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Research Report

Remote Sensing and Hydrologic Models for Performance Assessment in Sirsa Irrigation Circle, India

W. G. M. Bastiaanssen, D. J. Molden
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International Water Management Institute

Research Reports

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Contents

Abbreviations

CV	Coefficient of variation
EC	Electrical conductivity
GIS	Geographic information system
IRS	Indian Remote Sensing Satellite
NDVI	Normalized difference vegetation index
SAR	Sodium absorption ratio
SD	Standard deviation

Summary

This report describes the results of an irrigation performance evaluation using remote sensing techniques, GIS procedures, and hydrologic modeling at a regional scale. The study area was the Sirsa Irrigation Circle, which serves a gross area of 483,000 hectares within the Bhakra Irrigation System in northwest India. Satellite remote sensing information shows uniformity in wheat yields across the area but nonuniformity in irrigated wheat intensity. This nonuniformity is evidence that *warabandi*– the principle of allocating the right to irrigate in proportion to landholdings– is not delivering water in proportion to land area. Modeling revealed areas with differing hydrologic characteristics in the Sirsa circle. Correlation analysis between wheat yield and hydrologic terms indicated that variations in wheat yield are explained more by hydrologic factors such as tubewell use and underground water movement than by canal flows. Five hydrologic classes differing in agricultural practices and water management needs were identified in the study area. Most of the water entering the area was depleted through evapotranspiration– the overall depleted fraction of gross inflow was 82 percent. Productivity of water is reasonable in the area at an average value for wheat of 0.88 kg/m^3 of water consumed by evapotranspiration. However, a rising water table places the sustainability of this productive agricultural area in question. Each year soil water storage increases by 98 millimeters, and salts are accumulating at 1.8 t/ha annually.

This report demonstrates how advanced information technologies support the analysis of irrigation performance by facilitating an in-depth study of a large irrigated area. The study is more comprehensive than performance studies restricted to canal water supplies in that it considers the overall hydrologic processes and outputs of irrigated agriculture.

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Introduction

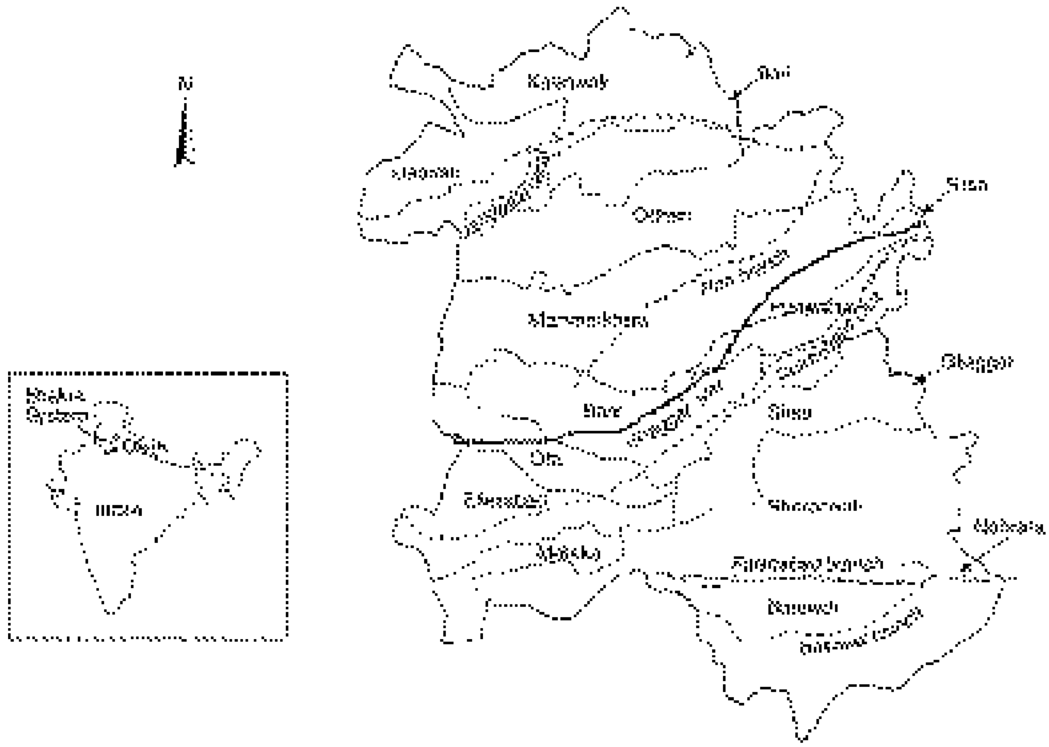
Studies of irrigation system performance are often restricted by practical limitations on the amount of data that can be collected in the field. Consequently, researchers tend to focus in detail on parts of an irrigated area or to make a less-detailed investigation of a whole system. This report demonstrates that remote sensing and hydrologic modeling combined with field-collected data provide a more complete view of an irrigation system.

The diagnostic analysis of the operation of the Bhakra Irrigation System in northwest India reported here is the result of collaborative research by the Indian National Remote Sensing Agency, the Irrigation and Water Resources Department of Haryana State, India, and the International Water Management Institute, using data from the DLO-Winand Staring Centre, The Netherlands. Satellite remote sensing was employed to obtain essential agronomic characteristics. The spatio-temporal behavior of surface, soil, and groundwater was simulated by means of a distributed computer model. Hydrologic analysis was aided by a geographic information system (GIS) that synthesized information obtained from ground data, remote sensing, and computer modeling. This information allowed the performance and sustainability of the irrigation system to be studied. The salient findings from this research are reported here and in *Performance evaluation of the Bhakra Irrigation System, India, using remote sensing and GIS techniques* (Sakthivadivel et al. Forthcoming).

Sirsa Irrigation Circle and Its Distribution Objectives

The study was conducted in the Sirsa Irrigation Circle of the Bhakra Irrigation System in northwest India during the 1995/96 *rabi* season (November to May). The Sirsa circle (fig. 1) lies at the tail end of the Bhakra system, which covers 1.3 million hectares in the State of Haryana. The town of Sirsa is at the downstream end of the Ghaggar River, which drains naturally in the direction of the Indus River. Irrigation water originates from the Gobind Storage Reservoir behind the Bhakra dam in the state of Himachal Pradesh. The system has been operating since the mid-1950s. The major characteristics of the Sirsa Irrigation Circle are as follows:

FIGURE 1.
Distributary command areas of the Sirsa Irrigation Circle in the Bhakra Irrigation System.



- Average annual rainfall, 191 mm
- Average annual reference evaporation (Hargreaves method), 1,721 mm
- Canal water duties,[1] 1.5 mm/day
- Current cultivation intensity, rabi, 80%
- Current irrigation intensity, rabi, 73%
- Current wheat intensity, rabi, 58%

Figure 2 shows the monthly rainfall and reference evapotranspiration (Hargreaves method) 1960–90 in the Sirsa Irrigation Circle.

The canal systems in Haryana were designed to serve the greatest number of farmers possible by distributing a limited supply of water over a large area. The major objective of irrigation development at that time was to prevent crop failure and avoid famine. To achieve that objective, the system was intended to be operated under the warabandi principle (described in Malhotra 1982).

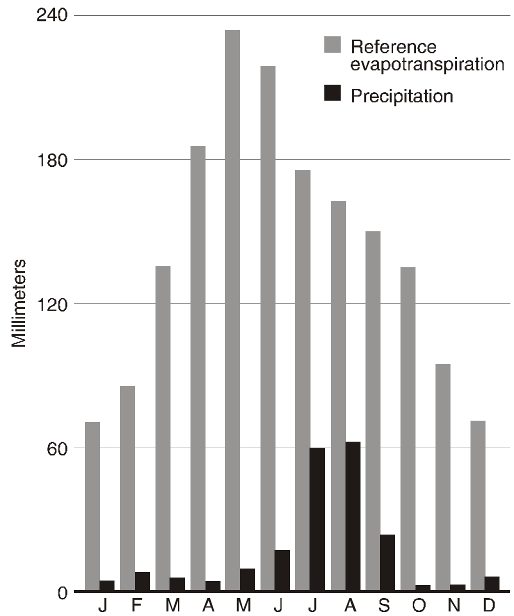
The principle of warabandi allocates the right to irrigate in proportion to landholdings. Typically it supports low cropping intensities through delivery of small duties of water on the order of 1.5 mm/day (Berkoff and Huppert 1987).

The Bhakra canal system was designed for an irrigation intensity of 62 percent of the cultivable command area (Reidinger 1971). The total area under cultivation in the Sirsa Irrigation Circle is 385,799 hectares, 80 percent of the gross area of 482,876 hectares (Thiruvengada-chari, Murthy, and Raju 1997).

During the rabi season, 73 percent of the cultivable land receives canal water, which farmers often supplement with groundwater. The main crops during this season are wheat,

[1]Amount of water the canals are supposed to deliver.

FIGURE 2.
Monthly average rainfall and reference evapotranspiration (Hargreaves method) 1960-90 in the Sirsa Irrigation Circle.



oilseeds, and gram (chickpea). Total rainfall during rabi ranges from less than 50 millimeters to about 130 millimeters.

Opinions on the success of irrigation performance in northwest India vary. Berkoff (1990) claimed that the success or failure of warabandi is a function of rainfall and that the successful warabandi systems like Bhakra are situated in the more arid west of India, while the less successful systems lie in the east where rainfall is higher and consequently drainage problems are greater. The study by Seckler, Sampath, and Raheja (1988) in parts of the Bhakra system used the total wetted area to show that the irrigation objective was satisfactorily met. In a study of warabandi in the Indian Punjab, Goldsmith and Makin (1988) measured flows and found no large head end/tail end differences in the ratio of actual flows to the flows the system was designed for. Merrey (1990) argued that the performance of warabandi is constrained by lack of local organizations to control water, but Berkoff (1990) said that warabandi is self-enforcing. Jurriens and Mollinga (1996) formed a less favorable impression of protective, warabandi-type canal water operations. They found that the operational targets of the system design were not being achieved, and they called for more detailed performance studies of these systems.

These conclusions on irrigation system performance are often drawn from studies that have limited spatial coverage, incomplete data on productivity to support the arguments, or limited perspective in that performance is evaluated against target duties only. There is abundant literature on the intentions of warabandi, but rarely is an entire irrigation system assessed to evaluate the overall performance of warabandi. Agarwal and Roest (1996) and Bastiaanssen et al. (1996) used hydrologic models and GIS databases to analyze the irrigation hydrology of the Sirsa Irrigation Circle. These studies revealed a large increase in salts and, in many places, a rapid rise in water tables, both of which threaten the sustainability of the system. The studies called for a review of allocation and distribution policies and practices, and they stressed the need for better drainage.

Canal Water Distribution in the Sirsa Irrigation Circle

Sirsa Irrigation Circle has 84 distributary and minor command areas varying in size from 198 to 41,000 hectares. The Fatehabad Branch taps water from the Bhakra Canal in the Hissar Irrigation Circle near the town of Tohana. The Ratia subbranch also emerges from Tohana town and feeds the Sukhchain Distributary. Other distributaries branch from the Bhakra Canal. The tails of the Jandwala, Sukhchain, and Baruwali distributaries carry canal water committed to irrigate approximately 70,000 hectares in the state of Rajasthan. The total annual volumetric intake for the Sirsa Irrigation Circle including the delivery to Rajasthan generally exceeds 2 cubic kilometers (2×10^9 m^3).

Because the reference evaporation is 1,721 mm/yr, or 4.7 mm/day, average canal water deliveries (1.5 mm/day) are sufficient for only about a third of each farmer's cultivable command area. In practice, however, many farmers irrigate much more of their area by drawing supplemental water from tubewells.

Canal water is allocated in proportion to land area. To facilitate this allocation procedure, a "structured" design is used to proportion flow. The main and branch canals operate with variable flow depending on water availability and the demands of crops. Distributaries and minor canals operate either on or off, that is, they operate at full supply level or with no water. Outlets from distributaries are ungated proportioning devices, dividing available water according to land area. Along watercourses, a rotation is practiced: each farmer receives the full flow of water for a preset, fixed amount of time. This system of fixed turns gives rise to the name warabandi.

The advantage of this rigid system of distribution is that when it functions properly, water is delivered in a reliable manner– farmers know what to expect. Because water is in short supply relative to land, farmers tend to optimize returns to water rather than land. Farmers typically plant a mix of irrigated and nonirrigated crops, and they may not fully saturate the root zone with water. Thus when rain falls, it benefits both irrigated and nonirrigated crops. With minimal monitoring of water levels to ensure that canals run full, the system can be self-policing in that farmers know when their turn is and can readily inspect for unauthorized use of water (Berkoff 1990).

Arguments against this rigid system center on the fact that timing and amounts of water deliveries are not based on the crop requirements. Water fees are based on land area rather than water use, and some researchers contend that farmers, rather than spreading water over their entire holdings, concentrate water and over-irrigate small plots of land.

There is indeed great debate about this type of system versus more flexible systems that can better match water supply to the demands of crops and farmers. There is, however, little empirical evidence to support arguments pro or con. The lack of evidence is due to the large area covered and the amount of data required to analyze the situation. It is also difficult to distinguish between irrigated and nonirrigated areas. The recent spread of tubewells in the Bhakra area has certainly given rise to more flexibility and more water supply than was originally envisaged.

Jacobs et al. (1997) made a detailed field study of two watercourses in the Hissar Irrigation Circle (which adjoins the Sirsa Irrigation Circle) and concluded that the amounts of water received by farmers do not correspond with the allocation principle of warabandi. Significant seepage losses from canals cause nonuniform spatial distribution of canal water in the Hissar Irrigation Circle. Land strips parallel to the distributaries contain shallow water tables that often reach the surface. Jacobs et al. (1997)

mentioned that drain pumps are installed for corrective management because the effluent can be evacuated into the main canal system, and complete waterlogging is prevented. In waterlogged areas further from the main system, farmers shift from cotton to rice during the *kharif* season (summer), while in water-short areas farmers move from cotton to pearl millet.

Material and Methods

In the present study, we relied on remotely sensed data combined with hydrologic modeling to better understand the irrigated hydrology of the region. Satellite information, outputs of hydrologic modeling, and field information were integrated through GIS to yield the results of this study. The satellite data were recorded in the rabi season to avoid problems related to cloud cover. Future studies will examine the feasibility of applying similar methods in the kharif season.

TABLE 1.
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%)	02	104
Other crops	2	2	76 (95%)	80
Total	309	100	80	489

Source: Thiruvengadachari, Murthy, and Raju 1997.

Remote Sensing

Multi-temporal measurements by the Linear Imaging Self-scanned Sensor (LISS-II) radiometer aboard the Indian Remote Sensing Satellite (IRS-1B) were used to identify the agricultural conditions in the Bhakra canal command area during rabi 1995/96 (Thiruvengadachari, Murthy, and Raju 1997). IRS measures the reflected radiance in four spectral channels between 0.45 to 0.86 mm, allowing for recognition of crop types based on spectral signature.

Thiruvengadachari, Murthy, and Raju (1997) designed a new hybrid classification procedure. They identified crop types through field visits in selected training areas. The spectral signatures of these training areas were extracted from three different IRS images acquired during rabi 1995/96 and used as a reference. A supervised classification (maximum likelihood) left 53 percent of the image pixels unlabeled. Thereafter, the unclassified portions of the image were exposed to an unsupervised classification (iso-clustering) yielding 50 "homogeneous" unlabeled clusters. The signature of each cluster was compared with the reference spectral signatures from which a new set of training areas was formed. This process was repeated until all pixels were classified as wheat, oilseed, or other.

To validate the procedure, satellite-derived classifications were compared with an independent set of training areas. The classification error matrix is presented in table 1. The Kappa accuracy (Congalton 1991) for the overall classification was 95.5 percent.

The irrigation intensity was inferred by assuming that wheat and oilseed crops can only be grown with irrigation water. Although oilseeds can be grown with less irrigation water than wheat, they require pre-sowing irrigation and at least one or two post-sowing irrigations to ensure crop development. The 30 m x 30 m pixel size of the IRS images created a unique opportunity to study the cropping patterns and irrigation intensity.

Chlorophyll absorbs most incoming spectral radiance from 0.6 to 0.7 μm (red) and reflects it in the 0.75 to 0.9 μm (infrared) range. Thus, composites of red and infrared spectral radiance were used to delineate vegetated from nonvegetated surfaces. The normalized difference vegetation index (NDVI) suggested by Tucker (1979) was computed on a pixel-by-pixel basis to yield the vegetation density.

Crop yields were obtained from satellite information by comparing information from crop cuts with the NDVI values. Yield data were obtained from crop-cutting experiments in 151 fields scattered throughout the entire Bhakra canal command area. The NDVI at the heading stage of wheat was determined from the NDVI time profile using four different IRS images acquired during rabi 1995/96. Thiruvengadachari, Murthy, and Raju (1997) showed that the NDVI of a single satellite image acquired during the crop heading stage is sufficiently accurate to predict crop yield. Applying the equation

$$Wheat\ yield = 10.99\ NDVI_{head} - 3.75 \qquad (1)$$

to the 151 plots, they found a coefficient of determination (R^2) of 0.86 for the relation of yield (in tonnes per hectare) to NDVI. That is, 86 percent of the measured variation in wheat yield can be explained by NDVI.

Equation (1) was then applied to estimate wheat yield on a pixel-by-pixel basis for the entire Bhakra command area. Procedures for estimating crop yield like equation (1), which is crop- and area-dependent, must be calibrated to local circumstances. Bastiaanssen (1998) appraises various methodologies based on remotely sensed data that can be used to assess yields of different crops.

The costs related to the application of remote sensing analysis vary with the type of analysis, the sensor used, and whether analyses are made by the public or private sector. Based on financial information collected from case studies in Philippines, Maldives, Morocco, Indonesia, Pakistan, and India, Bastiaanssen (1998) concluded that the average cost for land use mapping is approximately US$0.16/ha per growing season. This is a minor fraction of the total costs of construction and maintenance of irrigation canals. The costs related to crop yield forecasting from remote sensing data are expected to be similar because image processing is less intensive,[2] but the field work is more intensive (yield data have to be collected from several individual fields) than in land use classifications.

Hydrologic Model

Agarwal and Roest (1996), Boels et al. (1996), and Boonstra, Singh, and Kumar (1996) report the results of an integrated water management study that utilized FRAME, a hydrologic model package, in the Sirsa Irrigation Circle for the period 1977-90. A grid was imposed on remote sensing images of the study area to form cells, each of which contained several crop types and fallow land, and FRAME was employed to perform hydrologic computations for each cell. Hydrologically similar cells were grouped into 46 model units.

FRAME is composed of several sub-models describing the hydrologic subprocesses of an irrigation system. A model of the vertical crop water balance at field scale (FAIDS) was applied to each land use type. Horizontal water redistribution at field level before infiltration is taken into account. The lateral connections

[2] In their Bhakra case study, Sakthivadivel et al. (forthcoming) indicate that a single image suffices.

between the 46 units were established with a groundwater model (SGMP), a surface water allocation and distribution model (DESIGN), and a regional drainage model (REUSE). The interaction between surface and groundwater systems is formulated empirically so that leakage losses from the canal network and the Ghaggar River into the phreatic aquifers are taken into account.

The hydrologic model package FRAME was calibrated for 1977-81 using observed water table data. The period 1982-90 was used for validation. The model parameters considered in the calibration process were soil water-holding capacity, on-farm conveyance losses, and the effective porosity of the aquifer. For each model unit, the average annual water and salt balance data for 1977 through 1990 were extracted from the FRAME output (Annex 1).

Field Data

Data on daily canal discharge for rabi 1995/96 provided by the Haryana Irrigation Department was summarized into monthly and seasonal deliveries between October and May. Precipitation records for dates in 1995 and 1996 when the satellite images were captured were assembled from 12 stations. Other secondary information on groundwater depth, groundwater quality, canal layout, and soil types was incorporated in the analysis.

Geographic Information System

A geographic information system (GIS) was employed to integrate remotely sensed data, output from the hydrologic model, and field data (table 2). By merging remotely sensed data with command area projections, we obtained values for wheat yield, wheat intensity, and irrigated area for each command area. The GIS allowed for a better understanding of the hydrology of the area and was used in the analysis of results. The IRS-based crop data of the 84 administrative command areas of the Sirsa Irrigation Circle were re-gridded into the 46 units of the FRAME model.

TABLE 2.
Sources of data for analyzing irrigation practices in Sirsa Irrigation Circle.

Remote Sensing	Field	GIS	Frame
Wheat, oilseeds	Flow records	Command areas	Water balance
Wheat intensity	Precipitation	Canal layout	Salt balance
Irrigation intensity		Groundwater quality	
Wheat yield		Depth to water table	
Geometry		Soil type	

Crop Growing Conditions, Rabi 1995/96

The satellite-derived data indicated that the percentage of cropped area occupied by wheat (wheat intensity) and irrigated area as a percentage of the total cultivated land (irrigation intensity) were nonuniformly distributed (figs. 3 and 4). One possible explanation is that the physical environment (e.g., soils, topography, nutrients, salts) is not uniformly suited to wheat cultivation. Another possibility is that the nonuniformity is a function of farm and irrigation

FIGURE 3.
Wheat intensity in administrative command areas of the Sirsa Irrigation Circle, rabi 1995/96.

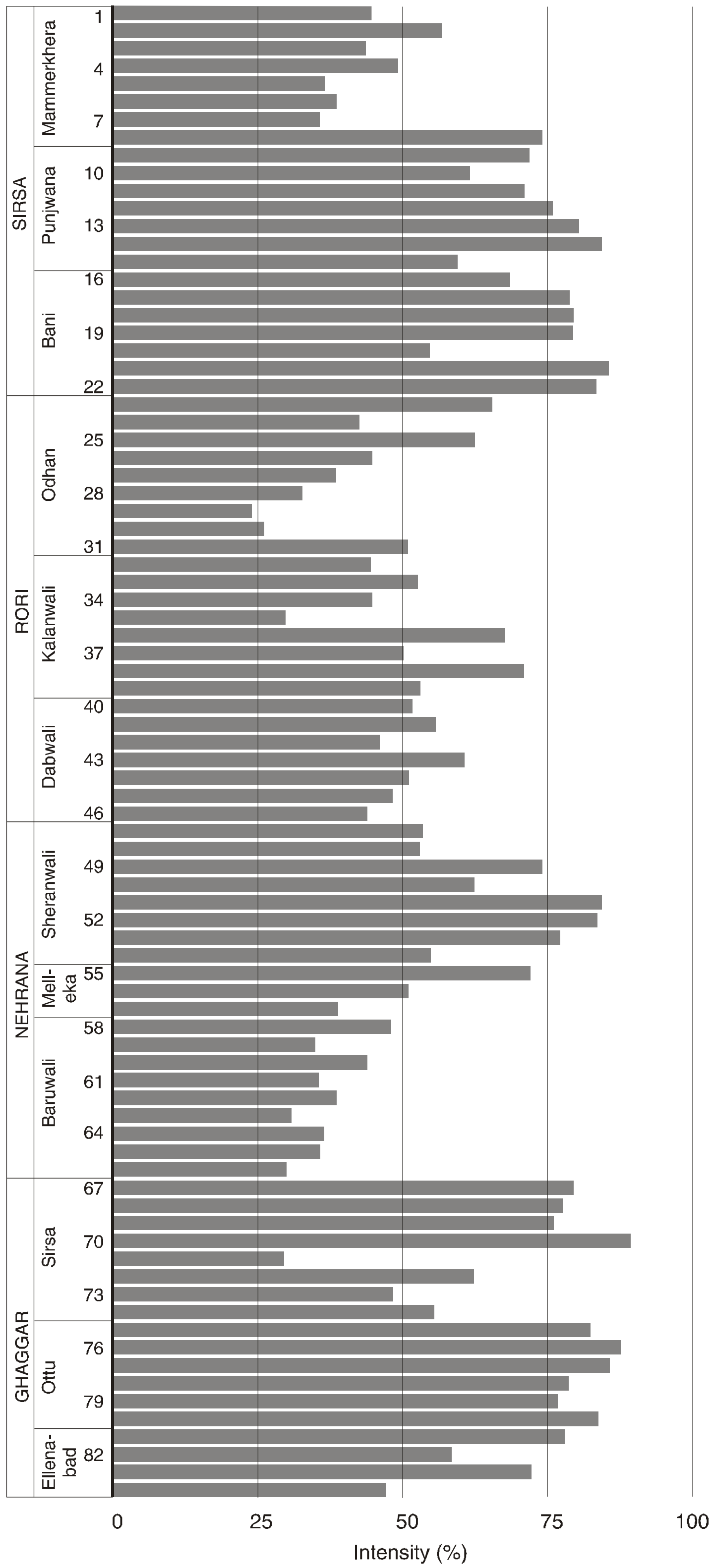
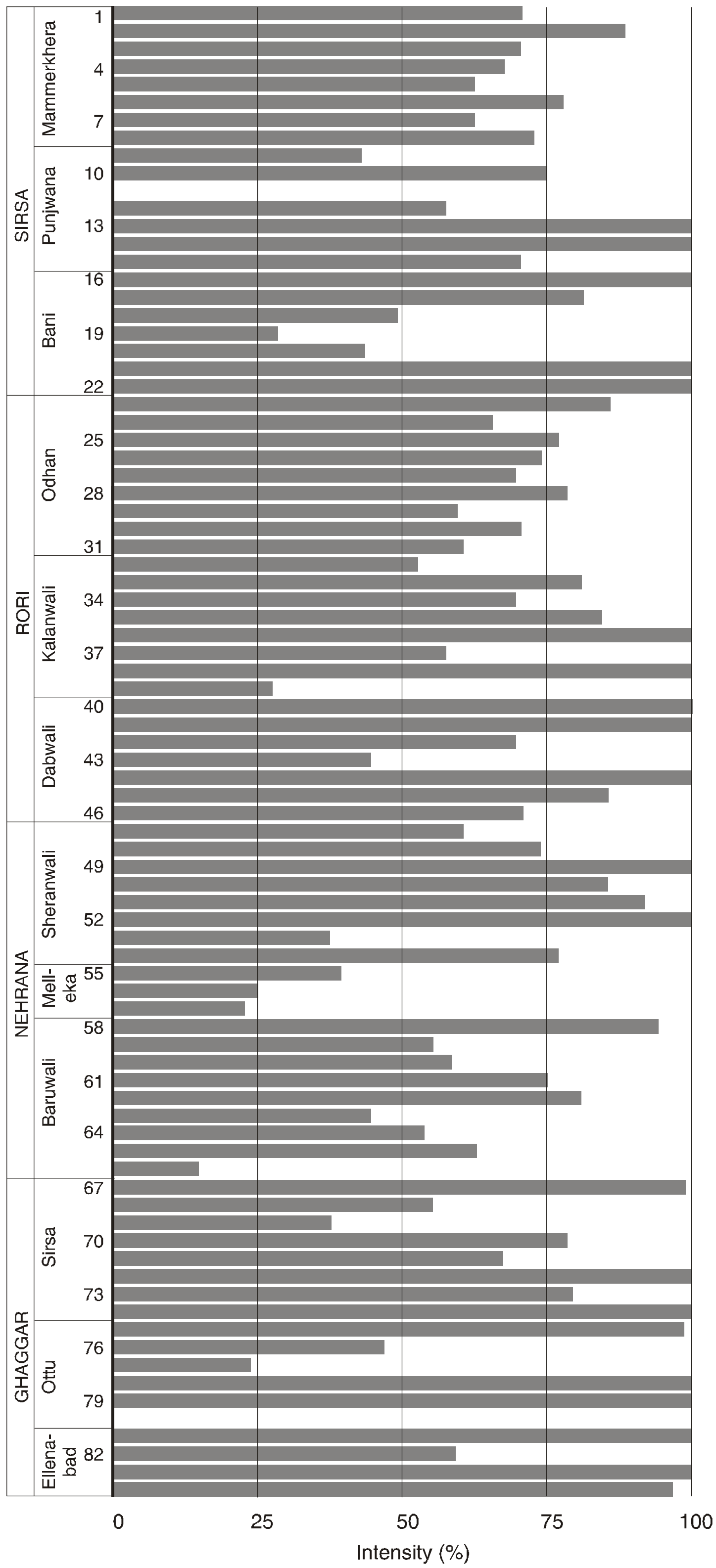


FIGURE 4.
Irrigation intensity in administrative command areas of the Sirsa Irrigation Circle, rabi 1995/96.



system management. In this case, corrective management could improve crop development. It is striking that wheat intensities ranged from 25 to 90 percent; further investigations are needed to determine farmers' underlying motives for crop selection.

Table 3 shows the wide variability among the administrative divisions and subdivisions. The Ghaggar division had an overall wheat intensity of 76 percent compared with 53 percent at the Nehrana division. Irrigation intensity in Ghaggar was 86 percent compared with 61 percent in Nehrana. Although figure 4 shows that the irrigation intensity was rather variable within a given division, no systematic trend in head-tail conditions could be determined.

Yields, estimated with equation (1), are surprisingly homogeneous for all administrative command areas (fig. 5). The coefficient of variation of wheat yield for the 84 command areas was only 9 percent. But the yield variation within each command area was 21 percent. Thus among command areas yield variation is low, but within command areas, variation is substantially higher, perhaps because of differences in the physical environment, water delivery, or farm management at the *chak* (tertiary) level.

Wheat yields at field scale were seldom below 2.2 t/ha. A plausible explanation for this lower limit on wheat yield is that farmers make an economic decision to abandon wheat cultivation under conditions where they cannot obtain sufficient yields to cover costs. For Haryana farmers, the breakeven point for investing in seeds, fertilizers, pesticides, and tubewells for irrigating wheat apparently lies somewhere around 2.5 t/ha. If the expected yield falls below 2.5 t/ha, farmers will decide to plant oilseeds instead of wheat. The average wheat yield of the Sirsa Irrigation Circle, 3.76 t/ha, is lower than the average of the whole Bhakra canal command area (4.09 t/ha). Compared with other irrigation circles in the Bhakra system, the Sirsa Irrigation Circle has more coarsely textured and inferior soils.

TABLE 3.
Wheat and irrigation intensities by subdivision in the Sirsa Irrigation Circle interpreted from the Indian Remote Sensing Satellite during rabi 1995/96.

Division and subdivision	Distributary	Wheat intensity (%)	Irrigation intensity (%)
Sirsa division		60	80
Mammerkhera	Mammerkhera	44	72
Punjwana	Bhakra Main	70	82
Bani	Bani	73	94
Rori division		49	71
Odhan	Kawal	44	70
Kalanwali	Maujgarh	51	67
Dabwali	Tejakhera	52	78
Nehrana division		53	61
Sheranwali	Sheranwali	63	77
Melleka	Kumthal	53	27
Baruwali	Baruwali	38	57
Ghaggar division		76	86
Sirsa	Sukhchain	75	75
Ottu	Balasar	77	100
Ellenabad	Ellenabad	72	95

The flood plain of the Ghaggar River is the major wheat belt in the Sirsa Irrigation Circle. Soils of the flood plain are finer textured than those in surrounding areas in the Nehrana and Rori divisions, and the water quality is generally good (EC <4 dS/m) though somewhat sodic (SAR >10). For the environmental conditions in the Hissar Irrigation Circle of the Bhakra system, Manchanda, Karwasra, and Sharma (1993) confirmed that sodic waters can successfully be used for wheat irrigation.

Some farmers in the freshwater belt of the Ghaggar flood plain use tubewells to augment the canal irrigation water supply. Figure 6 shows the relationship between the annual tubewell extraction and the quality of the groundwater. It indicates that large amounts of groundwater (over 200 mm/yr.) are generally drafted when the solute concentration is less than 1,500 ppm. Smaller extractions occur up to salinity levels of 4,000 ppm, and this groundwater is often mixed

FIGURE 5.
Average wheat yield in administrative command areas of the Sirsa Irrigation Circle, rabi 1995/96.

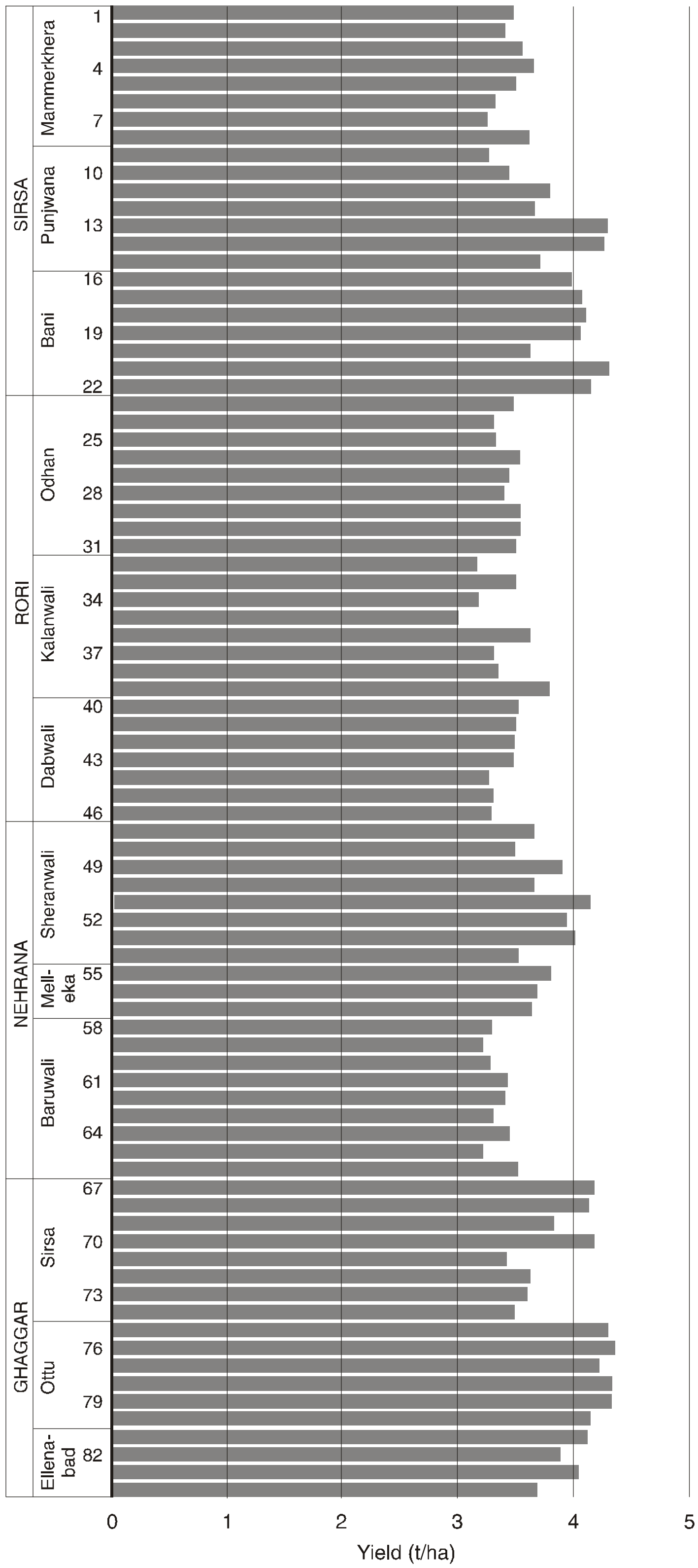
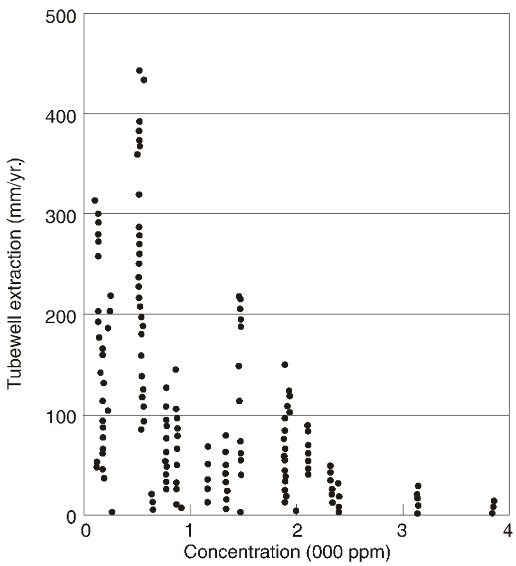


FIGURE 6.
Annual groundwater draft as a function of the solute concentration of groundwater.



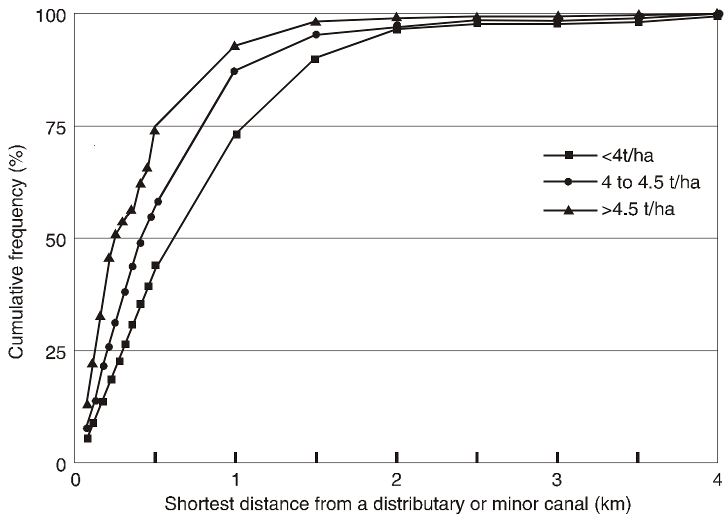
with canal water for irrigation purposes. Theoretically, wheat does not suffer greatly from salt-induced yield depression if the soil electrical conductivity remains below 6 dS/m (950 ppm). Farmers who draft saline groundwater with a solute concentration higher than 1,500 ppm must either apply sufficient leaching water or accept a minor depression in yield.

Does adequacy of water supply in the Sirsa Irrigation Circle affect crop selection? Satellite images show wheat yield gradients follow the fingered pattern of the canal network. In other words, cropping intensity and wheat yields are higher closer to the canal network. Some possible explanations are that canal water supply is greater near the offtakes of the minor canals, that underground water seeping from the distributaries is available for crop use, that tubewell density is higher near canals because the quality of the groundwater is good, or that the water table is at an optimal depth in relation to undulating terrain. Because this issue is outside the scope of the present investigation, we did not collect field data to resolve the causal factors. However, a hydrologic analysis by Jacobs et al. (1997) in the Hissar Irrigation Circle of the Bhakra system supported the hypothesis that a freshwater belt exists in areas adjacent to canals.

We used GIS procedures to calculate distribution of wheat yields as a function of the shortest distance from a canal. Figure 7 shows that 72 percent of pixels with wheat yields above 4.5 t/ha fell within 500 meters of a distributary, while only 42 percent of the pixels with yields below 4.0 t /ha were found within 500 meters of a distributary, indicating that the high yield class is dominant in the vicinity of the canal. Only 5 percent of pixels with a wheat yield higher than 4.5 t/ha were found at distances greater than 1,200 meters from a distributary, which implies that high yields are difficult to achieve for farmers located more than a kilometer away from distributaries.

Although flow records at all hierarchical canal levels were not available, spatial patterns of crop intensity and yield suggest that availability of good quality surface water or groundwater is more adequate in the vicinity of distributaries and minor canals. As a consequence, large tracts of land that are more than 1,500 to 2,000 meters from minor canals are kept fallow, and there is evidence that these abandoned fields are rapidly salinizing as a result of the capillary rise of shallow, poor quality groundwater. If the hypothesis of leaking canals holds true, it should be recognized that a substantial part of these conveyance losses are beneficially taken up as groundwater contribution for consumptive use. This is a good example of unintended water "losses" from the system being beneficially used in a regional perspective, a principle of water accounting in river basins (Molden 1997).

FIGURE 7.
The cumulative frequency of wheat yields in relation to the shortest distance from distributaries or minor canals for the Kalanwali, Dabwali, Odhan, Mammerkhera, and Punjwana subdivisions of the Sirsa Irrigation Circle, rabi 1995/96.



Hydrologic Analysis for 1977–90

For each model unit, the FRAME model provides spatio-temporal output on the following water and salt balance components of the crop root zone:

$$\Delta W = IRR + P + TW + SEE - ET - LEA - DR \qquad (2)$$

$$\Delta C = (IRR \times C_{IRR}) + (TW \times C_{TW}) + (SEE \times C_{SEE}) - (LEA \times C_{LEA}) - (DR \times C_{DR}) \qquad (3)$$

where

- ΔW = change in water storage (mm/yr)
- IRR = canal water irrigation
- P = precipitation
- TW = tubewell irrigation
- SEE = seepage
- ET = actual evapotranspiration
- LEA = leakage
- DR = drainage
- ΔC = salt storage change
- C = solute concentrations (mg cm^{-2} yr^{-1}) related to the water fluxes that convey solutes

Figure 8 is a schematic representation of the most important water and salt balance terms. Equations (2) and (3) apply to a soil column of an unconfined aquifer overlying and connected to a deeper confined groundwater system. The water balance of the confined aquifer underneath the unconfined upper system (expressed in millimeters per year) can be characterized as

$$Q_{inf} + LEA = SEE + TW$$

where Q_{inf} is the net subsurface water inflow. A positive Q_{inf} value implies that inflow exceeds outflow. The water and salt balance components were determined for the 46 units of the FRAME model on a 10-day basis and were integrated to annual values afterwards. The average annual area-weighted values for 1977 through 1990 (fig. 8), obtained from A. A. M. F. R. Smit (personal communication), were taken for a further hydrologic analysis. The data is presented in Annex 1.

FIGURE 8.
Average annual water and salt balances, Sirsa Irrigation Circle, 1977–90 (ΔW = change in water storage; ΔC = salt storage change).

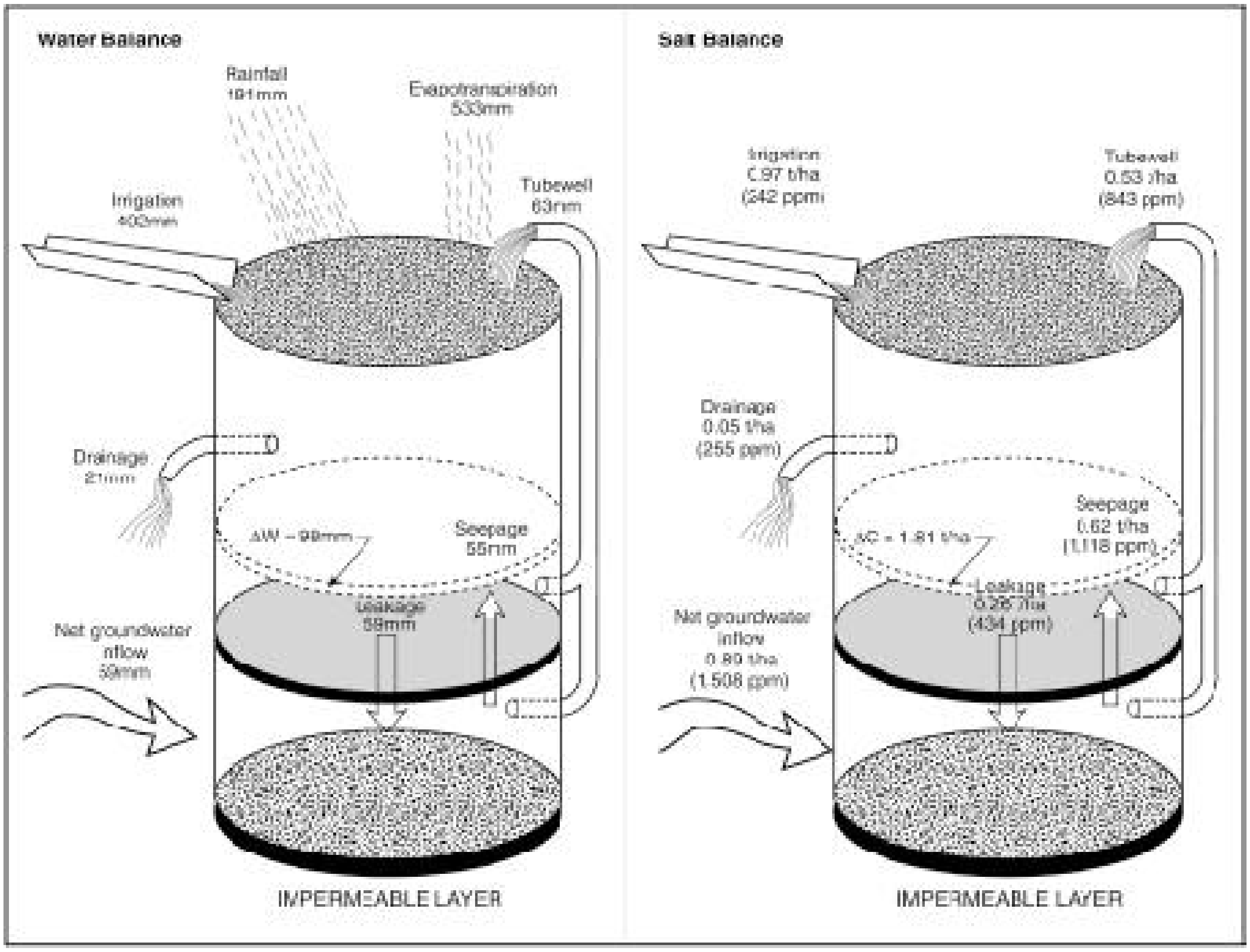
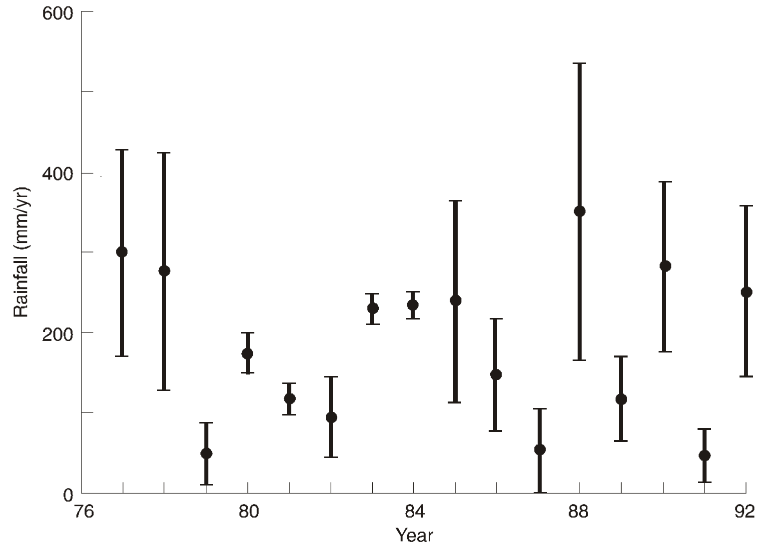


Figure 9 shows that average annual rainfall over the Sirsa Irrigation Circle can be extremely low in some years. For example, in 1979 the rainfall was about 50 millimeters. In contrast, for 1977 and 1988 the area-averaged rainfall exceeded 300 mm/yr., and some individual stations received more than 500 mm/yr. The spatial and temporal-average rainfall for the 1977–90 period is 191 mm/yr. Canal water supply adds an area-averaged 402 mm/yr., and tubewell irrigation adds 63 mm/yr.

The spatial patterns of tubewell irrigation differ considerably, ranging from 307 mm/yr. near the town of Sirsa to zero near the Rajasthan Feeder at the end of the Bhakra main canal in the Dabwali district. This variation is directly related to groundwater quality– areas of good groundwater quality have more tubewells. Model units that contain more tubewells evaporate substantially more (ET = 889 mm/yr., TW = 307 mm/yr.) than other units (ET = 557 mm/yr., TW = 66 mm/yr.). The lowest evapotranspiration, 339 mm/yr., occurs near the undulating sands of Rajasthan in the Baruwali district where a high proportion of the land is barren.

Tubewell-based groundwater extraction generates a gradient in hydraulic head that results in large net subsurface inflow rates, sometimes up

FIGURE 9.
Annual precipitation data gathered from nine rain gauges in Sirsa Irrigation Circle 1977–92. Broken lines indicate one standard deviation above and below the mean precipitation.



to 260 mm/yr. Seepage and leakage zones can be identified (Annex 1) by positive or negative values for the net subsurface inflow, Q_{inf}. The rising water table indicates an alarming imbalance between inflow and outflow of water. The build-up of the water table varies from slow (19 mm/yr.) to fast (182 mm/yr.). The largest values occur at the end of the Bhakra main canal in Kalanwali and Dabwali subdivisions.

The overall drainage outflow for the entire Sirsa Irrigation Circle via the Ghaggar River is 21 mm/yr. That amount is less than the capacity needed to dispose of salts carried in by surface irrigation water and groundwater sources. Salt build-up occurs without exception in all units of the model. Annual salinization rates vary from 0.7 t/ha in Punjwana subdivision to 3.6 t/ha in the percolation-prone areas of the Dabwali and Kalanwali subdivisions. The inflow of saline groundwater is the cause in the latter two subdivisions. This brief analysis shows that irrigation and the environment are not in harmony and that strong interventions are urgently needed to make the system more sustainable.

Water Balance Classifications

To describe hydrologic processes on a regional scale, a small number of subsets, or hydrologic classes, are often used (e.g., Wood, Lettenmaier, and Zartarian 1992; Koster and Suarez 1992). As demonstrated in Annex 1, there is substantial hydrologic heterogeneity in the Sirsa Irrigation Circle. Although this distributed model output provides great detail on spatial variations, it lacks the simplicity needed for rapidly assessing how the system behaves. The model output was therefore reduced in a way that the information on spatial variation was not lost. A cluster-analysis procedure (Annex 2) was applied to regroup the 46 model units into five classes based on hydrologic homogeneity as measured by the water balance terms *IRR, P, TW, SEE, ET, LEA, DR,* Q_{inf}, and ΔW (table 4).

The five hydrologic classes differ mainly in their canal water deliveries, tubewell irrigation, and annual changes in water storage (table 4). The hydrologic classes derived from the cluster analysis result in groupings of contiguous model units, as shown in figure 10. The longitudinal shapes of the hydrologic classes agree with the east-west pattern of the main irrigation canals.

The areas that fall into hydrologic classes 4 and 5 have lower irrigation intensity than other classes. These two classes are fed by the Fatehabad Branch, which has fewer canal running days than the other branch canals, resulting in smaller canal irrigation amounts.

Class 3 receives water from both the Sukhchain Distributary and the Rori Branch of the Bhakra main canal. The areas in this hydrologic class are underlain by fresh groundwater, thus farmers utilize tubewells. Because many farmers have access to tubewells, the Irrigation Department delivers less water to this area than to classes 1 and 2.

Extensive tubewell use is not an option in the areas of hydrologic classes 1 and 2 because of the saline groundwater (843 to 1,990 ppm). In class 1, as a result of a shallow water table, farmers are planting more oilseed crops, leading to lower consumptive water use, and (in the absence of reduced canal inflows) continued groundwater build-up (148 mm/yr.).

TABLE 4.
Water balance typology based on a cluster analysis of the annual values of nine water balance terms for 1977 to 1990. All water balance terms are based on unit gross area.

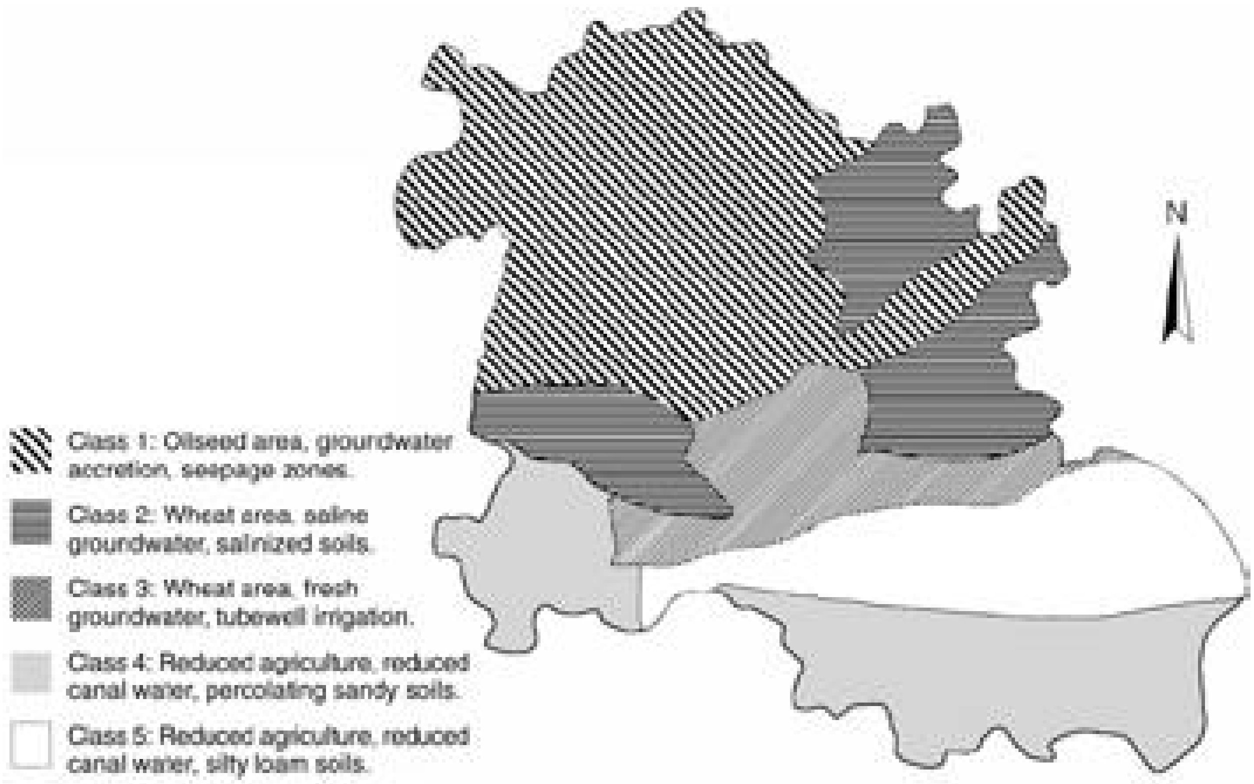
Hydrologic class	Area (km^2)	Water balancea (mm/yr.) IRR	*P*	TW	SEE	ET	LEA	DR	Q_{inf}	ΔW
1	86	505	201	30	71	541	77	41	23	148
2	76	506	182	59	30	651	51	17	38	58
3	99	397	223	235	29	753	48	5	216	78
4	118	271	173	45	81	385	78	10	49	97
5	109	252	196	46	23	464	8	2	62	43
Total	488	402	191	63	55	533	59	21	59	98

[a]IRR = canal water irrigation, *P* = precipitation, TW = tubewell irrigation, SEE = seepage, ET = actual evapotranspiration, LEA = leakage, DR = drainage, Q_{inf} = subsurface water inflow, ΔW = change in water storage.

Agricultural Practices as a Function of Hydrologic Conditions

Farmers respond to hydrologic conditions that are outside their direct control– such as erratic rainfall, short canal water supply, subsurface salt intrusion from neighboring areas, and leakage from the main conveyance network– by planting more or less of a certain crop or by using a combination of tubewell and surface water. At the same time, farmer practices such as the area cropped and groundwater extraction with tubewells affect the hydrologic conditions. There is a clear feedback mechanism between land use and

FIGURE 10.
Hydrologic classification of the Sirsa Irrigation Circle on the basis of distributed water balances and cluster analysis.



hydrology.[3] To determine the link between agricultural practices (wheat, yield, wheat intensity, and irrigation intensity) and hydrologic processes (water and salt balance terms) a correlation analysis was carried out.

Because the period of hydrologic analysis did not coincide with the remote sensing image during rabi 1995/96, 1988 was chosen as a year hydrologically similar to 1995. The 365-day period from May 1995 to April 1996 was characterized with an average rainfall for the Sirsa Irrigation Circle of 369 millimeters and a standard deviation across 12 stations of 170 millimeters (CV = 0.46). These values compare fairly well to the records for January 1988 to December 1988 (mean 352 mm, SD = 187 mm, CV = 0.53, see fig. 9). The average irrigation depth in the distributaries for the gross area in the Sirsa Irrigation Circle was 427 mm/yr for rabi 1995/96. The average irrigation depth for 1988 was similar: 390 millimeters. The dependent variables were wheat yield, wheat intensity, irrigation intensity, and canal water supply; they were chosen because they can be affected by management interventions. To make an analysis between agricultural practices and hydrologic conditions feasible, hydrologic data from 1988 were combined with the agronomic remote sensing data of rabi 1995/96 (table 5). The spatial scale of the

[3]Perry and Narayanamurthy (1998), who investigated the farmer response to reliability of the irrigation service in the Barwala-Sirsa system of Haryana, reached the same conclusion.

TABLE 5.
Correlation coefficients between agronomic and hydrologic features.

	Wheat yield	Wheat intensity	Irrigation intensity	Canal water
Wheat yield	-1.00	-0.77**	-0.73	-0.22
Wheat intensity	-0.77**	-1.00	-0.67**	-0.20
Irrigation intensity	-0.73**	-0.67**	-1.00	-0.32*
Canal irrigation	-0.22	-0.25	-0.32*	-1.00
Tubewell irrigation	-0.36	-0.58**	-0.29*	-0.09
Seepage	-0.49**	-0.60**	-0.40**	-0.05
Actual evapotranspiration	-0.43**	-0.72**	-0.51**	-0.59**
Relative evapotranspiration	-0.34*	-0.57**	-0.44**	-0.64**
Drainage	-0.01	-0.14	-0.06	-0.54**
Water storage change	-0.29	-0.48**	-0.15	-0.40**
Subsurface inflow	-0.29	-0.48**	-0.18	-0.22
Solute concentration leakage	-0.02	-0.02	-0.17	-0.48**
Soil salinity	-0.19	-0.35*	-0.13	-0.16*

*95% probability. **99% probability.

hydrologic data, i.e., the FRAME model units, was used as a basis, and the agronomic data were rescaled to fit with the hydrologic data.

Wheat yield was correlated with wheat intensity, irrigation intensity, seepage, actual evapotranspiration, and relative evapotranspiration (table 5). Hence, on statistical grounds, it may be concluded that the intensively cultivated wheat areas result in a higher crop yield, as a mere consequence of adequate water quality and soil moisture availability. The combination of environmental conditions and the availability of canal water seems to be of paramount importance for farmers in deciding whether to sow wheat. It also conforms with the known relationship between yield and evapotranspiration: that crop water stress and soil moisture conditions are the prevailing constraints for crop yields (Hanks 1974; Doorenbos and Kassam 1979). Furthermore, it is remarkable that wheat yield was not significantly correlated with the use of tubewells (r = 0.36), indicating that tubewell irrigation is not a prerequisite for favorable crop yields in the Sirsa Irrigation Circle.

Wheat intensity shows a high correlation with hydrologic processes (i.e., tubewell irrigation, seepage, actual evapotranspiration relative evapotranspiration, water storage change, and subsurface inflow). An important finding is that wheat intensity is significantly related to seepage (r = -0.60) but not to canal irrigation (r = 0.25), and that the presence of tubewells is also significant (r = 0.58). This confirms that farmers in the Sirsa Irrigation Circle decide whether to cultivate wheat largely based on prevailing hydrologic conditions and the possibility for augmenting canal water deliveries with groundwater.

The general lesson of this exercise is that knowledge of the water balance and farmer decisions related to crop selection and irrigation intensity are essential for understanding how irrigation systems operate. Irrigation performance assessment studies should not be restricted to canal water supply practices in isolation, but should consider the overall hydrologic processes of an area. Sakthivadivel et al. (forthcoming) applied the same remote sensing information to the entire Bhakra system and found that farmer decision making is heavily influenced by the availability of good quality groundwater, a conclusion in line with the present observations. Hence, the presence of a canal water distribution system affects the subsurface water balance, thereby inducing different hydrologic conditions. Canal water thus only indirectly affects the selection of agricultural practices and the performance of irrigation systems.

The Performance of Irrigated Agriculture at Sirsa

From a hydrologic perspective, the performance of an irrigation system is evaluated by focusing on the productivity of water resources and land. In the present study, the productivity of water can be estimated if the 1995-96 yield data are fused with the hydrologic data of 1988. This gives only a first order approximation of the overall utilization of water and may not be regarded as a sound quantification. As demonstrated above, farmers' practices are heavily influenced by the induced hydrologic conditions in which they are operating. This type of study corresponds to works such as those by Visser et al. (1993) and Keller and Keller (1995), which show that water diversions and depletions should be considered in a regional context because local water losses may be taken up and productively used elsewhere. Water accounting procedures (Molden 1997) to analyze uses, depletions, and productivity of water are combined with other measures to represent the present performance of irrigated agriculture in the Sirsa Irrigation Circle over the period 1977 to 1990 (table 6).

In spite of leaky canals, or inefficient on-farm practices, nearly all the water that enters into the Sirsa Irrigation Circle is productively depleted by agricultural crops, as shown by the large depleted fraction of the gross inflow (82%). The low value for relative water supply is characteristic of protective irrigation, which intentionally keeps supply low relative to potential demand.

The irrigation intensity of 73 percent for rabi, compared with an annual intensity of 60 percent expected in the system design, shows that the area irrigated is much larger than the designed area of the system. This difference must be due to tubewell use, and results in the higher-than expected value for the depleted fraction. Farmers are adapting to the system in ways not

TABLE 6.
Water management indicators for the entire Sirsa Irrigation Circle.[a]

	Average value	Spatial coefficient of variation
Hydrology, 1997–90		
Depleted fraction[b] (%)	82	0.08
Evaporative fraction[c] (%)	28	0.05
Relative water supply[d] (%)	34	0.06
Irrigated agriculture, rabi 1995/96		
Irrigation intensity (%)	73	0.37
Wheat intensity (%)	58	0.18
Oilseed intensity (%)	31	0.17
Other crops intensity (%)	11	0.04
Agricultural productivity, rabi 1995/96		
Wheat productivity (t /ha)	3.76	0.34
Water productivity (kg/m^3)	0.88	0.20
Water productivity (US$/m^3)	0.14	0.30
Sustainability, 1977–90		
Water storage change (mm)	98	46
Salt storage change (t/ha)	1.81	0.66

[a]Including noncultivated lands, swamps, cities, etc.
[b]Depleted fraction of gross inflow = Actual evapotranspiration/(precipitation + canal water inflow + groundwater inflow).
[c]$ET_{actual}/ET_{potenet\ ial.}$
[d](Canal water supply + tubewell water supply + precipitation)/ Potential evapotranspiration.

anticipated by the original designers. That surely can be considered a success story. However, the large coefficients of variation of intensity of irrigation, wheat, and oilseeds tell another story. Whether the warabandi water allocation principle is strictly followed must be questioned. Further research is required here, and the remote sensing results point to areas where this research could be done.

A special method was used to estimate the water productivity of wheat– combining the results of the FRAME model for 1988, a year hydrologically similar to 1995, with satellite-derived productivity information (Annex 3). However, if future studies successfully derive seasonally accumulated evapotranspiration from satellites, a unique opportunity will arise to express yield per unit of water or water use efficiency regionally from space measurements. A water productivity of US\$0.14/m^3 for wheat is reasonable compared with other systems worldwide (Molden et al. 1998), though for the entire Bhakra command, Sakthivadivel et al. (forthcoming) found a value of US\$0.20/m^3.

The sustainability of irrigated agriculture can be evaluated by considering the changes in storage of water and salts. If over the long term, there is a positive or negative change in groundwater storage, or a gain in salts, sustainability is probably threatened. Despite a high depleted fraction, groundwater build-up at Sirsa continues as a result of inadequate drainage. The groundwater storage change of 98 mm/yr indicates a rising water table in spite of the pumping. This is equivalent to a rise in the water table of 81.6 cm/yr. at a specific aquifer yield of 0.12. The addition of salts at a rate of 1.81 t/ha annually should also be of great concern. The area is in danger of waterlogging and salinity in the near future.

To study the variation in performance in the area, each of the five hydrologic classes was considered (table 7). Wheat yields vary slightly across the hydrologic classes; there is much more variation in evapotranspiration. Consequently class 3, where there is heavy tubewell use and high wheat and irrigation intensities, has the lowest water productivity (0.83 kg/m^3; US\$0.14/m^3). Class 5, comprising the southern stretches of the Sirsa Irrigation Circle, has the highest productivity per unit of water consumed by evapotranspiration. Class 5

TABLE 7.
Performance information for the five hydrologic classes of the Sirsa Irrigation Circle.[a]

Class	Area (km^3)	Irrigation: Canal	Irrigation: Tubewell	Evapotranspiration (mm): Total[b]	Evapotranspiration (mm): Wheat[c]	Depleted fraction (%)	Intensity (%): Irrigation	Intensity (%): Wheat	Wheat yield (t/ha)	Water productivity of wheat: Physical (kg/m^3)	Water productivity of wheat: Economic (US\$/m^3)	Annual increase: Groundwater storage (mm)	Annual increase: Salt (t/ha)
1	86	505	30	541	372	0.74	0.72	0.51	3.45	0.93	0.15	148	2.09
2	76	506	59	651	403	0.9	0.77	0.67	3.91	0.97	0.16	58	1.67
3	99	397	235	753	471	0.9	0.76	0.68	3.92	0.83	0.14	78	1.91
4	118	271	46	385	308	0.78	0.63	0.45	3.49	1.13	0.18	97	1.80
5	109	252	464	64	307	0.91	0.74	0.56	3.63	1.18	0.19	43	1.40

[a]Rabi 1995/96, except as noted.
[b]Annual average, 1977-90.
[c]See Annex 3.

also performs well in terms of slow groundwater and salt accretion.

Sirsa Irrigation Circle, with its practice of warabandi, is inherently a supply-based system in which a central authority makes the decisions about water supply. Delivering less canal water to tubewell areas because they have an alternate source of water appears to be an intentional practice. It is not clear why so much more water is delivered to hydrologic classes 1 and 2 than to 4 and 5. It is clear that water is not easily drained from hydrologic classes 4 and 5, and excess water percolating past the crop root zone is most readily recycled by tubewells. It appears that there is an oversupply to class 1 and much groundwater build-up. Class 4 receives a reduced supply, has lower wheat intensity, less yield, and suffers from groundwater build-up. This is probably due to a mismatch between water supply and requirements because of the low water holding capacity of sandy soils. In class 5, the silty soils have better water storage capabilities, so there is less deep percolation, resulting in less groundwater build-up and the highest productivity of water. One way to alleviate the problems of groundwater build-up in classes 1 and 4 is to deliver a reliable supply and let farmers spread the water thinly or to deliver water more frequently with less depth to avoid deep percolation.

Conclusions

Combining information from hydrologic modeling, field data, and satellite remote sensing in a GIS format allowed for a view of the Sirsa Irrigation Circle of the Bhakra command area that had not previously been available. Remote sensing revealed a complete picture of agricultural productivity for a season. Modeling allowed detailed study of hydrologic processes in the region. GIS facilitated integration and analysis of the information.

Through satellite remote sensing, information on wheat yield and irrigation intensity was obtained. Wheat yield was relatively uniform throughout the area, but the wheat intensity was highly variable. Through satellite remote sensing, the average wheat yield was found to be 3.76 t/ ha. Modeling revealed an average water consumption through evapotranspiration of 428 millimeters, yielding a productivity of water of 0.88 kg/m^3, which is equivalent to US$0.14/m^3 at the 1996 international wheat price (US$163/t). Because the Irrigation Department of Haryana has adjusted the number of running days of the Fatehabad Distributary to respond to the lower cultivation densities, the highest productivity of water was found in the area south of Sirsa town (1.18 kg/m^3; US$0.19/m^3). Tubewell irrigation gave the lowest water productivity (0.83 kg/m^3; US$0.14/m^3).

Higher wheat intensities and wheat yields were found in the vicinity of main and distributary canals. The further from the canals fields are located, the less likely it is that wheat will be grown, and the more likely it is to find large portions of land that do not receive canal water in sufficient quantities. From this information, we postulated that canal water in the Sirsa Irrigation Circle is not supplied according to the allocation principle of warabandi. It has been shown that the cultivation of wheat, a decision that is in the hands of farmers, is more closely related to subsurface hydrologic conditions (tubewell irrigation, seepage) than to canal water supply.

Considering the irrigated hydrology, the overall depleted fraction of gross inflow is 82 percent. In other words, crops consume 82 percent of all incoming surface water, groundwater, and rainwater even though there may be canal seepage and deep percolation. A major factor must be the reuse of water through tubewells.

The area of the Sirsa Irrigation Circle was classified into five hydrologic classes, each of which displayed differing patterns of irrigation inflow, tubewell use, and groundwater build-up. As a result, agricultural practices and performance were quite different across these hydrologic classes. Irrigation managers could use this information to respond to differing needs of farmers by adjusting water supplies.

There are major issues that must be addressed to sustain the agricultural productivity of the area. Groundwater levels are rising at an average rate of 98 mm/yr. in spite of the pumping. Salts are being added to the Sirsa area at an annual rate of 1.81 t/ha. This is due largely to a combination of subsurface water inflow in tubewell areas, the lack of drainage outflow from the area, and the high depleted fraction, which enhances the salt concentration. Remedial actions are required immediately to halt the imbalance between the regional inflow and outflow of water and salts.

With improvements in remote sensing technology, even more detailed analyses will be possible. Currently, water consumption from irrigated areas can be estimated for single days (e.g., Roerink et al. 1997). It is foreseeable that estimates of seasonal evapotranspiration for a region can be made using remotely sensed data (Bastiaanssen et al. Forthcoming). If this proves to be the case, satellite remote sensing will provide an excellent tool to study productivity of both land and water on a regional scale.

ANNEX 1.

Annual Water and Salt Balanace in the Sirsa Irrigation Circle

Distributed annual average salt balance, 1977–90 (mm/yr.).

Model unit	IRR	TW	P	ET	SEE	LEA	DR	ΔW	Q_{inf}
1	507	1	203	546	86	75	11	166	-13|
2	494	47	265	599	79	99	25	162	-27
3	499	6	265	583	77	99	14	150	16
4	502	74	265	592	62	111	47	153	-25
5	498	5	265	573	70	62	22	182	-13
6	509	3	203	553	63	51	6	168	-15
7	508	3	203	536	67	51	28	167	-19
8	500	5	265	558	66	85	35	157	14
9	499	8	265	583	50	76	19	144	18
10	507	69	224	707	34	13	34	80	-90
11	505	8	224	662	40	11	25	77	-36
12	508	1	203	477	102	72	83	182	-30
13	494	33	203	484	69	118	79	119	16
14	498	112	203	545	93	122	64	175	-83
15	503	7	118	463	62	63	23	141	-6
16	505	34	224	692	47	14	21	83	-67
17	501	8	118	449	77	64	32	160	-21
18	496	59	118	468	60	98	39	129	-21
19	501	24	118	456	51	89	36	114	14
20	539	39	224	684	90	30	79	98	-100
21	536	102	118	596	53	27	90	96	-128
22	489	211	243	819	25	53	8	88	-183
23	494	66	86	557	12	34	16	52	-45
24	477	74	86	560	31	21	2	84	-84
25	483	146	145	686	32	46	6	69	-132
26	488	307	243	889	33	77	9	96	-262
27	549	65	217	689	36	136	16	27	34
28	524	68	217	640	26	147	30	19	52
29	489	191	243	813	27	53	5	78	-165
30	267	247	145	607	53	29	2	75	-271
31	283	149	86	468	78	56	9	63	-171
32	289	56	86	401	89	18	31	70	-126
33	245	39	145	399	22	7	2	44	-54
34	250	220	243	638	6	28	0	52	-198
35	507	0	217	669	12	36	2	28	25
36	253	45	182	457	27	8	0	42	-64
37	252	77	182	472	23	10	1	52	-89
38	251	64	243	518	19	13	0	45	-70
39	256	21	243	487	21	3	8	41	-38
40	285	35	243	402	45	102	16	87	22
41	284	32	243	402	61	89	13	116	-4
42	256	14	182	360	72	72	0	93	-14
43	256	33	182	450	28	7	0	41	-53
44	259	34	182	356	111	115	2	113	-30
45	257	11	182	339	95	83	4	120	-29
46	255	37	182	356	101	91	2	127	-47

Source: A.A.M.F.R. Smit (personal communication).

Note: IRR = canal water irrigation; TW = tubewell irrigation; P = precipitation; ET = actual evapotranspiration; SEE = seepage; LEA = leakage; DR = drainage; ΔW = change in water storage; Q_{inf} = net subsurface water inflow.

Distributed annual average salt balance, 1977-90 (mg/cm^2).

Model unit	IRR	TW	DR	LEA	SEE	ΔC	Q_{inf}
1	12.3	0.0	0.2	4.4	5.1	12.8	0.7
2	12.0	8.4	0.6	6.8	14.1	27.0	15.7
3	12.1	0.5	0.3	5.7	6.6	13.1	1.3
4	12.2	10.3	1.1	5.9	8.7	24.1	13.0
5	12.1	1.3	0.5	3.9	20.7	29.8	18.2
6	12.3	0.9	0.1	3.1	22.9	33.0	20.7
7	12.3	0.3	0.6	2.8	5.7	14.9	3.2
8	12.1	1.4	0.8	4.6	19.5	27.6	16.2
9	12.1	1.8	0.5	4.9	11.1	19.7	8.1
10	12.3	9.7	1.1	0.1	4.7	25.4	14.2
11	12.2	0.5	0.5	0.2	2.6	14.6	2.9
12	12.3	0.0	1.9	3.1	5.8	13.2	2.8
13	12.0	2.8	1.8	4.6	5.9	14.3	4.2
14	12.1	3.0	1.4	6.0	2.5	10.5	-0.2
15	12.2	0.6	0.5	3.3	5.2	14.2	2.5
16	12.2	3.7	0.5	0.1	5.2	20.6	8.8
17	12.1	0.6	0.7	2.8	6.5	15.7	4.3
18	12.0	5.0	1.0	4.5	5.0	16.5	5.5
19	12.1	2.6	0.8	3.7	5.7	15.9	4.6
20	13.0	4.3	2.0	0.1	9.9	25.1	14.1
21	13.0	18.1	4.5	0.0	9.5	36.0	27.5
22	11.8	11.7	0.2	2.2	1.4	22.5	10.9
23	12.0	5.6	0.4	1.6	1.0	16.5	5.0
24	11.5	1.4	0.0	0.1	0.6	13.4	1.9
25	11.7	2.9	0.1	0.9	0.6	14.1	2.5
26	11.8	17.0	0.3	1.7	1.8	28.7	17.1
27	13.2	5.5	0.4	14.2	3.0	7.2	-5.6
28	12.7	13.6	1.0	17.6	5.2	12.9	1.1
29	11.8	10.6	0.2	0.5	1.5	23.2	11.6
30	6.5	4.1	0	0.1	0.9	11.3	4.9
31	6.7	16.4	0.4	0.1	8.6	31.3	24.9
32	7.0	4.2	0.9	0.0	6.6	17.0	10.9
33	5.9	4.9	0.0	0.1	2.8	13.5	7.6
34	6.0	16.3	0.0	0.6	0.5	22.2	16.1
35	12.2	0.0	0.0	0.9	0.0	11.4	-0.9
36	6.1	3.8	0.0	0.1	2.3	12.1	6.0
37	6.1	9.7	0.0	0.1	2.9	18.5	12.4
38	6.1	8.0	0.0	0.3	2.4	16.2	10.1
39	6.2	4.6	0.2	0.1	4.6	15.1	9.1
40	6.9	4.5	0.4	3.4	5.6	13.2	6.7
41	6.9	2.7	0.3	2.3	5.1	12.1	5.5
42	6.2	1.8	0.0	1.9	9.1	15.2	9.0
43	6.2	2.7	0.0	0.1	2.3	11.2	5.0
44	6.3	4.3	0.0	2.7	14.0	21.8	15.6
45	6.2	1.3	0.1	1.6	12.0	17.8	11.7
46	6.2	6.5	0.1	2.7	18.0	28.0	21.9

Source: A.A.M.F.R. Smit (personal communication).

Note: IRR = canal water irrigation; TW = tubewell irrigation; DR = drainage; LEA = leakage; SEE = seepage; ΔC = salt storage change; Q_{inf} = net subsurface water inflow.

ANNEX 2.

Cluster Analysis

Cluster analysis is a technique that can be used to group objects by the similarity or distance between them. First, a matrix of distances between all pairs of objects in terms of the variables describing the objects is computed. Then a clustering method is used to group the objects based on the calculated distances (see Manley 1986; Norusis 1993; Everitt 1980). The following are the main parameters of the cluster analysis.

Variables. The variables used in the cluster analysis to find homogenous groupings of the 46 model units were

ΔW	change in water storage
IRR	canal water irrigation
P	precipitation
SEE	seepage
TW	tubewell irrigation
ET	actual evapotranspiration
LEA	leakage
DR	drainage
Q_{inf}	subsurface water inflow

Distance Measure. Squared Euclidean distance was used to measure the degree of similarity of objects. The variables were first standardized to have a mean of 0 and variance of 1 to adjust for the dissimilar scales of measurement and to give all variables equal weight.

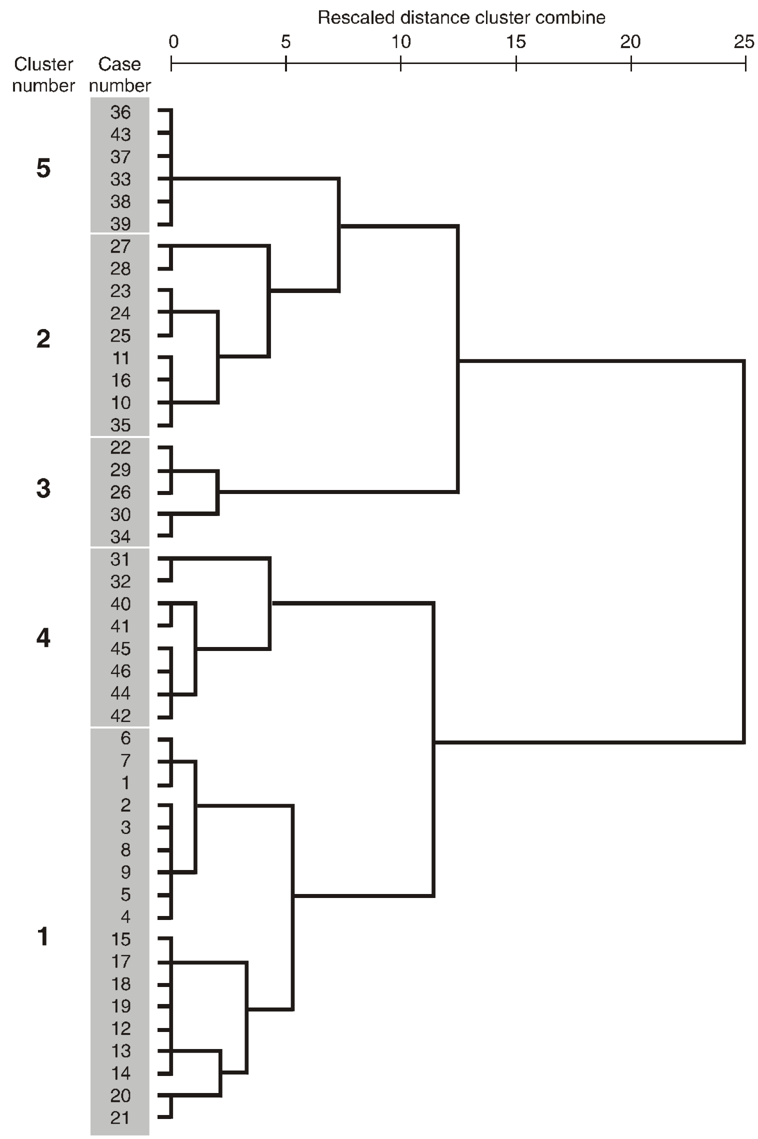
Clustering Method. Ward's method was used for agglomerative hierarchical cluster analysis. In agglomerative methods, each model unit is initially considered a separate cluster and then grouped into bigger clusters until all units end up in a single cluster. Ward's method combines clusters with the smallest increase in the overall sum of the squared within- cluster distances.

Dendrogram. The results of the cluster analysis are shown in the dendrogram. The five clusters are labeled. These correspond to the five hydrologic classes discussed in the text. The axis "Rescaled distance cluster combine" shows the distance at which the clusters combine. These distances are obtained by rescaling the calculated distances to 1 to 25.

Interpretation and Assessment of the Solutions. Solutions with different numbers of clusters were assessed by examining the summary statistics of the individual variables calculated for each cluster to determine the properties of each cluster and which variables were most instrumental in defining the separation between clusters. Solutions with more than five clusters had insufficient distinction between some of the defined clusters; solutions with less than five clusters resulted in the joining of relatively nonhomog-enous clusters. For example, the four-cluster solution joins clusters 5 and 2, which are relatively nonhomogenous judging from the distance at which they combine. The five-cluster solution was found to be clearly interpretable.

Software. Statistical Package for the Social Sciences, v. 6.1, was used for statistical analysis.

DENDROGRAM.
The results of the cluster analysis.



ANNEX 3.

Estimating the Water Consumption of a Wheat Crop

Because no direct measurement or estimate of actual crop evapotranspiration was available for rabi 1995/96, this information was inferred. According to Thiruvengadachari, Murthy, and Raju (1997), the irrigated land-use pattern in the Sirsa Irrigation Circle is wheat, 58 percent; oilseeds, 31 percent; and other crops, 11 percent. FRAME output indicates that the actual evapotranspiration during 1988 for the gross area of the Sirsa Irrigation Circle was 641 mm/yr. Assuming that all nonirrigated land (built-up areas and bare soil) has negligible evaporation and that 73 percent of the land is irrigated, the irrigated land should have an actual evapotranspiration of 879 mm/yr.

Based on computer-simulated annual water cycles (Bastiaanssen et al. 1996), crop water consumption during rabi is 44 percent of the annual value. Thus the evapotranspiration of the irrigated lands during rabi is assumed to be 387 millimeters. The same computer simulation indicated that wheat used 321 millimeters (evaporation plus transpiration) and oilseeds used 243 millimeters per growing season in Sirsa and Hissar circles during 1991-93. Therefore a value of 1.3 was used for the ratio of wheat evapotranspiration to oilseed evapotranspiration in this analysis. Other crops are assumed to have a consumptive use identical to oilseeds. By applying those values, crop water consumption can be estimated:

$$387 = ET_{oil}(1.3x_{wheat} + x_{oil} + x_{other})$$

where ET_{oil} (mm) is the actual evapotranspiration of oilseeds and other crops and x is the relative area of each irrigated crop. From the equation, ET_{oil} is 329 millimeters, thus actual wheat evapotranspiration is 428 millimeters.

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