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Research Report

Satellite Remote Sensing for Assessment of Irrigation System Performance: A Case Study in India

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and
R. Sakthivadivel

International Irrigation Management Institute

Research Reports

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Summary

The use of advanced technology tools such as satellite remote sensing, geographic information system (GIS) techniques, and hydrologic modeling can greatly help improve irrigation management. The International Irrigation Management Institute is planning a long-term program for developing a package of these tools to aid irrigation management at the policy, strategic, and tactical levels. This case study in the Bhadra Project in India is an attempt in this direction. It focuses on the application of satellite remote sensing and GIS techniques in a rice irrigation system. Multiyear satellite data have been analyzed to provide spatially distributed information on irrigated area, cropping pattern, and rice yield. This spatial and temporal information has helped analysts evaluate the performance of the agricultural system over several years and across the irrigation scheme. The data have confirmed that changes initiated by the National Water Management Project have resulted in significant improvements as indicated by extent of irrigation and changes in agricultural productivity. In addition, problem distributaries that have subpar irrigation intensity, rice productivity, and equity have been identified for follow-up action to improve performance.

The case study has resulted in a methodology package for use in other irrigated rice environments. The cost of satellite remote sensing application in this 100,000-hectare irrigation scheme works out to US$0.10/ha per irrigation season at 1994-95 price levels. The cost would decrease to US$0.03/ha or less for schemes larger than 250,000 hectares. Improving the methodology will require the development of a vegetation index that is optimally sensitive to rice characteristics and better spectral modeling of rice yield. Extension to irrigation schemes in which crops other than rice predominate will require modifications in the methodology.

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Introduction

It is estimated that half to two-thirds of the increases in food production needed in the future will have to come from irrigated lands, which are currently contributing about 40 percent of the world's food requirement (Serageldin 1995). The global irrigation scenario, however, is characterized by poor performance, increased demand for higher agricultural productivity, decreased availability of water for agriculture, increasing soil salinity, possible effects of global climate change, and the changing public-sector role. A major challenge is to sustain or increase the yield of irrigated agriculture while reducing water consumption (Lenton 1992). Improved irrigation management and informed decision making call for the adoption of new tools such as satellite remote sensing and geographic information systems to provide the necessary spatial and temporal information on different subsystems and for different user groups (Thiruvengadachari 1996). The logistic requirements of remote-sensing applications for agricultural management have been discussed by Steven (1993).

Performance assessment is considered the most critical element for improving irrigation management (Abernethy and Pearce 1987). Irrigation performance indicators range from water distribution to agricultural, economic, social, and environmental aspects (Bos et al. 1994). Though remote sensing was identified as a tool for assessing performance more than a decade ago (Abernethy and Pearce 1987), it has been applied infrequently. Early applications focused on mapping irrigated crop lands (Huston and Titus 1975; Draeger 1976; Wall 1979; Thiruvengadachari 1981). Mapping has continued in recent years with increased capabilities for inventorying irrigated area from different irrigation sources, such as surface water, groundwater, and irrigation tanks (Thiruvengadachari 1983), for discriminating crop species and assessing crop stress (Azzali and Menenti 1989), and for monitoring temporal changes in irrigated area (Rao and Mohankumar 1994). Another application uses actual evapotranspiration and evaporative fraction maps derived from high resolution Thematic Mapper data for assessing the performance of an irrigation system at various hierarchical scales (Bastiaanssen, Van Der Wal, and Visser 1996). The same approach can also be applied with low-resolution data, offering possibilities for concurrently monitoring several irrigation schemes within a region. The availability of evaporation data and records of water flow allows computation of classical inflow-outflow efficiencies.

This study of the Bhadra Project in India is perhaps the first to use a package of satellite remote-sensing applications to develop agricultural system performance indicators for an irrigation system. In the study, several years of satellite data for the Bhadra

Project were used to develop a disaggregated inventory for irrigated area and cropping patterns and to estimate the yield of a major crop, rice.

A diagnostic analysis of selected poorly performing pockets of the command area complemented the performance assessment. The study involved the application of known procedures in an operational context as well as the extension and improvement of these techniques to address field complexities. Initial development efforts were funded by the Irrigation Department of the Government of Karnataka, but subsequent analysis, which included many innovations, was supported by IIMI. IIMI has drawn up a long-term program to develop a package of tools for sustainable basin-wide water resources development, and the current study marks a substantial step in this direction.

Although the package of satellite remote sensing applications has been developed in a rice-based irrigation system, a similar approach with suitable modifications could be developed for irrigation systems involving other crops. The results warrant more widespread use of this exciting new technology in system performance assessment and diagnostic analysis.

The Bhadra Project and the National Water Management Project

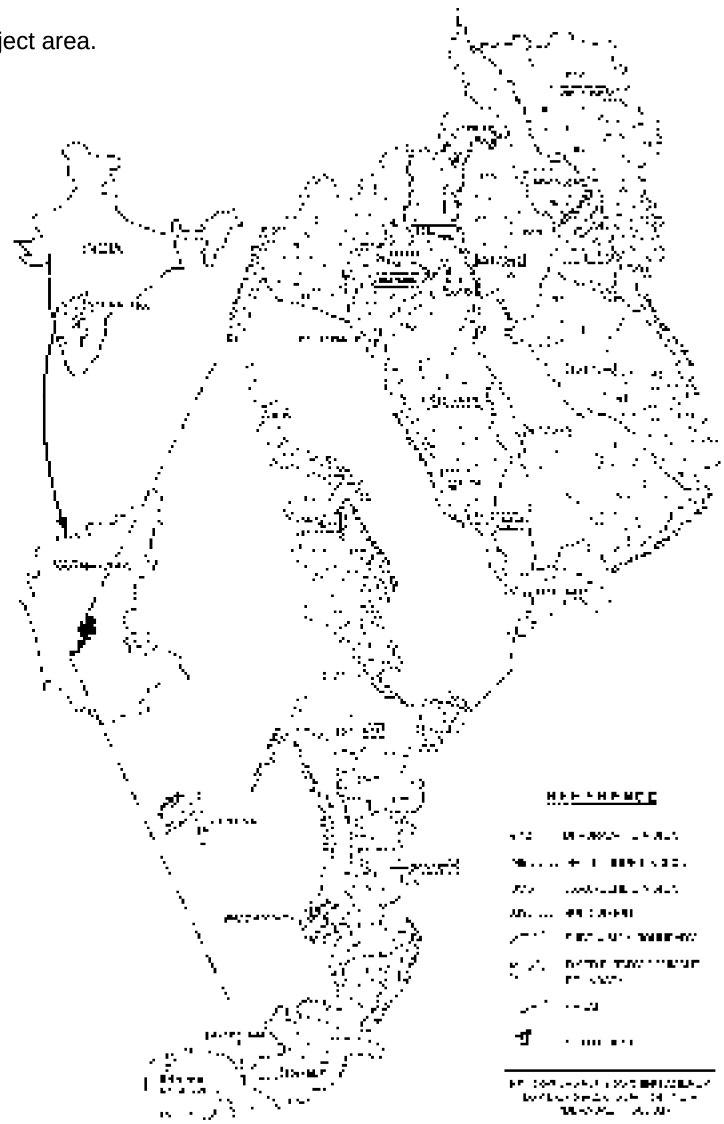
The Bhadra Project was the first irrigation scheme to be taken up by the National Water Management Project (NWMP), which was established to raise agricultural productivity and farm income by providing more equitable, predictable, and reliable irrigation service. NWMP is a major initiative to improve irrigation management in selected irrigation schemes in various states of India with World Bank assistance. The project is intended to help the participating states and the Government of India to develop the institutional capacity to plan, implement, and monitor improved operational and maintenance practices that would provide low-cost infrastructural improvements designed to support an improved operational plan in selected schemes.

Located on the Bhadra River in the State of Karnataka, the Bhadra Project comprises a dam with a gross storage capacity of 2,025 million cubic meters, a left bank canal serving 8,290 hectares, and a right bank canal serving 92,360 hectares. The NWMP activities were directed at the area served by the Right Bank Canal.

The Bhadra dam is situated 50 kilometers upstream of the point where the Bhadra River joins the Tunga River to form the Tungabhadra, a tributary of the Krishna River, and intercepts a catchment of almost 2,000 square kilometers. The Bhadra reservoir is indicated at the bottom of map 1; the canal flows along the right-hand side of the command area while the Bhadra River flows along the left-hand side of the command area. On this map, the tail reaches extend from bottom to top and from right to left. The Bhadra basin gets rainfall during both the southwest and northwest monsoon seasons, but about 80 percent of the stream flow is generated during the southwest monsoon period. Based on a 25-year record, the average annual precipitation is 827 millimeters, and the mean annual evapotranspiration has been estimated as 1,678 millimeters. The command has 60 percent well-drained red soils and 40 percent poorly drained black soils.

Components of the Bhadra Project were constructed between 1948 and 1966. The

MAP 1.
The Bhadra Project area.



Source: IIMI 1995.

project was designed to have rice occupy about 40 percent of its command area and other crops the remainder, with an overall annual cropping intensity of 200 percent. But as agricultural development progressed, rice became the predominant crop, covering about 56 percent of the area under the Right Bank Canal. The heavy plantings of rice led farmers to draw too much water, which interfered with irrigation managers' plans for equitable distribution of the irrigation water. Also because of the rice farmers' copious use of water, the canals flowed full, infringing on the freeboard and causing damage to the canal system. These problems not only threatened the physical collapse of the system but also provoked dissatisfaction among farmers in tail-end areas. The objective of the NWMP in the Bhadra Project was to restore the physical structure of the system under the Right Bank Canal and to develop and implement an appropriate water distribution policy. The NWMP work in the scheme was carried out between 1988 and 1994.

Satellite Data Collection

To monitor irrigated area, cropping pattern, and rice yield during the *rabi* (post-monsoon) seasons from 1986-87 to 1993-94,[1] high resolution data from Landsat-5 and Indian remote-sensing satellites (IRS-1A and IRS-1B) were used. Satellite data were directly received at the Indian Earth Station at Shadnagar about 60 kilometers from Hyderabad and processed at the National Remote Sensing Agency facilities in Hyderabad.

Data from the Landsat Multispectral Scanner (MSS) (80 m ground resolution), the Landsat Thematic Mapper (TM) (30 m resolution), and the IRS Linear Imaging Self-Scanning Sensor (LISS I) (72.5 m resolution) were analyzed (see annex for orbital and sensor characteristics of remote sensing satellites). At the time of the study, India had not yet launched the satellites IRS-1C and IRS-P3. Hence, the data from Wide Field Sensor (WiFS) of 188 meters resolution and 5-days revisit capability were simulated from LISS I data and evaluated.

To maintain consistency in the results generated through the years, MSS and LISS I data, which have a similar spatial resolutions, were selected for analysis. A preliminary analysis of a sample area with both LISS I and LISS II data showed that acceptable crop classification accuracy could be achieved even with LISS I. This finding significantly reduced the cost of acquiring satellite data and carrying out analysis because each LISS I scene covers an area equal to the area of four LISS II scenes.

[1]Out of the eight rabi seasons from 1986-87 to 1993-94, six seasons of satellite data were analyzed for this study: 1986-87 is the season before implementation of the National Water Management Project; 1987-88 to 1988-89 is the period of NWMP implementation; 1989-90 is the season after NWMP implementation in which only 75% of the command area was irrigated; and 1992-93 and 1993-94 are seasons in which the full command area was irrigated.

Overview of Data Analysis

The analysis of satellite data involved:

- mapping irrigated crop areas and discriminating rice from other crop areas
- mapping spatial variability of the rice transplanting period across the command area
- estimating rice yield through spectral index yield models
- measuring yields from satellite-derived data on the condition of the rice crop, using an improved design for selecting representative sample areas
- evaluating the impact of reported waterlogging on rice productivity
- radiometric normalization between satellites, sensors, and acquisition periods
- comparative evaluation of satellite data of different spatial resolution
- integrating cadastral maps with satellite data

To evaluate the system performance and to diagnose and analyze the poorly performing distributaries, a geographic information system (GIS) was developed at two levels of the command area and for selected distributaries.

Crop classification

Approaches selected for classifying crops in earlier studies have been dependent on the context, with no single classifier having universal applicability. In Sweden, Hall-Konyves (1990) used the maximum likelihood algorithm to discriminate important agricultural crops, while in southeastern Italy, Ehrlich et al. (1994) attempted optimal crop type determination in four crops—maize, soybean, sugar beet, and small grains—with a sequential masking procedure giving the best results. Tennakoon, Murthy, and Eiumnoh (1992) reported a classification accuracy of 94 percent using supervised classification. For land-cover mapping in an agricultural region, Kontoes et al. (1993) showed that the use of a knowledge-based system with GIS data gives 13 percent better accuracy than a parametric image classifier. Although generating an ancillary database obviously requires greater effort, it would be justified in complex situations where normal methods fail.

In the Bhadra irrigation system the major area is under rice. Other crops are sugarcane, groundnut, sunflower, and garden crops such as coconut, betel nut, and vegetables. Rice transplanting is staggered over a period of more than a month, and other crops are sown considerably earlier than rice. Because of this heterogeneity in the crop calendar, we analyzed satellite data from two dates: (1) the time of maximum ground cover and canopy growth and (2) when rice was being transplanted and other crops had already grown to the vegetative stage. The objective was to ensure a complete estimate of the area under crops and to achieve better discriminability. Based on a review of alternative approaches, a multivariate classification approach was selected in an attempt to merge the data from the two dates into a single multichannel data set.

Seventy-five percent of landholdings in the study area are smaller than 1 hectare. The pixel size is 0.64 hectare for sensor data from Landsat MSS, 0.09 hectare for data from Landsat TM, and 0.5 hectare for data from IRS LISS I. Major crops can be accurately classified because of the fine pixel size and because the crop area is reported at the level of distributary or the reach within a distributary. Crops that are patchy in nature—occurring in very small segments—may be sometimes inaccurately classified, but not rice or other major crops. Hence, Landsat MSS and IRS LISS I data were considered adequate for crop inventory.

Although the initial crop classification included all principal crops, the final classification was divided into rice and non-rice crops to maintain acceptable accuracy even at the distributary level. A post-classification check through field visits to more than 300 randomly selected points confirmed the classification to be 90 to 95 percent accurate. In future evaluations, the Kappa statistic will be adopted in preference to overall accuracy as a means of testing classification accuracy based on error matrices, particularly for evaluating inter-classification problems (Fitzgerald and Lees 1994). Statistics on crop area at the distributary level were extracted by digitally overlaying the base map of the command area on the geometrically rectified crop classification map.

Spatial variability in the rice calendar

Spatial information on the transplanting time for rice across the command area has been mapped (map 2). The seasonal NDVI[2] profile of every pixel of rice crop was analyzed to identify the peak greenness stage. The fact that this stage corresponds to the heading stage of rice was used to calculate the time of transplanting and to generate information on spatial staggering of rice transplantation, i.e., the time of transplanting in different areas. This information is useful for evaluating the compatibility between the canal delivery schedule and the rice transplanting calendar at the distributary level. This capability will be further enhanced when WiFS data from IRS-1C and IRS-P3 are operationally available. Those satellites provide individual 5-day revisit periods and a combined 2- to 3-day revisit period.

Concurrent monitoring of rice growth and stress

Satellite data of IRS and Landsat satellites are available only at certain times during the growing period, and this availability is further limited by cloud cover. Although a combination of satellites can provide frequent coverage, the process of data normalization from multiple satellites can significantly overload analysts. Hence, to concurrently monitor crop growth and crop condition through the season, satellite sensors such as IRS-1C's WiFS, with a 5-day revisit period, must be used. NOAA-11's AVHRR sensor, though providing twice-daily revisit capability, has a spatial resolution of 1.1 kilometers at nadir, which is too coarse for effective spatial monitoring within the command area.

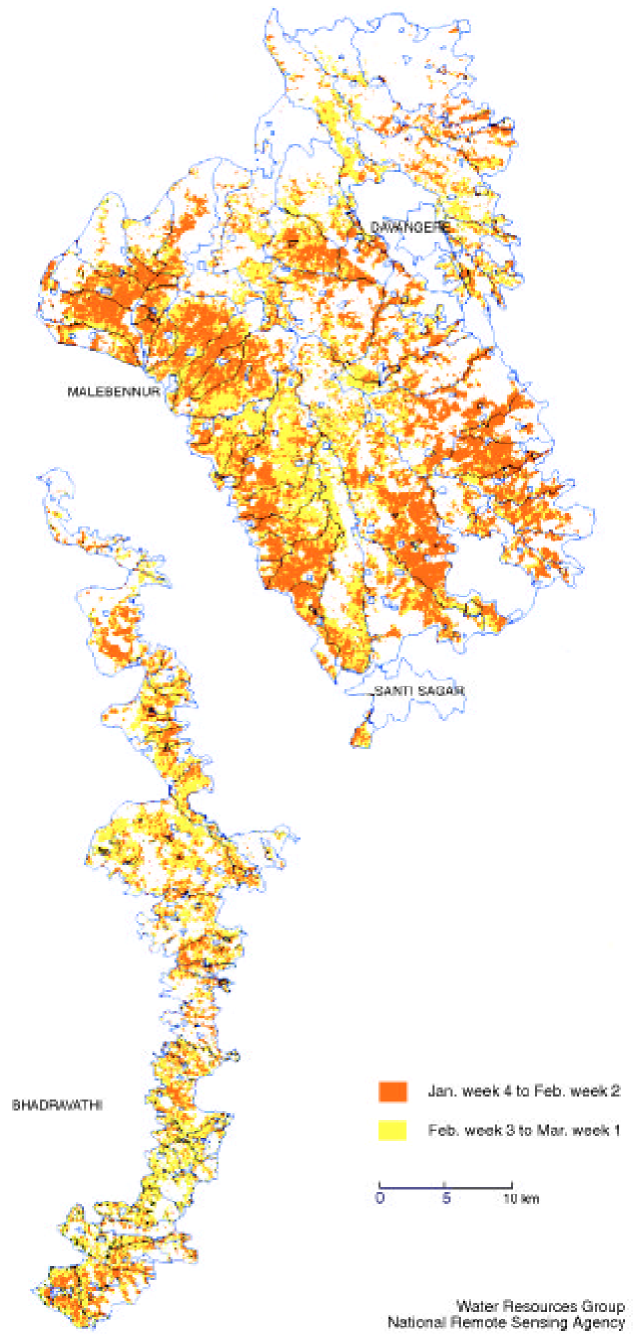
Analysis of simulated WiFS data indicated that temporal information on rice development can be effectively captured (Jonna et al. 1995). In spite of its 188-meter resolution, WiFS allows satisfactory classification of large-area crops such as rice even at the distributary level. The profiles of rice growth obtained from the NDVI of WiFS data at the distributary level were very similar to those obtained from LISS I data. NDVI provides the capability of monitoring not only the physiological development of rice over time and in its spatial variability, but also its condition, because many studies have related abnormal NDVI to crop stress. The effect of stress is to decrease the near-infrared reflection and to increase the reflection in the red wavelengths, giving lower-than-normal NDVI values. Based on analysis of high resolution field spectrometer measurements, Shibayama et al. (1993) showed that NDVI is a sensitive measure of stress in rice 2 weeks after drainage. The effective use of WiFS data requires radiometric correction to compensate for changing illumination geometry between successive revisits (because the WiFS paths shift by 117 kilometers every 5 days) and across the scan (in case of latitudinally oblong irrigated areas) and for atmospheric effects. WiFS data from the IRS-IC satellite have been operationally available from the Indian Earth Station since June 1996. Where direct reception is not available, the on-board tape recorder permits acquisition of data over such areas, which subsequently can be downlinked to the Indian Earth Station.

Data normalization

To use data from multiple satellites with different sensor characteristics for close monitoring of irrigated areas, the data must be normalized geometrically and radiometrically. A technique for radiometrically rectifying multiple Landsat images of a

[2]NDVI (normalized difference vegetation index) is defined as *NIR-R/NIR+R*, where *NIR* and *R* are radiance measured by the sensor in near-infrared and red wavelengths, respectively.

MAP 2.
Time of rice transplanting, Bhadra command, 1992–93 rabi season.



scene to a reference image was described by Hall et al. (1991). The basic approach consisted of identifying landscape elements whose reflectance changed little with time and using these control sets to radiometrically transform other images. The method worked well for the visible and near-infrared bands of the Landsat Thematic Mapper. A procedure for selecting appropriate bands to compare NDVI values from multiple satellites (IRS-1A and -1B LISS I and Landsat-4 and -5 MSS) has been described by Jeyaseelan and Thiruvengadachari (1994). Jonna et al. (1994) reviewed existing procedures such as histogram normalization, use of scene statistics, linear transformation, and use of spectrally invariant features, and, for this study, a simple regression between different data sets was adopted.

Estimation of rice productivity

Growing vegetation has a low red reflectance, due to absorption by chlorophyll and other plant pigments, and a high near-infrared reflectance, due to internal reflectance involving the mesophyll structure of green leaves (Knipling 1970). Vegetation indices computed from these two bands have been related to various vegetation canopy properties, such as green leaf area index (Price 1992), canopy biomass (Anderson and Hanson 1992), absorbed photosynthetically active radiation (Daughtry et al. 1992), and grain yield (Ashcroft et al. 1990). The most common of these indices is the NDVI, which has been shown to have a lag relationship to potential evapotranspiration and actual evapotranspiration, where moisture is not strongly limiting. Actual evapotranspiration for the total growing season was found to be closely related to NDVI (Deblonde and Cihlar 1993). A lag relationship between cumulative NDVI derived from the NOAA AVHRR global vegetation index data and cumulative actual evapotranspiration was demonstrated over Senegal (Kerr et al. 1989). The feasibility of retrieving data on land surface temperatures and spectral emissivity directly from radiances measured by NOAA AVHRR was established by Li and Becker (1993). Actual evapotranspiration was estimated in irrigated areas in Argentina and Egypt through the use of thermal data from the Landsat Thematic Mapper (Bastiaanssen, Van Der Wal, and Visser 1996).

Efforts to account for background soil reflectance and atmospheric effects have led to continual improvements of the vegetation index (Heute 1988; Guyot and Baret 1990; Kaufman and Tanre 1992; Qi et al. 1994; Rondeaux, Steven, and Baret 1996). The perpendicular vegetation index (PVI) was computed for rice paddies by devising a turbid water line (Yamagata et al. 1988).

Many of the advances are developed with limited empirical evaluation or are evaluated using tested models of vegetation bidirectional reflectance such as the SAIL model (Verhoef 1984). Before new developments are routinely used in operational applications, standardization of vegetation indices along with more comprehensive empirical evaluation in different agricultural environments is important.

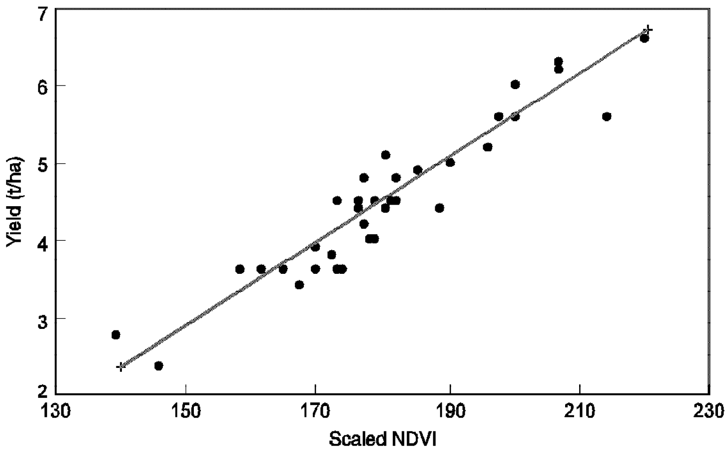
Yield models based on remote sensing have been investigated in a variety of crop and agricultural situations by many investigators (Tucker, Holben, and McMurtrey 1980; Idso et al. 1980; Gill et al. 1997; Beneditti and Rossini 1993; Dubey et al. 1994; Pestemalci et al. 1995; Carbonne, Narumalani, and King 1996). In rice, the ratio of near-infrared to red at panicle differentiation or heading could be used to forecast yield through the dry matter-grain yield relationship, but it becomes less sensitive during grain filling and grain maturation (Miller et al. 1983). Leblon, Guerif, and Baret (1991) proposed a model of biomass production for flooded rice crops based on an "energetic" yield approach in which photosynthetically active radiation interception efficiency is estimated through a vegetation index. Rice yield has been related to senescence rate (Rao, Rao, and Suryanarayana 1985) as well as to NDVI derived from Landsat TM bands 3 and 4 (Mohammed, Ahmed, and Abdullah 1994). Tennakoon, Murthy, and Eiumnoh (1992) estimated rice yield by developing a relationship between NDVI values and actual grain yield.

In this study, a simple rice yield model was developed based on the relationship between peak NDVI at the heading stage to the yield of 72 plots obtained through crop-cutting experiments during the 1992-93 rabi season. Although the correlation coefficient was statistically significant even as early as the panicle initiation stage, it was highest at the heading. After that, the correlation became weaker (Murthy et al. 1996).

Because rice transplantation is staggered across the command area, satellite data from any one date do not represent the same growth stage at all locations. Consequently, an innovative approach of time composition was attempted, using co-registered multi-date satellite data derived from IRS LISS I data. The maximum NDVI value for each rice pixel was picked from among the satellite overpasses encompassing the period of rice heading across the command area. These values are called the time-composited vegetation index (TCVI)

The rice yield model (fig. 1) is defined as yield (measured in kilograms per hectare) = 42.23 TCVI – 3,439. The standard error of estimate is 507 kg/ha with the coefficient of determination statistically significant at 0.76. The yield model developed from satellite and ground data of the 1992-93 rabi season was validated during the 1993-94 rabi season, and the maximum deviation of the yields from crop-cutting experiment yields was less than 10 percent, indicating the stability of the model. The

FIGURE 1.
Model relating NDVI and yield from crop-cutting experiments, Bhadra Project, 1992–93 rabi season.



model coefficients are expected to change when data from other satellites are used without radiometric normalization or when NDVI is based on spectral reflectance instead of radiance, as in this study.

The rice yield model is currently location-specific because the differences in rice variety, atmospheric effects, and the fertilizer-vegetative growth relationship may require modification of the model coefficients.

Improved sampling design for yield assessment

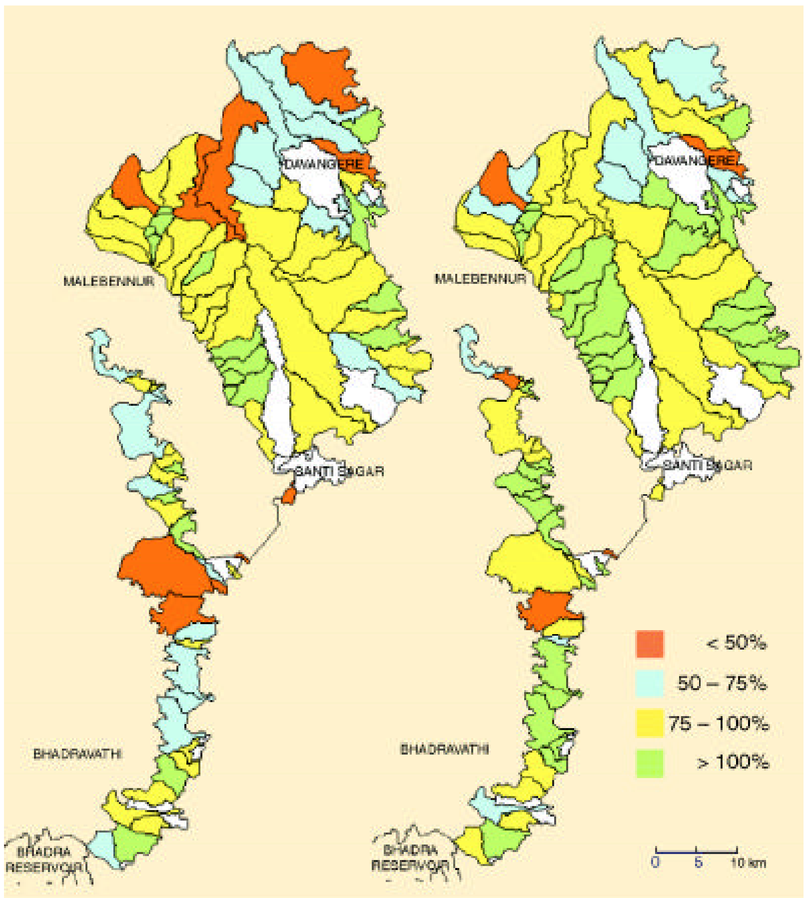
The crop-cutting experiments were based on a simple random-sampling technique in which the sample size is proportional to the cropped area. The crop-cutting experiments for any specified crop involve the selection of a plot of size specified in a sampling design and harvesting the crop to obtain yield estimates. However, analyses of the sampling design during the 1992-93 and 1993-94 rabi seasons based on satellite-derived spatial rice yield patterns showed that simple random sampling techniques could lead to biased results. Stratification of rice plots based on rice condition and subsequent selection of rice plots provide more homogenous samples and thus reduce errors in estimates. An improved design for crop-cutting experiments, with more reliable yield estimates, has been developed based on satellite-derived rice area and crop condition at the time of heading (Murthy et al. 1996). This design was discussed with the officers from the Command Area Development Authority, Agriculture Department, Department of Economics and Statistics, and the Irrigation Department in Karnataka State and was implemented in the 1994-95 rabi season.

GIS development

A geographic information system (GIS) using PAMAP software was developed to improve evaluation of system performance (Rajagopal 1995) and to facilitate diagnostic analysis (Srinivas 1995). The digitized base of the irrigated command area map provided the geographical framework. The necessary ground and satellite data were incorporated into GIS, and temporal and spatial data of agricultural productivity from each distributary were analyzed (maps 3, 4, 5, and 6). The GIS approach was also used for diagnostic analysis of three distributaries in the Malebennur Division selected on system performance criteria. This analysis involved digitizing relevant cadastral maps and superimposing satellite imagery. Field boundaries identified in enhanced satellite images and topographic maps facilitated geometrical rectification of cadastral maps. Satellite-derived cropped area, cropping pattern, and rice yield were averaged over the head, middle, and tail reaches of each distributary to allow irrigation performance characterization with regard to yield, cropped area, cropping pattern, etc.

Irrigation intensity before and after NWMP, Bhadra Project.

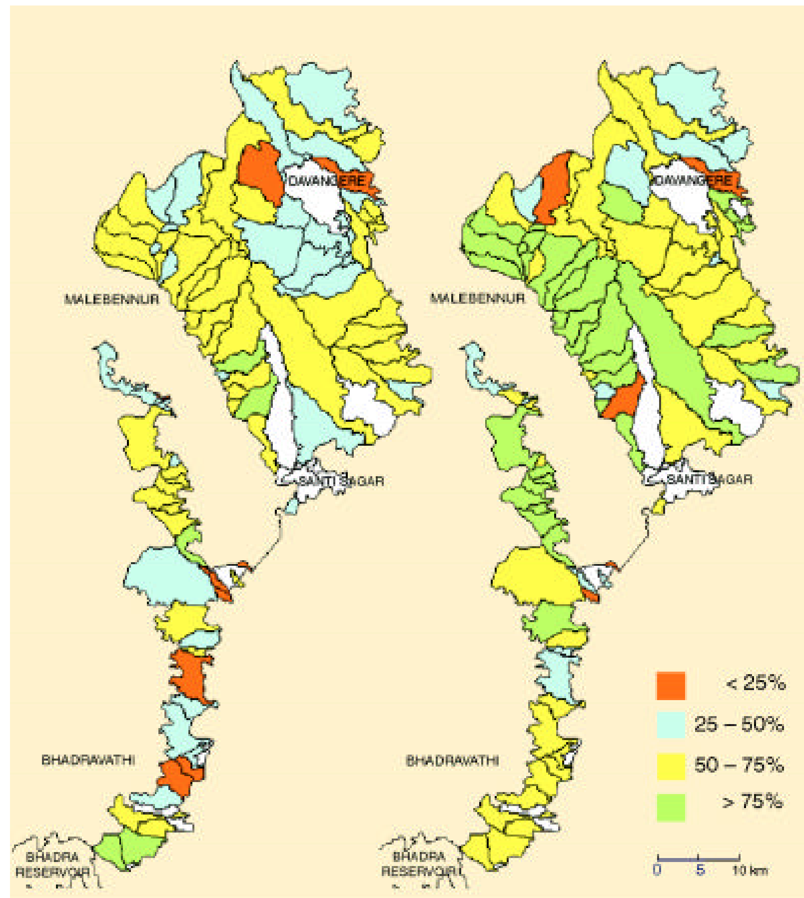
Pre-NWMP (1986-87 rabi) Post-NWMP (1992–93 rabi)



MAP 4.

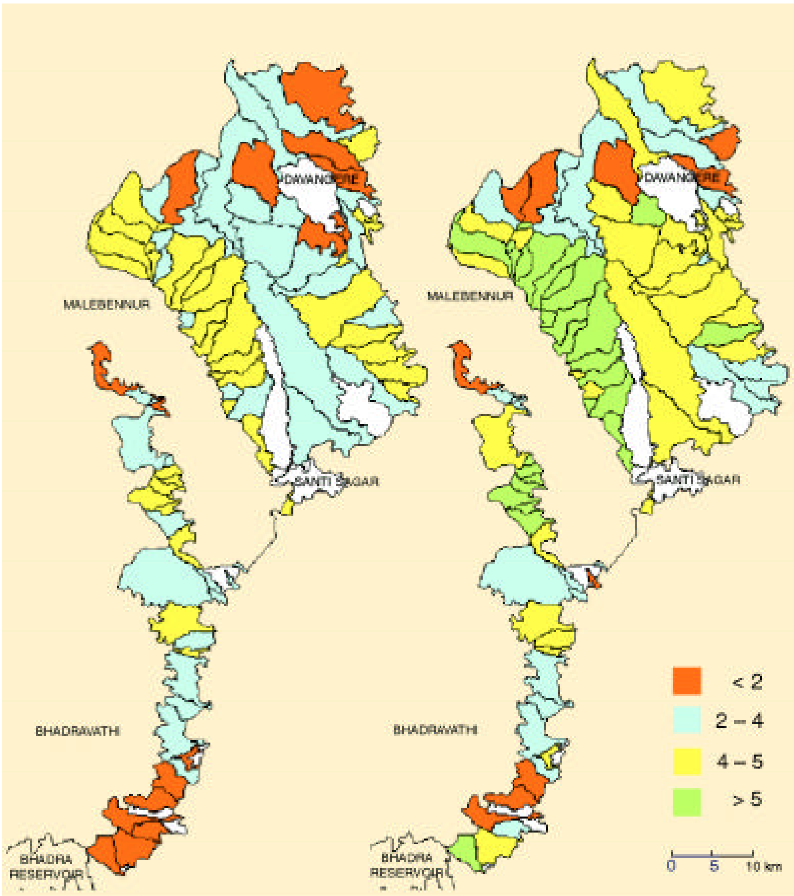
Percentage rice area before and after NWMP, Bhadra Project.

Pre-NWMP (1986-87 rabi) Post-NWMP (1992–93 rabi)



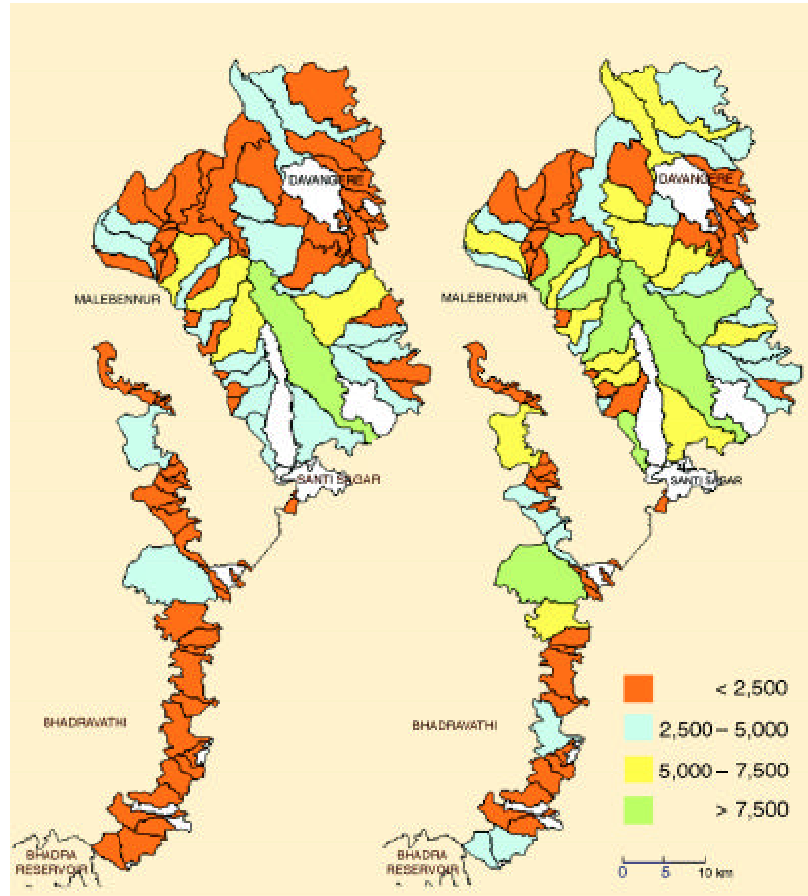
MAP 5.
Rough rice yield (tonnes/ha) before and after NWMP, Bhadra Project.

Pre-NWMP (1986-87 rabi) Post-NWMP (1992–93 rabi)



MAP 6.
Rough rice production (tonnes) before and after NWMP, Bhadra Project.

Pre-NWMP (1986-87 rabi) Post-NWMP (1992–93 rabi)



Information from a revenue survey conducted among 103 farmers randomly chosen from the three selected distributaries and officials of the state irrigation and agriculture departments was averaged over the head-, middle, and tail-reach areas. The poor performance of distributary 15 in the third subdivision of Malebennur Division, for example, was attributed to poor water availability resulting from the closing of canals long before the crop harvesting period and the failure of water to arrive at the tail reach along the dilapidated canal. An additional cause was low fertilizer use.

Linking GIS with the irrigation information system will enable project officials to manage canal delivery and scheduling more efficiently, increase their awareness of crop water requirements, and facilitate analysis of hydrometrological data and formulation of operational plans.

Discussion of Results

System performance evaluation

Primary data on agricultural productivity (cropping pattern and rice yield) have been generated at the distributary and reach levels as well as at division and subdivision levels from satellite data for rabi seasons (tables 1, 2, and 3), and the improvement in system performance after implementation of NWMP started in 1988 has been evaluated (table 4). Map 3 shows that irrigation intensity increased in every sector of the command area, and hardly any distributaries have less than 50 percent irrigation intensity. And not only has the cultivated area of rice expanded (map 4), but yields (map 5) and production (map 6) have increased. Although NWMP intended to limit rice growing during the rabi season and encourage irrigation of other crops, this study found that between 1986-87 and 1993-94 irrigation intensity during the rabi season rose from 76 percent to about 91 percent, rice area from 56 to 69 percent, and rice yield from 3.8 t/ha to 4.9 t/ha.

TABLE 1.
Irrigated crop area and irrigation intensity by division in the Bhadra Project between 1986–87 and 1993–94, based on satellite data.

	Davangere		Malebennur		Bhadravathi		Total command	
Year [a]	Area (ha)	Intensity (%)	Area (ha)	Intensity (%)	Area(ha)	Intensity (%)	Area (ha)	Intensity (%)
1986–87	33,838	75	28,242	81	11,449[b]	67	73,529	76
1987–88	15,848	35	12,677	36	5,856[b]	34	34,381	35
1988–89	31,760	70	23,260	66	13,945[b]	82	68,965	71
1989–90	39,038	69	23,027	66	13,311[b]	78	67,366	69
1992–93	39,436	87	31,738	91	17,250	101	88,424	91
1993–94	38,107	84	30,610	87	15,695	92	84,412	87
Planned command	45,280	–	35,030	–	17,050	–	97,360	–

Source: IIMI 1995.

[a]1986–87: prior to implementation of NWMP (no cutoff); 1987-88 and 1988-89: initial period of NWMP implementation; 1989-90: first season after NWMP implementation (75% of command area irrigated); 1992-93 and 1993-94: full command area irrigated.

[b]Ground data.

TABLE 2.
Percentage of area in rice by division and subdivision during the rabi season, selected years, based on satellite data.

Unit	1986–87	1988–89	1989–90	1992–93	1993–94
			Davangere		
Subdivision 1	45	39	23	51	60
Subdivision 2	54	49	40	67	69
Subdivision 3	59	57	44	78	78
Subdivision 4	42	37	35	63	74
Division	51	46	35	66	71
			Malebennur		
Subdivision 1	72	83	90	88	83
Subdivision 2	56	33	46	66	54
Subdivision 3	59	61	60	73	75
Subdivision 4	61	42	79	77	72
Division	65	64	76	81	76
			Bhadravathi		
Subdivision 1	60[a]	53[a]	21[a]	61	64
Subdivision 2	41[a]	33[a]	33[a]	61	53
Subdivision 3	36[a]	33[a]	34[a]	49	30
Division	48[a]	5[a]	46[a]	58	49
Command	56	53	51	69	69

Source: IIMI 1995.

[a]Ground data.

TABLE 3.
Rough rice yield (t/ha), rabi season, selected years.[a]

Unit	1986–87	1989–90	1992–93	1993–94
		Davangere		
Subdivision 1	3.8	4.9	4.0	4.8
Subdivision 2	4.0	5.2	4.5	4.6
Subdivision 3	3.7	4.5	4.4	4.4
Subdivision 4	3.4	5.2	4.5	4.9
Division	3.8	5.1	4.4	4.6
		Malebennur		
Subdivision 1	4.3	6.1	5.8	5.6
Subdivision 2	3.3	5.0	4.0	4.5
Subdivision 3	4.1	6.0	4.9	5.2
Subdivision 4	3.7	5.7	4.9	5.2
Division	4.1	5.9	5.3	5.3
		Bhadravathi		
Subdivision 1	2.4	4.5	3.8	4.2
Subdivision 2	3.7	4.7	4.1	4.2
Subdivision 3	3.4	4.2	3.8	4.6
Division	3.2	4.6	4.0	4.3
Command	3.8	5.4	4.7	4.9

Source: IIMI 1995.

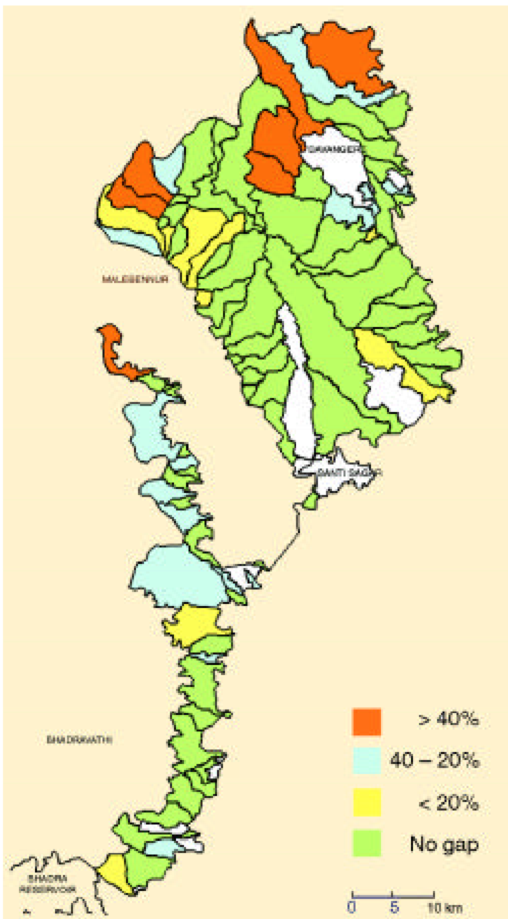
[a]1986–87: pre-NWMP and no cutoff; 1989–90: 25% of command area cut off from irrigation; 1992-93 and 1993–94: without cutoff.

Satellite data have allowed reliable and more detailed system performance evaluations. The equity of water distribution between head- and tail-reach areas of long distributaries was evaluated in terms of shortfalls in irrigation intensities (referred to as gaps in utilization) and rice yield differences. Map 7 (for 1993-94) shows a significant gap in the tail-reach areas, particularly the upper tail-reach areas, compared with 100 percent irrigation in the head-reach areas. Satellite data also provide objective rice yield information, even at reach levels within the distributary (map 8). Yield estimates hitherto were not available at the distributary level or other disaggregated levels. Conventionally, yields were estimated when needed from sample surveys of farmers in selected distributaries. Additional information can be derived from comparing maps 7 and 8, which indicates that there is no strong correlation between irrigation intensity and yield. Map 9 shows that rice production per unit of water along the Right Bank Canal is considerably lower than that in other areas of the command. Evidently other factors besides inefficient irrigation depress rice yields in these distributaries.

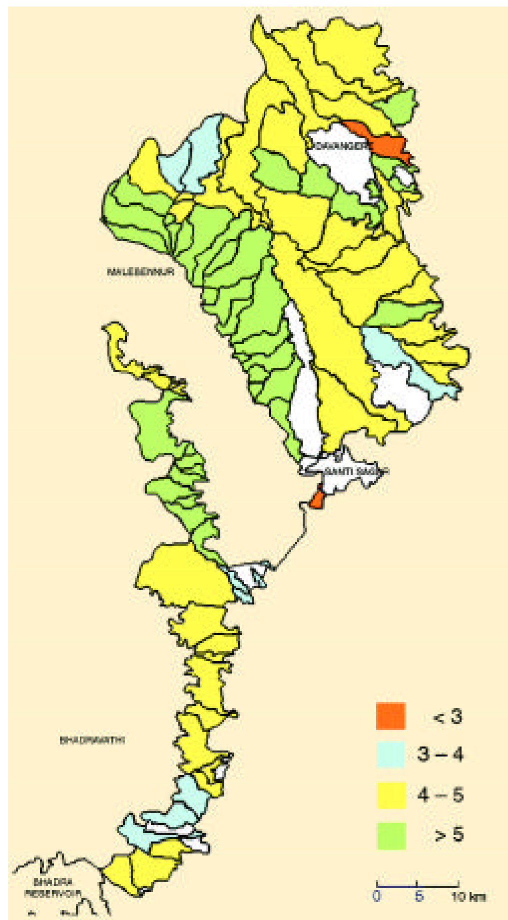
Other performance indicators such as depth of water application and rice production per unit of water can be derived from satellite data in conjunction with ground-reported data on rainfall and canal discharge. In this initial study, the effective rainfall was considered by the Project Office to be 80 percent of the value measured on ground. The water delivery is measured at the off-take point of the distributary. The system losses in the distributary have not been accounted for.

The equity of the water supply is measured through Christiansen's Uniformity Coefficient (table 5).

MAP 7.
Gap in irrigation utilization, rabi 1993–94, Bhadra Project.



MAP 8.
Rough rice yield (tonnes/ha), rabi 1993–94, Bhadra Project.



MAP 9.
Rough rice production per unit of water (kg/m ^{3}), rabi 1993–94, Bhadra Project.

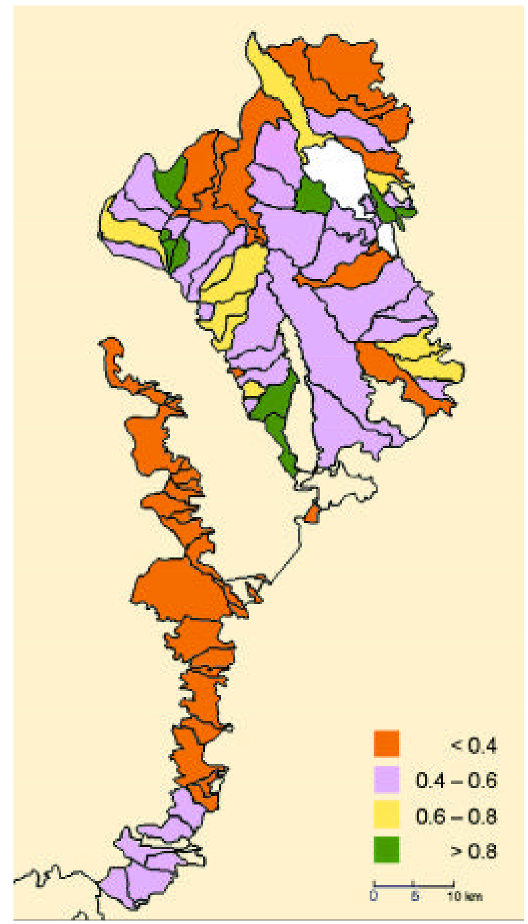


TABLE 4.
System performance changes under NWMP, Bhadra Project, rabi season, selected years.

Year[a]	Irrigated crop area (ha)	Rice area (%)	Depth of water application (m)	Area irrigated per unit of water (ha/ha-m)	Rice output per unit of land (t/ha)	Rice output per unit of water (kg/m^3)
1986-87	73,529	56	1.06	0.94	3.8	0.3
1989-90	67,366	51	1.04	0.96	5.4	0.4
1992-93	88,424	69	0.80	1.25	4.7	0.5
1993-94	84,412	69	0.86	1.16	4.9	0.5

Source: IIMI 1995.

[a]1986-87: pre-NWMP and no cutoff; 1989-90: 25% of command area cut off from irrigation; 1992-93 and 1993-94: without cutoff.

TABLE 5.
Equity in water supply as measured by Christiansen's Uniformity Coefficient,[a] 1993–94 rabi season.

Division	Subdivision 1	Subdivision 2	Subdivision 3	Subdivision 4	Total
Davangere	0.66	0.84	0.93	0.89	0.92
Malebennur	0.85	n.a.	0.69	n.a.	0.93
Bhadravathi	0.91	0.80	0.75	–	0.75

Source: IIMI 1995.

[a]Estimated as the ratio of the weighted sum of deviations of the depth of water supply from the mean to the mean depth of water supply.

TABLE 6.
Poorly performing distributaries during rabi season, 1992–93 and 1993–94.

Division	Subdivision	1992–93	1993–94
		Gap in irrigation utilization[a]	
Davangere	1	HPD	9C, HPD
	4	12A, 12B, 13, 14	12A, 12B, 13
Malebennur	3	14, 15, 16	12, 14, 15, 16
	4	28	7-8, 10, 27[b], 31-40
Bhadravathi	2		24
	3	17	17
		Low rice yield compared with division average	
Davangere	1	HPD	15
	3	3	3
Malebennur	3	15, 16, 17	15, 16, 17
	4	26, 40	26, 40
Bhadravathi	1	6, 7, 8	6
	2	23, 25, 26	23, 25, 26
	3	9	
		Low rice production per unit of water[c]	
Davangere	1	9B, 14	9C, HPD, HPD1, 15
	2	CHM	8A, CHM
	3	3	3
	4	12A, 12B	
Malebennur	1	HSD, 2	HSD, 1, 2
	3	12, 15, 16, 17	11E, 12, 15
Bhadravathi	1	6, 7, 8	
	2	22	22, 25
	3	17	

[a]Irrigation intensity <75%.

[b]Included in distributary 26 (map 1).

[c]Less than 90% of division average.

The performance of the Bhadra Project through the years as measured by area irrigated and agricultural productivity has significantly improved. In the 1993–94 rabi, equity of water distribution was also high. Equity is one of the key objectives of NWMP. Only a few pockets of inequity remain to be improved by the management.

Diagnostic analysis

The diagnostic analysis of the Bhadra Project consisted of identifying problem distributaries and analyzing reasons for poor performance that will have to be rectified by the management. Analyses of satellite data from the 1992-93 and 1993-94 rabi seasons revealed problem distributaries as indicated by low irrigation intensity, low rice yield, and low rice production per unit of water (table 6). Low irrigation intensity is mainly observed in the tail end of the branch canal while insufficient water—both low quantity and poor timing of distribution—seems to be the major factor for low rice yield. Other indicators of poor performance used in this study were persisting low irrigation intensity and rice yield through the years and large difference in rice yield between head-reach and tail-reach areas of a distributary.

Waterlogging, salinity, and crop productivity

A pilot study was conducted in distributary 8A of Davangere Branch Canal to evaluate the impact of waterlogging, salinity, and alkalinity on rice productivity. The revenue survey numbers[3] of plots reportedly affected in three villages (Turchagatta, Ballapur, and Kuniapalanhalli) under the 8A distributary were collected from the State Soil Conservation Department. A revenue survey map of distributary 8A was photographically scaled to 1:50,000, and then the map was geometrically rectified to match the satellite data of the 1992-93 rabi season that was already registered to topographic maps. Village boundaries and affected revenue survey numbers were located on this reduced co-registered map. Vegetation index statistics for the reportedly affected areas were extracted from the satellite data. Preliminary analyses did not indicate any adverse effects in terms of lower-than-normal NDVI values from waterlogging, salinity, or alkalinity in any of the three villages. A further intensive study of the three villages and other distributaries reported to have been affected by waterlogging is underway.

[3]Revenue survey numbers function as plot identification numbers and are mostly used when levying taxes.

Comparison of data from remote sensing and ground methods

Table 7 compares data on rice area gathered using the satellite technique and ground coverage. The values are reasonably close, and the maximum error is only 7 percent.

TABLE 7.
Satellite-derived data on rice area compared with ground coverage data.

Year	Satellite (ha)	Ground (ha)
1986-87	41,176	40,768
1989-90	34,357	33,852
1992-93	61,013	56,788

Source: IIMI 1995.

Cost-effectiveness of remote sensing techniques

The cost of applying satellite remote sensing to produce a disaggregated irrigation inventory in the 100,000-hectare Bhadra Project is about US$0.10/ha for each irrigation season at 1994–95 price levels. This estimate includes the cost of satellite data, analysis, and statistics generation. The unit cost decreases to about $0.03/ha for irrigation schemes larger than 250,000 hectares, due to economies of scale. Similar unit costs for monitoring waterlogging and soil salinity status work out to $0.05/ha and $0.02/ha, respectively, when carried out along with crop inventory. The satellite remote sensing application costs are less than 1 percent of the annual operation and maintenance costs for irrigation schemes in India. In an alternative approach, the satellite remote sensing application can be assumed to have a positive cost-benefit ratio even if rice yield increases by as little as 1 kg/ha in the Bhadra command.

Future Research and Development Focus

This case study in the Bhadra Project in India demonstrates that satellite remote sensing techniques can be cost-effectively applied to generate timely disaggregated information for diagnostic analysis and improving agricultural production and productivity. The study also highlights the extent of equity in water distribution based on area to be irrigated as well as variability in rice production per unit volume of water. The spatial variability in the rice growth calendar has been assessed to check the compatibility of the irrigation schedule with farmers' needs and has been used in modeling rice productivity. An improved sampling design for estimating rice productivity has been developed. Various methodological developments in this case study have contributed to operationalizing satellite remote sensing applications in rice systems. The development of an operational satellite remote sensing package will be helped by application and validation in a variety of irrigation environments.

Major efforts are needed to develop an appropriate vegetation index that is optimally sensitive to rice characteristics (and less sensitive to the background) and better spectral modeling of rice yield. While remote sensing of irrigation schemes in the microwave spectral region has not generally yielded satisfactory results so far, the application in the rice irrigation system has been encouraging. Use of radar data on two to three dates during the season has helped in crop discrimination (Bouman and Uenk 1992) and in monitoring rice areas because of standing water conditions (Staples et al. 1994). The use of single frequency—single polarization radar data—seems to have limited potential for crop classification or condition assessment. The synergic use of optical and microwave data, however, is considered to have great potential for improved monitoring capabilities (Brisco, Brown, and Manore 1989). An ongoing study at NRSA envisages the use of data from the Radarsat, ERS, and IRS satellites for monitoring the Bhadra Project during the cloud-covered *kharif* (southwest monsoon) season, as well as during the relatively cloud-free rabi season.

Conclusions

This case study demonstrates the potential and cost-effectiveness of satellite remote sensing techniques for inventorying irrigated area and monitoring agricultural productivity in a large rice irrigation system in India. Effective integration of GIS with satellite remote sensing techniques enhances performance evaluation and diagnostic analysis capabilities. The study indicates that enhanced operational use of such techniques calls for further development work on optimum crop classification algorithms, yield prediction models, more appropriate vegetation indices, and satellite data normalization procedures.

IIMI is now formulating a long-term program for development of advanced technology and tools to aid irrigation management, and the Bhadra study is a beginning. The satellite remote sensing techniques used in this study are also being applied on a wheat irrigation system in northwest India to extend the application package to other food crops.

Orbital and Sensor Characteristics of Satellites

ANNEX TABLE 1.
Orbital characteristics of remote-sensing satellites.

Satellite	Altitude (km)	Orbital period (min)	Equatorial crossing time (h)	Revisit period (days)
		In orbit at time of NWMP study		
IRS-1A, IRS-1B	904	103	1000	22
IRS-P2	817	101	1030	24
Landsat-5	705	99	0930	16
Spot-1, 2, 3	832	101	1030	26
NOAA-11	833	102	1430	0.5
ERS-1	817	102	1030	3, 35, 168
		Launched after 1994[a]		
IRS-1C	817	102	1030	PAN: 5; LISS III: 24; WiFS: 5
IRS-P3	817	101	1030	MOS: 2; WiFS: 5
ERS-2	780	102	1030	35
Radarsat	798	101	dawn/dusk	24
		Not yet launched		
Landsat-7	705	99	0930	16

Source: IIMI 1995.

[a]IRS-1C, IRS-P3, ERS-2, and Radarsat satellites were launched in December 1995, March 1996, April 1995, and November 1995, respectively.

ANNEX TABLE 2.

Sensor characteristics of remote-sensing satellites in orbit at time of NWMP study.

Satellite	Sensor	Band no.	Band width (microns)	Ground resolution (m)	Swath width (km)	Radiometric resolution (bits)
IRS-1A, IRS-1B	LISS I	1	0.45-0.52	72.5	148	7
		2	0.52-0.59	72.5	148	7
		3	0.6Z-0.68	72.5	148	7
		4	0.77-0.86	72.5	148	7
	LISS II	1	0.45-0.52	36.25	74	7
		2	0.52-0.59	36.25	74	7
		3	0.62-0.68	36.25	74	7
		4	0.77-0.86	36.2S	74	7
IRS-P2	LISS II	1	0.45-0.52	32 x 37	131	7
		2	0.52-0.59	32 X 37	131	7
		3	0.62-0.68	32 X 37	131	7
		4	0.77-0.86	32 x 37	131	7
Landsat-5	MSS	1	0.5-0.6	80	185	8
		2	0.6-0.7	80	185	8
		3	0.7-0.8	80	185	8
		4	0.8-1.1	80	18S	8
	TM	1	0.45-0.52	30	185	8
		2	0.52-0.60	30	185	8
		3	0.63-0.69	30	185	8
		4	0.76-0.90	30	185	8
		5	1.55-1.75	30	185	8
		6	10.4-12.5	120	185	8
		7	2.08-2.35	30	185	8
SPOT 1, 2, 3	MLA	1	0.50-0.59	20	60	8
		2	0 61-0 68	20	60	8
		3	0.79-0.89	20	60	8
	PLA	1	0.51-0.73	10	60	8
NOAA-11	AVHRR	1	0.55-0.68	1100	2700	10
		2	0.73-1.10	1100	2700	10
		3	3.55-3.93	1100	2700	10
		4	10.3-11.3	1100	2700	10
		5	11.5-12.5	1100	2700	10
ERS-1	SAR	1	5.3GHz(C; Band)	25	100	2.5(dB)

Source: IIMI 1995.

ANNEX TABLE 3.

	Sensor	Band no.	Band width	resolution (m)	Swath width (km)	Radiometric
IRS-1C	LISS lil		0.52-0.59	23.5		7
		3		23.5	141	
		4	0.77-0.86		141	7
			1.55-1.70	70.5		7
	PAN		0.50-0.75	5.8		6
	WiFS		0.62-0.68	188		7
		4		188	774	
Landsat-7[a]		1	0.45-0.52		185	8
			0.52-0.60	30		8
		3		30	185	
		4	0.76-0.90		1 S5	8
			1.55-1.75	30		8
		6		120	185	
		7	2.08-2.35		185	8
			0.50-0.90	15		8
IRS-P3		4	0.755-0.768		195	16
		13	0.408-1.01		200	16
		1	1.6		192	16
		3	0.62-0.68		804	7
			0.77-0.86	188		7
		5		188	804	
ERS-2	SAR		5.3 GHz (bBand) VV-Polarization	25 X 22		2 dB
	SAR	1	HH-PolaHzafon	28X 30	100	

Source: IIMI 1995.

[a]

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