG6 software (EC-EARTH, GFDL-CM, HadGEM2-ES, MIROC5, and MPI-ESM-MR). The outputs of all five models showed an increase in temperature and a decrease in precipitation for the near future (2020–2050). In another study, Rezazadeh *et al.* (2018) carried out a study on climate change in Kerman province using the CCT software to downscale and undertake bias correction. They introduced the GFDL-ESM2M as a suitable model for this purpose.

Climate change effects on water and irrigation requirements

Considering the rapid expansion of agricultural cultivation in the Bardsir plain in recent years, which has resulted in the conversion of almost all fertile lands in the area to farms, the next step of the study was to use the results obtained from the climate change scenarios for projecting the irrigation and water requirements of the crops cultivated in this area. As shown in Figure 2 under both models/scenarios, the rise of temperature (related to the base period) will increase the evapotranspiration of the area in all months of the year. The projected increases in evapotranspiration based on GFDL-ESM2M are 11.4 and 13.2% under RCP4.5 and RCP8.5 scenarios, respectively, and the corresponding values projected by Had GEM2-ES are 4 and 5.4%. These figures are estimated by the Blaney–Criddle equation using temperatures projected by mentioned models and scenarios.

Table 5 shows the area under the cultivation of different crops and their method of irrigation in the Bardsir plain according to the agricultural statistics report published by the Information and Communications Technology Center of the Ministry of Agriculture of Iran. Based on the Iranian agricultural upstream documents, no permission can be issued in order to increase the cultivation area and change the land use in the coming 30 years, although almost there is no other fertile land remains for cultivation in this region so far (Agricultural Statistics Report, Crop year 2017–18). On the other side, Iranian government policy is to encourage more production in all fields including agricultural productions, so these data were assumed unchanged for the near future in our analysis. Indeed, the main purpose of this study is to evaluate the future situation of the plain groundwater resources by continuing this policy. To estimate the water requirement, the obtained ET_o values must be multiplied by a crop-specific coefficient (k_c), which changes over the initial, middle, and final stages of plant growth. In the present study, k_c values were obtained from FAO56 (Allen *et al.* 1998), and, then, the irrigation requirement was calculated by deducting the effective rainfall and applying the irrigation efficiency to the water requirement. The estimation of irrigation and water requirements of the crops in the area of research indicates that under both models/scenarios, the water and irrigation requirements of all crops will be increasing in the near future. Table 6(a) and 6(b) shows near future irrigation and water requirement projections, using GFDL-ESM2M and Had GEM2-ES models, under two RCP4.5 and RCP8.5 scenarios, briefly.

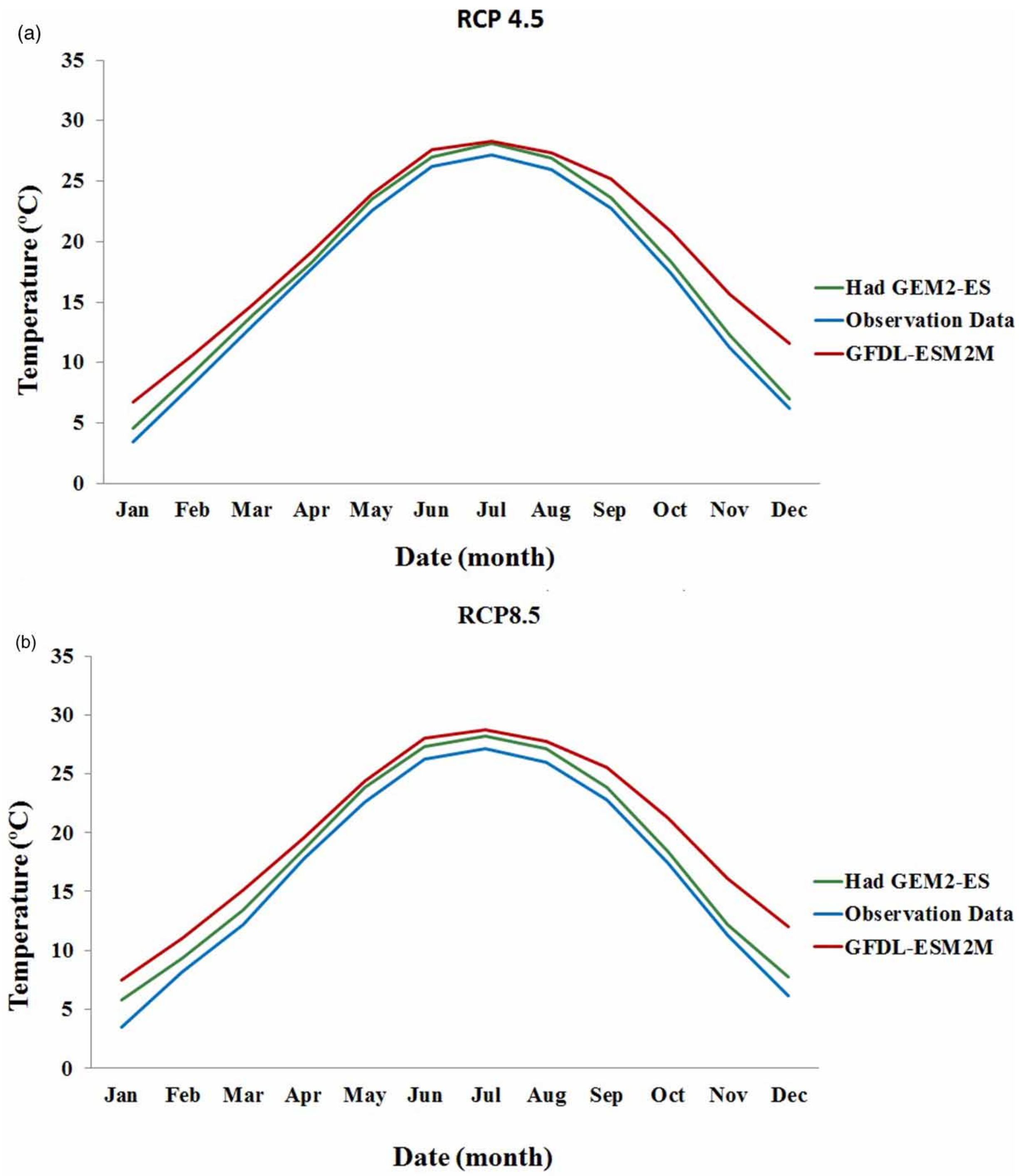

Figure 2 | Results of the climate change model for the mean monthly temperature in the projected and base periods with (a) RCP4.5 and (b) RCP8.5 scenarios.

Figures 4 and 5 show the changes in irrigation and water requirements of different crops in the Bardsir plain under the RCP8.5 and RCP4.5 scenarios. As can be seen, the increase in the irrigation requirement varies from crop to crop but is generally highest for forage and tuber crops. Since these crops account for about 45% of the area under cultivation in the Bardsir plain, it could be expected that climate change has a massive effect on water consumption in this area.

According to the 2016 statistics published by the regional water organization of Kerman, the aquifer of the Bardsir plain is recharged by, on average, 261.7 million m^3/year. In this study, however, the current water consumption of this area was

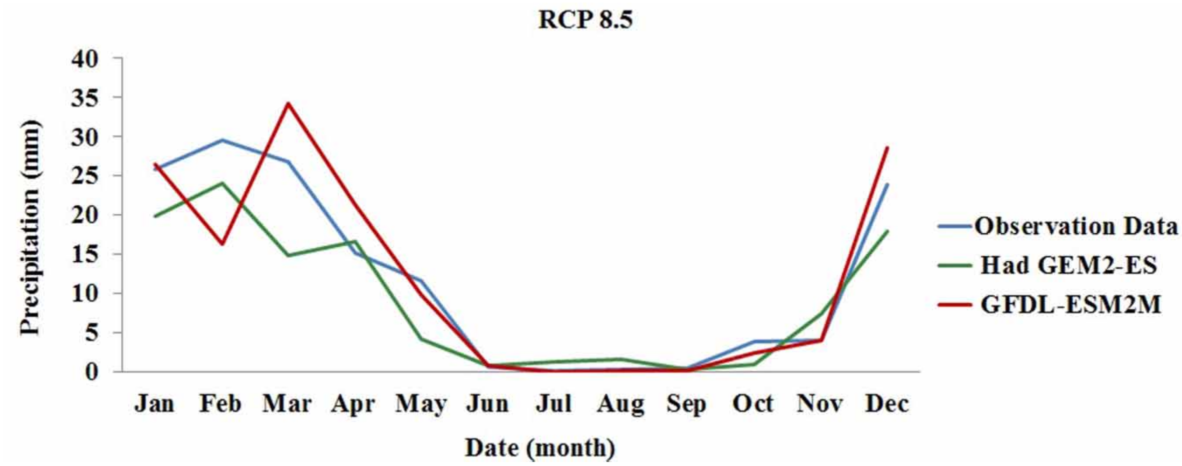

Figure 3 | Results of the climate change model for the mean monthly precipitation in the projected and base periods under RCP8.5.

Table 5 | Area under the cultivation of different crops in the Bardsir plain

Crop	Area (ha)	Flood irrigation (ha)	Mechanized irrigation (ha)
Wheat	5,500	1,375	4,125
Barley	5,000	1,250	3,750
Rape	1,500	375	1,125
Corn,	2,000	500	1,500
Alfalfa	7,500	1,875	5,625
Potato	2,500	625	1,875
Onion	1,500	375	1,125
Total	25,500	6,375	19,125

estimated to be 331.9 million m^3/year, which means excess withdrawal from the aquifer is currently about 70.2 million m^3. With the projected increase in temperature and evapotranspiration and no change in precipitation, by 2051, water consumption increases due to an increase in temperature would be 369.99 and 375.58 MCM under RCP4.5 and RCP8.5 scenarios, respectively, based on the GFDL-ESM2M model. Also, these values based on Had GEM2-ES would be 345.11 and 349.85 MCM under RCP4.5 and RCP8.5, respectively.

Since above 90% of water resources in this plain is consumed in agriculture and this plain is already in critical water balance conditions, it is crucial to adopt proper planning and management measures for preventing excessive water consumption and mitigating the forthcoming impacts of climate change. One recommended solution is to encourage traditional farmers to switch from flood irrigation methods to modernized irrigation systems. Currently, the Iranian government has provided large budgets in form of grants, up to 85% of the total cost, to encourage farmers to change their irrigation systems to modernized ones. If this solution is implemented, the water balance of the plain under the two climate change models/scenarios will be as shown in Table 7. The efficiency of drip, sprinkler and traditional flood irrigation methods were assumed to be 90, 80 and 45%, respectively (Agricultural Statistics Report 2017–2018).

As shown in Table 7, if all farms of the area are equipped with modernized irrigation systems, the total irrigation requirement of the area would be about 272 million m^3/year. Even if all farms use modern irrigation systems, the present water balance of the plain will still be negative 10.3 million m^3, and by the year 2051, water consumption will rise to 303.35 and 282.73 MCM under RCP4.5, based on GFDL-ESM2M and Had GEM2-ES models, respectively. These values are projected to receive 308.16 and 286.59 MCM under RCP8.5. Thus, it is not possible to achieve water resources balance just by improving irrigation efficiency. It seems changing cropping pattern and reducing cultivation area are two other alternatives that

Table 6 | Irrigation and water requirements of different crops cultivated in the Bardsir plain: (a) GFDL-ESM2M and (b) HadGEM2-ES

Current conditions				RCP4.5			RCP8.5			
Crop	Area (ha)	CWR (mm)	IWR (mm)	Q_{IWR} (mm³)	CWR (mm)	IWR (mm)	Q_{IWR} (mm³)	CWR (mm)	IWR (mm)	Q_{IWR} (mm³)
(a)										
Wheat	5,500	686.1	922.8	52.41	819.6	1,138.3	62.6	840.1	1,166.8	64.17
Barley	5,000	485.4	674.1	33.7	585.7	813.4	40.67	601.1	834.86	41.74
Rape	1,500	692.4	961.6	14.42	821.8	1,141.4	17.12	841.7	1,169	17.53
Corn	2,000	744.9	1,112.1	22.24	799	1,192.5	23.85	807.3	1,205.3	24.1
Alfalfa	7,500	1,354.4	2,022.1	151.66	1,465.7	2,188.3	164.12	1,482.9	2,214	166
Potato	2,500	1,001.2	1,390.5	34.76	1,080.8	1,501.1	37.52	1,093.1	1,518.1	37.95
Onion	1,500	1,090.4	1,466.6	22.7	1,177.3	1,583.5	23.75	1,190.2	1,600.85	24.01
(b)										
Wheat	5,500	686.1	952.9	52.41	731.81	1,016.4	55.9	748.24	1,039.22	57.15
Barley	5,000	485.4	674.1	33.7	519.76	721.8	36.09	532.1	739.02	36.95
Rape	1,500	692.4	961.6	14.42	736.73	1,023.2	15.34	752.65	1,045.34	15.68
Corn	2,000	744.9	1,112.1	22.24	763.32	1,130.6	22.79	770.01	1,149.66	22.99
Alfalfa	7,500	1,354.4	2,022.1	151.66	1,392.1	2,078.48	155.8	1,405.87	2,099.04	157.42
Potato	2,500	1,001.2	1,390.5	34.76	1,028.11	1,427.9	35.69	1,037.97	1,441.62	36.04
Onion	1,500	1,090.4	1,514.4	22.7	1,122.39	1,558.8	23.38	1,132.68	1,573.16	23.59

CWR, crop water requirement; IWR, irrigation water requirement.

water resources managers of the region must take seriously. Although, changing cropping pattern needs a national pattern which must be derived under water, food, energy, and environment nexus requirements, in lack of it the following recommendations are presented.

According to Tables 6 and 7, the crops with the highest irrigation requirement in the Bardsir plain are forage and tuber crops. Since 45% of all cultivated areas in this plain are dedicated to these crops, another water conservation solution is to reduce the area under the cultivation of tuber and forage crops by replacing them with crops that have lower water consumption. As Tables 6 and 7 show, crops such as wheat, barley, rapeseed, and corn have far lower water consumption than tuber and forage crops. Therefore, they can be recommended as less water-intensive replacements for tuber and forage crops.

The ultimate management scenario for dealing with the worst-case scenario (RCP8.5) using GFDL-ESM2M is to reduce the total area under cultivation by 17.7% to reach water balance in the plain. What is certain is that climate change would massively affect the water amount available for agriculture, drinking, industry, animal husbandry, etc., in the Bardsir plain. As a result, proper planning and management strategies are needed to deal with the effects of this phenomenon in a not-too-distant future. Measures that can be effective in this area include the expansion and proper management and utilization of modern irrigation systems, improvement of cropping patterns, use of improved varieties with lower water consumption, modification of cropping calendar, cultivation of cereals instead of tuber and forage crops, and expansion of greenhouse farming.

CONCLUSION

The agricultural sector is the largest consumer of freshwater globally, including Iran. With the current trends of population growth, in the next 20 to 30 years, freshwater resources of Iran are expected to become highly strained and vulnerable to overexploitation. This indicates the significance of the potential climate change impact on agricultural water consumption. The daily reference plant evapotranspiration in the Bardsir plain in southeastern Iran was estimated in the present study based on the measurements made by two micro-lysimeters on an alfalfa farm over two growth cycles. The reference plant evapotranspiration was also estimated with eight widely used evapotranspiration estimation models. We compared the results with the data provided by the micro-lysimeters to determine which model produces the most realistic estimates from the study area. Among the tested equations, the Blaney–Criddle equation had the highest R^2 (0.892) and the lowest RMSE

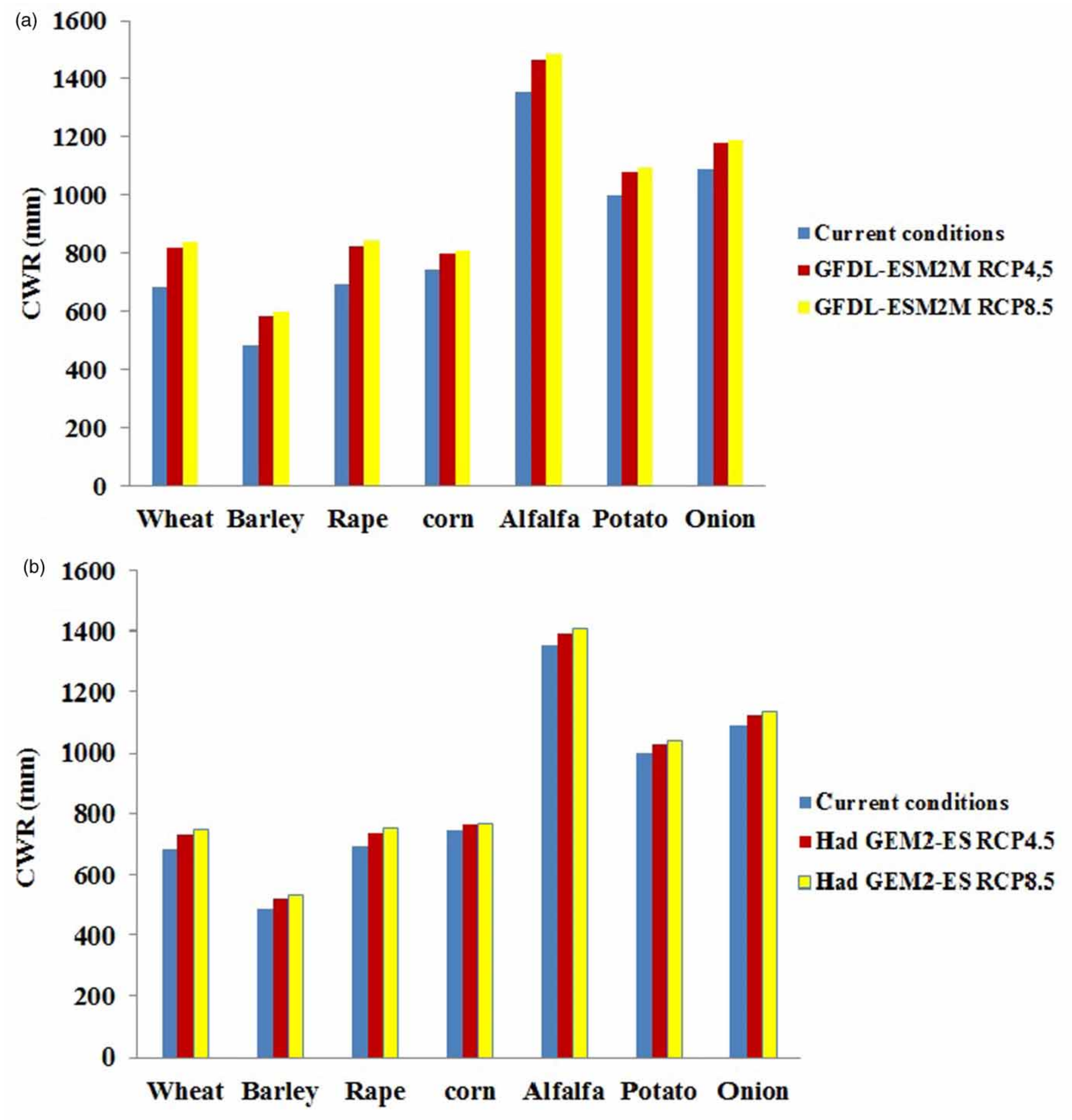

Figure 4 | Water requirement of different crops in present and near future, under the RCP8.5 and RCP4.5 scenarios.

(0.103), which means it offers the most accurate results for the study area. Therefore, all subsequent projections were made based on the Blaney–Criddle equation. Finally, the mean annual temperature would increase by 1.4 and 1.8 °C under RCP4.5 and RCP8.5 scenarios, respectively, based on the GFDL-ESM2M model output by the year 2051. The Had GEM2-ES model shows a 0.9 and 1.2 °C of increase under RCP4.5 and RCP8.5 scenarios, respectively. The model output indicates no significant change in annual precipitation amount. Hence, it is the rising temperature that will bring about the greatest adverse effect of climate change, i.e., the increase in evapotranspiration. Also, the temperature increase will certainly increase the evaporation rate and thus decrease water available for aquifer recharge and green water storage of the region that are not considered in this study (Iranmanesh *et al.* 2021). Another phenomenon, which is ignored in this research, is the elimination of irrigation water return that would be happened by switching from flood irrigation methods to modernized irrigation systems. It is estimated that about 13% of flood irrigation water returns back to the aquifer in this region (Rajabi *et al.* 2020).

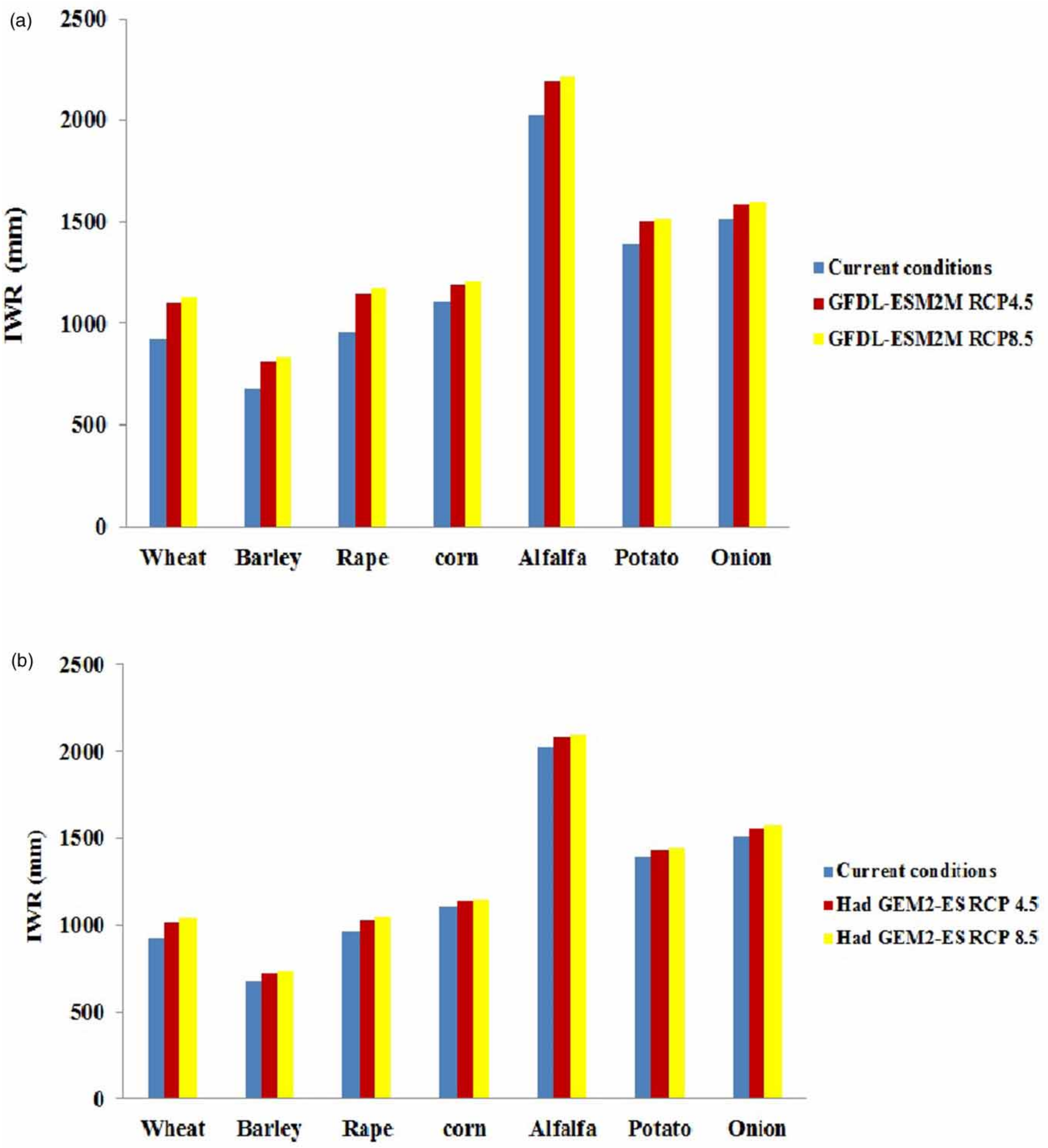

Figure 5 | Irrigation requirement of different crops in present and near future under the RCP8.5 and RCP4.5 scenarios.

However, climate change will certainly impose several other impacts on the region, like changes on single event precipitation temporal and spatial patterns that lead to severe hydrologic events. They are not considered in this study.

It is estimated that in RCP4.5 and RCP8.5 scenarios, evapotranspiration in the Bardsir plain will increase by 11.4 and 13.2% in the near future using the GFDL-ESM2M model compared to the base period, respectively. Also, the corresponding percentages according to the Had GEM2-ES model output are estimated to increase by 3.95 and 5.36%.

According to these estimates, it was projected that under both scenarios, the area will see a significant rise in irrigation and water requirements of the agriculture sector in the near future. Although the climate change effect on irrigation and water requirements varies from crop to crop, forage and tuber crops were found to have the highest sensitivity to climate change. Given the large area under the cultivation of these crops in the Bardsir plain, climate change will significantly

Table 7 | Irrigation and water requirements of the crops cultivated in the Bardsir plain under the assumption that all farms use mechanized irrigation: (a) GFDL-ESM2M and (b) HadGEM2-ES

Current conditions					RCP4.5			RCP8.5		
Crop	Area	CWR (mm)	IWR (mm)	Q_{IWR} (mm³)	CWR (mm)	IWR (mm)	Q_{IWR} (mm³)	CWR (mm)	IWR (mm)	Q_{IWR} (mm³)
(a)										
Wheat	5,500	686.1	762.3	41.92	819.6	910.66	50.08	840.1	933.44	51.33
Barley	5,000	485.4	539.33	26.96	585.7	650.77	32.53	601.1	667.88	33.39
Rape	1,500	692.4	769.34	11.54	821.8	913.11	13.69	841.7	935.22	14.02
Corn	2,000	744.9	931.12	18.62	799	998.75	19.97	807.3	1,009.1	20.18
Alfalfa	7,500	1,354.4	1,693	126.97	1,465.7	1,832.1	137.4	1,482.9	1,853.6	139.02
Potato	2,500	1,001.2	1,112.4	27.81	1,080.8	1,200.8	30.02	1,093.1	1,214.5	30.36
Onion	1,500	1,090.4	1,211.5	18.17	1,177.3	1,308.11	19.62	1,190.2	1,322.4	19.83
(b)										
Wheat	5,500	686.1	762.3	41.92	731.81	813.12	44.72	748.24	831.37	45.72
Barley	5,000	485.4	539.33	26.96	519.76	577.51	28.87	532.1	591.22	29.56
Rape	1,500	692.4	769.34	11.54	736.73	818.58	12.27	752.65	836.27	12.54
Corn	2,000	744.9	931.12	18.62	763.73	954.15	19.08	770.01	962.51	19.25
Alfalfa	7,500	1,354.4	1,693	126.97	1,392.1	1,740.12	130.5	1,405.8	1,757.33	131.8
Potato	2,500	1,001.2	1,112.4	27.81	1,028.1	1,142.34	28.55	1,037.9	1,153.3	28.83
Onion	1,500	1,090.4	1,211.5	18.17	1,122.39	1,247.1	18.7	1,132.6	1,258.53	18.87

affect water consumption in this area. Already, this plain has a critical water balance condition. With the projected increase in temperature and evapotranspiration, based on the GFDL-ESM2M model output, by 2051, water consumption of the Bardsir plain will increase from its present value, which is 331.9 to 369.66 million m^3 in the RCP4.5 scenario and 375.58 million m^3 in the RCP8.5 scenario. The corresponding values based on the Had GEM2-ES model output will rise to 345.11 and 349.85 under RCP4.5 and RCP8.5 scenarios, respectively.

Considering the critical water balance condition of the Bardsir plain, it is imperative to adopt strong planning and management measures for dealing with the imminent impacts of climate change. To conserve the current cultivation area, GCM models indicate under a pessimistic scenario, even after modernizing the irrigation systems of the region, the plain will encounter a negative balance due to groundwater overdraft. Two recommended measures to tackle this challenge are to change the cultivation pattern or to decrease the cultivation area. Considering the population growth, it seems the first measure is preferable.

The recommended measure to tackle this challenge is promoting the construction of modern irrigation systems in all farms of the area to improve their irrigation efficiency accompanied by modifying cropping patterns and the reduction of cultivation area to ultimately decrease the water consumption of the plain by 17.7% in order to achieve and maintain water balance.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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