

SATELLITE REMOTE SENSING AND GIS TECHNOLOGIES TO AID SUSTAINABLE MANAGEMENT OF INDIAN IRRIGATION SYSTEMS

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ABSTRACT

Increasing concern in recent years in India is on the issue of long-term prospects of irrigation and the consequences of continuing current water management practices on the sustainability of irrigation systems which have been created with huge financial investments. The selective studies mentioned in this paper describe the application of advanced technologies namely Remote Sensing and Geographic Information System, which has been demonstrated recently, in many irrigation systems in India to address the various issues relevant to sustainable management of irrigation systems. The primary agricultural information at disaggregated level derived from the analysis of high resolution satellite data has formed the basic input in all these studies. A set of indicators of agricultural situation over time and space were derived exclusively from satellite data analysis and validated at grass root level irrigation units in Bhakra irrigation system, Haryana state. Indicators of irrigation system performance such as irrigation intensity, principal crop intensity, equity in water distribution and agricultural production per unit volume of water were developed and applied in Bhadra command area, Karnataka state. Thus, the geo information derived from remote sensing and data analysis tools like GIS provide excellent opportunities to measure the spatio-temporal changes in land and water productivity and to achieve sustainable management of irrigation systems. The demonstrated capabilities would hopefully lead to more wide spread and operational use of these advanced technologies in India and elsewhere, in the world.

1 INTRODUCTION

Development of irrigation in India has been driven by the overriding compulsion of providing food grains for a large growing population. Massive financial investments were made in irrigation sector during the last five decades. As a result, the irrigation potential created has gone up to 91.8 million hectares by 1997 from 22.6 million hectares in 1951. During this period, the food grain production has risen to 198 million tonnes from 51 million tonnes and the country has achieved food security. The large scale capital investments for irrigation development along with green revolution in agriculture has resulted in nearly quadrupling of food grains production over a period of last five decades in India. However, during the process of harnessing the resources certain inequalities/ imbalances/ anomalies have occurred and hence the sustainability of present day irrigated agriculture has become doubtful. It would be almost impossible to increase the present level of food grain production to meet the future requirement of 450 million tonnes by the year 2050, without substantially increasing the irrigated area and managing it for sustainable optimal productivity. The achievement of sustainable management of irrigation systems reinforces and extends the main principles of land and water management and the crux of the problem in this direction is how best we can put these principles in practice. Evaluation of the performance of the irrigation system in its existing form at different spatial and temporal scales and under different hydrological/ agricultural conditions is crucial for designing and implementation of any plans to achieve sustainable management of irrigation systems. Non-availability of objective data on agricultural situation in irrigated command areas at desired spatial level is today's major problem for performance evaluation of the irrigation systems. In the last few years, various studies have demonstrated the usefulness of satellite remote sensing data for generating the information on total irrigated area and area under different crops (John et. al 1978, Kolm 1984, Nageswara Rao and Mohan Kumar, 1994), condition of crops (Williamson, 1989, Daniel, 1989, Stone, et.al, 1994) and crop production (Pinter 1981, Hatfield 1983, Murthy et.al, 1996). The capabilities of emerging technologies like satellite remote sensing and Geographic Information System (GIS), for generation and analysis of objective information across space and time to achieve realistic evaluation of the agricultural situation and irrigation performance of canal irrigation systems are demonstrated in this paper.

2 PERFORMANCE INDICATORS OF IRRIGATION SYSTEMS

Sustainable development is the development that meets the needs of the present without compromising the abilities of future generation to meet their own needs. Although the attention of irrigation engineers is currently captured by sustainability it is less elaborated on its meaning and what it stands for (Agarwal and Roest, 1996). The performance of irrigation system is a very complex aspect and a variety of indicators have been developed/proposed by various researchers (Rao, P.S. 1993, Seckler et al 1988, Bos and Nugteren 1990, Azzali and Menneti 1989). The indicators of sustainability have been defined as relative crop transpiration, degree of moisture saturation, annual change in soil water storage, soil moisture, salt concentration and its fluctuations followed by acceptable crop productivity (Agarwal and Roest, 1996). The indicators of agricultural performance include cropping intensity, cropping pattern and crop productivity. Rao, P. S., 1993, has broadly categorised the irrigation system performance into four sub-systems namely (1) water sub-system, (2) human sub-system, (3) economic sub-system and (4) environmental system. In water sub-system, three water based performance indicators are selected that can help rate the success in achieving crop production objective. They are productivity, equity and efficiency. Productivity performance is assessed by (a) area utilisation-defined by the ratio of the harvested and theoretically serviceable area i.e. culturable command area, (b) yield potential-absolute yield as well as relative yield, (c) irrigation water output-productivity per unit of water. Equity achievement is described by production distribution, flow distribution and production and flow distribution. Under human system, the indicators are response capacity of farmers and farmers' satisfaction. Environmental sub-system uses impact on environment in terms of water logging, soil toxicities and irrigation water quality as indicators. The economic sub-system emphasises the economic stability in the short and long run periods.

3 AGRICULTURAL PERFORMANCE OF WATER COURSES IN BHAKRA IRRIGATION SYSTEM

In this study, multi spectral and multi temporal data data from Landsat and IRS satellites were analysed for the rabi seasons (October - April) of five years namely 1986-87, 1989-90, 1992-93, 1995-96 and 1996-97. A set of indicators of the agriculture performance in the command area of water courses were derived from satellite data analysis and applied to evaluate the spatio-temporal changes as well as the sustainability in the agricultural performance. The Bhakra irrigation system has a culturable command area of 1.2 m ha, with five water service circles namely, Ambala, Kaithal, Hisar-1, Hisar-2 and Sirsa which are in turn divided into 13 divisions and 41 sub-divisions. Water course is the ultimate irrigation unit in the system and normally serves an area of about 400 ha. The index map of the Bhakra irrigation system and the water courses selected for the study are shown in figure 1. During rabi season wheat is predominantly cultivated followed by toria, mustard and bengal gram.

3.1 Data analysis

Geo referenced data base was first created in polyconic projection with a pixel resolution of 30 metres using Survey of India topographic maps of 1:50000 scale. The digital data of each satellite overpass was first converted into radiance and then registered into reference map base. The water course maps which were in the scale of 1:6000, were first registered to the panchromatic data of IRS-1C of 6 metres resolution, and then registered to the main database of 30 metres resolution. This facilitated more accurate registration of water course maps by minimising the gap between pre and post registration gross areas. Maximum likelihood classification was performed on the data of December and February/March to achieve classification of wheat and non-wheat crops. Kappa coefficient was calculated for overall classes as well as for individual classes. The evaluation was done at two levels, one at total scene level and the other at water course level. Due to time and logistic constraints it was not possible to carry out evaluation in each water course. Hence, two water courses were randomly selected. In the evaluation at total scene level, 20 points for wheat and 10 points for non-wheat were selected at random. At water course level 15-20 points for wheat and about 10 points for non-wheat were randomly selected. The Kappa coefficient of accuracy for overall accuracy as well as for individual classes was found to be above 90 %.

3.2 Agricultural performance of water courses

The agricultural performance of water courses can be explained by cropping intensity and crop condition across time and space. The differential performance of water courses in a given area can be attributed to various factors such as (1) irrigation related and (2) others. Some of the irrigation related factors include the location of water course in the respective source/parent canal, factors related to lining of water courses such as age of lining and extent of lining. Lining of watercourses in Haryana state has been going on since 1973. The purpose of lining is simply to reduce seepage losses and hence to improve the equity in water supply by increasing deliveries to tail-end users. The non-irrigation factors affecting

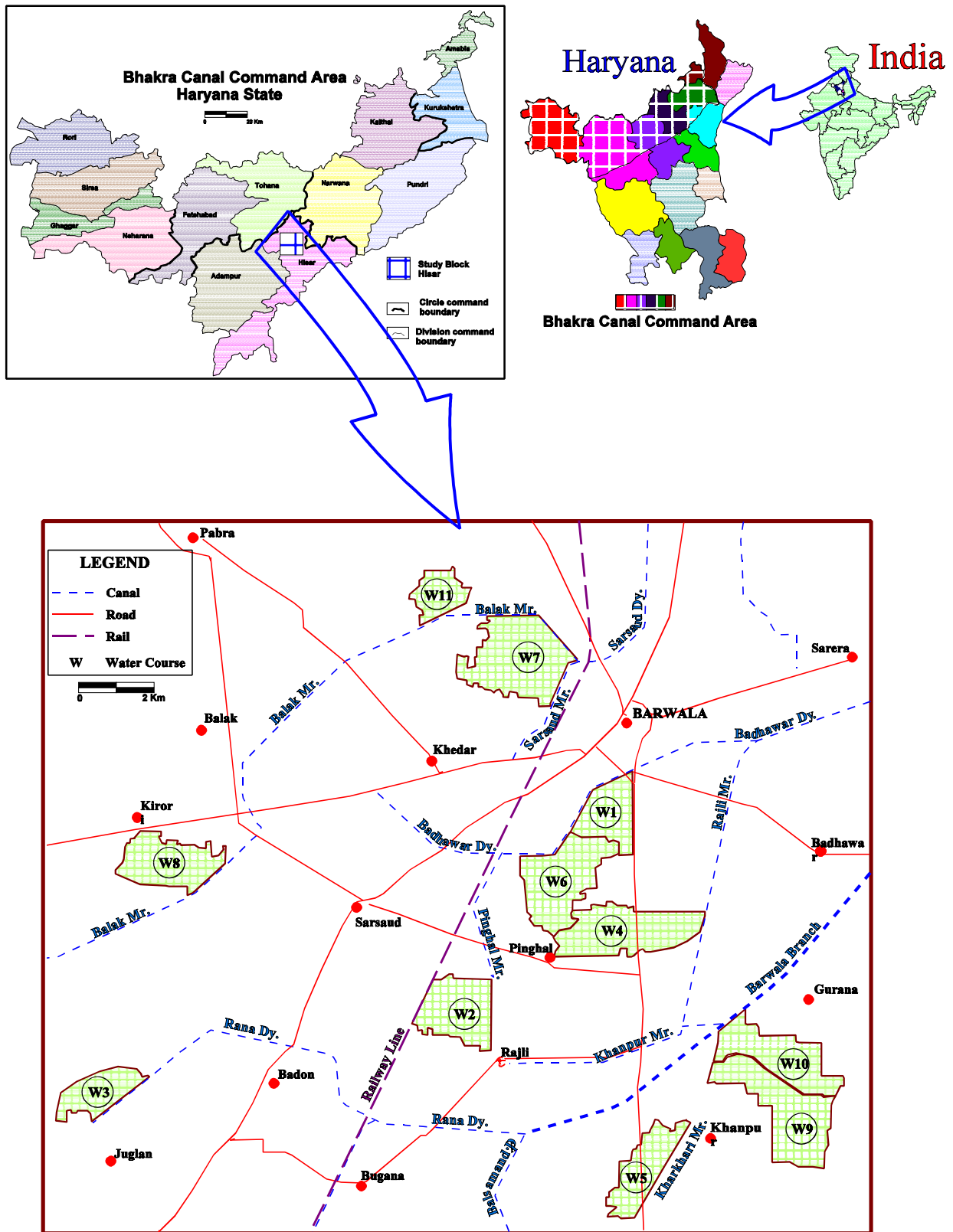


Figure 1. Index map and location of water courses selected for the study

the performance are soil type, ground water quality, agronomic practices, crop varieties etc., can be assumed to be more or less homogeneous over smaller areas such as in the current study. Therefore, only the irrigation related parameters were considered. Three irrigation related factors identified for further analysis were (1) Location of water courses in the parent

canal (2) Age of lining of water course (3) Extent of lining i.e., per cent of lined area of water course. The location of water course in the parent canal will be in “Head Reach Area (HRA)”, if the water course off takes from the first 1/3 rd length of the parent canal. Similarly, if the water course off takes from the last 1/3 rd length of the parent canal, it is called “Tail Reach Area (TRA)” and lastly, it is called “Mid Reach Area (MRA)”, if it off takes from the middle 1/3 rd length of the parent canal. The water courses located in the HRA of parent canal perform better than that located in the TRA of parent canal due to better water availability. As the age of lining increases, the performance gets deteriorated. The water courses which were lined to a greater extent perform better than those lined to a lesser extent i.e., the per cent of lining and performance are directly related. The performance of water courses in the post-lining period is significantly better than that in the pre-lining period.

3.3 Satellite derived indicators of agricultural performance

In the current study, five indicators of performance were developed. These indicators were derived for remote sensing data. They are (1) Wheat crop Intensity (WI), (2) Equivalent Wheat crop Area Intensity (EWAI), (3) Sustainability in crop intensity, (4) Tail - Head Ratio of NDVI (THR_{NDVI}), and (5) Coefficient of variation of NDVI (CV_{NDVI}). The first three indicators are crop area based and the last two are crop condition based.

3.3.1 Wheat crop Intensity

Wheat is the most preferred crop in the study area. Subject to the availability of sufficient irrigation water, farmers generally prefer wheat crop to non-wheat crop. Hence the extent of wheat crop is directly related to the degree of

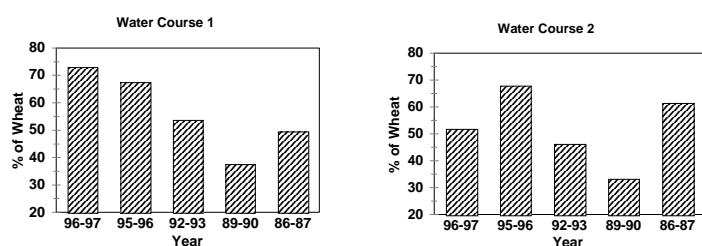


Figure 2. Typical trends in wheat intensity in two water courses

availability of irrigation water. The typical trends in wheat intensity in two of the water courses are shown in figure 2. It was observed that the intensity of wheat crop was influenced by the location of water courses in the respective parent canal. Water courses off taking from the head reach areas have increasing wheat intensity over time while water courses in tail reach area have declining wheat intensity. Water courses which were lined recently i.e., after 1992 have shown significant improvement in wheat intensity in the post-lining periods. In the water courses which were lined in 1975-76, there was no clear relation between wheat intensity and age/extent of lining.

However, in this group, location of water courses seems to be an important factor i.e., water courses located in the head reach area of respective distributary / minor have higher wheat intensity.

3.3.2 Equivalent Wheat crop Area Intensity

EWAI is the index which expresses the total crop area in terms of wheat crop area to facilitate easy and straight forward comparison of cropping intensity and irrigation water consumption. The non-wheat crops acreage was converted into wheat with the factor 1 acre of non wheat = 0.6 acre of wheat, which is approximately proportional to the ratio of their average irrigation water requirements. In the current study, EWAI was found to be influenced by the location of water courses with head reach area water courses having more crop area and tail reach area water courses having less area. In the water courses having same age of lining but different length of lining, the EWAI is more in water courses though the length of lining is less because of its location in HRA. Thus the factor of location of water course looks to be having more influence than extent of lining. The EWAI was more in an unlined water course located in head region than lined water courses located elsewhere.

3.3.3 Sustainability in crop intensity

The coefficient of variation (CV) in crop intensity during 1986-87 to 1996-97 reflected the sustenance in irrigated agriculture. Temporal changes in crop intensity could be attributed to changes in water availability. High values of CV signify inconsistent/deteriorating performance. The values of CV at water course level as well as at head and tail reaches within water courses for the water courses which were lined before 1986 are presented in table 1. The CV values up to 10 percent may be considered insignificant.

Table 1 Coefficient of variation in crop intensity

Water course no.	Total water course	Head Reach	Tail Reach
1	12	15	15
2	9	10	13
3	18	17	19
4	10	10	16
5	17	12	27
6	10	9	18

3.3.4 Tail-Head Ratio of NDVI

Normalized Difference Vegetation Index (NDVI) which is a mathematical combination of the reflectance values of near infrared and red bands of electromagnetic spectrum is found to be a potential indicator of density and health of vegetation. THR_{NDVI} of a water course is the ratio between the Tail Reach Area NDVI and Head Reach Area NDVI of the water course. The observed deviations of NDVI from head to tail reaches can be attributed to disparities in water distribution since the other factors contributing to crop condition such as soil characteristics, plant varieties, agronomic practices, meteorological parameters could be assumed to be uniform at micro level i.e., at water course level. THR_{NDVI} values, close to

one, indicate better performance of water courses with less disparities in crop condition between Tail and Head regions. In the present study area, the disparities between Tail and Head regions of water courses were in general not significant as indicated by the THR_{NDVI} values closer to 1. Location of water course in the parent canal and age of lining and extent of lining did not have any impact on crop condition disparities in Tail and Head regions.

3.3.5 NDVI variability in Tail and Head Regions

NDVI variability expressed as coefficient of variation reflects the variability in crop condition in a given area. High variability may be due to the differences in the resources available to crop such as soil, meteorological factors, agronomic practices, water etc. The NDVI variability can also be attributed to some extent to the degree of water availability. It is a common phenomenon happening in Indian irrigation systems that the tail reach farmers suffer from insufficient canal water supplies. In the present study area, the CV_{NDVI} was more or less same in both head and tail regions. The CV_{NDVI} has decreased significantly over time from 1987. The CV_{NDVI} values were mostly around 0.1 i.e., 10 per cent in all the water courses.

4 IRRIGATION SYSTEM PERFORMANCE ASSESSMENT IN BHADRA IRRIGATION SYSTEM

The Bhadra irrigation system has a command area of about 100,000 ha under Right Bank Canal served by 128 distributaries in the three canal divisions of Bhadravathi, Malebennur and Davangere. During the rabi (post-monsoon) season, rice is a dominant crop followed by sugarcane, irrigated dry crops and garden crops. There is no significant rainfall in the rabi season. Remote sensing inventory involved the analysis of 1986-87, 1988-89, 1989-90, 1992-93, 1993-94 and 1994-95 rabi seasons satellite data for generating primary data on agricultural situation, for evaluating improvement in system performance through the years, and to diagnose problem pockets within the command area. Multi date satellite data during each rabi season were used to classify rice, dry foot crops and garden crops. Rice areas could be classified with an accuracy of more than 92 per cent, while the overall classification accuracy is 90 per cent. The actual cropping pattern derived from satellite data differed significantly from planned/recommended pattern. The crop area has increased by 21724 ha and moreover it is dominated by high water consuming crops like paddy. The spatial variability in paddy intensity among the distributaries indicate that in most of the distributaries paddy is predominant. As a result, the water supply rate recommended in the plan was not sufficient to the real cropping pattern. In the absence of supplementary source of irrigation, the situation leads to unbalanced water supply which would be reflected through productivity. The satellite inventory also involved many methodological improvements in regard to spatial mapping of staggered rice transplantation, spectral modeling of rice yield and improved statistical design for ground sampling of rice yield, use of GIS and radiometric normalization of multi satellite-sensor-date data. The rice yield prediction model based on 1992-93 rabi harvested rice yield in sample plots and the corresponding satellite derived vegetation index, has been validated with farmer enquiries (Murthy et al. 1995). The spatial variability in rice transplantation period was taken care off by time compositing of satellite data over the appropriate calendar period before use in rice yield model.

4.1 Indicators of irrigation system performance

The satellite derived agricultural information along with relevant ground data was used to compute the irrigation system performance parameters as shown in table 2. The spatial and temporal analysis of disaggregated statistics indicated that overall irrigation intensity had increased by 15 per cent, paddy area by 13 per cent and paddy productivity by 26 per cent between 1986-87 and 1994-95 rabi seasons. The increase in paddy productivity was seen all over the command area. Paddy

output per unit of water was computed based on proportionate allocation of canal supplies to paddy areas and satellite derived paddy production. This performance indicator showed increasing efficiency of water use for paddy production. The satellite data analysis had facilitated the identification of canals with poor performance in respect of irrigation intensity, paddy yield and water use efficiency.

Table 2 System performance of Bhadra project through the years

Parameters	Rabi season			
	1986-87	1989-90	1992-93	1993-94
Irrigated crop area (ha)	73,529	67,366	88,424	84,412
Percentage of paddy area	56	51	69	69
Average paddy (rough paddy) yield (tonnes/ha)	3.8	5.4	4.7	4.9
Depth of water application (m/ha)	1.06	1.04	0.80	0.86
Area irrigated per unit volume of water (ha/ham)	0.94	0.96	1.25	1.16
Paddy (rough paddy) output per unit of land (tonnes/ha)	3.8	5.4	4.7	4.9
Paddy (rough paddy) output per unit volume of water (tonnes/m ³)	0.3	0.4	0.5	0.5

4.2 Chronological synchronization between crop calendar and water delivery

An ideal irrigation system should meet the water requirements all crops in its command during all the physiological stages. The existing water discharge pattern is compared with crop calendar derived from satellite data. Here the emphasis is on the chronology of canal operation but not on the volume of water supplied. Multi date NDVI statistics over paddy area was generated for each distributary. The satellite over passes represent in general broad spectrum of paddy growth cycle from panicle initiation to grain formation. Analysis of NDVI profiles of various distributaries revealed three distinct growth patterns of paddy crop. Murthy et al, (1998) interpreted these growth profiles with the aid of ground truth and derived the crop calendar information for each profile indicating the estimated time of transplantation and crop harvest for paddy crop corresponding to each NDVI profile. Consequently, the distributaries of the command area were grouped in to three categories namely early transplantation (first fortnight of February), normal transplantation (second fortnight of February) and late transplantation (first fortnight of March). The spatial variability in canal opening and closure is derived from ground data and was compared with satellite derived crop calendar. This analysis which was done in GIS environment, had resulted in the identification of 21 distributaries in two categories. The first category of distributaries has a lag of 30 days and the second category has a lag of 20-30 days between canal closure i.e., cessation of water supply and crop harvesting (figure 3). The time lag between canal closure and harvesting could be explained in relation to paddy growth cycle and water requirements in various stages to infer the implications. About 4-7 days prior to maturity, water is let out completely, to facilitate harvesting. Therefore, in the first category distributaries, the effective duration water shortage for crop is 16 days assuming that one week before harvest no water is needed and the fields continue to get water for one week after canal closure. During this period the crop would be in grain formation stage which may result in yield reduction subsequently. In the second category of

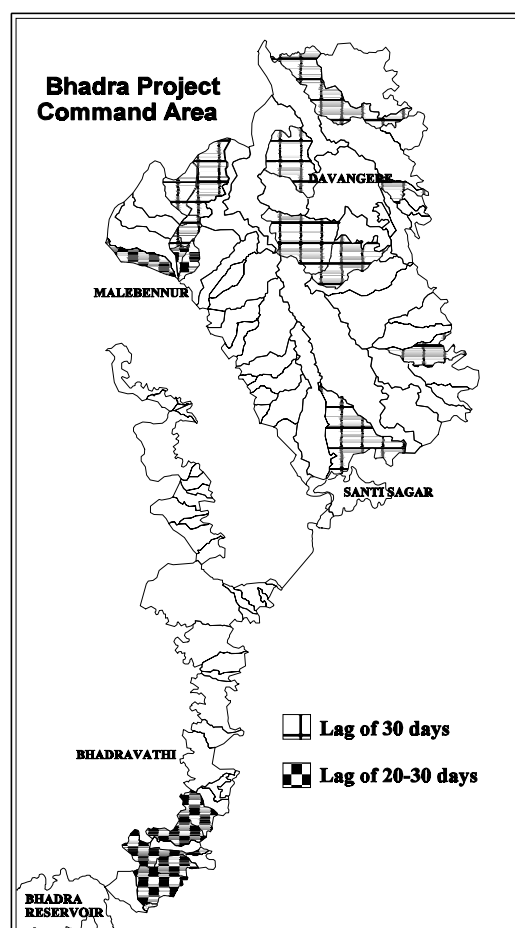


Figure 3 Time lag between cessation of water supply and crop harvest

distributaries with a lag of 20-25 days the effective water shortage is for 6-11 days during grain formation stage.

5 CONCLUSIONS

Emerging technologies like Satellite remote sensing can be successfully utilised for deriving the spatial and temporal agricultural information in irrigated command areas. Such information which is generally not collected and maintained in any organised fashion in the conventional mechanisms is very useful for developing performance indicators of irrigation system. Indicators revealing the spatial and temporal trends in agricultural situation in the irrigation system command area can be derived exclusively from remote sensing data analysis. Organising the satellite derived spatial data and ground observations /measurements and non-spatial attribute data, in a GIS environment, would be highly desirable to facilitate analysis of irrigation performance and also for effective use of irrigation management models towards achieving the sustainable management of irrigation systems.

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