

Original Research Article

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Evaluation of Evapotranspiration Methods for Rice Yield Simulation in a Tropical River Basin

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ABSTRACT

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Rice is the world's most consumed cereal grain, making up the dietary staple food of more than 60 percent of the world's population. For agriculture dominated country like India, the assessment of rice yield is of utmost importance for policy makers in managing the food security and water resources. The present study evaluates the efficiency of Soil and Water Assessment Tool (SWAT) to simulate rice yield during both *kharif* and *rabi* seasons in Brahmani River basin, and subsequently, identifies the appropriate evapotranspiration estimation approach for accurate quantification of crop water requirement, and irrigation scheduling. The outcomes of this study revealed that the two crop-specific model parameters, i.e., maximum leaf area index and radiation use efficiency affect the rice yield to greater extent. The SWAT simulates the rice yield better in the *kharif* season with NSE estimates of 0.81 and 0.79 during the calibration and validation period, respectively as compared to the *rabi* season. The crop growth dynamics is better conceptualized by the physically based FAO-56 PM approach than the Priestley and Taylor method in the study area. The outcomes of the study could be useful for the hydrologist and agronomist in developing decision support system for irrigation water management and crop yield assessment.

Introduction

Evapotranspiration (ET) is one of the key factors that influences the crop growth, dry biomass production, and yield. To improve the crop water productivity, accurate estimation of ET during the crop growing phases is of utmost importance. Hence, advanced techniques of ET estimation continue to draw the attention of meteorology,

hydrology, agronomy, and ecology community. Rice is the staple food of more than half of the world's population which consumes large amount of water due to the presence of shallow ponding water throughout its growing period (Dash *et al.*, 2018).

In general, ET possess a linear relation with the crop yield, and the inherent moisture stress phases affect the yield in an adverse

manner. Therefore, quantification of ET for the rice crop is of great importance for proper irrigation management and assessment of its yield. Numerous studies have been conducted on the ET estimation of rice crop using lysimeter (Shahrokhnia and Sepaskhah, 2013; Xu *et al.*, 2017), water balance (Choudhury *et al.*, 2007; Shao *et al.*, 2014) based approaches. Since direct measurement of ET is cumbersome and costly, many indirect methods have been developed for ET estimation based on the easily available meteorological parameters, viz., (i) temperature based (Hargreaves and Samani 1985), (ii) radiation based (Priestley and Taylor 1972), and (iii) combination method (FAO-56 Penman Monteith) (Allen *et al.*, 1998). However, their use is limited to region specific applications and accuracy may be compromised based on the input data availability. In this context, the hydrological modeling based indirect ET estimation proved to be a suitable alternative (Dash *et al.*, 2019; Padhiary *et al.*, 2019). Keeping this in mind, an overarching goal and contribution of this study is (i) to evaluate the efficiency of agro-hydrological model Soil and Water Assessment Tool (SWAT) for simulating rice yield in tropical climate; and (ii) to identify the appropriate ET estimation approach for accurate quantification of crop water requirement, and irrigation scheduling.

Materilas and Methods

Study area

The concerned study was carried out in a typical paddy-dominated sub-watershed of the Brahmani River basin (BRB), Odisha. The BRB is located between longitude 83° 52' to 87° 30' E and latitude 20° 28' to 23° 35' N constituting an area of 39,269 km² (Fig. 1). The basin experiences highly undulated topography with elevation ranges between 1 to 1169 m above the mean sea level (MSL). The BRB is characterized by tropical

monsoon climate which receives an average annual rainfall of 1305 mm with major portion (70%) of rainfall is confined to the monsoon season (June-October). The BRB encompasses a diversified land use land/ land cover (LULC) distribution with cropland as the major LULC class constituting 52.04% of total basin area. The major stakeholders of the basin are completely dependent on the agriculture for their livelihood. Paddy is major crop grown in the BRB and cultivated twice in the year during the two major crop-growing seasons. i.e., *rabi* and *kharif*.

SWAT Model set up

SWAT model is a physically based river basin scale model used widely for simulating streamflow, sediment yield, pollutant loading, and crop yield with utmost accuracy (Arnold *et al.*, 1998). The SWAT model has an extensive spatial discretization scheme starting from sub-basin to Hydrological Response Unit (HRU) to account for the minimal variation in catchment hydrological conditions. The SWAT agro-hydrological model was set up for the concerned basin using the 30 m resolution ASTER digital elevation model (DEM), 1 km resolution soil map collected from FAO soil database, and daily meteorological inputs (Rainfall, maximum and minimum temperature) collected from the Indian Meteorological Department (IMD), Bhubaneswar. The daily reservoir outflow from the Rengali reservoir was used to model the irrigation requirement during the crop growing periods. The model simulation for seasonal rice yield estimation was carried out for the duration 1998-2010, with initial three years (1998-2000) as the model warm-up period in order to simulate initial model wetness. The seasonal rice yield during both *rabi* and *kharif* seasons were duly calibrated and validated for the period 2001-2006 and 2007-2010, respectively. The sensitivity analysis was performed prior to the calibration using the crop parameters of

SWAT model. Further, the uncertainty was quantified by the 95 percent prediction uncertainty (PPU) plot derived P-factor and R-factor magnitude (Dash *et al.*, 2020).

ET scenarios for crop yield

ET is main driving factor that quantifies irrigation requirement during different growth phases; thereby affects the crop yield significantly. Hence accurate estimation of ET for crop yield estimation is highly essential. The chosen ET estimation algorithm in the SWAT model alters the water balance of the simulated hydrological fluxes substantially. The simulation of rice yield is quantified under two global ET estimation scenarios, i.e., FAO-56 Penman Monteith (PM) and Priestley Taylor (PT) approach as given below Eqs. (1) and (2), respectively:

$$\lambda E = \frac{\Delta \cdot (H_{net} - G) + \rho_{air} \cdot c_p \cdot [e_z^o - e_z]}{\Delta + \gamma \cdot (1 + r_c / r_a)} \dots (1)$$

where λE is the latent heat flux density ($\text{MJ m}^{-2} \text{d}^{-1}$), E is the depth rate evaporation (mm d^{-1}), Δ is the slope of the saturation vapor pressure-temperature curve, de/dT ($\text{kPa } ^\circ\text{C}^{-1}$), H_{net} is the net radiation ($\text{MJ m}^{-2} \text{d}^{-1}$), G is the heat flux density to the ground ($\text{MJ m}^{-2} \text{d}^{-1}$), ρ_{air} is the air density (kg m^{-3}), c_p is the specific heat at constant pressure ($\text{MJ kg}^{-1} \text{ } ^\circ\text{C}^{-1}$), e_z^o is the saturation vapor pressure of air at height z (kPa), e_z is the water vapor pressure of air at height z (kPa), γ is the psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$), r_c is the plant canopy resistance (s m^{-1}), and r_a is the diffusion resistance of the air layer (aerodynamic resistance) (s m^{-1}).

$$\lambda E_o = \alpha_{pet} \cdot \frac{\Delta}{\Delta + \gamma} \cdot (H_{net} - G) \dots (2)$$

where λ is the latent heat of vaporization (MJ kg^{-1}), E_o is the potential evapotranspiration (mm d^{-1}), α_{pet} is a coefficient, Δ is the slope of

the saturation vapor pressure-temperature curve, de/dT ($\text{kPa } ^\circ\text{C}^{-1}$), γ is the psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$), H_{net} is the net radiation ($\text{MJ m}^{-2} \text{d}^{-1}$), and G is the heat flux density to the ground ($\text{MJ m}^{-2} \text{d}^{-1}$).

Performance evaluation criteria

The efficiency of the SWAT model in simulating the rice yield during both the growing seasons with respect to the observed crop yield values was evaluated by widely used measures of goodness of fit indices, such as Nash and Sutcliffe Efficiency (NSE) (Nash *et al.*, 1970), coefficient of determination (R^2), and percent bias (PBIAS) as given below:

$$NSE = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - O')^2} \dots (3)$$

$$R^2 = \left\{ \frac{\left(\sum_{i=1}^n (O_i - O') (P_i - P') \right)^2}{\sum_{i=1}^n (O_i - O')^2 \sum_{i=1}^n (P_i - P')^2} \right\} \dots (4)$$

$$PBIAS = \frac{\sum_{i=1}^n (O_i - P_i)}{\sum_{i=1}^n O_i} \times 100 \dots (5)$$

where n is total number of observed data, O_i and P_i are observed and simulated data at time i , O' and P' are the mean of observed and simulated data. The value of NSE close to one corresponds to better agreement between the observed and simulated yield values and vice-versa.

Further, the ET estimation scenario which represented relatively lower disagreement between the observed and simulated yield

value will be treated as the best ET estimation approach to enhance further the quantification of crop water requirement, and irrigation scheduling.

Results and Discussion

Model calibration and validation

The SWAT model sensitivity analysis was performed for the top ten crop parameters followed by the calibration and validation of seasonal rice yield simulation. The sensitivity analysis revealed that maximum leaf area index (BLAI) and radiation use efficiency (BIO_E) are the two sensitive most parameters that affect the rice yield to greater extent. The annual rice yield variation across the BRB during two crop growing season is presented in Fig. 2. As envisaged from Fig.2 the *rabi* season rice yield is always higher than that of the *kharif* season.

Moreover, reduced yield estimates during the year 2005 and 2006 could be consequence as a result of significant drop in the rainfall magnitude. The goodness of fit statistics of seasonal rice yield simulation is presented in Table 1. It can be elucidated that the SWAT simulates the rice yield better during the *kharif* season as evidenced from the NSE estimates of 0.81 and 0.79 during the calibration and validation periods, whereas the corresponding *rabi* season NSE estimates reduced to 0.77.

The degree of mismatch between the yield is intensified during the mod-season stage of rice growth. This could be attributed to the inability of the SWAT model to account for sever moisture stress scenario of the *rabi* season. Furthermore, the RMSE estimates of 0.256 t/ha during the *rabi* season revealed that substantial reduction in rice yield could be caused due to the reduced irrigation application consequenced due to incorrect

quantification of ET. Alternatively, during less severe moisture stress scenario of the *kharif* season, the RMSE estimates substantially reduces to 0.116 t/ha.

Implications of ET methods on rice yield assessment

To analyze the implications of ET selection method on crop yield simulation, the annual ET estimates were quantified and presented in Fig. 3. As envisaged from the Fig. 3, the average annual (2001-2010) ET estimates simulated by the FAO-56 PM and PT are 900.59 ± 123.32 and 812.21 ± 101.24 mm, respectively, signifying considerable discrepancy between the two ET estimation approaches.

Moreover, the PET to ET conversion ratio was 46.62% for FAO-56 PM approach and the corresponding ratio was 62.21% for PT approach. The increased PET to ET conversion ratio for the PT approach corresponded to erroneous assessment of remaining water balance components of paddy field. This water balance could have resulted lower plant water availability for uptake by the plant roots. This process further gets aggravated during the mid-season stage of crop growth resulting reduced estimation of plant water uptake; thereby the model simulated irrigation water becomes unable to fulfill the crop water demand.

Moreover, the crop yield statistics revealed that the *kharif* season simulated yield under FAO-56 PM and PT scenario are 1.488 and 1.242 t/ha, respectively, with respect to the observed yield magnitude of 1.674 t/ha. Similarly, during the *rabi* season, observed, FAO-56 PM, and PT- based yield estimates are 2.456, 2.298, and 2.014 t/ha, respectively, signifying the *rabi* season yield estimation uncertainties are higher than that of *kharif* season.

As crop yield is affected the most by the plant water availability to fulfil the physiological requirement of crop, the accurate quantification of growth-stage specific ET is highly imperative. The outcomes of this study revealed that although the overall magnitude of ET is lower in case of FAO-56 PM approach, the crop growth dynamics is better conceptualized by the physically based FAO-56 PM approach.

application during the non-essential phases of crop growth; thereby results substantial reduction in the crop yield. Hence, for tropical monsoon climatic regions, FAO-56 PM approach can be treated as the best measure to quantify the crop water requirement to implement further water management operations. Nevertheless, the validity of the PT approach in crop yield estimation could be examined further under varying climatic conditions.

Moreover, the PT approach triggers irrigation

Table.1 Performance evaluation of rice crop yield during *rabi* and *kharif* season of BRB

Performance Indices	Rabi		Kharif	
	Calibration	Validation	Calibration	Validation
NSE (-)	0.77	0.72	0.81	0.79
R (-)	0.84	0.86	0.91	0.89
RMSE (t/ha)	0.256	0.201	0.116	0.129

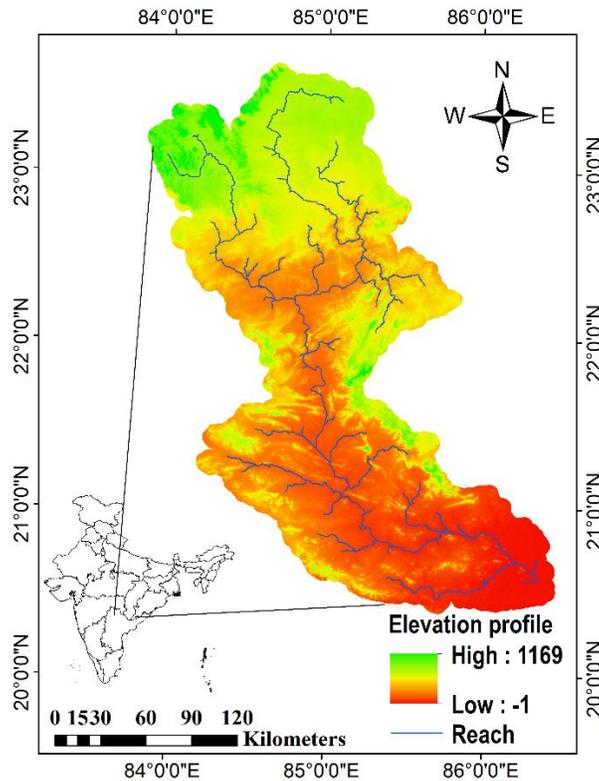


Fig.1 Index map of Brahmani River basin

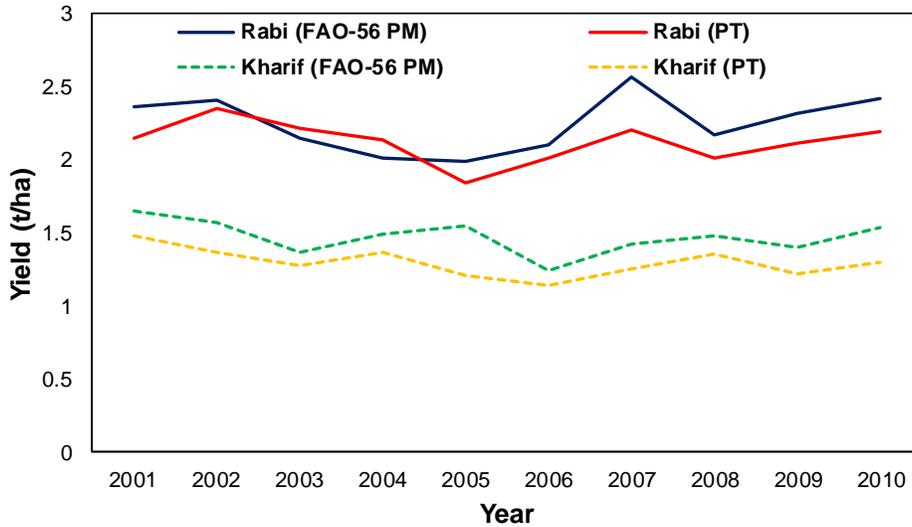


Fig.2 Reproduction of seasonal rice yield in the BRB for the period 2001-2010

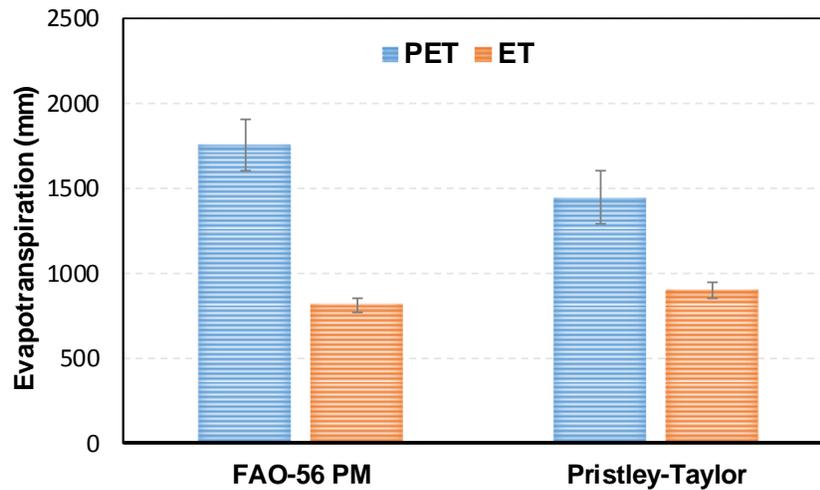


Fig.3 Average annual ET estimation by FAO-56 PM and Priestley-Taylor approach for the period 2001-2010

This study addresses an important concern regarding the effect of appropriate ET selection method on rice yield. The following conclusions are drawn from this study:

The SWAT is capable of reproducing the rice yield dynamics with utmost accuracy.

The uncertainty in rice yield simulation is higher during the rabi season as result of severe moisture stress scenario.

Out of the two considered ET scenario, the

FAO-56 PM approach represents the rice yield scenario with a more realistic manner.

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