Original Research Article

Impact Assessment of Climate Change on Water Requirements for Summer Paddy Cultivation in Raipur District, Chhattisgarh

ABSTRACT

Water is a crucial and finite resource, primarily utilized for irrigation, necessitating effective distribution for long-term sustainability. This study quantifies the water requirements for summer paddy cultivation in Raipur district, Chhattisgarh, and assesses its implications under changing climatic conditions.The FAO-CROPWAT 8.0 model was applied to assess irrigation parameters using historical meteorological data from 2000 to 2020 and projected meteorological data from 2040 to 2100. Reference evapotranspiration (ET_0) was estimated using the FAO Penman-Monteith method, incorporating crop coefficient (Kc) values to determine crop evapotranspiration (ETc). Irrigation water requirements were estimated by accounting for various losses and efficiencies of crop and field. Comprehensive water balance models were developed for across the century, focusing on a 20-year average time span, including the historical period as 2000-2020 and two socio-economic scenarios: SSP2-4.5 and SSP5-8.5 for predicted future climate, along with soil, meteorological, and phenological factors. Over the baseline period, the crop water requirement (CWR) for summer paddy was calculated as 751.4 mm, with net irrigation water requirement (NIWR) and gross irrigation water requirement (GIWR) as 1094.7 mm and 1563.8 mm, respectively. Under SSP2-4.5, the minimum and maximum temperatures are projected to rise by 1.3 °C and 1 °C respectively with rainfall increasing by 378.5 mm. This scenario anticipates a CWR increase of 32.6 mm by century's end, resulting in final values of CWR as 784 mm, NIWR as 1164.7 mm, and GIWR as 1663.9 mm. In the SSP5-8.5 scenario, temperatures are expected to rise by 4.4 °C and 3.1 °C as minimum and maximum temperature, leading to a CWR of 800.4 mm, with NIWR and GIWR as 1176.5 mm and 1680.7 mm, respectively. Overall, most parameters indicate an upward trend throughout the century. This study provides critical insights for efficient irrigation management in summer paddy cultivation and highlights the implications of future climate change on irrigation needs, promoting sustainable agricultural practices.

Keywords: Climate Change Adaptation, Sustainable Agriculture, Summer paddy, Water Requirements, Irrigation Management, Water Resource Management.

1. INTRODUCTION

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Water is a crucial resource, especially in agriculture, where it is vital for maintaining food production and guaranteeing food security. Agriculture in India constitutes over 70% of total freshwater withdrawals, underscoring its importance for the economy and lives (FAO, 2021). Nonetheless, the nation has significant water scarcity issues, with forecasts suggesting that 600 million people may experience water shortages by 2030 (NITI Aayog, 2018). Inefficient water management methods worsen this situation, resulting in water scarcity and deterioration of water quality (Sharma et al., 2018). Enhancing irrigation efficiency might save up to 50% of the water currently used in agriculture without diminishing crop yields (Kumar et al., 2019).

Paddy cultivation is vital in India, occupying a quarter of cultivated land and serving as a staple food source for half the population (FAO, 2020). Chhattisgarh, known as the "Rice Bowl" of Central India, is renowned for its significant paddy production (Ram et al., 2023). In addition to paddy, the summer months traditionally has cultivation of oilseeds, millets, and pulses. However, the recent increase in summer paddy cultivation raises concerns regarding sustainable water management (Mongabay India, 2020). Despite government recommendations favoring oilseeds and pulses, farmers increasingly choose summer paddy due to its higher yields linked to favorable weather and lower pest incidence (Mongabay India, 2020).

Effective irrigation management is crucial for maintaining food security in areas with unpredictable rainfall patterns, particularly during the summer season. Understanding the evapotranspiration (ET) and crop water requirement (CWR) is crucial for optimizing irrigation scheduling and enhancing water use efficiency in agriculture (Doorenbos & Pruitt, 1977). Accurate CWR estimation is vital for sustainable irrigation management (Allen et al., 1998; Smith et al., 2009). This study utilizes the CROPWAT 8.0 model to evaluate the irrigation requirements of summer paddy and the influence of climate on it, consequently helping to sustainable water management.

The FAO-CROPWAT 8.0 software estimates CWR based on environmental variables and specific crop needs (FAO, 2012). By leveraging computer-based simulation models like CROPWAT 8.0, researchers can enhance irrigation planning and water resource management strategies (FAO, 2012). Integrating accurate CWR estimation into irrigation scheduling minimizes water wastage, maximizes agricultural productivity, and ensures sustainable water resources in agriculture (Allen et al., 1998; Smith et al., 2009).

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Climate change poses significant challenges for agriculture through long-term alterations in temperature and precipitation patterns. These changes may increase the frequency and intensity of droughts and floods like extreme weather events, leading to reduced water availability and decreased crop yields in irrigated agriculture (FAO, 2020). Projections indicate that South Asia could experience a temperature rise of 3.5–5.5°C by 2100 alongside intensified monsoon precipitation (Pradhan et al., 2019), with economic implications such as a projected GDP decrease of 5% for every 2°C increase in temperature (Singh et al., 2014).

Effective adaptation strategies will be essential to manage risks associated with climate change impacts on irrigation (FAO, 2020). Rising temperatures will increase evapotranspiration rates, heightening irrigation demands; however, altered precipitation patterns may reduce available water resources, leading to potential crop failures. Utilizing Global Circulation Models (GCMs) allows for assessments of future climate data to mitigate climate change impacts. These models simulate interactions among the atmosphere, ocean, cryosphere, and land surface using fluid dynamics and thermodynamics principles. They provide valuable insights into climate shifts over various time periods and help scientists detect resonances and thresholds that inform future research.

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In summary, addressing climate change and water scarcity challenges, particularly regarding summer paddy cultivation, underscores the importance of efficient water management practices. Tools like CROPWAT 8.0 for CWR estimation and irrigation scheduling can significantly enhance sustainable water use and food security in regions like Chhattisgarh that heavily rely on irrigation for crop production.

2. MATERIALS AND METHODS

2.1 Description of study area

Chhattisgarh, established as India's 26th state on November 1, 2000, is geographically located between 17°46' and 24°05' North Latitude and 80°15' and 84°20' East Longitude (Kumar et al., 2021). The state features three agroclimatic zones: the Bastar Plateau, Chhattisgarh Plain, and Northern Hill. The Chhattisgarh Plain Zone, defined by latitude 21°N to 23°N and longitude 81°E to 83°E, encompasses 15 districts, including Raipur. The region receives an average annual rainfall of approximately 1200 mm and has a net sown area of 4.67 million hectares, representing 34% of its total geographical area of 13.78 million hectares. The main crops of study areas are paddy, wheat, maize, sugarcane, and pulses. (Yadu et al., 2021). A field experiment was conducted in the Department of Soil Science and Agricultural Chemistry at Indira Gandhi Krishi Vishwavidyalaya to simulate crop responses and to collect field observations for the study.

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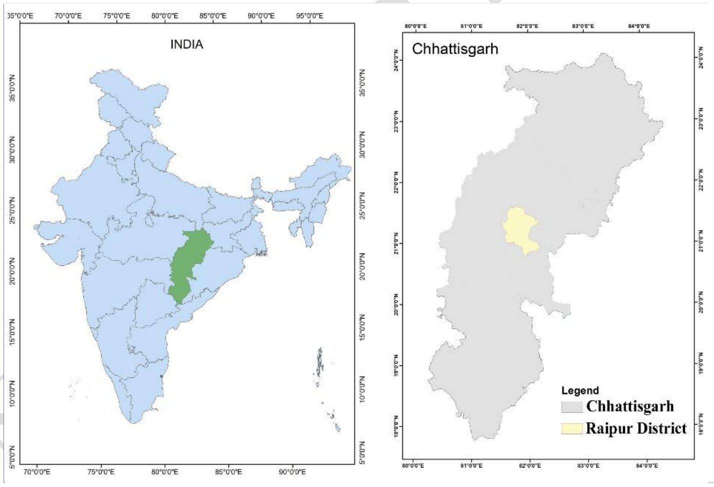

Fig. 1. Location map of study area

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2.2 Overview of the model

CROPWAT 8.0 is a software created by FAO that utilizes soil, climate, and agricultural management datasets to evaluate crop water requirements and irrigation demands. The program also facilitates the creation of irrigation schedules and is compatible with several crop management practices. The CROPWAT program uses FAO methods and the Penman-Monteith

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equation to compute reference crop evapotranspiration (ET_0). Crop evapotranspiration (ETc) is then calculated by taking into account the crop coefficient (Kc) for various phases of crop growth. Following accounting for the losses and irrigation efficiencies, the net irrigation and gross irrigation water requirements are calculated.

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2.3 Meteorological data

The study encompasses multiple temporal phases in the average time spans of 20 years, including the historical period from 2000 to 2020 (2020s) and future forecasts extending into the 2040s (2021–2040), 2060s (2041–2060), 2080s (2061–2080), and 2100s (2081–2100). The projections are based on selected shared socioeconomic pathways (SSPs), specifically SSP2_4.5 and SSP5_8.5. This analysis involves a comparative assessment between the baseline period and other time spans of future time periods, aiming to evaluate the impacts of climate change.

2.3.1 Historical data

The daily meteorological data from 2000 to 2020 (2020s) serve as the baseline period, encompassing parameters such as maximum temperature, minimum temperature, precipitation, relative humidity, wind velocity, evaporation, and sunlight duration. This data was sourced from the Department of Agrometeorology at Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh. The aforementioned data were utilized to accurately simulate the experimental location due to its proximity to the agro-meteorological observatory.

2.3.2 Projected climate data

The future simulation utilized climate data from the Coupled Model Inter-Comparison Project Phase 6 (CMIP6), comprising thirteen Global Circulation Models (GCMs) obtained from Zenedo, CERN Data Centre (Mishra et al., 2020). This dataset includes bias-corrected gridded data for precipitation, maximum and minimum temperatures, with each model representing five scenarios: historical, SSP1_2.6, SSP2_4.5, SSP3_7.0, and SSP5_8.5. Historical data spans from 1951 to 2014, while future projections extend from 2015 to 2100. These models simulate interactions among the atmosphere, ocean, cryosphere, and land surface using principles of fluid dynamics and thermodynamics.

2.3.3 Selection of GCM model

To assess model performance, a comparative analysis was performed for the historical period spanning 1951 to 2014. This analysis contrasted simulated data produced by the General Circulation Model (GCM) with observed data obtained from the Indian Meteorological Department (IMD), Pune. Gridded datasets from both sources were standardized in terms of scale and parameters, including rainfall, maximum, and minimum temperatures. The evaluation was done by utilizing a range of statistical metrics, including R^2, PBIAS, RMSE, and NSE. Figure 2 illustrates the methodology employed in selecting the most suitable GCM models.

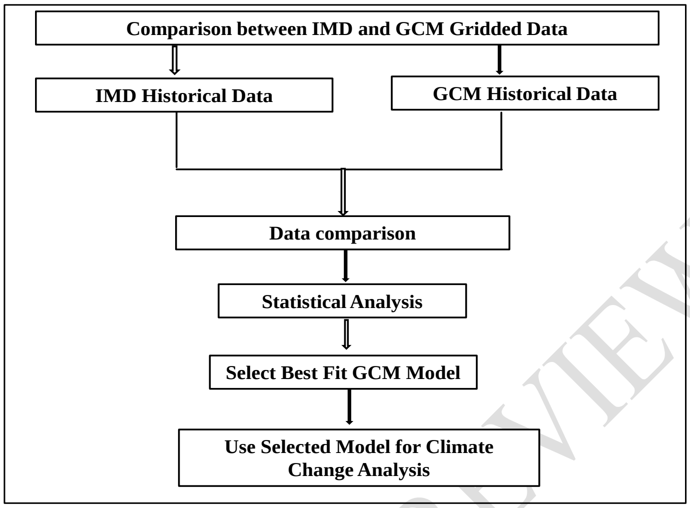

Fig.2. Flow chart for selection of climatic model

2.4 Field experiment and sampling details

During the summer seasons of 2023 and 2024, paddy trials were executed at the Department of Soil Science and Agricultural Chemistry, Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh.The research included the production of the rice variety MTU 1010, a 120-day crop recognized for its short lifespan and an average rooting depth of 50 cm,this quality makes it well-suited for summer cultivation. The summer paddy nursery is typically sown in mid-January and transplanted during the first week of February. The mature crop is usually harvested by mid-May after the full crop cycle has been completed.The trials involved systematic data collection on crop management and irrigation practices across various growth stages, focusing on yield forecasting metrics. Key crop attributes such as field preparation, growth phase durations, rooting depth, panicle initiation, and maturation times were meticulously recorded. Soil sampling from the experimental field was also collected and tested for relevant parameters. Technical information on data needed was obtained from the help section of the CROPWAT 8.0 model, which clarifies the essential inputs. Additionally, extensive datasets from credible sources, such as FAO publications and other research projects, were considered for further insights and verification. The sampling and outcomes from these summer experiments will help in climate change analyses by utilizing constant values for crop, soil, and related parameters, facilitating simulations for long-term irrigation management strategies.This rigorous methodology aimed to enhance understanding of paddy cultivation dynamics under varying environmental conditions of climate change.

2.5Soil data

The soil sample that was collected from the field experiment was gone through the laboratory analysis at the Department of Soil Science and Agricultural Chemistry, IGKV, Raipur, Chhattisgarh. The results show thesoil type in the field was identified as *vertisols*. The CROPWAT 8.0 program necessitates specific soil-related parameters, such as total available soil moisture, maximum rooting depthand initial available soil moisture. These parameters were determined based on correlated variables outlined in the FAO 56 manual.

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2.6 Rainfall data

Rainfall data spanning 20 years (2000 to 2020) was gathered from the agrometeorological Station at IGKV Raipur. The daily average data for these 20 years was computed using Excel and utilized as input in the CROPWAT software. To determine effective rainfall, a fixed percentage method was employed for the study, where effective rainfall was considered as 70 % of the total rainfall. Effective rainfall represents the portion of total annual or seasonal rainfall (or any precipitation event) that directly or indirectly contributes to crop production. The efficacy of rainfall is influenced by various factors, including land and soil physical and chemical properties, meteorological conditions, and rainfall characteristics.

2.7Irrigation Terminologies

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Evapotranspiration (ET) is the combined process of water vaporization from surfaces and transpiration from plant leaves. Reference evapotranspiration (ET_0) denotes the water demand of an ideal grass crop, defined by certain characteristics and an adequate water supply. It evaluates atmospheric evapotranspiration demand, irrespective of factors such as crop type, soil characteristics, growth phases, and management approaches. (Pereira et al. 2021). The FAO Penman-Monteith equation calculates ET_0 using variables such as radiation, temperature, humidity, wind speed, and precipitation etc. Crop water requirement (CWR) denotes the volume of water necessary to compensate for evapotranspiration losses from a crop, calculated using the equation ($CWR = Kc \times ET0$) in millimeters, where Kc represents the crop coefficient that indicates the specific water needs during different stages of crop development. (Pereira et al., 2015). The irrigation water requirement (IR) is the volume of water necessary to meet crop evapotranspiration, taking into account effective rainfall and the water supplied by precipitation. Net irrigation water requirement (NIWR) includes all water necessary for crop development, including for losses such as percolation, leaching, application, and other losses. Furthermore, including irrigation efficiency in NIWR results in the Gross Irrigation Water Requirement (GIWR) (Michael, 2008). Figure 3 illustrates a flowchart depicting the methodology for estimating crop water requirements and irrigation needs.

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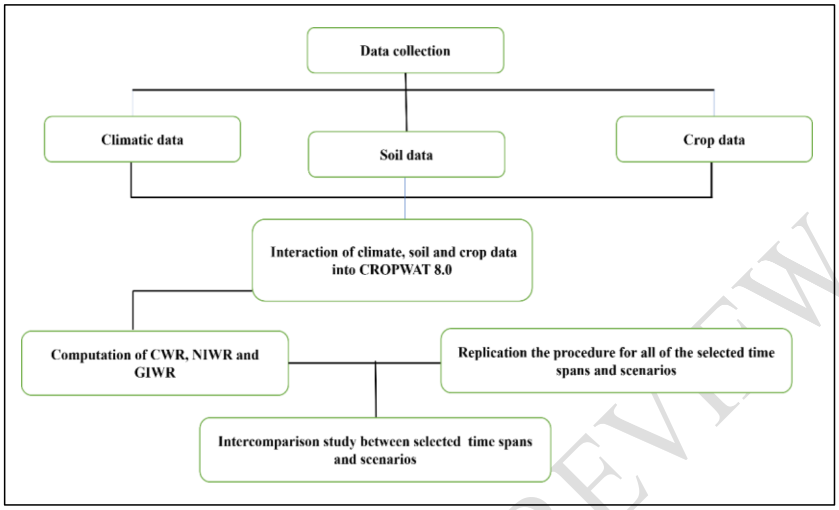

Fig. 3. Flowchart for approaches used in CROPWAT 8.0

2.8 Climate change study

The comprehensive study has done for across the century, focusing on a 20-year average time span, including the historical period as 2000-2020 and two socio-economic scenarios: SSP2-4.5 and SSP5-8.5 for predicted future climate, which represent moderate and extreme future climate changes, respectively. These scenarios are endorsed by the Intergovernmental Panel on Climate Change (IPCC) and the Scenario Model Inter-comparison Project (Scenario MIP) for assessing climate change impacts. The historical analysis utilizes daily average meteorological data from 2000 to 2020, incorporating key parameters such as minimum and maximum temperatures (°C), wind speed (km/day), relative humidity (%), sunlight duration, and topographical features including elevation, latitude, and longitude. In the projected future scenarios, all other variables were held constant, with the exception of temperature and precipitation (Allen et al., 2011; Kadioglu et al., 2019). This methodological framework enhances the precision of irrigation management and water resource planning by providing a robust basis for understanding the effects of climate variability on agricultural practices. The findings underscore the importance of integrating socio-economic pathways into climate impact assessments to inform effective adaptation strategies.

3. RESULTS AND DISCUSSIONS

3.1 Monthly average meteorological parameters for base period

The monthly average meteorological data for base period(2020s) were analyzed and shown in graph below which revealed that the lowest temperature in January as low as 11.56 °C and high as 27.82 °C, followed by December with minor deviations at 11.96 °C and 28.18 °C.In contrast, May was the hottest month, with a minimum temperature of 27.14 °C and a maximum of 42.05 °C, followed by June and April. The analysis of rainfall shows that the lowest rainfall occurred in November at 5.4 mm, whereas the highest rainfall occurred during the monsoon period, especially in July, at 361.1 mm.Figure 4 also shows the monthly average meteorological parameters for the cropping period from January to May.

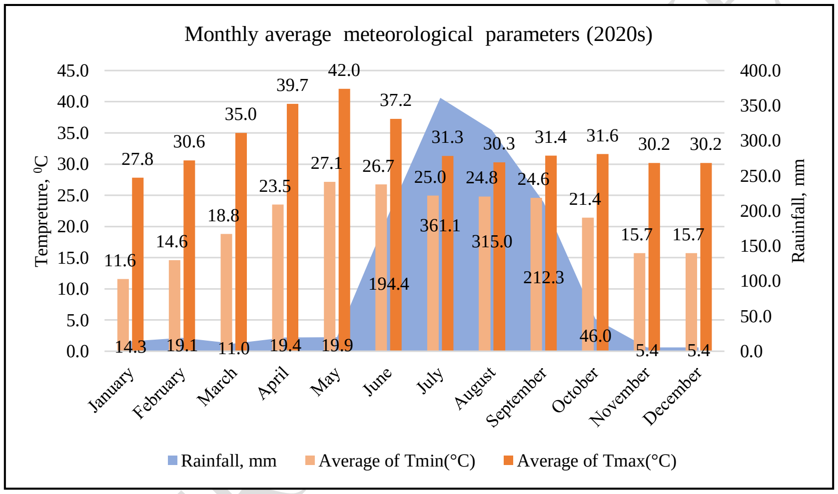

Fig.4.Monthly average meteorological parameters for base period (2020s)

3.2 Climatic variability during crop period

Climate change was studied using the General Circulation Model (GCM), where the ensemble of the best three models out of 13 available GCM models was used for further simulations. The top three models selected by statistical comparison were MPI-ESM1-2-LR, MPI-ESM1-2-HR, and NorESM2-MM. Figure5 shows the variation in climate parameters during the crop period from January to May with historical climate and predicted climate under the SSP2_4.5 scenario. The data shows that the lowest minimum (Tmin) and maximum (Tmax) temperature were found in the base period as 22.5 and 33.0 °C, which is showing a continuous increasing trend in the future time period as liner pace, as increased about 1.3 °C and 1 °C, respectively, and achieved its highest minimum and maximum temperature at the 2100s time period as 21.8 and 34 °C. but rainfall revealed an irregular pattern for the crop period, with minimum and maximum rainfall recorded in 2080s (18.7 mm) and 2020s (83.7 mm), respectively.

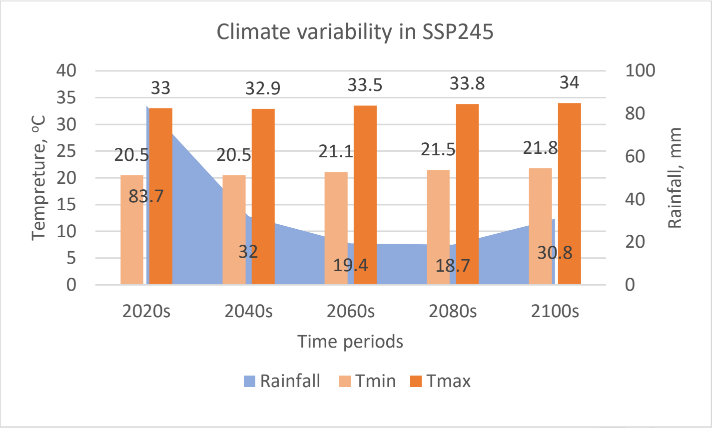

Fig. 5. Changes in climate parameters during crop period under SSP2_4.5 scenario

The study also examined and presented climate variability during the entire crop period for SSP5_8.5 scenarios, as shown in Figure6. The data indicated that the lowest minimum and maximum temperature are in the base period, and it showed a gradual upward trend throughout the time periods and touched its peak at the end of the century at 23.7 °C in minimum temperature and 35.5 °C in maximum temperature. which shows an increase of 15.6% and 7.6% for the century. Again, the rainfall has predicted an irregular pattern, with minimum and maximum rainfall recorded in the 2040s (25.37 mm) and 2020s (83.67mm), respectively. An illustration of the climate variability discussed is shown in Figure6.

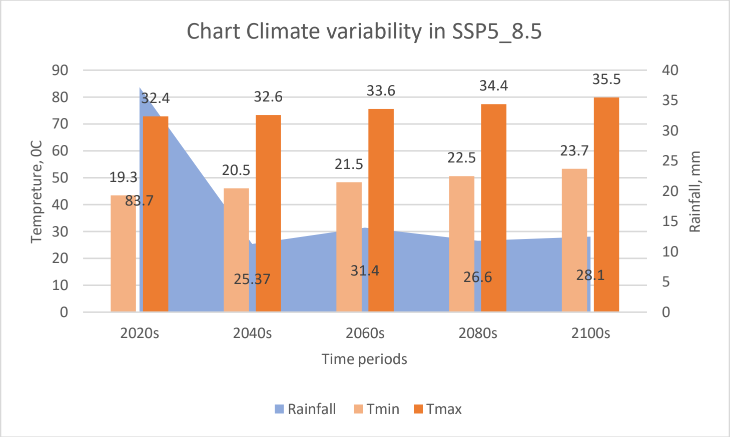

Fig. 6. Changes in climate parameters during crop period under SSP5_8.5 scenario

3.3 Impact of Climate Change in Various Parameters

3.3.1 Reference evapotranspiration (ET_0)

The study conducted a comprehensive analysis of the climatic factors affecting reference evapotranspiration (ET0) and its values over a 100-year span, from 2000 to 2100, on two different scenarios. SSP2_4.5 SSP5_8.5 was studied. In the summer paddy, high temperatures trigger a peak in solar radiation and sunshine duration, particularly in April and May, indicating heightened solar energy input. Low humidity also contributes to an increase in evapotranspiration rates during peak months such as March, April, and May, highlighting the increased water demand during the hot and dry seasons. The reference evapotranspiration (ET0) values for different time periods primarily rely on temperature and precipitation levels. As demonstrated above, the value of ET0 increases as the time period progresses. The reference evapotranspiration (ET0) follows the same trend. In the SSP2_4.5 scenario, the lowest value of average ET_0 for crop period was found as 4.2 mm/day in the base period, whereas it increased to 4.62, 4.69, 4.73, and 4.73 mm/day for 2040s, 2060s, 2080s, and 2100s, respectively. The increased values would also influence the water requirement of crops. The severe results were found in the SSP5_8.5 scenario, where the ET_0 values were observed as 4.6, 4.7, 4.8, and 4.9 mm/day for the 2040s, 2060s, 2080s, and 2100s time periods. Similar findings were obtained by Rajabi and Babakhani (2017), who saw an increase in potential transpiration and associated parameters across all projected future scenarios and time periods.The values also indicated the SSP5_5.5 as having higher values than the SSP2_4.5.

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3.3.2 Crop water requirement

The crop coefficient (Kc) quantifies the relationship between actual evapotranspiration (ETa) and reference evapotranspiration (ET0) specific to crops, and reflecting their water usage patterns, the product of crop coefficient and reference evapotranspiration makes the crop water requirement. For paddy crops, Kc values typically follow a trapezoidal trend throughout their growth stages. Initially, during the nursery stage, Kc remains stable (Kci). As the crop matures, Kc increases, peaking during mid-season (Kcmid), indicating heightened water demand. This is followed by a decline in Kc values during late-season growth (Kcend) as the crop nears maturity. For the base period (2000s), the average crop water requirement (CWR) was found to be 5.41 mm/day, with values ranging from 0.08 to 8.94 mm/day across growth stages. This analysis underscores the dynamic nature of water requirements in summer paddy (MTU1010), providing insights for optimizing irrigation practices for enhanced water management and crop productivity (Allen et al., 1998; Kumari et al., 2021).

The crop water requirement (CWR) was analyzed over a century, focusing on two scenarios: SSP2_4.5 and SSP5_8.5. In the SSP2_4.5 scenario, the CWR ranged from a minimum of 751.4 mm in the base period to a maximum of 792.2 mm in the 2080s, with subsequent values of 784 mm, 780.5 mm, and 768.8 mm for the 2100s, 2060s, and 2040s, respectively. These variations were attributed to inconsistent meteorological data, particularly rainfall trends. Conversely, the SSP5_8.5 scenario exhibited a linear increase in CWR, peaking at 800.4 mm in the 2100s and reaching values of 785.8 mm, 778.1 mm, and 760.6 mm for the 2080s, 2060s, and

2040s. Notably, CWR values in SSP5_8.5 were consistently higher than those in SSP2_4.5, indicating significant implications for agricultural water management

3.3.3 Irrigation water requirement

The irrigation water requirement (IR) is the quantity of water needed to satisfy crop evapotranspiration, considering effective rainfall. The irrigation water demand (IWR) was examined over a century, concentrating on two scenarios: SSP2_4.5 and SSP5_8.5. The IWR for the base period (2000-2020) was determined to be 853.4 mm. The findings of the research align with those of Mohanty et al. (2020), who projected a summer paddy water need of 844.95 mm in Orisha, India. In both instances, the IWR exhibits an upward trajectory. In SSP2_4.5, the peak irrigation water requirement was recorded in 2080s at 929 mm, followed by 916.3 mm in 2060s, 913.7 mm in 2100s, and 897.8 mm in 2040s. In the SSP5_8.5 scenario, the peak IWR was recorded in the 2100s at 927.7 mm, followed by 1667.2 mm, 1659.5 mm, and 1621.8 mm in the 2080s, 2060s, and 2040s, respectively. In SSP5_8.5, the IWR exhibited a linear rising trend, with values surpassing those of SSP2_4.5.

3.3.4 Net and gross irrigationwater requirementfor summer paddy

The Net Irrigation Water Requirement (NIWR) for summer paddy crops quantifies the total water volume supplied throughout the cropping season, from land preparation to harvest. It considers factors such as initial soil moisture, total irrigation, and cumulative precipitation, while accounting for losses from percolation, and leaching, Additionally, it includes the significant water needed for soil preparation, particularly during puddling, making it essential for effective irrigation management in paddy cultivation. The NIWR was estimated for both scenarios across the whole century, analogous to the other parameters. The NIWR for the base period was determined to be 1094.7 mm.The results correspond with the irrigation needs for paddy as delineated by Jangre etal. (2022), who indicated that the water requirements for rice, across different field conditions, ranged from 1192.3 mm to 1317.9 mm. This range includes application losses and certain agronomic requirements. In the SSP2_4.5 scenario, an upward trend is seen, with peak NIWR values of 1182.2 mm in the 2080s, followed by 1167.4 mm in the 2060s, 1164.7 mm in the 2100s, and 1138.9 mm in the 2040s. In the SSP5_8.5 scenario, the NIWR is much greater than in SSP2_4.5, with a peak NIWR of 1176.5 mm projected for the 2100s, followed by 1167.2 mm, 1161.7 mm, and 1135.2 mm for the 2080s, 2060s, and 2040s, respectively.

Moreover, the incorporation of irrigation efficiency in NIWR leads to the estimation of the Gross Irrigation Water Requirement (GIWR) (Michael, 2008). The irrigation efficiency of the field's water supply was estimated at 70%, resulting in a total gross irrigation water requirement of 1563.8 mm for the base period. In the SSP2_4.5 scenario, the maximum gross irrigation water requirements were 1688.9 mm and 1668.4 mm for the 2080s and 2060s, respectively, followed by 1663.9 mm and 1627 mm for the 2100s and 2040s periods. In the SSP5_8.5 scenario, the peak GIWR recorded was 1680.7 mm in the 2100s, followed by 1667.2 mm, 1659.5 mm, and 1621.8 mm in the 2080s, 2060s, and 2040s, respectively.

Conclusion

The study on the effects of climate change on water requirements for summer paddy cultivation in Raipur District, Chhattisgarh, provides significant advantages for sustainable agricultural practices and efficient water resource management. Utilizing the FAO-CROPWAT 8.0 model, the research offers essential insights into irrigation needs across various climatic scenarios, enhancing understanding of the relationship between climate factors and agricultural water demands. By quantifying irrigation requirements through historical and projected meteorological data, this study equips farmers and policymakers with crucial information for informed irrigation management. This is particularly vital in regions like Chhattisgarh, where agriculture heavily depends on irrigation due to erratic rainfall patterns. The findings emphasize the necessity of refining irrigation techniques to improve water use efficiency. Effective irrigation management can conserve substantial water while maintaining agricultural productivity, addressing the impending challenges of water scarcity that threaten food security in India. Additionally, the research advocates for adaptive strategies to mitigate the negative impacts of climate change on agriculture. By analyzing trends in agricultural water demands across varying socio-economic contexts, it promotes the development of customized irrigation plans that can adjust to changing climatic conditions. In summary, this study not only advances the field of agricultural science but also emphasizes sustainable practices essential for food security amid climate uncertainty. By focusing on effective water management and adaptive solutions, it lays a foundation for resilient agricultural systems capable of enduring future climatic challenges.

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