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Estimation of crop evapotranspiration of irrigation command area using remote sensing and GIS

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Abstract

This paper describes the use of satellite-based remote sensing (RS) data and geographic information system (GIS) tools for estimating seasonal crop evapotranspiration in Mahi Right Bank Canal (MRBC) command area of Gujarat, India. Crop coefficients (K_c) for various major crops grown in MRBC were estimated, empirically, from the RS derived soil adjusted vegetation index (SAVI) values. A reference crop evapotranspiration (ET_0) map was generated from point meteorological observations. The K_c and ET_0 maps were combined to generate seasonal crop evapotranspiration (ET_{crop}) map which highlighted spatial variation in ET_{crop} ranging from more than 600 mm for healthy tobacco crops to less than 150 mm for very poor wheat crops.

Keywords: Crop evapotranspiration; Crop coefficient; Soil adjusted vegetation index; Remote sensing; GIS

1. Introduction

Crop evapotranspiration (ET_{crop}) refers to evapotranspiration of a disease-free crop, grown in very large fields, not short of water and fertiliser (Doorenbos and Pruitt, 1977). Estimation of ET_{crop} is essential for computing the soil water balance and irrigation scheduling. ET_{crop} is governed by weather and crop condition. Mathematically, ET_{crop} can be expressed as

$$ET_{crop} = K_c\, ET_0 \quad (1)$$

where K_c is the crop coefficient which varies for different crops and their growth stages and ET_0 is the reference crop evapotranspiration. Most of the current water demand

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models are non-spatial models which uses point data of ET_0 and the K_c values from available literature (e.g. Doorenbos and Pruitt, 1977). However, the climate data used to measure ET are highly variable spatially. For instance, temperature and wind speed can vary greatly in distance of only a few kilometres. Also the land use and the crop condition can vary from field to field, thus affecting the crop coefficients and thus the ET_{crop} rates. Hence, using K_c values from available literature may provide a practical guide for scheduling irrigation, but considerable error in estimating crop water requirement can occur due to their empirical nature (Jagtap and Jones, 1989). Bausch and Neale (1987) have shown the usefulness of remotely sensed (RS) data to represent the crop coefficient. The feasibility of estimating K_c from spectral measurements occurs because both K_c and vegetation indices (derived from reflectance) are affected by leaf area index and fractional ground cover (Bausch, 1995). The advantage of RS derived crop coefficient over traditional crop coefficient is that it represents a real-time crop coefficient that responds to actual crop conditions in the field and captures the between field variability.

The objective of this work was to compute seasonal ET_{crop} of Mahi Right Bank Canal (MRBC) command area in Gujarat, India using RS data and geographic information systems (GIS) which was a part of a larger study on use of RS data for command area monitoring (Ray et al., 2000a). The crop-wise monthly K_c was estimated using multidate RS data. Point data of ET_0 were modelled spatially by using the interpolation techniques available in GIS.

2. Materials and methods

2.1. Study area

The study was conducted for the command area of MRBC in Kheda district of Gujarat state in western-central India (Fig. 1). The irrigation command area of MRBC lies between 22°26′N 72°49′E and 22°55′N 73°23′E. It serves 485 villages of seven talukas (sub-divisions of a district) covering a culturable command area (CCA) of 212.694 thousand hectares. The main canal has six branches with 38 distributaries.

The climate of MRBC command area is semi-arid with an average annual rainfall of 823 mm. The soils are deep, varying from loamy sand to clay in texture. The gross cropped area in the command has increased from 75.5 thousand hectares in 1975–1976 to 209.6 thousand hectares in 1995–1996.

2.2. Data used

Multidate RS data of WiFS (wide field sensor), on-board IRS-1C satellite was used for crop classification and computation of crop coefficient. WiFS has 188 m ground resolution and two spectral bands in red (620–680 nm) and near-infrared, NIR (770–860 nm) region. One scene for each month was used. The dates of satellite data are 21/11/1996, 15/12/1996, 27/01/1997 and 20/02/1997.

Monthly average temperature from the weather stations surrounding the command area was collected, along with climatic values of monthly averages of daytime wind speed,

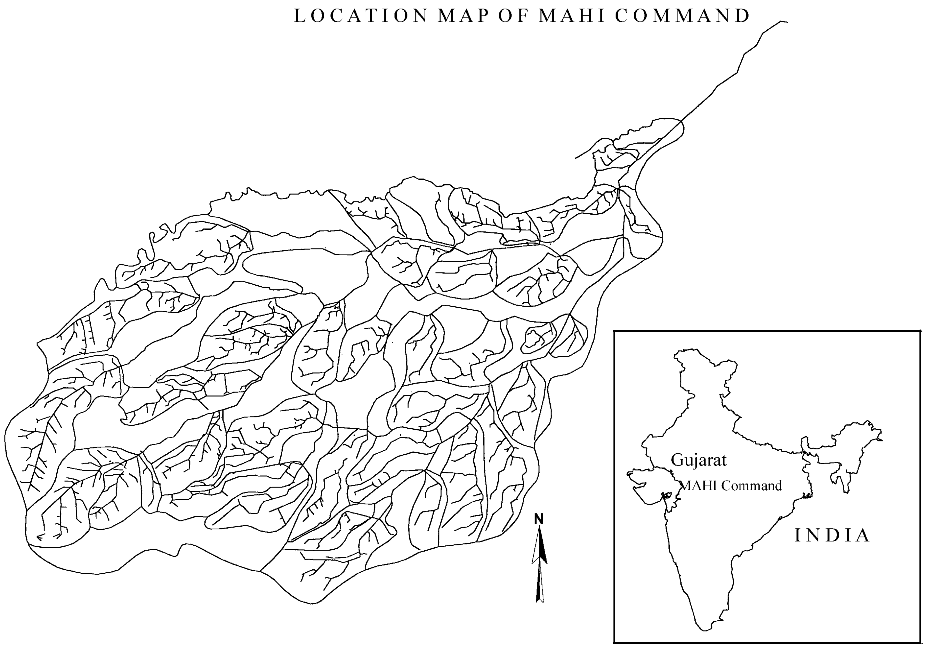

Fig. 1. Location map of Mahi Right Bank Canal command area.

sunshine hours and minimum relative humidity. These values were used to compute ET_0 using FAO-24 modified Blaney–Criddle method (Allen and Pruitt, 1986). The Blaney–Criddle method was used because of its simplicity and general availability of data. It has been found that this method's estimates for monthly ET_0 are fairly close to the estimates given by the more rigorous Penman method (Nir and Finkel, 1982; Mavi and Chaurasia, 1980).

2.3. Methodology

The steps used to compute crop evapotranspiration are presented in Fig. 2. The satellite data were geographically registered onto one another and to the map. Since the data were of different dates, which might have different atmospheric conditions, atmospheric normalisation was done by developing empirical transformation equations between digital numbers (DNs) of different dates for various pseudo-invariant features, PIFs (e.g. sand, urban, etc.). PIF technique, developed by Schott et al. (1988), is based on the statistical invariance of the reflectance of in-scene features such as sand, urban, etc. By using the knowledge about the temporal growth pattern of various crop types in Mahi command area, based on our field observations of various land cover classes during ground truth, a hierarchical classification approach was followed to classify the scene into various land cover classes. Soil adjusted vegetation index (SAVI) as defined by Huete (1988) was calculated for each pixel. SAVI is defined by

$$\mathrm{SAVI} = [(\mathrm{NIR} - \mathrm{R})/(\mathrm{NIR} + \mathrm{R} + L)](1 + L) \qquad (2)$$

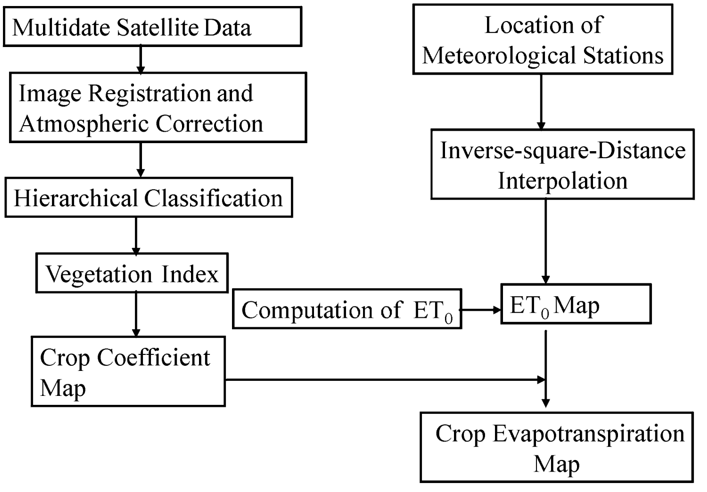

Fig. 2. Steps followed for estimation of crop evapotranspiration.

where NIR and R are reflectances in near-infrared and red wavelengths, respectively, and L, an adjustment factor. The DN values from WiFS sensor were converted to radiance using saturation radiance information and then to apparent reflectance using solar spectral irradiance and zenith angle information (Richards and Jia, 1999). Huete (1988) showed that soil background influences on canopy reflectance were adequately minimised for canopy cover ranging from sparse to dense with $L = 0.5$. Regression equations were developed between the average SAVI values of each crop type and the crop coefficient values for Mahi command area presented in WTC (1983). Using these empirical equations, crop coefficient maps were generated.

The point data of ET_0 were interpolated using the inverse-square-distance approach available in ARC/INFO GIS. The ET_0 map was combined with the crop coefficient map to compute the crop evapotranspiration for Mahi command area.

3. Results and discussion

3.1. Radiometric normalisation

Scene-to-scene radiometric normalisation corrects for atmospheric degradation, illumination effects, and sensor differences in multi-temporal, multi-spectral imagery. Differences in the grey level distributions of these PIFs are assumed to be due to these above-mentioned errors. The empirical equations between satellite data of various dates for PIFs were found to be having high r^2 (0.82–0.98) values (Table 1). These empirical equations were used to transform the data sets so that the change in spectral reflectance over the periods represented only the land cover changes.

Table 1
Regression equations between satellite data of various dates for PIFs

Equations[a]	r^2	SEE
$D2B1 = 1.0106 \times D1B1 - 1.8508$	0.96	4.43
$D2B2 = 1.0015 \times D1B2 - 1.7881$	0.98	3.98
$D2B1 = 1.0196 \times D3B1 - 2.0227$	0.88	7.96
$D2B2 = 1.0058 \times D3B2 + 3.1629$	0.92	7.67
$D2B1 = 0.6881 \times D4B1 + 18.4822$	0.82	10.12
$D2B2 = 0.8101 \times D4B2 + 7.3957$	0.96	5.72

[a] D1: 21/11/1996, D2: 15/12/1996, D3: 27/01/1997, D4: 20/02/1997, B1: red, B2: NIR.

3.2. Generation of a crop-type map

A hierarchical classification system (Wang, 1986) was used to identify the crops in the study area, as experience of using multidate WiFS data indicated it to be useful in class definition and identification in comparison to commonly followed maximum likelihood (MXL) classifier (Oza et al., 1996). The logic of this tree-classifier is presented in Fig. 3 and is based on the phenology of the major crops of the command area. SAVI, which minimises the soil background effect (Huete, 1988), is an indicator of crop condition. Analysing the image, it was found that if the SAVI value of November is less than −0.02, the class belonged to non-vegetation. If it was between −0.02 and 0.29, the pixel

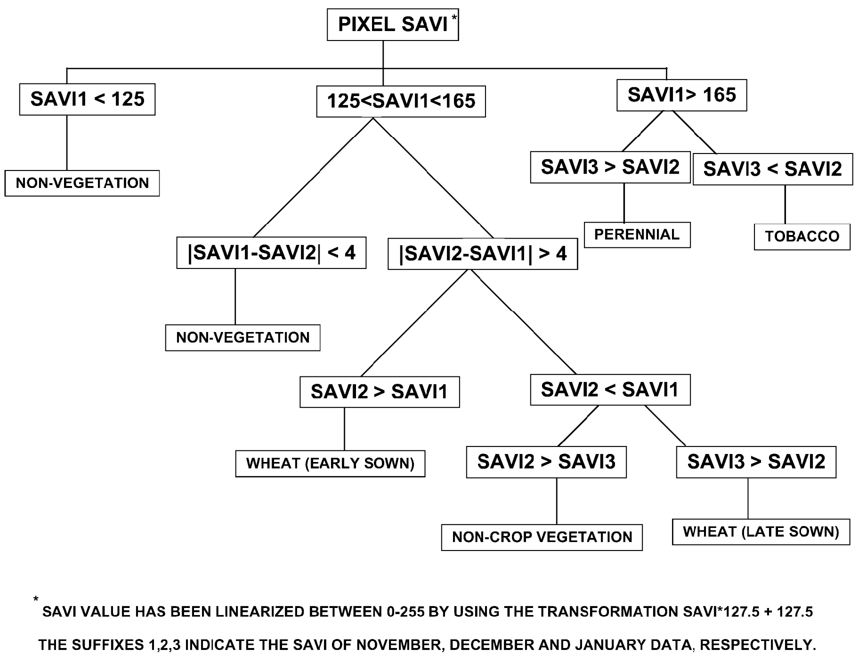

Fig. 3. Hierarchical logic used for classification of multidate data.

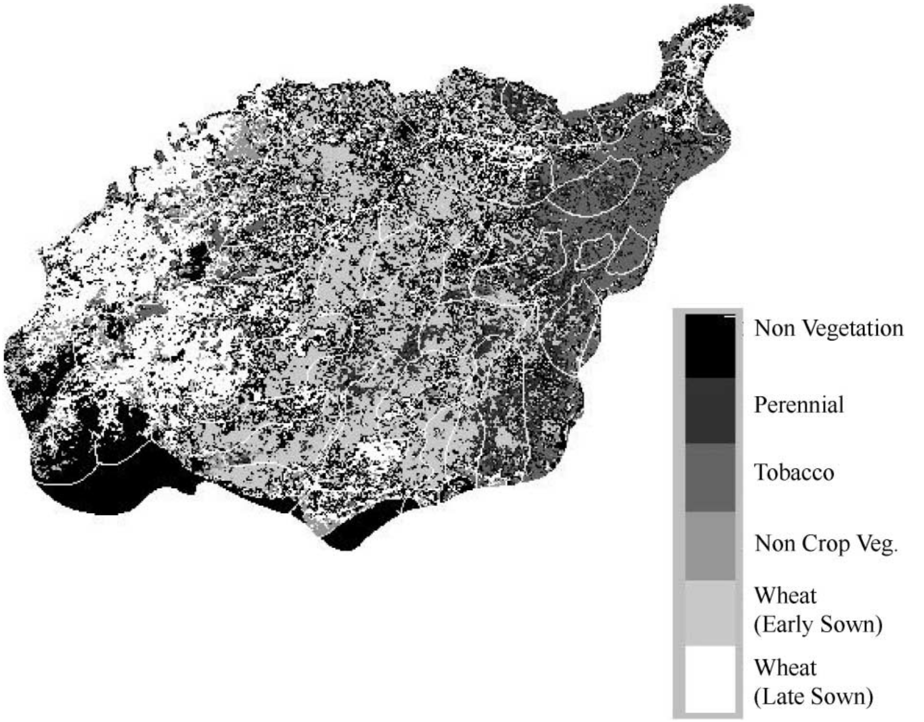

Fig. 4. Classified image for MRBC command area.

belonged to wheat or non-vegetation class depending upon the difference between SAVI of November and December. Similarly if the SAVI of November was greater than 0.29, the land cover class was perennial if December SAVI was less than January SAVI, else it was tobacco. The detail of the logic used for this classification is presented in Fig. 3. With this classification approach, it was found that in the Mahi command, area occupied by wheat, tobacco, perennial, non-crop vegetation and non-vegetation classes were 77.8, 15.8, 11.7, 13.3 and 50.9 thousand hectares, respectively. The classified map, presented in Fig. 4, shows the spatial extent of different land cover classes.

3.3. Reference crop evapotranspiration map

The ET_0 map, generated from point data, using inverse-square-distance interpolation technique for the month of December is presented in Fig. 5. Similar maps were also generated for all the other three months of the crop-growing season. There are three weather stations in and around the Mahi command area, which were used for interpolation. However, one of these stations being relatively at a large distance from the command area, values for only two stations were represented in the ET_0 map. This caused a regular pattern of spatial distribution of ET_0 values. Since the difference in the ET_0 determined by the two stations was low, i.e. 1.8 mm for the month of December, it

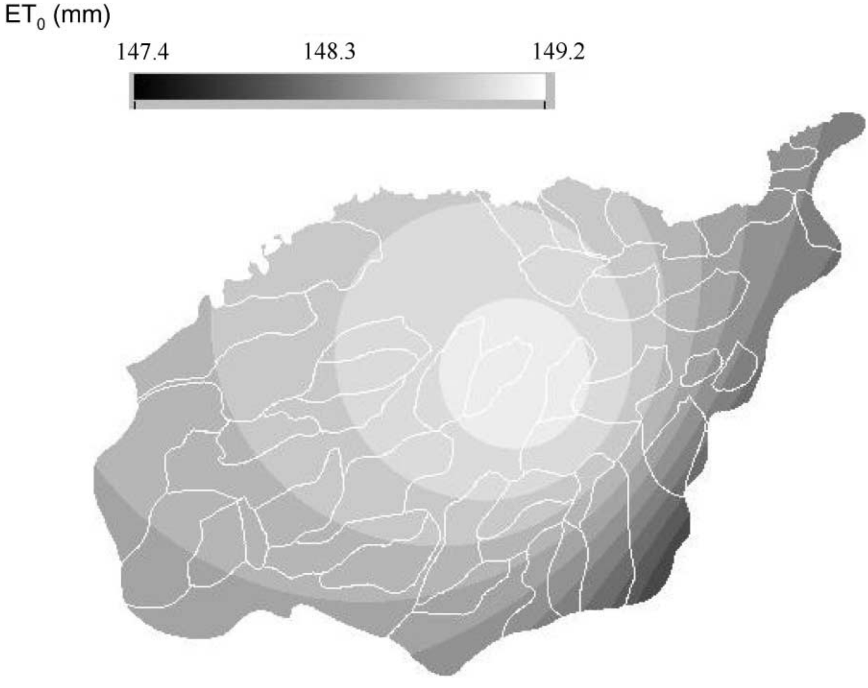

Fig. 5. Reference crop evapotranspiration map for MRBC command area for the month of December.

might seem that an averaging would have served the purpose. However, we have followed a standard approach, i.e. inverse-square-distance, which is a more accurate method of interpolation irrespective of number of data points. Hashmi et al. (1994) has also used the inverse-square-distance approach to interpolate ET values.

3.4. Crop coefficient

The average values of crop coefficients for the crops in the Mahi command area, collected from available literature (WTC, 1983) are presented in Table 2. These crop coefficients are valid for normal crop-growing condition and are regularly used for

Table 2
Values of crop coefficient for various crops

Month	Crop			
	Early wheat	Late wheat	Tobacco	Perennial
November	0.25	0.60	1.00	0.80
December	0.68	0.46	0.98	0.95
January	1.05	0.86	0.74	1.05
February	0.74	0.72	0.15	0.87

Table 3
Values of average SAVI for various crops

Month	Crop			
	Early wheat	Late wheat	Tobacco	Perennial
November	0.453	0.445	0.732	0.672
December	0.562	0.329	0.747	0.754
January	0.774	0.477	0.674	0.826
February	0.580	0.384	0.481	0.596

irrigation management in that region. The season for which the ET_{crop} was estimated did not experience any abnormal crop-growing condition. Hence it was assumed that, if estimated, the average value of the crop coefficient over the command area would match well with those available in literature.

SAVI value for each pixel was calculated using Eq. (2). Using the classified crop image, monthly average SAVI values for each crop class were determined (Table 3). The high SAVI values for the late sown wheat in the month of November is actually for the rice crop of the previous season which continued up to end of November. The data of different months were pooled together to obtain the empirical equation between SAVI and crop coefficient through regression. The analysis of regression (Table 4) showed that the equations were highly significant with high r^2 values and low F-values. These regression equations were used to compute pixel-wise crop coefficient values from their SAVI values. The crop coefficient values had high spatial variability. The coefficient of variation of the crop coefficient values, over the command area, ranged from 5.8% for perennial crops to 35.05% for tobacco, during the crop's maximum vegetative stage.

3.5. Crop evapotranspiration

The crop evapotranspiration (ET_{crop}) was estimated by multiplying pixel-wise, the crop coefficient and the ET_0 values. The integrated values over the season showed the seasonal crop evapotranspiration (Fig. 6). The seasonal ET_{crop} ranged from more than 600 mm for healthy tobacco crops to less than 150 mm for very poor wheat crops. The values matched well with the crop evapotranspiration values of various crops presented by Giriappa (1991).

Table 4
Parameters of regression equation between SAVI and K_c ($K_c = a\,\mathrm{SAVI} + b$)

Crop	a	b	r^2	SEE	F
Early wheat	1.9039	−0.4005	0.71	0.22	4.8
Late wheat	2.0039	−0.1591	0.60	0.13	2.9
Tobacco	3.2253	−1.4063	0.99	0.04	277.5
Perennial	0.8948	0.2804	0.69	0.07	4.4

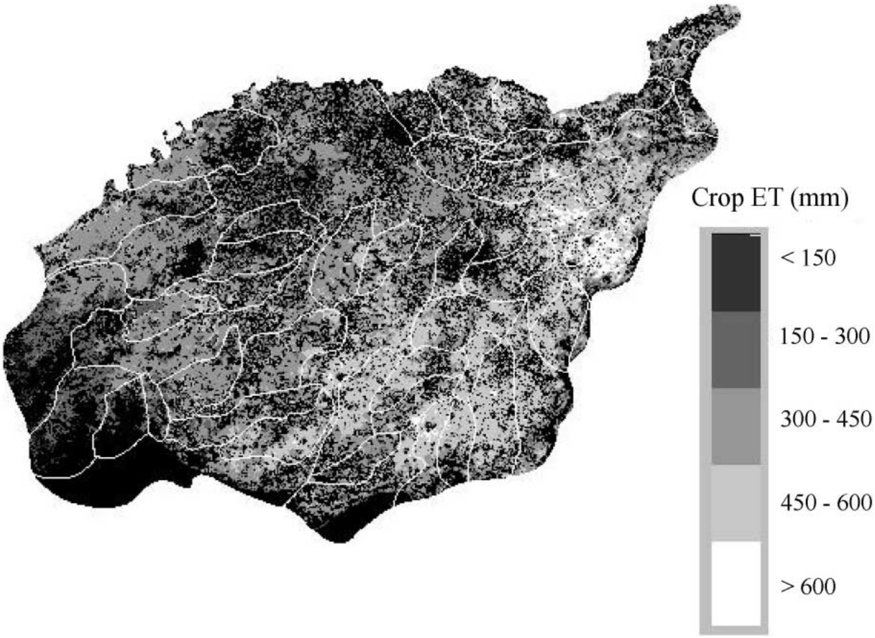

Fig. 6. Seasonal crop evapotranspiration map of MRBC command area.

3.6. Validation of crop ET values

The validation of pixel level values of crop evapotranspiration is a complex issue, since such distributed values of crop evapotranspiration related parameters generally do not exist. There can be two methods of validation for such regional level estimates. The first method tries to match the crop evapotranspiration estimated by this method with that from a field near the weather station. Caselles and Delegido (1987) have adopted such a method. In this study, the seasonal crop evapotranspiration values for MRBC command area were also computed for the weather data of Vallabh Vidyanagar station for the year 1995–1996 using the crop coefficient values provided by WTC (1983). It was found that the relative deviation between these two estimates were between 7.2 and 12.8%, with RS-based methodology giving a lower estimate. However, the strength of this RS-based estimate lies in giving a spatial information. The coefficient of variation of crop ET estimates over the command area ranged from 4.74% for perennial crop to 22.9 and 36.2% for wheat and tobacco crops, respectively. This highlighted the inadequacy of using a single value of crop evapotranspiration with respect to any particular crop for the whole command area.

The second method for validation is to look at water delivery records for the command and compare total water deliveries to the farmers plus rainfall during the time period to the total predicted crop water requirement in the area. However, this method will not be accurate as the water delivery is based on rotational water supply system, in which the farmer is given free access to water during his turn. As allocation is of time and not of amount, cases of excess application and inadequate water supply, depending upon the availability of water, are common (Palanisami, 1984). In this study, a comparison of ET_{crop} with water releases, after taking into account various distribution losses, indicated that similar range of values exist in many distributary commands but large difference in head and tail ends.

4. Conclusions

In this study, a procedure was developed to estimate the realistic spatial crop evapotranspiration. The pixel level crop coefficient values were estimated from the satellite RS-based crop reflectance values. This was combined with an interpolated map of meteorologically estimated reference crop evapotranspiration values.

This crop evapotranspiration map, overlaid with canal structure and command boundaries, can highlight the within-distributary difference in crop water requirement. As the crop evapotranspiration, estimated through this method, is a direct representation of the actual crop growth conditions in the field, this is better estimate of crop water use. When it is used as an input to any spatial irrigation-scheduling programme, it would minimise the impacts of over-irrigation as well as under-irrigation.

The present study has estimated the seasonal crop water requirement. However, the WiFS sensor on-board IRS satellite, whose data has been used for this study, provides data in every 5 days for any particular area. Hence this methodology can be used for weekly crop evapotranspiration estimation and thus a real-time irrigation scheduling. In an extension of this study, Ray et al. (2000b) have used the estimated seasonal crop evapotranspiration values for performance evaluation irrigation system, which has indicated a large variation in water requirement vs. availability with tail end distributaries obtaining much less water than required.

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