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RESEARCH ARTICLE - CIVIL ENGINEERING

To Develop a Crop Water Allocation Model for Optimal Water Allocation in the Warabandi Irrigation System

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Abstract

The water allowance for canal systems of Pakistan was designed considering the average values of cropping intensity and irrigation area. However, water allowances would be different if estimated on the basis of real cropping intensities, cropping pattern and actual evapotranspiration. This inequity of water allocation results in decreased agricultural production. Hence, optimal water allowances for given canal commands need to be developed to maximize the efficiency of the existing irrigation system. Therefore, present study aims to assess the difference between the available water supplies and those required on the basis of real field conditions. Crop Water Allocation Model has been used for this purpose. Discharge at the head of each watercourse was predicted on the basis of the actual evapotranspiration, cropping patterns, cropping intensity, the number of days of canal flows in a year and the irrigation efficiency. The predicted optimal water requirements and the design flow rate were also compared for Kasur minor and found that 59 watercourses out of 61 require less water for optimal operation than the designed flow rate. Only two watercourses require more water for optimal conditions than the designed flow rate. Sensitivity and scenario analysis were also performed to evaluate the impact of different agricultural and climatological parameters on the reference crop evapotranspiration and design discharges.

Keywords Water requirement · Warabandi · Irrigation efficiency · Canal command

List of symbols

ET_o	Reference evapotranspiration (mm)
ET_a	Actual crop water requirement (mm)
K_c	Crop coefficient
V_R	Annual volume of water required (lps)
I_i	Annual cropping intensity (ha/year)
Q_{eq}	Equivalent continuous rate of flow (lps)
V_R	Actually required volume of water at crop root zone (lps)
Q_R	Gross flow rate required at the head of a watercourse (lps)
E_i	Irrigation efficiency (%)
E_{Cw}	Conveyance efficiency (%)
E_A	Application efficiency (%)
$T\max$	Mean monthly maximum temperature (°C)
$T\min$	Mean monthly minimum temperature (°C)
CWR	Crop water requirements (mm)

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1 Introduction

Water is a fundamental source and critical component in the sustainable agricultural development of arid and semi-arid regions, where the irrigation water is the only option for attaining a major increase in the crop production. Pakistan has been blessed with facilities of both surface and groundwater resources and also a favorable climate in the Indus Basin System. Despite all these facilities, yet the crop production is lower in comparison to other countries in the world. Only 38 billion cubic meter water is available for crop use from the available 171 billion cubic meter measured at rim stations [1]. However, the cropping intensities across canal commands vary from less than 60% to 160%, annually [2]. The lower cropping intensities in Rabi as compared to Kharif support the factor, as Rabi is substantially dry with respect to rain and river water availability. Thus, it becomes more important to store as much water as possible during the high flow season for the use during low flow season. In Pakistan, although the growth rate of agriculture has increased from 1.27% during 2005-2006 to 3.81% in 2017-2018, the rate of increase does not correspond to the population growth rate [3]. In most of the areas, the present water distribution system is time-based in which the farmers receive equal time but do not receive an equal amount of water.

The major sources of water in Pakistan are the glaciers in the HinduKush region which are diminishing rapidly. The main cause of this retardation of glaciers is the climate change. Climate change has already affected the cropping patterns in the country with the changing rainfall patterns and intensity. For instance, in the past vegetables including turnip, maize, millet and onion were grown on large scale during the spring which has now drastically decreased. Similarly, maize, millet, okra, sorghum and other vegetables were grown on large scales during summer. Sorghum and millet are no more cultivated [4]. However, no management strategy has been adopted to tackle this problem. Kiktev et al. [5] assessed the uncertainty in the trend estimates and the field significance of the patterns of observed trends and have concluded that the human-induced forcing has recently played an important role in extreme weather conditions. Thiery et al. [6] used ensemble simulations with the Community Earth System Model for assessing impacts of irrigation on climate extremes and found that the irrigation has a small, yet overall, beneficial effect on the climate.

Abid et al. [7] analyzed the adaption of wheat farmers to climate change, its determinants and its impact on food productivity and crop income in Pakistan by using logistic regression analysis and found that the adaptation of wheat crops to climate change positively affects the productivity and net crop income. In another study, Abid et al. [8] stated that adaptation to climate change in agricultural sector is an important strategy to reduce damages related to climate change and to protect livelihoods in Pakistan. Waqas et al. [9] conducted comparative analysis of organic and conventional farming in Punjab province and found that the organic farming increases the crop production; however, adoption of conventional farming is more compared to organic farming. Zulfiqar et al. [10] investigated the resource and socioeconomic constraints of farmers in adopting the advanced agricultural technologies by identifying the technical and economic efficiencies as well as the factors determining the resource use efficiency. Ali and Erenstein [11] assessed the factors influencing the farmers choice to climate change adaptation practices in Pakistan and have found three major adaptation practices used by the farmers, i.e., adjustment in sowing time (22% farmers), use of drought tolerant varieties (15%) and shifting to new crops (25%). Imran et al. [12] investigated the impacts of climate smart agriculture on crop production through sustainable water use management in the Punjab province and found an increase in the resource use efficiency by adopting the climate smart agriculture technologies. Khatri-Chhetri et al. [13] have also discussed the factors influencing the farmers in adopting the climate smart agriculture to cope with the climate change impacts. Moreover, changes in monsoon patterns and increased temperatures are likely to bring considerable challenges to the agricultural sector in Pakistan and investment in climate smart agriculture is required to ensure a stable food supply in this dynamic economy in the face of climate change [14].

Warabandi is a system of water distribution among farmers practiced in India and Pakistan for more than hundred years. Warabandi is a rotational method for equitable distribution of the available water in an irrigation system by turns fixed according to a predetermined schedule specifying year, day, time and duration of supply to each irrigator in proportion to the size of his landholding in the outlet command. The rotational cycle is of 7 days, and the duration of supply is proportional to the farmer's landholding. In this system, there is a time compensation for the farmers who require compensation for conveyance time but no compensation for seepage losses. Water allowance is the design discharge assigned to the head of a distributary or a watercourse which is based on the area to be irrigated and is measured in (ft^3/sec) cusecs per acre [15]. The water allowance for the canals in the country was kept low to bring more area under irrigation, but the assumed cropping intensity was kept low as 75% to make the system more productive. With the increase in time, the cropping intensity has increased more than 160% making it difficult for the existing system to fulfill the water requirements. More recently, several researchers used various techniques to estimate the crop water requirements under different climatic and local conditions around the world [16–27].

Afzal [28] calculated that a water allowance of 0.085 m^3/s was equivalent to an application of 0.41 m and 0.55 m depth of water per acre at the farm and outlet command basis, respectively. Latif et al. [29] reviewed the water allocation methodologies in different countries and stressed the equity consideration in the rehabilitation and modernization of these systems. In the Warabandi system being practiced in Pakistan and India, the water users are given a proportionate share of time according to their land holding considering the availability of water as a constraint. Ahmad and Heermann [30] concluded that on-demand system of water delivery is best to get better crop productivity in Pakistan. On this basis, they developed a water allocation model. However, the implementation of this technique was not possible due to the existing sociotechnical conditions. Hannan and Coals [31] stated that the importance of water management throughout the world is becoming more important due to the shortage of water. Shafiq and Latif [32] developed a computer model to operate the canals and allocate water among distributaries on an equitable and reliable basis as close to a varying pattern of crop water needs as possible. Vander et al. [33] observed that the frequency of days without canal water at watercourse head increased clearly toward tail reaches of the main canal and among off-taking minors. The farmer in these watercourse commands did not receive canal water as much as 50% to 75% of the times. Moreover, GWP [34] found the significant gap between the canal water supplies and crop water requirements because of the rigidity of the system and thereby, negatively affecting the agricultural production. Sarwar et al. [35] stated that water allocation was not uniform among the perennial and non-perennial groups of distributaries while reviewing water allocation per 1000 acres of CCA for 14 distributaries of Chishtian subdivision. Osama [36] developed a linear optimization model to obtain the maximum output in Egypt. The model proposed a change in the cropping pattern to obtain maximum benefits. García-Vila and Fereres [37] analyzed the relationship of global climate and rainfall in Indonesia and proposed a change in cropping pattern.

Many studies have focused on water allocation models [38–51]. However, most of these studies were intended to use as a planning tool for crop selection and seasonal allocations of land and water to crop rotations. These choices are not intended for scheduling water applications during the growing season to maximize the return. Therefore, present study aims to assess the balance between the available water supplies and the water demands at the command area based on the crops grown in the area and cropping intensity.

2 Material and Methods

2.1 Study Area

This study was carried out in the Kasur district of Punjab province of Pakistan. The Kasur minor originates from the Thamman distributary as shown in Fig. 1. Thamman distributary originates from the Bhambanwala Ravi Bedian Depalpur (BRBD) canal. The total length of the Kasur minor is 18 km. The total discharge at the head of the Kasur minor is 1.97 m^3/s for a total culturable command area of 9113.53 hectares. The slope of the bed in Kasur minor is 0.3 m per kilometer. Two sub-minors, the Lakhneke and Kasur, off-take from the Kasur minor at RD (1 RD = 1000 m) of 8120-R and 51050-L. The head discharges of Lakhneke sub-minor and Kasur sub-minor are 0.39 m^3/s and 0.12 m^3/s, respectively. There are 42 outlets directly off-taking from Kasur minor, 14 outlets from Lakhneke sub-minor and 5 outlets from the Kasur minor. The crop-growing year is divided into two seasons, Kharif (April to September) and Rabi (October to March). Wheat, berseem and oilseed are the Rabi crops, while rice, cotton, maize and sorghum fodder are the Kharif crops. Sugar cane and fruit orchards are the annual crops.

2.2 Data Analysis

2.2.1 Assessment of Required Water Allowance

To calculate the water allowance at water course, sub-minor and minor level, a variety of data were needed. The design discharge data and cultural command area data of the watercourses off-taking from the Kasur minor, Lakhneke sub-minor and Kasur sub-minor were taken from the Irrigation & Power Department, Lahore Division. The climatic data for the Kasur minor command area were collected from the meteorological department, Lahore. The crop coefficient data as reported by [52] were used. Data for the cropping pattern and cropping intensity in the command area of Kasur minor were collected from the statistical department of agriculture Kasur. CROPWAT model [53] based on Penman–Monteith equation was selected for the estimation of reference evapotranspiration because the Penman–Monteith equation has the capability of adequately predicting ET_oin a wide range of locations and climates [54]. For the watercourses of the Kasur minor, the values of field application and conveyance efficiency of watercourses were taken as 70% and 60%, respectively, [55,56]. Thus, the irrigation efficiency for the study area is given as:

$$\begin{aligned}\text{Irrigation Efficiency} &= \text{Field application} \\ &\quad \times \text{conveyance efficiency (watercourses)} \\ &= 0.70 \times 0.60 = 0.42\end{aligned}$$

The conveyance efficiency for both the minor and sub-minor systems was used as 80% [55,56].

The actual volume of water required at the head of watercourse and corresponding water allowance at the head of the minor was estimated by using the following procedure:

1) Potential/ reference evapotranspiration (ET_o) for a given watercourse command was determined by using the climatic data and CROPWAT model.
2) The CROPWAT model was developed by Food and Agriculture Organization of United Nations, in 1990 for planning and management of irrigation projects. CROPWAT model based on Penman–Monteith equation was selected for the estimation of reference evapotranspiration because the equation has the capability of adequately predicting ET_o in wide range of locations

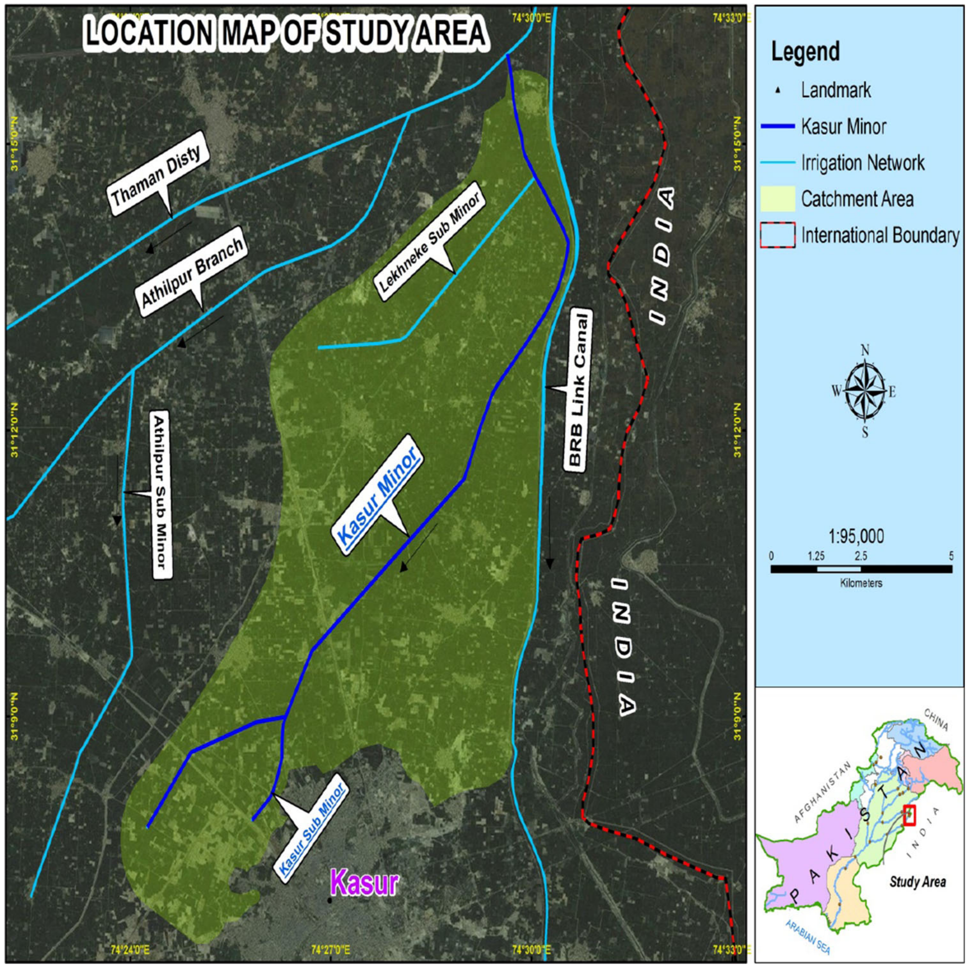

Fig. 1 Location of study area

and climates. CROPWAT model automatically calculated reference evapotranspiration of given crops using monthly climatic data.

3) Actual crop water requirement (ET_a) for the given crop area was determined by multiplying crop coefficient (K_c) and reference evapotranspiration (ET_o).

$$ET_a = ET_0 \times K_c \tag{1}$$

4) Actual seasonal or annual volume of water required (V_R) at the head of water course was determined by multiplying the culturable command area (A) with seasonal or annual cropping intensity (I_i) and ET_a

$$V_R = A \times I_i \times ET_a \tag{2}$$

where i represents the seasonal (Kharif or Rabi) or annual values of the volume of water and intensity.

5) The values of actually required volume of water at crop root zone in a given water course command were converted into an equivalent continuous rate of flow for given season or year by the following equation.

$$Q_{eq} = V_R / T \tag{3}$$

where T is in seconds or years according to intensity.

6) The gross flow rate required at the head of a watercourse was calculated by dividing the equivalent actual flow rate by the irrigation efficiency as given below:

$$Q_R = Q_{eq} / Ei \tag{4}$$

where Q_R is the gross required flow rate at the head of water course and E_i is the irrigation efficiency

7) Irrigation efficiency (E_i) was determined by the equation as given below:

$$Ei = (E_{cw}) \times (E_A) \tag{5}$$

where E_{Cw} is the conveyance efficiency of water course and E_A is the application efficiency in the above equation.

8) The gross flow rate for all the outlets along a given minor was summed up to calculate the required supply at the head of the minor by using the following equation:

$$Q_{\mathrm{R}}(\text{atheadof min}\, or) = \frac{\sum_{i=1}^{i=n} (Q_{\mathrm{R}})_i}{E_{\mathrm{c}}} \tag{6}$$

where Q_{R} is the flow rate required at the head of the water course/ minor and n represents the number of outlets on the selected minor and E_{C} represents the conveyance efficiency of the selected minor from which the watercourses are off-taking.

9) The required water allowance (lps per 404.686 hectares) at a selected minor was calculated by using the following equation:

$$W_{\mathrm{R}} = (Q_{\mathrm{R}} \times 404.686)/\text{Totalcommandarea} \tag{7}$$

The above equation was used to access the water allowance at the head of the branch canal or main canal, if Q_{R} is determined by adding the required flow rate at the head of all the distributaries, minors and sub-minors off-taking from the main or branch canal.

2.2.2 Net Crop Water Requirement

The net crop water requirement (CWR) at the root zone is given by the following equation:

$$\text{Net CWR} = \text{ET}_a + \text{ pre-sowing irrigation} - \text{effective rain fall} \tag{8}$$

2.2.3 Water Allowances for Watercourse Commands

- *Designed Water Allowance* The designed water allowance is defined as the flow rate designed by the Irrigation and Power department for 404.686 hectares (1000 acres) of the culturable command area. The designed water allowances for all the watercourse commands were calculated using the design flow rates and culturable command areas by using Eq. 9:

$$W_{\mathrm{D}} = (Q_{\mathrm{D}}/\text{CCA}) \times 404.686 \tag{9}$$

where,

Q_{D} = Designed discharge, lps
CCA = Culturable command area, ha
W_{D} = Designed water allowance of individual watercourse/minor or distributary, lps/404.686 ha

- Actual Crop Water Requirements It is the actual amount of water required for the agricultural production. Higher value of actual crop water requirement represents a less efficient irrigation system.
- CWAM-Predicted Water Allowance It is the amount of the water required predicted by the model based on the available water resources after incorporating the losses in the irrigation system. Higher value of CWAM-predicted flows depicts a more efficient irrigation system.
- Available Water Allowance It is the amount of the water available at head of the watercourse

2.2.4 Relative Designed Water Allowance

The weighted average water allowance of all the watercourses of minor or sub-minor was determined as:

$$\text{Designed Water Allowance} = \sum_{WC=1}^{WC=n} \frac{\text{CCA} \times W_D}{\sum_{1}^{N} \text{CCA}} \tag{10}$$

The relative designed water allowance was determined by the equation as follows:

$$\text{Relative designed water allowance} = \text{WD}/\text{WeightedaverageWD} \tag{11}$$

2.2.5 Development of Crop Water Allocation Model (CWAM)

The crop water requirement as calculated by CROPWAT model was used as input in Crop Water Allocation Model (CWAM). This model assessed the gross water requirement at the head of each watercourse. By summing the gross water requirements of each watercourse, the requirement of sub-minor and ultimately for minor was determined, based on the existing cropping pattern and cropping intensity of the watercourse. Further, the model distributed the excess or deficit water to all the components of the system, depending upon the availability of the water. The model compared the required water allowance at the head of the minor with the existing water allowance. The inequity indicated the degree to which the crops were being stressed due to the shortage of water supply at a given canal command. Using the actual evapotranspiration of crops, cropping pattern, cropping intensity, the number of days of canal flows in a year and the irrigation efficiency, the water allowance model predicted the required discharge at the head of the watercourse. The water allowance for that command was predicted using the culturable command area (CCA) and the required discharge (Q_{R}). Equation 6 was utilized to predict the water allowance at the head of the sub-minors and the minor. Finally, the Water Allowance Model predicted the actual water allocation for the watercourse commands, minors and the distributary on the basis of available supply at the head of the distributary. The model distributed the excess or shortage of available water to all the components proportionately. The Crop Water Allocation Model (CWAM) was developed in by using MS

Excel Spreadsheets. The input data required for the model are given below:

i. Location of watercourses along the minor and sub-minors
ii. Culturable Command Area (CCA) for each watercourse command.
iii. Climatic Data
iv. Cropping pattern of the command area.
v. Cropping intensity of each crop sown in the command of study area.
vi. Crop coefficient (K_c)
vii. Designed flow rates for each watercourse command
viii. Actual crop evapotranspiration (ET_a)
ix. Irrigation efficiency (E_i)
x. Conveyance efficiency of minor and sub-minors (E_c)
xi. Water available at the head of minor

3 Results and Discussion

3.1 Climate Change Patterns

An analysis of the climatic conditions of the area was performed and found that the means of Tmax and Tmin vary from 19.3 to 39.8 °C and from 12.9 to 33.6 °C, respectively, as shown in Fig. 2. Mean monthly precipitation varies from 6 mm up to 191 mm, whereas mean annual precipitation 627 mm as shown in Fig. 3. The mean annual and distribution of annual precipitation in different seasons is shown in Fig. 4.The climate is characterized by wet periods in June, July and August.

3.2 Designed and Required Water Allowances

The comparison of the designed and required water allowances for the watercourses of Kasur minor is given in Fig. 5. The average designed and required water allowances for the watercourses of Kasur minor are 0.228 lps per 404.686 ha and 0.760 lps per 404.686 ha, respectively. Designed and required water allowances for the water courses of Lakhneke and Kasur sub-minors were also assessed. The comparison of the designed and required water allowances for the watercourses of Lakhneke and Kasur sub-minors is given in Figs. 6 and 7. The average designed and required water allowances for the watercourses of Lakhneke sub-minor were 0.217 lps/404.686 ha and 0.760 lps/404.686 ha, and for Kasur sub-minor these were 0.237 lps/404.686 ha and 0.760 lps/404.686 ha.

3.3 CWAM-Predicted Required Water Allowance (W_R)

The model-predicted required flow rate ranged between 5.550 lps and 383.976 lps with an average value per watercourse command as 113.834 lps. The Crop Water Allocation Model (CWAM)-predicted average required water allowance was 0.760 lps per 404.686 ha for watercourse command. The CWAM-predicted required flow rate for Lakhneke and Kasur sub-minors was 1743.185 lps and 526.127 lps, respectively. The CWAM-predicted average required water allowance for all the sub-minors was found as 0.950 lps per 404.686 ha.

3.4 Model-Predicted Optimal Water Allocation (Q_o)

The CWAM gives the required flow rate (Q_R) on the basis of the crop water requirement. However, the flow rate available in the irrigation system may not match with the required quantities and thus needs to be proportionally decreased or increased to match with the availability. Optimal water allocation (Q_o) for watercourses or minors is the proportionate distribution of the available flow rate at the head of the distributary, to all of watercourses/minors on the basis of the required flow rate (Q_R). The optimal water allocation for the watercourse commands of the Kasur minor ranged between 0.003 lps and 0.219 lps with an average value per watercourse command as 0.064 lps. The optimal water allocation results from the Crop Water Allocation Model (CWAM) were compared with the existing designed flow rate (Q_D) for the watercourses of Kasur (Fig. 8).

3.5 Designed Flow Rate for Watercourses of Minor

The optimal water allocation for the watercourse commands of the Kasur minor ranged between 0.005 lps and 0.219 lps with an average of 0.07 lps, while the existing designed flow rate (Q_D) ranged between 0.003 lps to 0.253 lps with an average of 0.087 lps. By comparing the CWAM-predicted optimal water allocation with the existing designed flow rate, it was found that out of 61 watercourses of Kasur minor, 59 watercourses had less optimal water allocation (Q_O) than the designed flow rate (Q_D) and only two watercourses were found to have more optimal water allocation than the designed flow rate. Figure 9 shows the comparison between existing designed water allowance and CWAM-predicted water allowance for the Lakhneke and Kasur sub-minors. The results showed that the CWAM-predicted water allowance was less than the existing water allowance by 20% for both of the sub-minors.

The CWAM-predicted optimal water allowance (optimal water allocation in lps for 404.686 ha of culturable command area) for the watercourses of Kasur minor was found to be 0.176 lps per 404.686 ha, while for the sub-minors it was found as 0.173 lps per 404.686 ha. The CWAM-predicted

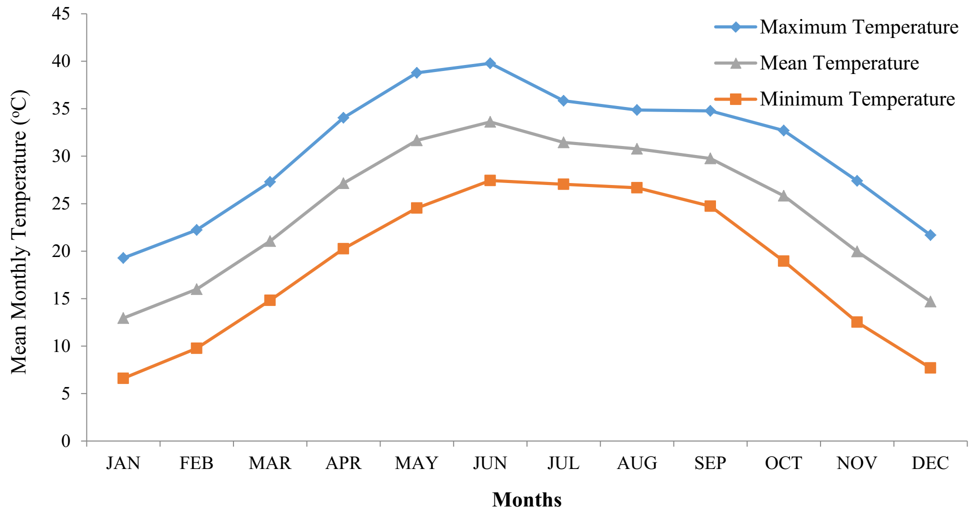

Fig. 2 Mean monthly maximum, minimum and mean temperature in distract Kasur for the period 1961–2015

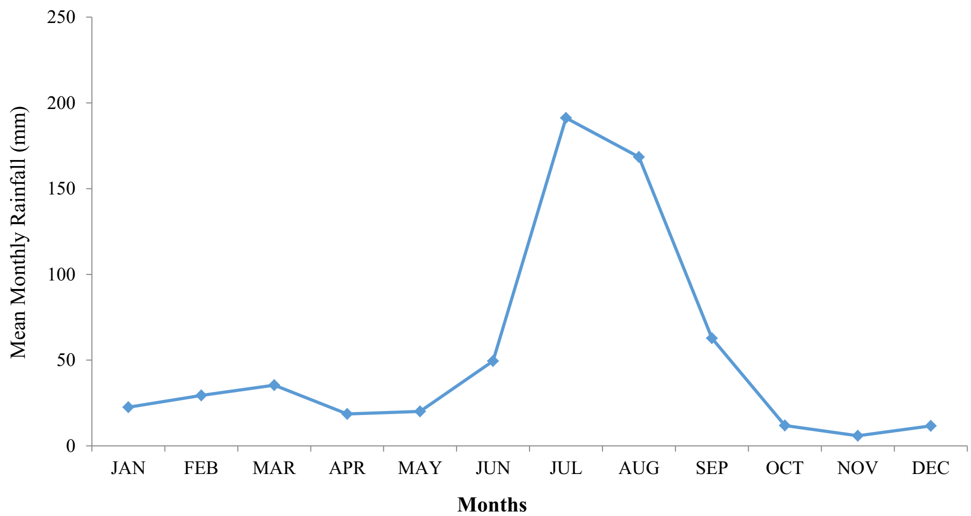

Fig. 3 Mean monthly rainfall in distract Kasur for the period 1961–2015

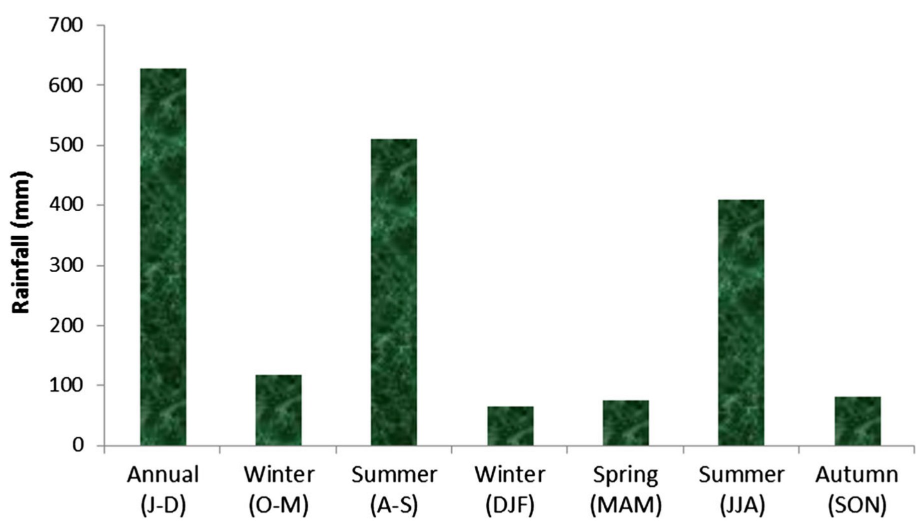

Fig. 4 Mean annual and distribution of annual precipitation in different seasons in Kasur

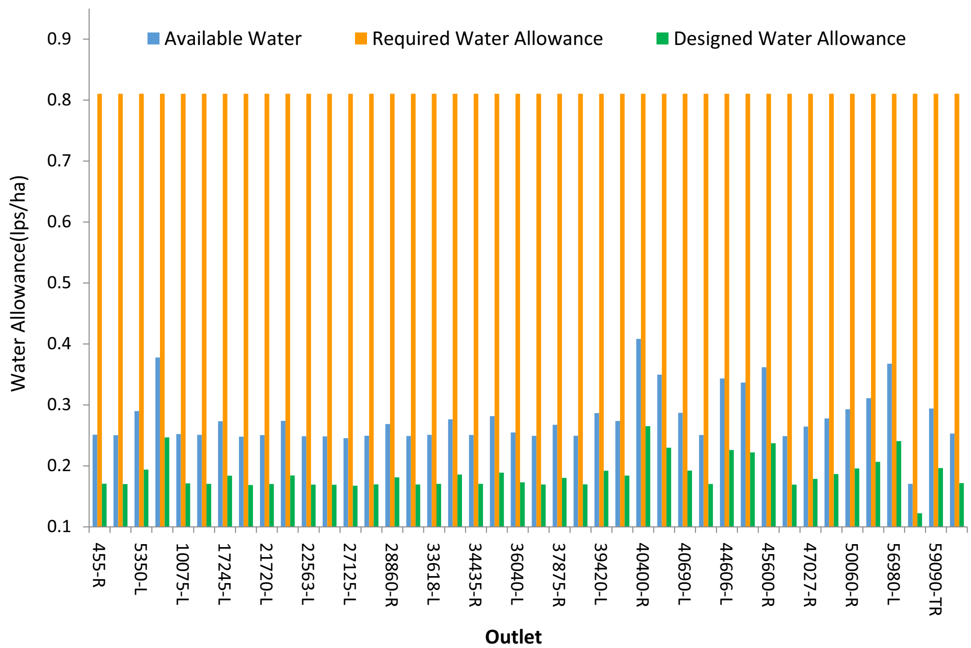

Fig. 5 Comparison of designed and required water allowances for Kasur minor

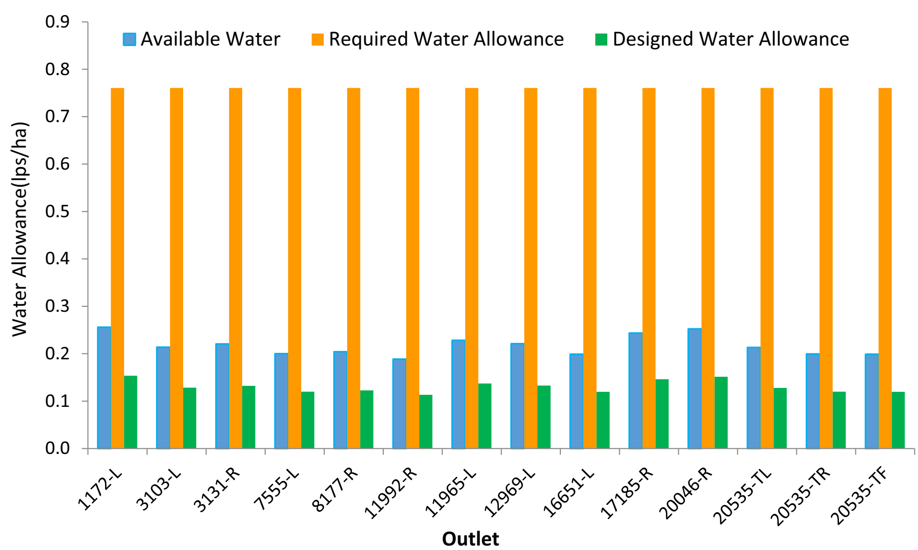

Fig. 6 Comparison of designed and required water allowances for Lakhneke sub-minor

optimal water allowance was more than the average existing designed water allowance which was found as 0.131 lps per 404.686 ha on the basis of all the watercourse commands of the Kasur minor. Therefore, the model-predicted flows were found higher than the designed flows and lead to the more efficient allocation of the limited available water resources.

3.6 Parametric Sensitivity and Scenario Analysis

Sensitivity analysis of different agricultural and climatological parameters were performed to investigate the role of each climate variable used in the computation of reference crop evapotranspiration (ET_o). The projected variations in the precipitation and temperature were estimated based on the previous studies [57,58], and its results are presented in Fig. 10. Sensitivity quantifies the variations in output of a model with respect to variation in the model parameters. Sensitivity analysis is important to understand the connection between climatic conditions and ET_o variability and between data availability and estimation accuracy of ET_o.

The changes in evapotranspiration and crop water requirements in different months with percent change in each climatic factor, i.e., precipitation, maximum temperature (Tmax) and minimum temperature (Tmin) are presented in

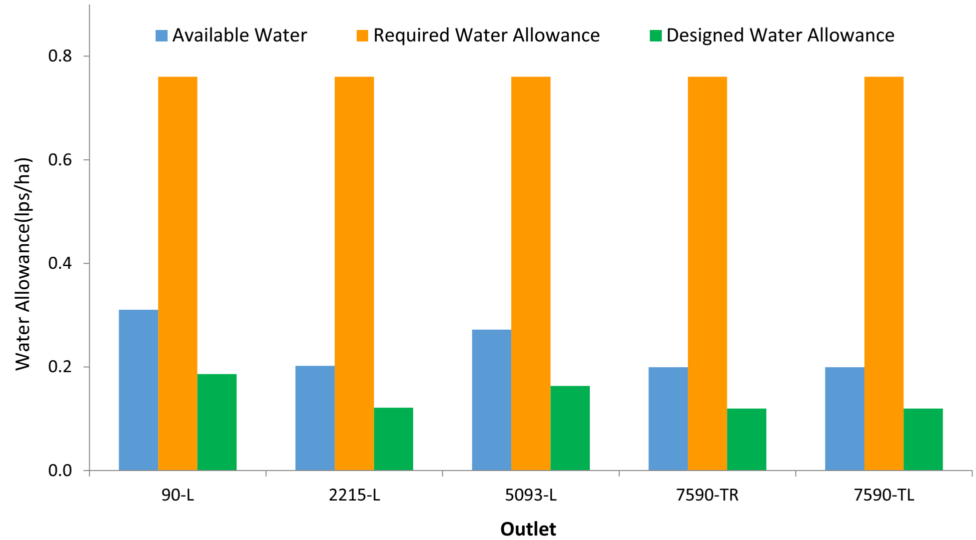

Fig. 7 Comparison of designed and required water allowances for Kasur sub-minor

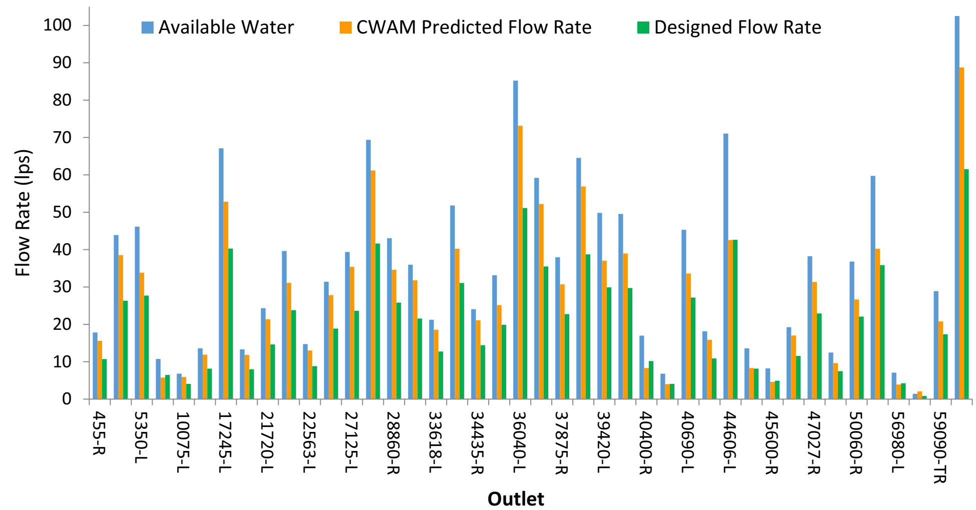

Fig. 8 Comparison of the CWAM-predicted optimal water allocation and the existing

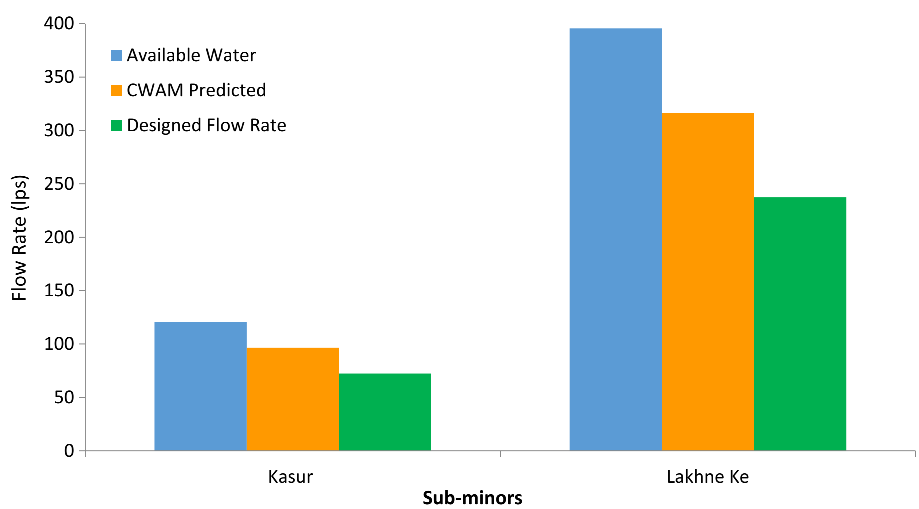

Fig. 9 Comparison of the CWAM-predicted optimal water allocation and the existing designed water allocation for different sub-minors of the Kasur Minor

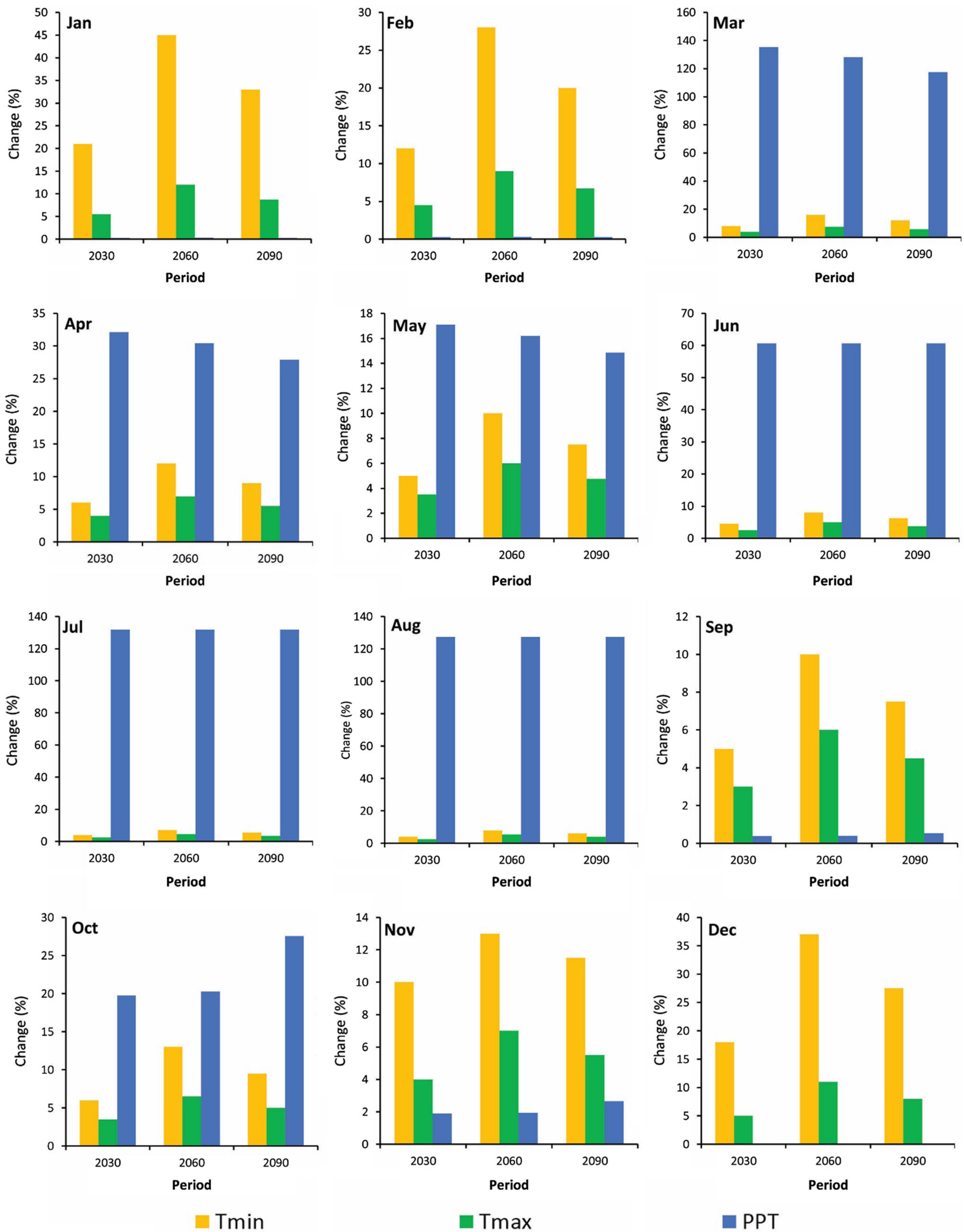

Fig. 10 Future projected changes in Tmin, Tmax and precipitation during periods of 2030, 2060 and 2090

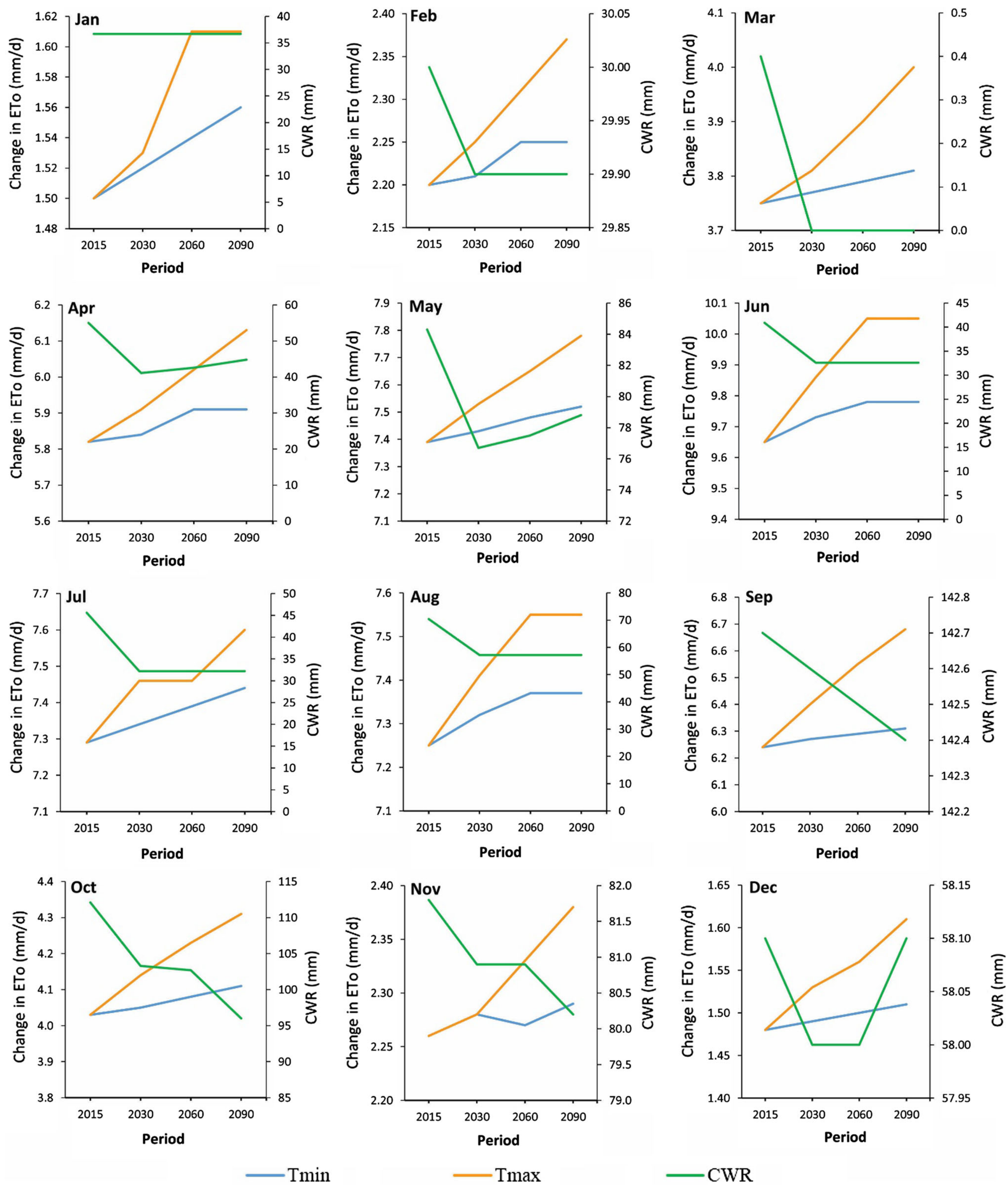

Fig. 11 Impacts of future projected Tmin, Tmax and precipitation on ET_o and crop water requirement (CWR)

Fig. 11. Three (03) separate lines are shown in each figure, which denote the future projected change in evapotranspiration and crop water requirements for percent increase or decrease in each climatic factor. It is observed that the response of evapotranspiration and crop water requirements to future projected change in climatic parameters was linear. It is clear from Fig. 11 that the evapotranspiration is increasing in almost all months due to the increase in the projected future Tmin and Tmax. Moreover, it can also be seen from Fig. 11 that the crop water requirement is decreasing due to the increase in the future projected precipitation.

4 Conclusions

In this study, the water allowance of Kasur minor system was determined by using a Crop Water Allocation Model (CWAM) based on crop water requirement under present conditions. It was found that the existing designed discharges at the head of watercourses, sub-minor and minor fulfill only 29.74, 25.05 and 23%, respectively, of required supplies based on the crop water requirement. The model predicted average optimal water allocation on the basis of available supplies for all the watercourses of minor and sub-minor. The optimal water allowance was found higher than the average designed water allowance. Currently, in Pakistan, supply-based system is practiced allocating the water resources without considering the crop water requirements in different stages of the crops. Therefore, for maximizing the per-unit productivities, crop water requirement-based system should be introduced in irrigation system management from top to bottom level. The designed water allowance at each component of the irrigation system should be modernized to minimize discrepancies among various minors, sub-minors and watercourse system preferably by adopting the crop water requirement-based system in which water should be released according to the crop requirements in different stages, and this may be achieved by the automation of each component of irrigation system.

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References

1. Bandaragoda, D.; Rehman, S.U.: Warabandi in Pakistan's Canal Irrigation Systems-Widening Gap Between Theory And Practice. IWMI, Colombo (1995)
2. Tahir, Z.; Habib, Z.: Land and water productivity trends: across Punjab Cananl, Pakistan. International Water Management Institute (IWMI) 35p. (IWMI working paper 14) (2000)
3. GOP: Agriculture Statistics of Pakistan 2017–18, Pakistan Bureau of Statistics, Govt. of Pakistan (GOP)., Islamabad, Pakistan (2018)
4. Ahmed, N.; Akmal, M.; Khan, A.; Ali, J.: Climate Change and Adaptation—Farmers' Experiences from Rainfed Areas of Pakistan. University of Agriculture, Climate Change Centre, Peshawar (2014)
5. Kiktev, D.; Sexton, D.M.H.; Alexander, L.; Folland, C.K.: Comparison of modeled and observed trends in Indices of daily climate extremes. J. Clim. **16**, 3560–3571 (2003). https://doi.org/10.1175/1520-0442(2003)016<3560:COMAOT>2.0.CO;2
6. Thiery, W.; Davin, E.L.; Lawrence, D.M.; Hirsch, A.L.; Hauser, M.; Seneviratne, S.I.: Present-day irrigation mitigates heat extremes. J. Geophys. Res. Atmos. **122**, 1403–1422 (2017). https://doi.org/10.1002/2016JD025740
7. Abid, M.; Schneider, U.A.; Scheffran, J.: Adaptation to climate change and its impacts on food productivity and crop income: perspectives of farmers in rural Pakistan. J. Rural Stud. **47**, 254–266 (2016). https://doi.org/10.1016/J.JRURSTUD.2016.08.005
8. Abid, M.; Ngaruiya, G.; Scheffran, J.; Zulfiqar, F.; Abid, M.; Ngaruiya, G.; Scheffran, J.; Zulfiqar, F.: The role of social networks in agricultural adaptation to climate change: implications for sustainable agriculture in Pakistan. Climate **5**, 85 (2017). https://doi.org/10.3390/cli5040085
9. Waqas, A.; Hong, C.; Maroof, A.M.; Rana, R.M.; Saima, A.; Ali, A.: Comparison of Organic Farming and Conventional Farming In the Punjab. Pakistan. **8**, (2017)
10. Zulfiqar, F.; Datta, A.; Thapa, G.B.: Determinants and resource use efficiency of "better cotton": an innovative cleaner production alternative. J. Clean. Prod. **166**, 1372–1380 (2017). https://doi.org/10.1016/J.JCLEPRO.2017.08.155
11. Ali, A.; Erenstein, O.: Assessing farmer use of climate change adaptation practices and impacts on food security and poverty in Pakistan. Clim. Risk Manag. **16**, 183–194 (2017). https://doi.org/10.1016/J.CRM.2016.12.001
12. Imran, M.; Ali, A.; Ashfaq, M.; Hassan, S.; Culas, R.; Ma, C.; Imran, M.A.; Ali, A.; Ashfaq, M.; Hassan, S.; Culas, R.; Ma, C.: Impact of climate smart agriculture (CSA) practices on cotton production and livelihood of farmers in Punjab. Pak. Sustain. **10**, 2101 (2018). https://doi.org/10.3390/su10062101
13. Khatri-Chhetri, A.; Aggarwal, P.K.; Joshi, P.K.; Vyas, S.: Farmers' prioritization of climate-smart agriculture (CSA) technologies. Agric. Syst. **151**, 184–191 (2017). https://doi.org/10.1016/j.agsy.2016.10.005
14. Bank, C.W.: Climate-Smart Agriculture in Pakistan. CSA Country Profiles for Asia Series. International Center for Tropical Agriculture (CIAT); The World Bank, Washington, DC (2017)
15. Bandaragoda, D.J.: Design and practice of water allocation rules?: Lessons from Warabandi in Pakistan ' s Punjab. Surviv. Commons mounting challenges new realities, Elev. Conf. Int. Assoc. Study Common Prop. 25 (2006). https://doi.org/10.3910/2009.002
16. Acharjee, T.K.; Ludwig, F.; van Halsema, G.; Hellegers, P.; Supit, I.: Future changes in water requirements of Boro rice in the face of climate change in North-West Bangladesh. Agric. Water Manag. **194**, 172–183 (2017). https://doi.org/10.1016/J.AGWAT.2017.09.008
17. Ahmad, S.; Abbas, Q.; Abbas, G.; Fatima, Z.; Atique-ur-Rehman, Naz, S.; Younis, H.; Khan, R.; Nasim, W.; Habib ur Rehman, M.; Ahmad, A.; Rasul, G.; Khan, M.; Hasanuzzaman, M.: Quantification of climate warming and crop management impacts on cotton phenology. Plants. 6, 7 (2017). doi:https://doi.org/10.3390/plants6010007
18. Shakir, A.S.; Khan, N.M.; Qureshi, M.M.: Canal water management: Case study of upper chenab canal in Pakistan. Irrig. Drain. **59**, 76–91 (2010). https://doi.org/10.1002/ird.556
19. Akhtar, M.; Ahmad, N.; Booij, M.J.: The impact of climate change on the water resources of Hindukush–Karakorum–Himalaya region under different glacier coverage scenarios. J. Hydrol. **355**, 148–163 (2008)

20. Amin, A.; Nasim, W.; Mubeen, M.; Ahmad, A.; Nadeem, M.; Urich, P.; Fahad, S.; Ahmad, S.; Wajid, A.; Tabassum, F.; Hammad, H.M.; Sultana, S.R.; Anwar, S.; Baloch, S.K.; Wahid, A.; Wilkerson, C.J.; Hoogenboom, G.: Simulated CSM-CROPGRO-cotton yield under projected future climate by SimCLIM for southern Punjab. Pak. Agric. Syst. (2017). https://doi.org/10.1016/J.AGSY.2017.05.010
21. Awan, U.K.; Liaqat, U.W.; Choi, M.; Ismaeel, A.: A SWAT modeling approach to assess the impact of climate change on consumptive water use in Lower Chenab Canal area of Indus basin. Hydrol. Res. **47**, 1025–1037 (2016). https://doi.org/10.2166/nh.2016.102
22. Volschenk, T.: Evapotranspiration and crop coefficients of golden delicious/M793 apple trees in the Koue Bokkeveld. Agric. Water Manag. **194**, 184–191 (2017). https://doi.org/10.1016/J.AGWAT.2017.09.002
23. Beshir, S.: Review on estimation of crop water requirement, irrigation frequency and water use efficiency of cabbage production. J. Geosci. Environ. Prot. **05**, 59–69 (2017). https://doi.org/10.4236/gep.2017.57007
24. Mahmoud, M.A.; El-Bably, A.Z.: Crop water requirements and irrigation efficiencies in Egypt, Part of the Handbook of Environmental Chemistry. 1–17
25. Kadbhane, S.J.; Manekar, V.L.: An experimental study on the grape orchard: effects comparison of two irrigation systems. J. Water L. Dev. **32**, 41–51 (2017). https://doi.org/10.1515/jwld-2017-0005
26. Tellen, V.A.: A comparative analysis of reference evapotranspiration from the surface of rainfed grass in Yaounde, calculated by six empirical methods against the penman-monteith formula. Earth Perspect. **4**, 4 (2017). https://doi.org/10.1186/s40322-017-0039-1
27. Liaqat, U.W.; Choi, M.; Awan, U.K.: Spatio-temporal distribution of actual evapotranspiration in the indus basin irrigation system. Hydrol. Process. **29**, 2613–2627 (2015). https://doi.org/10.1002/hyp.10401
28. Afzal, M.: Planning irrigation requirements. In: Symposium on Water Resources Development. West Pakistan Engineering Congress vol. 11, pp. 13–40 (1969)
29. Latif, M.; Sarwar, S.: Proposal for equitable water allocation for rotational irrigation in Pakistan. Irrig. Drain. Syst. **8**, 35–48 (1994). https://doi.org/10.1007/BF00880797
30. Ahmad, S.; Heermann, D.F.: Computerized scheduling for irrigation management and pumping operations in the watercourse command. Agric. Water Manag. **18**, 1–13 (1990). https://doi.org/10.1016/0378-3774(90)90031-S
31. Hannan, T.; Coals, V.: Real-time water allocation for irrigation. Water Environ. J. **9**, 19–26 (1995). https://doi.org/10.1111/j.1747-6593.1995.tb00922.x
32. Shafiq, M.; Latif, M.: A model for efficient distribution of irrigation supplies among distributaries. Pak. Eng. Congr. **64**, 167–200 (1992)
33. Vander Velde, E.J.; Kijne, J.W.: Salinity and irrigation operations in Punjab, Pakistan: are there management options? In: Proceedings of the Workshop on Research in Irrigation Management. International Irrigation Management Institute (IIMI), New Delhi, India. Colombo, Sri Lanka (1992)
34. Global Water Partnership: Towards water security: Framework for Action. Glob. Water Partnersh. **10**, (2000)
35. Sarwar, S.; Nafees, H.M.; Shafique, M.S.: Fluctuations in Canal Water Supplies (A Case Study). Research Report: R-27., Pakistan National Program. International Irrigation Management Institute, Lahore (1997)
36. Osama, S.; Elkholy, M.; Kansoh, R.M.: Optimization of the cropping pattern in Egypt. Alexandria Eng. J. (2017). https://doi.org/10.1016/j.aej.2017.04.015
37. García-Vila, M.; Fereres, E.: Combining the simulation crop model AquaCrop with an economic model for the optimization of irrigation management at farm level. Eur. J. Agron. **36**, 21–31 (2012). https://doi.org/10.1016/j.eja.2011.08.003
38. Shangguan, Z.; Shao, M.; Horton, R.; Lei, T.; Qin, L.; Ma, J.: A model for regional optimal allocation of irrigation water resources under deficit irrigation and its applications. Agric. Water Manag. **52**, 139–154 (2002)
39. Reca, J.; Roldán, J.; Alcaide, M.; López, R.; Camacho, E.: Optimisation model for water allocation in deficit irrigation systems. Agric. Water Manag. **48**, 117–132 (2001). https://doi.org/10.1016/S0378-3774(00)00127-X
40. Li, M.; Guo, P.; Singh, V.P.: An efficient irrigation water allocation model under uncertainty. Agric. Syst. **144**, 46–57 (2016). https://doi.org/10.1016/j.agsy.2016.02.003
41. Doulgeris, C.; Georgiou, P.; Papadimos, D.; Papamichail, D.: Water allocation under deficit irrigation using MIKE BASIN model for the mitigation of climate change. Irrig. Sci. **33**, 469 (2015). https://doi.org/10.1007/s00271-015-0482-4
42. Linker, R.; Ioslovich, I.; Sylaios, G.; Plauborg, F.; Battilani, A.: Optimal model-based deficit irrigation scheduling using AquaCrop: a simulation study with cotton, potato and tomato. Agric. Water Manag. **163**, 236–243 (2016). https://doi.org/10.1016/j.agwat.2015.09.011
43. Jiang, Y.; Xu, X.; Huang, Q.; Huo, Z.; Huang, G.: Optimizing regional irrigation water use by integrating a two-level optimization model and an agro-hydrological model. Agric. Water Manag. **178**, 76–88 (2016). https://doi.org/10.1016/j.agwat.2016.08.035
44. Fereres, E.; Soriano, M.A.: Deficit irrigation for reducing agricultural water use. J. Exp. Bot. **58**, 147–159 (2007)
45. Klocke, N.L.; Stone, L.R.; Clark, G.A.; Dumler, T.J.; Briggeman, S.: Water allocation model for limited irrigation. Appl. Eng. Agric. **22**, 381–389 (2006). https://doi.org/10.13031/2013.20458
46. Kloss, S.; Pushpalatha, R.; Kamoyo, K.J.; Schütze, N.: Evaluation of crop models for simulating and optimizing deficit irrigation systems in arid and semi-arid countries under climate variability. Water Resour. Manag. **26**, 997–1014 (2012). https://doi.org/10.1007/s11269-011-9906-y
47. Georgiou, P.E.; Papamichail, D.M.: Optimization model of an irrigation reservoir for water allocation and crop planning under various weather conditions. Irrig. Sci. **26**, 487–504 (2008). https://doi.org/10.1007/s00271-008-0110-7
48. Sadati, S.K.; Speelman, S.; Sabouhi, M.; Gitizadeh, M.; Ghahraman, B.: Optimal irrigation water allocation using a genetic algorithm under various weather conditions. Water (Switzerland) **6**, 3068–3084 (2014). https://doi.org/10.3390/w6103068
49. Garg, N.K.; Dadhich, S.M.: Integrated non-linear model for optimal cropping pattern and irrigation scheduling under deficit irrigation. Agric. Water Manag. **140**, 1–13 (2014). https://doi.org/10.1016/j.agwat.2014.03.008
50. Bernardo, D.J.; Whittlesey, N.K.; Saxton, K.E.; Bassett, D.L.: An Irrigation Model for Management of Limited Water Supplies. West. J. Agric. Econ. **12**, 164–173 (1987). https://doi.org/10.2307/40987866
51. Delavar, M.; Moghadasi, M.; Morid, S.: Real-Time Model for Optimal Water Allocation in Irrigation Systems during Droughts. J. Irrig. Drain. Eng. **138**, 517–524 (2012). https://doi.org/10.1061/(ASCE)IR.1943-4774.0000440
52. Ullah, M.K.; Habib, Z.; Muhammad, S.: Spatial Distribution of Reference And Potential Evapotranspiration Across The Indus Basin Irrigation Systems. International Water Management Institute, Lahore (2001)
53. Smith, M.: CROPWAT: A Computer Program for Irrigation Planning and Management. Food and Agriculture Organization, Rome (1992)
54. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M.; Ab, W.: Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. (1998)
55. PARC-FAO: Farm water management. Proceedings of Expert Consultation on Farm Water Management., Islamabad (1981)

56. WAPDA: Revised Action Plan for Irrigated Agriculture, Master Planning and Review Division, WAPDA, Pakistan (1979)
57. Ghumman, A.R.; Hassan, I.; Khan, Q.U.Z.; Kamal, M.A.: Investigation of impact of environmental changes on precipitation pattern of Pakistan. Environ. Monit. Assess. **185**, 4897–4905 (2013). https://doi.org/10.1007/s10661-012-2911-7
58. Fahad, S.; Ameen, A.; Ahmad, A.; Shahzad, B.; Mirza, N.; Amanullah,; Hammad, H.M.; Urich, P.; Khan, M.N.; Mubarak, H.; Alharby, H.; Ullah, A.; Saud, S.; Ata-Ul-Karim, S.T.; Ahamd, S.; Islam, F.; Mubeen, M.; Rehmani, M.I.A.; Khaliq, T.; Adnan, M.; Ali, Q.S.; Rasul, F.; Wahid, A.; Sarwar, S.; Amin, A.; Nasim, W.; Wajid, A.: Regional climate assessment of precipitation and temperature in Southern Punjab (Pakistan) using SimCLIM climate model for different temporal scales. Theor. Appl. Climatol. **131**, 121–131 (2016). https://doi.org/10.1007/s00704-016-1960-1