Journal of Agrometeorology 17 (1) : 1-10 (June 2015)

Study of spatial water requirements of rice under various crop establishment methods using GIS and crop models

M.D.M. KADIYALA[1], JAMES. W. JONES[2], R.S. MYLAVARAPU[3], Y.C. LI[3] , M.D. REDDY[4] and M. UMADEVI[4]

[1] *International Crops Research Institute for Semi-Arid Tropics (ICRISAT), Patancheru, Hyderabad, India-502324*

[2] *Department of Agricultural and Biological Engineering, University of Florida, Gainesville, FL, USA-32611*

[3] *Soil and Water Science Department , University of Florida, Gainesville, FL, USA-32611*

[4] *Water Technology Center, ANGR Agril Univ., Hyderabad, India-500030*

Corresponding author E-mail : d.kadiyala@cgiar.org

ABSTRACT

Application of crop simulation models at larger spatial scales is very essential to develop best management practices in order to maximize yields and reduce environmental pollution. In the present study, spatial analysis of long- term simulations were carried out with DSSAT spatial analysis tool linked with GIS to estimate irrigation requirements and nitrate leaching under alternate rice establishment methods in the Wargal watershed, Andhra Pradesh, India. Rice yields were compared among three management scenarios: rainfed, aerobic and flooded systems. Grain yield, seasonal water balance components, nitrate leaching and water use efficiency were calculated, visualized and mapped with GIS. The rice productivity increased by 22% and 27% under aerobic and flooded management compared to rainfed rice. The adoption of new water efficient aerobic rice cultivation in the watershed resulted in 36% water saving with a relatively small yield reduction of 4%, thus increasing the water productivity to 0.77 g kg^{-1} in aerobic compared to 0.56 g kg^{-1} in flooded rice. The aerobic rice method reduced the overall water pumping hours to 88 h ha^{-1} during rice crop season compared to 299 h ha^{-1} with flooded rice cultivation, resulting in 71% energy savings.

Keywords: CERES-Rice, aerobic rice, GIS, nitrogen leaching, irrigation, rice

Traditional rice transplanting method of cultivation faces severe yield limitations due to frequent monsoon rain failures, which results in water stress during critical periods of rice growth. To meet the water demands of traditional flooded rice, farmers need to pump water from the underground aquifers. This continuous pumping causes drying up of the underground water and creates serious ecological and environmental consequences. Conjunctive use of rainfall and irrigation can conserve precious underground water and increase the overall water productivity of irrigation schemes.Developing efficient irrigation scheduling procedures for rice can save water by minimizing the various losses and can enable to irrigate more area with the available water resources. Aerobic rice offers one such water saving rice technology (Bouman *et al.,* 2005; Kadiyala *et al.,* 2012), where rice crop is cultivated under non-puddled and non-saturated soil conditions. Further, rice growth and development depends up on the complex interactions between variety, soil, climatic and management factors all of which vary both in space and time (Rao and Rees, 1992) and hence development of efficient irrigation management packages requires careful monitoring of these factors continuously along with associated effects on crop growth and development.

Crop simulation models are valuable tools for evaluating potential effects of environmental, biological and management factors on crop growth and developments. These tools are handy in these situations and provide practical means for scheduling irrigations. Crop models were evaluated and used for many soil and environmental conditions across the world. In the past, these models have been successfully utilized in yield predictions (Jagtap and Jones, 2002), irrigation planning for crops (Behera and Panda, 2009), optimization of irrigation water use (Fortes *et al.,* 2005; Bulatewicz *et al.,* 2009), comparison of various scenarios and strategies (Rinaldi, 2004; Rinaldi *et al.,* 2007), analysis of yield trends over time (Liu *et al.,* 2011) and many more. These models are generally point-based systems as they mostly use site specific parameters such as weather, physical and chemical parameters of soil, water management, agronomic practices and the output simulation results can only be the representative of a small field. However, these models need to be applied at larger scales in order to be economically useful so that the effects of various alternate management strategies across the watershed or the region could be analyzed. Studies conducted in various parts of the world on linking crop models with a Geographical Information System (GIS) have demonstrated a strong feasibility of crop modeling applications at a spatial scale (Engel *et al.,* 1997; Thornton *et al.,* 1997; Heinemann *et al.,* 2001). GIS is capable of using spatial data and can be very handy in environmental and agricultural modeling (Hartkamp *et al.,* 1999; Beinroth *et al.,* 1998). Several researchers successfully utilized crop models that are part of Decision Support System for Agro Technology Transfer (DSSAT) and GIS in studying spatial water requirement of crops, yield forecast and climate change impacts at watershed and regional scales (Hansen *et al.,* 1998).

The main objective of present study was to investigate the spatial variations in the simulated yield, water balance and nitrogen (N) leaching from different rice cultivation scenarios in a semi-arid sub watershed in southern India. The calibrated and evaluated DSSAT CERES-Rice model was used to predict yield variations due to soil types and three rice establishment methods. The output results on yields, water applied, drainage and N leaching were spatially mapped in the entire watershed using Arc GIS thiessen polygon method.

MATERIALS AND METHODS

Description of study area

The Wargal village of Wargal mandal (an administrative unit containing 15-20 villages) is located at a latitude of 17^0 41’19.4’’N and a longitude of 78^0 29’24.0’’ E, with an elevation of 590 m above sea level in Medak district of Andhra Pradesh, India. The total geographical area of Wargal village is 2618 ha with 2522 ha of cultivable land, of which 405 ha are under irrigation by tanks and bore wells. The soils of the village are mostly red chalka (Red sandy/sandy clay loams – Alfisols, 2336 ha) and black cotton soils (Vertisols, 280 ha). The Kothakunta sub watershed in Wargal village with an area of 512 ha was selected for the study (Fig. 1).The watershed mostly consists of red soils. The physiography of the area is undulating having a slope of 1-5%, slightly eroded, and moderately drained. The annual average rainfall in the watershed is 780 mm; about 80% of which is received during June-September from the southwest monsoon. Rice is the major crop grown in the area which is planted during July, after the onset of monsoon, and is harvested in November.

The CERES- Rice model

The CERES-Rice model simulates crop growth and development on daily time step. Water balance component of the model calculates infiltration, runoff, drainage and evapotranspiration to assess the soil water balance. This is a one-dimensional model and computes the daily changes in soil water content in a soil layer due to infiltration, irrigation, vertical drainage, unsaturated flow, soil evaporation, plant transpiration and root water uptake (Ritchie, 1998). Infiltration is calculated based on difference between rainfall or irrigation and runoff. Drainage is assumed constant over entire day and computed for each layer using the drained upper limit and lower limit values of soil water content. When the water content in each layer is above the drained upper limit, water drains to next layer. The amount of water passing to each layer is then compared to statured hydraulic conductivity (K_{sat}) of that layer. If the K_{sat} is less than the drainage then the actual drainage is limited to the K_{sat} value. The model uses the Priestly–Taylor method to estimate daily potential evapotranspiration. The CERES-Rice model also simulates flood water depth, flood water evapotranspiration and runoff, only if the flood water depth exceeds bund height. The model also simulates the temporal changes in bulk density and saturated hydraulic conductivity due to puddling.

Soil data

Soil samples data collected from 34 locations across the watershed under INDO-US-AKI project were used for this study (Reddy *et al.,* 2010). Soil physicochemical properties such as texture, hydraulic parameters, bulk density, organic matter, available N, phosphorus and potassium were obtained from the study. Additional soil parameters, including the soil albedo, drainage constant, and runoff curve number were also estimated based on the soil texture data from the generic soil database available in the DSSAT-models (Tsuji *et al.,* 1998).The 34 soil reference points were converted into polygons using the thiessen method which is one of the simplest methods of interpolation by drawing boundaries according to the distribution of soil sample points using ArcGIS v10.0 software (Environmental Systems Research Institute, 2011). Later the converted polygons were clipped with soil and rice crop area maps (Fig. 2).

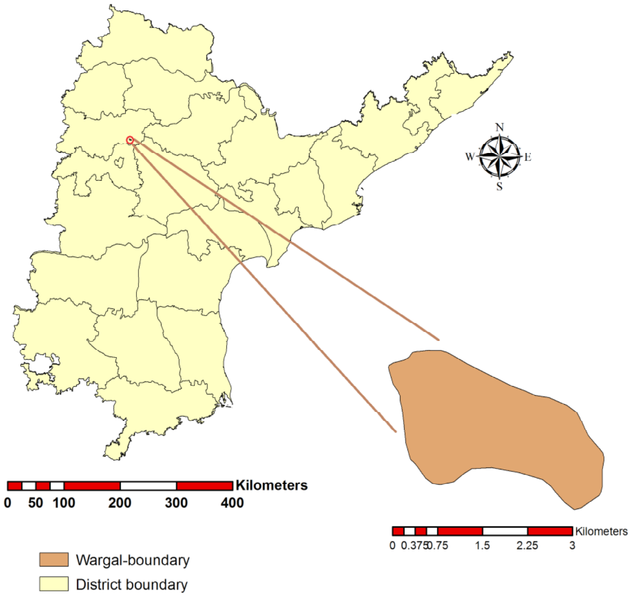

Fig. 1: Location of study area- Kothakunta sub watershed, Wargal, Medak District, A.P, India.

Weather data

Daily weather data of the area from 1975 to 2009 was obtained from the nearby weather station available at International Crops Research Institute for Semi-Arid Tropics (ICRISAT), Hyderabad. The weather parameters included daily solar radiation (MJ $m^{-2}day^{-1}$), maximum and minimum air temperatures (°C), and rainfall (mm day^{-1}).

Crop management inputs

Crop management data used for three simulations are presented in the Table 1. All the treatments received 180 kg N ha^{-1} applied in three equal splits, each one at the time of planting, maximum tillering and at panicle initiation stage. In the rainfed and flooded rice treatments, crop was planted initially in the nursery and 30-day old seedlings were transplanted in the main field. In aerobic rice treatment, seeds were planted at rate of 300 seeds m^{-2} in 22.5 cm rows apart.

Initial conditions

The initial conditions on soil water, nitrate and ammonium were the actual values estimated during the data collection for 34 soil sample. An estimate of the above and below ground residues from the previous crop also recorded and provided as an input for the model.

Model calibration and management options simulated

The CERES-Rice model in DSSAT v 4.5(Hoogenboom *et al.,* 2010) were used in the study. Model calibration involves the estimation of genotype coefficients to confirm an agreement between model predictions and observed values. The CERES-Rice model was calibrated with the data obtained from the 2009 field experiment with the treatment receiving 120 kg N ha^{-1}under flooded conditions, the treatment with minimum soil constraints (Jones *et al.,* 2010). The cultivar coefficients were estimated using the Generalized Likelihood Uncertainty Estimation (GLUE) method (Beven and Binley, 1992; Franks *et al.,* 1998; Shulz *et al.,* 1999; Jones *et al.,* 2010). In this method, the parameter space is first discretized by generating a large number (6,000) of parameter values from the prior distribution. Likelihood values are then calculated for each set of coefficients using differences between model predictions and measurements. Weights and probabilities are calculated with the Bayesian equation, and the posterior coefficients are estimated.

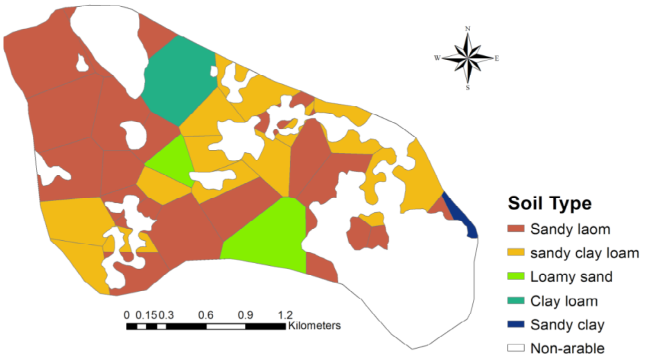

Fig. 2: Distribution of main soil types in Kothakunta sub watershed, Wargal, Medak District, A.P, India.

After estimating cultivar coefficients for rice the model was evaluated by comparing observed and predicted results for the remaining treatments in 2009. The days to anthesis and maturity, measured crop yield, and biomass factors were used to calibrate and evaluate the model. After successful calibration and evaluation the model was used to simulatethe following three scenarios

1. Puddled flooded rice receiving 180 kg N ha^{-1} grown under rainfed conditions (RR).
2. Puddled flooded rice receiving 180 kg N ha^{-1} rice grown under irrigated conditions maintaining 2 cm depth of water from transplanting to flowering and 5 depth of water from flowering to one week before maturity (FR).
3. Aerobic rice with 180 kg N ha^{-1} and automatic irrigation with 40 mm, when soil available water (ASW) in top 30 cm equals to 60% (AR)

Table 1: Crop management information

Scenario	Planting date	Plant population m^{-2}	Row spacing
Rainfed rice (RR)	5 August	33	30 cm
Flooded rice (FR)	5 August	33	30 cm
Aerobic rice (AR)	5July	150	22.5 cm

The basis for using 40 mm irrigation at 60% ASW was due to the fact that this treatment was found optimum for attaining the highest yields of aerobic rice under similar climatic conditions using the MTU 1010 variety (Kadiyala *et al.,* 2014). The output results on grain yield, seasonal evapotranspiration (ET), seasonal drainage, irrigation volumes and N balance components such as crop uptake, N leaching were mapped to visualize their spatial and temporal variability under three different scenarios. Total annual underground irrigation withdrawals, water pumping hours, runoff, and N leaching in each polygon were also calculated and summed to obtain the totals for the entire watershed under the three scenarios. Water productivity (g grain kg^{-1} of water) and irrigation water use efficiency (g grain kg^{-1} of water) were also calculated for each scenario.Annual irrigation withdrawals for each scenario were estimated as.

$$IRw = \sum_{i=1}^{n} Xi\, IRi \qquad (1)$$

Where IR_w is the annual irrigation withdrawals from the entire rice area of the watershed, X is the area of the each polygon and IR is the irrigation amount applied to rice crop grown in that particular polygon. Similar procedure was followed for calculating annual drainage and N leaching in the watershed.

Water productivity (WP, g grain kg^{-1} of water) and irrigation water use efficiency (IWUE, g grain kg^{-1} of water) can be estimated as.

$$WP = \frac{Y}{WA_{(I+R)}} \qquad (2)$$

$$IWUE = \frac{Y - Y_R}{IR} \qquad (3)$$

Where Y represents the rice grain yield, WA is the total water applied, includes irrigation (I) and rainfall (R), Y_R is the yield obtained under rainfed conditions, IR amount of irrigation water applied during crop growth.

RESULTS AND DISCUSSION

Model calibration and evaluation

The most commonly grown cultivar for rice in Wargal study area is a short duration, high yielding variety MTU 1010 was used for the simulations. The CERES-Rice modelwas calibrated with the experimental data collected during 2009 (Kadiyala *et al.,* 2012) which consists of two rice establishment methods, aerobic and flooded rice systems with four nitrogen rates (0, 60, 120 and 180 kg N ha^{-1}).The estimated cultivar coefficients for the rice cultivar MTU 1010 are presented in the Table 2. A close agreement was observed between the simulated and observed values for anthesis, maturity, grain yield, biomass yield and N uptake in rice crop (Table 3). The data collected from the remaining treatments in rice were also used to evaluate the accuracy of the model during 2009.The statistical indices (RMSE and ME) used to evaluate the accuracy of the model are presented in Table 4. The model well predicted the days to anthesis and maturity, grain yield, tops weight, and N uptake, in both aerobic and FR establishment methods, with NRMSE of 14.5%, d- values of 0.93 and with ME of 0.73. However, the model under-predicted leaf area index and over-predicted soil moisture content as suggested by the negative ME values. The model simulated grain yield under various N rates and different establishment methods with high r^2 values.

Exploration of various crop establishment options to rice cultivation

Results of model evaluations demonstrated that the models accurately predicted the phenological development, grain, total biomass, soil water content variations over time in response to variable weather conditions and response to different N levels. Thus, a model-based analysis was carried out to explore a range of crop establishment options to rice cultivation to identify best rice establishment method which not only reduces the water requirement but also maintains the rice yields.

Rice yields

The yields simulated by the model under rainfed conditions were fairly consistent with the typical range of yields reported for the area. Simulated rice yields varied with the soil type and were higher in sandy clay loam soil than in the sandy loam soil. Rainfed conditions resulted in lower yields with an overall mean of 5954 kg ha^{-1} (Table 5), ranging from 2746 kg ha^{-1} to 7217 kg ha^{-1}.This indicated

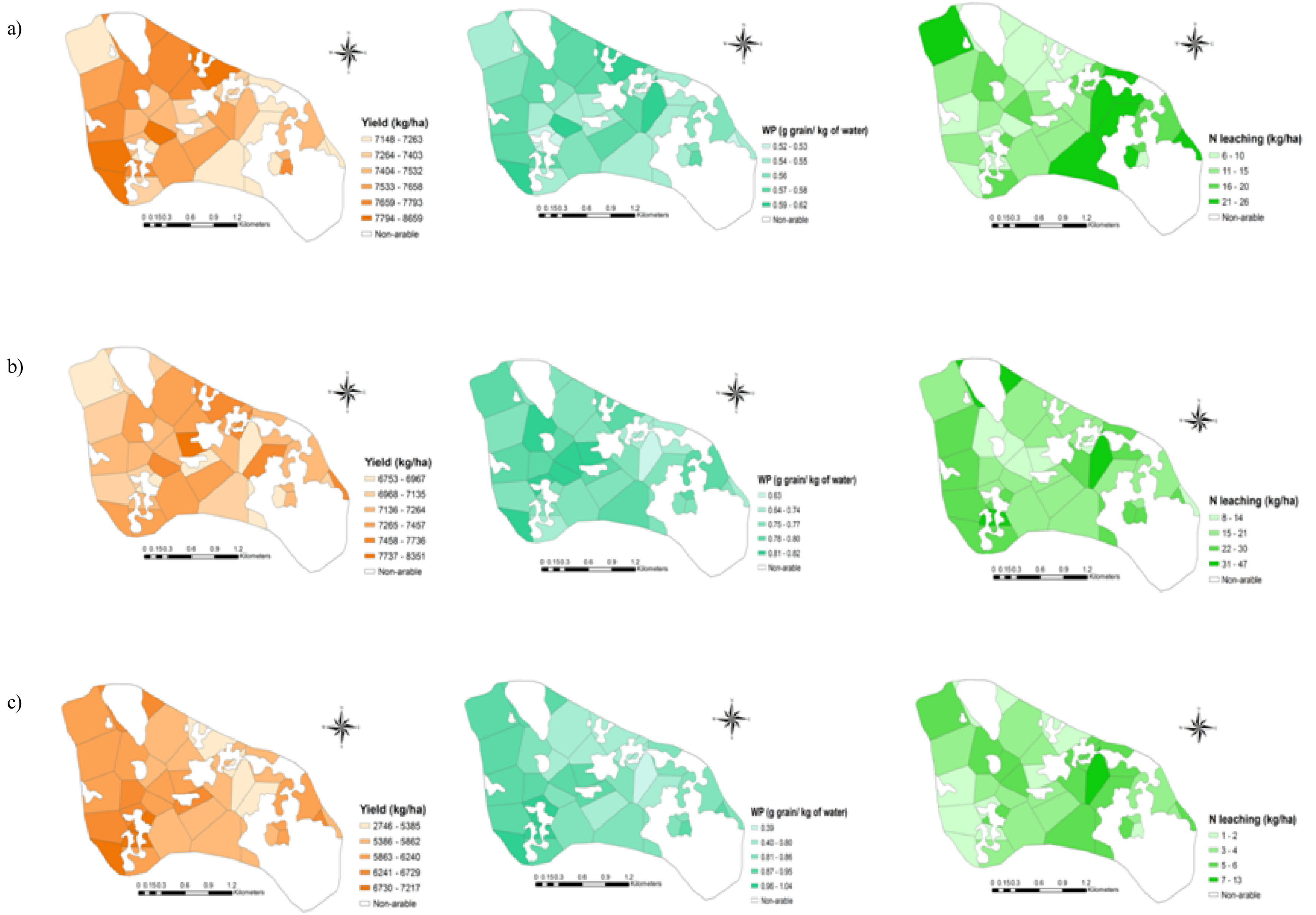

Fig. 3: Yield, WP, N leaching as simulated by the CERES-Rice model under a) Floodede rice b) aerobic rice and c) rainfed rice establishment scenario and mapped for the 34 soil polygons

Table 2: Genetic coefficients developed for rice variety MTU-1010.

Genetic parameters	Description	Coefficient for MTU-1010
P1	Time period (expressed as growing degree days [GDD] in °C above a base temperature of 9 °C) from seedling emergence during which the rice plant is not responsive to changes in photoperiod. This period is also referred to as the basic vegetative phase of the plant	407.0
P20	Critical photoperiod or the longest day length (in hours) at which the development occurs at a maximum rate. At values higher than P20 developmental rate is slowed, hence there is delay due to longer day lengths	173.0
P2R	Extent to which phasic development leading to panicle initiation is delayed (expressed as GDD in °C) for each hour increase in photoperiod above P20.	367
P5	Time period in GDD (°C) from beginning of grain filling (3–4 days after flowering) to physiological maturity with a base temperature of 9°C.	11.7
G1	Potential spikelet number coefficient as estimated from the number of spikelets per g of main culm dry weight (less lead blades and sheaths plus spikes) at anthesis. A typical value is 55.	61.3
G2	Single grain weight (g) under ideal growing conditions, i.e. non- limiting light, water, nutrients, and absence of pests and diseases.	0.022
G3	Tillering coefficient (scalar value) relative to IR64 cultivar under ideal conditions. A higher tillering cultivar would have coefficient greater than 1.0.	1.0
G4	Temperature tolerance coefficient. Usually 1.0 for varieties grown in normal environments. G4 for japonica type rice growing in a warmer environment would be 1.0 or greater. Likewise, the G4 value for indica type rice in very cool environments or season would be less than 1.0.	1.11

Table 3: Simulated and observed phenological dates, growth characters and grain yield of rice during 2009-10 in flooded rice receiving recommended package of practices.

Crop-variety	Anthesis (DAS)		Maturity (DAS)		Tops weight (t ha^{-1})		Grain N at maturity (kg ha^{-1})		Tops N at maturity (kg ha^{-1})		Unit grain weight (g)		Grain yield (t ha^{-1})	
	Obs	Sim	Obs	Sim	Obs	Sim	Obs	Sim	Obs	Sim	Obs	Sim	Obs	Sim
RiceMTU-1010	95	96	127	128	12.3	12.2	75.6	83	109	113	0.02	0.02	5.9	6.0

Sim - simulated; Obs- Observed. DAS- Days after sowing

there the crop yields varied greatly among the polygons across the region even though the weather is normally assumed to be uniform across the watershed area. The simulated yields under flooded and aerobic conditions were more than the general yields previously reported in the area which ranged between 7147 – 8659 kg ha^{-1} and 6753- 8351 kg ha^{-1} respectively. On average, the yields under the aerobic and flooded rice were 22% and 27% higher than the rainfed rice. Higher yields were simulated in western and central part of the watershed under both flooded and rainfed conditions while under aerobic rice, the central and eastern parts showed higher rice yields(Fig.3).

Water balance components

Information on water balance components is important to understand contribution of irrigation to the yields and various losses. Various water balance components such as irrigation volume, ET, drainage, runoff and soil water available after crop harvest were studied under flooded, rainfed and aerobic rice scenarios. In flooded rice scenario, the average amount of irrigation water applied was 861 mm compared to 253 mm in the aerobic rice suggesting

Table 4: Descriptive statistics showing the performance of CERES-Rice for treatments in 2009 that were not used to estimate cultivar parameters

Variable	Data numbers	Obs	SD	Sim	SD	RMSE	NRMSE (%)	d-index	ME	r
PI date (DAS)	7	60.00	5.60	57.0	4.30	3.50	5.80	0.86	0.56	0.99
Anthesis date (DAS)	7	91.50	4.10	91.5	4.80	0.86	0.90	0.99	0.95	0.99
Maturity date (DAS)	7	123.00	4.10	123	6.01	1.80	1.40	0.96	0.79	0.99
LAI ($cm^2 cm^{-2}$)	25	1.89	0.77	1.19	0.91	0.97	51.0	0.62	-0.62	0.68
Tops weight (t ha^{-1})	25	4.80	3.40	4.80	3.70	1.10	23.0	0.97	0.89	0.95
SWC 0-15 cm ($cm^3 cm^{-3}$)	18	0.25	0.03	0.27	0.07	0.05	22.2	0.62	-3.3	0.76
SWC 15-30 $cm^3 cm^{-3}$)	18	0.31	0.03	0.27	0.05	0.05	16.0	0.65	-1.5	0.89
Grain yield (t ha^{-1})	7	4.16	1.50	3.92	1.80	0.70	17.8	0.95	0.75	0.93
Straw yield (t ha^{-1})	7	4.76	1.50	4.30	2.10	1.00	21.0	0.91	0.50	0.90
Tops N at maturity (kg ha^{-1})	7	75.7	26.4	81.2	38.0	18.4	24.3	0.90	0.44	0.89
Grain N at maturity (kg ha^{-1})	7	52.3	29.0	54.6	21.5	14.9	28.4	0.89	0.70	0.84

Sim - simulated; Obs- Observed; SD-Standard deviation; RMSE- Root mean square error; ME – Modeling efficiency; r- Spearman correlation coefficient

Table 5: Average and standard deviation of rice yields, water productivity and irrigation use efficiency under different crop establishment method as simulated by CERES-Rice model in the watershed

Treatment	Water applied I+R (mm)	No. of pumping hours	Yield (kg ha^{-1})	WP (g grain kg^{-1} of water)	IWUE (g grain kg^{-1} of water)
Rainfed rice	699±5	-	5954±783	0.85±0.12	-
Flooded rice	1356±31	299±11	7572±349	0.56±0.02	0.19±0.10
Aerobic rice	948±51	88±18	7271±301	0.77±0.03	0.50±0.26
ANOVA					
Treatments		***	***	***	***

Pumping hours calculated based on normal discharge of 8 lps for a 5HPmotor.

* $P< 0.05$; ** $P<0.01$; *** $P<0.001$; NS= non-significant ($p>0.05$).

Table 6: Average and standard deviation of water balance components of rice as influenced by different crop establishment methods as simulated by CERES-Rice model in the watershed

Method	Irrigation volume (mm)	Seasonal ET (mm)	Drainage (mm)	Runoff (mm)	Soil water available after harvest (mm)
Rainfed rice	-	514±24	85±10	97±23	39±11
Flooded rice	861±30	434±4	522±5	193±1	164±34
Aerobic rice	253±53	478±10	289±56	137±67	79±17

ET- Evapotranspiration.

Table 7: Averages and standard deviations for 35 years of simulations for total rice production, irrigation amount, deep drainage, pumping hours, and N leaching for different rice crop establishment scenarios.

Method	Production ($1X 10^3 t$)	Irrigation ($1 X 10^5 m^3$)	Deep drainage ($1 X 10^5 m^3$)	Pumping hours ($1 X 10^4$ hr.)	N leaching (t $season^{-1}$)
Rainfed rice	2.21 ±0.76	-	3.0±2.9	-	1.34±0.9
Flooded rice	2.78±0.10	31.7±3.0	19.1±0.6	10.9±1.0	5.21±0.19
Aerobic rice	2.65±0.10	8.70±1.4	10.5±2.3	2.98±0.5	7.54±2.6

that substantial amount of water could be saved under the aerobic system (Table 6). The seasonal irrigation volume in flooded system ranged between 747 to 917 mm averaged across the locations compared to 187 -393 mm under the aerobic rice. Increased irrigation volumes under flooded system resulted in increased runoff as wells as increased drainage. In the aerobic system, the average amount of irrigation applied across the watershed was 53% of ET, while it was 198% of ET the flooded rice. Water productivity was calculated based on the simulated yield and total volume of water (I +R) for rainfed, aerobic and flooded rice. The seasonal drainage volumes in flooded rice were considerably high and ranged from 517 mm to 536 mm. This was one of the reasons for higher water requirement of rice under this system. The drainage volumes under aerobic system, on the other hand, were lower (119 mm to 410 mm) as there was no standing water maintained in the field throughout the crop growth. The results showed that among the three scenarios, the rainfed rice system showed the highest (0.38 – 1.03 g grain kg^{-1} of water applied) followed by the aerobic rice (0.63 – 0.82), and the flooded rice (0.52-0.62). The IWUE decreased with increased irrigation applications. Adoption of aerobic rice cultivation resulted in an average IWUE of 0.5 g grain kg^{-1} of water applied with a standard deviation of 0.26 across the study area compared to the 0.19 g grain kg^{-1} of water applied with a standard deviation of 0.1 with flooded rice. The spatial distribution of irrigation water used and water productivity in the three scenarios are presented in the Fig.3.

Nitrogen leaching

Among the irrigation scenarios studied, aerobic rice was associated with the greatest amount of N leaching. The simulated N leaching amounts varied considerably among different soil types across the study area with ranges of 8-47 kg ha^{-1}, 6-15 kg ha^{-1} and 0.6 to 13.2 kg ha^{-1} under aerobic, flooded and rainfed scenarios, respectively. The spatial distribution of leaching in various rice establishment methods was presented in the Fig. 3.

Watershed Level

Irrigation withdrawals: The mean seasonal irrigation withdrawals for the entire watershed under flooded and aerobic rice scenarios were 31.7 x 10^5 m^3 and 8.7 x 10^5 m^3 respectively. It was found that in order to meet the increased irrigation demand under flooded system, irrigation pumping hours needed to be increased to 3.66 times than the pumping hours under aerobic system (Table 7).

Deep drainage: The maximum amount of simulated drainage was 19.1 x 10^5 m^3 under flood irrigation scenario. In flood irrigation scenario, 60% of pumped irrigation water resulted in drainage while it was 120% under the aerobic rice suggesting that most of the rainfall directly contributes to drainage under aerobic system. The results also indicate that most of the water pumped in expense of electrical energy was lost through drainage rather than being utilized by the crop.

Nitrate leaching: Maximum amount of N leached was 7.54 t per season under aerobic rice, while the minimum amount N leached was 5.21 t per season under rainfed conditions. The lower leaching losses in flooded and rainfed rice were possibly because of the anaerobic growing conditions which normally result in reduced soil conditions as opposed to the aerobic rice where highly oxidized condition is likely to enhance nitrate leaching (Belder et al., 2005; Zhang *et al.,* 2009).

CONCLUSIONS

The present study on spatial water requirement of alternate rice irrigation management scenarios demonstrated the capability of DSSAT models coupled with GIS in presenting the spatial patterns of simulated results. Developing thematic maps on N and water balances at watershed or region level will make these models a useful tool for supporting policy making in integrated water resources management. In the study it was observed that irrigation played a crucial role in improving the rice yields and WP. The simulation results also indicate that IWUE is 50% higher in aerobic rice compared to rainfed rice. Higher water productivity and water savings are possible in rice cultivation by following aerobic rice method. The water balance studies indicates that in flooded rice, 63% of the total water applied (I+R) was from irrigation and the losses through deep percolation and runoff accounted for 53% of the total water applied. While, in aerobic rice only 27% of the total water applied was from irrigation with 45% of applied water lost through runoff and deep percolation. These type of studies up to watershed scales were very useful in decision making as most of the data presently available in countries like India were up to district level only. Further, there are many assumption and uncertainties in this study especially DSSAT one dimensional water balance model and simulating the crop yields based on single weather station data for entire watershed. Besides these there are other factors like weeds, pest and diseases that can influence crop yields especially under aerobic rice system which was not considered in the present study. Despite these limitations the integration of crop models with GIS can assists the researchers and policy makers in studying the overall water productivity up to the regional or watershed scales.

REFERENCES

Behera, S.K., and Panda,R.K. (2009). Integrated management of irrigation water and fertilizers for wheat crop using field experiments and simulation modeling. *Agric. Water Manage.*, 96: 1532-1540.

Beinroth, F.H., Jones, J. W., Knapp, E.B.,Papajorgji, P.,and Luyten,J. (1998). Evaluation of land resources using crop models and a GIS. In:"Understanding Options for Agricultural Production".(Eds. G.Y Tsuji, G. Hoogenboom and P.K. Thornton). pp.293-311. (Kluwer Academic Publishers, Dordrecht, the Netherlands)

Belder, P., Bouman, B. A. M.,Spiertz, J.H.J.,Peng, S.,Castaneda, A.R.,and Visperas,R.M. (2005). Crop performance, nitrogen and water use in flooded and aerobic rice. *Plant Soil.,* 273:167-182.

Beven, K.,and Binley, A. (1992). The future of distributed models: Model calibration and uncertainty prediction. *Hydrol. Processes.,* 6, 279–298.

Bouman, B.A.M., Peng, S.,Castaneda, A.R.,and Visperas. R.M. (2005). Yield and water use of irrigated tropical aerobic rice systems. *Agric. Water Manage.*, 74:87-105.

Bulatewicz, T., Jin, W., Staggenborg, S.,Lauwo, S.,Miller, M.,Das, S.,Andresen, D.,Peterson, J., Steward, D.R.,and Welch,S.M. (2009). Calibration of a crop model to irrigated water use using a genetic algorithm. *Hydrol. Earth Syst. Sci.,* 13: 1467–1483.

Engel, T., Hoogenboom, G.,Jones, J.W.,and Wilkens,P.W. (1997).AEGIS/WIN: A computer program for the application of crop simulation models across geographic areas. *Agron. J.*, 89: 919-928.

Fortes, P.S., Platonov, A.E.,and Pereira,L. S. (2005). GISAREG—A GIS based irrigation scheduling simulation model to support improved water use. *Agric. Water Manage.*, 77: 159–179.

Franks, S.W.P., Gineste, P.,Beven, K.J.,and Merot, P. (1998). On constraining the predictions of a distributed model: The incorporation of fuzzy estimates of saturated areas into the calibration process. *Water Resour. Res.*, 34: 787–797.

Hansen, J. W., Beinroth, F.H.,and Jones,J.W. (1998). Systems-based land-use evaluation at the south coast of Puerto Rico. *Appl. Eng. Agric.*, 14: 191-200.

Hartkamp, A.D., White, J.W.,and Hoogenboom,G. (1999). Interfacing geographic information system with agronomic modeling: a review. *Agron. J.*, 91: 761-772.

Heinemann, A.B., Hoogenboom, G.,and de Faria,R.T. (2002). Determination of spatial water requirements at county and regional levels using crop models and GIS. *Agric. Water Manage.*,52: 177-196.

Jagtap, S.S., and Jones,J.W. (2002). Adaptation and evaluation of the CROPGRO-soybean model to predict regional yield and production. *Agric. Ecosyst. Environ.*, 93: 73-85.

Jones, J. W., He, J.,Boote, K.J.,Wilkens, P.,Porter, C.H.,Hu, Z. (2010). Estimating DSSAT Cropping System Cultivar-Specific Parameters Using Bayesian Techniques. In: Methods of Introducing system models into agricultural research (Eds. L.R. Ahuja,and L. Ma).pp. 365-393. (Advances in Agricultural Systems Modeling 2. ASA, Madison, WI).

Kadiyala, M.D.M., Mylavarapu, R.S., Li, Y.C., Reddy, G.B., Reddy, M.D.(2012). Impact of aerobic rice cultivation on growth, yield, and water productivity of Rice–Maize rotation in semiarid tropics. *Agron. J.,* 104, 1757-1765.

Kadiyala, M.D.M., Jones, J.W., Mylavarapu, R.S., Li,Y.C.,and Reddy M.D. (2014). Identifying Irrigation and Nitrogen Best Management Practices for Aerobic Rice-Maize Cropping System for Semi-Arid Tropics using CERES-Rice and Maize models. *Agric. water Manage.*, (In review).

Liu, H.L., Yang, J.Y.,Drury, C.F.,Reynolds, W.D.,Tan, C.S.,Bai, Y.L.,He, P.,Jin, J.,and Hoogenboom,G. (2011). Using the DSSAT-CERES-Maize model to simulate crop yield and nitrogen cycling in fields under long-term continuous maize production. *Nutr. Cycling Agroecosyst.*, 89: 313–328.

Rao, N.H., and Rees,D.H. (1992).Irrigation scheduling of rice with a crop growth simulation model. *Agric. Syst.,* 39: 115-132.

Rinaldi, M.(2004). Water availability at planting and nitrogen management of durum wheat: a seasonal analysis with the CERES- Wheat model. *Field Crops Res.*,89: 27-37.

Rinaldi, M., Ventrella, D.,and Gagliano,C. (2007).Comparison of nitrogen and irrigation strategies in tomato using CROPGRO model. A case study from Southern Italy. *Agric. Water Manage.,* 87: 91-105.

Ritchie, J.T. (1998). Soil water balance and plant stress. In:"Understanding Options for Agricultural Production".(Eds. G.Y Tsuji, G. Hoogenboom and P.K. Thornton). pp.41-54. (Kluwer Academic Publishers, Dordrecht, the Netherlands)

Reddy, M. D, Uma Devi, M., Mani, A., Raji Reddy, D., Vijay Kumari, R., and Murthy, K. M. D. (2010). Indo – US AKI project on Sustainable water resources management. Project report, Acharya NG Ranga Agricultural University, Hyderabad. Pp.1-158.

Shulz, K., Beven, K.J.,and Huwe,B. (1999). Equifinality and the problem of robust calibration in nitrogen budget simulations. *Soil Sci. Soc. Am. J.,* 63: 1934–1941.

Thornton, P.K., Bowen, W.T.,Ravelo,A.C.,Wilkens, P.W.,Farmer, G.,Brock, J.,and Brink,J.E. (1997). Estimating millet production for famine early warning: an application of crop simulation modeling using satellite and ground-based data in Burkina Faso.*Agric. For. Meteorol.*,83: 95- 112.

Tsuji, G. Y., Hoogenboom, G.,and Thornton. P.K. (1998). "Understanding options for agricultural production. Systems approaches for sustainable agricultural development". Kluwer Academic Publishers, Dordrecht, the Netherlands.

Zhang, L., Lin, S. Bouman, B.A.M. Xue, C. Wei, F. Tao, H. Yang, X. Wang, H. Zhao, D. and Dittert,K. (2009). Response of aerobic rice growth and grain yield to N fertilizer at two contrasting sites near Beijing, China. *Field Crops Res.*,114:45-53.

Received : July 2014 ; Accepted : April 2015