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Original Article

Assessment of crop yield and water footprint of kharif paddy production under different rainfall years

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Abstract

The assessment of the water footprint of paddy production has been of great significance to water resource planning and management. This study quantifies the paddy yield and water footprint under different rainfall conditions for the period 2011-2020. In agriculture, water footprint, crop yield, and evapotranspiration need to be estimated. AquaCrop GIS software is used to simulate the yield of paddy and evapotranspiration. The results show the average yields of Imphal East and Imphal West as 3.27 t/ha and 3.32 t/ha, respectively. The R^2-value of simulated and actual yields in Imphal East and Imphal West as 0.916 and 0.911, respectively. The green water footprint of paddy is found to be higher than the blue water footprint. This study shows the importance of rainwater and allows increasing the paddy yield by more use of green water and reduced blue water use in the future.

Keywords: AquaCrop GIS, water footprint, crop yield, paddy, evapotranspiration

1. Introduction

Agriculture is an important occupation for many Indian households. The agricultural sector consumes 70% of the global fresh water and a shortage in agricultural water will affect the socio-economic development of a country (Li *et al.*, 2022). With the changing climatic conditions, the future rainfall characteristics will also change (Takhellambam *et al.*, 2022a). Therefore, it is necessary to reduce the consumption of water for crops in the agricultural sector (Hoekstra & Mekonnen, 2012). The “water footprint” was introduced to impart a link to estimate the water consumption by humans and the available freshwater (Mekonnen & Hoekstra, 2011). Water footprint and crop productivity analysis have become an important part in the economic argument of the country (Abdullah, 2020; Aldaya *et al.*, 2019). The most of crops are grown using irrigation water (blue water footprint) and effective precipitation (green water footprint). In agriculture, the water footprint of crops can be evaluated using crop evapotranspiration and crop yield. Evapotranspiration and crop yield can be simulated using a crop growth model. AquaCrop and CROPWAT are two widely used models for estimating WF. These models were developed by FAO’s Land and Water Division. Tsakmakis, Zoidou, Gikas, and Sylaios (2018) studied AquaCrop and CROPWAT to estimate WF and concluded that the AquaCrop model showed better results to assess green, blue, and total water footprints while CROPWAT has limitations in larger spatial resolution. Lorite, García-Vila, Santos, Ruiz-Ramos, and Fereres (2013) used the AquaData and AquaGIS for the simulation of yield in Southern Spain and they found that it could reduce the time of simulation by more than 99%. Due to the possibility to run multiple simulations at one, AquaGIS has been chosen as the crop growth model for the estimation of ET and crop yield in this study.

Among the crops, paddy requires a huge amount of fresh water in production. Paddy is the most cultivated crop in India which is the second ranked rice producing country in the world. It is an important staple food for Northeast India. In Manipur, paddy occupies 90% of the Gross Cropped Area (GCA) and stands as the main Kharif crop (Bidyapati & Jha, 2020). Paddy cultivation is mostly started by the arrival of the southwest monsoon. The demand for paddy crops in Manipur has increased significantly over the years, being now much higher than its supply capacity. Paddy production is affected by the reduction in available water resources as well as

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cultivable areas. Thus, proper management of water resources is necessary with increasing demand of agricultural water, for sustainable development with a rising population. Increasing the production of rice with less water use will reduce the water footprint. This study estimated the yield and water footprint of paddy crops from the year 2011 to 2020.

2. Materials and Methods

2.1 Study area

Manipur is situated in the north-eastern border of India. It has a total population of 2.856 million in the 2011 population census. Geographically, the region can be broadly divided into two components, viz. the hill and the valley regions. The study area is located between latitudes 24°27′ to 25°6′ N and longitudes 93°46′ to 94°9′ E with a total area of 853.39 sq. km. The climatic conditions of this area have the minimum and the maximum temperatures of 12°C and 31°C respectively, and the average rainfall is 1,350 mm/year. From the year 2017-2018 report of Department of Agriculture (DOA), in Manipur the total area for rice cultivation in the valley region covered 62.5% and in the hill region it covered 37.5% (DOA, Manipur). The two most populated districts of valley region (Imphal West and Imphal East) were selected for study due to their rising population as well as water shortage, which affects the productivity of the area.

2.2 Data collection

The daily meteorological observations, including maximum and minimum temperature, relative humidity, sunshine hours, rainfall, and wind speed, which were required for calculating crop yield and water footprint, were collected from the ICAR, Lamphel, Directorate of Environment, government of Manipur, for the years from 2011 to 2010. The agricultural data, such as planting date, harvesting data, crop yield, sowing area, and fertilizer application were collected from DOA, Government of Manipur. Soil data were downloaded from National Bureau of Soil Survey and Land Use Planning (NBSS & LUP). Irrigation data were collected from Minor Irrigation department, Manipur.

2.3 Simulation of rice yield using FAO-AQUACROP GIS

AquaCrop-GIS has been developed by the FAO to ease the use of AquaCrop. It provides a large number of simulation runs. It also has simplified input and output files. The AquaCrop-GIS tool shows the results in a Geographic Information System. AquaCrop-GIS has been designed for use with xlsx files. Input data required in this model are crops files, initials files, soils files, groundwater files, and management files. Aquacrop-GIS model gives the evapotranspiration and yield of the crop, which are required for the estimation of water footprint (Ignacio, Margarita, & Elias, 2015).

2.4 Methodology

The agriculture water footprint consists of blue, green and grey water footprints. The green water component

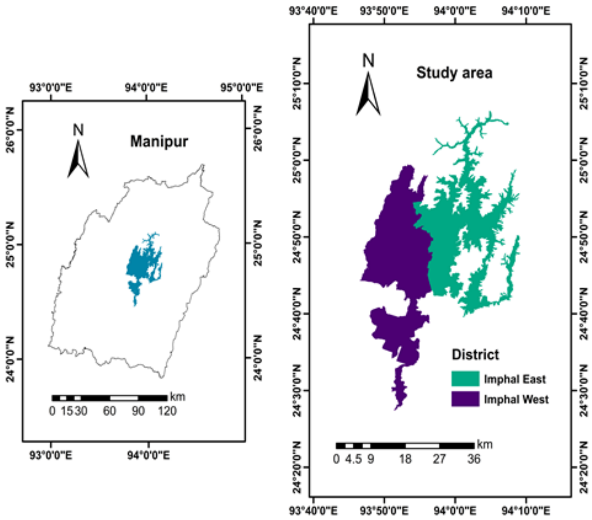


Figure 1. Location map of the study area.

refers to the rain water used in agriculture. The blue water footprint indicates the amount of surface and groundwater used during cultivation of crop. The grey water footprint refers to the amount of freshwater required to assimilate the pollutants caused during the cultivation (Hoekstra, Chapagain, Aldaya, & Mekonnen, 2009). For estimation of water footprint, the framework given by Hoekstra (2011) was followed for this study. The total water footprint can be expressed as

$$WF_{total} = WF_{green} + WF_{blue} + WF_{grey}$$

where WF_{total} is the total water footprint of the crop, WF_{green} and WF_{blue} are the green water footprint and blue water footprint respectively. WF_{grey} represents the grey water footprint.

Green water footprint (WF_{green}): It is calculated by dividing green water by yield of the crop.

$$WF_{green} = \frac{CWU_{green}}{Y} = \frac{ET_{green}}{Y}$$

where

WF_{green} = green WF (m^3/kg)

CWU_{green} = crop water use (m^3/ha)

ET_{green} = green water evapotranspiration (mm)

Y = crop yield (kg/ha)

The ET_{green} is calculated as the minimum between effective rainfall and crop evapotranspiration for the entire crop period.

$$ET_{green} = \min(ET, P_{eff})$$

where P_{eff} is efficient precipitation (mm) determined using USDA SCS method (Serhan & Levent, 2020). It can be expressed as

$$P_{eff} = P_{total}\,(125 - 0.2P_{total}) / 125;\ \text{for } P_{total} < 250\ \text{mm},$$
$$P_{eff} = 125 + 0.1P_{total},\ \text{for } P_{total} > 250\text{mm}$$

where P_{total} = Total precipitation (mm)

Blue water footprint (WF_{blue}): This component is calculated as blue water use by crop yield.

$$WF_{blue} = \frac{CWU_{blue}}{Y} = \frac{ET_{blue}}{Y}$$

where

WF_{blue} = blue WF (m^3/kg)

ET_{blue} = blue water evapotranspiration (mm)

The ET_{blue} represents the crop ET from irrigation requirement. It is assumed that the crop evapotranspiration requirement is met by the effective rainfall when irrigation water requirement of the crop is fully met and taken as zero.

$$ET_{blue} = \max(0, ET - P_{eff})$$

Grey water footprint (WF_{grey}): It is calculated as the product of application of chemical rate and leaching runoff fraction divided by maximum acceptable concentration minus concentration in natural water then divided by crop yield.

$$WF_{grey} = \frac{\alpha \times AR}{C_{max} - C_{nat}} \times \frac{1}{Y}$$

where

WF_{grey} = grey WF (m^3/kg)

AR = rate of chemical application (kg/ha)

α = leaching runoff fraction

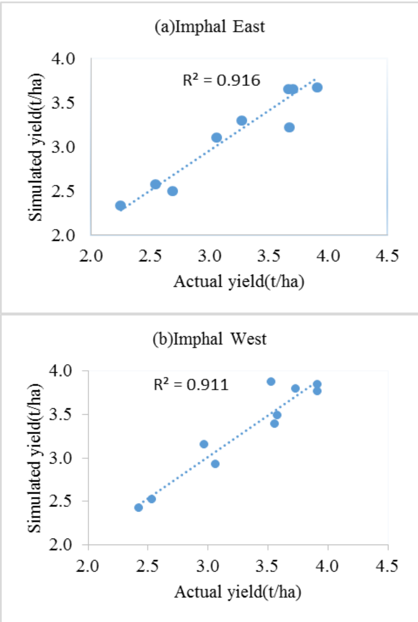
C_{max} = maximum acceptable concentration (mg/l)

C_{nat} = concentration in natural water (mg/l)

In this study, only nitrogen contamination was considered due to the lack of assessable data on other fertilizers and pesticide. AR, the rate of chemical application of fertilizer was taken as 25 kg/ha (the recommended dose of nitrogen fertilizer, DOA). The leaching factor, α was taken as 0.1 for nitrogen fertilizers (Franke, Boyacioglu, & Hoesktra, 2013). The maximum acceptable concentration C_{max} and concentration in natural water C_{nat} were assumed to be 10 mg/l and 0 mg/l respectively (Fu *et al.*, 2019).

Table 1. Comparison of observed and simulated yields of paddy for the years from 2011 to 2020

Year	Imphal East		Imphal West	
	Actual yield (t/ha)	Simulated yield (t/ha)	Actual yield (t/ha)	Simulated yield (t/ha)
2011-2012	3.29	3.28	3.74	3.79
2012-2013	3.65	3.71	3.91	3.76
2013-2014	3.11	3.06	3.06	2.93
2014-2015	4.01	3.91	3.91	3.84
2015-2016	2.50	2.69	2.53	2.52
2016-2017	3.22	3.67	2.97	3.16
2017-2018	2.34	2.25	2.42	2.43
2018-2019	3.65	3.67	3.58	3.49
2019-2020	3.67	3.91	3.53	3.87
2020-2021	2.58	2.54	3.56	3.39



Figures 2. (a) & 2(b) Graphs showing simulated and actual paddy yields of Imphal East and Imphal West

3. Results and Discussion

3.1 Simulation of paddy yield

The paddy yields of Imphal East and Imphal West for the years 2011-2020 were simulated in AquaCrop-GIS model. The average yields of Imphal East and Imphal West for the last 10 years were 3.27 t/ha and 3.32 t/ha, respectively.

The model was calibrated using the trial-and-error method of yield data obtained from DOA, Manipur. The validation of the model was conducted using the statistical parameters with percentage error, regression coefficient (R^2) and root mean square mean error (RSME). The percentage errors of Imphal East and Imphal West were -1.71 and -0.28, respectively. The negative percentage errors indicate underestimation by the simulated yields. The underestimation in yield is due to the underestimation of ET (Rupinder & Suat, 2019). The R^2 and RSME for the Imphal East and Imphal West were 0.916 to 0.911 and 0.06 to 0.08, respectively. Overall, the comparison of observed and simulated yields of the paddy show a reasonably good calibration of the model.

From the results, the average yield of Imphal East was found to be less than in Imphal West. This is due to the uneven rainfall in Imphal East during crop season. The Imphal East received the highest rainfall in the year 2017, which caused the lowest yield during the study period. The crop production is becoming increasingly vulnerable to frequent extreme weather events linked to rainfall intensity, density, and frequency distribution, which eventually can lead to drought and flood (Douglas, 2009). Takhellambam *et al.*, 2022b predicted that rainfall characteristics such as amount, frequency, and duration are expected to change with climate change and climate variability. In this study, only rainfall was considered to explain their effects on rice production, which may not have produced the desired outcomes. In order to better understand the situation, it is therefore necessary to evaluate other climatic parameters (Rahman, Kang, Nagabhatla, & Macnee, 2017).

3.2 Evaluation of WF under different rainfalls by year

The WF varied from year to year due to variations in climatic and environmental impacts. The total WF of Imphal East is composed of 62% green water, 30% blue water and 8% grey water. The Imphal West districts had 70% green water, 22% blue water and 8% grey water. Comparing the amounts of green water and blue water for the two districts show the impact of green water (rain water) in paddy production. The green WF has not influenced negatively the environment and the socioeconomics of the country (Chukalla, Krol, & Hoekstra, 2015; Uma & Shivakumar, 2021). It is safe to say that proper use of green water can improve the future paddy production. The grey water footprint is relatively less due to the consideration of nitrogen fertilizers (Naresh *et al.*, 2017). Figures 3(a) & 3(b) show comparison of green, blue and grey WF in Imphal East and in Imphal West for the years from 2011 to 2020, respectively. The average WF of Imphal East and Imphal West for the last decades are 974.82 m^3/t and 969.88 m^3/t, respectively. The WF of paddy for Punjab, India was evaluated as 1097 m^3/t (Durba & Tripti, 2021). The lower WF of the paddy crop can be due to the temperate climatic conditions of Manipur, which lead to comparatively reduced evapotranspiration. Analyzing the graphs in Figures 4(a) & 4(b) between WF and rainfall shows that the total water footprint depends on the amount of rainfall during the cropping season. It is mainly due to relying on seasonal rainfall for the cultivation of paddy in this area.

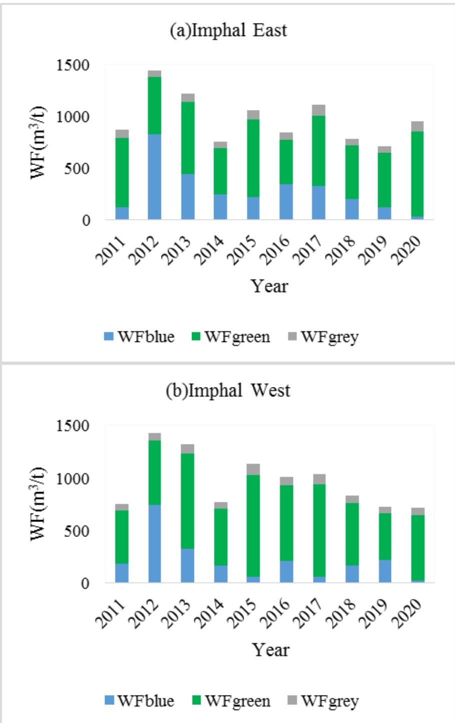


Figure 3. (a) & 3(b) Comparison of green, blue, and grey water footprints of paddy production in Imphal East and in Imphal West in the years from 2011 to 2020.

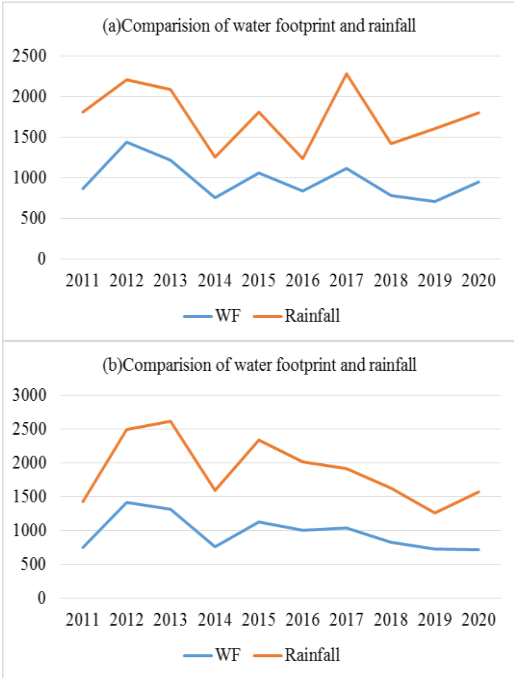


Figure 4. (a) & 4(b) The trends showing water footprints under different rainfalls by year in Imphal East and in Imphal West

4. Conclusions

This study showed that the AquaCrop model accurately predicted the yield of rice under different rainfalls by year, although the percentage error indicated slight underestimation in the yield for both districts. The uneven rainfall events during crop season in Imphal East caused lesser average yield than in Imphal West. The green water footprint constitutes the largest portion of the total water footprint, which shows the importance of rainfall in paddy production. A comparison of blue water use in the two districts indicates that Imphal East used more irrigation water than Imphal West. The grey water footprint was relatively small because in our study we considered only nitrogen fertilizers. There will be a great opportunity in the future to increase the yield through improving rainwater use. In this way we can reduce the use of irrigation water, which is a necessary input. Reducing irrigation water use will also help in reducing water footprint in the production of paddy.

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