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Evaluation of crop water demand for sustainable crop production using geospatial tools in a canal command of West Bengal

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ABSTRACT

The agricultural sector is the primary consumer of water resources around the world, and the need for additional food production for growing population further exerts more pressure on water resources. In this study, crop water demand was assessed spatially and temporally for a case study area, Damodar Canal Command (DCC) using geospatial techniques. Crop evapotranspiration was estimated for all the crop seasons using reference evapotranspiration and Fraction of Vegetation cover (FV) that was used as a surrogate for crop coefficient. The reference evapotranspiration (ET_o) was calculated using the FAO Penman-Monteith method. FV was computed based on Normalized Difference Vegetation Index (NDVI) derived from MODIS satellite imagery and its value ranges from 0 to 1. The maximum and minimum reference evapotranspiration values were estimated as 8.44 and 1.88 mmday^{-1} in May and September, respectively during the normal year 2004. The average monthly crop water demand was maximum in May i.e. 8.08 mmday^{-1}. Among all crop seasons, *Boro* season has the maximum crop water demand followed by *Aus* and *Aman* seasons with maximum ET_c as 496, 438 and 328 mm, respectively. Total annual crop water demand for normal year, 2004 was estimated at 1237 mmyr^{-1} in the study area. Spatially and temporally distributed crop water demand estimates help the irrigation planners to devise the strategies for effective irrigation management.

Keywords: Reference evapotranspiration, NDVI, fraction of vegetation cover, normal year, crop water demand.

Increased demand for water due to rapid growth in agricultural, domestic, and industrial sectors is exerting enormous pressure on water resources, thereby reducing per capita water availability year by year. This has led to a decline in natural resources globally that pose a greater threat to all living beings. Water being the most critical component of all living beings on the earth for food security, industrial production, and sustaining ecosystems as well as for socio-development; thereby efforts need to be made for sustainable management of water resources. Water consumption in the agricultural sector is approximately 75% of the global water utilized (Falkenmark and Rockström, 2004). Sustainable crop production faces several challenges with increased water scarcity situations and increased production costs. However, despite these constraints, crop production needs to rise drastically over the next decade to meet the food demand and especially those of the developing countries. Thus, future food demand requires an additional 5,600 km^{3}yr^{-1} of consumptive water by the year 2050 (Falkenmark and Rockström, 2006; Falkenmark, 2006). Hence, achieving higher crop production with optimum resources is a significant challenge in the future, while ensuring food security, economic security, and water security in the agricultural sector. Hence, in the recent past, efforts to develop the standardized analytical tools for addressing major environmental concerns were initiated. These tools help us to assess freshwater use at regional and global scales to improve the overall management of freshwater resources and to improve the overall environmental performance of products and operations (Kounina *et al.,* 2013).

Assessment of availability of water and also the crop water demand at a spatial scale is an essential requirement not only for sustainable management of water resources but also for sustainable crop production (Bal *et al.,* 2018). Satti and Jacobs (2004) assessed water demand based on spatially varied soil, land use, and climatic data using a lumped model for regional irrigation planning. Supit *et al.* (2010) evaluated trend analysis of the water requirements, consumption, and deficit for field crops in Europe. Yang *et al.* (2010) estimated water requirement for wheat, maize, cotton, vegetables and

Table 1: Crop-wise area under different cultivation during the normal year, 2004

Crop	Area (ha)
Aus paddy	21977
Aman paddy	495537
Boro paddy	258297
Wheat	4613
Jute	23077
Mustard	38720
Sesame	26083
Potato	101388

fruit trees using DSSAT and COTTON 2K crop models along with crop coefficient methods for sustainable water resources reallocation in North China. Zhao *et al.* (2010) compared water requirements of maize crop in the middle Heihe River basin, China using six crop evapotranspiration (ET_c) methods. Kokilavani *et al.* (2018) computed crop water requirement (ETc) for Sorghum crop at Coimbatore by accounting future food demand and anticipated water shortage. Lee and Dang (2019) studied irrigation water requirement of rice crop in the Long Xuyen Quadrangle area of Vietnam in the context of climate change.

Varied climatic conditions, soil, and cropping pattern spatially needs to be accounted for assessment of agricultural water demand. In India, irrigation is the primary water consumption, which accounts for more than 80% of the total water used (MOWR, 1999). Conventionally, crop coefficients obtained from experimental station/literature were upscaled to large command area for estimation of crop irrigation requirements. Thus, lumped crop water demand estimates at command scale using upscaled crop coefficients results in either over or underestimation of crop water requirements resulting in poor irrigation efficiencies. Thus, in this study pixel-level crop condition analyzed through Normalized Difference Vegetation Index (NDVI) derived fractional vegetation cover (FV) is proposed as a surrogate for crop coefficient, K_c for crop water demand estimation. FV provides the physiological status of the crop and is highly beneficial for better irrigation planning. The use of geospatial tools could be faster and more reliable in identifying the variability of crop water demand over conventional methods.

MATERIALS AND METHODS

Study area

Damodar Canal Command (DCC) of West Bengal is selected for the study which is geographically situated between 22°31′25″ - 23°42′48″ N latitude and 87°15′14″ - 88°26′22″ E longitude and is selected as the case study area in this study (Fig. 1). The geographical area of the study command is nearly 7470 km^2 with an elevation ranges between 1 to 98 m amsl. The mean annual rainfall of the study area is 1913 mm. The study area falls into two agro-climatic zones, namely the Gangetic alluvial zone and red and laterite zone. Major soil textural classes in the study area are mostly silt loam, clay, and sandy loam. The major crops grown in this region are paddy, potato, jute, mustard, sesame, wheat, etc. Crop area statistics grown during the normal year 2004 in the study area are given in Table 1.

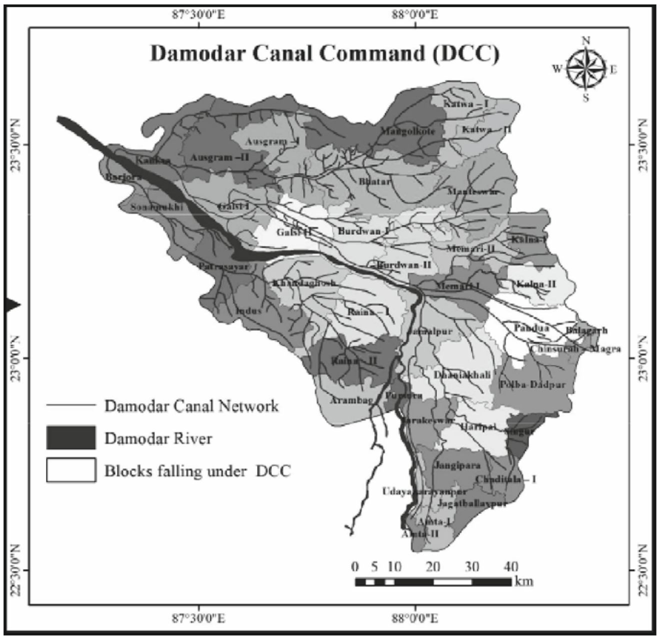

Fig. 1 : Location map of the study area.

Data collection

The MODIS Vegetation Indices 16-Day L3 Global 250 m (MOD13Q1) of 250 m resolution were collected from http://earthexplorer.usgs.gov/. The Climate Forecast System Reanalysis (CFSR) meteorological data available from open source domain http://globalweather.tamu.edu/ was used in this study. The CFSR product was generated by coupling atmospheric, oceanic, and surface-modeling with cutting-edge data-assimilation techniques (both conventional meteorological gauge observations and satellite irradiances) at 38 km resolution (Saha *et al.*, 2010). The meteorological data such as rainfall, maximum and minimum temperature, relative humidity, solar radiation, and wind speed pertaining to for 14 locations covering the study area was used in this study. Meteorological parameters corresponding to the normal year were used in this study.

Assessment of normal year

Normal year in the study period (1979-2013) was identified by computing long term average annual rainfall of the study area. The year 2004 was considered as 'normal' year for this study since the rainfall in the year 2004 is the nearest to the average annual rainfall among all rainfall years considered.

Method used for interpolation

Kriging method was used in this study for interpolation of reference evapotranspiration. Kriging technique was found to be superior to other techniques and has been used by many researchers in the past (Krishnamurthy, 2005; Ferrand et al., 2014; Hodam et al., 2017). The kriging interpolation algorithm

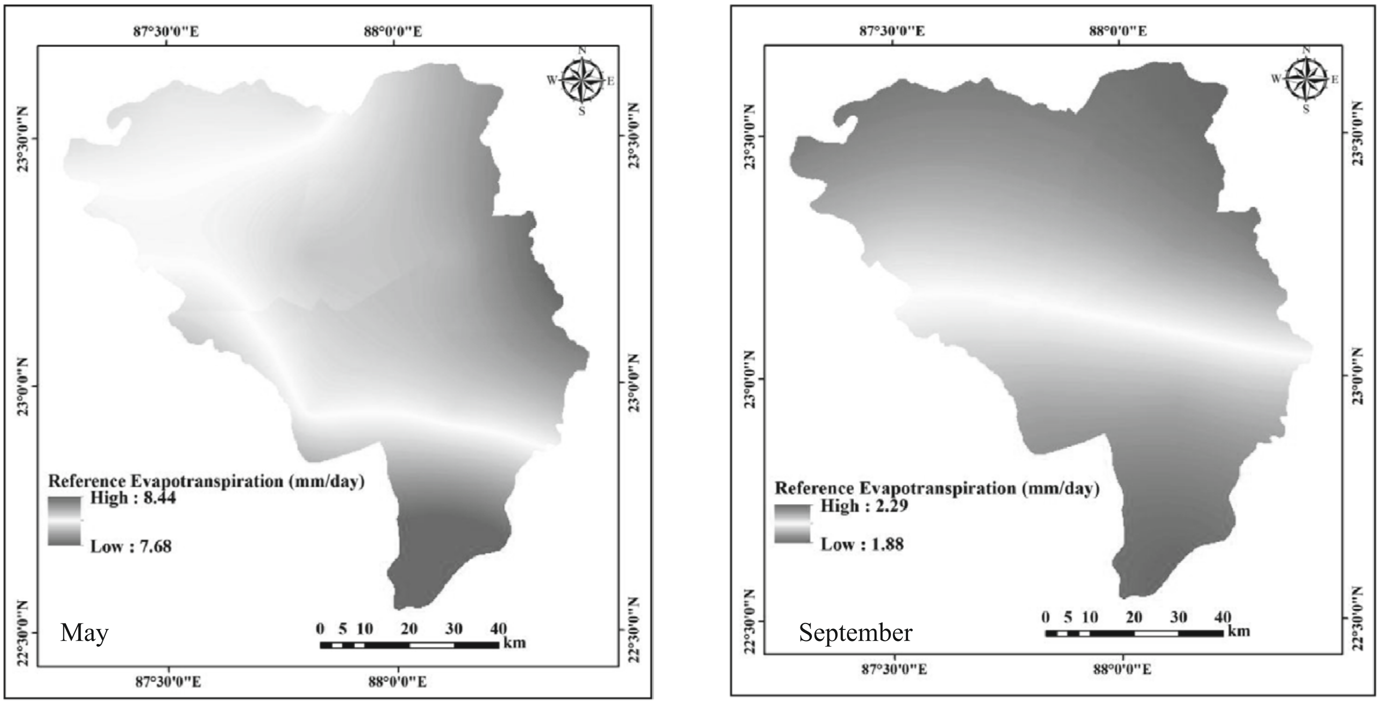

Fig. 2: ET_o during May and September 2004

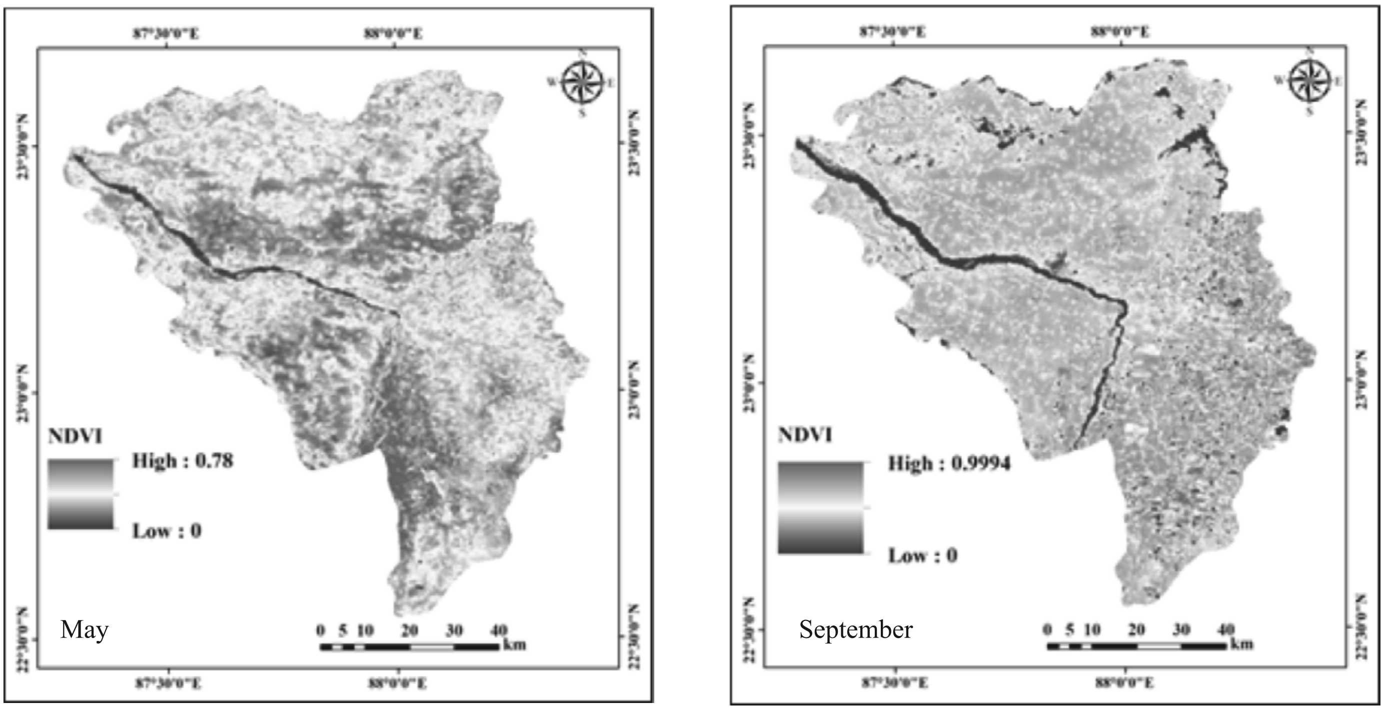

Fig. 3: NDVI during May and September 2004

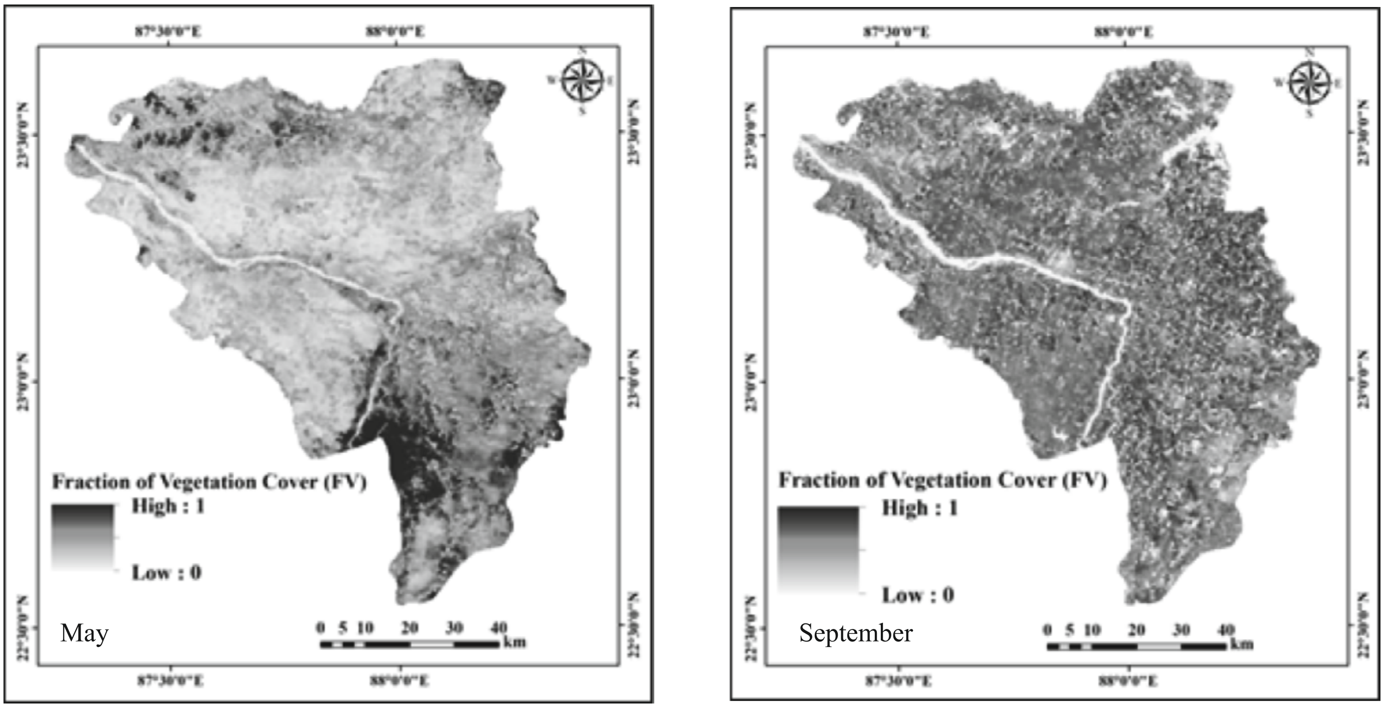

Fig. 4: FV during May and September, 2004

generates an unbiased forecast as well as the capacity to calculate the uncertainty spatial distribution (Mahmoudabadi and Briggs, 2016). The gridded data collected from CFSR, of 38 km resolution was used for estimation of reference evapotranspiration and was further resampled to 250 m corresponding to MODIS Vegetation Index (VI) 16-Day L3 Global 250m (MOD13Q1) product.

Estimation of crop evapotranspiration

The crop evapotranspiration (ET_c) was estimated by multiplying crop coefficient (K_c) with reference evapotranspiration (ET_o), and ET_c can be obtained by the following formula.

$$ET_c = ET_o \times K_c \tag{1}$$

In this study, the crop coefficient was replaced by the fraction of vegetation cover (FV), which is the significant component for the estimation of crop evapotranspiration. It is considered as a surrogate to crop coefficient for ET_c computations as suggested by Allen *et al.*, (2010).

Reference evapotranspiration

FAO Penman–Monteith method is robust and widely used for computation of reference evapotranspiration using weather data such as air temperature, air humidity, radiation, and wind speed (Allen *et al.*, 1998).The FAO Penman–Monteith method was successfully used for the given study area (Singh *et al.*, 2017). The reference evapotranspiration is computed by the following equation.

$$ET_0 = \frac{0.408\Delta(R_n - G) + \frac{\gamma(900)}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1+0.34u_2)} \tag{2}$$

where, Et_o is the reference evapotranspiration (mmday^{-1}), R_n is the net radiation at the crop surface (MJm^{-2}day^{-1}), G is the soil heat flux density (MJm^{-2}day^{-1}), T is the mean daily air temperature at 2 m height (ºC), u_2 is the wind speed at 2 m height (ms^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), e_s - e_a is the saturation vapour pressure deficit (kPa), Δ is the slope vapour pressure curve (kPaºC^{-1}), and γ is the psychometric constant (kPaºC^{-1}).

Normalised difference vegetation index (NDVI)

MODIS derived Vegetation Index (VI) products are mainly useful in vegetation monitoring over the land surface due to its wide spectral range i.e., 0.4µm to 14.4µm, wide swath i.e., 2330 km and high revisit capability, particularly over the tropical region where cloud and atmospheric disturbances are regular phenomena (Lu *et al.*, 2007). MODIS Vegetation Index (VI) 16-Day L3 Global 250m (MOD13Q1) product such as NDVI is used the world over to measure the presence of green vegetation on the land surface. Normalised Difference Vegetation Index (NDVI) proposed by Tucker (1979) is given as follows:

$$NDVI = \frac{NIR - R}{NIR + R} \tag{3}$$

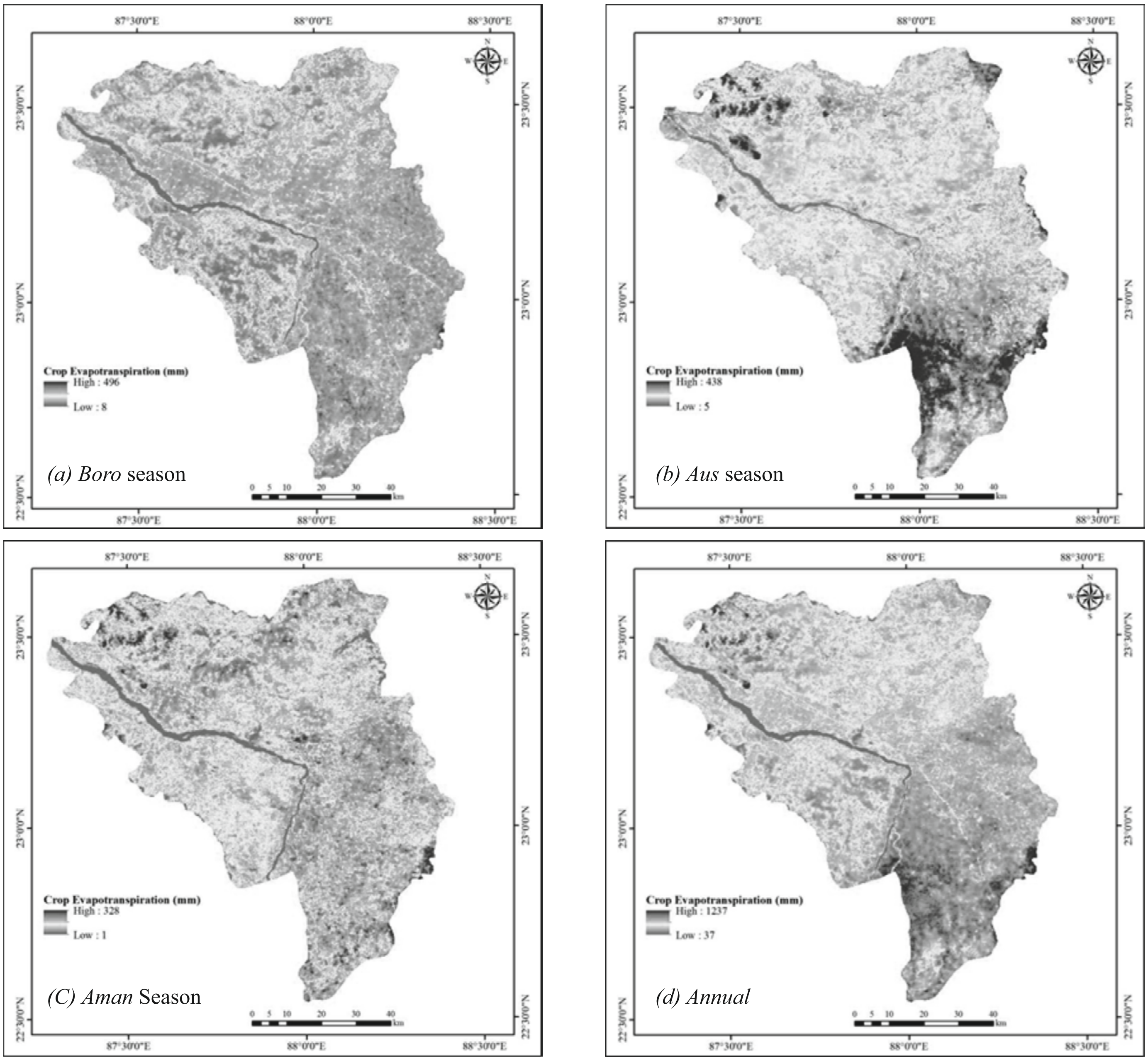

Fig. 5: ET_c of the study area during *(a) Boro* season (January-April) (b) *Aus* season (May-July) (c) Aman season and (d) annual

where, NIR and R are reflectance in near-infrared and red wavelengths, respectively and it ranges between -1 to 1.

Vegetation fractional cover as a surrogate to crop coefficient

The fraction of vegetation cover (FV) is the significant component of crop evapotranspiration and represents the crop coefficient, K_c occurring from a land surface (Allen *et al.,* 2010).The Fraction of Vegetation cover (FV) was computed based on the MODIS NDVI data at monthly scale. Several researchers reported strong relationships between FV and NDVI (Carlson and Riziley, 1997; Brunsell and Gillies, 2002; Reyes-González *et al.*, 2018). The values of vegetation fraction range from 0 to 1. Vegetation fraction is given by the following equation Gillies *et al.* (1997); Brunsell and Gillies (2002):

$$FV = \left[\frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}\right]^2 \qquad (4)$$

where, NDVI is Normalized Difference Vegetation Index. The fraction of vegetation cover (FV) is the significant component of crop evapotranspiration and represents the K_c occurring from a land surface (Allen *et al.,* 2010). The NDVI values were used for the analysis of the fraction of vegetation cover. Researchers explained the strong relationship between

FV and NDVI in the past (Carlson and Riziley, 1997; Brunsell and Gillies, 2002; Reyes-González *et al.,* 2018).

RESULT AND DISCUSSION

Spatial distribution of reference evapotranspiration

The reference evapotranspiration (ET_o) map was generated from the point data of 14 stations using kriging interpolation technique for all the months during the normal year, 2004. Maximum and minimum reference evapotranspiration was estimated at 8.44 and 1.88 mmday^{-1} during May and September months, respectively (Fig. 2) .

NDVI and fraction of vegetation Cover (FV)

Crop condition in the study area in terms of NDVI during the May month was spatially represented in Fig. 3. The *Boro* paddy is mostly harvested by the end of April or the first week of May while other summer crops like sesame, jute and *Aus* paddy still grow at large in the study area. The *Aman* paddy covers the most significant area among all the different crops grown in this canal command. Maximum NDVI value observed during the month of September (Fig. 3) can be attributed to the peak growth period of *Aman* paddy. The fraction of vegetation cover (FV) computed based on max NDVI and Min NDVI values for the months of May and September were shown spatially in Fig. 4. The FV is considered as the primary identifier for crop growth performance that influences the crop evapotranspiration and ranges from 0 to 1.

Map of crop evapotranspiration and crop water demand

Crop water demand at monthly, seasonal, and annual scale in terms of crop evapotranspiration (ET_c) was estimated at 250 m resolution. Among the crop seasons practiced in the study area, *Boro* season has the maximum water demand followed by *Aus* and *Aman* seasons (Figs. 5). The average monthly crop water demand was maximum in the month of Mayas 8.08 mmday^{-1}. Annual crop water demand in the study area was estimated at 1237 mmyr^{-1} (Fig. 5d). Among all the crop seasons, *Boro* season has the maximum water demand followed by *Aus* and *Aman* seasons. The maximum water demand during the *Boro* season can be obvious being it is the summer season. During the *Aus* season rainfall generally occurs during the development and final stage of the crop, while during the *Aman* paddy, maximum crop area is grown during the monsoon season. Thus water demand during this season is comparatively less as compared to the other seasons. Spatially and temporally distributed crop water demand estimates help the irrigation planners to devise the strategies for effective irrigation management.

CONCLUSIONS

In this study, crop water demand was estimated temporally and spatially for Damodar Canal Command using the fraction of vegetation (FV) as a surrogate to crop coefficient. The pixel-level crop condition analyzed through NDVI based fraction of vegetation cover indicates crop physiological status. This helps in capturing the spatial variability of crop coefficient at the pixel level, while estimating crop water demand. Further, over and underestimation of crop water demand can be eliminated by considering the spatial variability of crop coefficient as it is one of the important parameters. Crops are grown during all seasons in the study area with significant irrigation sources from the canal, pond, tank, and groundwater. Among all the crop seasons, *Boro* season has the maximum water demand followed by *Aus* and *Aman* seasons. Spatial and temporal distribution of crop evapotranspiration indicates crop water demand variability within the canal command and is highly useful for better irrigation planning.

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