Satellite Remote Sensing for Improving Irrigation System Performance

A report based on a consultancy study
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Satellite Remote Sensing
for Improving Irrigation System Performance

Acronyms

AVHRR	Advanced Very High Resolution Radiometer
CCE	Crop Cutting Experiments
ERS	European Remote Sensing Satellite
GIS	Geographical Information System
ha	hectare
HRV	High Resolution Satellite
IR	Infer Red
IRS	Indian Remote Sensing Satellite
LISS	Linear Imaging Self-Scanning Sensor
MBN	Malebennur
MIR	Middle Infra Red
MOS	Modular Opto-Electronics Scanner
MSS	Multi Spectral Scanner
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
NRSA	National Remote Sensing Agency
NWMP	National Water Management Project
PAN	Panchromatic
PSLV	Polar Satellite Launch Vehicle
Qtls	Quintals
SAR	Synthetic Aperture Radar
SPOT	System Probatoire d'Observation de la Terre
SRS	Satellite Remote Sensing
TCVI	Time Composited Vegetation Index
TM	Thermatic Mapper
UCC	Christiansen's Uniformity Coefficient
WiFS	Wide Field Sensor

1. INTRODUCTION

1.1. IIMI's Role

Following improvements to the Bhadra Reservoir and Sathanur projects made under the National Water Management Project (NWMP), the Government of India and the World Bank requested the International Irrigation Management Institute (IIMI) to evaluate the performance of these projects. As part of this study, IIMI coordinated research conducted under the intellectual leadership of the National Remote Sensing Agency (NRSA) of India to evaluate Satellite Remote Sensing (SRS) techniques as an operational tool for monitoring and evaluating irrigation projects.

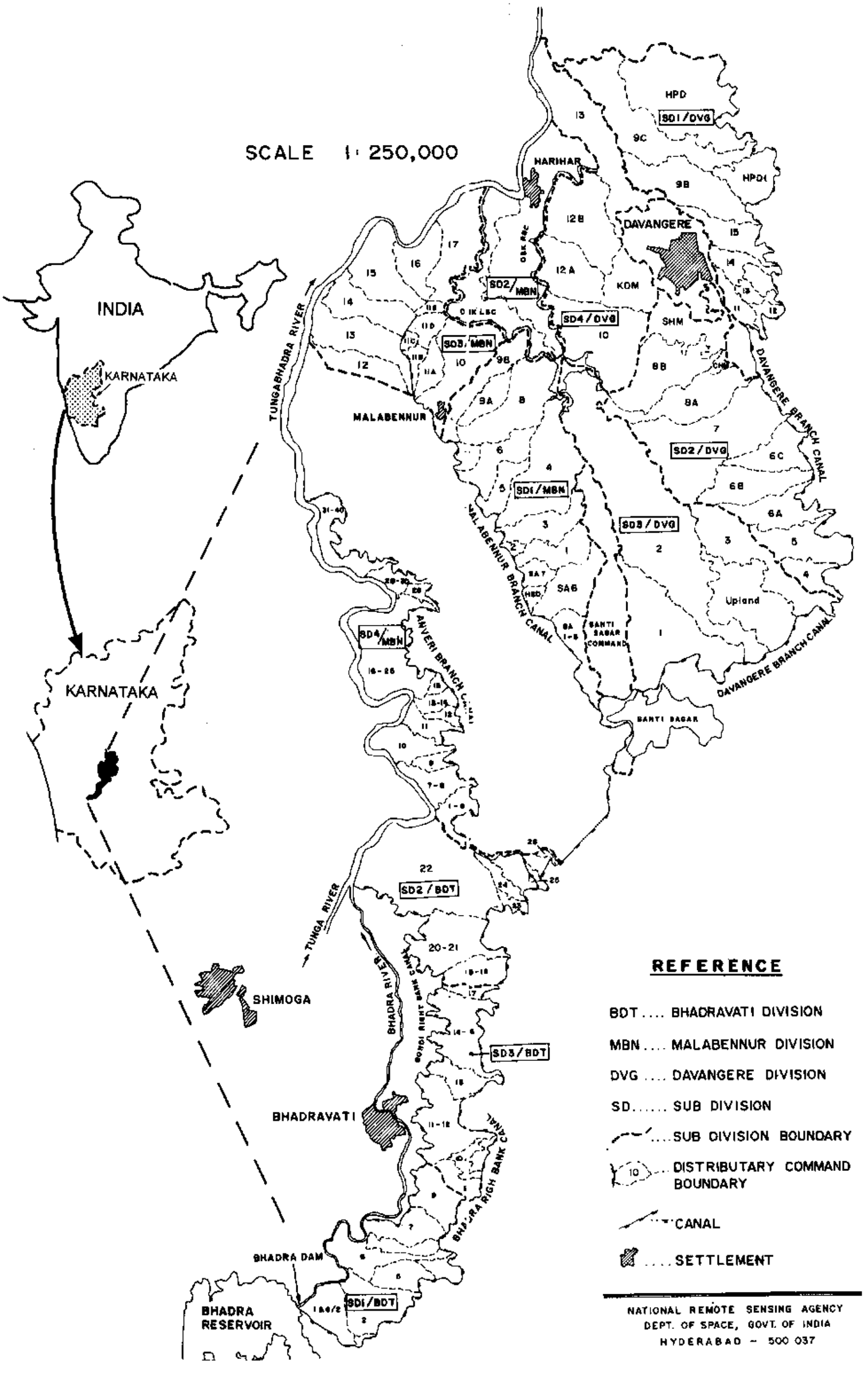
Although evaluations were conducted both in the Bhadra and Sathanur projects, the Bhadra Project produced a wider range of results. This monograph is based on the evaluation of the Bhadra Project and the survey of SRS applications done by Dr. Thiruvengadachari, the Director of the Water Resources Group of NRSA. Also discussed are issues relating to the use of SRS techniques as an operational tool for monitoring and evaluation of irrigation projects.

1.2. Bhadra Project

The Bhadra Project is located on the Bhadra River, a tributary of the Krishna River, in the State of Karnataka in India. The project comprises a dam with a gross storage capacity of 2,025 Mm^3, a Left Bank Canal of 10.7 m^3/s capacity serving 8,290 hectares (ha), and a Right Bank Canal of 70.8 m^3/s capacity serving 92,360 ha. The Bhadra dam is situated 50 km upstream of the point where the Bhadra River joins Tungabhadra, another tributary of Krishna, and intercepts a catchment of almost 2,000 km^2. On the map in Figure 1, the Bhadra Reservoir is located on the lower left-hand corner; the canal flows up along the right-hand side of the command area while the Bhadra River flows up 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. Although the Bhadra basin gets rainfall during both southwest and northeast monsoon seasons, about 80 percent of the stream flow is generated during the southwest monsoon period.

The different components of the Bhadra Project were constructed between 1948 and 1966. The project was designed to irrigate semi-dry crops that were to occupy more than 60 percent of its command area, with an overall annual cropping intensity of 200 percent. But, as agricultural developments progressed, it was found that rice dominated to the extent of occupying 90 percent of the irrigated land on the Left Bank and about 50 percent on the Right Bank.

Figure 1. Location of the Bhadra Project command area.



The heavy demand for rice led to inequitable use of the irrigation supply, and resulted in the rapid deterioration of the irrigation system as farmers intervened to modify the water management plan. This 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 this scheme was to restore the physical structure of the system, and develop and implement an appropriate water distribution policy.

1.3. Overview of SRS Applications for Bhadra Project Evaluation

Satellite remote sensing of the Bhadra Project is the first attempt at obtaining primary data on agricultural productivity under disaggregated conditions in India. Figure 1 illustrates the location and geography of the project's command area. Data on cropping pattern and major crop condition[1] have been gathered at disaggregated distributary and canal-reach levels for rabi seasons since 1986. The project's performance, before and after the NWMP implementation in 1988, was evaluated by NRSA—and it was found to have improved (Table 1).

Table 1. System performance under NWMP, Bhadra Project.

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 rice area	56	51	69	69
Average rice (rough rice) yield (Qtls/ha)	37.86	53.99	46.85	48.71
Depth of water application (m/ha)	1.059	1.040	0.799	0.859
Area irrigated per unit volume of water (ha/m^3)	94.44	96.12	125.21	116.37
Rice (rough rice) output per unit of land (tonnes/ha)	3.786	5.399	4.685	4.871
Rice (rough rice) output per unit volume of water (kg/m^3)	0.282	0.396	0.495	0.478

¤ Near real time monitoring in the 1992-93 and 1993–94 rabi seasons provided primary data on the cropping pattern to project authorities before the end of the rabi season. These data, along with those of the previous rabi season, helped the Irrigation Department authorities to identify problem distributaries in the Bhadra Project for corrective action.

1 Crop condition is the extent of healthy crop growth at any particular growth stage.

- An improved design for crop cutting experiments based on satellite-derived data on crop area and crop condition was also developed and implemented by the Command Area Development Authority during the 1994–95 rabi season.

- Analyses of multi-date satellite data of the rabi season have helped identify spatial variability of the rice transplantation period throughout the command area.

- The impact of waterlogging on rice productivity was evaluated in three villages.

- A Geographic Information System (GIS) was developed by NRSA at two levels of the command area to evaluate system performance, and to diagnose and analyze problem distributaries. The latter was supported by a ground survey in which 103 farmers, and Irrigation and Agriculture Department officials were interviewed with a questionnaire on irrigation, agricultural, and socioeconomic aspects.

- Cadastral maps of distributaries have been digitized and successfully integrated with satellite data. NRSA believes that the collection of primary data even at the village level is now feasible if high resolution satellite data are used.

The study in the Bhadra Project has proved the utility and effectiveness of SRS as an operational tool for monitoring and evaluating irrigation water management. Integration of GIS has enhanced the capacity to refine the system performance evaluation and diagnostic analyses.

2. SATELLITE REMOTE SENSING (SRS)

2.1. SRS Data Availability in India

At the time of this study, six satellites—IRS-1B, IRS-P2, Landsat, ERS-1, and NOAA 11 and 12—provide remotely sensed data over India. The data are received at the Indian Earth Station in Shadnagar about 60 km from Hyderabad and are processed at NRSA facilities in Hyderabad. At present, the combined revisit period for the study is about nine days.

2.2. Evaluation of New Sensors

Since India had planned to launch two new remote sensing satellites, IRS-IC and IRS-P3, during 1995–96, the utility of improved WiFS information from these satellites was evaluated through simulations. Evaluation of simulated Wide Field Sensor (WiFS) data in the Bhadra Project has indicated that rice condition assessment is possible even at distributary level in spite of its coarse spatial resolution of 188 m. Crop classification, however, is limited by the

spatial resolution. While these initial results are encouraging, further research is needed in regard to radiometric corrections for differences in scan-angle, sun-angle and in regard to the effect of bidirectional reflectance of vegetation, when the same area is viewed from different angles during repetitive WiFS coverage. The scan angle changes from about -25^0 to $+25^0$ during seven WiFS repeat visits within 35 days. Detailed information of orbital and sensor characteristics of current and future satellites are given in the Appendix.

2.3. Cost-Effectiveness of SRS Techniques

At present, SRS techniques of crop evaluation, including data acquisition and interpretation, cost a minimum of two US cents per hectare for command areas larger than one million hectares, and a maximum of about thirty US cents per hectare for command areas smaller than 10,000 ha. SRS for monitoring waterlogging and salinity cost less than one US cent per hectare for large commands, and 10 US cents per hectare for small commands.[2] It is evident that this cost is a very small percentage of the operation and maintenance costs.

3. CRITICAL EVALUATION OF SRS APPLICATIONS IN THE BHADRA PROJECT

The SRS and the GIS achievements of NRSA are briefly described and critically evaluated below.

3.1. Crop Classification

In the early stages of the study, primary data on cropping pattern (rice/non-rice) were generated by visual interpretation of images. Subsequently, information on cropping pattern has been generated by digitally analyzing two-date satellite data. Two-date data analysis was found to be superior to single-date data analysis. Ground truth data were acquired in order to maximize crop discriminability. The sample sites representing the crop groups were selected such that nearby landmarks could be identified on satellite images as well. But this restricts the availability of training sites. Thus, Global Positioning System receivers are recommended for obtaining accurate locations of ground truth data.

The final classification of crops consisted only of rice and non-rice crop groups to maintain acceptable levels of accuracy at the distributary level within the spatial resolution of IRS LISS I sensor data. A more comprehensive classification into rice, sugarcane, semi-dry

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2 Unit costs are based on 1993–94 data, and it is assumed that waterlogging and salinity are monitored along with crop inventory and crop condition.

crops, and garden crops, even at the distributary level, is feasible if LISS II sensor (with 36.25 m resolution) data are used. The selection of the type of satellite data to be used, LISS I or LISS II, will be determined by the degree of detail of the information required, in relation to costs of data acquisition and interpretation.

The multivariate-classification algorithm that was used in the Bhadra study uniquely classified different crop categories in multi-dimensional spectral space. A post-classification validation check was conducted through field visits to more than 300 randomly selected points, and the classification was found to be 90 to 95 percent accurate. Distribution-level statistics were extracted by digitally overlaying the base map of the command area on geometrically rectified crop classification maps. Figure 2 is an example of a superimposed map. The base map was prepared from revenue survey maps and topographic maps. Improvements in classification level and accuracy can be made by adopting knowledge-based image analysis in which spectral classification can be refined by integrating non-spectral parameters such as those associated with soil type and slope.

3.1.1. Alternate Classifications

Classification alternatives may include multistage classification, cross classification, interactive classification, and fuzzy classification. In multistage classification, the purest possible crop cover of different types are first separated; the mixed cover is handled by using additional processing algorithms like principal component analysis or proportionate allocation for classifying the mixed areas. Cross classification is performed several times by giving a larger weight to one crop each time and the intersected crop areas from all these classifications are taken as pure areas; the mixed pixels are treated separately. This package is being conceptualized and developed by the Water Resources Group of NRSA. In fuzzy classification, fuzzy logic is used to classify crop areas. In interactive classification, the classification is repeated automatically to achieve preset accuracy by employing one or more processing algorithms. Contextual classification is knowledge-based classification taking into account neighbourhood associations. Textural classification is based on tonal variation rather than tone alone, and is especially useful for handling mixed areas. Most of these classification schemes require significant computer time, and should be used only if very high accuracy is required or if the cropping situation is very complex.

3.2. Rice Yield Assessment

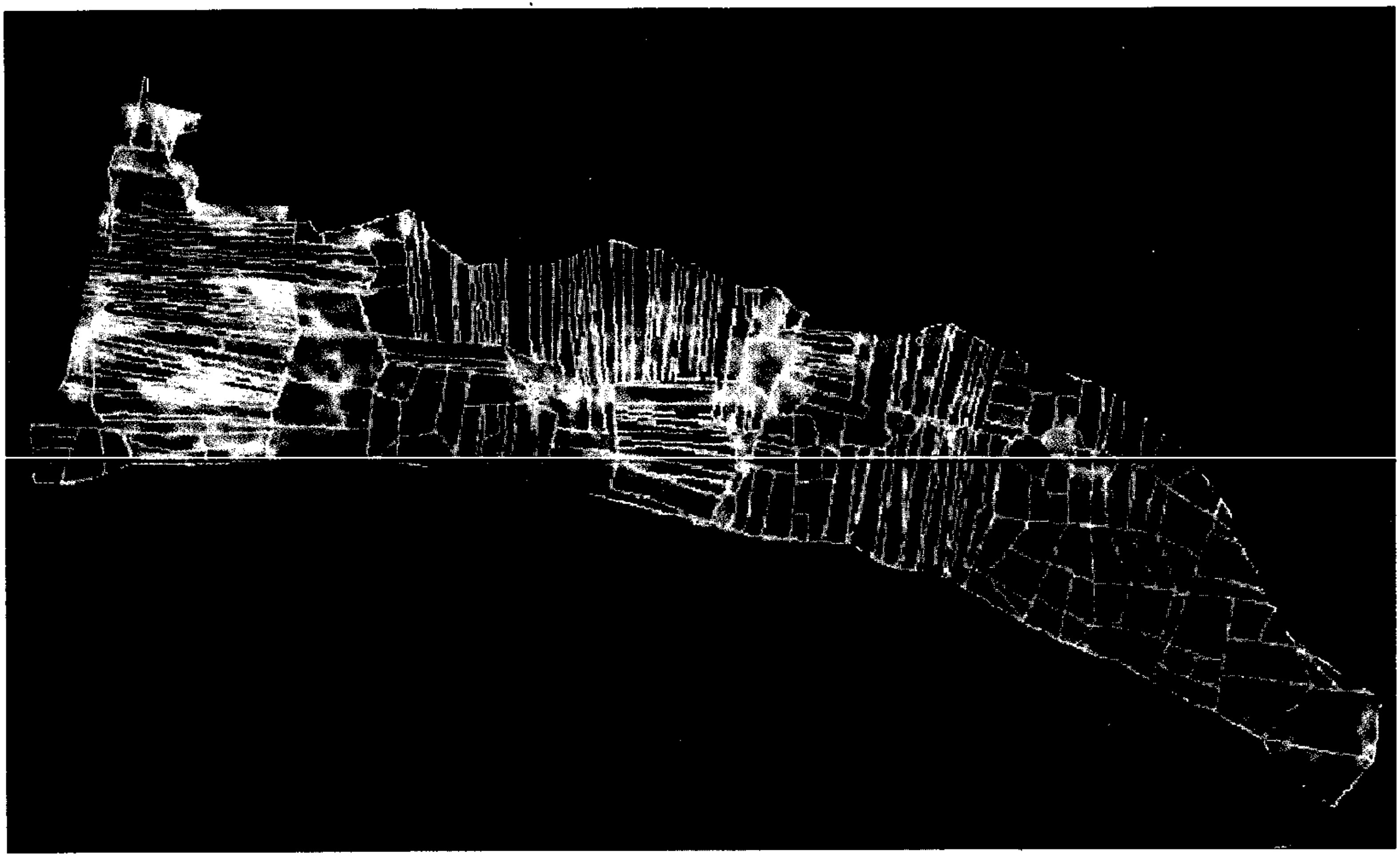
The normalized difference vegetation index[3] (NDVI) is the most commonly used indicator of rice crop condition.

$$\text{NDVI (for IRS data)} = \frac{CH4-CH3}{CH4-CH3}$$

where CH4 and CH3 are the radiance in infrared and red wavelength bands, respectively.

3 Vegetation index is defined as the arithmetic combination of reflected radiation in different bands of the electromagnetic spectrum.

Figure 2. Satellite image (of 12 March 1994) overlaid with cadastral details in Bhadra command.



The rice yields at the crop cutting experiment (CCE) plots in the 1992–93 rabi season were compared with the corresponding NDVI from satellite data. The correlation coefficient is statistically significant as early as panicle initiation stage, and is highest when the crop is at the heading stage. Beyond the heading stage, the correlation coefficient decreases significantly. Since rice is transplanted over a period of days, single-date satellite data do not represent a uniform growth stage of the crop over the command area. To overcome this obstacle, the maximum NDVI value for each rice pixel was picked from multi-date satellite data around the heading stage, since NDVI is maximum at the heading stage. The standard error of the yield model estimate with this approach is smaller than that with single-date satellite data.

Analysis of data resulted in the following rice yield model:

$$\text{Yield (kg/ha)} = 42.23\ \text{TCVI} - 3439.05;$$
$$\text{with standard error of estimate} = 507\ \text{kg/ha};$$
$$\text{and } r^2 = 0.76.$$

The TCVI is the time composited vegetation index value for any rice pixel. This yield model has been validated through farmer surveys and crop cutting experiment data of the 1993–94 rabi season.

3.3. Spatial Variability in Rice Calendar

Spatial information on the transplantation time for rice across the command area has been mapped, and illustrated in Figure 3. The seasonal VI profile of every pixel of rice crop was analyzed to identify the peak-greenness stage. This knowledge was used to calculate the transplantation time, and generate information on spatial staggering of rice transplantation. This is useful for evaluating the compatibility between canal delivery schedule and rice crop calendar at the distributary level. This capability will be further enhanced when IRS-1C WiFS and IRS-P3 WiFS data are available.

3.4. Seasonal Rice Development Profiles

Another part of the Bhadra study was to generate simulated WiFS data of seasonal rice development profiles at distributary and canal-division levels by using data from IRS LISS-I, and Landsat TM for the 1993–94 rabi season.

Figure 3. Spatial variability in rice transplantation.

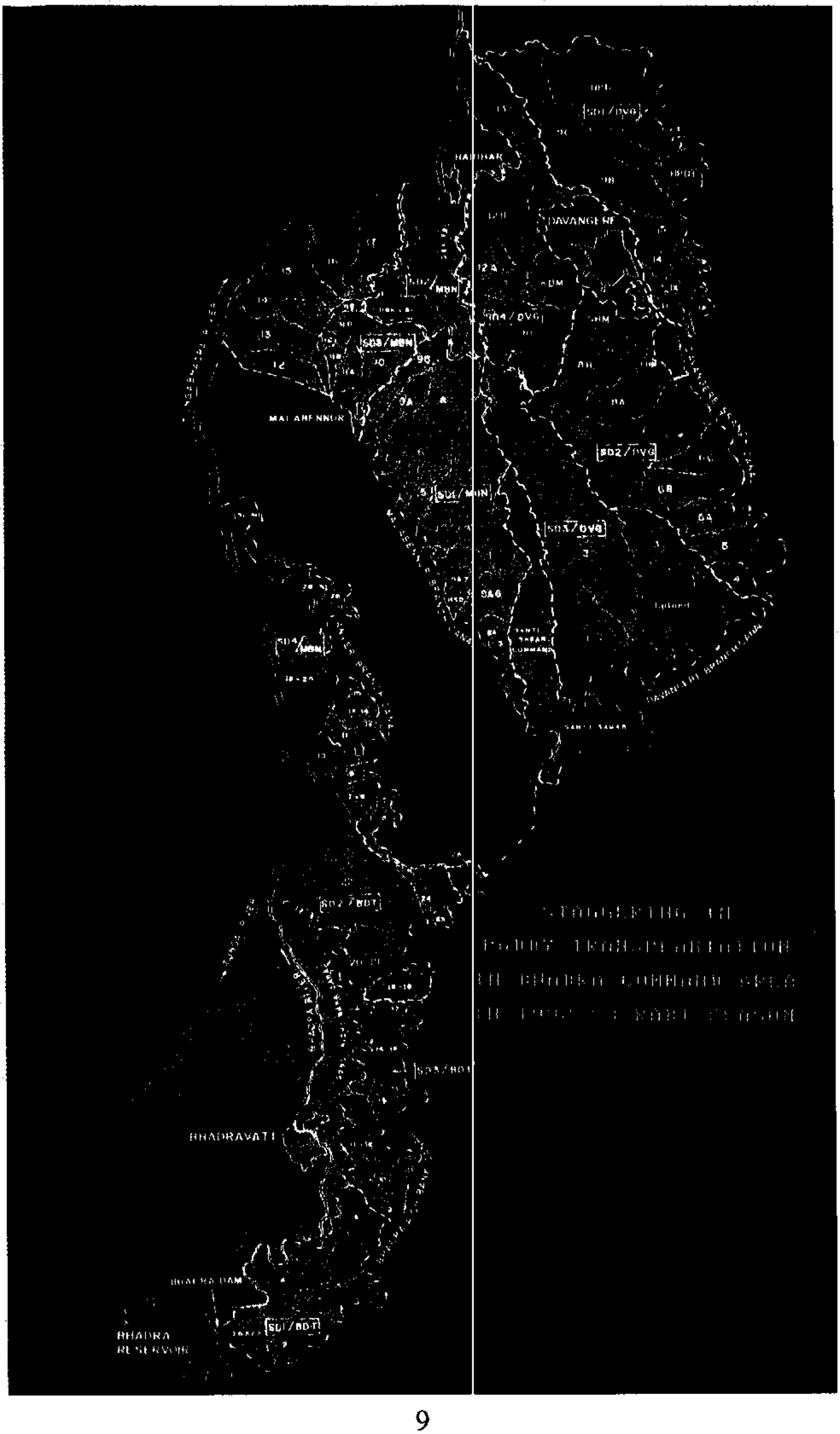


Figure 4a. System performance under NWMP, Bhadra Project: Irrigation intensity and percentage rice area.

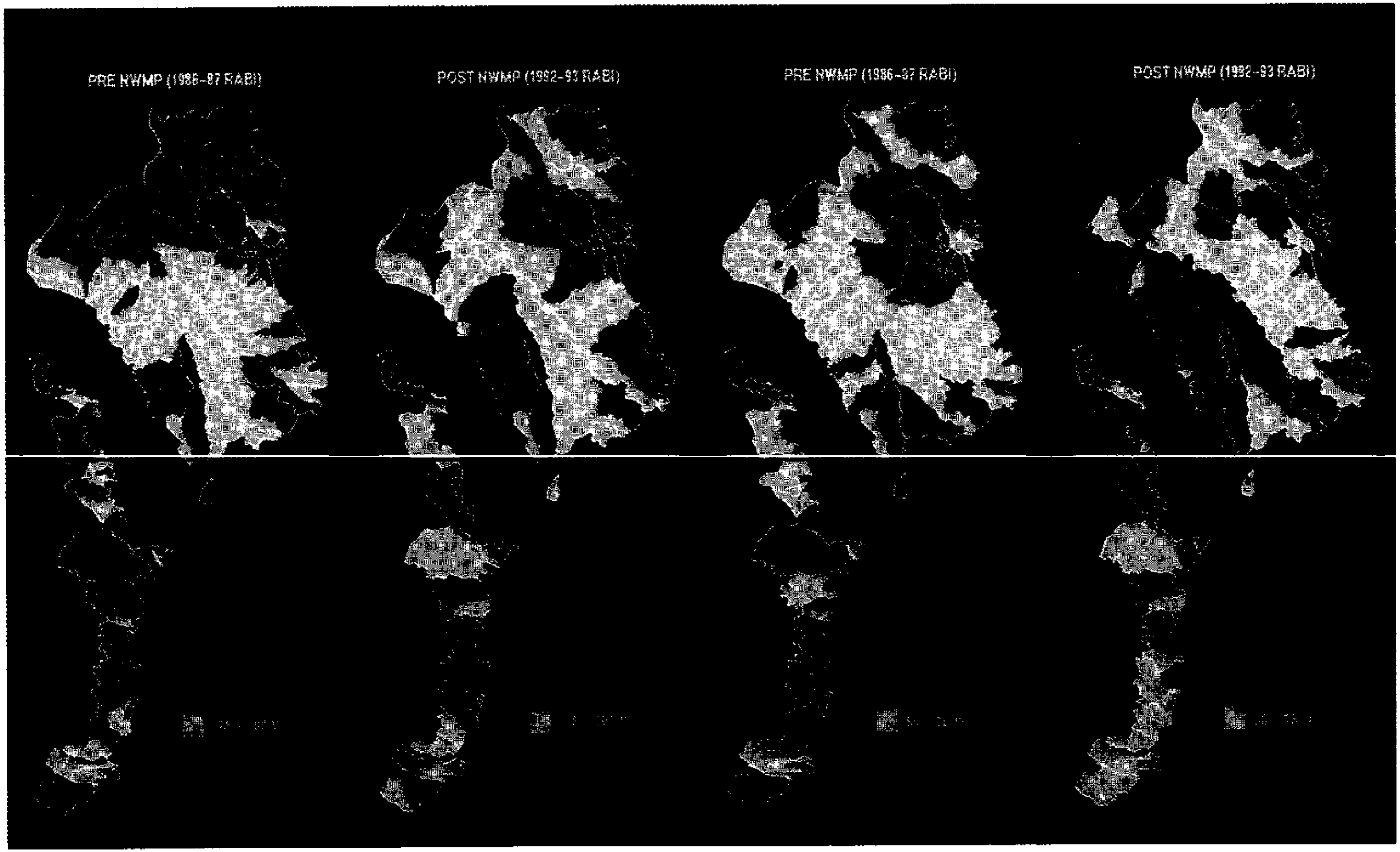
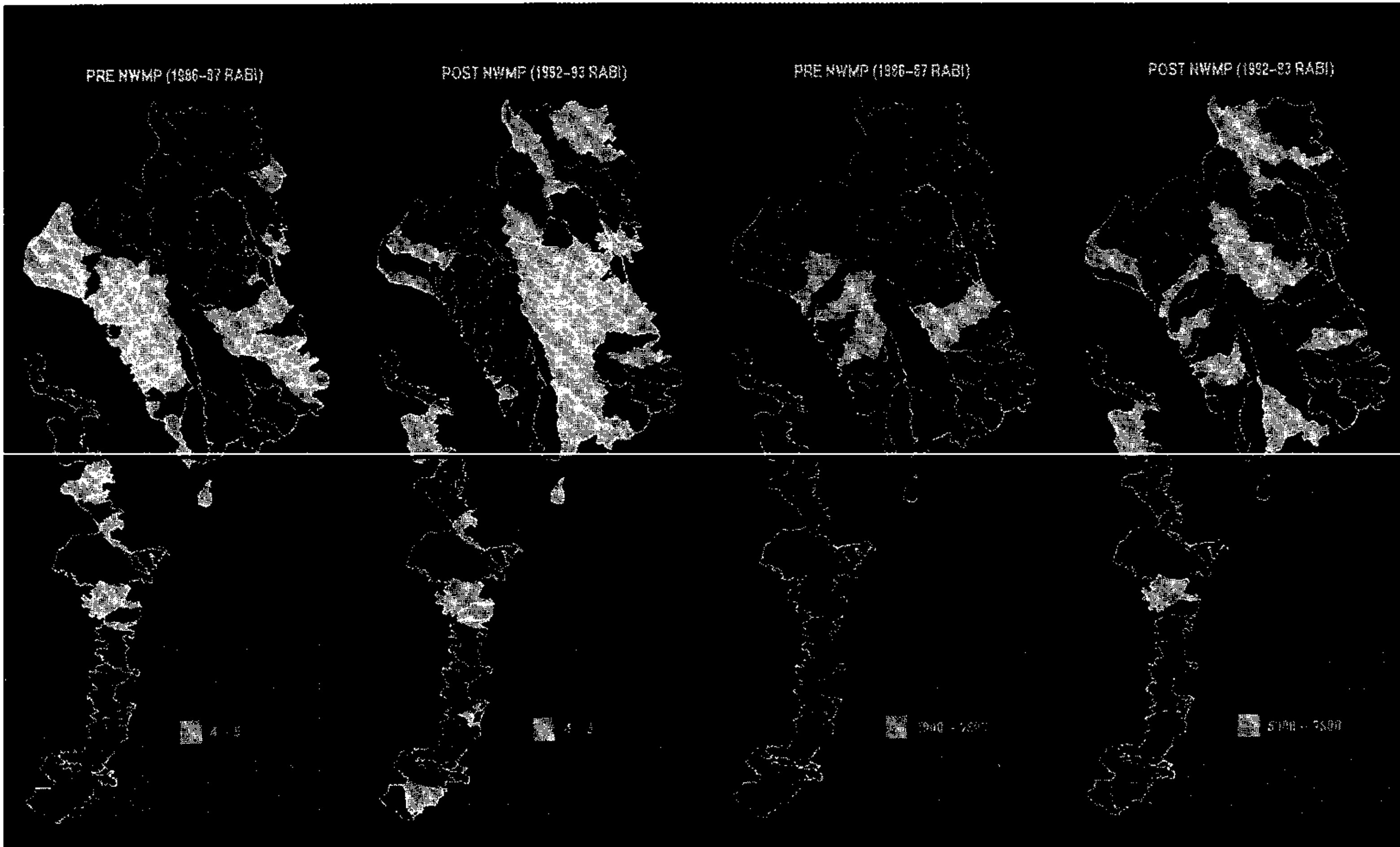


Figure 4b. System performance under NWMP, Bhadra Project: Rice (rough rice) yield and rice production.



Analysis of the above data indicated that WiFS data, in spite of the sensor's coarser resolution of 188 meters compared to 72.5 meters of the LISS-I sensor, effectively captured the time profile of rice development and thus can be used to monitor the rice condition throughout the season even at distributary levels.

This analysis, however, did not consider the radiometric noise due to different illumination geometry from repetitive coverage. While the path radiance variability can be easily corrected, the effect of bidirectional reflectance of vegetation has to be modeled meticulously.

Together, IRS-1B, IRS-P2 and Landsat satellites now provide closer coverage of the command area. Once data from IRS-1C WiFS are available, the dynamic changes in crop condition will be monitored even more effectively. This sensor will have a five-day revisit period that will be improved to 2–3 days when combined with IRS-P3 WiFS in 1996.

3.5. System Performance Evaluation

Primary data on agricultural productivity (cropping pattern and rice yield) have been generated at distributary and reach levels from satellite data for rabi seasons from 1986–87 to 1993–94 (Tables 2, 3 and 4). And the improvement in system performance after NWMP implementation has been evaluated (Table 1). According to Figure 4, irrigation intensity has increased in every sector of the command area, and distributaries with less than 50 percent irrigation intensity are almost negligible. The same figure illustrates that rice production has grown not only in terms of cultivated area, but also in yield intensity and production. Although rice was to be precluded and semi-dry crops encouraged during the rabi season under the NWMP, NRSA found that irrigation intensity during the rabi season increased from 76 percent to about 91 percent, rice area from 56 to 69 percent, and rice yield from 3,786 kg/ha to 4,871 kg/ha during the above period.

Table 2. Irrigated crop area (ha) through the years

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

*As per ground data.

Note: Figure within brackets represents irrigation intensity in percent.

Equity between head- and tail-reach areas of long distributaries has been evaluated in terms of rice yield differences and shortfalls in irrigation intensities (referred to as gap in utilization). From Figure 5, it is evident that the gap in the tail-reach areas, particularly the upper tail-reach areas, is significant when compared to 100 percent irrigation in the head-reach areas. Crop yield estimates have not been available at distributary level. Conventionally, they have been calculated when needed from sample farmer surveys of selected distributaries. Now, for the first time, satellite data have provided objective rice yield information even at reach levels within the distributary, and enabled reliable and more detailed system performance evaluations. For instance, a comparison between Figures 5 and 6 indicates that there is no strong correlation between irrigation intensity and yield intensity. Yield intensities in some of the distributaries with 100 percent irrigation, particularly in the eastern command area, are smaller than yield intensities in other distributaries with lower irrigation intensities. Furthermore, Figure 7 denotes that the rice production per unit of water along the Right Bank Canal is considerably lower than that in other areas. Therefore, it is evident that negative factors besides inefficient irrigation also affect rice yields in these distributaries.

Table 3. Comparison of percent rice area during the rabi season.

Division/Subdivision	Percentage of rice area				
	1986–87	1988–89	1989–90	1992–93	1993–94
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
Davangere Division	51	46	35	66	71
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
Makebennur Division	65	64	76	81	76
Subdivision 1	60*	53*	21*	61	64
Subdivision 2	41*	33*	33*	61	53
Subdivision 3	36*	33*	34*	49	30
Bhadravathi Division	48*	51*	46*	58	49
Total command	56	53	51	69	69

* As per ground data.

Figure 5. Gap in irrigation utilization during rabi 1993–94, Bhadra Project (Scale - 1: 235,500).

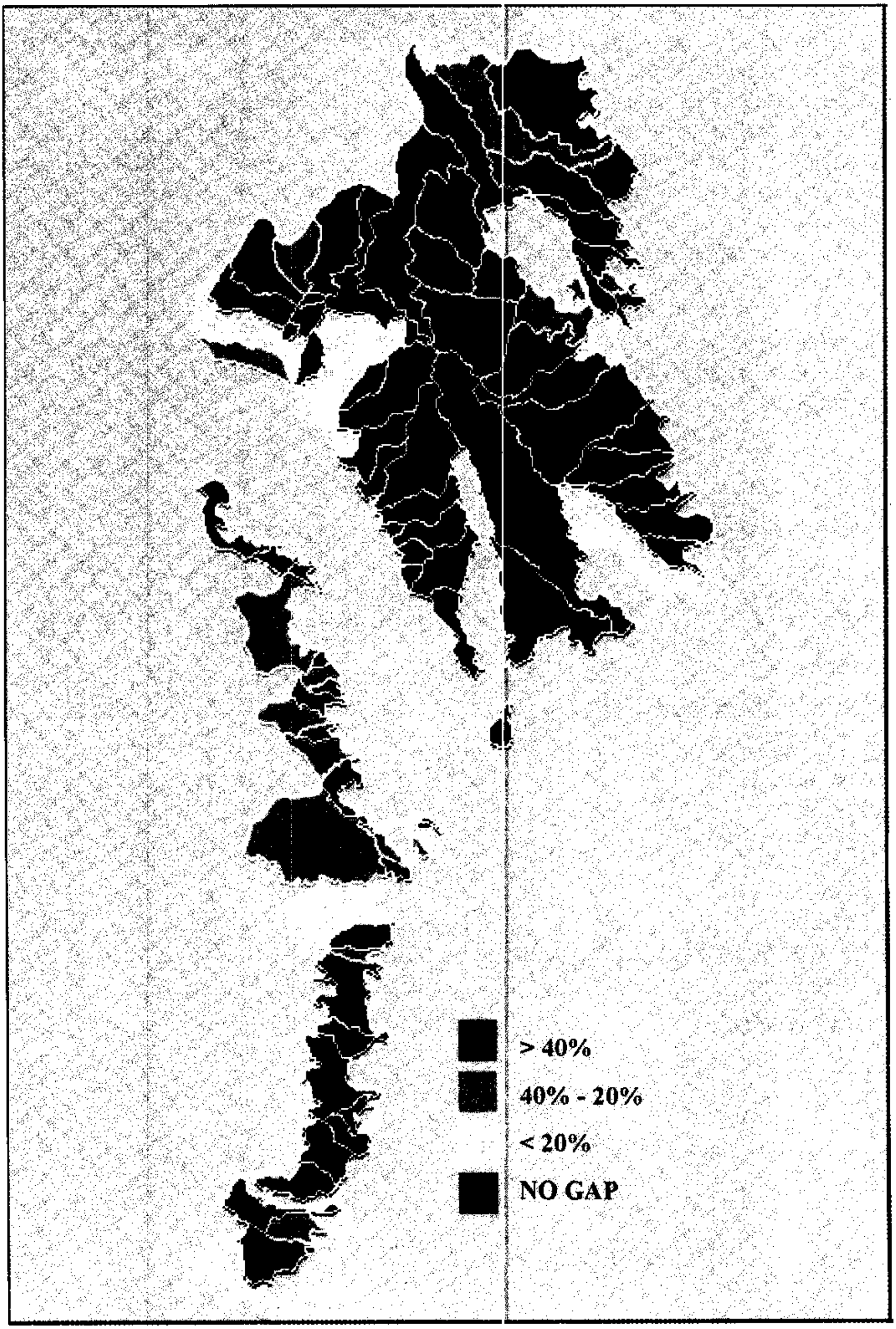


Figure 6. Spatial variability in rice yield during rabi 1993–94, Bhadra Project (Scale - 1: 235,500).

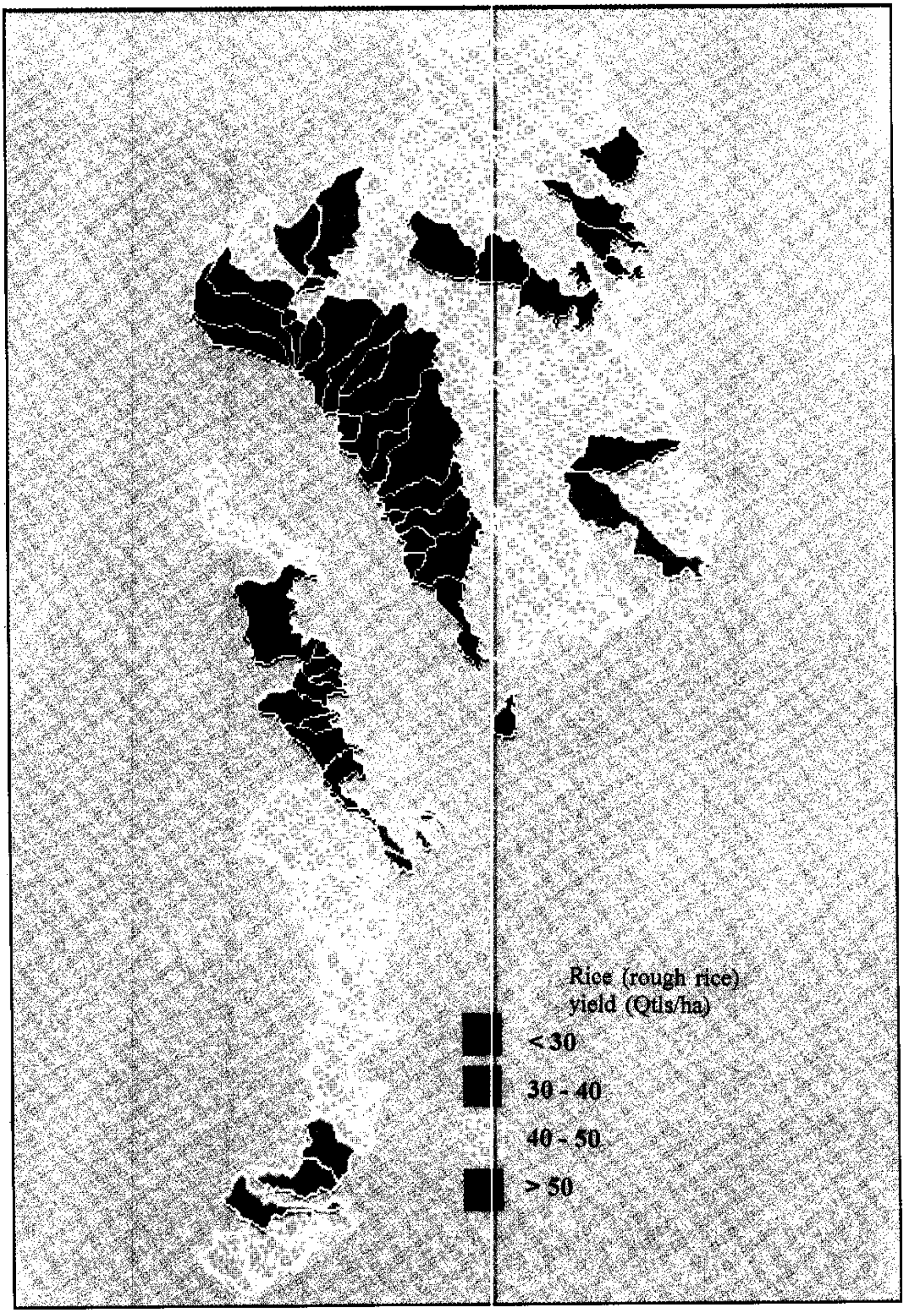


Figure 7. Spatial variability in rice production pre unit of water during rabi 1993–94, Bhadra Project (Scale - 1: 235,500).

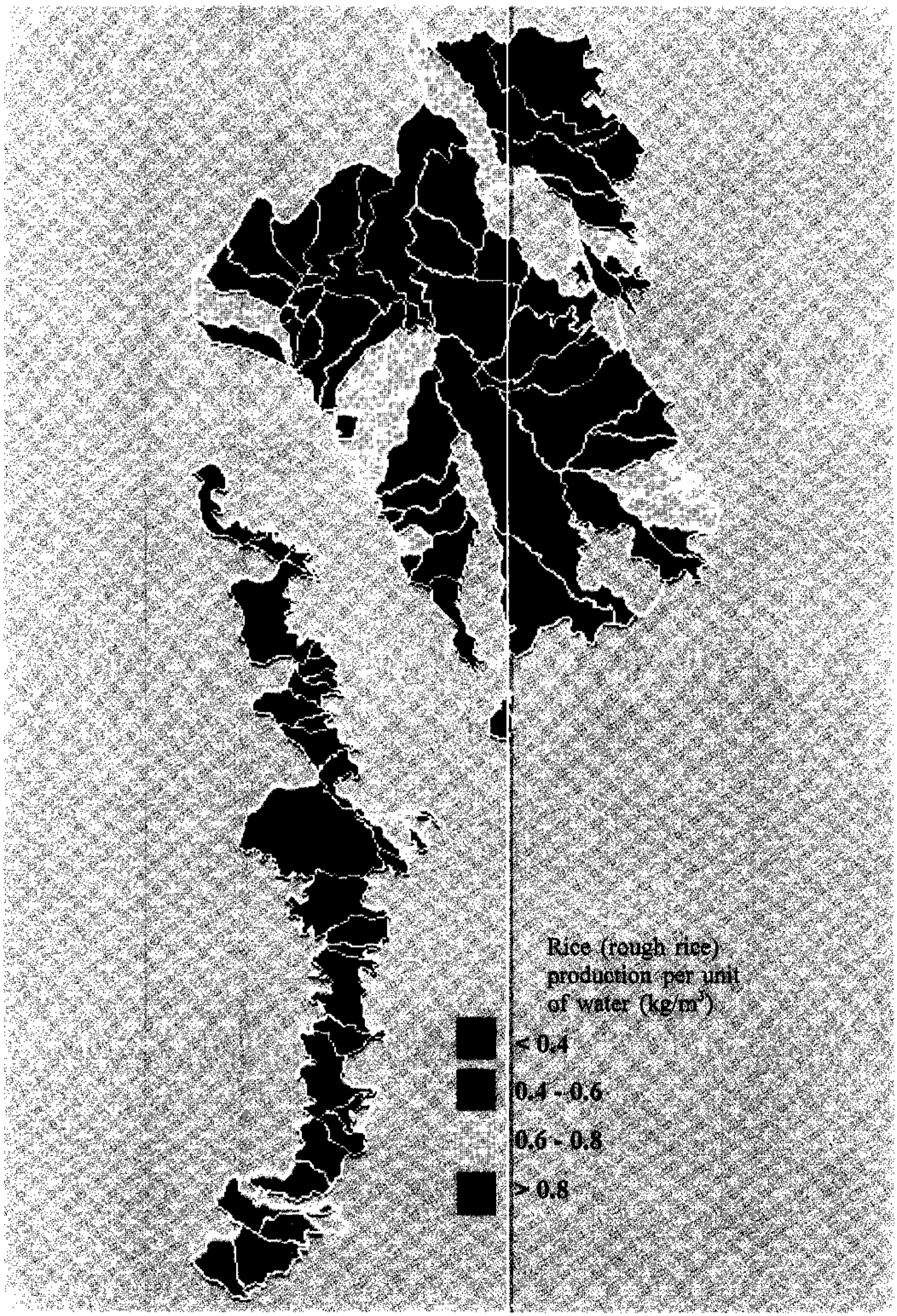


Table 4. Rice (rough rice) yield through the years.

Division/Subdivision	Yield (Qtls/ha)			
	1986-87	1989-90	1992-93	1993-94
Subdivision 1	24.47	45.08	38.03	42.29
Subdivision 2	36.90	46.71	41.82	42.27
Subdivision 3	33.79	42.16	37.98	45.51
Bhadravathi Division	32.18	45.75	39.67	42.88
Subdivision 1	43.45	60.62	57.58	55.82
Subdivision 2	33.08	49.71	39.82	44.79
Subdivision 3	41.28	59.70	49.45	51.77
Subdivision 4	37.43	57.02	48.93	52.36
Malebennur Division	41.10	59.03	52.89	53.38
Subdivision 1	38.16	49.28	40.06	47.50
Subdivision 2	40.31	52.42	44.78	45.90
Subdivision 3	36.83	45.12	43.83	44.16
Subdivision 4	34.13	51.96	44.69	49.39
Davangere Division	37.78	50.53	43.62	46.35
Total command	37.86	53.99	46.85	48.71

Notes: 1986–87 rabi pre-NWMP and no cutoff.
1989–90 rabi with 25 percent cutoff.
1992–93 rabi without cutoff.
1993–94 rabi without cutoff.

Yield estimates can be extended even to non-rice crops and, if non-rice crops are mapped accurately, system performance studies in regard to total agricultural production will also be possible.

Other performance indicators such as depth of water application and rice production per unit of water (Table 1) can be derived from satellite data in conjunction with ground reported rainfall data and canal delivery data. For this initial study, the effective rainfall was considered to be 80 percent of the value measured on ground. The water delivery is measured at the offtake 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 (UCC), which is estimated as the ratio of the weighted sum of deviations of the depth of water supply from the mean and the mean depth of water supply (Table 5).

Table 5. Equity in water supply during the 1993–94 rabi season.

Branch Canal	Christiansen's Uniformity Coefficient among:				
	Subdivision	Distributaries			
		Sub-distributary 1	Sub-distributary 2	Sub-distributary 3	Sub-distributary 4
Bhadravathi	0.752	0.909	0.799	0.750	—
Malebennur	0.929	0.852	—	0.688	—
Davangere	0.919	0.663	0.839	0.934	0.882

Under the NWMP, the performance of the Bhadra Project has shown significant improvement in regard to area irrigated, agricultural productivity, and equity of distribution. Only a few pockets of inequity remain to be corrected by the management.

3.6. 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.

NRSA analyses of the 1992–93 and 1993–94 rabi seasons' satellite data indicated problem distributaries of low irrigation intensity, low rice yield and rice production per unit of water, and high inequity in depth of water application (Tables 6, 7 and 8). These problem distributaries have been identified in terms of the extent of performance inadequacy.

3.7. Waterlogging/Salinity and Crop Productivity

To evaluate the impact of waterlogging and salinity/alkalinity on rice productivity, NRSA started a pilot study in the 8A Distributary of Davangere Branch Canal. Information on revenue survey numbers[4] of plots affected by waterlogging and salinity/alkalinity in three villages (Turchagatta, Ballapur and Kuniaplanhalli) under the 8A Distributary were collected from the Soil Conservation Department. A revenue survey map of the 8A Distributary was photographically scaled down by 1:100,000. The map was then geometrically rectified to match the satellite data of the 1992–93 rabi season that was superimposed on topographic maps. Village boundaries and affected revenue survey numbers were digitized on this reduced map. Vegetation index statistics for the command area were extracted from the satellite data. Preliminary analyses do not clearly indicate any adverse effects from waterlogging and salinity/alkalinity in any of the three villages. A further intensive study of the above three villages, together with additional distributaries reported to have been affected by waterlogging, is underway.

Table 6. Distributaries with a gap in irrigation utilization during 1993–94 rabi (irrigation intensity < 75%).

Division	Subdivision	Distributaries
Bhadravathi	3 2	17 24
Malebennur	3 4	12, 14, 15, 16 7–8, 10, 27, 31–40
Davangere	4 1	12A, 12B, 13 13, 9C, HPD

4 Revenue survey numbers function as plot identification numbers, and are classified according to the quality of the land and are mostly used when levying taxes.

Table 7. Distributaries with persisting gap in irrigation utilization during 1986–87 rabi and 1993–94 rabi (irrigation intensity < 75%).

Division	Subdivision	Distributaries
Bhadravathi	2	24
Malebennur	3	14, 15, 16
	4	10, 31–40
Davangere	4	12A, 12B, 13
	1	13, 9C, HPD

Table 8. Distributaries with low rice yield compared to division average yield.

Division	Distributaries
Bhadravathi	6, 23, 25, 26
Malebennur	15, 16, 17, 26, 40
Davangere	3

4. IMPROVED DESIGN OF CROP CUTTING EXPERIMENTS

The present design of the crop cutting experiments (CCE) is proportional to crop area. This is a simple random sampling technique. Analyses of the design during the 1992–93 and 1993–94 rabi seasons based on spatial rice yield patterns showed that simple random sampling techniques can lead to biased results. Stratification of rice plots based on rice condition and subsequent selection will provide more homogenous samples, and thus, will reduce errors in estimates. An improved design of CCE, with more reliable yield estimates, has been developed based on satellite-derived rice area and crop condition at the time of flowering. This design was discussed with the officers from the Command Area Development Authority, Agriculture Department, Department of Economics and Statistics, and the Irrigation Department, and was implemented in the 1994–95 rabi season.

5. GIS DEVELOPMENT

A Geographic Information System using PAMAP software was developed to help the system performance evaluation and diagnostic analysis. The digitized base map provided the geographical framework. The necessary ground and satellite data were incorporated into PAMAP, and temporal and spatial data of agricultural productivity from each distributary

were analyzed (Figures 5 and 6). The GIS approach was also used for the diagnostic analysis of three distributaries selected on system performance criteria from the Malebennur Canal Division. This involved digitizing and superimposing relevant cadastral maps with satellite imagery. Field boundaries identified in enhanced satellite images and topographic maps helped geometrical rectification of cadastral maps. Satellite-derived cropped area, cropping pattern and rice productivity were averaged over three reaches of each distributary to enable problem characterization.

Information from the revenue survey conducted among 103 farmers and Irrigation and Agriculture department officials was averaged over the head-, middle- and tail-reach areas. The poor performance of the 15th distributary was attributed to poor water availability due to two reasons—canals closed long before the crop harvesting period and water did not arrive at the tail reach along the dilapidated canal; a supplementary reason was low fertilizer use.

Linking GIS with the irrigation information system will facilitate effective and efficient management of canal delivery and scheduling, increase awareness of crop water requirements, and facilitate analysis of hydrometrological data and operational plans.

6. COMPARISON OF DATA FROM SRS AND GROUND COVERAGE

A comparison of data on rice area gathered using the satellite technique and ground coverage is presented in Table 9. The data are reasonably close, and the maximum error is only 7 percent.

Table 9. Comparison of satellite-derived data with ground-coverage data.

Year	Area under rice (ha)	
1986–87	41,176[a]	40,768[b]
1989–90	34,357	33,852
1992–93	61,013	56,788

Sources: [a]NRSA Report, December 1994, Tables 1 and 2, pp.12–13.
[b]WBA-NWMP Phase II, Bhadra Reservoir Project, August 1994, Table 8, p.34.

7. LIMITATIONS OF SRS AND POTENTIAL FUTURE ENHANCEMENT

Some of the main limitations are discussed below. It is hoped that with further research and improved technology, NRSA and IIMI will be able to overcome these shortcomings in the future.

- An analysis of percentage cloud cover during the twelve months of 1993 indicated that cloud cover will significantly restrict the application of SRS technology over much of India during the monsoon calling for improved methodology using microwave data.

- Spectral emergence of crops is detected by the increase in the vegetation index value. This is the earliest time at which a crop inventory can be done using SRS. When satellite revisit periods are long, the time of spectral emergence is not precisely identified. It is hoped that the IRS-IC WiFS sensor that will gather data with five-day repetitivity will overcome this deficiency.

- Satellite data obtained on different days/years used to assess crop conditions or to make yield estimates need to be normalized: for radiometric differences due to atmospheric effects and sensor characteristics, for geometric differences due to sun angle, and for the ageing of the satellite sensor used. The existing procedures such as linear transformation, regression analysis, mean and standard deviation normalization are not suitable when dynamic changes like crop conditions are to be monitored. The procedure adopted in the Bhadra study proved to be more effective when multi-date satellite data were available.

- The spatial resolution of WiFS can also limit crop condition assessment capabilities when the crops are not contiguous but distributed in small patches. A priori knowledge of the cropping pattern and the typical temporal profiles of individual crops can help decompose the WiFS profile into crop-specific components.

- Improved crop classification methodologies are required to improve spectral differetiation among crops.

8. CONCLUDING REMARKS

The Bhadra study has demonstrated the potential and cost-effectiveness of SRS techniques for routine monitoring and performance evaluation of large-scale irrigation systems in developing countries. Effective integration of GIS with SRS techniques further enhances performance evaluation and diagnostic analysis capabilities.

The study has also indicated that the operational use of such techniques called for research and development work in regard to better crop classification algorithms, yield prediction models, development of more appropriate vegetation indices, and satellite data normalization procedures.

SRS techniques can be used in irrigated agriculture not only as an operational tool for monitoring and evaluation, but also in project formulation and in identifying areas that need corrective management strategies.

IIMI is now undertaking a comprehensive study to explore the potential of this cost-effective tool as a regular operational tool in irrigation water management.

Appendix

ORBITAL AND SENSOR CHARACTERISTICS

OF

CURRENT AND FUTURE SATELLITES

Table A.1. Orbital characteristics of current remote sensing satellites.

	SATELLITE					
	IRS-1A/ IRS-1B	**IRS-P2**	**Landsat-5**	**Spot 1/ Spot 2**	**NOAA-11**	**ERS-1**
Altitude (km)	904	817	705	832	833–870	817
Orbital period (minutes)	103	101	99	—	102	102
Equatorial crossing time (hours)	10.00	10.3	9.3	10.3	14.3	10.3
Repetitivity (days)	22	24	16	26	0.5	3,35,175

Table A.2. Sensor characteristics of current remote sensing satellites.

Satellite	**Sensor**	**Band no.**	**Band width**	**Ground resolution (m)/Swath (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	0.62–0.68	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	36.25/ 74	7
IRS-P2	LISS II	1	0.45–0.52	32X37/ 131	7
		2	0.52–0.59	32X37/ 131	7
		3	0.62–0.68	32X37/ 131	7
		4	0.77–0.86	32x37/ 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/ 185	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/SPOT 2	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		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
ERS -1	SAR	1	5.3 GHz (C - Band)	25/ 100	2.5 (dB)

Table A.3. Orbital characteristics of future remote sensing satellites.

	SATELLITE				
	IRS-1C	**IRS-P3**	**Landsat-7**	**ERS-2**	**Radarsat**
Altitude (km)	817	817	705	780	798
Orbital period (minutes)	102	101.35	99	102	101
Equatorial crossing time (hours)	10.3	10.3	9.3	—	—
Repetitivity (days)	LISS III - 24 days WiFS - 5 days	MOS - days WiFS - 5 days	16	35	24

Table A.4. Sensor characteristics of future remote sensing satellites.

Satellite	Sensor	Band No.	Band Width	Ground resolution (m) /Swath (km)	Radiometric resolution (Bits)
IRS-1C	LISS III	2	0.52-0.59	23.5/ 141	7
		3	0.62-0.68	23.5/ 141	7
		4	0.77-0.86	23.5/ 141	7
		5	1.55-1.70	70.5/ 148	7
	PAN	PAN	0.50-0.75	5.8/ 70	6
	WiFS	3	0.62-0.68	188/ 774	7
		4	0.77-0.86	188/ 774	7
Landsat-7	ETM	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
		8 (PAN)	0.50-0.90	15/ 185	8
IRS-P3	MOS - A	4 BANDS	0.755-0.768	1569x1395/195	16
	MOS - B	13 bands	0.408-1.01	523/ 200	16
	MOS - C	1 band	1.6	523x644/192	16
	WiFS	3	0.62-0.68	188/ 804	7
		4	0.77-0.86	188/ 804	7
		5	1.55-1.70	188/ 804	7
ERS-2	SAR	1	5.3 GHz (C-band)	25x22/ 100	2 (dB)
Radarsat	SAR	1	5.3 GHz (C-band)	28x30/ 100	