Application of Remote Sensing and GIS in Performance Evaluation of Irrigation Project at Disaggregated Level

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Abstract

The performance evaluation of surface irrigation projects has been hitherto done at regional or project level due to the non-availability of a detailed spatial database of irrigation projects. Recent advancements in the capabilities of remote sensing techniques and Geographical Information System (GIS) have opened avenues of field level mapping and database creation for irrigation projects. In view of this, the application of remote sensing and GIS in command area mapping and detailed performance evaluation at the sub-project level (division level) was attempted, in the present study. The command area of Upper Wardha irrigation project in Amravati district of Maharashtra, India was mapped for irrigation infrastructures (canals, hydraulic structures, etc.), crop acreage, and other infrastructures (viz. road, railway, settlement, etc.) using high resolution Cartosat-1, IRS P6 LISS-IV data, and temporal IRS P6 LISS-III data. The performance of the irrigation project was evaluated using eight comparative indicators classified under three groups, namely agricultural performance, water-use performance, and physical performance. Remote sensing data along with field observed data were used to derive inputs for these performance indicators. The results indicate that the project has a positive impact on agriculture and economic growth of the region; however, water has been excessively used in some parts of the command area while supply has been inadequate in the tail region of the command. The water supply in the command area was reliable, however, not equally distributed among all the distributaries. The overall performance of the irrigation project was evaluated, and the divisions, which need immediate attention to improve the efficiency, were identified in this study.

Keywords Command area mapping · Crop acreage · Crop water requirement · Performance evaluation · Upper Wardha project

Introduction

Agriculture sector is the largest employer in India's economy contributing a share of 16% in the country's gross domestic product as per the estimates in the year 2017–2018 (Bisht et al. 2018). Realizing its importance, due weightage has been given toward agriculture development. Attempts have been made by the Government of India to utilize the maximum possible irrigation potential for accelerated food production to meet the needs of the ever-growing population

(Prasad et al. 1996). Irrigation potential has been increased from 22.6 M ha in year 1951 to 102.77 M ha by the end of the Xth five year plan, i.e., year 2007 with the total investment of more than 71,21,300 Million (GOI 2010). In spite of such a large investment and phenomenal growth of irrigation potential, the performance of several irrigation projects in India has not been encouraging. According to the World Bank report (World Bank 1991), most of the large irrigation projects in India are running at overall efficiency as low as 20–35%. On the other hand, increasing water scarcity has led to increased pressure on the irrigation sector to utilize water resources more efficiently. The major emphasis has been given on improving the performance of irrigation projects which are currently running at 35–40% efficiency levels (GOI 1999). Therefore, it is important to raise the performance of low productive irrigation systems, while

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sustaining the performance of more-productive systems (Sakthivadivel et al. 1999b).

All these subtleties make benchmarking of irrigation projects based on its performance, the most critical element in improving irrigation water management (Abernethy and Pearce 1987; Gorantiwar and Smout 2005; Smout and Gorantiwar 2005). However, traditional analyses of irrigation performance, especially the concept of irrigation efficiency, if considered alone, can mislead planners and policymakers (Perry 1999). Hitherto, due to the non-availability of detailed data and complexity in evaluating a project at a disaggregated level (branch/distributary/minor level), the performance evaluation was usually done at the project level only. Attempts have been made in past to formulate a procedure for evaluating performance of irrigation systems based on different indicators (Bos and Nugteren 1974; Levin 1982; Menenti et al. 1989; Bos 1997; Thiruvengadachari and Sakthivadivel 1997; Molden et al. 1998; Bastiaanssen and Bos 1999; Molden and Sakthivadival 1999; Ray et al. 2002; Droogers and Bastiaanssen 2002; Bandara 2003; Sener et al. 2007; Karatas et al. 2009; Bumbudsanpharoke and Prajamwong 2015). However, practical applicability of such methods is restricted, especially in developing countries like India, due to limitations in the availability of details about actual crop acreage, the spatial distribution of irrigation infrastructure, etc., at the microscale (farmer's field). In such conditions to make a performance assessment task effective, it is necessary to couple advanced tools and techniques with existing practices. In this regard, the synoptic and repetitive coverage of the command area from the satellite would be helpful in providing regular information on the agricultural and hydrological conditions of the project area. Such spatial and temporal information, derived from space inputs, can be coupled with ground observations to improve the irrigation water management (Menenti 1990; Vidal and Sagardoy 1995; Bastiaanssen 1998). Remote sensing coupled techniques have distinct advantages over traditional performance evaluation techniques (Elshaikh et al. 2018). Few attempts have been made by Bastiaanssen and Bos (1999), Bastiaanssen et al. (2000), and Bos et al. (2005) to use remote sensing and GIS for performance evaluation of irrigation projects at different hierarchical levels.

Keeping this in mind, an attempt has been made, in the present study, to use remote sensing and GIS for creating a detailed database of the Upper Wardha irrigation project. The performance of the project have been evaluated at sub-project level (division level). The irrigation and other infrastructure in the command area has been mapped using high spatial resolution remote sensing data. The spatially distributed crop water demand has been estimated by fusing remote sensing and field observations. The performance of the project has been evaluated using eight indicators viz. relative water supply (RWS), depleted fraction (DF), relative irrigation supply (RIS), irrigation efficiency (IE), irrigation ration (IR), reliability, crop productivity and yield per unit water. These indicators have been used to evaluate the extent to which the allocation and scheduling objectives of the Upper Wardha irrigation project are met.

Study Area

Upper Wardha project is a multipurpose project providing water for irrigation, drinking, and industrial use. The command area of Upper Wardha irrigation project extends from 21° 20′ N, 77° 55′ E to 20° 35′ N, 78° 20′ E (Fig. 1). The average annual rainfall in the area is 840 mm, with around 95% of the rainfall occurring during the monsoon period.

The total irrigable area of this project (70,169 ha) spreads over 300 villages of two districts, Amravati and Wardha, Maharashtra, India, comprising predominantly of black cotton soil. The gross command area (GCA) of the project is around 1,16,970 ha, and the annual irrigation potential (IP) created is around 75,080 ha. Salient features of the Upper Wardha project are given in Table 1. Major crops grown in the command area are wheat, gram, soybean, tur (red gram), cotton, groundnut. The canal system is designed to supply irrigation water for *Rabi* season (winter season: November–March). However, in *Kharif* season water is supplied on the request basis, however, since the command area falls under the assured rainfall zone, there is very little or no demand for canal water during the *Kharif* season.

Methodology

The methodology adopted in the present study is discussed in detail in this section.

Database Generation

In most of the developing countries, and particularly in India, performance evaluation of irrigation projects is hampered by lack of a adequate, reliable, and timely data. Usually, performance indicators such as yield, cropping intensity, and irrigation intensity are measured at an aggregated level, often at the regional or state levels. Data at project or sub-project level (division level) are rarely collected, even if collected, most of the time this data is unreliable or not easily accessible (Murray-Rust and Merrey 1994).

Geo-spatial technology provides a powerful tool for mapping earth's surface features, i.e., different land use, crops, manmade infrastructure, etc., at a pixel scale
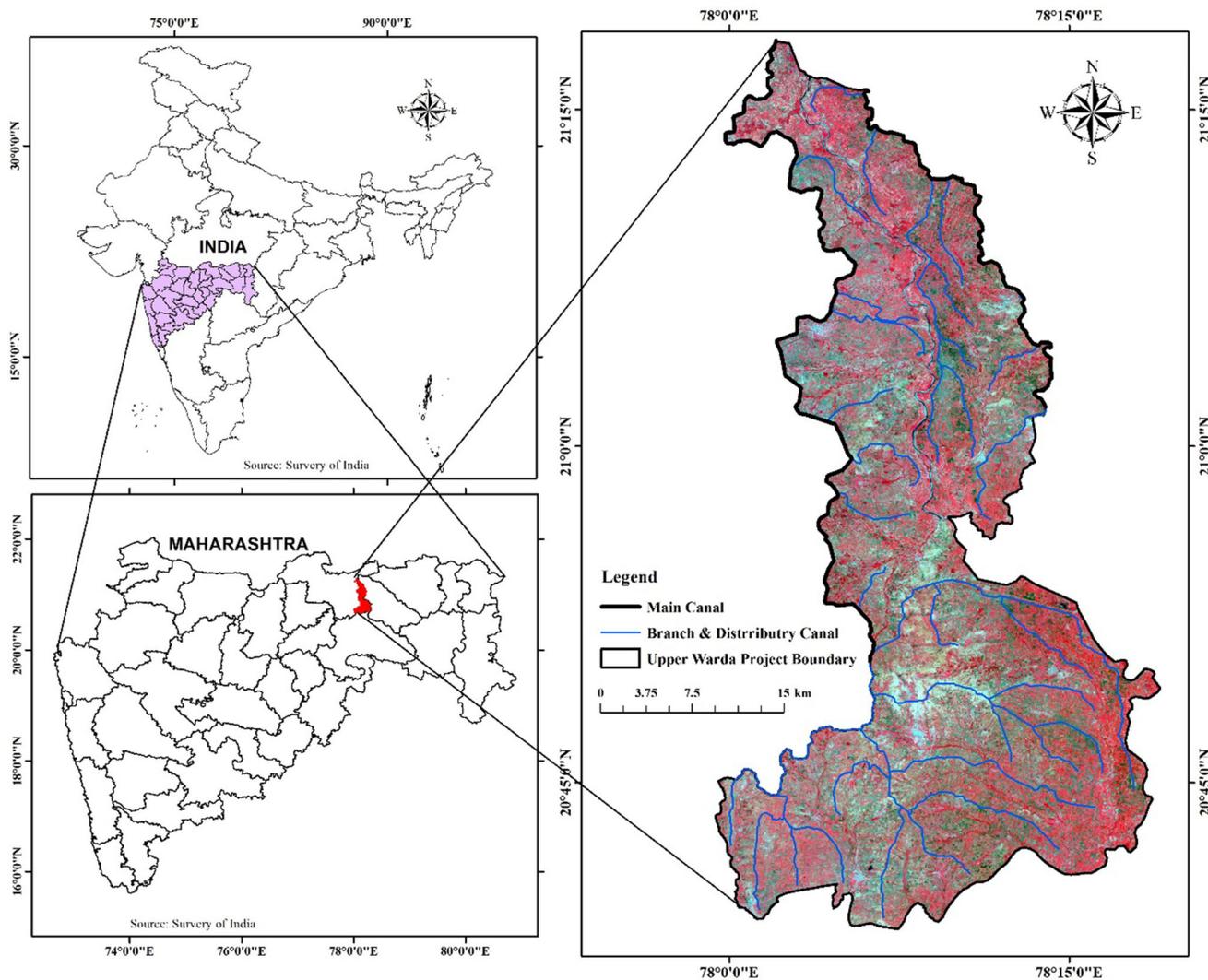
Fig. 1 Location of Upper Wardha canal command in India and index map of the project

Table 1 Salient features of Upper Wardha project

GCA (ha)	CCA (ha)	ICA (ha)	IP (ha)	Canal length (km)		Discharge at off take (cumec)	
				RBMC	LBMC	RBMC	LBMC
116,970	93,603	70,169	75,080	95.0	42.40	37.00	10.42

CCA Cultivable command area, *ICA* irrigable command area, *RBMC* right bank main canal, *LBMC* left bank main canal

(Anderson et al. 1976; Nirala and Venkatachalam 2000; Su 2000; El-Magd and Tanton 2005). Recent developments in the field of high spatial resolution panchromatic imaging through the Indian Remote Sensing Satellite-Earth Observation (IRS-EO) program have an added advantage of infrastructure mapping in the sector like irrigation. The irrigation infrastructure maps along with associated features like hydraulic structures could play a vital role in the analysis of water distribution mechanisms. In light of this,

remote sensing data from Resourcesat-1 (IRS P6) Linear Imaging Self Scanning Sensor- III and IV (LISS-III and LISS-IV) and Cartosat-1 has been used in the present study, to generate a detailed database of irrigation project and land use (crop) map for *Rabi* season of the year 2007–2008. The remote sensing data were obtained from the National Data Centre of National Remote Sensing Centre (NRSC), Hyderabad. Along with the remote sensing data, ground observed data viz. meteorological parameters,

canal discharge, and crop yield at field level have also been utilized in the present study.

Irrigation Infrastructure Mapping

Canal network maps available in hard copy format generally do not have any spatial reference attached with them and hence are not compatible in the GIS environment for any spatial analysis. To overcome this limitation, in the present study, the orthorectified Cartosat-1 (PAN) images and IRS P6–LISS-IV (MX) have been used to generate the canal network database compatible with GIS.

The Cartosat-1 PAN and LISS-IV (MX) images were checked for image quality standards of irrigation infrastructure mapping, given by Shanker et al. (2011). Scale for infrastructure mapping corresponding to the spatial resolution of available remote sensing data (Cartosat-1, 2.5 m) was fixed to 1:5000 with reference to Accelerated Irrigation Benefit Programme (AIBP) monitoring guidelines (Shanker et al. 2011). Remote sensing images along with canal index maps were used to map the canal network and associated features by on-screen digitization in Arc GIS 10.0. The canal network and other infrastructure layers were stored in geo-database. The attribute information of the canal network was obtained from the Upper Wardha project authorities. The digitized canal network and

impression of the canal network on the Cartosat-1 (PAN) image are shown in Fig. 2.

The irrigation projects are characterized by variation in soil, cropping patterns, irrigation efficiencies, climate, multiple users, water scarcity, and complex network of canals (Gorantiwar and Smout 2005). Hence, it is necessary to know the temporal and spatial variation of these parameters in the command area. The irrigation projects are, therefore, generally disaggregated/divided into different divisions and sub-divisions for the purpose of administrative and on-field operation (i.e., water distribution). However, the boundary maps of such divisions are seldom being prepared or published by irrigation authorities. Since irrigation water distribution in all the divisions is controlled by separate divisional authorities under the common umbrella of the main irrigation project authority, the performance of all the divisions is bound to vary from each other. However, the non-availability of a detailed database at the divisional level limits the intra-project performance evaluation and comparison. To overcome this limitation the database of the Upper Wardha irrigation project has been generated at the finest possible level, e.g., sub-minor level, however the delineation of sub-command has been done up to distributary level only. In the present study, the delineation of the sub-command boundary of distributary/branch canals has been done using Cartosat-1 Digital
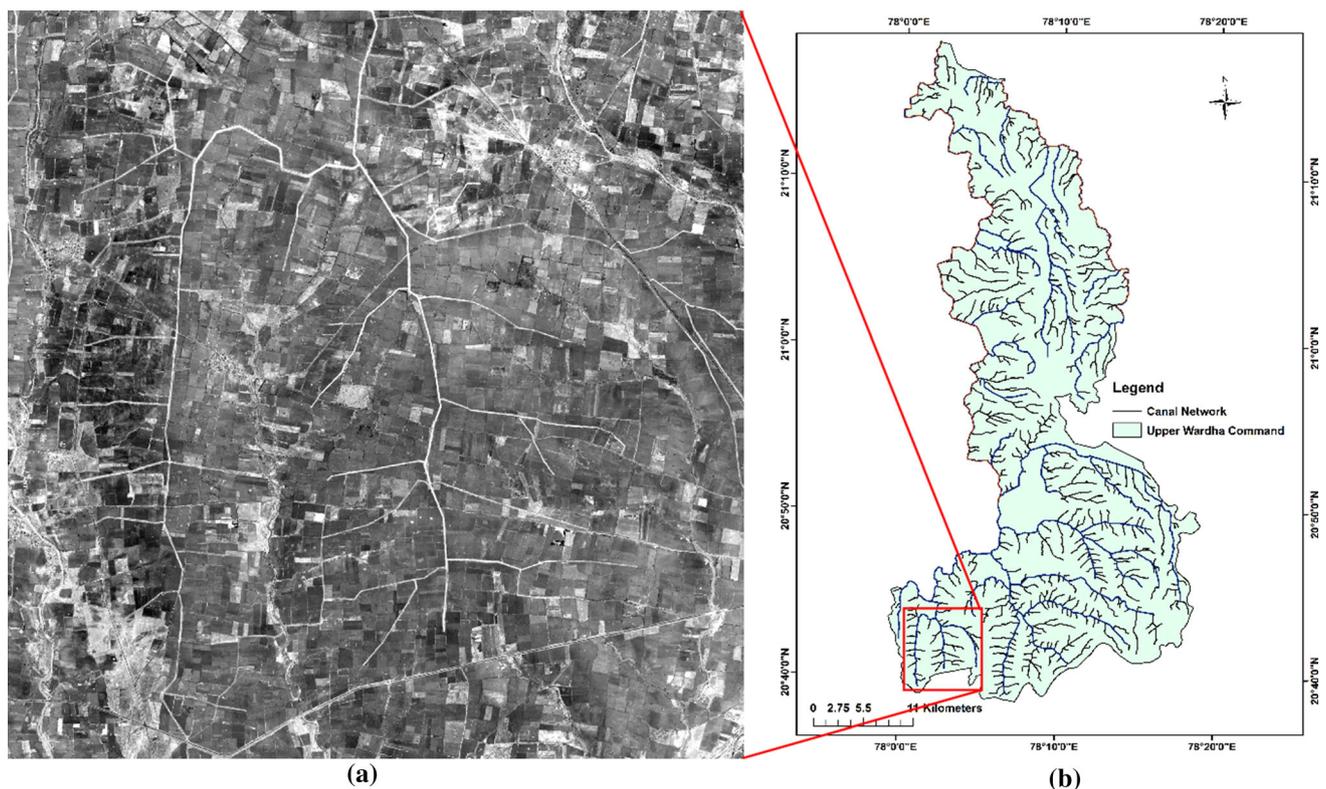
Fig. 2 **a** Part of canal network visible on orthorectified Cartosat-1 (PAN) image and **b** digitized canal network map of Upper Wardha project

Elevation Model (DEM; source: https://bhuvan.nrsc.gov.in/), aspect map, canal network map and project index map. The anal network and project index maps were provided by Upper Wardha irrigation authorities. These boundaries were delineated in consultation with the design and field engineers of the project using administrative information of each division (e.g., which canal/s or up to how much length of the particular canal/s fall under the jurisdiction of each division). The quality of the generated database was evaluated (i.e., quality Assurance: at the individual process level and quality evaluation: internal and external) with reference to AIBP standards (Shanker et al. 2011).

Crop Area Mapping in the Command

For effective water management, large irrigation schemes need-real time information on the irrigated area and the crops prevailing in the command area of each canal along with their water requirement. Due to the large size of irrigation schemes, the collection of such information through traditional techniques is not feasible (El-Magd and Tanton 2005). The advantage of spatial coverage and temporal resolution of remote sensing data was utilized, in the present study, to generate the crop acreage map of the Upper Wardha Command area for *Rabi* season of year the 2007–2008. Multi-spectral (four bands) LISS-III images from IRS-P6 Resoursat-1 satellite (date of pass: 20/10/2007, 13/11/2007, 31/12/2007, 24/01/2008, 17/02/2008, 12/03/2008 and 23/05/2008) were used for land use classification with the goal of mapping area under major crops grown in the command area.

Initially, all the images were analyzed for the possible number of spectrally separable land use classes. Using an unsupervised classification algorithm (iso-clustering) with convergence threshold 0.95, all the images were classified into 25 classes. Around 70% area was classified under different vegetation classes in the final output of this step. The spectral signatures for all the dominant vegetation classes and other permanent land use land cover classes viz. water body, settlements, barren land, etc., derived from the first step were analyzed. This analysis revealed the existence of a wide range and a possible mix-up in signature spectra among many classes. Conventional supervised classification using these signatures may not have served the objective of this project. So, in the present study the modified approach of supervised classification suggested by Sakthivadivel et al. (1999a), the iterative methodology that combines maximum likelihood classification (supervised classification) with iso-clustering (unsupervised classification) to analyze the temporal satellite data, was used to derive land use and cropped area map (Fig. 3). In this approach, a supervised classification was applied first. The unclassified portions of the images were then subjected to the unsupervised classification that yielded around 20 homogeneous spectral clusters. The signature of each cluster was compared with earlier training sets to create additional training sets. The earlier and additional training sets were then combined and spectrally clustered to provide revised training sets, which were used for further supervised classification. Dobbertin and Biging (1996) found that this approach of random selection of pixels in training sets improves classification accuracy in satellite images that have high spatial autocorrelation. The process has been repeated until all pixels were classified.

Normalized Difference Vegetation Index (NDVI; Tucker 1979; Crippen 1990) maps derived using LISS-III data and DEM, slope map of the project area were used to aid in discriminating natural vegetation from cropped land. Settlement mask was generated from Survey of India (SOI) Toposheets and Cartosat-1 image. The riverbed mask was developed using IRS P6 LISS-IV (MX) images. The barren land within the riverbed mask was merged with the dry riverbed class to avoid unnecessary complexity in land use classes. These knowledge-based classification improvements were incorporated through a the model developed in model builder of ERDAS Imagine software. Furthermore, the accuracy of land use/crop acreage map was evaluated using ground truths collected during the field visit.

Estimation of Irrigation Water Requirement

The majority of performance assessment indicators of irrigation projects are the function of crop evapotranspiration, ET_c (Bastiaanssen et al. 1996). Mathematically ET_c can be represented as the product of reference evapotranspiration (ET_0) and crop coefficient (Kc). Crop coefficient (Kc) varies with crop type, their phenological conditions, and soil moisture available (Thakur et al. 2017), while ET_0 varies only with meteorological parameters like temperature, relative humidity, wind speed and solar radiation, etc. (Allen et al. 1998). The spatial variations in micro-climatic parameters and soil moisture conditions on which the evapotranspiration process depends, makes the accurate estimation of crop evapotranspiration very difficult task, using conventional point-based measurements (Bastiaanssen et al. 1996). The fusion of point-based meteorological observations and spatial remote sensing derived data for estimating ET_c has been attempted by many researchers (Choudhury et al. 1994; Bausch 1995; Bastiaanssen et al. 1996; Michael and Bastiaanssen 2000; Ray and Dadhwal 2001). Michael and Bastiaanssen (2000) have mentioned that maps of crop coefficients can help in better spatial estimation of ET_c and can avoid the frequent need for remote sensing data. Bausch and Neale (1987) have shown the usefulness of remote sensing data to represent the crop coefficient. Moreover, remote sensing derived

Fig. 3 Flowchart of land use
land cover/crop acreage
mapping methodology.
Modified after Sakthivadivel
et al. (1999a)
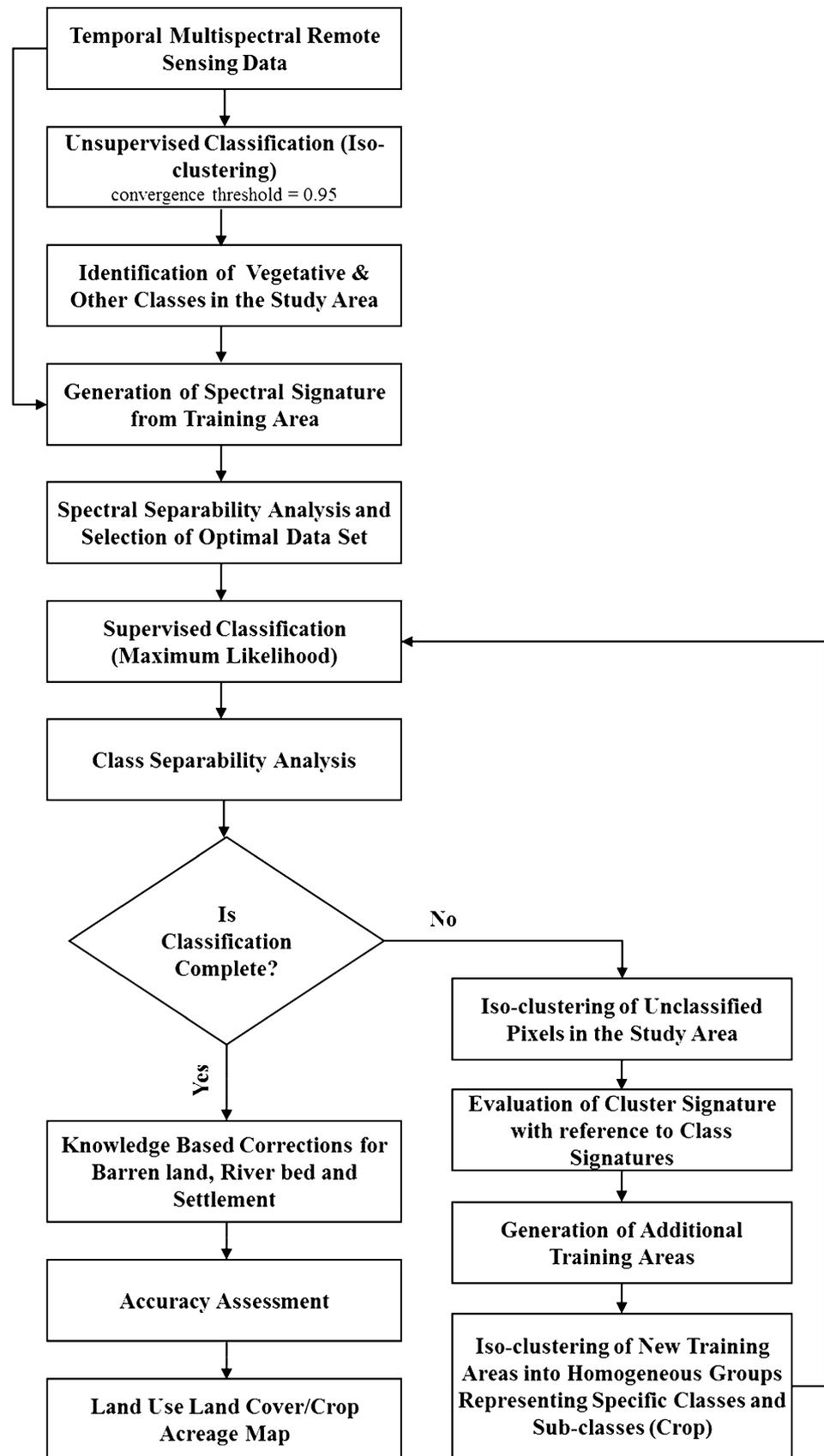
crop coefficient comprises the spatial and temporal variability of the command area and hence, it better represents the real-time crop condition of the command area (Choudhury et al. 1994).

In the present study, the seasonal actual crop evapotranspiration (ET_a) was estimated using point-based meteorological observations in conjunction with remote sensing data. The daily meteorological data (temperature, relative humidity, wind speed at 2 m height, sunshine hours) of four observation stations located around the study area (Amravati, Warudbagagi, Sirpur, and Hinganghat) was collected from State Hydrological Data Centre, Nasik and used for estimation of ET_0 using FAO Penman–Monteith (FAO-PM) method (Allen et al. 1998). Raster layers of monthly ET_0 were generated by interpolating point-based monthly ET_0 using Inverse Distance Weighted (IDW) technique in Arc GIS 10.0. The remote sensing data from IRS-P6 LISS-III sensor was used to generate monthly NDVI maps for the *Rabi* season of the year 2007–2008. The NDVI values of well-distributed and randomly selected 50 points for each crop and each month were extracted using the 'Extraction' tool of Arc GIS. The mean NDVI value for each month and each crop was then calculated using these extracted values. The regression analysis has been performed between mean NDVI values and respective crop coefficients (Kc) of each crop each month as suggested by Ray and Dadhwal (2001). The Kc values for each crop grown in the command area in the *Rabi* season were taken from Water and Land Management Institute (WALMI), Aurangabad, India. The empirical relationship between Kc and NDVI for each crop was generated through linear regression analysis of these values. These empirical equations were further employed to derive spatially distributed monthly crop coefficient maps from monthly NDVI maps. Consequently, spatially distributed monthly ET_a was estimated for each pixel by multiplying monthly Kc maps with monthly ET_0 maps. The flowchart of this procedure is shown in Fig. 4.

Selection of Performance Indicators

Irrigation performance is a broad concept having varying scope and meaning as per the context of the application. In order to measure and evaluate irrigation performance effectively, it is very important to select the appropriate evaluation method (Elshaikh et al. 2018). In the early days, the focus of irrigation performance evaluation was on assessment of the economy, efficiency, and effectiveness of the project (Bumbudsanpharoke and Prajamwong 2015). Later, the attention shifted toward the quality aspect and satisfaction of end-users (Kouzmin et al. 1999). However, in recent times, the use of different performance indicators for the evaluation of the overall performance of the irrigation system has gained importance (Bos et al. 2005). The performance of irrigation project can be evaluated under five broad categories, i.e., (1) water use performance, (2) agricultural performance, (3) physical performance, (4) economic performance and (5) environmental performance (Bos et al. 2005; Sener et al. 2007). However, availability of the data for the evaluation of an irrigation project under such categories is uncertain. In the present study, indicators were selected from the literature to evaluate the Upper Wardha irrigation project under water use performance, physical performance, agricultural performance, and economic performance. While selecting the indicators it was taken care that each indicator should also represent any one of 'the essentials of good irrigation system', i.e., adequacy, efficiency, reliability and timely supply (Michael 1978; Bastiaanssen and Bos 1999; Ray et al. 2002; Gorantiwar and Smout 2005). Brief description of each indicator used in the present study is given below:

1. Relative Water Supply

The relative water supply (RWS), which falls under the category of scheduling type of performance indicator, is an indicator of the adequacy of irrigation water delivery (Gorantiwar and Smout 2005). It is derived by comparing water supplied with the water demand (Perry 1996). The RWS is calculated as:

Fig. 4 Flowchart for estimation of spatially distributed ET_a
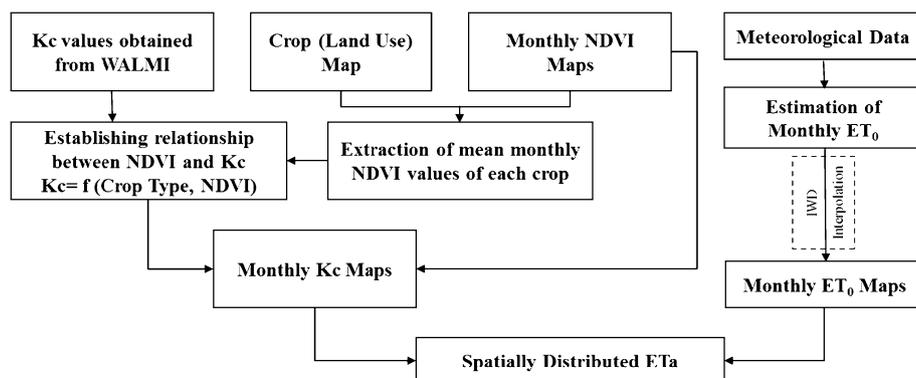
$$RWS = \frac{I + P_e}{ET_0} \qquad (1)$$

where P_e is effective precipitation in mm and I is volume of irrigation water diverted in mm. Generally, the performance assessment is done by comparing the measured/estimated value of the indicator with its reference/target value (Bos et al. 2005). The reference value of the RWS proposed by Molden et al. (1998), as 2.0 for an adequate irrigation system, was used, in the present study, to evaluate the adequacy of irrigation supply in different divisions of Upper Wardha irrigation project.

2. Depleted Fraction

Depleted fraction (DF) shows changes in actual water use by crops and quantifies differences in the water balance of the areas under study (Bandara 2006). The depletion in an irrigation scheme is governed by ET_a, hence, DF has been defined by Molden (1997) as;

$$DF = \frac{ET_a}{I + P_e} \qquad (2)$$

where ET_a is actual evapotranspiration in mm and P_e is effective precipitation in mm. DF is considered as a function of time. For semi-arid and arid regions, the critical value of the DF averages about 0.6 (Bastiaanssen et al. 2000; Bos et al. 2005).

3. Relative Irrigation Supply

The relative irrigation supply (RIS) is also an indicator of the adequacy of irrigation water delivery, and it compares supplied water with actual irrigation water demand (Sakthivadivel et al. 1993) as:

$$RIS = \frac{I}{ET_a - P_e} \qquad (3)$$

The reference value for RIS can be considered in the range of 1.5–2.0 (Droogers and Bastiaanssen 2002).

All three indicators mentioned above evaluate the irrigation system for water use performance and indicates the adequacy of the water supply.

4. Irrigation Efficiency

This is the most popular performance indicator, used widely to assess the performance of the irrigation systems (Bandara 2003; Karatas et al. 2009). Irrigation efficiency (IE) is defined as the ratio of actual irrigation water demand to water supplied;

$$IE = \frac{ET_a - P_e}{I} \qquad (4)$$

Considering the values of water application efficiency (0.65–0.75) and conveyance efficiency (0.80–0.85)

achievable in surface irrigation projects, the reference value for IE can be accepted as 0.5–0.6 (Bos et al. 2005).

5. Irrigation Ratio

Irrigation ratio (IR) evaluates the physical performance of the irrigation projects in the particular period. This indicator is a ratio of actual area irrigated to total/designed potential area to be irrigated in that particular period (Sener et al. 2007).

$$IR = \frac{\text{Irrigated Land (ha)}}{\text{Irrigable Land (ha)}} \qquad (5)$$

The reference value of IR in a particular season should be 1.

Irrigation efficiency (IE) and irrigation ratio (IR) evaluates the physical performance of the irrigation system along with this, irrigation efficiency also evaluates the water use performance of the system.

6. Reliability

The reliability of the irrigation system can only be evaluated on a broader scale (branch or distributary level). In the present study, the canal operation schedules were examined to evaluate the reliability of the supply system to understand how well the design objective/s of irrigation project have been achieved by the existing operational schedule.

7. Crop Productivity

Productivity represents the economic performance of the project and can be categorized under the allocative type of performance indicator (Gorantiwar and Smout 2005). Productivity (t/ha) data for major crops grown in the command area were collected by interacting with farmers during the field survey. Productivity values for the same crops in the non-command area were obtained from the Office of the Director of Agriculture, Department of Agriculture, Govt. of Maharashtra, Amravati, India. The comparison between productivity values of major crops from the command area and non-command area was done for evaluating the agricultural performance and economic performance of the irrigation system.

8. Yield Per Unit Water

To evaluate the physical and economic performance of the irrigation system the crop yield per unit water used (tons per cubic meter) was calculated for all the major crops in all distributary command areas (sub-command). These values were further compared to evaluate the relative performance of each division of the Upper Wardha project.

Results and Discussion

Land Use Mapping and Database Creation

Using high-resolution remote sensing data (Cartosat-1 and LISS-IV) the canal network and other features like road network, railway lines, settlements, etc., were digitized. The length of the digitalized canal network, sub-minor level, was verified from the information provided by the project authorities. All other relevant information on the individual canals were stored as attributes. The quality assessment of the generated database revealed that the desired accuracy level in terms of location and length of features mapped ($\pm$ 25 m) was achieved in infrastructure mapping. The digitized canal network of the Upper Wardha irrigation project is shown in Fig. 2b. These datasets were also used for the delineation of sub-command of each branch and distributary canal.

Temporal multi-spectral satellite data from IRS P6 LISS-III sensor were used to generate land use map of the Upper Wardha command area. Remote sensing images were first analyzed using unsupervised classification technique to find out different spectrally separable classes in the command area. The spectral mix-up between some of the dominant land use classes made the application of conventional supervised classification techniques more vulnerable to erroneous results. The modified iterative approach of using maximum likelihood techniques and iso-clustering technique with knowledge-based correction at the final step was applied to generate the seasonal land use land cover map of the command area. The ancillary data like slope map and temporal vegetation index maps were also used in this process. The final land use land cover map of the Upper Wardha command area and distribution of each land use land cover classes is shown in Fig. 5a, b. The Upper Wardha command area was majorly covered by soybean/red gram, wheat, gram, and cotton during the period of analysis. Out of all major crops red gram, soybean, and cotton do not utilize the canal supplies as the crops were at their harvesting stage in the period under consideration, in the present analysis (Rabi season). These Kharif season crops (soyabean, red gram and cotton) were merged in one class to reduce the dimensionality problem in the assessment of classification accuracy.

Any land use land cover classification is not complete until its accuracy is assessed (Lillesand et al. 2004). The accuracy of the generated land use map was tested using ground information collected through personal interviews of farmers during the field visit. The attempt was made to keep the ground truth points well distributed in the entire command area. The classification error matrix presented in Table 2 represents an overall classification accuracy of

(Congalton 1991; Congalton and Green 1999) as 94.5%. In conjunction with overall classification accuracy researchers also prefer the $\hat{k}$ (KHAT) statistic as a measure of the difference between the actual agreement between reference data and classified data, and the chance agreement between reference data and random classification output (Lillesand et al. 2004), the $\hat{k}$ statistics can be estimated as;

$$\hat{k} = \frac{\text{Observed accuracy} - \text{chance agreement}}{1 - \text{chance agreement}} \qquad (6)$$

The $\hat{k}$ statistics value of 0.93 in the present study indicates the better true agreement between reference data and classified data due to accurate classification rather than by chance. The crop acreage map of the Upper Wardha command area for the Rabi season of 2007–2008 was generated using this land use land cover map of the area. It is clear from Fig. 5a, b that around 83% of GCP of Upper Wardha project was under cultivation and around 7% was fallow during Rabi season of 2007–2008.

Estimation of Spatial Irrigation Water Requirement

Daily meteorological data of four stations located around the study area were used to estimate reference evapotranspiration (ET_0) using FAO-PM method (Allen et al. 1998). The point-based monthly ET_0 values were interpolated using the IDW interpolation technique. The data from two of the stations (Warudbagaji and Sirpur) were not consistent, so the remaining two stations (Amravati and Hinghangat) were used in interpolation of the ET_0. The ET_0 map of the command area for anuary 2008 and the location of meteorological stations is shown in Fig. 6.

The Kc values for major crops in the command area were obtained from WALMI Aurangabad, India. The monthly Kc values for gram, wheat, cotton, and red gram are given in Table 3. These values of Kc represent the standard condition of crop in the command area and since the canal was designed to supply water for Rabi season, it was assumed that these Kc values were applicable throughout the command area. The NDVI values for each crop from 50 well-distributed points (Fig. 7) for each month were obtained using the 'Point Data Extraction' tool of Arc GIS 10.0. The extracted NDVI values show a standard deviation less than 0.05 and variance less than 0.004. The monthly mean NDVI value for each crop was estimated using all the NDVI values extracted for the particular crop in the specific month. The relation between mean NDVI and Kc for each crop on the temporal scale was analyzed as suggested by Ray and Dadhwal (2001). The parameters of the regression equation between mean monthly NDVI and monthly Kc are given in Table 4.

Fig. 5 a Land use land cover
map of the command area and
b distribution of each land use
land cover class in the area

(a)

(b)
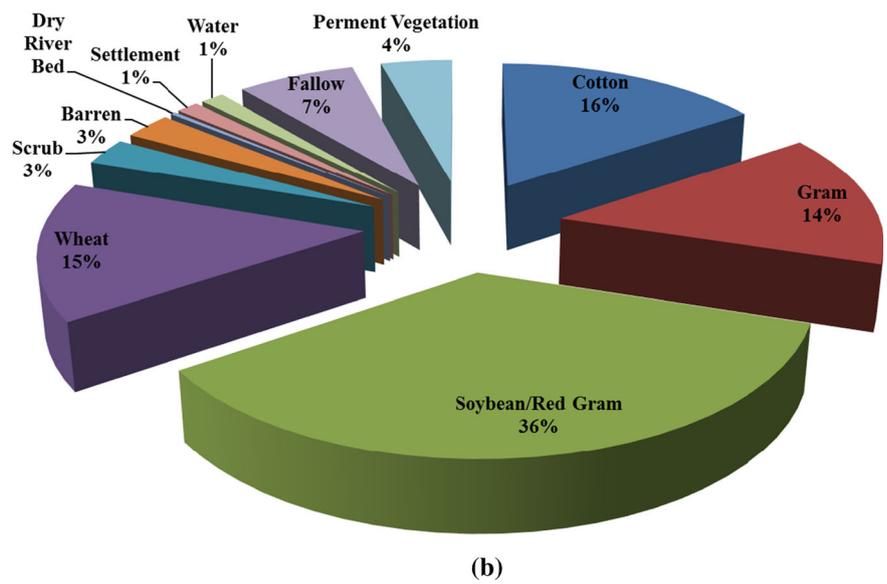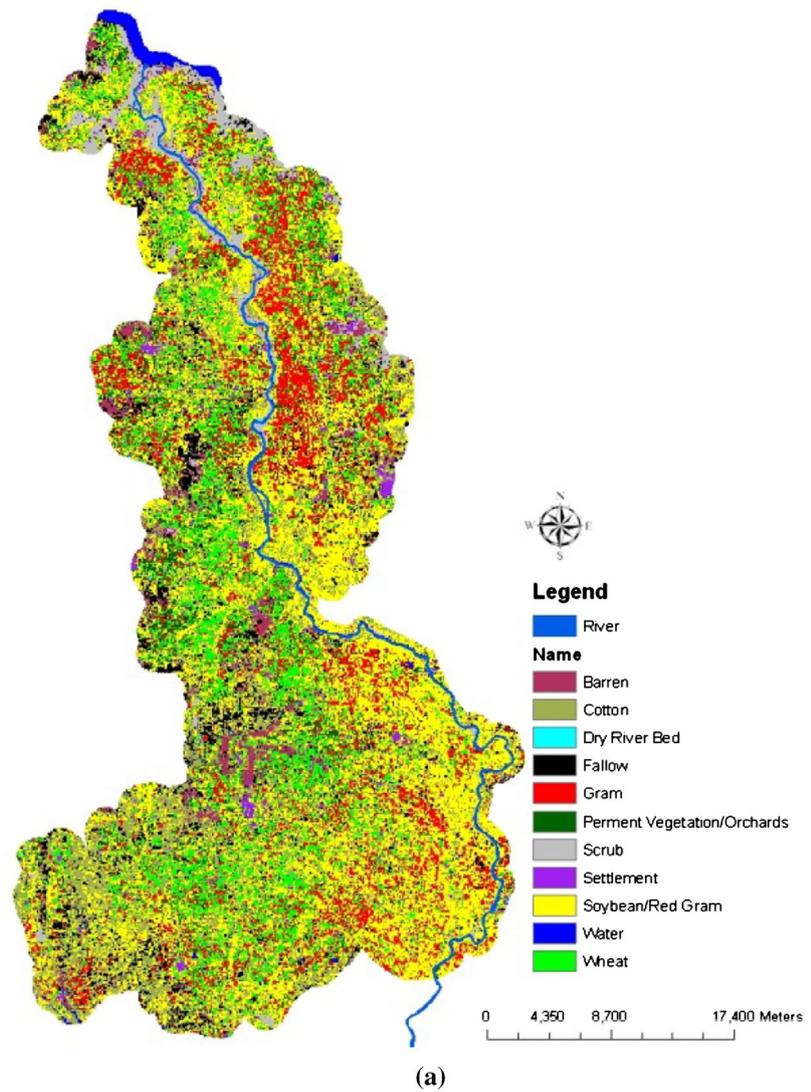
Table 2 Error matrix of land use classification of Upper Wardha command area

	Reference data[a]						
	W	G	RSC	F	O	Row total	Accuracy
Classification data							
W	28	2	1	0	0	31	90.32
G	1	32	1	0	0	34	94.12
RSC	0	0	26	1	0	27	96.30
F	0	0	0	7	0	7	100.00
O	0	0	0	0	10	10	100.00
Column total	29	34	28	8	10	109	
Accuracy	96.55	86.67	88.89	87.50	100.00		94.50
$\hat{k} =$	0.923						

[a]*W* Wheat, *G* Gram, *RSC* red gram + soybean + cotton, *F* fallow, *O* orchard

Fig. 6 Monthly ET_0 January 2008 and the location of meteorological stations
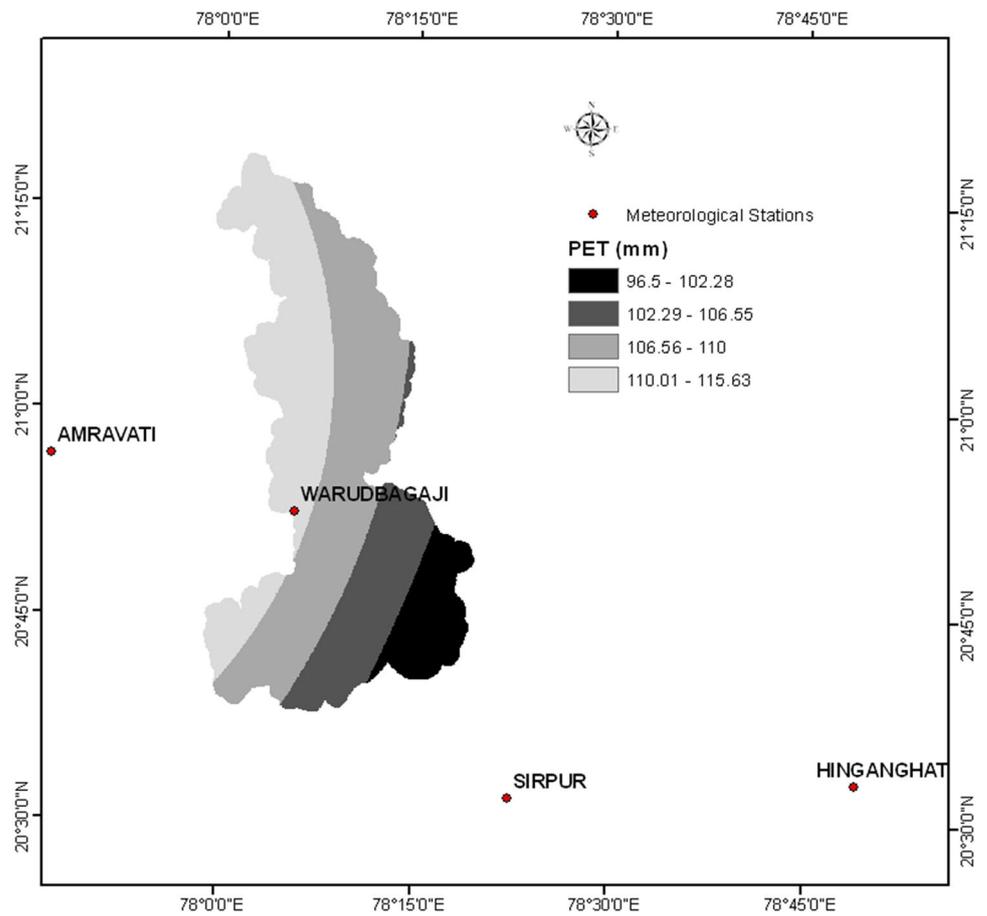
Table 3 Crop coefficient (Kc) values for major crops in the Upper Wardha command

	October	November	December	January	February	March	May
Gram	0	0.195	0.8	1.11	0.625	0	
Wheat	0	0.18	0.405	1.025	1.09	0.24	0
Cotton	1.01	0.805	0.715	0.68	0	0	0
Red gram	1.1	0.99	0.59	0.195	0	0	0
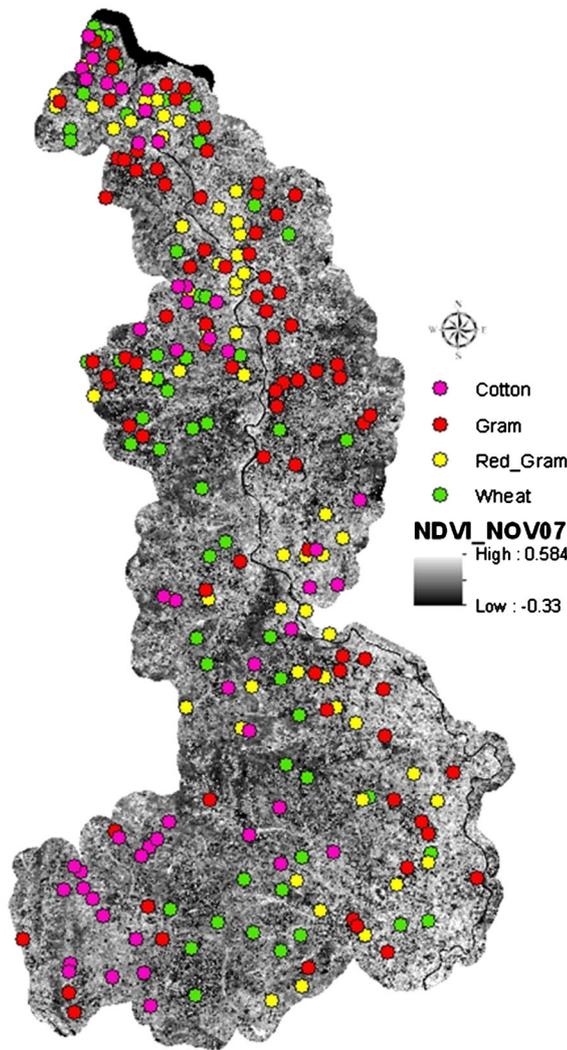
Fig. 7 The well distributed points for all major crops to collect monthly NDVI values

Table 4 Parameters of regression equation between NDVI and Kc ($Kc = m \times NDVI + c$)

Crops	m	C	r^2
Gram	3.368	0	0.968
Wheat	3.290	0	0.987
Cotton	1.068	0.617	0.845
Red gram	3.781	0	0.972

Monthly spatial Kc maps were generated with the help of corresponding NDVI maps and land use land cover map by employing these regression equations. The spatial monthly actual crop evapotranspiration (ET_a) was calculated using Kc maps and ET_0 maps of each month. The seasonal ET_a was estimated by aggregating monthly ET_a at

each pixel. The seasonal ET_a map of the Upper Wardha command area is shown in Fig. 8. It is worth noting here, that the traditional Kc approach considers the crop to be at standard condition at each stage. If the crop is under non-standard/stress condition, the actual evapotranspiration from the crop can be calculated by multiplying the ET_a with crop stress coefficient Ks or by adjusting Kc for all kinds of stresses and environmental constraints on the crop (Thakur et al. 2017). Getting spatial information about the status of stresses on the crop, through the tradition techniques, is very difficult in the command area due to the large spatial extent of the command. However, NDVI can represent the health condition of the crops grown in the area. The stress on the crop gets reflected in the NDVI value of the crop, hence the approach used, in the present study, has the inherent capability of adjusting the ET_a for
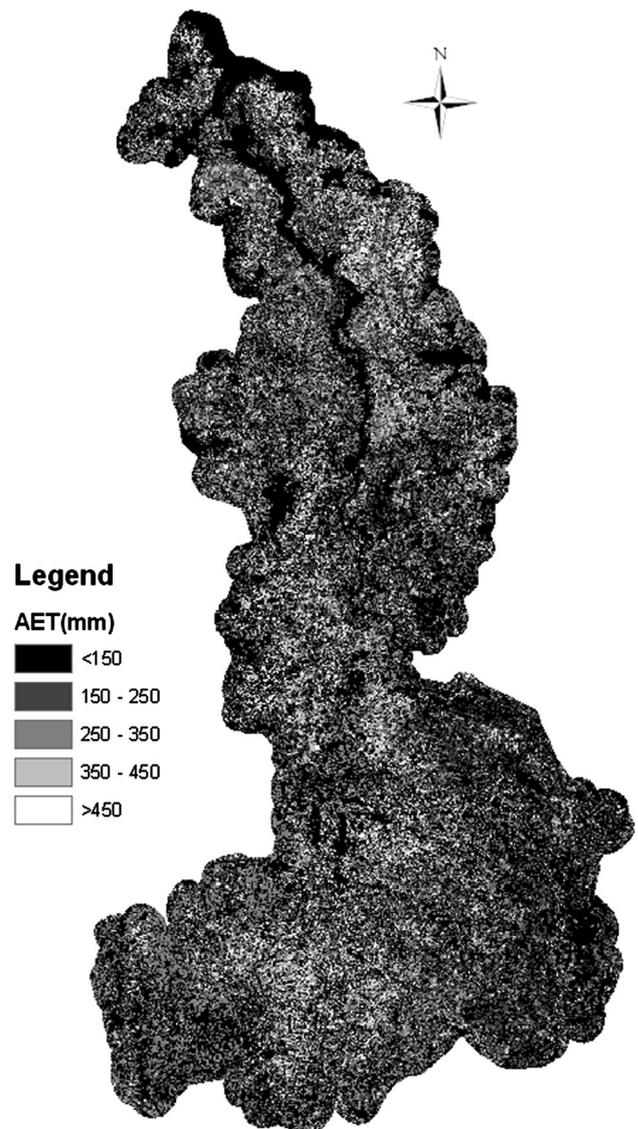
Fig. 8 Seasonal ET_a map of Upper Wardha command

the non-standard conditions. In the present study, the seasonal ET_a estimate was used as the seasonal crop water requirement of each crop hereafter. The value of seasonal crop water requirement varies from more than 450 mm for healthy wheat and less than 150 mm for poor gram crop.

Performance Evaluation

Data on seasonal values of irrigation supply through the -canal was obtained from the canal authorities. The irrigation water requirement of crops was estimated using the approach described in the pervious section. The performance of six divisions of Upper Wardha project (Fig. 9) i.e., Division 1: Chandrabhaga branch canal; Division 2: Vidarbha branch canal (14–25 km); Division 3: Dhamangaon branch canal; Division 4: Devgaon sub-division; Division 5: Dhamangaon sub-division–Vidharbha branch canal (1–13 km); and Division 6: Jalka and Ghusali distributaries, was evaluated using performance indicators derived with the aid of remote sensing and field data. For the purpose of simplicity, hereafter these six divisions will be labeled by their respective division number, i.e., Divisions 1–6. The analysis period in the present study, i.e., *Rabi* season, receives a negligible amount of rainfall, so water input through rainfall was ignored while calculating performance indicators.

1. Relative Water Supply (RWS)

The RWS indicates the adequacy of irrigation supply. The estimated values of RWS for six divisions are given in Table 5. Molden et al. (1998) mentioned the reference value of the RWS indicator as 2.0 or more for an adequate

Table 5 Performance indicators representing adequacy of supply

	RWS	DF	RIS
Division 1	1.82	0.28	3.61
Division 2	1.42	0.41	2.43
Division 3	1.34	0.45	2.22
Division 4	0.68	0.92	1.09
Division 5	0.85	0.79	1.27
Division 6	1.06	0.55	1.82

supply system. The irrigation systems having RWS more than 1 and less than 2 can be termed as a system providing adequate supply to the crops. However, in rotational water delivery system, Warabandi/Turn Fixation (Michael 1978) followed in India, assuming the value of irrigation efficiency to be around 60–65%, RWS value more than 1.5 indicates excess supply/use of water, similarly RWS values less than 1 indicates inadequate supply, these limits (1–1.5) are considered for analyzing the adequacy of the irrigation water supply of Upper Wardha project. From Table 5, it is clear that the first three divisions (i.e., Division-1, Division-2, and Division-3) had adequate but excess irrigation water supply, however, farmers in Division-1 were getting excess water. Division-6 is having RWS values just more than one which indicates probable water inadequacy. Division-4 and Division-5 with RWS value less than 1 indicates inadequate water supply to the crops. The lowest value of RWS is in Division-4, which is the tail division of the right bank main canal (RBMC) as shown in Fig. 9. This result supports the general impression that water does not reach the tail section of the canal, due to excessive use of water in head reach.
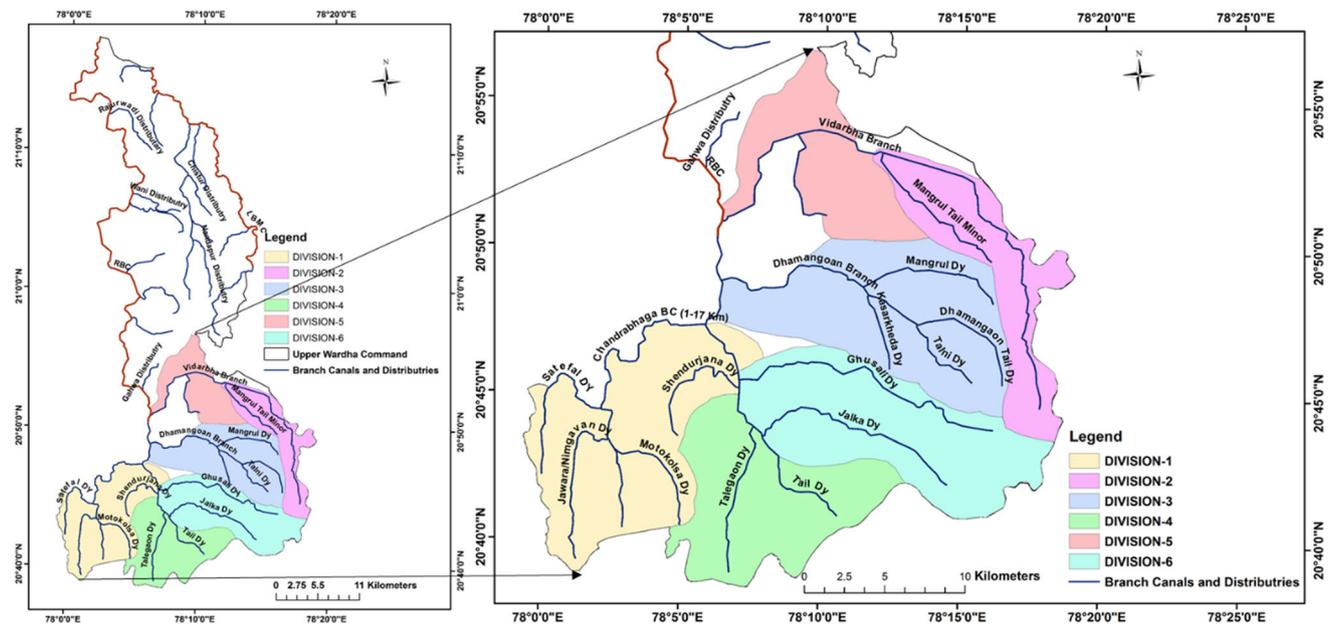
Fig. 9 Location of six divisions considered for performance evaluation

2. Depleted Fraction (DF)

For semi-arid and arid regions, Bos et al. (2005) proposed the reference value of the DF as 0.6. Depleted fraction (DF) less than 0.6 indicates that the water supply is more, the ET_a is less than $0.6(I + P_e)$ and the excess water will join the ground water or may flow as surface runoff out of the fields. Depleted fraction values from the first three divisions are less than 0.6 (i.e., 0.28, 0.41 and 0.45, respectively) indicating excess supply in these three divisions. Depleted fraction values of 0.55 in Division 6 indicate the marginally excess water supply which can be termed as adequate and efficient supply. The DF in Division-4 and Divison-5 is around 0.92 and 0.79 indicates of inadequate supply in these divisions.

3. Relative Irrigation Supply (RIS)

Relative irrigation supply (RIS), an indicator of the adequacy of irrigation water supply, was calculated using actual irrigation water demand and irrigation water supplied in a period. According to Droogers and Bastiaanssen (2002), the reference value for RIS can be considered from 0.55 to 0.80. However, the command area of the Upper Wardha project receives minimal or no rainfall during *Rabi* season, hence the effective rainfall term of Eq. 3 will be zero. Keeping in mind the assumption that irrigation efficiency is around 60–65%, the reference value for RIS for adequate but not excess irrigation supply system was considered in the range of 1.25–1.5. Higher RIS values in Divison-1, Division-2, and Division-3 indicate the excess supply of water. Division-6 indicates adequate, however, slightly excess supply condition. Lower RIS values in Division-4 and Division-5 ascertains the findings of RWS and DF, that these two divisions were getting inadequate water supply. Combined analysis of RWS, DF, and RIS indicates that Division 6, which was termed as inadequate supply division was actually delivering adequate supply in its command area.

Comprehensive analysis of RWS, DF, and RIS indicates that the existing operational plan of the Upper Wardha project does not uniformly achieve the scheduling objective of the project. There is a need for improvement/modification in the scheduling plan of the project to increase the adequacy at the division level. The disaggregated performance evaluation has enabled the path for the identification of underperforming sub-system/s (Division/s) within the system (irrigation project). The change in the operational schedule of underperforming sub-system/s will ensure the enhancement of the performance of those sub-systems and the entire system as well. However, the same cannot be guaranteed, if the performance evaluation is being done only at the project level. Since the results of such exercise will yield average performance of all the sub-systems and changes proposed to improve performance of entire project may degrade the performance of better performing sub-system/s due to difference in soil, climate, agricultural practices, etc., in sub-command areas of those sub-systems.

4. Irrigation Efficiency (IE)

Irrigation efficiency (IE) is the most popular and commonly used performance indicator for the evaluation of irrigation systems. Assuming water application efficiency around 0.65–0.75 (i.e., 65–75%) and conveyance efficiency of lined canal system around 0.8–0.85 the overall efficiency value of 0.5–0.6 can be achieved in the surface irrigation supply system. So, the same range was used as a reference for evaluating the physical performance of the Upper Wardha irrigation project. The IE values of different divisions are listed in Table 6. Irrigation efficiency values of 0.28, 0.41 and 0.45, for Division-1, Division-2, and Division-3, respectively indicate excess water supply in these divisions. The IE of 0.55 in Division-6 indicates the adequate and efficient supply in this division. The deviation on the excess side in IE values in Division-4 and Division-5 indicates inadequate water supply in these divisions.

5. Irrigation Ratio (IR)

Irrigation ratio (IR) represents the physical performance of the irrigation projects (Sener et al. 2007). Higher IR indicates the better physical performance of irrigation projects in terms of supplying water to the majority of the command area. The IR values for six divisions calculated using the data collected from project authorities for the *Rabi* season of the year 2007–2008 are given in Table 6. High IR values in Division-4 Division-6 and Division-5 indicate better water distribution in these divisions, whereas lower values of IR in Division-1, 2, and 3 indicate inefficient distribution system which fails to cater to the demands of all farmers in the sub-command.

Irrigation efficiency and IR represent the physical and water distribution performance of the irrigation system. The results of IE and IR (Table 6) also endorse the findings of the first three performance indicators (i.e., RWS, DF,

Table 6 Performance indicators representing physical performance of irrigation system

	Irrigation efficiency	Irrigation ratio
Division 1	0.28	0.35
Division 2	0.41	0.33
Division 3	0.45	0.40
Division 4	0.92	0.65
Division 5	0.79	0.53
Division 6	0.55	0.63

and RIS). The excess water use/supply in Division-1, Division-2, and Division-3 have brought down the IE values of these three divisions. On the contrary, the exceptionally high values of IE in Division-4 and Division-5 clearly indicate that the irrigation water demand is not adequately met by canal supply. In the case of Divisions-1–3, lower IR values again indicate that the water supplied to irrigate the designed CCA or ICA was not distributed uniformly across all the stakeholders (farmers). In ideal cases, the IR value should be 1, if canal supplies water at full supply level, however, practically IR values never touch the ideal standard (e.g., 1) due to technical limitations (microrelief in the command area, change in agriculture practice, damage or maintenance activities in canal network, spatial variability in climate, etc.). The combined analysis of IE and IR of Division-6 indicates that a maximum of (63%) the stakeholders in this sub-command get irrigation supply and this division utilizes the supplied water at the highest efficiency (55%).

A peculiar point observed from Table 6 is that, though Division-4 and Division-5 are getting less irrigation supply than their respective demands, however, these divisions show higher efficiency in the distribution of irrigation water among stakeholders with higher IR values (0.65 and 0.53, respectively) compared to first three divisions. If, in a hypothetical scenario, these divisions bring down the actual area under irrigation (i.e., area getting irrigation supply form canal) in Rabi season in their respective sub-command area, in other words, reduce their IR, the total irrigation demand will also come down. Assuming irrigation supply at the same level, this reduction in irrigation demand will force IE values within the limits of adequate and efficient system, on the other side, the values of RWS, DF, and RIS will also improve. By reducing IR, these divisions can bring their system within an adequacy and efficiency limits of performance evaluation criteria. However, the design objective and operational schedule of any irrigation project aim to supply water at a higher efficiency levels to the entire ICA, rather than to a part of ICA. Hence, reducing the actual area under irrigation (IR) cannot be permitted to increase irrigation efficiency (IE) or any other performance indicator. Other interpretation of this discussion could be, only higher performance in terms of adequacy do not make the overall performance of the irrigation system satisfactory. The system must achieve all its design objectives, which only can be evaluated using multiple performance indicators in conjunction with each other, as done in the present case. From these results and their discussion, it can be concluded that the single performance indicator may mislead the evaluator.

6.   Reliability

To check the reliability of supply, the canal operation schedule was examined for water supply period and canal off period with the assumption that residual moisture from the previous season was sufficient to meet the water demand of pre-sowing operation and germination. It is clear from the canal supply schedule (Table 7) obtained from the project authorities that the first irrigation started from 15 November and after every 15 days the canal supply was 'ON' mode which indicates that water was available after around every 20 days, which matches the surface water irrigation cycle in this region. This indicates the timeliness of irrigation supply by which the Upper Wardha project fulfills the reliability criteria. Reliability is a part of scheduling type of performance measures and it also represents the management performance, in other words, it can be concluded that the existing operational schedule satisfies the timeliness objective of the project operations and hence qualifies for reliability. However, readers must understand that timely supply does not guaranty adequate supply. In the present study, the adequacy of supply was evaluated using RWS, DF, and RIS, hence the reliability was as a function of timeliness of irrigation supply.

7.   Crop Productivity

Productivity is an allocative type of performance indicator that can assess the agriculture and economic performance of the irrigation system. The crop productivity (t/ha) values of major crops in the command area were obtained from farmers in the command area through personal interviews. The productivity of the same crops in the non-command area was obtained from the Office of the Director of Agriculture, Department of Agriculture, Government of Maharashtra, Amravati, India. A comparison between productivity values of major crops from the command area and non-command is given in Table 8. This comparison highlights that the productivity of all major crops (i.e., Wheat, Gram, and Red Gram) was higher in the command area. This indicates the positive impact of an irrigation project on agricultural system and economic system of the farmers of the command area.

8.   Yield Per Unit Water

To evaluate the physical and economic performance of the irrigation system the crop yield per unit water consumed by crop (tons per cubic meter) was calculated for all the major crops in all the distributaries. This term does not indicate whether the irrigation supply was efficient or inefficient. To assess the efficiency of water use along with yield per unit water, the Delta of each division was also calculated and depicted in Table 9. Delta is the total depth of irrigation to crops in centimeters (Michael 1978). In India Warabandi (Turn Fixation) system is followed for distribution of canal water, wherein, the water is distributed to each farmer in accordance with the landholding of the farmer in the ICA. The type of crop grown in the land is not considered as the criteria for fixing the irrigation turn (irrigation period) of the

Table 7 Water supply schedule of right bank main canal and left bank main canal

RBMC				LBMC			
From	To	Canal supply status	Days	From	To	Canal supply status	Days
12/11/2007	16/11/2007	Off		10/11/2007	14/11/2007	Off	
17/11/2007	2/12/2007	On	16	15/11/2007	30/11/2007	On	16
3/12/2007	7/12/2007	Off		1/12/2007	5/12/2007	Off	
8/12/2007	20/12/2007	On	13	6/12/2007	19/12/2007	On	14
21/12/2007	25/12/2007	Off		20/12/2007	24/12/2007	Off	
26/12/2007	7/1/2008	On	13	25/12/2007	6/1/2008	On	13
8/1/2008	12/1/2008	Off		7/1/2008	11/1/2008	Off	
13/1/2008	25/01/2008	On	13	12/1/2008	24/01/2008	On	13
26/01/2008	30/01/2008	Off		25/01/2008	29/01/2008	Off	
31/01/2008	12/2/2008	On	13	30/01/2008	11/2/2008	On	13
13/02/2008	17/02/2008	Off		12/2/2008	16/02/2008	Off	
18/02/2008	29/02/2008	On	12	17/02/2008	29/02/2008	On	13
1/3/2008	6/3/2008	Off		1/3/2008	6/3/2008	Off	
7/3/2008	15/03/2008	On	9	7/3/2008	15/03/2008	On	9
Total			89	Total			91

Table 8 Productivity of major crops in command area and surrounding non-command area

Crop	Productivity (t/ha)	
	In command	In non-command
Wheat	3	1.89
Gram	1.5	1.057
Red gram	1.8	1.07

farmer. So, the Delta value calculated for each division will remain constant/same for every crop grown in the sub-command of that division. The Delta of each division shown in Table 9 is considered as the delta of each crop grown in the division. Higher Delta values in the first three divisions (i.e., Divisions 1–3) indicated the excess water availability or water wastage in these divisions compared to the rest of the divisions. Relatively small values of yield per unit of water in Division-4 and Division-5 with minimum values of Delta indicate that the inadequate water supply in these divisions, which is also being supported by results of RWS, DF, RIS,

and IE. This inadequate supply of irrigation water resulted in a reduction of yield level in these divisions, as evident from Table 9. The high values of yield per unit of water in Division-6 and relatively less value of Delta indicate the adequate water supply and efficient water utilization in this division which is also supported by values of IE, IR, and RIS.

Overall combined analysis of all the performance indicators unanimously indicates that Division-6 was the best performing division out of all the divisions under the Upper Wardha Project. Divisions 1, 2, and 3 were the divisions where excess water was used which brings down the overall efficiency of the entire project as well. On the other hand, Division-4 and Division-5 had better water distribution performance; however, the overall performance of these divisions was poor due to inadequacy of water supply.

Summary and Conclusions

In the present study, an attempt was made to showcase the applicability of remote sensing and GIS in mapping, parameter estimation, and evaluation of the performance of an irrigation project at a disaggregated level. The high-

Table 9 Yield per unit ET_a and delta of each crop in command area

Crop	Yield per unit ET_a (t/m^3)					
	Division 1	Division 2	Division 3	Division 4	Division 5	Division 6
Wheat	0.82	0.81	0.82	0.77	0.75	0.91
Gram	0.58	0.63	0.63	0.65	0.58	0.46
Red gram	1.51	1.38	1.35	–	–	1.38
Delta (cm)	10.537	7.861	70.499	3.817	4.695	5.978

resolution Cartosat-1 and LISS-IV MX data along with canal index maps were used to generate irrigation infrastructure database and other base layers of the Upper Wardha command. The temporal LISS-III data was used to generate the land use land cover map with the main emphasis of mapping acreage of major crops grown in *Rabi* season of the year 2007–2008. Monthly vegetation index maps (NDVI) were used to generate spatially distributed crop coefficient (Kc) maps, using which the actual evapotranspiration was estimated at a pixel level. The canal water supply data along with other field-collected data were used to estimate eight indicators to assess the performance of the Upper Wardha irrigation project at the division level.

The values of RWS, DF, RIS, IE, and IR indicate that water was supplied in excess in three out of the six divisions (Division-1, Division-2 and Division-3) and two divisions (Division-4 and Division-5) were receiving less than actual demand. Though the results of RWS indicate probable inadequate supply in Division-6, however, after a comprehensive analysis of results of RIS, DF, IR, IE, and yield per unit water and Delta, it can be concluded that Division-6 receives adequate water and utilizes it efficiently. This example strengthens the claim that a single performance indicator may mislead the evaluator. The combined analysis of different performance indicators, complementary and/or supplementary to each other in their type, yields a concrete assessment of the performance of the irrigation system.

Analysis of the water supply schedule of the Upper Wardha project indicates that there was a timely and reliable supply of water in the canal command. The highest value of RWS and RIS, the lowest value of IE and IR in Division-1 indicates that excess water was supplied/used in this division and this sub-system (division) fails to distribute it to all the stakeholders within its command area. This has brought down the irrigation efficiency and water productivity of this sub-system. The analysis of agricultural productivity reveals that the irrigation project definitely has a positive impact on the agricultural system and socioeconomic system of the command area with an around twofold increase in agricultural productivity as compared to the non-command area. The values of yield per unit water used for each crop were almost similar in all the divisions, however, Delta of each crop indicates excessive water usage in Division-1, Division-2, and Division-3. The high value of IE and IR along with the high value of yield per unit water used and the low value of Delta in Division-6 compared to other divisions getting adequate supply makes this division the best performing division among all under consideration.

It is noteworthy, that even with inadequate supply in Division-4 and Division-5 the irrigation distribution among the stakeholders was better in these divisions compared to all other divisions. However, due to inadequate supply in Divisions-4 and 5, the yield per unit water used was reduced, indicating unplanned deficit irrigation resulting in water stress conditions of agriculture crops. Based on a comprehensive analysis of all the performance indicators the need of modifying the existing operational schedule/police of the Upper Wardha irrigation project, to improve the overall performance of the project, can be confirmed. The modification should be done at the finest possible level (divisional level) to simultaneously improve the performance of all sub-systems, otherwise, change in operation schedule at the project level may adversely affect the existing efficient sub-systems like Division-6.

The integration of geo-spatial techniques (remote sensing and GIS) helps in estimating the irrigation water requirement and performance indicators in a spatially distributed and efficient manner. The geo-spatial approach makes the performance evaluation process less dependent on field data and also less time consuming than the traditional approach. The irrigation authorities can use these performance indicators as feedback to improve the performance of the irrigation system.

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