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Research Report

Using Remote Sensing Techniques to Evaluate Lining Efficacy of Watercourses

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and
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International Water Management Institute

Research Reports

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IWMI's research is funded by the Consultative Group on International Agricultural Research (CGIAR) and other donors. Support is also given by the Governments of India, Iran, Mexico, Nepal, Pakistan, South Africa, and Sri Lanka.

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R. Sakthivadivel, Upali A. Amarasinghe, and S. Thiruvengadachari. 2001. Using remote sensing techniques to evaluate lining efficacy of watercourses. Research Report 46. Colombo, Sri Lanka: International Water Management Institute.

/ water management / water distribution / remote sensing / watercourses / canal linings/
seepage loss / SRS data analysis / groundwater development / surface water / performance
evaluation / equity / India /

ISBN 92-9090-416-X

ISSN 1026-0862

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Summary

The cost of developing new irrigation potential is escalating. A low-cost alternative strategy of selective lining of watercourses to reduce seepage and increase irrigated area is being increasingly adopted in the Indian subcontinent. However, studies on assessing the efficacy of such lining are few. These studies have depended mainly on a few sample watercourses supported by limited water measurement and agricultural data, and their results are not conclusive.

Satellite Remote Sensing (SRS) is seen as a cost-effective evaluation tool in view of its large area of coverage, which is synoptic and repetitive. The analysis of multiyear satellite data has enabled to evaluate the lining efficacy of about 30 watercourses located in the fresh, marginal and saline groundwater zones of the Bhakra canal command in Haryana, India. The

lined watercourses together with concomitant groundwater development and use have sustained tail-to-head uniformity of water distribution even after 20 years of lining. The SRS technique can be used as a stand-alone tool in an environment where only small amounts of groundwater supplies are used to support surface water supplies. In areas with substantial groundwater supplies, isolation of lining efficacy will require additional data on groundwater support. The SRS technique is particularly useful as a screening tool to identify problem watercourses where field verification data can be collected for cost-effective and quick evaluation of watercourse lining. The cost of using this technique works out to only US\$0.17 per hectare of the area served by the watercourses. This cost is based on the 1996 cost of satellite images, covering a geographic area of about 225 square kilometers.

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Introduction

Irrigation diversion of river water through run-of-river systems and supply from storage dams have a long history in the Indian subcontinent. In the postindependence years, both Pakistan and India invested heavily in developing new irrigation potential, which currently supports about 30 percent of the world's irrigated area. The rate of expansion of irrigated area has slowed down in recent decades with the cost of developing irrigation potential becoming very high, along with the rising cost of environmental management. Externally assisted as well as government-funded irrigation development programs have now focused attention on conserving the potential created so far, ensuring its optimum utilization through better infrastructure development and water management practices. The alternative strategy of increasing irrigation water supplies through reducing water "losses"¹ from canals and watercourses by selective lining has been increasingly adopted on the subcontinent.² Since watercourse conveyance losses in a typical distribution system in alluvial soils are nearly three times that of a distributary and one and a

half times that of a main canal, the lining of watercourses has been embraced by the engineering community as a means of ensuring water supplies to the "unreached" in the tail areas (National Seminar 1983). Methods have been evolved for optimizing the length of a watercourse to be lined to minimize cost (Malhotra 1975). Watercourse lining is recommended in saline groundwater areas (to arrest the rising water table). Lining programs have also been implemented in fresh groundwater areas where the impact is to reduce dependence on groundwater supplies (World Bank 1995).

In spite of huge investments being made in lining watercourses, definitive studies on evaluating efficacy of lined watercourses in maintaining flow and equity in water distribution are limited in number and scope. The evaluation studies done so far have depended heavily on farmer surveys, inspection of sample watercourses, and water measurements in a few watercourses, as well as on a limited collection of data on productivity of water consumed. While these evaluations have indicated varying

¹"Loss" is the normally used term, but in nonsaline areas the "lost" water is either conventionally stored underground for later use or moves downstream for possible further use. Many people believe that by increasing the "efficiency" of irrigation (i.e., by reducing losses), the water saved can be used elsewhere or be transferred to other sectors. IWMI's work suggests the potential for such savings is not as great as often assumed. For example, techniques to save water at the farm level may not translate into water savings at the system or basin level due to recycling (Seckler, Barker, and Amarasinghe 1999).

²The cost of water saved through watercourse improvement was about 25 percent of the cost of developing an equal volume of new water supply in Pakistan (World Bank 1995).

degrees of reducing seepage through watercourse improvement, reliable information and data on the effect of extent of lining and its age on performance have been relatively poor and scattered. The sustainability gains by lining have also not been adequately evaluated, although one study in Pakistan indicated that benefits have been sustained for 10 years and can be expected to continue for some more years (World Bank 1995).

Because of the large number of watercourses covering hundreds of kilometers ground surveys become costly, time-consuming and subjective, and staff from many departments are required for data collection. It is in this context that SRS techniques are seen as promising tools to monitor and evaluate the efficacy of watercourse lining. The large area with synoptic coverage (over hundreds of square kilometers) coupled with frequent revisits (limited to a few days) and archived historical data (more than a decade), enable to generate time series on agricultural productivity at watercourse level for detailed analysis. The increasing spatial resolution (better than 10 meters) of current and future satellites will further enhance the capability to study spatial variability of irrigation intensity, cropping pattern and crop productivity of major crops across the watercourse command.

The International Water Management Institute (IWMI) undertook an investigation in collaboration with the National Remote Sensing Agency (NRSA) of India and the Haryana State Water Resources Department in the Bhakra canal command of Haryana, India, with the main objective of answering the following two research questions:

1. Can SRS techniques be used as a cost-effective tool to evaluate efficacy and equity in water distribution of a lined watercourse?
2. For what period of time can a lined watercourse maintain its ability to preserve equitable water distribution between the head reach and the tail reach of a watercourse with the existing level of maintenance?

Twenty-eight lined sample watercourses were selected from three blocks³ on a stratified random basis and analyzed. The methodology adopted was: a) generation of spatial data from satellite imagery for a study period of 5 years on irrigated area, area under wheat and non-wheat crops and averaged NDVI⁴ of wheat crop in the head and tail reaches of each selected watercourse; b) spatial and temporal analyses of changes in irrigation extent and crop condition as a function of lining extent and age; and c) analyzing the effect of canal lining on irrigation extent in the presence of groundwater development. The utility of SRS techniques was demonstrated as a cost-effective tool for objective and large-scale evaluation of efficacy of watercourse lining, in the context of large investments already made and planned in this intervention. In view of cloud cover limitations, this study focuses on SRS application only in the rabi season.

In this water-short system with rotational water supply, sample watercourses in three zones with different groundwater quality were studied through an analysis of satellite data from the rabi seasons of 1987–1997. Information on

³Three sets of terminologies are used to describe the command area: the first is based on administrative unit: districts, tesils (subdivision of a district) and blocks; the second is based on water distribution units: circles, divisions and subdivisions; and the third is based on quality of groundwater: saline, marginal and fresh groundwater zones.

⁴NDVI is derived from satellite spectral measurements and is a measure of green vegetation biomass and vigor (Tucker 1979).

irrigated area, area under wheat and non-wheat crops and wheat condition was generated for spatial and temporal analyses. Efficacy of lining is a function of many factors, including discharge at the outlet of a watercourse; length of watercourse; maintenance standard and history; farmer organization at watercourse level; and

extent and age of lining. Only the last two factors—extent of lining⁵ and age of lining—will be addressed in this study. The results derived from SRS techniques were supplemented with data collected from field visits to selected watercourses to investigate the conclusions arrived at in this study.

Study Area

Bhakra Irrigation Project

Haryana is a chronically water-deficit state in India. Eighty percent of the cultivated area of the state (2.8 million hectares), is irrigated. The extent of area irrigated by canal water is roughly the same as that irrigated by groundwater and, in many instances, conjunctive use of canal water and groundwater is practiced.

The two major canal systems of the state are the Bhakra canal system, which is fed from the Indus basin, and the Western Yamuna canal system, which receives its supply from the Yamuna river. They make a 12,100-km long network, providing 88 percent of the surface irrigation supplies. The study area is situated in the “Bhakra System.” The Bhakra canal network with a cultivable command area (CCA) of 1.2 million hectares (figure 1) has three operational systems: Narwana–Sirsa system, Barwala–Sirsa system, and Bhakra Main Line (BML) system. The command area is divided into five water services circles: Ambala, Kaithal, Hisar-1, Hisar-2, and Sirsa that, in turn, are divided into 13 divisions and 41 subdivisions. Box 1 presents the system details.

Groundwater accounts for more than half the irrigated area in the Bhakra canal command. The Groundwater Cell of the Agriculture Department monitors the depth to groundwater table and groundwater quality. Groundwater levels are observed twice a year, in June (pre-monsoon) and October (post-monsoon). In the Hisar, Sirsa and parts of Jind districts, where groundwater development is low due to poor water quality, the water table has risen over time. In parts of Kaithal, Kurukshetra and Ambala districts, the water table has gone down due to extensive extraction of good quality groundwater. The Agriculture Department reports areas irrigated by canal water and groundwater separately while the Irrigation Department reports areas irrigated only by canal water. However, the area irrigated by the conjunctive use of canal water and groundwater within the canal command is not reported by either department.

Irrigation water is supplied according to the warabandi principle, which follows a rigid rotational cycle of fixed duration, frequency, and priority level (Berkoff 1987; Malhotra 1982).

⁵In Northwest India, watercourse lining always began from the head of a watercourse and proceeded downstream; generally, the tail end of a watercourse is left unlined. Because of the uniformity in soil strata, very few partially lined watercourses were found with breaks in lining in between.

FIGURE 1.

Index map of Bhakra canal command area showing study area blocks.



Originally, the warabandi principle was designed to equitably distribute the uncertain run-of-river flow through a procedure known as “rostering” (Sakthivadivel et al. 1999). The system of allocating water through rostering remains unchanged even after creating a sustainable reservoir storage in the Bhakra system that provides stable and reliable supplies, although the supply is inadequate to fully meet the irrigation needs.

Kharif (June–October) and rabi (November–April) are the two principal agricultural seasons. When the irrigation system was planned, the assumed cropping pattern of the Bhakra canal

command in kharif was fodder, cotton, gram, barley, orchards, and vegetables and in rabi it was wheat, fodder, gram, barley, and vegetables. Presently, the cropping pattern and the cropping intensity have changed dramatically, with most of the irrigated area occupied by high-yielding varieties of rice, wheat, and cotton. The total irrigated wheat areas during the rabi seasons of 1992–93 and 1993–94 were 68.6 and 71.4 percent, respectively, of the total irrigated area, each percentage being more than double the percentage of the planned total irrigated area in the project. During rabi, in addition to wheat, toria is the principal oilseed crop in Ambala and

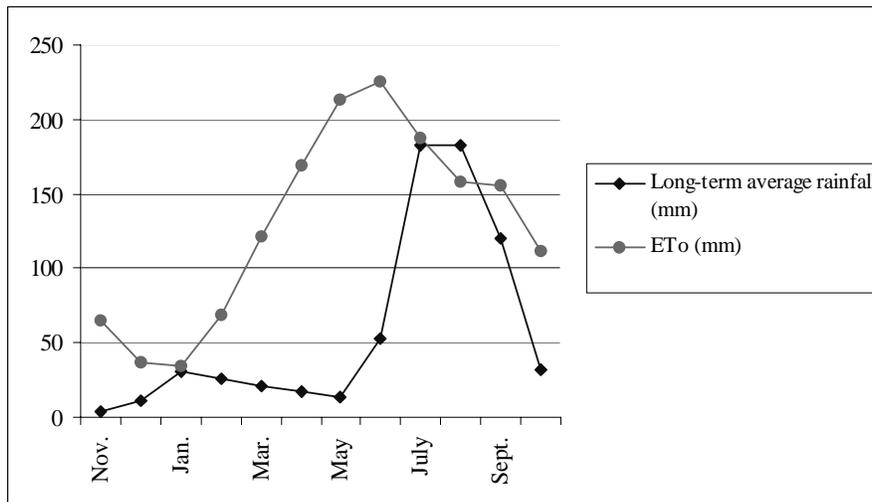
BOX 1.

Profile of the Bhakra irrigation system.

- Cultivable command area (CCA) : 1.265 million ha
- Cultivable area (rabi 1995/96) : 1.056 million ha
- Annual average rainfall : 686 mm
- Annual average evaporation (ET_o) : 1,544 mm
- Source of water supply : Storage reservoirs; run-of-river system and groundwater
- Mode of water use : Conjunctive
- Delivery structures : Gravity type; lined and unlined canals; structured system below distributary
- Predominant on-farm irrigation practice : Surface flooding
- Major crops : Kharif (rainy) season : Rice, cotton
Rabi (dry) season : Wheat, oilseeds
Two-season : Sugarcane
- Average farm size : 4.8 ha (Standard Deviation: 3.83 ha)
- Type of management : Government (main stream); farmer-managed (tertiary)

Two-Season: Sugarcane

Cropping pattern	Rabi: Wheat, oilseed						Kharif: Cotton, rice					
	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.
Long-term average rainfall (mm)	3.5	10.9	30.5	25.6	20.6	17.0	13.1	52.4	182.9	183.2	120.7	31.9
ET_o (mm)	65.0	36.4	34.8	68.6	121.1	168.6	213.4	225.5	187.8	158.2	156.1	111.1



Kaithal circles and mustard is the principal oilseed crop in the other three circles. Bengal gram is cultivated mostly in the Hisar-1 circle. Sowing of oilseed crops commences and ends in November while wheat sowing commences in late November and extends up to December.

With a semiarid to arid climate, prolonged hot periods persist in the command between March and October with rainfall concentrated from July to September. The average annual rainfall in the northeastern part of the command is 750 mm and decreases to 400 mm in the southwestern part. Rabi rainfall varies from 100 mm in the east to 50 mm in the west with annual evapotranspiration varying between 1,250 mm in the northeastern part and 1,650 mm in the southwestern part (IIMI 1997). This means that the crop water requirement is high and much of it must come from surface water and groundwater sources during the rabi season.

Canal Watercourses

According to the Haryana State Canal and Drainage Act of 1974, a watercourse means any channel taking its supply from a government canal (distributary, minor) through an ungated outlet designed as an Adjustable Proportional Module (APM) or Open Flume (OF) to irrigate fields called a chak. The upkeep and maintenance of canal watercourses are the responsibility of the shareholders in a chak irrespective of whether the watercourses are earthen or lined. However, the government is spending between Rs 2 and 5 (US\$0.05 and US\$0.15)⁶ per meter of watercourse per year in maintaining and repairing the lining (Sabherwal 1998). Generally, a watercourse serves a chak of 200 to 350 hectares and about 50–70 farmers. Watercourses with a flat slope of 0.01 percent to 0.02 percent are aligned along the micro-topographical ridges with a turnout or a

cut called nakka made in the bank to divert the full stream to the field for the duration of a wari or turn. The wari duration of the shareholders of a chak is equal to the division of a week (7 x 24 = 168 hours) in the ratio of irrigator's holding to the chak's culturable command area (CCA). Weekly wari timings are fixed, taking into account the filling (bharai) time and the emptying (jharai) time of the watercourse. During the operational turn of a watercourse, the parent canal (distributary, minor) must run to its full supply for the period of rotation to enable APM or OF outlets to draw their designed discharge. This proportionality of entitlement period to holding size, and watercourse flow to size of chak, is intended to ensure uniform volumetric allocation per hectare per week for all the farmers in the command under distributaries that receive a supply during that week.

The design duty at the chak level is generally 0.17 l/s/ha of command area so that the capacity of watercourses ranges from 30 to 60 l/s. Seepage and percolation losses ranging from 6.75 to 13.5 liters per 1,000 square meters (20–40 cusecs per million square feet) of wetted perimeter were reported in unlined watercourses of Bhakra and Western Yamuna canal commands of Haryana (Sabherwal 1998). Seepage is then 10 to 15 percent of watercourse discharge. Much of the watercourse seepage and percolation reaches the groundwater and get mixed with it diluting the saline groundwater in and around the watercourses; this process has been going on since Bhakra water was brought to the area about 40 years ago. This explains why the increase in shallow tube wells (STWs) is mainly confined to the head reaches of the watercourses where the mixing of seepage water is high, though in a few cases, the number of STWs in the middle reach has also increased. Groundwater, which is used to make up, to a certain extent, for the shortages or mismatch in

⁶Rs refers to Indian rupees; in 1998, US\$1.00=Rs 40.00.

canal supplies also helps to bring more area under irrigation.

Lining of Watercourses

Watercourse lining was identified as an effective intervention strategy to reduce seepage since major water losses occur at this level of the conveyance system (National Seminar 1983). About 8,700 (66%) of Haryana's 13,000 watercourses have been lined since 1973, a length of over 20,000 km. The target is to additionally line 2,800 watercourses at a total cost of about Rs 400 million. In addition to reducing seepage, the watercourse lining program has relevance in controlling the water table in the saline areas, which cover 65 percent of the canal command. Another advantage of lining is the reference level it provides for annual desiltation of watercourses. However, farmers perceive additional benefits that are far more important than mere water saving.

From farmers' perspectives, watercourse lining has a number of additional advantages, especially in areas underlain with saline groundwater. The foremost benefit of lining the watercourses is in making water available at the remotest end of the watercourse. Previous to the lining, water in earthen canals could not reach the tail end of a watercourse. Due to this, mixing of canal water with saline groundwater took place only in the head reach of a watercourse. Consequent to lining, extensive spreading of canal water over a larger area enabled mixing of fresh canal water with saline water and farmers have constructed cavity type wells to skim this mixed and diluted groundwater to supplement their canal water. This, in effect, increased their available water share for irrigation. Also, improved canal water distribution in lined irrigation channels together with conjunctive use of groundwater and canal water

has resulted in an increased irrigation intensity during rabi. An improved water supply for irrigation due to lining has also resulted in a changed cropping pattern. There is a significant increase in oilseed crops, especially in the tail end of the watercourse in the Sirsa block. The time taken and the number of laborers required to irrigate one hectare of land, according to farmers, have been reduced considerably after lining of watercourses. Also, both filling and emptying times have been reduced due to improved conveyance efficiency. This improvement or saving in operational time in an average chak was about an hour and was added proportionally to the wari of each shareholder resulting in an increased wari time.

Selection of Watercourses for the Study

The study covers 28 watercourses distributed among three blocks: Narwana, Hisar, and Sirsa (figure 1). The selection scheme of the watercourses consisted of the selection of three blocks located in a satellite image covering 15 km x 15 km and having a different groundwater quality and hence varying groundwater contributions to irrigation. From each block about 10 watercourses were selected, based on the age of lining and length of watercourse lined.

The quality of groundwater in Narwana, Hisar, and Sirsa blocks with 82, 96, and 132 watercourses, respectively, is good,⁷ marginal, and poor, also respectively. Satellite Remote Sensing (SRS) data are available from 1986 onwards only. Therefore, to represent conditions before and after lining, the watercourses in each block were grouped to fall into four cells of an approximately equal number of watercourses, two cells containing watercourses lined before 1985 and two cells after 1985. The two cells also represent watercourses located in the head

⁷Groundwater quality: good, if salinity < 2 ds/m; marginal, if salinity = 2–6 ds/m; poor, if salinity > 6 ds/m.

and tail ends of the minor/distributaries. From each of the first and last two cells, three and two watercourses, respectively, were randomly selected, giving a total of 10 lined watercourses representing different ages of lining and locations within a minor.

The salient features of the selected watercourses and their locations along the

distributary/minor are shown in table 1. The length of watercourse lined (extent of lining) ranges from 34 percent of total length in the Hisar block to more than 80 percent in all three blocks. The earliest lining was started in 1975 and lining continued till as recently as 1996 in the Hisar block. All watercourses in the Sirsa block were lined before 1986.

TABLE 1.
Characteristics of the watercourses.

Name of block	Water-course no.	Minor/distributary	Distance from the minor distributary		Extent of lining		Lining period and age of lining by 1986			Groundwater development		
			RD %	Location	Length lined %	Extent high/low	Year of lining	Age of lining (years)	Lining period (years)	CCA ha/tube well		
											1986	1996
Narwana	1	Barsola mr*	15	Head	59	High	1981	5	2	-	-	
	2	Chusdu mr**	90	Tail	80	High	1983	3	2	-	-	
	3	Ghasso mr.	28	Head	55	Low	1981	5	2	-	-	
	4	Mohalgorh mr.	45	Head	55	Low	1992	-6	1	-	-	
	5	Molgarh mr.	50	Head	74	High	1982	4	2	-	-	
	6	Shudkan dy.	99	Tail	54	Low	1983	3	2	-	-	
	7	Sinor	67	Tail	40	Low	1983	3	2	-	-	
	8	Sirsa parallel	89	Tail	44	Low	1995	-9	1	-	-	
Hisar	1	Badhawar dy.	65	Tail	72	High	1975	11	3	-	-	
	2	Pinghal mr.	100	Tail	34	Low	1975	11	3	-	-	
	3	Rana dy.	26	Head	36	Low	1975	11	3	-	-	
	4	Rajli mr.	81	Tail	79	High	1977	9	3	-	-	
	5	Kharkheri dy.	29	Head	53	Low	1976	10	3	-	-	
	6	Badhawar dy.	73	Tail	83	High	1977	9	3	-	-	
	7	Balak mr.	1	Head	53	Low	1992	-6	1	-	-	
	8	Balak mr.	46	Head	55	Low	1992	-6	1	-	-	
	9	Kharkhari dy.	7	Head	77	High	1996	-10	1	-	-	
	10	Kharkhari dy.	1	Head	74	High	1995	-9	1	-	-	
Sirsa	1	Chormar dy.	73	Tail	71	High	1976	10	3	66	17	
	2	Chormar dy.	85	Tail	71	High	1976	10	3	455	41	
	3	Kaluana dy.	53	Head	63	High	1977	9	3	167	20	
	4	Maujgarh dy.	23	Head	79	High	1984	2	2	47	17	
	5	Maujgarh dy.	99	Tail	68	High	1985	1	2	62	31	
	6	Panna dy.	91	Tail	68	High	1978	8	3	39	21	
	7	Mithri dy.	26	Head	80	High	1982	4	2	101	41	
	8	Mithri dy.	100	Tail	69	High	1986	0	2	75	37	
	9	Maujgarh dy.	100	Tail	67	High	1978	8	3	68	34	
	10	Panna dy.	26	Head	76	High	1981	5	2	47	23	

* mr. = minor.

** dy. = distributary.

RD = Relative distance.

Basic Data

For a comparative analysis of the performance of watercourse lining, covering five selected rabi seasons between 1986 and 1997, data from a number of Indian Remote Sensing (IRS) satellites (IA, IB and IC) and Landsat with different spatial and spectral characteristics were used. Three overpass dates in each rabi season were selected for optimum crop classification from available cloud-free satellite data (table 2).

Field-level data of the selected watercourses were collected during three field visits in February, July and November 1997, both to identify sample areas for computer-aided crop classification and to validate classification results obtained from satellite images.

Additionally, data were collected through questionnaires (current and temporal changes in cropping pattern and productivity level, source and extent of irrigation support, etc.) and through crop mapping on chak maps, which were completed by field officers in a few selected watercourses. A subsequent evaluation, however, indicated large subjectivity in the completed questionnaires and chak maps, and hence questionnaire data were used after verification with field-collected data. Topographic maps (1:50,000 scale) of the three blocks and chak maps (1:6,000 scale) of all the watercourses were obtained for digitization and overlaying on the satellite imagery.

TABLE 2.

Satellite data analyzed in the study.

Period	Overpass date/Satellite *		
	Hisar block	Narwana block	Sirsa block
1996-97	15 Dec 96 IRS-1C	15 Dec 96 IRS-1C	22 Dec 96 IRS-1B
	12 Jan 97 IRA-1B	12 Jan 97 IRA-1B	13 Jan 97 IRS-1B
	17 Feb 97 LANDSAT	17 Feb 97 LANDSAT	26 Feb 97 IRS-1B
		02 Nov 96 IRS-1C**	21 Mar 97 IRS-IC **
1995-96	21 Nov 95 IRS 1B	21 Nov 95 IRS 1B	22 Nov 95 IRS 1B
	4 Jan 96 IRS 1B	4 Jan 96 IRS 1B	27 Jan 96 IRS 1B
	26 Jan 96 IRS 1B	26 Jan 96 IRS 1B	18 Feb 96 IRS 1B
	17 Feb 96 IRS 1B	17 Feb 96 IRS 1B	11 Mar 96 IRS 1B
	10 March 96 IRS 1B	10 March 96 IRS 1B	02 Apr 96 IRS 1B
	01 Apr 96 IRS 1B	01 Apr 96 IRS 1B	
1992-93	22 Feb 93 LANDSAT	22 Feb 93 LANDSAT	27 Dec 92 LANDSAT
	10 Mar 93 LANDSAT	10 Mar 93 LANDSAT	01 Mar 93 LANDSAT
	26 Mar 93 LANDSAT	26 Mar 93 LANDSAT	02 Apr 93 LANDSAT
1989-90	12 Dec 89 LANDSAT	12 Dec 89 LANDSAT	03 Dec 89 LANDSAT
	02 Mar 90 LANDSAT	02 Mar 90 LANDSAT	20 Mar 93 LANDSAT
	04 Apr 90 LANDSAT	04 Apr 90 IRS 1A	10 Apr 90 LANDSAT
1986-87	20 Dec 86 LANDSAT	20 Dec 86 LANDSAT	27 Dec 86 LANDSAT
	10 Mar 87 LANDSAT	10 Mar 87 LANDSAT	01 Mar 87 LANDSAT
	26 Mar 87 LANDSAT	26 Mar 87 LANDSAT	17 Mar 87 LANDSAT

* Sensors are TM in Landsat, LISS II in IRS-1A, and 1B, LISS III and PAN in IRS-1C.

** PAN data only.

Analysis of Multiyear Satellite Data

The methodology used to analyze digital images includes a geo-referencing procedure for co-registering the watercourse map in a large scale (1:6,000) to the satellite imagery and a robust approach for crop classification at watercourse level, commanding only a limited areal extent (of a few hundred hectares). The results are in the form of spatial maps of cropping pattern and statistics of cropped areas and NDVI for head, middle and tail reaches of each watercourse.

The topographic maps (1:50,000 scale) covering the watercourse commands were digitized and mosaicked to form the reference map base, to which the satellite imageries were geometrically rectified (root mean square < 15 m) and co-registered. Due to the large difference in chak maps and image scales and the difficulty in locating control points, an improved approach was called for, since accurate co-registration of both is essential to generate reliable statistics at watercourse level. The chak maps of 1:6,000 scale were digitized at 6-m resolution, vectorized and registered first to IRS-IC Pan image with 6-m resolution. After registration, the watercourse vectors were encoded in a channel along with Pan image data and geometrically corrected using the rectification model between the Pan and LISS II data sets, to achieve an RMS error of 15 m. This innovative approach significantly improved the location accuracy to enable micro-level inventories using satellite data.

The next step was to delineate the wheat and non-wheat growing areas in the selected rabi seasons. Multi-date cloud-free satellite

data through the rabi season were acquired and analyzed through a hybrid classification approach of iteratively supervised and unsupervised techniques to achieve complete and accurate classification (figure 2). In the supervised approach, useful information categories such as wheat area and non-wheat area are defined and then their spectral separability is examined; in the unsupervised approach, separable classes are determined and then their informational utility defined. Thiruvengadachari et al. (1997) have provided complete details of this approach. The kappa coefficient of classification accuracy (Congalton 1991) was computed at overall block level as well as for two randomly selected watercourses in the Hisar block, three each in the Narwana and Sirsa blocks. The field verification was conducted in at least 20 randomly selected locations for wheat and in 10 locations for non-wheat crops in each block and in each selected watercourse. The average classification accuracy was 92 percent at the watercourse level.

The satellite analysis results in statistics of cropped area, area under wheat and non-wheat crops, and NDVI of wheat and non-wheat crops at pixel level. A typical map of temporal changes in the rabi cropping pattern in a watercourse of the Hisar block is shown in figure 3. The unit cost of SRS analysis works out to US\$0.17 per hectare of irrigated area (1996 prices), which includes the cost of satellite data covering 22,500 hectares of geographic area, field visits, processing and analysis of data.

The next section provides a brief description of performance descriptors used and their justification for analysis purposes.

FIGURE 2.

Registration of watercourse chak map with satellite database.

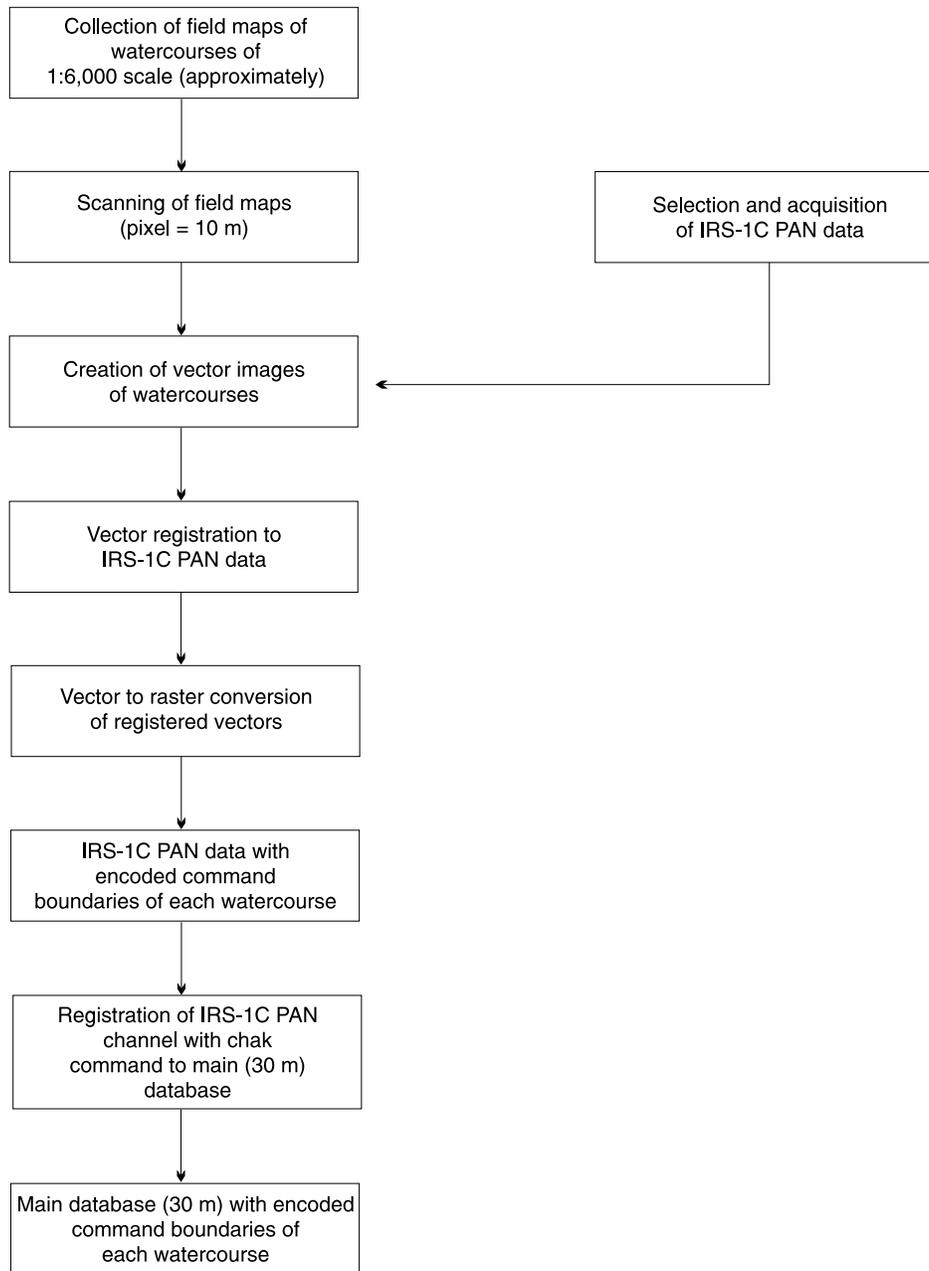
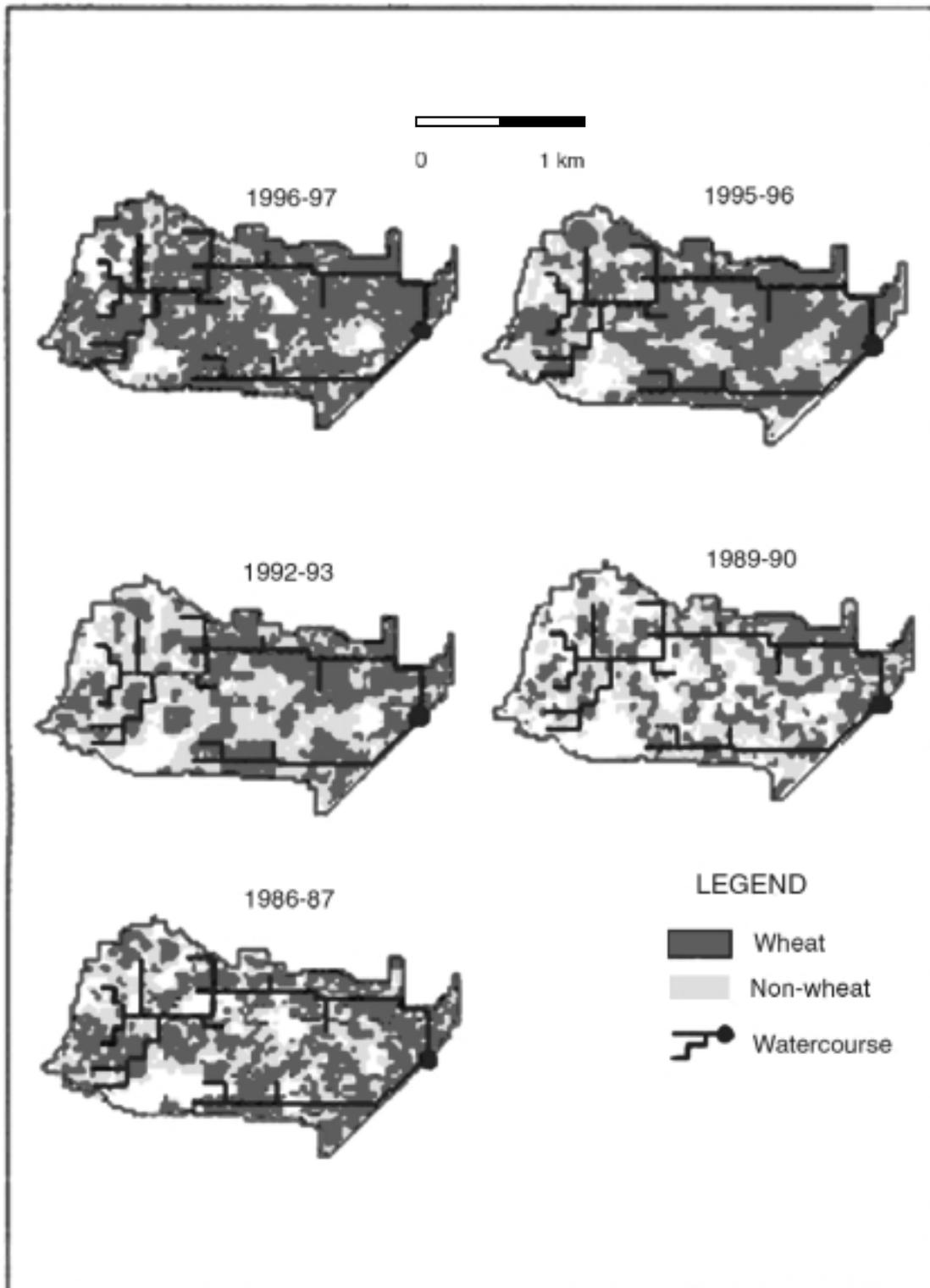


FIGURE 3.

Temporal changes in rabi cropping pattern in a watercourse of the Hirsra block (watercourse@45872-R, Balak minor).



Performance Descriptors

The direct effect of watercourse lining is to reduce seepage and leakage losses and make more water available for crop production. The extent to which seepage is reduced over a period is an indication of how well lining is sustained. In the case of the Bhakra canal command, one of the major objectives of lining watercourses is to convey and distribute the canal water to the remotest area of a watercourse and allow farmers to tap the percolated and diluted groundwater for further improving the irrigated extent. This, in effect, has a marked effect on agricultural performance of a chak on two counts: one is that a larger area, which has hitherto not been cultivated, has been brought under cultivation and the other is that farmers have pumped additional groundwater diluted by percolated canal water to increase the extent of area irrigated and/or cropping intensity. Because of these, evaluating the agricultural performance of a chak with a lined watercourse is more meaningful than just to evaluate the extent of water saved due to lining. Moreover, evaluating the efficacy of lining through the extent of seepage reduction requires considerable discharge measurements in the field, which is difficult and costly to achieve.

Watercourse lining is one of many factors that contribute to improved performance of irrigated agriculture. Apart from lining characteristics, the location of the watercourse with respect to the offtake channel and the groundwater contribution are the two additional factors contributing to a chak's agricultural performance. Agronomic factors such as soil type, groundwater quality, agronomic practices, crop varieties, etc., also contribute to performance. However, they are assumed to be uniform among the watercourses within a block. During the field visits, these factors were looked into and information obtained from the farmers leads us to conclude that this assumption is valid and is not likely to negatively impact on the conclusions arrived at in this study. However, it must be stated that no physical tests were performed to ascertain the authenticity of farmers' statements and general uniformity of the tracts with regard to spatial variability. The surface water supply does not figure in the list of variables because each watercourse in a block gets the same water allowance per hectare. Also, rainfall contribution in the rabi season in the Bhakra canal command is minimal and, therefore, it is not accounted for. To evaluate the agricultural performance of a chak, six indirect descriptors (defined on p. 14, were selected for the analysis.

No.	Descriptor	Definition	Remarks
1.	Wheat Area Intensity (WAI)	$\frac{\text{Irrigated wheat area}}{\text{Cultivable area}}$	Extent of wheat crop and its increasing trend over time is related to the availability of sufficient good quality water from a canal and wells.
2.	Equivalent Wheat Area Intensity (EWAI)	$\frac{\text{Total irrigated area converted to equivalent wheat area}}{\text{Cultivable area}}$	1 ha of non-wheat area = 0.6 ha of wheat area-based on crop water consumption. EWAI is a surrogate for total water consumption. An increasing trend of EWAI over time represents possible augmentation of additional water.
3.	Irrigation Intensity (II)	$\frac{\text{Irrigated area}}{\text{Cultivable area}}$	Increasing trend in II indicates additional water supply available for crop production and/or cropping pattern change with less water-consuming crops.
4.	Normalized Difference Vegetation Index (NDVI)	$\frac{r_o(\text{infrared}) - r_o(\text{red})}{r_o(\text{infrared}) + r_o(\text{red})}$	High NDVI represents good crop condition and hence better productivity.
5.	Coefficient of Variation of NDVI (CV_{NDVI})	$\frac{\sqrt{\sum_{i=1}^n (\text{NDVI}_i - \text{NDVI}_{mean})^2}}{\text{NDVI}_{mean}}$	Reflects the variability in crop condition.
6.	Tail-Head Ratio of NDVI (THR_{NDVI})	$\frac{\text{Average NDVI of tail-reach area}}{\text{Average of NDVI of head-reach area}}$	Reflects the equity of irrigation service.

r_o = Land surface spectral reflectances.

Method of Analysis

Field visits and focused group discussion with farmers have indicated that agricultural performance of lined watercourses has been superior to that of unlined watercourses and that this superiority is closely linked to the greater development of groundwater in lined

watercourses. Therefore, improvement in agricultural performance is closely linked to the extent to which groundwater development has taken place since the lining and its contribution to agricultural performance, in addition to the contribution of watercourse lining.

Detailed groundwater information is not available for all the sampled blocks except for Sirsa. For the Sirsa block, the irrigation intensities before and after 1986 and groundwater development details after 1986 are available. In view of the data limitation, the analysis was carried out in two stages.

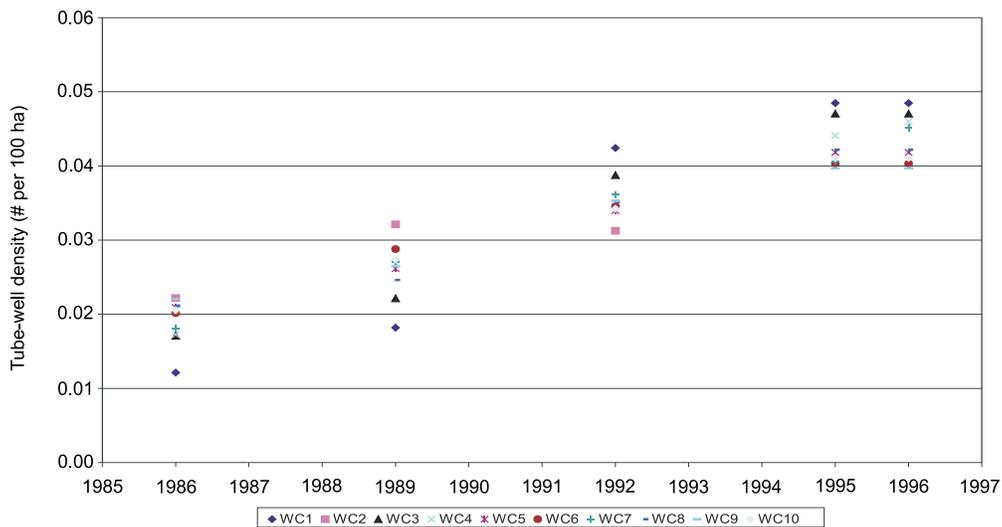
In the first stage, no distinction was made in agricultural performance due to lining and groundwater development. A trend analysis of agricultural performance indicators of all blocks was conducted. Trends, if identified at this stage, may be due to both watercourse lining and groundwater development. In the second stage, data of the Sirsa block for which groundwater data are available (figure 4) were used to separate the effect of groundwater development factors from the lining-related factors.

Head-Reach and Tail-Reach Classification

The watercourses were classified into two groups: head reach and tail reach (table 1). The watercourses close to the offtake point of the distributary/minor are in the head reach. The head-reach watercourses are those where percent relative distance (% RD)⁸ of distributary or minor is less than 55; watercourses with more than 55% RD are in the tail reach. Four watercourses in the Narwana block, 6 in the Hisar block and 3 in the Sirsa block are in the head-reach area, while 4, 4 and 6 watercourses in the Narwana, Hisar, and Sirsa blocks, respectively, are in the tail-reach area.

FIGURE 4.

Tube-well density of Sirsa watercourses.



⁸Percent Relative Distance (% RD) = $\frac{\text{Distance of the watercourse along the distributary/minor from offtake}}{\text{Total distance of the distributary/minor}} \times 100$

High and Low Extent of Lining

The extent of lining of a watercourse is the lined length of the watercourse as a percent of its total length. The incremental benefits of the extent of lining beyond 60 percent of its total length are not significant (Malhotra 1975). A 60-percent extent of lining of a watercourse would have, for example, the same influence as that of an 80-percent extent of lining. Therefore, watercourses are classified into two groups: "high" extent of lining and "low" extent of lining (table 1). The watercourses with less than 59 percent extent of lining are in the "low" group. Those with more than 59 percent extent are in the "high" group.

Five watercourses (with 40–55% extent of lining) and 3 watercourses (with 59–80% extent of lining), respectively, are in the low and high extent of lining groups in the Narwana block (table 1). In the Hisar block, 5 watercourses (with 34–55% extent of lining) and 5 (74–83% extent of lining) are in the low and high group, respectively. All watercourses (with 63–80% extent of lining) in the Sirsa block are in the group of high extent of lining.

Period of Lining

The lining of watercourses was carried out to enhance the water delivery performances. As

the age of lining (defined as the number of years that have elapsed after completion of lining) increases, its performance gets reduced. The age of lining can be computed with respect to the current year or any base year. In this study, the base year is selected as 1986 since satellite data are available from that year and the age of lining is computed with respect to 1986 as the base year.

For analyzing the effect of age of lining on the trends of performance, the sampled watercourses are grouped into three distinct periods of lining (table 3). The trends of performance for different periods are estimated.

Results

The satellite data of sampled watercourses are available for five years: 1986, 1989, 1992, 1995, and 1996. Time series cross-sectional analysis was employed to assess the trends of performance of the sampled watercourses. The trends of performance descriptors of watercourses that were lined in different periods were assessed separately for each block. In addition to estimating trends, the differences between blocks, between head-reach and tail-reach watercourses, and between watercourses with high and low extent of lining were captured. The appendix describes the complete model used for trend assessment and the results of the

TABLE 3.
Periods of lining.

Name of Block	Period 1 of lining (lined 8 years before 1986)	Period 2 of lining (lined 1–5 years before 1986)	Period 3 of lining (lined after 1986)
Narwana	-	6	2
Hisar	6	-	4
Sirsa	5	5	*

* All the watercourses in this block were lined before 1986.

TABLE 4.

Characteristics of selected watercourses.

1. Factor		WAI	EWAI	II	A_{NDVI}	CV_{NDVI}	THR_{NDVI}
2. Differences between blocks	Narwana	S+	S+	S+		S-	
	Sirsa	S+	S+				
3. Differences between head and tail reach	Narwana		S-	S-			
	Hisar	S+	S+				
	Sirsa						S-
4. Differences between high and low extent of lining and low-extent of lining	Narwana	S+	S+	S+			S-
	Hisar						
5. Trends-Narwana	Period 2	S+			S+	S-	
	Period 3					S-	
6. Trends-Hisar	Period 1	S+	S+	S+		S-	
	Period 3	S+	S+	S+		S-	
7. Trends-Sirsa	Period 1	S-		S+		S-	
	Period 1	S-	S+	S+		S-	

regression analysis. This section discusses only the major findings.

Table 4 summarizes the statistically significant results of the analysis for the performance descriptors: wheat area intensity (WAI), equivalent wheat area intensity (EWAI), irrigation intensity (II), average NDVI (A_{NDVI}), coefficient of variation of NDVI (CV_{NDVI}), and the ratio of tail and head NDVI (THR_{NDVI}). The notations "S+" and "S-" in table 4 indicate that there is a statistically significant positive or negative difference (in the rows 2, 3 and 4) or a statistically significant increasing or decreasing trend (in the last three rows). The blank cells indicate no statistically significant differences or trends.

Differences between Blocks

The watercourses in the Narwana block have, on average, a significantly higher wheat area intensity, equivalent wheat area intensity and

irrigation intensity and a significantly lower coefficient of variation of NDVI (figures 5, 6, 7, and 9, and table 4). That is, a higher quantity of good-quality water supply, both canal water and groundwater, is more equitably available in the Narwana block than in the other two blocks. This is not surprising since the Narwana block is in a fresh groundwater area while both the other blocks, Hisar and Sirsa, are in marginal and saline groundwater areas. Also the wheat area intensity and equivalent wheat area intensity in the Sirsa block are significantly higher than those of the Hisar block. This is primarily because of the stable water supply from the Bhakra dam and the higher water allowance per hectare in the Sirsa block.

Differences between Head- and Tail-Reach Watercourses

The influence of the location of the watercourses from the offtake of the distributary canal or minor

on the performance descriptors is mixed for the three blocks. In the Hisar block, the wheat area intensity and the equivalent wheat area intensity of the watercourses located in the head reach of the canals are higher than those of the watercourses located in the tail reach. This is primarily due to percolation of additional canal water from the canal network in the head reaches. In the Narwana block, the equivalent wheat area intensity and the irrigation intensity of the head-reach watercourses are lower than those in the tail-reach watercourses. In the Sirsa block, there is no significant locational effect. The locational differences in the Narwana may be due to several factors: reliability of canal water supply, the extent of groundwater use and quality of pumped water supply, etc. Unfortunately, there were no data to verify these.

Differences between High and Low Extent of Lining

The effect of the extent of lining of watercourses on the performance is also mixed. Only a few of the performance descriptors in the Narwana block had some significant effect. In the watercourses of the Narwana block, the higher the extent of lining, the higher the wheat area intensity, the equivalent wheat area intensity and the irrigation intensity. In the other two blocks, the extent of lining is not a significant factor for farmers to grow more wheat crops. This indicates that only watercourses with a high extent of lining and located in the fresh groundwater areas have a higher wheat intensity. A conclusion that can be drawn from this is that farmers, who do not have provision to supplement canal water with fresh groundwater, do not prefer a higher wheat area even after lining of watercourses. A plausible reason for this is that groundwater supply in the Hisar and Sirsa blocks is not suited for excessive wheat growing.

Trends of Performance

The trend analysis shows that the trends of most descriptors of performance of watercourses in all blocks are affected to some extent by the period of lining. An important observation is that regardless of the period of lining, none of the descriptors show a significant decreasing trend of performance between 1986 and 1996. The wheat area has increased significantly in all blocks, except in the Sirsa block (figure 5) where it has decreased significantly. Farmers in this block opted for salt-tolerant low water-consuming crops with an increasing water supply. Indeed, increasing trends of equivalent wheat area intensity and irrigation intensity (figure 6 and 7) of watercourses in the Sirsa and Hisar blocks indicate an increasing water supply.

The average NDVI (figure 8), which is a measure of overall productivity over the years, has improved. Moreover, the variation of the crop condition (indicated by the coefficient of variation of average NDVI) within watercourses has decreased significantly in all three blocks (figure 9).

What prompted the increase in performance of watercourses in all blocks? Within a watercourse, it cannot be presumed that there are significant variations of agronomic conditions and agronomic practices because of a uniform NDVI within a block (figure 10). Given this, water supply and distribution within watercourses are the most plausible factors influencing the increase in performance. This is especially true in the Hisar and Sirsa blocks.

In the fresh groundwater zone of the Narwana block, almost all the area is irrigated with wheat and the wheat intensity is high. So there is no scope for further significant increase in wheat area or intensity. However, there is a significant reduction in the variation of crop condition indicating better water distribution within watercourses.

FIGURE 5.

Wheat area intensity.

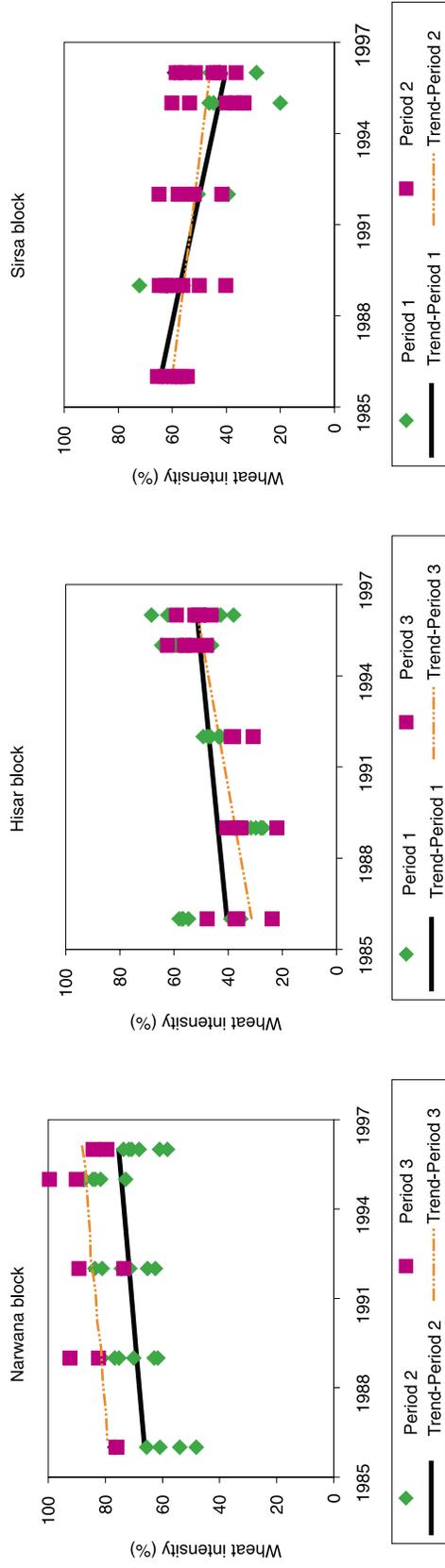


FIGURE 6.

Equivalent wheat area intensity.

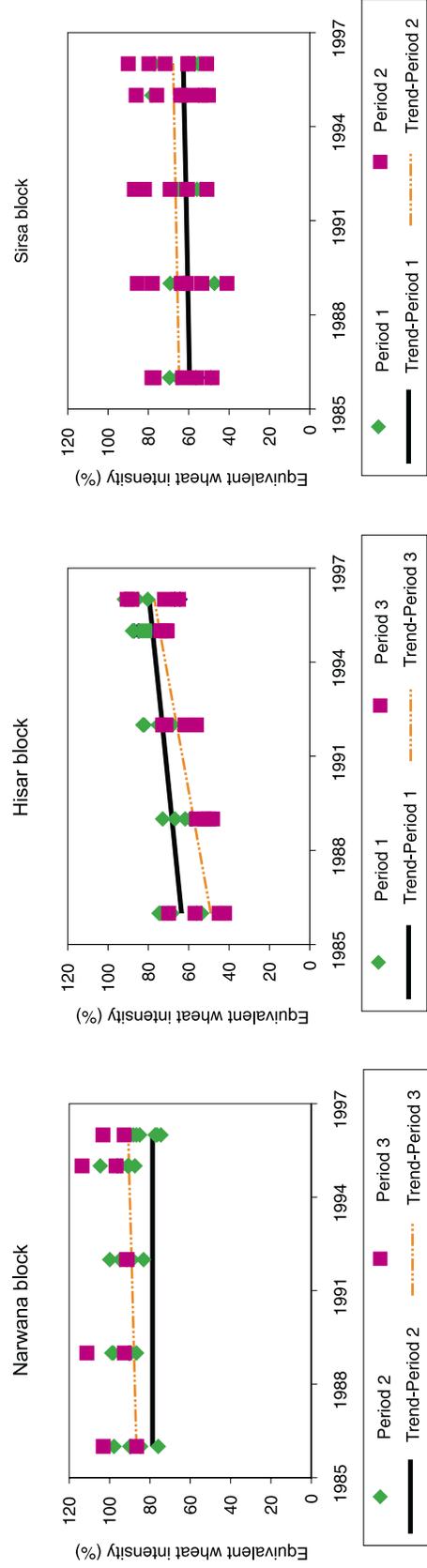


FIGURE 7.

Irrigation intensity.

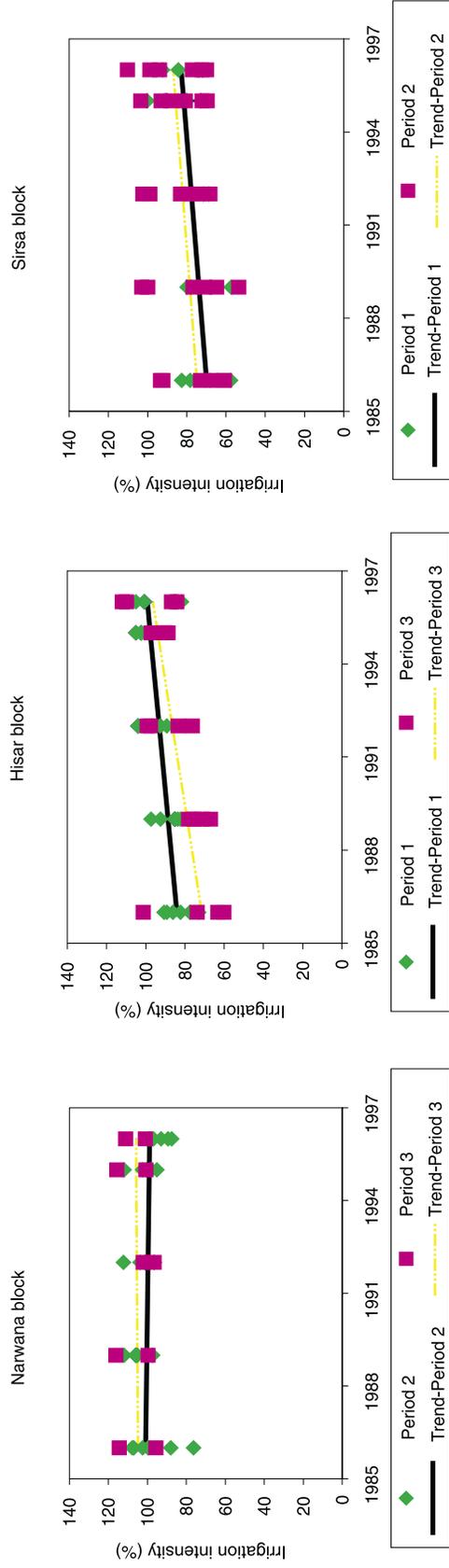


FIGURE 8.

Average NDVI.

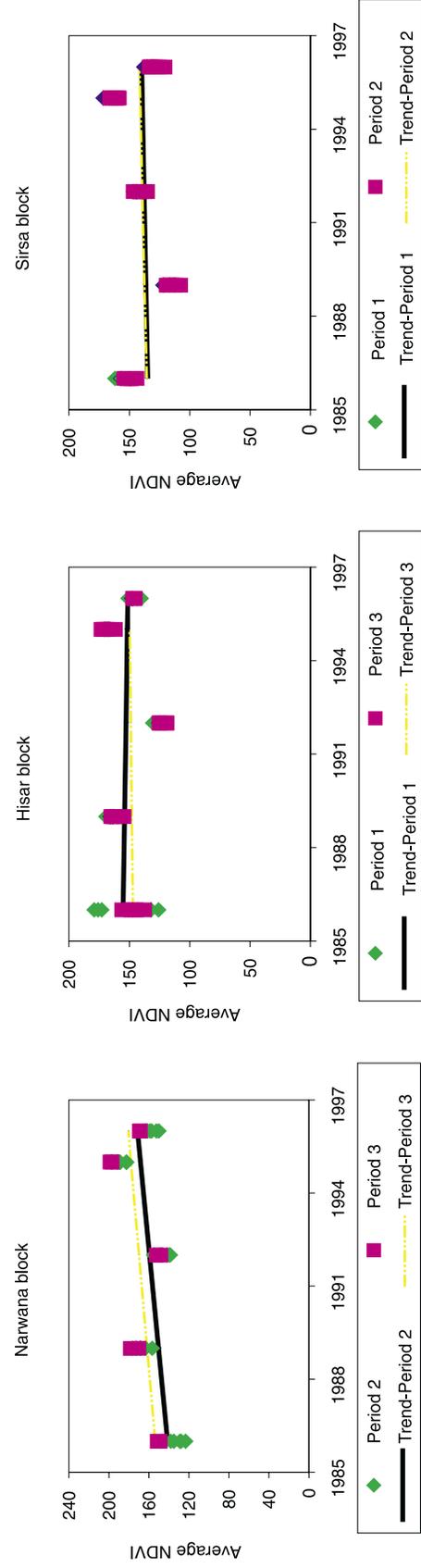


FIGURE 9.

Coefficient of variation of NDVI.

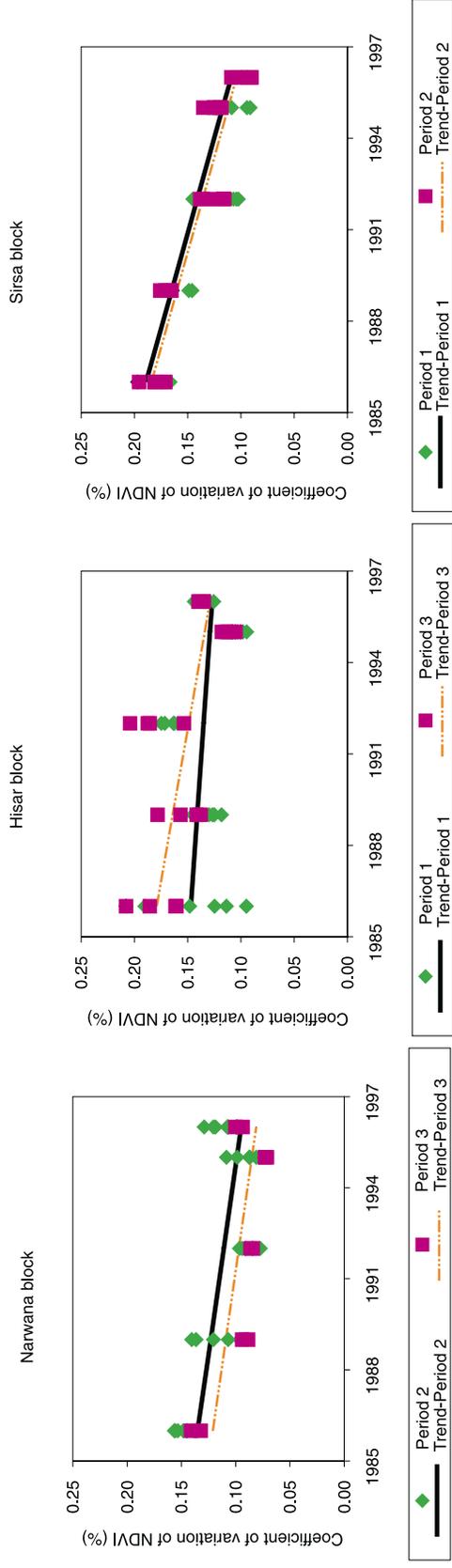
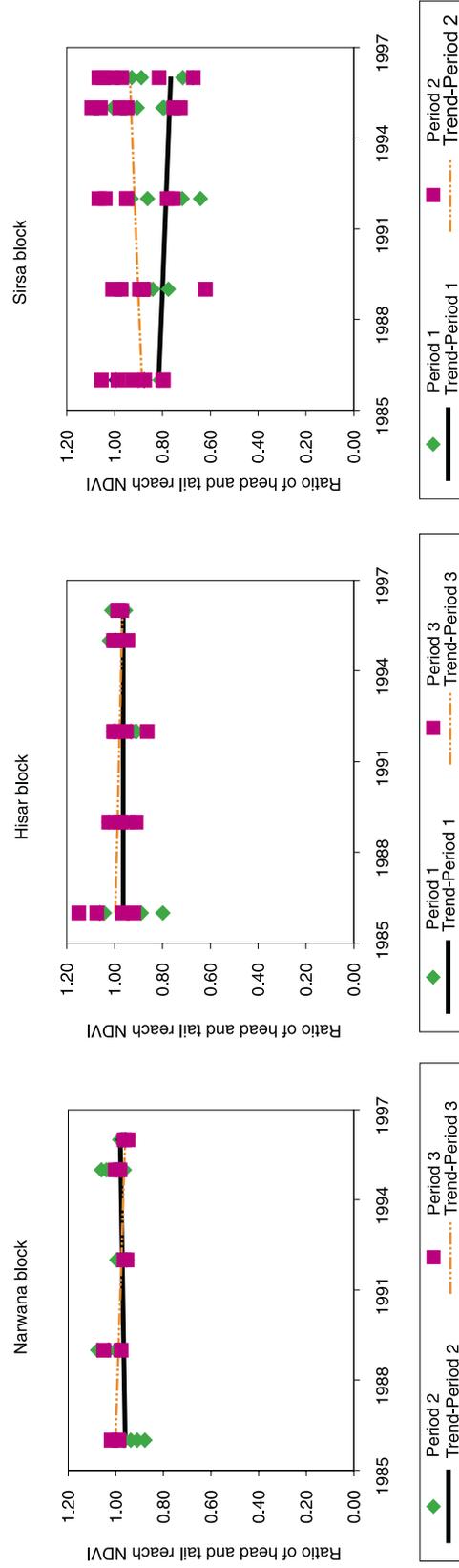


FIGURE 10.

Ratio of tail NDVI to head NDVI.



In the marginal groundwater zone of the Hisar block, an increasing water supply was used for increasing the wheat area, increasing the wheat intensity and reducing the variability of distribution. Watercourse lining has helped reduce the conveyance losses making it possible to distribute water even to the remotest area. This has contributed to increasing the wheat area of the watercourses, which were lined recently. With the increase in the age of lining of watercourses, the surface water seeping into the aquifer increases, diluting more of marginal groundwater. Pumping this groundwater contributes to increasing the wheat area of the watercourses, which were lined several years before 1986. Indeed, it was observed that groundwater development has increased rapidly in these areas.

In the saline groundwater zone of the Sirsa block, wheat area was decreasing, but the water supply was increasing (slightly) and the irrigation intensity was increasing; but the variation of the crop condition within watercourses was decreasing. With the increase in the age of lining, the surface water seeping into the aquifers makes the shallow groundwater less saline. In the watercourses of the Sirsa block, farmers use this less-saline groundwater in conjunction with surface water for growing more salt-tolerant crops such as oilseed. This has resulted in significantly decreasing the wheat area and significantly increasing the irrigation intensity. This, in turn, implies that the irrigation performance in the watercourse command areas stayed the same or improved because of the additional water available to the farmers from pumped groundwater.

The preceding discussion leads us to conclude that lining of watercourses and the consequent groundwater development affect the trends of performance of all blocks. Indeed, the almost similar trend of performance for different periods of lining within a block indicates the combined effect of watercourse lining and groundwater development. The challenge,

therefore, is to separate the effect of lining on the performance from that of groundwater development. This is the objective of the second part of the analysis.

Effect of Lining in the Presence of Groundwater Development

In the method employed in assessing the influence of lining the "before" and "after" type of analysis was used. Here, the effect of groundwater development on the performance descriptors was controlled while the differences of performance before and after lining of watercourses were assessed. This type of analysis requires performance and other data both before and after lining of watercourses.

Groundwater development data, in terms of number of tube wells in the command area, were available only for the Sirsa block. Therefore, this part of the analysis was carried out only for this block. Irrigation intensity data, both before and after lining of the watercourses in the Sirsa block, were obtained from the Irrigation Department. These data were used for assessing the effect of lining in the presence of groundwater development. However, some additional data are required for this analysis. Even though the irrigation intensities were available for years both before and after lining, the groundwater development information for the watercourses was available only after 1986 (table 1). Therefore, estimates of groundwater development within watercourses before 1986 were first obtained. Then these were used to assess the impact of lining.

Groundwater Development

The groundwater development in the watercourses indicates different growth patterns (table 1). For example, the command area served in one watercourse decreased from 455

hectares per tube well in 1986 to 41 hectares per tube well in 1992. In another watercourse, the corresponding values decreased from 66 in 1986 to 17 in 1992. Therefore, the possible different growth patterns of groundwater development for watercourses after 1986 were estimated. Next, estimated annual growth rates were used to extrapolate the extent of groundwater development before 1986.

The tube-well intensity, i.e., number of tube wells per unit command area, which is the reciprocal of command area served per tube well, was used as an indicator for groundwater development. A regression analysis, with stepwise model selection was used to estimate the overall trends of tube-well density and any significant deviation from it for different watercourses (table 5).

Analysis shows that, in 1986, the tube-well density of watercourse numbers 2, 3, 7 and 8 was higher than in others. Also the growth rates of groundwater development in watercourse

numbers 2 and 3 were higher while the growth rates of the watercourse numbers 5 and 6 were lower than those of the others. The estimated growth rates were then used in extrapolating the tube-well density of watercourses before 1986.

Impact of Lining

In impact of lining, the differences of irrigation intensities before and after watercourse lining in the presence of groundwater development were estimated. The tube-well density was used to filter the effect of groundwater development. To capture the differences before and after lining three dummy variables (equal 0 for years before lining completed and equal 1 for years after lining completed) were introduced for watercourses where linings were completed by 1977, 1982 and 1986. Additionally, a dummy variable was used to capture the differences between watercourses (offtaking from a distributary canal or a minor) located in the head reach and those located in the tail reach.

Regression estimates show (table 6) that tube-well density is indeed significant in explaining the variations of irrigation intensity. However, even after filtering the effect of groundwater development, the irrigation intensity before the lining of watercourses is significantly lower than after lining in all three lining periods. For example, of the watercourses that were lined before 1977, the average irrigation intensity before lining is about 12 percent lower than after lining. Of the watercourses that were lined before 1982, the irrigation intensity before lining is about 10 percent lower than that after lining. Similarly, in those watercourses that were lined recently (between 1982 and 1986), the irrigation intensity before lining is 12 percent lower than that in the years after lining.

TABLE 5.
Estimates of trends of ln (well density) in the Sirsa block.

Variable	Coefficient
Intercept	-3.98*
Intercept difference - WC2 ^a	-2.26*
Intercept difference - WC3	-0.94*
Intercept difference - WC7	-0.72*
Intercept difference - WC8	-0.58*
Trend	0.098*
Trend difference - WC2	0.152*
Trend difference - WC3	0.102*
Trend difference - WC5	-0.048*
Trend difference - WC6	-0.057*
R ²	0.90

^a WC2 means watercourse 2 in table 2.

* Statistically significant at .05 level of significance

TABLE 6.

Effect of lining on irrigation intensity in the Sirsa block.

Variable	Coefficient estimate	T-value
Constant	41.4	15.4*
Tube-well density	344.0	3.4*
Location dummy for head and tail watercourses	-5.3	-1.8
Time dummy for before and after lining – watercourse lining completed by 1977	12.4	2.2*
Time dummy for before and after lining – watercourse lining completed by 1982	10.4	3.1*
Time dummy for before and after lining – watercourse lining completed by 1986	11.7	2.4*
R ²	0.30	

* Statistically significant at .05 level.

Conclusions

The SRS data were used for assessing the recent trends of performance of watercourses. It was seen that performance of the watercourses from 1986 to 1992 shows no deteriorating trend. In fact, some of the indicators show a significant increasing trend. Both water supply and irrigation intensity are increasing. Equity of water distribution was maintained and the variation of water supply is seen to be still decreasing. Indeed, the performance of most descriptors has increased over time. Some of the watercourses in the analysis were lined 20 years before the data collection period. The lining is not the only factor that contributed to the significant increase in trends of performance. The groundwater development, as a result of lining of watercourses, is also seen to be contributing to performance increase. However, as shown in the second part of the analysis, even after accounting for the contribution of groundwater, performance—for example the irrigation intensity—after watercourse lining is significantly higher than before the watercourse lining,

regardless of the lining period. This supports the hypothesis that lining has improved the performance. Further research needs to be continued in this area to answer specific research questions such as:

- What is the contribution of groundwater development in a lined watercourse chak as compared to an unlined one?
- To what extent do factors such as groundwater quality, management efforts, reliability of canal supplies, in addition to lining, contribute to agricultural performance?

The SRS data can be used very effectively to look at the trend of several performance parameters after watercourse lining. The fact that NDVI values within a block are not very much different corroborates the assumption made with regard to uniform agronomic factors such as soil type, groundwater quality and agronomic practices within a block. In fact, the

SRS can be used very effectively in assessing the efficacy of watercourse lining in an environment where very little groundwater is used to support surface water supplies. In areas with groundwater support, it provides information on the combined effect of groundwater development and watercourse

lining. Isolation of the latter will require data on surface water and groundwater supplies. The SRS technique can particularly be useful as a screening tool for identifying watercourses where more ground data need to be collected to make the evaluation of watercourse lining holistic.

Appendix

Trend Analysis of Performance Descriptors

The SRS data of watercourses are available for five time periods: 1986, 1989, 1992, 1995 and 1996. Therefore, time series cross-sectional analysis was used to assess the trends of performance.

To capture the average difference between blocks dummy variables were introduced to the Narwana and Sirsa blocks. For example, for the Narwana block, the dummy variable equals one if an observation is from a watercourse in the Narwana block, and zero otherwise. Dummy variables were also introduced to each block, to capture the possible effect of the watercourse location from the offtake of the distributary or minor.

The incremental effect of the extent of lining beyond 60 percent of the total length is not significant. Therefore, the extent of lining is divided into two groups, one more than 60 percent and the other less than 60 percent. The extent of lining of each sampled watercourse from the Sirsa block is beyond 60 percent of its length. Therefore, only two dummy variables were introduced to the Hisar and Narwana blocks to indicate whether the watercourses selected from those blocks have extents of lining more than 60 percent.

The lining of the watercourses within a block was completed in one of three time periods. Some of the watercourses were lined 8–11 years before 1986, some 1–5 years before 1986 and others after 1986. The trends of performance between 1986 and 1996 may be different for watercourses having different lining periods. Therefore, for each block separate slope coefficients were estimated for trends of performance of watercourses with different lining periods.

The trends of performance descriptors, Wheat Area Intensity, Equivalent Wheat Area Intensity, Irrigation Intensity, Average NDVI, Coefficient of Variation of NDVI, and the Ratio of Tail to Head Reach NDVI were assessed. Appendix table 1 presents the results of the regression analysis.

Wheat Area Intensity (WAI): The average WAI of watercourses in the Narwana and Sirsa blocks is significantly higher (about 49% and 32%) than that in the Hisar block. The location of the watercourses from the head of the canal has no significant effect on WAI in any block except in the Hisar. The extent of lining has a significant effect only on the Narwana block, where the higher the extent of lining the higher the WAI. The WAI of the watercourses in the Narwana block that were lined between 1981 and 1985 shows a significant increasing trend. By 1986, almost all the area in this fresh groundwater zone was irrigated with wheat. The WAI of the Hisar block shows a significant increasing trend regardless of the period of lining. In the Sirsa block, WAI is decreasing for all watercourses regardless of the period of lining.

Equivalent Wheat Area Intensity (EWAI): The differences of Equivalent Wheat Area Intensity (EWAI) between blocks are similar to those of WAI of the three blocks (column 4, appendix table 1). The differences of EWAI between head and tail reach watercourses follow a similar pattern to those of WAI in the Hisar and Sirsa blocks. Surprisingly, the EWAI of the head reach watercourses in the Narwana block is significantly lower than that in the tail reach. As in WAI, the higher extent of lining has a significant positive effect on EWAI only in the

Narwana block. The EWAI in the Narwana block has no significant increasing trend (figure 6) indicating no change in crop water consumption. The EWAI in the other two blocks indicates an increasing crop water consumption within watercourses but a decreasing rate of growth with the age of lining. The trends of EWAI in the Hisar block are significant for both lining periods, but the rate of growth is higher in the recently lined watercourses. The trends in the Sirsa block are significant only for the recently lined watercourses.

Irrigation Intensity (II): The irrigation intensity in the Narwana block is significantly higher than that in the other blocks (figure 7). There is no difference of II in the other two blocks. The II of head-reach watercourses in the Narwana block is lower than that of the tail-reach watercourses. There are no differences in II due to location in the other two blocks. The higher extent of lining has a significant effect only in the Narwana block. Irrigation intensity is high in the Narwana block and shows no significant trend after 1986.

Irrigation intensity of watercourses in the Hisar and Sirsa blocks shows significant increasing trends regardless of the period of lining. However, the watercourses that were lined recently (in the Hisar block after 1986) have a higher rate of increase.

It appears that in the watercourses where the saline or marginal groundwater is mixed with canal water, the pumping of diluted water has increased resulting in an increase in the

irrigation intensity. Cropping pattern changes also add—especially in the Sirsa block—to positive trends in II. With the pumping of diluted water, farmers in the Sirsa have switched from wheat to oilseeds that require less water and hence have a higher cropping intensity.

Average NDVI (A_{NDVI}): There is no significant difference of average NDVI between blocks. There is a significantly increasing trend in crop condition after 1986 in the Narwana block.

Coefficient of Variation of NDVI (CV_{NDVI}): The coefficient of variation of NDVI indicates the overall variability of crop condition within a watercourse. This is lowest in the Narwana block and is significantly different from that in other blocks. The location of the watercourses or the extent of lining has no effect on CV_{NDVI} .

The CV_{NDVI} of watercourses in all blocks shows a decreasing trend regardless of the time of lining. This trend indicates improvements in water distribution within watercourses. The increasing use of tube wells in this area indicates the increasing contribution of groundwater in improving the variation of water supply.

Ratio of Tail-End Area NDVI to Head-End Area NDVI (THR_{NDVI}): The ratio of tail-end area NDVI to head-end area NDVI within a watercourse indirectly indicates uniformity of water distribution between the head and tail ends. These NDVI ratios for the three blocks are not significantly different and are close to 1. There are no significant trends in the ratios within any of the blocks.

APPENDIX TABLE 1.

Trends of performance from 1986 to 1996.

Explanatory variable	Wheat area-% of total	EWAI	II	A _{NDVI}	CV _{NDVI}	THR _{NDVI}
Constant	29.3	46.3	68.9	146.7	0.184	1.000
Dummy – Narwana block	49.1*	40.0*	35.8*	4.2	-0.059*	0.005
Dummy – Sirsa block	32.1*	18.1*	4.8	-11.7	0.008	-0.119
Dummy – Head reach of Narwana	-2.9	-14.2*	-14.9*	-1.6	0.008	0.021
Dummy – Head reach of Hisar	10.4*	7.1*	3.1	6.8	-0.017	-0.024
Dummy – Head reach of Sirsa	5.2	-1.9*	-5.8	4.0	-0.006	-0.108*
Extent of lining – Narwana	10.1*	15.4*	12.2*	5.6	-0.007	-0.046*
Extent of lining – Hisar	3.2	-2.9	-5.3	0.8	-0.005	-0.004
Trend – Lining period 2, Narwana	0.9*	0.0	-0.2	3.0*	-0.004*	0.002
Trend – Lining period 3, Narwana	0.9	0.4	0.1	2.7	-0.004*	-0.004
Intercept difference – Period 2&3	-13.0	-7.7	-3.6	-12.4	0.014	-0.046
Trend – Lining period 1, Hisar	1.1*	1.6*	1.5*	-0.4	-0.002*	0.000
Trend – Lining period 3, Hisar	2.0*	2.8*	2.5*	0.3	-0.005*	-0.003
Intercept difference – Period 1&3	10.0*	15.6*	13.8*	8.9	0.035	-0.036
Trend – Lining period 1, Sirsa	-2.4*	0.3	1.3*	0.5	-0.008*	-0.005
Trend – Lining period 2, Sirsa	-1.4*	0.3*	1.2*	0.6	-0.008*	0.005
Intercept difference – Period 1&2	5.3	-5.1	-5.1	-0.7	0.005	-0.061
R ²	0.63	0.59	0.49	0.19	0.6	0.38

* Significant at 95% confidence level.

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ISSN 1026-0862
ISBN 92-9090-416-X