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Research Report

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R. Sakthivadivel
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International Water Management Institute

Research Reports

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Research Report 28

Performance Evaluation of the Bhakra Irrigation System, India, Using Remote Sensing and GIS Techniques

*R. Sakthivadivel, S. Thiruvengadachari,
Upali Amerasinghe, W. G. M. Bastiaanssen,
and David Molden*

International Water Management Institute
P O Box 2075, Colombo, Sri Lanka

The authors: R. Sakthivadivel, Upali Amerasinghe, W. G. M. Bastiaanssen, and David Molden are, respectively, senior irrigation specialist, research associate, remote sensing specialist, and research leader, performance program, IWMI, Colombo, Sri Lanka. S. Thiruvengadachari was formerly group director, water resources, National Remote Sensing Agency, Hyderabad, India, and is now a private consultant.

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The International Irrigation Management Institute, one of sixteen centers supported by the Consultative Group on International Agricultural Research (CGIAR), was incorporated by an Act of Parliament in Sri Lanka. The Act is currently under amendment to read as International Water Management Institute (IWMI).

Contents

Acronyms

APAR	Absorbed photosynthetically active radiation
AVHRR	Advanced very high resolution radiometer
BML	Bhakra Main Line canal
CCA	Culturable command area
GIS	Geographic information system
GPS	Global positioning system
IRS	Indian Remote Sensing satellite
LISS	Linear Imaging Self-Scanning sensor
NDVI	Normalized difference vegetation index
NRSA	National Remote Sensing Agency
PAR	Photosynthetically active radiation
SPOT	Satellite pour l'Observation de la Terre
WiFS	Wide field sensor

Summary

Synergistic application of satellite remote sensing and geographic information system (GIS) techniques were used to analyze the agricultural performance and sustainability of the Bhakra Irrigation System in India. Although this large wheat-based irrigation system is operated under the *warabandi* principle of rotational water supply, its high agricultural productivity is supported significantly by heavy withdrawal of groundwater. Analysis of multidate satellite data during the 1995/96 rabi season helped to generate spatially distributed information on total cropped area, area under wheat, and wheat productivity per unit area. This information was integrated with other relevant ground-derived data on soil type, water-table depth and its long-term trend, groundwater quality, distributary-level discharge, rainfall, and evapotranspiration in a GIS environment using IDRISI software. The agricultural and hydrologic setting of the command area as well as the long-term trends in agricultural productivity and groundwater regime was assessed. Diagnostic analysis of problem areas and the development of possible action plans at the regional level are made feasible with information from the GIS on crop yield, canal water supply, and soil salinity. The study thus demonstrates the synergy possible from applying satellite remote sensing and GIS to evaluate trends in rising water tables and salinity, which are two important threats to the sustainability of irrigation systems.

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Introduction

Irrigated agriculture will play a major role in determining the future food security of most Asian countries, and it will also be the major contributor to the additional food production required as world population expands (Svendsen and Rosegrant 1994). Therefore, it is important to raise the agricultural performance of low-productivity irrigation systems, while sustaining the performance of more-productive systems.

In many countries, and particularly in India, accurate evaluation of irrigation system performance and sustainability is hampered by lack of adequate, reliable, and timely irrigation statistics. Usually, performance indicators such as yield, cropping intensity, and irrigation intensity are measured at an aggregated level, often at the state or national levels. Data at project level are rarely collected. If collected, they frequently are unreliable or not easily accessible (Murray-Rust and Merrey 1994). It is in this context that IWMI, as part of its ongoing research program on the use of emerging technologies in irrigation management, applied remote sensing and geographic information system (GIS) techniques to study the Bhakra Irrigation System and to analyze agricultural performance issues.

The diagnostic analysis of the operation of the Bhakra canal command area in northwest India reported here was the result of collaborative research by the National Remote Sensing Agency, Hyderabad, India, the Haryana State Irrigation and Water Resources Department, Chandigarh, India, and the International Water Management Institute, using data from the DLO-Winand Staring Centre, Wageningen, The Netherlands. Satellite remote sensing was utilized to obtain data on basic agronomic characteristics and crop yield. Hydrologic analysis based on ground data was carried out, aided by GIS and supplemented with output data from a distributed computer model that simulates the spatio-temporal behavior of canal water, soil water, and groundwater. The salient findings from this research are reported here and in Remote Sensing and Hydrologic Models for Performance Assessment in Sirsa Irrigation Circle, India (Bastiaanssen et al. 1998).

The Bhakra Irrigation System is above average in agricultural performance compared with other irrigation systems in Haryana (Economic and Statistical Organization 1995). Currently, Bhakra contributes about 40 percent of Haryana's wheat production and 6 percent of national production. Through its warabandi principle (see box) of rigid rotational water distribution, Bhakra is designed to deliver water equitably to farmers over an extended area. But farmers' success in growing a high proportion of wheat and reaching high production levels is being achieved by pumping groundwater. Thus whether the high agricultural productivity can be sustained with the present water use pattern is in doubt.

The Warabandi Principle

The Bhakra project, like other surface irrigation schemes in Haryana, was designed to distribute a limited supply of water to the greatest number of farmers possible over a large area. The distribution of water is governed by the warabandi principle, a rigid rotational cycle of fixed duration, frequency, and priority level (Malhotra 1982). The attraction of warabandi system is that it allocates water in proportion to the size of the farmer's land holding, and it is simple to plan and operate. The key features of the warabandi system are as follows:

- Individual farms are aggregated into hydrologic units (chaks) of 100 to 400 hectares (50 to 200 farms).
- Each chak is served by a watercourse whose capacity is proportional to the size of the chak. Design duty at the chak level in the Bhakra system is 0.17 $l\ s^{-1}\ ha^{-1}$ (1.5 mm/day, one-fifth to one-third of peak evapotranspiration in the irrigation season), so that watercourses range in capacity from 17 to 70 l/s (Berkoff and Huppert 1987).
- Each farm holding in the chak is entitled to take the full supply in the watercourse during a specified period proportional to its size. By having the entitlement period proportional to the size of holding and having watercourse flow proportional to the size of the chak, all farmers in the command under distributaries that receive water in that week are ensured a uniform volumetric allocation per hectare per week.
- Watercourses are ungated and are served by parent channels (minor canals) that have a capacity exactly equal to the sum of the capacity of the off-taking watercourses (allowing for losses).
- Minor canals in turn are usually gated and are served by a distributary whose capacity is exactly equal to the combined capacity of off-taking minors and direct outlets to watercourses (again allowing for losses).

Since the water allowance per hectare is very low, water scarcity is a built-in feature of the system. Originally, the operating principle was conceived to ensure equitable distribution of run-of-river flows. Since the pattern of availability of water was unpredictable, a further procedure was required to deal with uncertainty.

This procedure, known as "rostering," consists of assigning the distributaries into groups and establishing rotating performance orders (priority orders) for the groups. Typically, a large command has three groups, say, A, B, and C. In the first week, group A has first priority, B the second, and C the last priority. In the second week, group C moves to first priority, A to the second, and B to third. In the third week, the priority order changes again, and in the fourth week the cycle begins all over. Fluctuations in flow during a week are absorbed in the lower priority groups. Reidinger (1971), Malhotra (1982), and Berkoff and Huppert (1987) provide further details about the warabandi principle.

Construction of reservoirs added a substantial degree of control to irrigation systems, and it became possible to schedule water deliveries to coincide with critical periods of the agricultural year. Yet, despite these infrastructure improvements, the procedure of allocating water through the turn system at the chak level and through canal rostering has remained essentially unchanged.

The research program involved both methodological developments and operational application to generate required agricultural performance data at the pixel level of satellite data, which could then be aggregated to any desired level, including the entire project area. This study complements an earlier IWMI study on the Bhadra project, a rice-based irrigation system in Karnataka, India (Thiruvengadachari and Sakthivadivel 1997). These two studies demonstrate the potential of remote sensing and GIS for evaluating the performance of irrigation systems under two of India's major food crops.

Multispectral satellite data can be used to derive information on cropped area, cropping pattern and calendar, and crop productivity in irrigation systems (Thiruvengadachari and Sakthivadivel 1997). Waterlogged and salt-affected soils have been mapped (Dwivedi 1992). The unique capabilities of satellite remote sensing techniques for generating spatial data and for monitoring change during a season and across years allow the performance of irrigation systems to be assessed effectively (Thiruvengadachari 1996). Conventional surveys typically provide only overall estimates for the total command area; they are rarely adequate to provide spatially distributed estimates of crop yield within a command area.

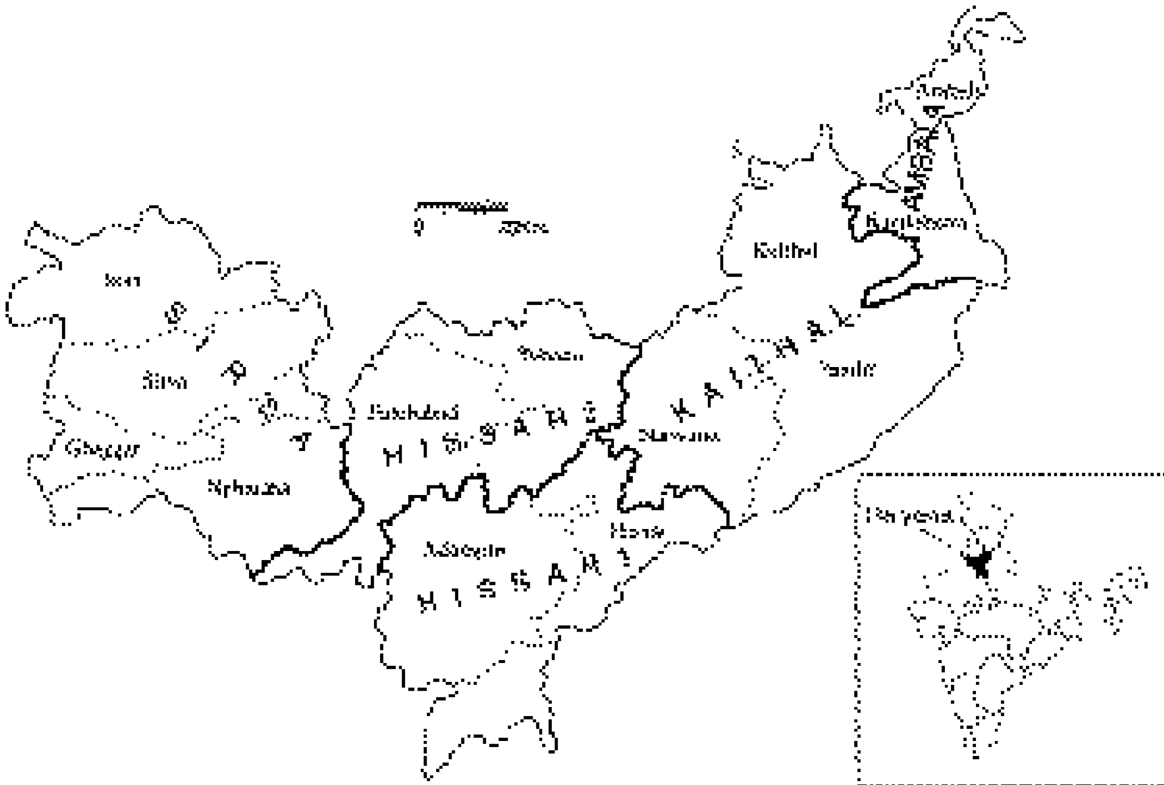
Earlier studies have shown the usefulness of some specific applications of satellite remote sensing technology, such as inventory of irrigated land (Huston and Titus 1975; Draeger 1976) or estimates of the size of the wheat and barley area (Pestemalci et al. 1995). The Bhakra system study, however, was initiated specifically to demonstrate the application of satellite remote sensing and GIS techniques for evaluating the current performance and sustainability of a large wheat-based irrigation system and to show the utility and cost-effectiveness of those techniques as diagnostic tools for irrigation system improvement. The raster format of satellite-derived data is ideal for importing into a GIS environment. The information can then be combined with other spatial and nonspatial data, such as water-table depth, groundwater quality, long-term groundwater trend, problem soil area, canal discharge, and well discharges, for correlation analysis. Effective water resources management increasingly calls for integration of these technologies with hydrologic modeling (Tim 1996). Bastiaanssen et al. (1998) provides an example of integrating satellite remote sensing and GIS with hydrologic models.

Specific objectives of the Bhakra system study were, first, to generate disaggregated data on total irrigated area, area under major crops, and wheat productivity and, second, to integrate satellite-derived data with ground-measured data to identify factors that constrain agricultural performance and threaten the sustainability of the agricultural production system. A critical issue that this research addresses is whether present practices for allocating and distributing canal water supplies can continue without detriment to agricultural production and the groundwater regime.

The Bhakra Irrigation System

The Bhakra canal system in Haryana State has a cultivable command area of 1.3 million hectares. This system and the Western Yamuna canal systems supply water to 88 percent of the 2.8 million hectares of surface-irrigated land in the state of Haryana. The Bhakra command area in Haryana is divided into five water service circles (fig. 1).

FIGURE 1.
Water service circles and their divisions in the Bhakra Irrigation System, Haryana State, India.



Climate

The area has a semiarid to arid climate, and hot weather prevails in the command between March and October. Most rainfall occurs from July to September. According to the *World Water* and *Climate Atlas,*[1] the weighted annual average rainfall over the command area is roughly 600 millimeters. It varies from 750 millimeters in the northeastern part of the command to less than 400 millimeters in the southwestern part. Rainfall in the dry season (rabi) ranges from 100 millimeters in the east to less than 50 millimeters in the west. Irrigation requirements also vary from east to west. Annual evapotranspiration over the command ranges from 1,250 millimeters in the northeastern part to 1,650 millimeters in the southwestern part.

Cropping Patterns

Kharif (June-October) and rabi (November-April) are the principal agricultural seasons. When the Bhakra canal command was being planned, the cropping pattern assumed in kharif was fodder, cotton, gram (chickpeas), barley, orchards, and vegetables. The pattern assumed in rabi was wheat, fodder, gram, barley, and vegetables. Now the cropping pattern and the cropping intensity are quite different. Most of the irrigated area is occupied by high yielding varieties of rice, wheat, and cotton. Also, the irrigated area has expanded over the years. Irrigated wheat occupied 69 percent of the total irrigated area during rabi 1992/93 and 71 percent during rabi 1993/94, about double the percentage of wheat area planned for the project.

[1]Accessible through the Internet (www.iwmi.org) or on CD-ROM.

Canal Terminology

Main canal. The *main canal* is the principal artery of the distribution system. It takes off from the reservoir. In the Bhakra system, the main canal carries a discharge ranging from 250 to 400 m^3/s.

Secondary canals. Secondary canals take off from the main canal. Large secondary canals—*branch canals*—carry 30 to 150 m^3/s. Small secondary canals—*distributaries*—carry 10 to 30 m^3/s.

Tertiary canals. Tertiary canals take off from secondary canals. Large tertiary canals—*distributaries*—carry 10 to 30 m^3/s. Small tertiary canals—*minors*—carry 5 to 10 m^3/s.

Other canals and channels. Fourth-order canals take off from tertiary canals. *Minors* carry 5 to 10 m^3/s. *Watercourses* carry less than 5 m^3/s. *Field channels* take off from watercourses. Other terms, such as *sub-branch, subdistributary,* and *subminor* are used to subclassify larger units, but no well-defined discharge ranges are associated with them.

Canal Water Supplies

The Bhakra canal network has three operational systems: the tail of Bhakra Main Line (BML Tail), the BML-Barwala link, and the Narwana-Sirsa system. The three operational systems receive their water supplies from the Gobind Sagar Reservoir and from the diversion barrage at Tajewala on the Yamuna River. The Gobind Sagar Reservoir is impounded by the Bhakra dam. It provides Haryana with its share of the flows of the Ravi, Beas, and Sutlej rivers of the Indus River system. The diversion barrage at Tajewala on the Yamuna River provides Haryana with its share of the uncontrolled Yamuna flows from the Ganges River system.

The Narwana-Sirsa system and the BML-Barwala link are supplied partly from the Yamuna and partly from waters of the Indus rivers stored by the Bhakra dam. Water from Gobind Sagar Reservoir is used to supplement the run-of-river availability from the Yamuna through two links—the Narwana branch and the BML-Barwala link. The BML Tail system, however, is entirely supplied from the Gobind Sagar Reservoir, giving it the most stable and predictable water supplies among the three operational systems.

Groundwater

In addition to canal water, groundwater plays a major role in the irrigated agriculture of the Bhakra canal command. Shallow and deep tube wells irrigate an area equal to or greater than the area irrigated by canal water (Economic and Statistical Organization 1995).

Twenty-four percent of the command area is underlain by marginally saline to saline water, and in the last two decades the water table has risen substantially (5 to 10 m) in a large portion (64%) of the command. The continuing rise in water tables in these areas is one of the major problems in the command. But in Kaithal, Kurukshetra, and Ambala districts, due to extensive development of good quality groundwater, the water table dropped by 2 meters, 8 meters, and 4.7 meters, respectively, between 1979 and 1994.

Infrastructure Improvement

To reduce seepage and to improve the conveyance efficiency of canal networks, as well as to control the groundwater rise, lining of canals and watercourses was begun two decades ago and is continuing. Seventy percent of the 17,500 kilometers of watercourses in the command are now lined.

Rabi Season Canal Rotations

During rabi 1995/96, the Bhakra system was operated from 3 October 1995 to 14 April 1996, following a set pattern of rotations among the three operational systems (table 1). As a result of the allocation schedule and the fixed water allowance per unit area, the command area serviced by the BML Tail channels received the largest quantity of water per unit area because water was supplied on more days during the season than it was in the other two operational systems. Compared with the supply per unit area of BML Tail, the BML-Barwala link received only 75 percent as much and the Narwana-Sirsa system received only 50 percent as much.[2] It is noteworthy that zones that have fresh groundwater (Narwana-Sirsa system) received the smallest amount of canal water per unit area, and the zones that have saline or marginally saline groundwater[3] (BML Tail) received the most.

TABLE 1.
Canal rotational schedule for rabi season.

Operational system	Groups of distri-butaries	Groups getting water simulta-neously	Rotation (days)	
	(no.)	(no.)	"On"	"Off"
Narwana-Sirsa	3	1	8	16
BML-Barwala Link	2	1	16	16
BML Tail	3	2	8	8

Materials and Methods

The present study relies on data from remote sensing combined with ground observations and data collected in the field. All sources of information were integrated through GIS for correlation analysis. Crop area, cropping pattern, and crop yields were analyzed with measurements from IRS-LISS (Indian Remote Sensing Satellite—Linear Imaging Self-Scanning sensor) (Thiruvengadachari and Sakthivadivel 1997). Data on daily canal discharges were provided by the Haryana Irrigation and Water Resources Department and were summarized into monthly and seasonal deliveries between October 1995 and May 1996. Data from crop-cutting experiments were obtained from the Haryana Agricultural Department. In addition, ancillary information on water-table depth, groundwater quality, cropping calendar, and soil types obtained from Haryana Minor Irrigation Tubewell Corporation was incorporated in the GIS.

Satellite Inventory of the Bhakra Command

Earlier studies have demonstrated the usefulness of satellite remote sensing data in generating information on total irrigated area and area under various crops within a project area (Estes, Jensen, and Tinney 1978; Kolm and Lee 1984; Nageswara Rao, Mohan Kumar, and Chandrasekhar 1990). To monitor irrigated orchards and nine crops in South Australia,

[2]In the Narwana-Sirsa system, groups receive water 8 days out of 24, or one-third of the time. In BML-Barwala Link, groups receive water half the time. In BML Tail, because two of the three groups, in rotation, receive water simultaneously, each individual group receives 16 days of water every 24 days, or two-thirds of the time. Thus, for example, over a 96-day period, groups in Narwana-Sirsa receive 32 days of water, groups in BML-Barwala Link receive 48 days of water, and groups in BML Tail receive 64 days of water.

[3]Groundwater salinity classes: fresh, <2 dS/m; submarginally saline, 2 to 4 dS/m; marginally saline, 4 to 6 dS/m; saline, >6 dS/m.

Williamson (1989) analyzed multispectral SPOT data and airborne data. Because chlorophyll absorbs most incoming spectral radiance in the red range between 0.6 and 0.7 µm and reflects it in the 0.75 to 0.90 µm near-infrared range, composites of red and infrared spectral radiances can be used to distinguish vegetated from nonvegetated surfaces. Kennedy (1989) showed that one such composite, the normalized difference vegetation index (NDVI), is a sensitive indicator of variations in biomass. NDVI correlates with spatial and temporal changes in growing conditions. Many attempts to estimate crop yields from satellite data have been made (Pinter et al. 1981; Quarmbay et al. 1993). Hatfield (1983) recommended the use of NDVI at crop heading stage for estimating potential harvestable yield. Figure 2 shows the method followed in the current study for analyzing satellite data .

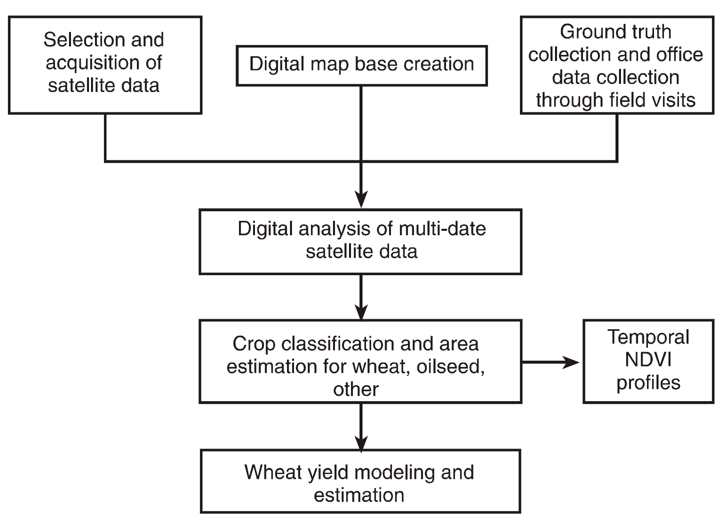
To identify the agricultural conditions in the Bhakra canal command area during rabi 1995/96, we used multi-temporal measurements by the LISS-II radiometer aboard IRS-1B. The command area is covered by nine LISS scenes, each encompassing 74 km x 74 km. On five of the six overpass dates during rabi 1995/96, fully or predominantly cloud-free satellite images of seasonal agricultural progress were obtained (table 2).

TABLE 2.
Dates of satellite coverage of the Bhakra command area during the rabi season, 21/22 November 1995 to 01/02 April 1996.

Satellite overpass	Status of crops
21/22 Nov	Beginning of rabi season. Oilseed crops already sown; some early sown wheat.
4 Jan[a]	Oilseeds and early sown wheat in growing stage.
26/27 Jan	Oilseeds and other crops in peak greenness stage. Wheat in active vegetative phase.
17/18 Feb[b]	Wheat in maximum greenness stage; other crops flowering or in senescence.
10/11 Mar[c]	Wheat in maximum greenness stage; other crops in senescence or harvested.
01/02 Apr	Wheat in senescence; other crops harvested.

Source: Thiruvengadachari, Murthy, and Raju 1997.
[a]5 January data not available.
[b]Based on crop calendar and date of sowing, maximum greenness on this date is considered to correspond with crop heading.
[c]Only 40% of the command area was cloud-free.

FIGURE 2.
Flowchart of analysis methodology.



The satellite scenes, in which digital counts were first transformed into radiance values, were geometrically corrected from accurate topographic maps in 1:50,000 scale and assembled in mosaic form to provide complete coverage of command area. The corrected data set had a location accuracy within 15 meters and a pixel size of 30 m x 30 m; it was oriented North-South in a polyconic projection.

The canal network, major roads and railroads, rivers, and settlements as well as the command boundaries of 364 distributaries and minors were digitized, geometrically corrected, and co-registered with the satellite data set so that they could be overlaid on hard copies or used in generating statistics for specified areas such as distributary command areas. The base map showing the area commanded by distributaries and minors had to be specially prepared in consultation with field officers, as this was not previously available.

The analysis was supported and the results were validated by ground-truth campaigns from 10 January to 5 February and from 14 to 28 June 1996. During the field visits, sample sites representing target crops to be classified were selected along with crop-cutting plots where wheat was harvested and yields estimated. The location of sample sites and crop-cutting plots was obtained within 100 meters accuracy with a hand-held global positioning system (GPS) receiver. The satellite-related analysis was completed in 8 months for about US$0.03/ha. This amount includes the Indian Remote Sensing Data Center's charges for satellite data and the cost of processing.

Crop Classification

The classification of satellite remote sensing images is an information extraction process that involves pattern recognition of spectral properties of various surface features and then categorizing the similar features. The goal of classification in the current study was to delineate wheat, oilseed crops, and other crops. Crop classification work was carried out by the scientists of the National Remote Sensing Agency, India, under the direction of S. Thiruvengadachari.

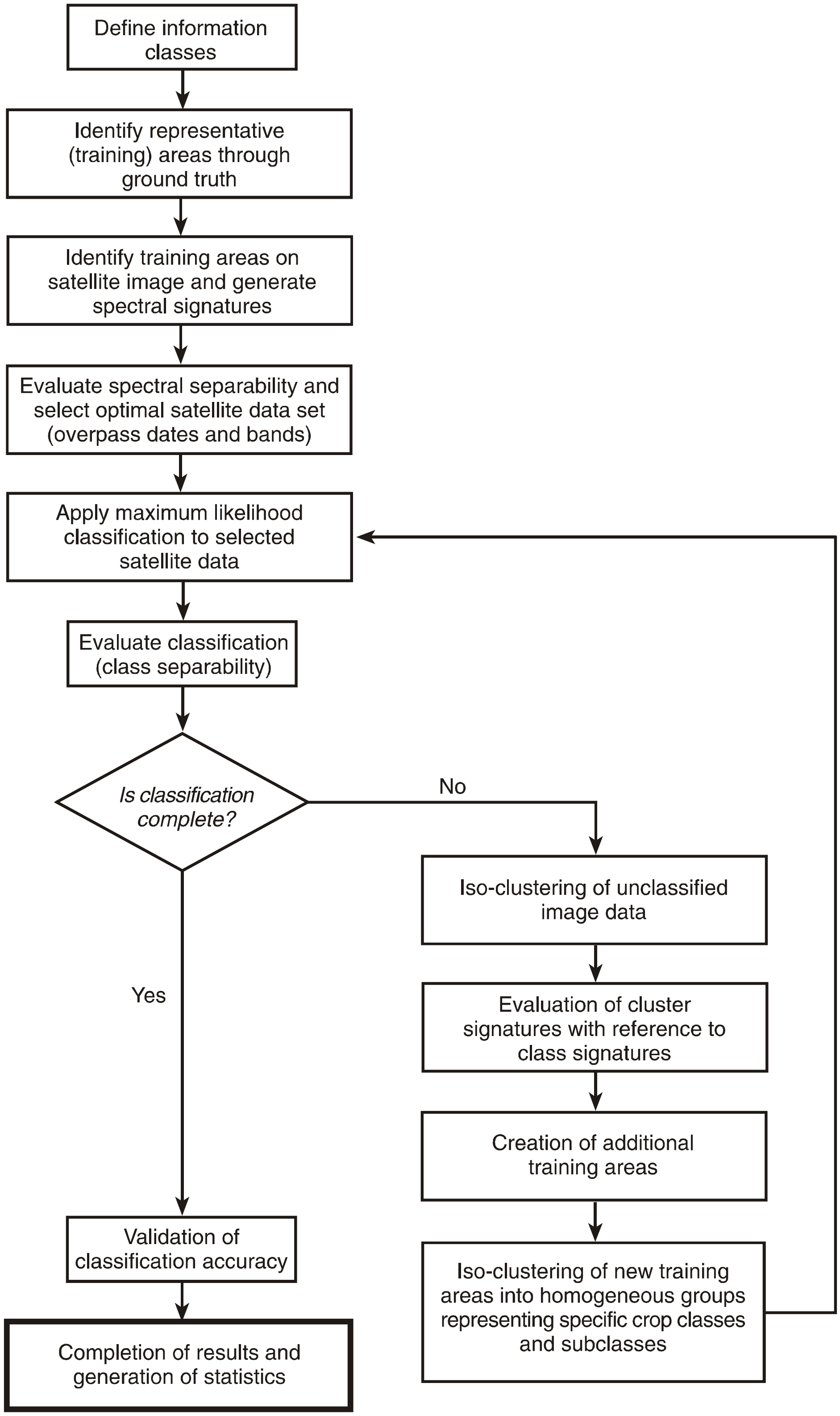
A review of spectral signatures of wheat, oilseeds, and other crops obtained by conventional supervised classification indicated a wide range and possible mix-up among classes. Conventional supervised classification is not highly accurate. Pestemalci et al. (1995) applied a supervised classification of wheat and achieved only 85 percent accuracy. Furthermore, our data lacked fully cloud-free coverage in March 1996 (table 2), which would have been essential for using simple or sequential maximum-likelihood classifiers.

Consequently, we developed an innovative iterative methodology (fig. 3) that combines maximum likelihood classification (supervised classification) with iso-clustering (unsupervised classification) to analyze the satellite data acquired in November, January, and February. These three periods were selected as optimal based on analysis of the spectral signatures on all five dates for which data was available and after evaluating a separability index developed from the Bhattacharya distance measure (Jensen 1986).

From images on the three selected dates, we chose only the green (0.52–0.59 μm), red (0.62–0.68 μm), and near-infrared (0.77–0.86 μm) spectral band data and combined them in a nine-dimensional data set for analysis. Lee and Richards (1985) showed that in the maximum-likelihood classifier, accuracy and computational speed decrease as the number of spectral channels increases.

A supervised classification was applied first. The multidimensional nature of the data set provided pure spectral signatures of classes, allowing 47 percent of the image pixels to be labeled as wheat, oilseed, or other. Areas that had even marginally different signatures were left unlabled. Those unclassified portions of the

FIGURE 3.
Flowchart of classification methodology.



images were then subjected to unsupervised classification that yielded 50 homogeneous spectral clusters. The signature of each cluster was compared with earlier training sets to create additional training sets. The earlier and additional training sets were combined and spectrally clustered to provide revised training sets, which were used for further supervised classification. Dobbertin and Biging (1996) found that this approach of random selection of pixels in training sets improves classification accuracy in simulated satellite images that have high spatial autocorrelation. We repeated the process until all pixels were classified as wheat, oilseed, or other. Once the classification was completed, the results were confirmed by reference to data from 01/02 April, the date when NDVI values indicated most of the crops were in the senescence phase.

The crop classification was validated against sample areas identified during the first field visit but not used in classification and against an area randomly selected during the second field visit. The classification error matrix presented in table 3 has an overall kappa accuracy (Congalton 1991) of 95 percent. Satellite inventory provided data on the total area irrigated in the command (both by canal water and groundwater) in contrast with the irrigation department reports, which cover only the area irrigated by canal water.

TABLE 3.
Error matrix of pre-selected sites occupied with rabi crops in the Bhakra Irrigation System classified with a new dual-crop classification procedure. Accuracy is shown in parentheses.

	Satellite-derived classification			
Verified	Wheat	Oilseeds	Other crops	Total
Wheat	298 (98%)	5	2	305
Oilseeds	9	93 (89%)	2	104
Other crops	2	2	76 (95%)	80
Total	309	100	80	489

Source: Thiruvengadachari, Murthy, and Raju 1997.

[4]Crassulacean acid metabolism

Wheat Yield Estimation

Information on vegetation density is of paramount importance for estimating biomass accumulation. Grain yield is related to the photosynthetically active radiation—the solar radiation in the visible part of the spectrum (0.4 to 0.7 µm)—that is absorbed by the crop. Absorbed photosynthetically active radiation (APAR) (J m^{-2} $time^{-1}$) is related to photosynthetically active radiation as follows:

$$APAR = \sum f PAR_{(t)} \times PAR_{(t)}$$

where $PAR_{(t)}$ (J m^{-2} $time^{-1}$) is the accumulated photosynthetically active radiation that reaches the crop during the growing season, and $fPAR_{(t)}$ is a proportionality factor describing the chlorophyll, which varies with time, t. $fPAR$ is zero for bare soil.

APAR is the principal parameter that controls the total biomass accumulated by the crop through photosynthesis and assimilation. Thus yield can be given as:

$$Y_{act} = z \in APAR \qquad (1)$$

where Y_{act} (kg/m^2) is the actual grain yield, z is the ratio between grain yield and total aboveground biomass, and $\in$ (kg/J) is the photosynthetic efficiency depending on crop's carbon fixation pathway (C_3, C_4, or CAM[4]) (Prince 1991). The validity of equation (1) has been demonstrated both theoretically (Monteith 1972) and experimentally (Daughtry et al. 1992; Field, Randerson, and Malmstorm 1995).

Because

$$fPAR = a + b\ NDVI_{(t)} \qquad (2)$$

where a and b are constants, NDVI is an indirect linear expression of crop yield with offset "a" and slope "b."

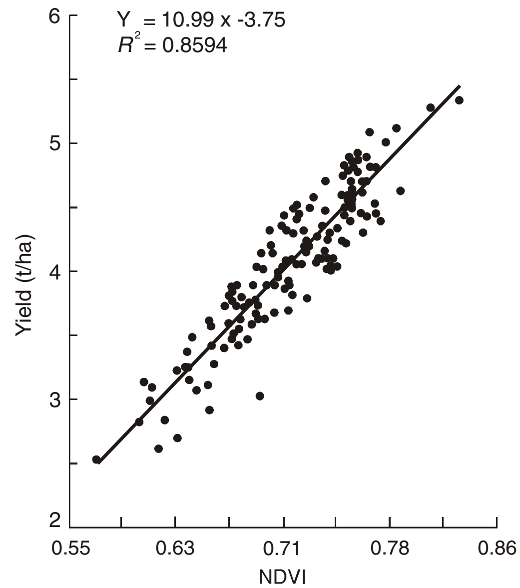
Many studies have attempted to use satellite-derived NDVI at the crop heading stage to estimate end-of-season yield because the crop condition at this stage is a major determinant of yield. For example, Pestemalci et al. (1995) used a single-date regression model similar to equation (2) for a limited number of wheat parcels in Turkey and obtained a correlation coefficient of 0.84 between NDVI at heading and crop yield.

In the present study, yields of wheat harvested in 270 crop-cutting experiment plots were obtained from the Haryana Agriculture Department. The latitudes and longitudes of the plots were determined with a hand-held GPS receiver. Each plot was represented by a window of five pixels by five pixels (150 m x 150 m) to account for the residual location inaccuracy in GPS readings.

The yield for every wheat pixel was estimated with a linear regression model. In the regression analysis, the NDVI of 17/18 February 1996 was used as independent variable. On this date, the NDVI was at the maximum value corresponding to heading phase of wheat. Data from crop-cutting experiment plots where farm size was less than 0.4 hectare and where within-window NDVI variability was high were excluded. The outliers in the scatter plot of yield versus NDVI were also removed from further analysis. The wheat yield model based on the remaining 151 plots was computed as yield (t/ha) = –3.75 + 10.99 NDVI, with coefficient of determination of 0.86 and a standard error of estimate of 0.217 t/ha (fig. 4). The regression coefficient was significant at the 1 percent level.

The yield estimates can be aggregated over any desired area such as distributary or minor command (fig. 5), canal subdivision, division, or water service circle.

FIGURE 4.
Wheat yield in relation to NDVI.

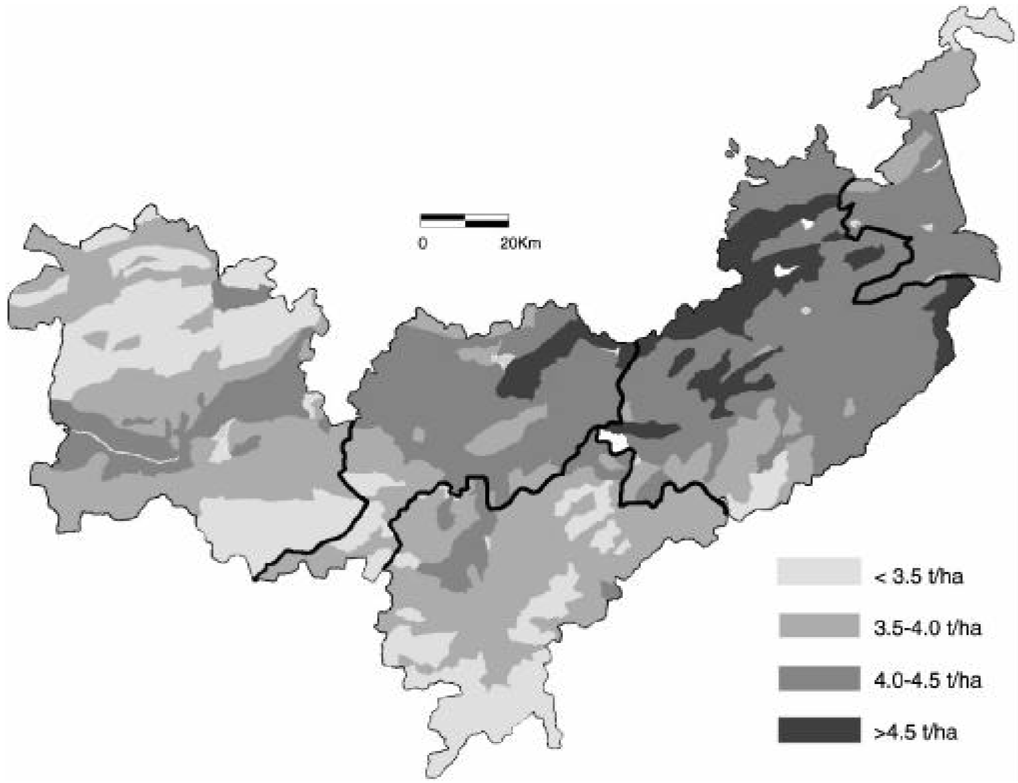


Integration of Geographic Information System

To permit more comprehensive spatial analysis and to integrate relevant ground data, which are different in scale and information level, all data were organized in a GIS environment using IDRISI software. Table 4 characterizes the spatial and nonspatial data used in GIS analysis. Information integration and analysis for specific objectives were attempted through union and intersection techniques.

The GIS applications allowed characterization of the command area's agricultural productivity, canal water supply, groundwater regime, and their interrelationships. These parameters were used to clarify policy issues related to long-term sustainability. In addition, the GIS applications were a means for uncovering the need for location-specific corrective management, such as identifying areas that have potential waterlogging problems, that require reclamation, or that have soil limitations to wheat productivity. The regional scale of information on some parameters, such as water-table depth and groundwater quality, prevented microlevel analysis, however.

FIGURE 5.
Spatial variability of wheat yield, Bhakra canal command area, rabi 1995/96.



Results of Analysis

Agricultural Characterization of the Bhakra Command

The spatial variability of irrigation intensity (irrigated cropped area relative to cultivable command area) and of wheat, oilseeds, and other crop areas as a percentage of total cropped area was determined and mapped. Table 5, which is derived from this analysis, gives an irrigation statistics for the command area in rabi 1995/96. The command's overall irrigation intensity (from groundwater as well as canal water) was 83 percent compared with a designed surface-water irrigation intensity of 32 percent. Wheat predominates, occupying more than 70 percent of irrigated crop area. These results are comparable to the data published by the government of Haryana (Economic and Statistical Organization 1995).

The average wheat yield over the whole command area is estimated to be 4.09 t/ha. Kaithal circle, which has mostly fresh groundwater, has the highest wheat yield; Hissar-1 and Sirsa circles, which are underlain by marginally saline and saline groundwater, have the lowest wheat yields (table 5).

Wheat yields were computed for the command areas of 364 distributaries and minors to identify ones that suffer constraints to productivity. In 53 of the commands, wheat yields were less than 90 percent of the divisional mean (table 6). These poorly performing command areas covered 8 percent of the irrigated area during 1995/96 rabi season.

TABLE 4.
Summary of data types used in GIS analysis.

Data	Type	Scale	Source[a] and notes
Crop type	Raster	30 x 30 m[b]	NRSA. Every pixel within the command classified into wheat, oilseeds, other crop, or no crop.
Wheat yield	Raster	30 x 30 m[b]	NRSA. In tonnes per hectare.
Soil	Vector	1:250,000	NRSA. Saline, saline-sodic, and sodic classes, in three severity levels, based on extent of area covered in mapping unit derived from satellite data of 1986.
Groundwater quality	Vector	1:500,000	HSMITC/GWD. Four quality classes (fresh, <2 dS/m; submarginally saline, 2 to 4 dS/m; marginally saline, 4 to 6 dS/m; saline, >6 dS/m), extracted from state map.
Water-table depth	Vector	1:500,000	HSMITC/GWD. Contours of depth to groundwater in June 1995, October 1995, and June 1996 extracted from state map.
Long-term groundwater trend	Vector	1:500,000	HSMITC/GWD. Positive and negative changes in water-table depth 1974–95 extracted from state map.
Annual potential evapotranspiration	Vector	1:2,500,000	IMD. Annual potential evapotranspiration contours in millimeters extracted from the state map.
Rainfall	Vector	1:2,500,000	IMD. Contours of rainfall during year, July-Sept., April-June, and October extracted for command area from state map.
Canal network	Vector	1:50,000	Haryana Irrigation Dept. Showing branch canals, distributaries, and minor canals.
Distributary or minor command	Vector	1:50,000	Haryana Irrigation Dept. Area commanded by distributaries or minor canals.
Canal discharge	Direct-input data		Haryana Irrigation Dept. Rabi-season discharge measured selectively at distributary off-takes.
Crop-related statistics	Direct-input data		NRSA. Crop area; area under wheat, oilseeds, and other; wheat yield.

[a]NRSA: National Remote Sensing Agency. HSMITC/GWD: Haryana State Minor Irrigation and Tubewell Corporation/Groundwater Directorate. IMD: India Meteorological Department.

[b]Pixel size.

TABLE 5.
Land use in the Bhakra command area, rabi 1995/96.

	Command area			Irrigated crop area (000 ha)				Irrigation	Wheat		
	Total	Cultivable[b]						intensity[a]	Intensity[b]	Yield	Production
Circle	(000 ha)	(000 ha)	(%)	Wheat	Oilseed	Other	Total	(%)	(%)	(t/ha)	(000 t)
Ambala	94	86	91	62	10	5	77	90	80	4.10	254
Kaithal	381	343	90	271	37	8	316	92	86	4.36	1,181
Hissar-1	295	244	83	59	21	174	71	54	3.73	352	
Hissar-2	255	206	81	156	34	17	207	100	75	4.20	654
Sirsa	483	386	80	163	86	32	281	73	58	3.76	614
Total	1,508	1,265	84	747	227	82	1,056	83	71	4.09	3,055

Source: Thiruvengadachari, Murthy, and Raju 1997.
[a]Irrigated crop area divided by cultivable area.
[b]Wheat area divided by irrigated crop area.

TABLE 6.
Distributaries and minor command areas that had low wheat productivity, rabi 1995/96.

Circle and division	Low productivity command area[a]	Irrigated area (ha)
Ambala		
Ambala	Minors: Panjokra; sub-minors: Dangheri, Garnala, Tandla	4,500
Kurukshetra	—	—
Kaithal		
Kaithal	—	—
Pundri	Minors: Badhana, 2R Badhana	3,643
Narwana	Tail branch: Sudhkan 1L, 2L, 3L, and 4L; distributary: Surban; minors: 1R Badhana, Songri, Bithmara, Barsola, 1-R Barsola	13,404
Hissar-1		
Adampur	Minors: Dabra, Dhansu, Gaushala; sub-minors: Jagan, Gorchi, New Sarsana, Basra, Dhansu	4,969
Hissar	Feeder: Deosar; minors: Chirod, Chandarywas, Gawar, Garanpura, Haritha, Nalauli, Shikarpur, Talwandi, Siwani; sub-minors: Daha, Nalauli	11,895
Hissar-2		
Tohana	—	—
Fatehabad	Distributary: Kheri; minors: Manawali, Old Mochiwala, Ding, Bhattu, Khabra, Dhabi, Chuli, Jogiwala	23,145
Sirsa		
Sirsa	Minors: Kishangarh, Nathour	6,871
Rori	Distributary: Phaggu	1,178
Neharana	Sub-minor: Jandwala	4,512
Ghaggar	Distributary: Kutiyana; minors: Jamal, Kishanpura; sub-minors: Baruwali, Salapur	76,906

Source: Adapted from Thiruvengadachari, Murthy, and Raju 1997.

[a]Command areas that had less than 90% of the divisional average wheat yield.

Spatial Variation in Wheat Area and Yield

An analysis of irrigation statistics, including wheat yield, by irrigation circle (table 5) indicates that wherever irrigation intensity was higher, both wheat intensity and wheat yield were high, and all parameters seem to reflect total water availability. The relationship between the percentage of wheat in a distributary command area and mean wheat yield is statistically significant (R^2 = 0.73) (fig. 6). Similarly, wheat yield and the coefficient of variation in yield in a distributary command are well correlated (R^2 = 0.54) (fig. 7).

Groundwater quality also was related to yield. In distributary commands that had low wheat yield, only 6 percent of the area had good groundwater quality. In distributary commands that had high wheat yield, 18 percent of the area had good groundwater quality. These observations suggest that good quality water has a critical role to play especially in increasing wheat irrigated area and wheat yield.

To study the spatial variation of irrigated wheat area and yield as function of distance from the supply channels, two typical water circles—Kaithal and Sirsa—were selected. Kaithal has a high percentage of fresh groundwater and the Sirsa has marginally saline groundwater. Due to differences in the depth and quality of groundwater, the mean wheat yield in the two circles differed by 0.6 t/ha. Using the GIS, the shortest distance from the supply channel

FIGURE 6.
Wheat yield in relation to wheat area.

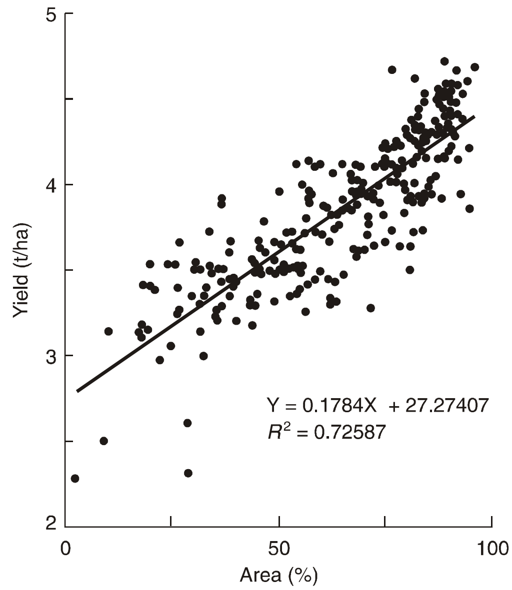
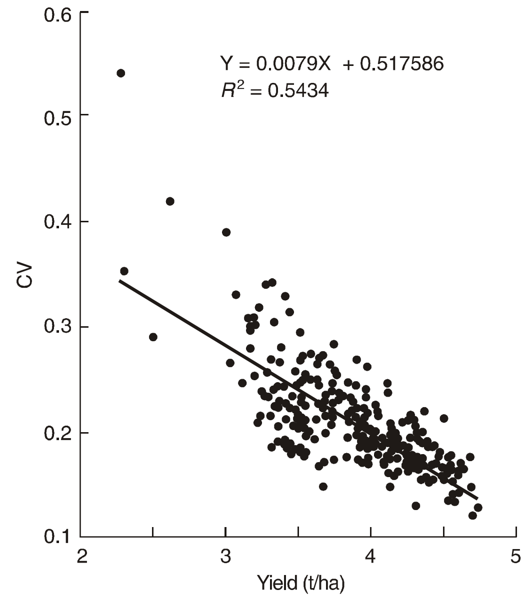


FIGURE 7.
Coefficient of variation of wheat yield in relation to yield.



network (main canal, branch canal, distributary, or minor) to each pixel was calculated, and the average wheat yield and irrigated wheat area were computed at 100 meter intervals from the supply channel. In the Sirsa circle, which has poor groundwater quality, about 45 percent of the irrigated wheat area was concentrated within 500 meters of the canal network. In contrast in Kaithal circle, which had good groundwater quality, only 28 percent of wheat area was concentrated within 500 meters. However, in both circles, the greater the distance from the canal network, the lower was the percentage of wheat area.

These results indicate that the irrigated wheat area is concentrated near canal networks because of the availability of seepage water and nearness to the freshwater source. To increase their irrigated wheat area, farmers appear to capture seepage water from canals through dug-cavity wells. However, within a circle, spatial wheat yield variation was not statistically significant.

Canal Water Supply

The spatial variability in canal water supplies (fig. 8) is related to groundwater quality. Areas supplied with relatively small amounts of canal water are mostly in zones of fresh groundwater, and areas of high canal water supply are in zones of marginally saline to saline groundwater (table 7). Under the warabandi principle, all areas should receive a roughly equal supply of water per unit command area. However, the canal water supplies vary. Thirty-five percent of the command area received less than 150 millimeters and 41 percent received over 300 millimeters. The rest of the command area received 150 to 300 millimeters.

IDRISI GIS helped in defining and analyzing the interrelationships of agriculture, groundwater, and canal water supply. Table 7 reveals that in zones of marginally saline to saline groundwater, both the percentage of rabi irrigated area and the percentage of wheat area are low. On the other hand, only 9 percent of command area in

FIGURE 8.
Amount of canal water supply (in millimeters) reaching distributary command areas, Bhakra Irrigation System, rabi 1995/96.

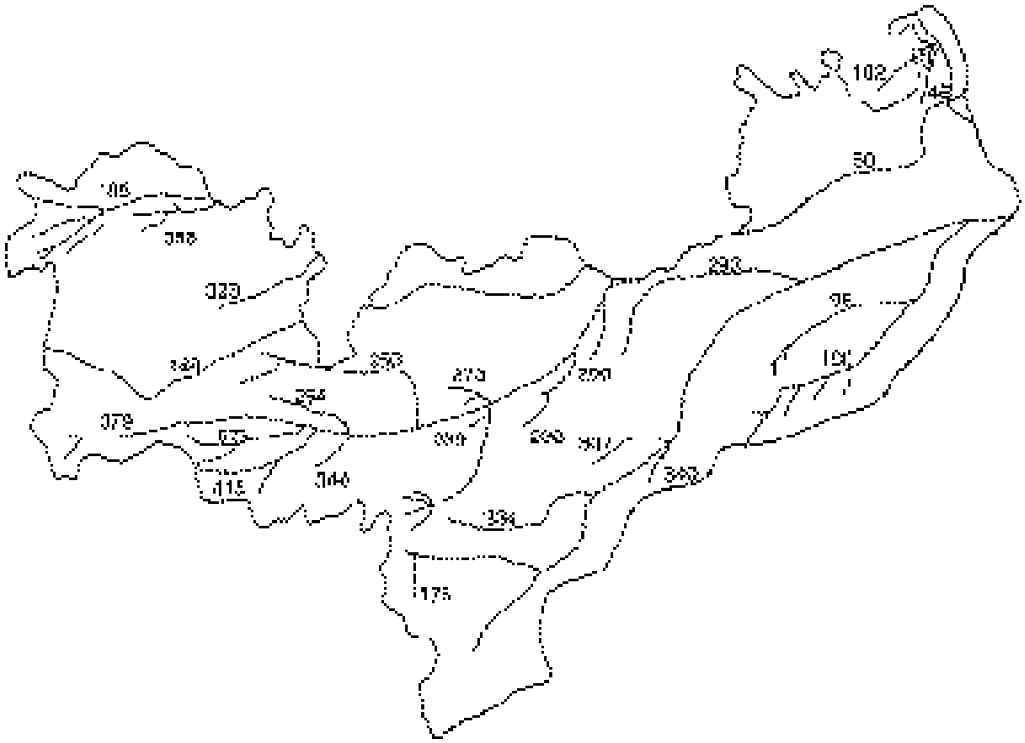


TABLE 7.
Groundwater quality in relation to canal water supply, rabi 1995/96.

Groundwater quality	Irrigated area	Wheat area[a]	Low yield area[ab]	Command area with		
				Low canal water supply[a c]	Falling water table[a]	Deep water table[a d]
	(%)	(%)	(%)	(%)	(%)	(%)
Fresh	37	32	12	70	49	51
Submarginally Saline	42	27	20	19	12	45
Marginally saline to saline	21	12	9	9	10	47
Total command area	100	71	41	35	25	48

[a]Relative to the irrigated area in each category of groundwater quality.
[b]Wheat yield below 4 t/ha.
[c]Less than 150 mm canal water supply.
[d]Groundwater more than 10 m from surface.

marginally saline to saline groundwater zones gets low canal water supply compared with 70 percent of the command area in the freshwater zones. The irrigation agency seems to have consciously implemented this unequal spatial distribution of water based on the assumption that farmers who have fresh groundwater can pump it to supplement their canal water supplies, while those in saline groundwater areas need more canal water to support their crop. However, this assumption has implications for sustainability of the system, discussed later.

Under the warabandi principle, the equal distribution of water should occur in a rather automatic manner through rostering of distributary and minor canals. The present water distribution practices vitiate the warabandi principle, however.

Table 8 shows key irrigation management indicators as a function of distance along five major canals. Two principal observations can be made. First, in Narwana, the canal command that has fresh groundwater, the mean wheat yield and wheat intensity are high and the canal water supply per unit area is low. Along the channel length, wheat yield, wheat intensity, and canal water supply vary little. In 15 percent of the command area, the water table is more than 10 meters deep and has been falling moderately over the years.

Second, in canal commands underlain by marginally saline to saline water, mean wheat yields are low and canal water supply is high. Wheat yield and wheat intensity decrease along the canal length, while canal water supply remains constant or increases (except in Barwala). The groundwater level is rising, and in many places the water-table depth is 3 meters or less.

These observations led us to carry out a multiple regression of wheat yield as a dependent variable against several parameters including canal distance for the five canals. We found (table 9) a statistically significant decline in wheat yield with

- increasing distance along the canal length (as indicated by cumulative percentage of cultivable command area)
- increase in the share of cultivated area that has a shallow water table
- increase in the share of cultivated area that has a rapidly rising water table

Variations in groundwater quality and canal water supply were not significantly related to wheat yield.

TABLE 8.
Variations in wheat yield, wheat intensity, cropping intensity, and canal water supply along the length of five canals.[a]

	Wheat yield		Wheat intensity		Cropping intensity		Canal water supply		Groundwater		
Branch	Mean (t/ha)	Variation along canal	Mean (%)	Variation along canal	Mean (%)	Variation along canal	Mean (mm)	Variation along canal	Depth (m)	Quality	Level fluctuation
Narwana	4.13	Constant	75	Constant	93	Increase	69	Constant	3-20	Fresh	Moderately falling
Sirsa	4.19	Decrease	71	Constant	88	Constant	150	Increase	3-10	Fresh or submarginally saline	Moderately rising
Barwala	3.78	Slight decrease	43	Steep decrease	65	Decrease	157	Decrease	3-10	Marginally saline to saline	Moderately rising
Fatehabad	3.87	Steep decrease	54	Steep decrease	90	Decrease	207	Constant	3-10	Marginally saline to saline	Fast rising
BML Tail	3.93	Steep decrease	62	Steep decrease	87	Decrease	193	Increase	3-20	Marginally saline to saline	Fast rising

[a]All data is for rabi 1995/96 except groundwater level fluctuation, which covers 1979–94.

TABLE 9.
Multiple regression of wheat yield and irrigation analysis.

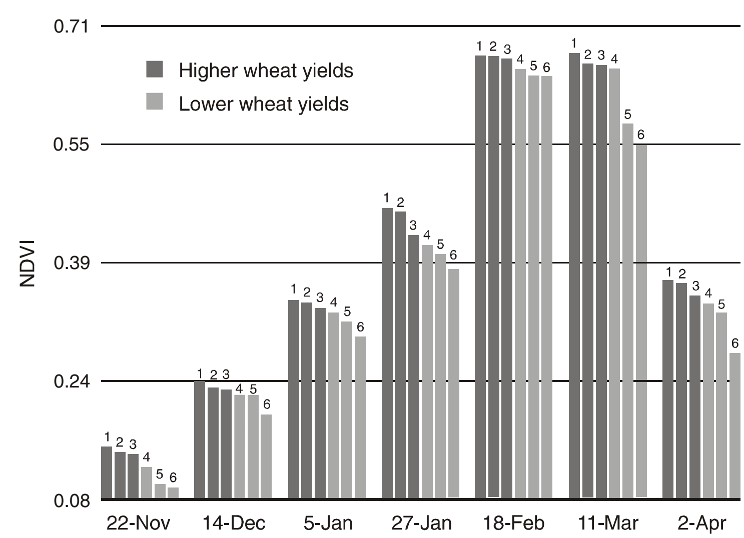
Explanatory Variables	Dependent variable (wheat yield[a]) Coefficient	T-value
Constant	4.29105	4,397*
CPCCA[b]	–0.00853	–8.63*
GWDL3[c]	–0.00419	–3.28*
WTCG10[d]	–0.00308	–4.24*
GWQS[e]	–0.00129	–0.83
SWMM[f]	0.00005	0.94
R^2		0.69

*Significant at 5% confidence level.
[a]Tonnes per hectare.
[b]Cumulative percentage of cultivable command area.
[c]Percentage of cultivable command area with groundwater less than 3 m from the soil surface.
[d]Percentage of cultivable command area in which the water table has risen over 10 m in 15 years.
[e]Percentage of cultivable command area with saline groundwater.
[f]Canal water supply (mm).

We made field visits to answer several questions about the present canal operation practices: Why does the canal water supply in the Barwala and BML Tail branch canals increase along their lengths, and how does this additional water affect wheat area and yield in downstream reaches? Canal managers suggested that the increasing discharge along the canal length probably is related to the lining of major reaches of the canals. The water supply allowances originally stipulated when the canals were unlined were not adjusted after lining. Consequently, water that previously would have been lost to seepage moves downstream without being redistributed among the distributaries and minors. In addition, canal managers were supplying more canal water per hectare to the command areas served by these two branch canals to offset pumping from saline underground water.

Ordinarily, increasing the amount of water delivered to an area of the Bhakra system should result in higher wheat yields and more wheat growing, but for the tail reach areas of Barwala, Fatehabad, and BML Tail canals, wheat yield and wheat intensity are low (table 8). Table 9 shows that the wheat yield decrease is significant with cumulative percentage of cultivable command. The water supply, based on the warabandi principle, follows a rigid rotational cycle of fixed

FIGURE 9.
Seasonal NDVI profile of three higher yielding and three lower yielding distributary commands of the Sirsa branch canal in Rori division, 22 November 1995 to 2 April 1996.



duration, frequency, and priority level. Our hypothesis is that when water is supplied to the tail reach, an area of highly permeable sandy loam, at fairly long intervals (once in 8 to 16 days), most of the water is not retained and available in the root zone for crop growth. Instead the water percolates to the underlying saline groundwater. Inadequate root-zone soil moisture probably is a major factor in the low wheat yield. Figure 9 shows that the NDVI values of lower yielding distributary commands are consistently lower than those of higher yielding commands, suggesting that irrigation support is inadequate throughout the season. Farmers who face low prospective wheat yields switch to oilseed crops, which consume less water. As a result more canal water reaches the saline groundwater, and the water table rises rapidly.

Thus, although the irrigation agency provides more water to areas that have saline groundwater in an attempt to meet the wheat crop's water requirement, the additional water has not had the desired impact. Instead it has aggravated the build-up of the water table and the potential for waterlogging and soil salinization. When this finding was discussed at a workshop with officials of the Haryana Water Resources Department, they did not dispute it. They have agreed to monitor these parameters more carefully in the future seasons to test the hypothesis and to develop possible remedial measures such as supplying less water to tail reach distributaries of Barwala, Fatehabad, and BML Tail canals or shortening the water-supply interval.

Sustainability of the Bhakra System

In terms of agricultural production, the Bhakra Irrigation System is performing well, especially in comparison with other wheat-growing irrigation systems in India. Performance parameters (Molden et al. 1998) calculated for rabi 1995/96, based on wheat as the sole crop in the command area, indicate that the gross value of output per unit of irrigation supply is US\$0.20/m^3, which is roughly three times better than that of Mahi-Kadana system, one of India's outstanding irrigation systems[5] (Sakthivadivel 1996).

But how sustainable is this high level of performance? In zones with poor quality (submarginally saline to saline) groundwater, the water table is rising in 78 percent of the area (table 7), leading to potential waterlogging and secondary salinization. The water tables in areas that already have poor groundwater within 3 meters of the surface have generally continued to rise in recent years.[6] In zones that have fresh groundwater, the water-table depth in about half the area already exceeds 10 meters and is falling (table 7), which will raise pumping costs and impact farm income. Thus the high irrigation intensity, the high percentage of wheat area, and the low canal water supplies and consequent groundwater extraction in the Bhakra system place its long-term sustainability in doubt.

Analysis of canal water supplies in the Sirsa irrigation circle for rabi 1995/96 found that the wheat productivity per unit of water consumed was high, 0.8 to 1.1 kg/m^3 (Bastiaanssen et al. 1998). However, in areas of submarginally or marginally saline groundwater, the combined effect of water distribution practices, canal seepage, water-holding capacity of soils, and irrigation methods used by farmers causes considerable percolation losses to the aquifer. In a large portion of the Bhakra command, as a result of those percolation losses, the water tables have risen more than 10 meters in 15 years in the saline and marginally saline groundwater zones.

[5]The system won an award from the Indian Ministry of Water Resources as the best performing system in 1993-94.

[6]Due to the heavy rainfall in the command area in the latter part of the 1995 southwest monsoon, the water table rose within 3 meters of the surface in about 100,000 hectares (most of Hissar-1 circle and parts of Hissar-2 and Sirsa circles).

The effective porosity in the aquifer system of the Sirsa irrigation circle varies from 0.08 to 0.16 m^3/m^3 (Boonstra 1996). Consequently a recharge of 80 to 160 millimeters raises the water table by 1 meter. This suggests that, on average, 60 to 100 millimeters of water is being added annually to the saline groundwater zones where soils are porous. The impact of recharge by fresh canal water on the salt balance of the deep aquifer, which is generally saline, needs to be studied. Sulaimi et al. (1996) showed that because of high evapotranspiration in arid areas, salt concentration increases in already-saline groundwater, which could have serious consequences in areas where water tables are rising.

Future water management strategies for the Bhakra command should address the problem of rising water tables in the zones that have saline groundwater and the problem of declining water tables in the zones that have fresh groundwater. Although a lasting solution to salinity problems cannot be achieved without a drainage outlet to remove the salts imported with irrigation water (because of poor natural drainage condition in this saucer-shaped basin), better management strategies could delay the rise or fall of the water table in the endangered zones. One such strategy should focus on reducing aquifer recharge and increasing groundwater use in the areas where the water table is rising.

Decreased groundwater use in areas that have rising water tables and poor groundwater quality is an issue that should be solved through on-farm water management. One option for diminishing the recharge to the aquifer is to curtail canal seepage losses. But substantially lowering conveyance losses in this already heavily lined system will be difficult to achieve. Another option would be to reduce the irrigation application per unit area by changing the frequency of water application. At present, under the warabandi principle, distributaries and minors have a turn of 8 to 16 days. The rotational period could be shortened by about half, and more frequent turns could be introduced, with a smaller depth of water application for each turn. In the coarse-textured soils found in the tail end of channels, this would be sufficient to replenish the root-zone soil moisture without leading to deep percolation.

Conclusions

The issues raised in this report urgently need to be thoroughly investigated by combining satellite remote sensing and GIS techniques with hydrologic modeling, supported by selective and intensive data collection campaigns. Hydrologic modeling is an important tool for understanding the transfer process of salt and water from surface to groundwater and the causes of rising groundwater.

Combining information obtained through satellite remote sensing with ground data in a GIS format has proved to be efficient in identifying major crops and their condition and determining area and yield of wheat, the major crop in the Bhakra command in the rabi season. In addition, for diagnosing problems associated with performance of a wheat-based irrigation system, these techniques are cost-effective. The satellite inventory was completed for about US$0.03/ha.

In the Bhakra Irrigation System, the practice of allocating and distributing the canal water supplies under the warabandi principle leads to the current high productivity of water. The long-term sustainability of agricultural productivity seems threatened, however. In some areas, saline water tables are rising, and soils are becoming sodic, while in areas that have fresh groundwater, water tables are falling.

There is an urgent need for the irrigation agency to thoroughly examine water management problems on the farm, regionally, and systemwide. By combining satellite remote sensing and GIS techniques with hydrologic modeling, appropriate ways can be found to modify the present water allocation and distribution practices to sustain productivity and maintain the health of the Bhakra system.

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INTERNATIONAL WATER MANAGEMENT INSTITUTE
P O Box 2075, Colombo, Sri Lanka
Tel (94-1) 867404 • Fax (94-1) 866854 • E-mail iimi@cgiar.org
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