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Variability mapping of crop evapotranspiration for water footprint assessment at basin level

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ABSTRACT

Knowledge about variability in crop evapotranspiration (ETc) is essential for realistic assessment of crop water footprint. In this study, administrative districts falling under the Gomati basin were divided into 21 Agricultural Production Units (APUs) on the basis of homogeneity of soil and agro-ecology. Blue and green components of ETc of 15 major crops grown in each APU were assessed using CROPWAT model. Ordinary kriging and ordinary co-kriging were evaluated for mapping spatial variability of ETc. Prediction error was lowest for ordinary co-kriging. Etc variability maps for *kharif* and *rabi* crops were developed using ordinary co-kriging. In case of *kharif* crops, the maximum Etc values were located in the central region and that for *rabi* crops in the lower region of the Gomati basin. Variability in green crop water use was high. Green water use by paddy was 425.0 mm, 420.4 mm and 410.4 mm in the lower, upper and middle regions, respectively. The green water use of winter crops varied from 0.2 mm for mustard to 25.8 mm for wheat crop. In general, the blue water use by *rabi* crops was considerably higher than that of *kharif* crops and it varied from 5.3 to 942.5 mm for maize and sugarcane, respectively. Sugarcane had maximum blue and green water use. In view of large variations, estimation of crop water footprint considering average value of ETc for entire basin will not be appropriate.

1. INTRODUCTION

Increasing consumptive and non-consumptive use of water and changing climatic conditions are causing a great stress on water resources. Freshwater supply for irrigation is decreasing and the agricultural production in many river basins, especially in arid and semi-arid regions of the world, is greatly affected (Jose *et al.,* 2010; Vorosmarty *et al.,* 2010). The increasing water scarcity is forcing the water managers to evolve better crop water use indicators to decide upon the import-export policies of the region or country. Virtual Water Content (VWC) and Water Footprint (WF) are the relatively new indicators that look into water use from production and consumption perspectives. The virtual water content of a product refers to the volume of water used in its production (Allan, 1998). The concept of Water Footprint introduced by Hoekstra and Hung (2002) is closely related to VWC in the sense that it is the total VWC of a product consumed by an individual, business, town, city or country (Chapagain and Orr, 2009).

Assessment of WF of agricultural produce requires spatially explicit estimates on blue (surface and ground water) and green (effective rainfall) water use of crops. Water requirements of crop are governed by several climatic factors like temperature, wind velocity, solar radiation and relative humidity (Allen *et al.,* 1998). Depending on the size of the study region, researchers have used different resolutions and approaches to estimate the blue and green components of the crop evapotranspiration (ETc) in WF accounting. Here resolution refers to the size of the spatial unit within which crop, climate and soil parameters are assumed to be uniform. Many national level WF accounting studies (Mubako and Lant, 2013; Ge *et al.,* 2011; Bulsink *et al.,* 2010) have used province as the spatial resolution to estimate crop evapotranspiration. Feng *et al.* (2012) divided the yellow river basin into upper, middle and lower regions and the blue water use per region per crop was estimated. Rao and Rajput (2005 and 2008) evaluated the rainfall effectiveness (green water use) for different crops in

Nagarjuna Sagar canal command area of Andhra Pradesh. Considering entire basin as a spatial resolution unit, Vara Prasad *et al*. (2013) quantified the blue and green proportions of ETc of six important crops and four major land use types of Kothakunta sub watershed in Andhra Pradesh.

At national or basin scale, the size of the spatial resolution unit considered for ETc assessment is very large. Climate and soil variability within these units may result in significant variation in the blue and green crop water use. ETc estimated at one location cannot be presumed to be applicable for entire spatial resolution unit. Studies (Jing Lei *et al.,* 2013; Alexandrov and Hoogenboom, 1999; Heinemann *et al.,* 2002) suggested that ETc varies in space even within a smaller region. Therefore, decision on appropriate size of spatial resolution of ETc and consequent water footprints estimation requires spatial patterns of ETc within the basins. Geostatistics is one of the interpolation techniques that provide a set of statistical tools for spatial interpolation and analysing spatial variability. Geostatistical methods like kriging and co-kriging have been increasingly used to map the variability parameters like precipitation (Sarangi *et al.,* 2005), crop evapotranspiration (Sharma and Irmak, 2012), groundwater table and hydro-geochemical processes (Gundogdu and Guney, 2007) and climatic parameters (Ibrahim, 2011). The aim of this study was to estimate the total green and blue water use of crops in a spatially explicit way using FAO CROPWAT model and map the variability within the basin using suitable kriging interpolation technique. These estimates of spatial ETc will improve the accuracy of water footprint accounting at basin level.

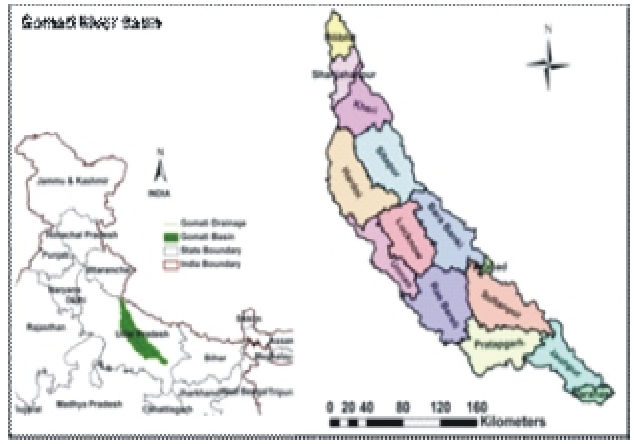


Fig. 1. Location and geographic domain of the Gomati basin.

2. MATERIALS AND METHODS

The present study aims at estimating blue and green components of ETc at appropriate spatial unit and mapping ETc variability for accurate WF accounting in Gomati River basin, a tributary of River Ganges. Gomati sub-basin represents part of agriculturally important region called Indo-Gangetic plains (Fig.1). Spatial units referred as 'Agricultural Production Unit' (APU) were delineated based on climate, soil type and district boundaries within the basin. Water requirement of a crop can be assumed to be unique in a particular APU. Fifteen major crops covering about 89.79 % of the gross cropped area in the Gomati basin were considered for variability mapping of ETc.

The ETc of selected crops was estimated for normal

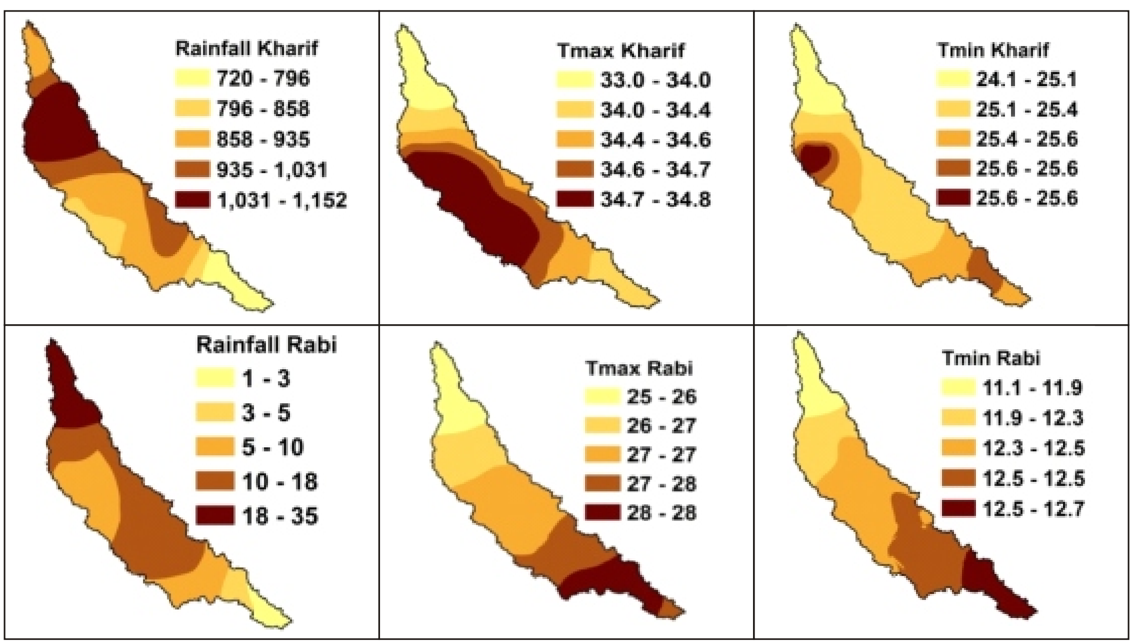


Fig. 2. Spatial distribution of annual rainfall (mm), mean maximum temperature (^{0}C) and mean minimum temperature (^{0}C) during *kharif* and *rabi* seasons in the year 2011.

year in terms of rainfall. If annual rainfall of a place is within ±19 % of normal rainfall, the year is said to be a normal year (IMD, 2013). In present study, year 2011 was considered as normal year for the Gomti basin. Spatial distribution of rainfall, mean maximum and mean minimum temperature of the *kharif* and *rabi* seasons of 2011 is shown in Fig. 2. During *kharif* and *rabi* seasons, rainfall was higher in the upper region of the basin. Mean maximum temperature and mean minimum temperature during *kharif* season was higher in the central region while for *rabi* season these parameters increased gradually from upper to lower reaches of the basin.

Data Acquisition

Digital Elevation Model (DEM) of the basin was obtained from Shuttle Radar Topographic Mission (SRTM) of USGS (USGS, 2012). Agro Ecological Sub Regions (AESR) map developed by Nation Bureau of Soil Survey and Land Use Planning was obtained from Gajbhiye and Mandal (2000). District wise time series data of monthly precipitation, monthly mean maximum and monthly mean minimum temperature data available with NICRA was used (NICRA-ICAR, 2013, available at www.nicra-icar.in). Spatial distribution of major soil types and sand, silt and clay content of these soils was taken from grid based Harmonized World Soil Database (HWSD) (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2008). Crop coefficients at different crop development stages (initial, middle and late stage), length of crop development stage and crop rooting depths required as input to CROPWAT were taken from FAO (Allen *et al.,* 1998). The crop planting and harvesting dates for the state of Uttar Pradesh were adopted from information published by Department of Economics and Statistics, Ministry of Agriculture, GOI (MoA, 2011).

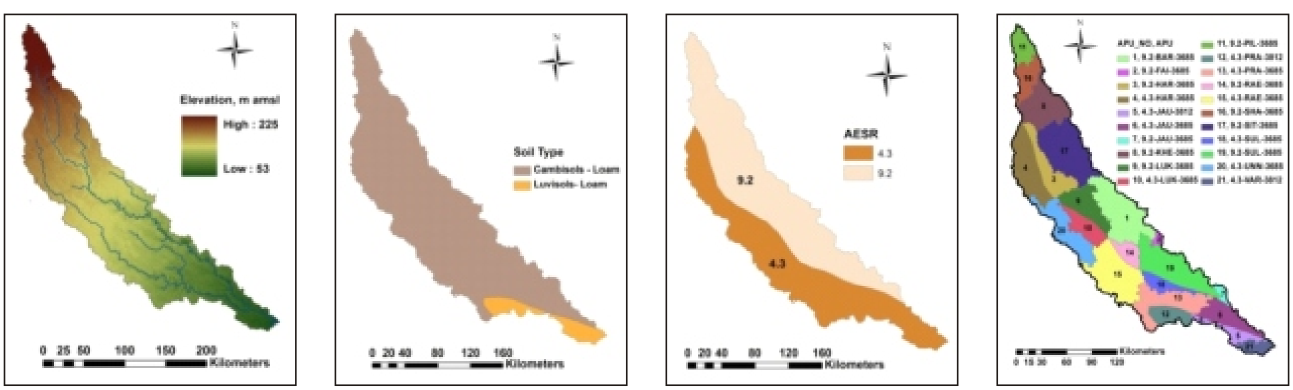
Delineation of Agricultural Production Units

The basin boundary was delineated using digital elevation data captured by the Space Shuttle (SRTM DEM) at a resolution of 1 arc second (about 90 m). The standard process of delineation, such as creating a depression less DEM, flow direction, flow accumulation, pour points, and watershed delineation, available in ARCGIS was used. The drainage area of Gomati basin, as delineated using SRTM DEM with WGS_1984_Albers projection, was about 31240 km^2 (Fig. 3a). The information on soil properties was extracted from HWSD soil raster in GIS environment. The soil type information, as derived from gridded raster soil dataset of HWSD, is presented in Fig. 3b. Soil properties like, field capacity, wilting point and maximum infiltration rate were determined using the pedotransfer functions for Indian soils developed by Adhikari*et al.,* (2008) (Table 1).

Table: 1
Important soil properties of the Gomati basin

Soil Code	USDA Texture Class	Particle distribution Sand (%)	Silt (%)	Clay (%)	BD (g cc^{-1})	FC (%)	WP (%)	AWHC (mm m^{-1})	K (mm day^{-1})	D (cm)
3685	loam	42	36	22	1.37	25.23	10.4	148.4	102.2	200
3812	loam	47	32	21	1.42	23.76	10.0	138.1	116.8	200

BD=Bulk density, FC=Field capacity, WP=Wilting point, AWHC=available water holding capacity, K=Saturated hydraulic conductivity, D=Maximum rooting depth.



a. Gomati basin and its drainage network
b. Soil Map
c. Agro-ecological sub regions
d. Agricultural Production Units

Fig. 3. Thematic layers used in delineation of the Agricultural Production Units and the delineated APUs of Gomti River basin

The Agro-Ecological Sub Regions (AESRs) map was imported in ArcGIS and the AESR map of the basin was created (Fig. 3c).Thematic layers pertaining to soil, AESR, basin and district boundaries were overlaid and APU polygons were formed for each district using intersect feature in ArcGIS. Since statistical data related to area and production is maintained at district level and is easily available, defining APUs for each district separately will help in partitioning these datasets to APU level. In this study, the Gomati basin was divided in to 21 APUs (Fig. 3d).

Assessment of Crop Evapotranspiration

In this study, FAO CROPWAT model (FAO, 2012; Allen *et al.,* 1998) was used to estimate the green (effective rainfall) and blue (irrigation) consumptive water use of a crop. CROPWAT model estimates reference crop evapotranspiration (ET_0) over the cropping season using Penman-Monteith equation. Values of crop coefficient (Kc) for initial, middle and end stage were adopted from FAO irrigation and drainage paper No-56 (Allen *et al.,* 1998). CROPWAT also requires information on rooting depth of crops and critical depletion to be specified for each crop (Table 2). Contribution of rainfall in crop evapotranspiration (green water use) was estimated using daily dynamic soil water balance approach available in CROPWAT. In this approach CROPWAT estimates ETc as well as effective rainfall (P_{eff}) considering crop, climate, soil parameters and daily soil profile moisture status. If total soil moisture depletion on a particular day is below the critical depletion, an irrigation event is scheduled to avoid water stress to crop.

Green Crop Water Use (ETc_{green})

The green crop water use (ETc_{green})) is the volume of the total rainfall that is actually used for evapotranspiration by the crop field over the complete growing period. The green water use is equal to the effective rainfall (P_{eff}) or the crop evaporation requirement (ETc) whichever is lower. Total ETc_{green} in crop production is calculated by summing-up green water use over the entire length of crop period.

$$ETc_{green} = \sum \min (P_{eff} ET_C)$$

Blue Crop Water Use (ETc_{blue})

The blue water use (ETc_{blue}) is the portion of irrigation water actually used by the crop in ETc. It is the amount of irrigation water (I_{eff}) in addition to effective rainfall. It is also referred as effective irrigation supply. Blue water use is zero if the entire crop evaporation requirement is met by the effective rainfall. Total blue water use ETc_{blue} in crop production is calculated by summing-up blue water use for each time-step over the entire cropping season.

$$ETc_{blue} = \sum \min (ET_C P_{eff})$$

Table: 2

Crop parameters used in estimation of crop evapotranspiration

Crop	Date of Sowing	Length of growth stage, Days				Kc			Rooting Depth ‡, m	CDF
		Ini	Dev	Mid	Late	Ini	Mid	End		
Black Gram	05-Jul	20	30	35	15	0.40	1.10	0.30	0.6	0.55
Chick Pea	25-Oct	20	30	45	25	0.40	1.00	0.35	0.6	0.50
Groundnut	10-Jul	25	35	45	25	0.40	1.15	0.60	0.5	0.50
Lentil	15-Oct	15	25	55	35	0.40	1.05	0.50	0.6	0.50
Maize	01-Jul	20	30	40	15	0.30	1.20	0.50	1.0	0.55
Paddy	05-Jul	20	30	50	30	1.05	1.20	0.75	0.5	0.20
Pearl Millet	01-Jul	20	30	45	25	0.30	1.00	0.30	1.0	0.55
Peas	05-Nov	20	30	35	15	0.40	1.10	0.30	0.6	0.35
Pigeonpea	10-Jul	20	40	60	30	0.40	1.15	0.35	1.2	0.60
Potato	20-Oct	25	30	45	30	0.50	1.15	0.75	0.4	0.35
Rapeseed	15-Oct	20	30	40	25	0.35	1.10	0.35	1.0	0.60
Sesame	01-Jul	20	30	40	20	0.35	1.10	0.30	1.0	0.60
Sorghum	05-Jul	20	25	40	25	0.30	1.05	0.60	1.0	0.55
Sugarcane	05-Mar	30	50	180	60	0.40	1.25	0.75	1.2	0.65
Wheat	20-Nov	15	25	50	30	0.70	1.15	0.30	1.2	0.55

Kc=Crop coefficient, CDF=Critical depletion fraction, ‡irrigated conditions.

Data Sources: Length of growth stages, Kc, Rooting depth and CDF- Allen *et al.,* (1998); Sowing time- Agricultural Statistics at a Glance-2011, DoES, Min of Agriculture, available at http://eands.dacnet.nic.in (last accessed July, 2013).

Mapping Variability Using Geostatistical Approach

The estimated crop evapotranspiration values at 21 APUs and the base map of Gomati basin were projected to the WGS_1984_Albers projection system with the ground distance represented in meters. Kriging interpolation technique was used to interpolate the point values of ETc and ETc_{green} Kriging was selected as it is most robust and is frequently used technique to account for data fluctuations (Webster and Oliver, 2001). In this study, two kriging interpolation methods, Ordinary Kriging (OK) and Ordinary Co-Kriging (OCK) were evaluated. In case of ordinary co-kriging, mean maximum (Tmax) and mean minimum (Tmin) temperature were used as co-variates for *kharif* and *rabi* crops respectively. Spherical model was used as it is one of the most widely used semivariogram models (Goovaerts, 2000) and is commonly available in many geostatistical software packages (ESRI, 2008; Robertson, 2008). Prior to semivariogram fitting and actual kriging, an exploratory data analysis was carried out for both primary and secondary variates to ascertain the normality in data, data trend and presence of any outliers. The accuracy of prediction was assessed in terms of mean error (ME) and Root Mean Squared Error (RMSE). The geostatistical analysis extension module of ArcGIS 9.3 was used for analysis and development of kriged surfaces. Kriged surfaces are developed for seasonal (ETc) crop evapotranspiration (ETc) and *green* component of crop evapotranspiration (ETc_{green}) of 15 major crops of the Gomati basin.

1. RESULTS AND DISCUSSION

Based on the topography, temperature and rainfall patterns observed in the basin (Fig 2), APUs were grouped into upper, middle and lower regions. APUs 1,2,3, 13, 14 and 17 were in upper region, 4, 5, 6, 7, 11, 12, 18, 20 and 21 were in middle region and APUs 8, 9, 10, 15, 16 and 19 were in lower region of the basin. The blue and green components of ETc of different crops, estimated as average of the ETc of all APUs in a region, are presented in Table 3. Green water use was higher for *kharif* crops. Among the *kharif* crops, paddy utilized rainwater most efficiently with maximum green water use of 425.0mm in the lower reaches of Gomati basin. Since the year 2011 received scanty winter rainfall, the green water use of most of the *rabi* crops was very low. It varied from 0.2 mm for mustard crop grown in lower region to 19.1 mm for wheat crop in upper region of the basin. Due to longer growing period, estimated blue and green water use was highest for sugarcane crop.

Evaluation of Ordinary Kriging and Ordinary Co-kriging

The exploratory data analysis performed on the primary variate (ETc) and the secondary variates revealed that the data are not exactly normally distributed. Transformations of data using 'logarithmic' or 'box-cox' methods did not show any improvement in results. So, the original data on ETc at 21 locations (centroid of APUs) was subjected ordinary kriging and ordinary co-kriging. In case of ordinary kriging, the coefficient of determination (R^2) of fitted semivariogram model ranged between 0.82

Table: 3
Blue and green components of ETc in upper, middle and lower regions of Gomati basin

Crop	Blue water use			Green water use		
	Upper	Middle	Lower	Upper	Middle	Lower
Paddy	72.0	85.3	54.5	420.4	410.4	425.0
Pearl Millet	82.7	85.1	77.6	277.5	280.7	273.6
Maize	10.1	14.3	5.3	447.4	453.1	443.2
Pigeonpea	262.5	283.2	261.1	268.3	262.9	274.6
Groundnut	73.4	85.1	62.0	419.3	418.5	424.4
Sesame	58.0	63.5	48.9	306.6	305.8	305.2
Sorghum	74.1	75.5	68.6	355.3	347.7	352.1
Blackgram	274.2	286.7	287.8	151.7	159.8	156.1
Wheat	299.3	333.5	358.5	19.1	13.2	4.3
Chickpea	268.5	296.3	317.8	15.5	11.0	3.9
Mustard	278.0	299.9	306.7	1.5	0.5	0.2
Potato	325.3	355.4	377.7	13.5	9.5	3.5
Peas	265.2	287.2	298.9	2.1	0.7	0.2
Lentil	313.1	342.2	357.0	11.0	7.6	2.9
Sugarcane	859.5	942.5	925.1	603.1	591.8	590.3

(pigeonpea) to 0.99 (sesame) (Table 4). The cross validation statistics revealed that ordinary co-kriging performed better. In ordinary co-kriging, use of T_{max} as covariates resulted in favourable mean error (ME) and root mean squared error (RMSE) for *kharif* and *rabi* crops. Hence, the OCK algorithm, with T_{max} as covariate was used to develop the spatial variability maps.

Variability in ETc and *ETc_{green}*

The best performing ordinary co-kriging spherical semivariogram model was used to generate the interpolated surfaces for estimated seasonal ETc and *green* component of ETc at 21 locations. For all the *kharif* crops and sugarcane, the centre of maximum ETc was at the central region of the Gomati basin (Fig. 4). ETc was highest in western side of the central region which includes Lucknow, Unnao and Rae Bareli districts of Uttar Pradesh. In case of *rabi* crops, the ETc increased from upper to lower reaches of the basin. Upper most districts of the basin, namely, Pilibhit and Shahajahanpur, showed lowest ETc while the districts Jaunpur and Varanasi, located near the outlet of the basin, showed highest ETc for *rabi* crops. The spatial distribution of ETc of *kharif* and *rabi* crops closely resembled the temperature distribution pattern of 2011. ETc of *kharif* and *rabi* crops showed similar spatial distribution as that of mean maximum temperature and mean minimum temperature respectively. ETc for *kharif* and *rabi* crops exhibited different spatial patterns.

The green ETc of crops was also interpolated using ordinary co-kriging with T_{max} as covariate. Spatial variation in rainfall and differences in sowing and harvesting dates of different crops might have resulted in considerable variability in green water use of all the crops throughout the basin (Fig. 5). Hardoi and Rae Bareli districts located in upper and lower part of the middle region of basin respectively had highest green crop water use for most of the *kharif* crops. *Rabi* crops showed higher green ETc in the upper reaches of the basin with decreasing trend towards the outlet of the basin. Spatial distribution of ETc and green crop water use of sugarcane followed the same pattern as that of *kharif* crops. The results of the variability mapping showed that the spatial variation in the climatic parameters across the basin lead to significant spatial variability in ETc. This was also confirmed by results of the t-test obtained in previous section. So, while considering basin as a basic unit for crop water footprint assessment the intra-basin variation in ETc should be accounted.

Table: 4
Cross validation results of ordinary kriging and ordinary co-kriging with T_{max} and T_{min} as co-variates

Crop	Ordinary Kriging			Ordinary co-kriging					
	R^2 of SVM (Spherical)	Cross validation statistic		R^2 of cross-SVM (Spherical)		Cross validation statistics			
						T_{min}		T_{max}	
		ME	RMSE	T_{max}	T_{min}	ME	RMSE	ME	RMSE
Paddy	0.96	0.30	2.48	0.30	0.71	0.33	2.65	0.22	2.13
Millet	0.97	0.06	2.58	0.35	0.74	0.08	2.66	-0.02	2.21
Maize	0.88	0.15	2.89	0.50	0.78	0.13	2.87	-0.06	3.40
Groundnut	0.82	0.38	5.07	0.60	0.81	0.31	4.74	0.11	3.08
Pigeonpea	0.82	0.44	6.78	0.81	0.84	0.30	5.71	0.12	4.22
Sorghum	0.82	0.60	6.09	0.68	0.82	0.40	6.30	0.28	5.65
Sesame	0.99	0.08	3.08	0.26	0.79	0.12	3.24	0.01	2.77
Black gram	0.88	0.06	4.73	0.73	0.86	0.49	3.75	0.32	2.35
Wheat	0.92	0.76	5.81	0.92	0.91	0.53	4.91	0.35	3.41
Chickpea	0.92	0.29	4.28	0.92	0.92	0.09	2.59	-0.04	1.72
Potato	0.92	-0.72	4.26	0.92	0.93	-0.20	2.74	-0.37	2.67
Rapeseed	0.92	0.02	5.47	0.92	0.92	-0.19	3.07	-0.35	3.02
Lentil	0.92	0.03	4.14	0.92	0.93	-0.13	2.42	-0.25	2.40
Peas	0.90	-0.01	4.95	0.86	0.89	-0.25	2.91	-0.39	2.34
Sugarcane	0.87	1.19	14.73	0.87	0.88	0.43	8.20	0.28	6.22

SVM: Semivariogram model, ME: Mean error, RMSE: Root mean square error, T_{max}: Mean maximum temperature during *kharif*, T_{min}: Mean minimum temperature during *rabi*.

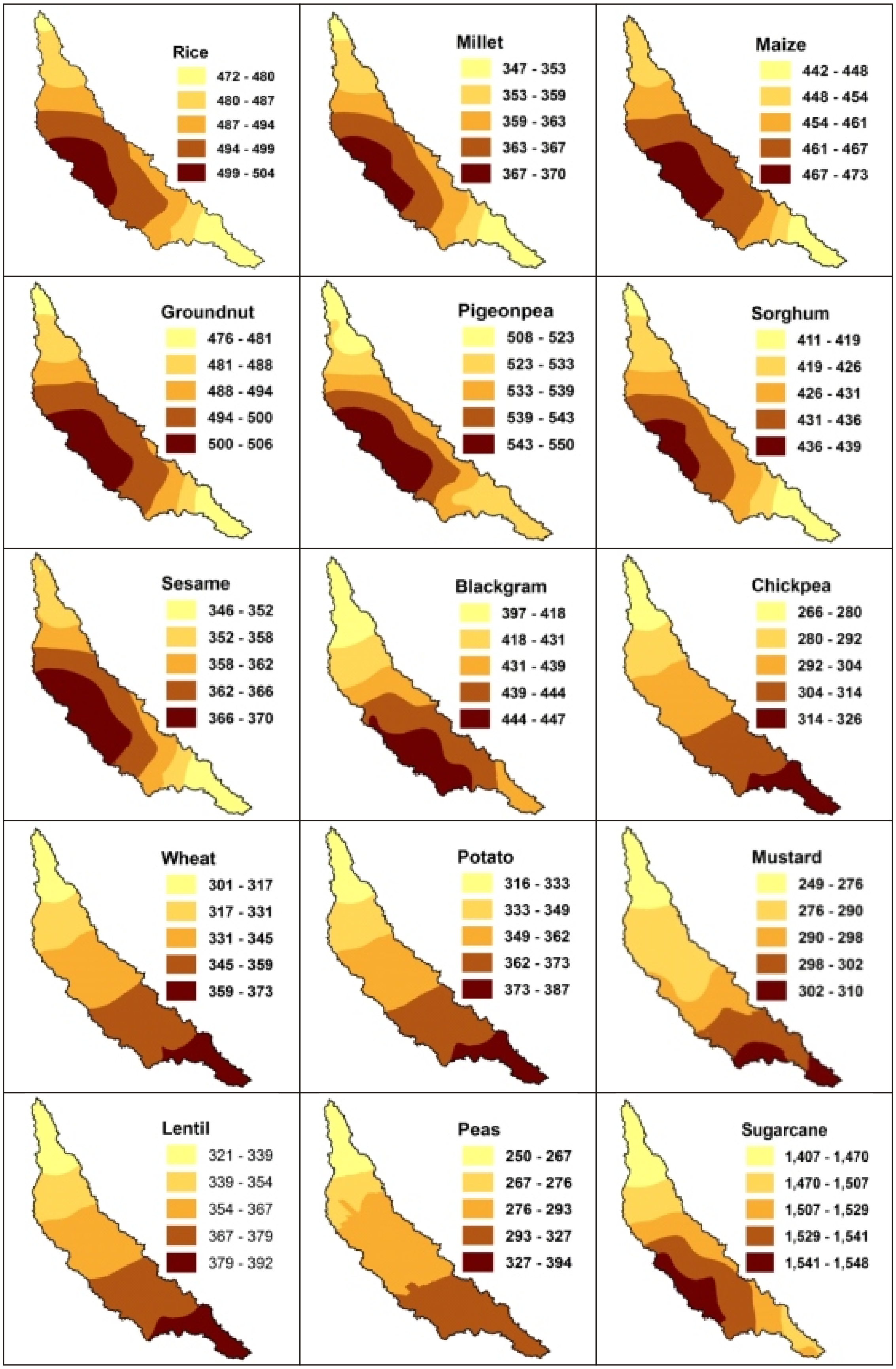


Fig. 4. Spatial distribution pattern of seasonal crop evapotranspiration (ET_c,mm) of selected crops in Gomati basin.

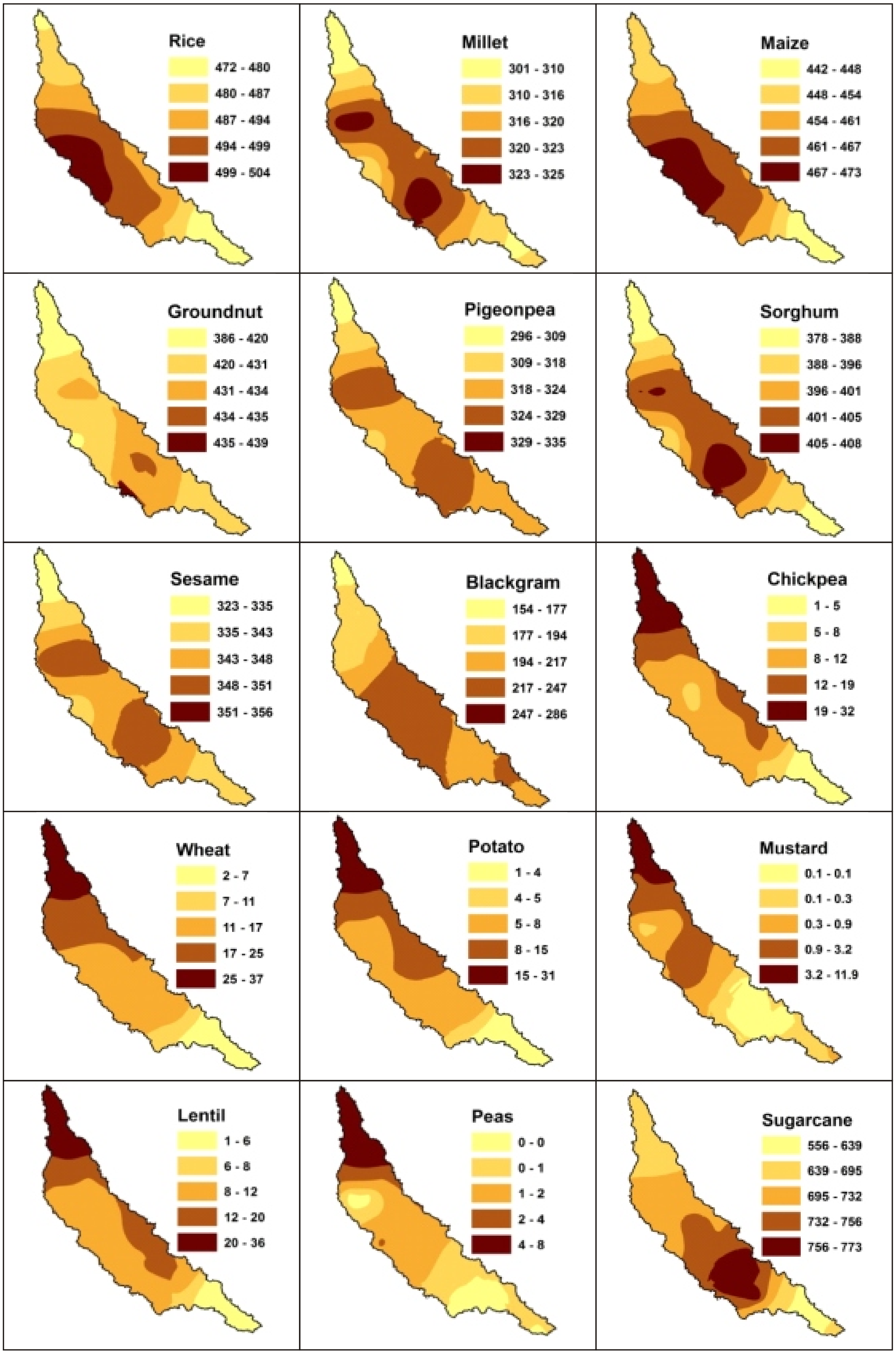


Fig. 5. Spatial distribution of green component of crop evapotranspiration *(ETc_{green}, mm)* **of selected crops in Gomati River basin**

1. CONCLUSIONS

Crop evapotranspiration (ETc) variability map for Gomati basin was developed using geospatial techniques. The ETc for *kharif* and *rabi* season crops were estimated using FAO-CROPWAT model. Among the *kharif* crops, paddy utilized rainwater most efficiently with maximum green water use in the middle region of basin. Statistical analysis showed that ETc of *kharif* crops was significantly higher in the middle region of the Gomati basin. However, ETc of *rabi* crops was significantly higher in the lower region of the basin. Based on the prediction accuracy, ordinary co-kriging was found to be a better method for mapping variability of ETc with mean maximum temperature as co-variate in *kharif* and mean minimum temperature in *rabi*. The variability map of ETc showed significant regional differences within the basin. There was gradual increase in evapotranspiration of *rabi* crops from north-west to south-east direction of the basin. In view of significant variation in ETc within the basin, assessment of crop water footprint with average value of ETc for entire basin will not be appropriate. The crop evapotranspiration variability maps developed in this study can be used for assessing the crop water footprint in the Gomati basin.

REFERENCES

Adhikary, P.P., Chakraborty, D., Kalra, N., Sachdev, C.B., Patra, A.K., Kumar, S., Tomar, R.K., Chandra, P., Raghav, D., Agrawal, K. and Sehgal, M. 2008. Pedotransfer functions for predicting the hydraulic properties of Indian soils. *Aust. J. Soil Res.*, 46:476–484.

Alexandrov, V. And Hoogenboom, G. 1999. Crop water use as a function of climate variability in Georgia. *In:* Proceedings of the *'Georgia Water Resources Conference'*, The University of Georgia, Athens, GA, USA, pp. 425-428.

Allan, J.A. 1998. Virtual water: a strategic resource global solutions to regional deficits. *Ground Water*, 36(4): 545-546.

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. 1998. Crop Evapotranspiration: Guidelines for computing crop water requirements. *Irrigation and Drainage Paper No. 56*, Food and Agriculture Organization of the United Nations, Rome, Italy.

Bulsink, F., Hoekstra, A.Y. and Booij, M.J. 2010. The water footprint of Indonesian provinces related to the consumption of crop products. *Hydrol. and Earth System Sci.*, 14: 119–128.

Chapagain, A. and Orr, S. 2009. UK water footprints: The impact of the UK's food and fibre consumption on global water resources (Vol. 1). *WWF-UK* Godalming, UK.

ESRI. 2008. ArcGIS Desktop: Release 9.3. Redlands, CA: Environmental Systems Research Institute.

FAO. 2012. *CROPWAT 8.0*, Food and Agriculture Organization of the United Nations, Rome, Italy, available at: www.fao.org/ (last access: March 1, 2012).

FAO/IIASA/ISRIC/ISS-CAS/JRC, 2008. *Harmonized World Soil Database* (version 1.0). FAO, Rome, Italy and IIASA, Laxenburg, Austria.

Feng, K., Siu, Y.L., Guan, D. and Hubacek, K. 2012. Assessing regional virtual water flows and water footprints in the Yellow River Basin, China: A consumption based approach. *App. Geography,* 32:691-701.

Gajbhiye, B.S. and Mandal, C. 2000. Agro-Ecological Zones, their soil resource and cropping system, Status of Farm Mechnization in India, Page 13 available at www.indiawaterportal.org (last access: August 11, 2012).

Ge, L., Xie, G., Zhang, C., Li, S., Qi, Y., Cao, S. and He, T. 2011. An Evaluation of China's Water Footprint. *Water Res. Manage.*, 25: 2633–2647.

Goovaerts, P. 2000. Geostatistical approaches for incorporating elevation into the spatial interpolation of rainfall. *J. Hydrol.*, 228(1-2): 113-129.

Gundogdu, K.S. and Guney, I. 2007. Spatial analyses of groundwater levels using universal kriging. *J. Earth System Sci.*, 116(1): 49–55.

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- An example for the State of Parana, Brazil. *Agril. Water Manage.*, 52: 177-196.

Hoekstra, A.Y. and Hung, P.Q. 2002. Virtual water trade: A quantification of virtual water flows between nations in relation to international crop trade. *Value of Water Research Report Series No. 11*, UNESCO-IHE, The Netherlands.

Ibrahim, A.A.M. 2011. Production of Digital Climatic Maps Using Geostatistical Techniques (Ordinary Kriging) Case Study from Libya. *Internl. J. Water Res. and Arid Environments,* 1(4): 239-250.

IMD, 2013, Terminology and Glossary, India Meteorological Department. Available at http://www.imd.gov.in/doc/termglossary.pdf (last accessed July 15, 2012).

Jing Lei, W., Shao Zhong, K., Jing Sheng, S. and Zhi Fang, C. 2013. Estimation of crop water requirement based on principal component analysis and geographically weighted regression, *Chinese Science Bulletin*, 58(27): 3371-3379.

Jose, A., Elena, C. and Javier, T. 2010. Water quality and non-point pollution*, in*: Re-thinking Water and Food Security, CRC Press, pp. 251–256.

MoA, 2011.Agricultural Statistics at a Glance-2011, DoES, Min of Agriculture, Govt of India. Data available at http://eands.dacnet.nic.in/ (last accessed July, 2012).

Mubako, S.T. and Lant, C.L. 2013, Agricultural Virtual Water Trade and Water Footprint of U.S. States, *Annals of the Association of American Geographers*, 103(2): 385-396.

NICRA-ICAR. 2013. *National Initiative on Climate Resilient Agriculture*, Indian Council of Agricultural Research, New Delhi India. Weather data available at http://www.nicra-icar.in/ (Last Accessed on July 11, 2013).

Rao, B.K. and Rajput, T.B.S. 2005. Effective Rainfall and its Significance in Crop Water Requirements in Canal Command Areas. *J. Water Manage*., 13(1): 36-42.

Rao, B.K. and Rajput, T.B.S**.** 2008. Rainfall Effectiveness for Different Crops in Canal Command Areas. *J. Agro Meteorology,* 10(2): 328-332.

Robertson, G.P. 2008. GS+: Geostatistics for the environmental sciences, Gamma Design Software, Plainwell, MI.

Sarangi, A., Cox, C.A. and Madramootoo, C.A. 2005. Geostatistical methods for prediction of spatial variability of rainfall in a mountainous region. *Trans. ASAE*, 48(3): 943−954.

Sharma, V. and Irmak, S. 2012. Mapping spatially interpolated precipitation, reference evapotranspiration, actual crop evapotranspiration, and net irrigation requirements in Nebraska: Part II. Actual crop evapotranspiration and net irrigation requirements. *Trans. Amer. Soc. Agril. Biol. Engineers*, 55(3): 923-936.

USGS. 2012. Shuttle Radar Topography Mission, 1 Arc Second scenes, n25_e081_3arc_v2 to n28_e083_3arc_v2, Void Filled, Global Land Cover Facility, University of Maryland, College Park, Maryland.

Vara Prasad, A.B.K., Mani, A., Uma Devi, M. and Reddy, M.D. 2013. Blue and green water quantification for sustainable water resources management in Kothakunta sub-watershed, Andhra Pradesh. *Ind. J. Soil Cons.,* 41(3): 241-247.

Vorosmarty, C.J., McIntyre, P., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., and Liermann, C.R. 2010. Global threats to human water security and river biodiversity. *Nature,* 467: 555–561.

Webster, R. and Oliver, M.A. 2001. Cross-correlation, co-regionalization, and co-kriging. *In*: Geostatistics for Environmental Scientists, Chichester, U.K., John Wiley and Sons.