RESEARCH REPORT

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Land and Water Productivity of Wheat in the Western Indo-Gangetic Plains of India and Pakistan

A Comparative Analysis

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International Water Management Institute

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Summary

In much of the recent discussions on wheat yields for India and Pakistan, attention has been drawn to irrigated wheat yield differences in Bhakra (India) and Punjab (Pakistan), with average wheat yields generally reported in Bhakra (little less than 4 t/ha) almost double than in Punjab (around 2 t/ha). These discussions have raised an important research question on why wheat yields vary to such a magnitude under fairly similar agro-climatic, socioeconomic and management conditions.

The purpose of this study is to analyze variations in wheat yields and to assess the range of factors affecting wheat yields and profitability of wheat production in the selected irrigation systems in India and Pakistan. The study attempts to identify constraints and opportunities for closing the existing yield gaps. It is hypothesized that substantial gains in aggregate yields can be obtained by improved water management practices at the farm and irrigation-system levels.

The study was conducted in the Bhakra canal system of the Kaithal Irrigation Circle in India (BCS-India) and the Lower Jehlum Canal system in Chaj sub-basin in Pakistan (LJCS-Pakistan). Six watercourses on head, middle and tail reaches of two distributaries in each country were selected for detailed field-level data collection. Data on various wheat production activities and input use, including irrigation water use from both canal-water and groundwater sources were collected for 216 farms in BCS-India and 218 farms in LJCS-Pakistan on a daily basis throughout the *rabi* season (winter cultivation season) from October 2000 to May 2001.

Findings show that the average wheat yield in the selected irrigation system in India is somewhat higher (4.48 t/ha) than in the selected system in Pakistan (4.11 t/ha). However, there are significant differences in yields across farms and locations within the selected irrigation systems in both countries, with yields ranging from 2.96 t/ha to 5.73 t/ha in BCS-India, and 0.12 t/ha to 7.82 t/ha in LJCS-Pakistan. Overall yield gaps across farms are much wider in the study area in LJCS-Pakistan than in BCS-India. Wheat yield differences are also much higher across watercourses within a single distributary than across distributaries.

There is a significant inequity in distribution of canal water in the study areas in both BCS-India and LJCS-Pakistan, with tail reaches receiving less canal water than head and middle reaches. However, inequities in canal-water distribution in the study areas are higher in LJCS-Pakistan than in BCS-India. Gini coefficients[1] for canal-water distribution across watercourses are 0.29 and 0.42 for BCS-India and LJCS-Pakistan, respectively. Groundwater use is, obviously, higher in reaches receiving less canal-water supplies and vice versa. Average productivity of consumed water is fairly similar for the selected systems in both countries, i.e., 1.36 kg/m^3 and 1.37 kg/m^3. However, average productivity of diverted water is higher for BCS-India (1.47 kg/m^3) than for LJCS-Pakistan (1.11 kg/m^3).

In both study areas, BCS-India and LJCS-Pakistan, average land productivity/yields are lower in locations and reaches where groundwater is of relatively poorer quality. In the study areas in both countries, more canal water is supplied to distributaries where groundwater is more saline (Batta and Lalian) as compared to those where groundwater is less saline (Rohera and Khadir),

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[1] The Gini coefficient is based on the Lorenz curve and is a commonly used measure of inequity. The value of the Gini coefficient ranges between 0 and 1. A zero value shows a completely equal distribution (Lorenz curve is located on the 45 degree line so that the area between the 45 line and the Lorenz curve is zero). The greater the value of Gini, the greater the degree of inequity in distribution.

which is appropriate. However, groundwater quality varies significantly across reaches within a distributary. In general, groundwater quality deteriorates towards middle and tail reaches (except for Khadir in LJCS-Pakistan where groundwater is less saline in the tail ends). These saline groundwater areas presently receive less canal water, and productivity of wheat is low in these reaches. Thus, intra-distributary canal-water allocation is an important issue in reducing the yield gap in wheat. The locational unevenness in distribution of canal water, quality of groundwater and level of input use leads to significant variations in productivity of wheat, which has financial implications for wheat growers across locations.

Using farm-level data, yield functions were estimated to analyze the effects of a range of factors of production. The estimated functions were then used to calculate the contribution of various factors to the variability in yields among farmers at head, middle and tail reaches of distributaries. Finally the impact of canal-water reallocation within a distributary on average wheat yields and profitability of wheat production were estimated.

Results suggest that improvements in water management practices at the system level will contribute to increased yields and overall profitability of wheat production. Improving on timings of canal-water deliveries and adoption of an effective canal-water allocation strategy will result in overall socioeconomic gains in wheat production. Surface water reallocations will be mainly effective in situations where they provide a considerable proportion of total water use per hectare. The results of the study suggest that poor groundwater quality leading to accumulation of salts is one of the key factors influencing wheat yields, and that groundwater quality varies significantly across reaches in command areas of the systems. Further findings suggest that existing yield gaps can be narrowed by promoting improved farm-management practices such as, replacing older wheat varieties with newer varieties, avoiding delays in wheat sowing, and improving on timings and application rates of fertilizers and weedicides.

The study presents alternative scenarios on impacts of water use from two sources of socioeconomics of wheat production. Wheat production is found to be highly profitable with exclusive canal-water use and least profitable with the sole use of poor-quality groundwater. Findings suggest that overall gains from wheat production will increase if canal water is reallocated so that more canal water is supplied to canal reaches where groundwater is of poorer quality. Accounting for the constraints on availability of total canal-water supplies and locational variations in quality of groundwater, the study concludes that: (1) where groundwater quality varies across reaches in the system, aggregate gains in yields and overall profitability of crop production can be increased by promoting conjunctive use of canal water and groundwater through canal-water reallocations; (2) however, in systems where canal water is in extremely short supply (as in Khadir and Rohera), no significant gains in aggregate yields and crop profitability can be expected through such reallocations—even if there are significant inequities in canal-water distribution across reaches; and (3) in systems, where canal water provides a considerable proportion of total water use per hectare, as in Lalian, significant gains in aggregate yields and overall crop profitability can be achieved through canal-water reallocations to reaches where groundwater is of poorer quality, and particularly so in situations of significant head-tail inequities. Under such situations, canal-water reallocation would be helpful in achieving not only efficiency and equity of canal-water distribution, but also sustainability of resource use—the three pillars of sustainable development. The policy implication of these findings is that, under conditions of canal-water scarcity and locational variations in quality of groundwater, conjunctive use and joint management of surface water and groundwater is essential to increase overall gains from crop production.

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Introduction

Rice-wheat systems will continue to be important sources of food production in subtropical Asia (figure 1). These systems are complex, not only in terms of interactions that affect productivity of individual crops, but also in the contrasting conditions that management must provide for the crops individually to increase yields. Timsina and Connor (2001) state that average combined yields of rice and wheat systems in the western Indo-Gangetic plains are in the order of 6-8 t/ha while yields attainable with higher fertilizer and better management inputs are much greater (9-11 t/ha).

Wheat production in both India and Pakistan has increased significantly over the past three decades, due to expansion in the sown area as well as yield improvements (figure 2). Average wheat yields in India and Pakistan have increased from 1.35 t/ha and 1.42 t/ha in 1975-76 to 2.45 t/ha and 2.17 t/ha in 1998-99, respectively. However, in recent years, the rate of growth in average yields in both countries has been slower than in the past, with only slight year-to-year fluctuations. Deceleration in yield growth rate has caused concerns among policymakers and planners in both countries.

In much of the recent discussions on wheat yields for India and Pakistan, attention has been drawn on irrigated wheat-yield differences in Bhakra (India) and Punjab (Pakistan), with average wheat yields in Bhakra (a little less than 4 t/ha) almost double than in Punjab (around 2 t/ha). These discussions have raised an important research question on why wheat yields vary to such a magnitude under fairly similar agro-climatic, socioeconomic and management conditions (Molden, Sakthvadivel and Habib 2001). The purpose of this study is to understand differences in irrigated wheat yields in India and Pakistan, identify factors affecting productivity and profitability of wheat production and to suggest methods to improve yields and close existing yield-gaps[2] among farmers as well as canal reaches.

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[2] A yield-gap can be defined in several ways; by comparing the average yields with yields obtained at experimental stations, with maximum yields obtained with on-farm trials, with maximum yields obtained at farmers fields and with the computed potential yields. In this report, the yield gap is defined as the difference between the minimum and maximum yield obtained at the farmers fields.

FIGURE 1.
Map of Asia showing subtropical wheat growing regions.

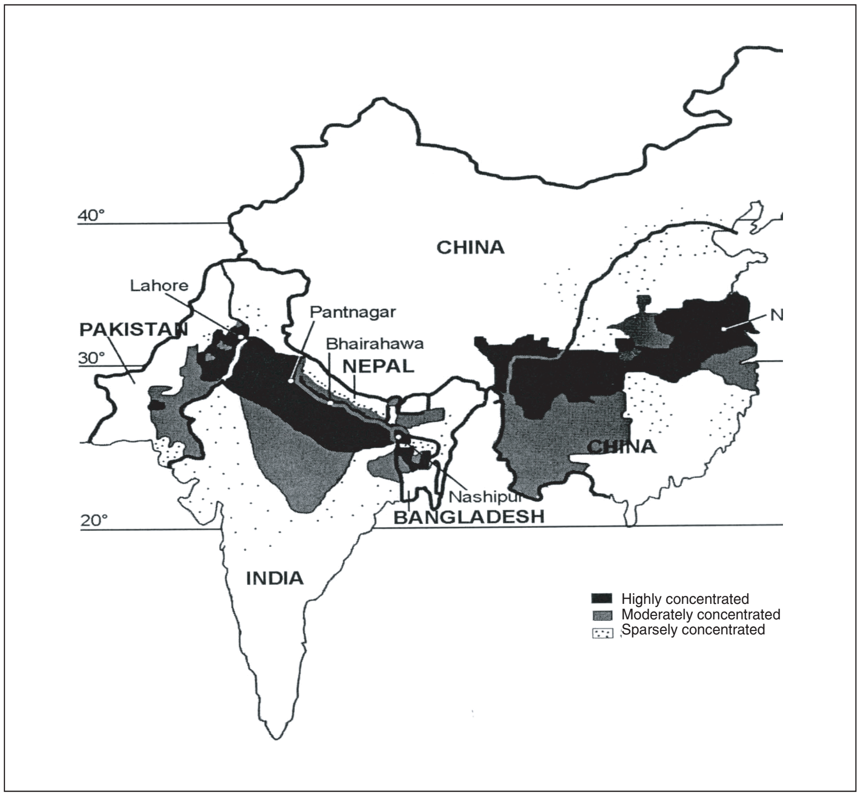
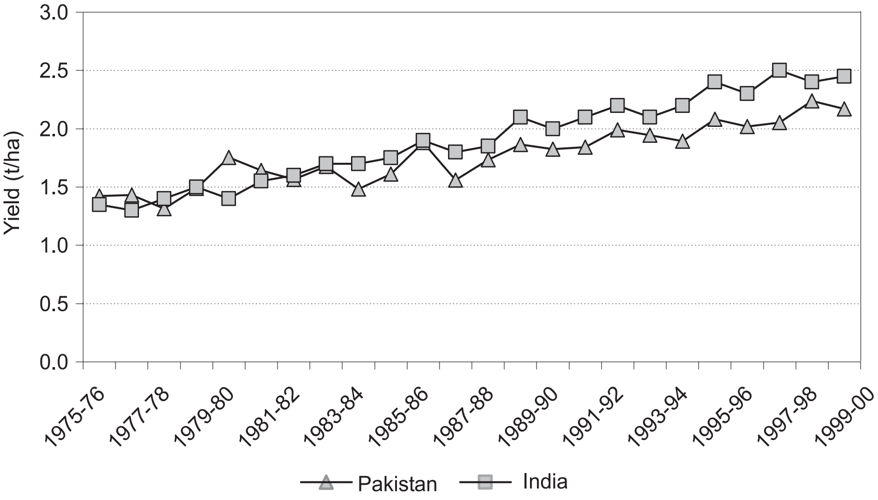


FIGURE 2.
Average wheat yields in India and Pakistan (1975-76 to 1998-99).



Sources: Official statistics from Ministries of Agriculture of the governments of Pakistan and India, 1998-99.

Objectives

The aim of this study is to understand farm-level wheat yield variations, and to identify constraints and opportunities for increasing yields and overall profitability of wheat production. Specific objectives are to:

- Analyze inter- and intra-country variations in wheat yields in the selected irrigated agricultural systems in India and Pakistan
- Analyze factors contributing to such variations
- Identify constraints and opportunities and possible methods of reducing existing yield gaps and to increase production

The key hypothesis to be tested is that substantial gains in aggregate yields and overall profitability of wheat production can be obtained by improved water management practices at the farm- and irrigation-system levels.

There is an enormous amount of literature analyzing determinants of wheat yields in India and Pakistan. Most past studies undertaking inter-country comparisons are those analyzing macro-level productivity differentials (Ahmed and Chaudhry 1996), with less attention to basic micro-level differences. Most past studies analyzing determinants of wheat productivity have focused mostly on soil and agronomic factors, with only few attempting to analyze water-related factors at the system and farm levels in a more rigorous manner.

This study takes a holistic approach by rigorously analyzing a fairly comprehensive set of factors including soil, agronomic and water-related factors (such as quantity, quality and timing of applications), and their influence on wheat yields in the selected irrigation systems in India and Pakistan, with analysis of factors at both farm and irrigation system/sub-system levels. The study adds to the previous literature by developing a set of scenarios for improved water management and its socioeconomic implications for farmers.

In the following section we provide a brief review of related literature. For a comprehensive review of literature on determinants of wheat productivity in India and Pakistan see Tyagi and Sharma (2001) and Mudasser , Hussain and Aslam (2001).

The performance of crop systems is influenced by climate and soil-water related management factors as well as socioeconomic and institutional constraints. Crop production is directly related to water supply allocation, its distribution and use. In the widely practiced *warabandi* system[3] of water distribution in canals in both India and Pakistan, water allowance is generally not sufficient to irrigate the total landholding of a farmer. Therefore, farmers having access to fresh groundwater supplement canal-water deliveries with groundwater pumping. Also, farmers distribute the available canal water over a large area to reduce the impact of soil salinity and groundwater salinity and they also practice deficit irrigation. Typically tail-end farmers in the distributaries and watercourses receive less canal water compared to the head-enders, and must depend more heavily on groundwater of variable quality. Yield variations in these systems at distributory levels are very high. Yield variations among farms could be even higher. This is primarily attributed to water-related constraints—namely, inadequate and untimely canal-water

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[3] Warabandi is a fixed water-distribution system in which water is distributed to the farmers according to their landholdings. Water flows in a minor according to a “roster”. In the roster system, minors of one system are divided into three groups. Each group is operated according to its preference order. The group, which has preference order 1, is operated first and if additional water is available in that turn, then the next group is operated and so on. In the next turn, the turns are rotated among these groups. Generally after one operation of minors, the next turn comes after two weeks.

supply and poor-quality groundwater. These constraints to a great extent affect agricultural practices among farmers in terms of input variables such as number of waterings, source of watering, fertilizer application, varietal differences, date of sowing, etc., giving rise to large yield variations.

If water is not a constraint, farmers will maximize net value of production by delivering the quantity of water that maximizes net returns from a unit of land. As canal water becomes scarce, farmers try to augment their canal supplies with groundwater or else under-irrigate to maximize returns to water. However, if there is uncertainty in canal-water supplies, it modifies farmer incentives to maximize returns to water. Narayanamurthy and Perry (1997) have shown that the degree of deficit irrigation that farmers allow in their fields is strongly affected by perceived reliability of canal-water supplies. If this is the case, farmers who have access to good/bad quality groundwater as well as those who do not have access to groundwater will perceive availability and reliability of water supply in different ways. Such a situation would lead to a wide variation in yield depending on the perception of farmers about the availability and reliability of canal supplies and the risk-taking nature of the farmers.

Mismatch of water delivery schedules with optimum timing of irrigation is a major constraint to increasing the irrigation efficiency of wheat. Mishra and Tyagi (1988) reported that irregularity and inadequacy contributed to a loss in yield of wheat to the extent of 53.7 percent in Gohana (western Yamuna canal system) and 34.9 percent in Adampur (Bhakra canal system) in Haryana. Irrigation scheduling for optimizing production with limited supplies is a bigger challenge than adequate water supplies. The first step for optimal scheduling of irrigation with limited water is to assess the relative sensitivity of different growth stages of the crop to water stress. Irrigation should be so managed that the inevitable stress synchronizes with the least sensitive stage of water stress. Chaudhary et al. (1980) reported that when the first irrigation was applied 26 days after sowing, the roots proliferated extensively. Delaying irrigation for 54 days after sowing resulted in the soil layer, where the roots were located, getting more intensively depleted of moisture and the dry zone extending to a greater depth and, in consequence, the root growth being reduced. Under limited water supply conditions, it would be desirable to apply a relatively larger proportion of water during the pre-anthesis as compared to the post-anthesis stage in order to obtain a greater yield advantage in wheat. Tyagi and Sharma (2001), based on a review of past research, suggest that properly timed one or two irrigations would provide 79 to 89 percent of the maximum yield obtained with a ratio of 5:6 irrigation to wheat.

In Pakistan, Pintus (1997) reported that there was no set rule prevalent within the farming community regarding the number of irrigations applied from sowing till crop (wheat) maturity. Mostly, it depended upon the farmer's own perception. Some farmers applied water to the field on the basis of the plant's appearance while others applied after every 30 days without actually considering the crop requirements. It was found that a majority of the farmers irrigated their fields five to six times during the season, and that the number of irrigations increased with the availability of tubewell water. Aslam (1998) found that wheat yields increased with the number of irrigations applied. Farmers who irrigated less than four times obtained 765 kg/ha, and those who applied four to seven irrigations obtained 1,410 kg/ha of wheat, and those who applied more than eight irrigations obtained 1,641 kg/ha. Also, he reported that farms near the source of irrigation water were getting higher wheat yields as compared to those located at the tail reaches.

Groundwater in the semi-arid and arid zones invariably contains moderate to high amounts of salts. About 22, 8, 20 and 16 percent of groundwater in Punjab, Haryana, Uttar Pradesh and Rajasthan, respectively, are marginal in quality (EC 2-6 dS/m). The corresponding values for poor-quality water (EC > 6 dS/m) are 19, 55, 43 and 68 percent . Through increased use of groundwater, salts accumulate in the root zone, adversely affecting the growth and yield of wheat. Salts also affect certain physio-chemical properties and impair the soil capability as a medium of growth. The major problems created by water of poor quality are salinity, sodicity and specific ion toxicity.

The salinity problem arises if the salt accumulation in the root zone reaches levels high enough to interfere with plant growth. Doorenbos et al. (1979) indicated that while wheat can be grown on a wide range of soils, medium textures are preferable. They suggested that wheat cultivation on peaty soils containing high sodium, magnesium or iron should be avoided. The optimum pH range for wheat cultivation was 6-8. Wheat was found to be moderately tolerant to soil salinity, with ECe[4] not exceeding 4 dS/m[5] in the upper soil layer during germination. Yield decrease due to salinity was estimated at 0, 10, 25, 50 and 100 percent at ECe of 6, 7.4, 9.5, 13, and 20 dS/m, respectively. Also, wheat was found to be relatively tolerant to a high groundwater table, with rise in groundwater tables to 0.5 m for long periods reducing yields by 20-40 percent. Siddiq (1994) estimated a yield loss of 231-411 kg/ha due to soil sodicity. The tail-reach farmers were found to be affected most due to sodicity problems as compared to head and middle reaches of the distributaries. Pintus (1997) indicated that salinity affects wheat plant growth at germination and tillering stages, weakening root development and shoot growth. Aslam (1998) found salinity and waterlogging to be major constraints to increasing wheat productivity in Pakistan. He found that losses in wheat yields in slightly saline soils could be about 36 percent compared to normal soils, and in moderately saline and highly saline soils, wheat yield could be reduced by 68 percent and 84 percent, respectively. Further, he found that wheat yield could reach potential threshold only when water tables are below 1.5 meters. Wheat yields begin to be affected when water tables rise above 1.5 meters.

Mixing of fresh and saline/sodic waters is practiced to bring the salinity of the applied water to levels that are not harmful to the crop. Cyclic use is practiced when one wants to avoid the use of marginal water at a growth stage where damage due to salinity is unacceptable. Results from field studies (Minhas et al. 1998) indicated that the response of wheat to various modes of application is not much, though cyclic use is a preferable mode as it allows choice of growth stage for saline water application. The conclusion of multi-location studies are: (1) yields close to those obtained under freshwater application can be maintained by delayed substitution of freshwater by saline water after two initial irrigations with freshwater—the next best alternative is to practice alternate fresh and saline water irrigation; and (2) irrigation with saline water should not be practiced at the pre-sowing stage. High salinity hinders germination and seedling establishment.

The time of wheat sowing could significantly influence yields. Rehman (1986) found that early wheat sowing in October/November resulted in higher yields compared to sowning in December/January. Altaf (1994) indicated that each day of delay in wheat sowing (after mid-November) in Pakistan could result in a 1 percent loss in yield because of forced wheat flowering and temperature stress during the grain formation stage resulting in forced ripening of underweight grains (in March/April). For India, Nagaranjan (1998) reports that each day of delay in wheat sowing after mid-November could reduce yield by 30 kg/ha.

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[4] Electrical conductivity of saturation paste extract.

[5] dS/m is deci-siemens per meter.

Study Locations

The study was conducted in two irrigation systems—Bhakra canal system (BCS-India) of Haryana and Punjab in India and the lower Jehlum canal system (LJCS-Pakistan) of Punjab in Pakistan. Specific study sites were chosen from two distributaries selected from each of these systems. The key characteristics of these systems and of the specific study sites are given below.

India

The Bhakra canal starts from the tailrace of the Nangal Hydel canal. The Bhakra canal is a lined canal with a capacity of 212.75 m^3/s. This system was planned to serve the arid tracts of Punjab, Haryana and parts of Rajasthan. The water allowance of the Bhakra canal system at the field outlet is 0.0679 m^3/s/1,000 ha and at the distributary[6] head, water allowance is 0.77 m^3/s/1,000 ha. It commands around 0.117 million hectares, and it was designed for 62 percent irrigation intensity per year. In Haryana, the Bhakra canal service is divided into five irrigation circles, the Kaithal circle is one of them in which the study site is located.

In BCS-India, water is distributed to the farmers through minors[7]/distributary canals and through ungated and fixed discharge using the warabandi system.

For the present study two minors of the Kaithal irrigation circle (figures 3 and 3a), Batta minor (Sirsa branch) and Rohera minor (Habri branch) were selected. The Batta minor gets its offtake from the Sirsa branch canal at RD number 225,950 L. It is a 19.08 km long channel and serves a 3,669.2 hectares command area. It's design discharge at the head is 0.65 m^3/s. The Rohera minor starts from the Rajound distributary of the Habri system at RD number 38,000 R. It is a 14.24 km long channel, which serves a 4,130.8 hectares cultural command area. It's design discharge at the head is 1.37 m^3/s. The details of the selected watercourses are given in table 1. The head, middle and tail watercourses of Batta minor lies in the Chandana, Batta and Kalayat villages. Similarly the head, middle and tail watercourses of Rohera minor lies in the Mandwal, Serheda and Rohera villages.

Agro-climate of the Study Area

The climate of the study area is semi-arid. The normal annual rainfall varies from 500 to 600 mm per year. There are three dominant seasons during the year. The summer season is from around 15 March to 15 June. During this season temperatures reach up to 44 °C. The rainy season starts around 15 June and continues up to September and contributes about 70 to 80 percent of the total annual rainfall. The winter season starts from November and extends upto February. During this season the temperature varies between 5 °C to 20 °C.

Soils of the study area are light to medium textured, varying from sandy loam to clay loam and low in organic matter. The phosphorus content is medium but the potassium content varies from medium to high. The soil pH ranges from 7.8 to 9.5. The fields in the tail end of the selected minors are generally saline in nature.

In the study area, farmers mainly grow paddy in the *kharif* (summer cultivation season) and wheat during the rabi season. Some farmers also grow sugarcane, mustard (oil seed crop), local variety of cotton, bajra (millet) and barseem

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[6] Takeoff from branch canal. It can carry discharges up to 10 to 30 m^3/sec.

[7] Takeoff from distributaries. It can carry discharges up to 5 to 10 m^3/sec.

(fodder crop). In the summer season some farmers grow sunflower. The cropping intensity of the Kaithal district varies from 170 to 185 percent.

Irrigation in the Study Area

Kaithal district lies in the fresh groundwater and deep watertable zone of Haryana. The electrical conductivity (EC) of groundwater varies from 0.4 dS/m to 8.5 dS/m. Soluble salts of chloride and sulphates also prevail in the groundwater.

In Kaithal district, out of 0.202 million hectares of cultivable land, 0.198 million hectares of land is irrigated. Out of this, 0.097 million hectares falls under canal irrigation and the rest of the irrigated area is under tubewell irrigation. The main source of canal water in the district is the Narwana-Sirsa branch of BCS-India system. The Kaithal circle receives water from the Markanda distribution system, Sarusti system, Sirsa branch, Habri system, Dhamtan system and the Shudjan system of the BCS-India system. The farmers receive water on warabandi rotation.

TABLE 1.
General characteristics of selected watercourses.

Outlet/distributary	GCA	DC	AD	WAPA	Groundwater EC (dS/m)
Batta head	167	0.027	0.028	0.00016	1.37
Batta middle	226	0.037	0.039	0.00016	4.22
Batta tail	254	0.042	0.047	0.00017	5.76
Rohera head	146	0.023	0.021	0.00016	1.41
Rohera middle	81	0.013	0.020	0.00016	2.41
Rohera tail	204	0.034	0.036	0.00017	5.04
Batta all	3,669		-	-	3.81
Rohera all	4,131		-	-	2.95
All	-		-	-	3.39
Lalian head	179	0.036	0.039	0.00020	1.07
Lalian middle	130	0.026	0.040	0.00020	0.66
Lalian middle (FAO)	189	0.038	0.062	0.00020	1.56
Lalian tail	248	0.049	0.033	0.00020	1.71
Khadir head	180	0.018	0.018	0.00010	1.05
Khadir middle	178	0.027	0.023	0.00015	1.02
Khadir tail	457	0.049	0.018	0.00011	0.79
Lalian	19,785	-	-	-	1.31
Khadir	25,859	-	-	-	0.95
All	-	-	-	-	1.13

Notes:
GCA = Gross command area in hectares (secondary data from irrigation departments).
DC= Design capacity in m^3/s.
AD= Average discharge in m^3/s (as measured through field data).
WAPA= Water allowance per hectare in m^3/s.

FIGURE 3.
Map showing Kaithal irrigation circle, India.

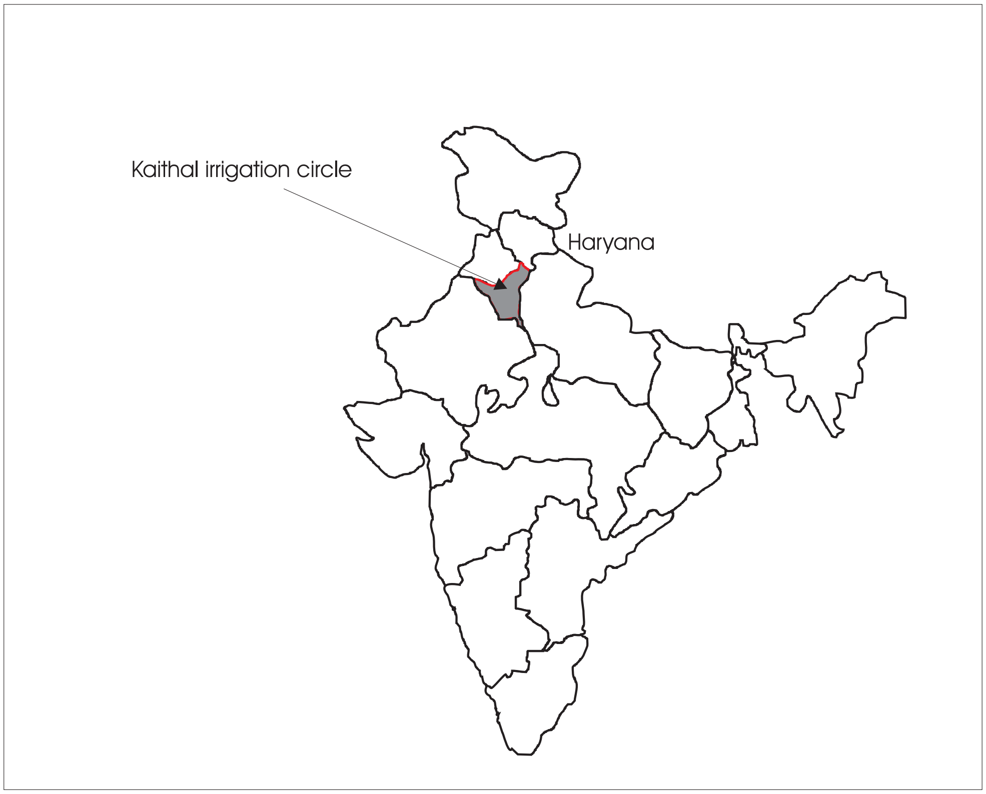
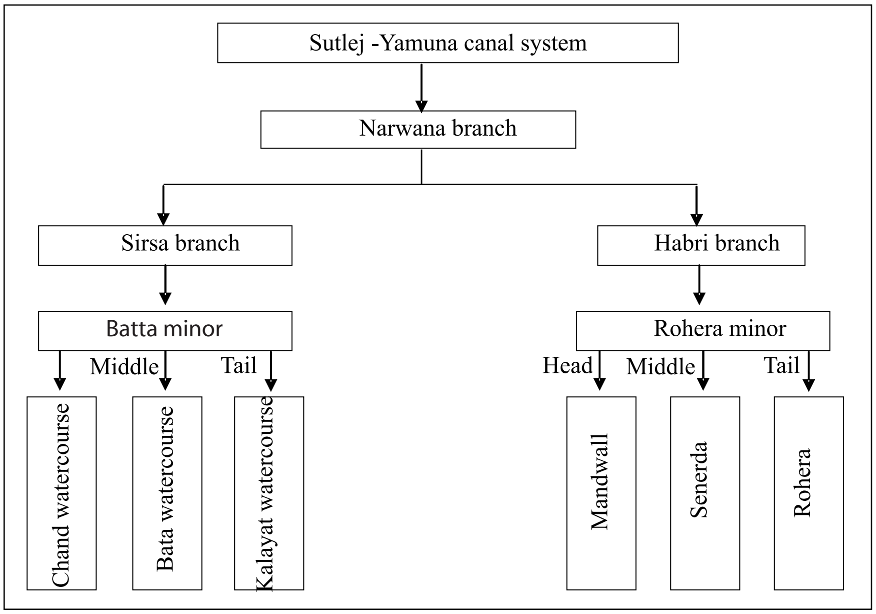


FIGURE 3a.
System outlay of the study area.



Pakistan

In Pakistan, the study was conducted in the Chaj Doab subbasin of the upper Indus basin. The Chaj area lies between the rivers Chenab and Jehlum (figure 4). On the river Jhelum, water is diverted by the Mangla dam towards the Rasul barrage that diverts water towards the Tremu barrage. Water from the river Chenab is diverted by the Marala head works to the Khanki barrage, from where water is diverted towards the Qadirabad barrage that leads river Chenab water towards the Tremu barrage. Both rivers join at the Tremu barrage.

The Chaj Doab is irrigated by the lower Jhelum canal and the upper Jhelum canal. Most of the Chaj area is located in the Sargodha district. The lower Jhelum canal emerges from the Rasul head works and irrigates a major part of the Chaj Doab area. It has a gross canal command area of 0.66 million hectares with a culturable command area of 0.61 million hectares. The system outlay of the lower Jehlum canal is shown in figure 4a.

The Lower Jhelum canal system (LJCS-Pakistan) is divided into four irrigation divisions—Sargodha, Kirana, Shahpur and Rasul. The Kirana irrigation division, selected for this study, is further divided into four sub-divisions: Hujjan, Kirana, Laluwali and Khadir.

Two distributaries, Lalian and Khadir, located in the Laluwali and Khadir irrigation subdivisions, respectively, were selected for this study (figures 4 and 4a).

Lalian Distributary

The Lalian distributary originates from the southern branch canal at RD 104300-T. It has a design discharge of 10.63 m^3/s, and is about 59.3 km long. One branch distributary, eight minors and two subminors originate from Lalian. One hundred outlets originating from Lalian, irrigate an estimated area of about 19,785 hectares in fifty-two villages (partially or fully).

Khadir Distributary

The Khadir distributary originates from the Khadir branch canal at RD 117,220. It has a design discharge of 6.66 m^3/s, and is about 88.1 km long. One branch distrubutary and 11 minors originate from Khadir. About ninety-eight outlets originate from Khadir, irrigating an estimated area of 25,859 hectares in 69 villages (partially or fully).

Agro-climate of the Study Area

The climate of the study area is hot summers and cold winters. Summer starts in late March, and May, June and July are the hottest months. The mean minimum and maximum temperatures are 25 °C and 39 °C, respectively. During summer, maximum rainfall occurs during July (136 mm) and August (76 mm). Winter starts in late October/ early November and extends up to February. During this season the temperature varies between 6 °C and 21 °C . The winter season also shares a part of the annual rainfall with December (27 mm) and January (33 mm).

Soils of the Chaj Doab are mostly calcareous loamy soils. The rivers sometime change their paths, meandering and abandoning their courses. These abandoned river channels are often waterlogged with numerous swamps. Moreover, the Chaj Doab possesses 0.48 million hectares of highlands formed by ancient rivers within the limits of the *baars* (barren mountain ranges).

The cropping pattern of the study area is mixed. Wheat is a dominant rabi crop followed by rice and fodder. Some farmers also grow sugarcane, maize and vegetables. Fruits such as citrus is commonly grown in the area.

Irrigation in the Study Area

The total irrigated area of the Sargodha district is 0.51 million hectares, with most of it irrigated by both canal and groundwater. In 1998, there were

FIGURE 4.
Map of the Chaj subbasin, Pakistan.

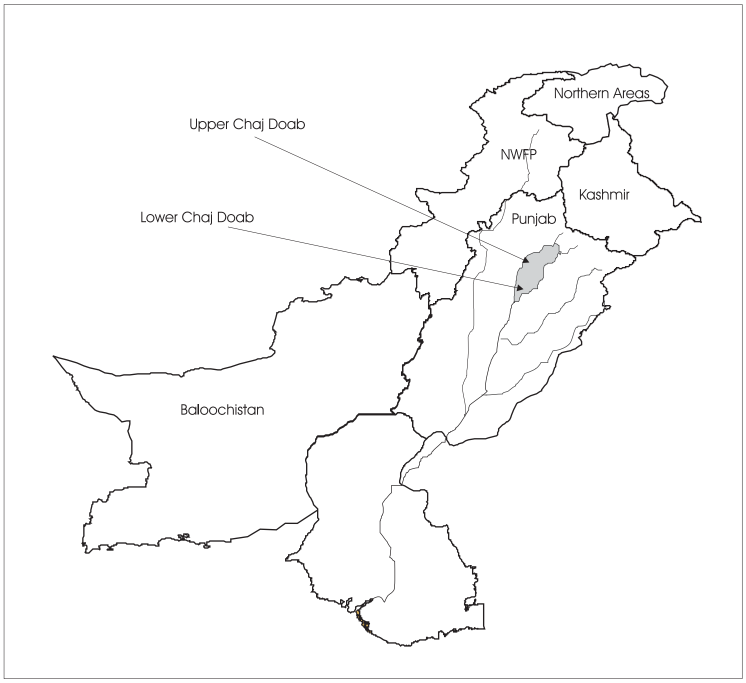
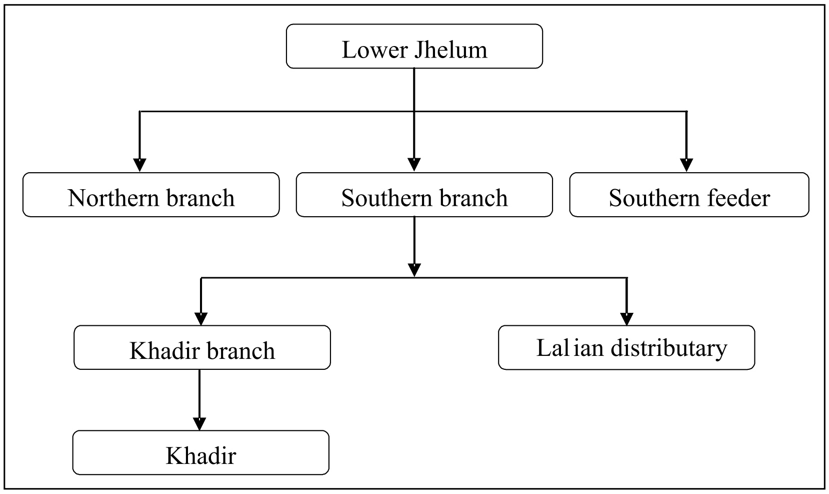


FIGURE 4a.
System outlay of the Lalian and Khadir distributaries.



14,823 tubewells (13,312 private and 1,511 public tubewells), with the majority of the private ones being diesel tubewells (almost all public tubewells are electric tubewells). Out of 497,143 hectares surveyed in Sargodha district, in recent years, 59,484 (12%) and 2,887 (0.6%) were found to be affected by salinity and waterlogging, respectively (Bureau of Statistics 1999).

The farm area is usually divided into plots, i.e., one fourth of an acre or one-half of an acre. The plots are irrigated by the flooding method. Often, available canal-water is not sufficient for irrigation and farmers use tubewells and practice conjunctive use. For canal irrigation, farmers follow the warabandi system, where they receive water on a rotational basis.

Study Design, Methodology and Data

Two distributaries, in BCS-India and LJCS-Pakistan representing relatively inadequate canal-water environments, practicing conjunctive use of cana -water and groundwater of differing quality, and having large variations in farm-level wheat yields were selected. For comparison purposes, a consistent study design and methodology was adopted for both locations. The specific study sites were selected in four stages.

Stage 1

In stage 1, in each selected distributary, three watercourses, with one each on head, middle and tail ends, were selected. This was done by taking into account the total length of the selected distributary, its total command area and total number of watercourses along the distributary. In Pakistan, an additional fourth watercourse in the middle part of the Lalian distributary—where the Food and Agriculture Organization of the United Nations (FAO) is implementing demonstrative interventions on the effects of laser leveling and raised bed furrow cultivation practices on crop yields—was also included in the study for comparison purposes.

Stage 2

In stage two, a complete census of all farms along each selected watercourse was undertaken to enumerate the total number of farms, total watercourse command area, and most importantly to know if there were wide variations in wheat yields within and across watercourses. A mini questionnaire was used to obtain the required data for rabi 1999-2000, through face to face interviews with farmers, from each farm along each selected watercourse. Collected data, which formed the basis for initiating in-depth study, indicated significant yield variations within and across watercourses.

Stage 3

In stage three, considering data requirements for reliable statistical and econometric analysis and research manageability and logistics, a sample of 36 farms along each watercourse (12 each on head, middle and tail ends of each watercourse—based on watercourse command area and the total number of farms along each watercourse) was selected. Total sample size was 216 farms for India and 218 farms for Pakistan.

Since each farm has several field plots/parcels, yields may vary on each of these plots due to possible differences in dates of planting and input applications (including land preparation, fertilizer application, etc.). Considering these intra-farm yield differences, only one plot on each farm was selected randomly for in-depth data collection, including water measurements at the plot level. Data were also collected for the remaining plots on each selected farm, but these data represent averages across the remaining plots on each farm.

All primary data for this study were collected during rabi 2000-2001, i.e., from October 2000 to May 2001. Data were collected by a team of field research assistants living within the watercourse command areas (one for each watercourse), with one field engineer supervising the field work throughout the season. The team was given a two week intensive training on socioeconomic and engineering aspects of data collection. Prior to digitizing, collected data/measurements were double-checked and verified at the end of each week by the field supervisor and data entry operator and suspected errors were corrected. Data collection began in October 2000 and ended in May 2001.

Two types of questionnaires were used to collect primary farm/plot-level data: (1) general questionnaire—to collect basic information including farm location, size, tenurial status, crop areas and production activities during the season (rabi 2000-2001); (2) process questionnaire—to record daily observations from the beginning of the crop season till crop harvesting, on farmers production activities on each of the selected plots, including water measurements at the plot level (water from both surface and groundwater sources).

In addition, data on farmers' warabandi schedule, water measurements at the watercourse level, water table depth fluctuations (at head, middle and tail ends of each watercourse), salinity of both surface and groundwater, soil salinity and rainfall were also collected on a regular basis.

Characteristics of Selected Watercourses

Table 1 provides key characteristics of the selected watercourses in both locations. Gross command area (GCA) of the selected watercourses varies from around 81 ha to 457 ha, with relatively higher GCA of tail-end watercourses. Design capacity of the selected watercourses varies from 0.013 m^3/s to 0.049 m^3/s. Average discharge measured at the outlet head varies from 0.018 m^3/s to 0.062 m^3/s. From the point of view of comparability in size, both Lalian and Khadir in LJCS-Pakistan have a large GCA (20,000–26,000 ha) compared to Batta and Roherra in BCS-India (roughly 4,000 ha). On the other hand, the GCA of the selected watercourses both in BCS-India and LJCS-Pakistan are of comparable sizes. Another noteworthy point is that in both the systems, the tail-end watercourses have larger command areas compared to head- and middle-reach watercourses.

The water allowance per hectare at the watercourse level in the Indian system is more or less uniform (0.0017 m^3/s) across water courses. In the LJCS-Pakistan system, water allowance is the same across water courses on Lalian, while there are differences in water allowances in Khadir. There are significant differences in average discharge across head, middle and tail water courses (as measured through field data) in both the systems.

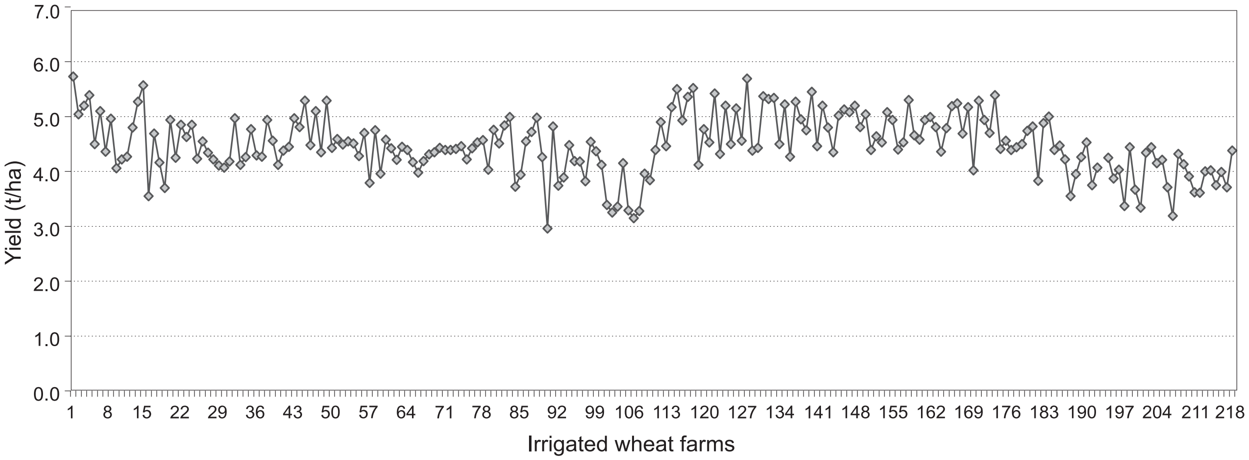
Variations in Wheat Productivity/Yields

To determine wheat yields, crop cutting experiments were undertaken in all the selected plots, i.e., 216 plots in BCS-India and 218 plots in LJCS-Pakistan.[8]

As shown in figures 5 and 6, inter-farm yield variations in the study areas in LJCS-Pakistan are much higher than in the study areas in BCS-India. The yield gap in the study area in LJCS-Pakistan is much wider than that in BCS-India. Average wheat yields are higher in the study area in BCS-India (4.48 t/ha) than in the study area in LJCS-Pakistan (4.11 t/ha). In BCS-India, yields are higher in both distributaries compared to those in LJCS-Pakistan. However, these yield differences are not as high as generally perceived (as discussed earlier).

In BCS-India, there is a small difference in average yields (figure 7) on Batta (4.39 t/ha) and Rohera (4.58 t/ha), where as in LJCS-Pakistan the average wheat yields (figure 8) on both distributaries are fairly similar (4.04 t/ha for Lalian and 4.0 t/ha for Khadir). In BCS-India, minimum and maximum yields obtained by farmers on Batta are 2.96 t/ha and 5.73 t/ha respectively, where as on Rohera the minimum and maximum yields are 3.19 t/ha and 5.69 t/ha. In LJCS-Pakistan, minimum and maximum yields obtained by farmers on Lalian are 0.12 t/ha and 7.82 t/ha respectively, where as on Khadir the minimum and maximum yields are 1.68 t/ha and 6.99 t/ha. There are significant differences in wheat yields across head, middle and tail reaches within and across watercourses along the two distributaries. In general, wheat yields are higher in head-reach water courses, and decreases towards tail reaches for all watercourses in both locations (except for

FIGURE 5.
Farm-level irrigated wheat yields in BCS-India, 2000-2001.



Note: Based on crop cutting experiment in the study areas, 2000-2001.

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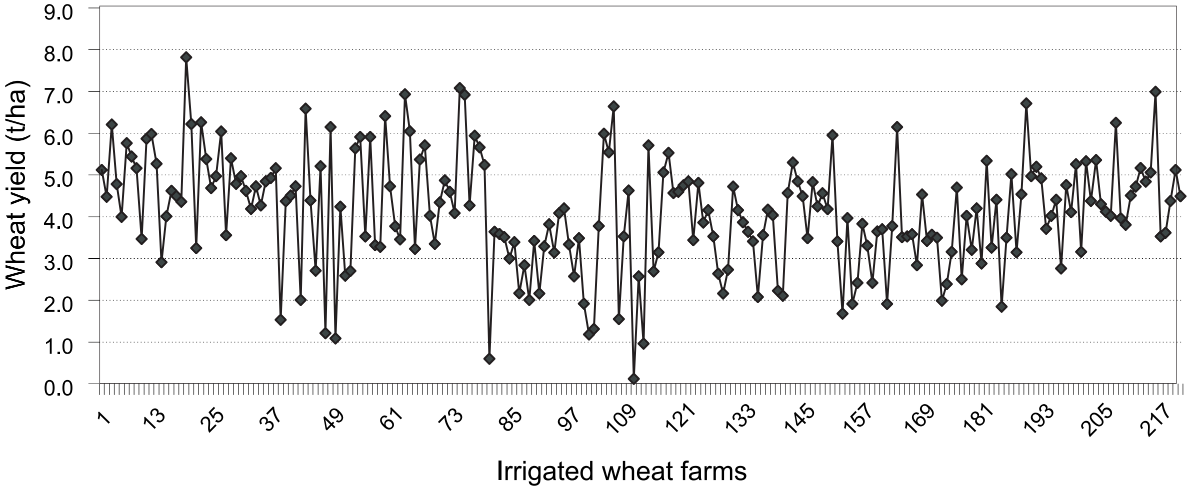
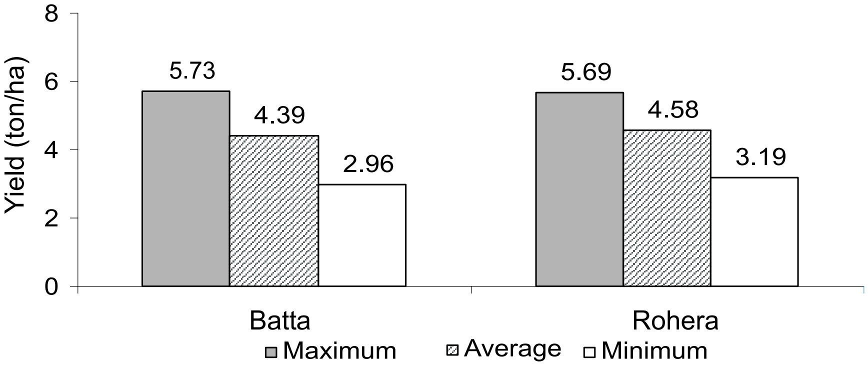
[8] Two samples were taken from each selected plot from different places with a view to best reflect the average yield of the plot, where the wheat plants were uniform all over the plot. Then samples were taken from two places randomly. If there was no uniformity, samples were taken purposively to reflect average of both good and poor parts of the plot. The crop was harvested from a one square meter area from each plot. Threshing was done manually, seed was separated from the chaff and each sample was weighed.

FIGURE 6.
Farm-level irrigated wheat yields in the Chaj subbasin.



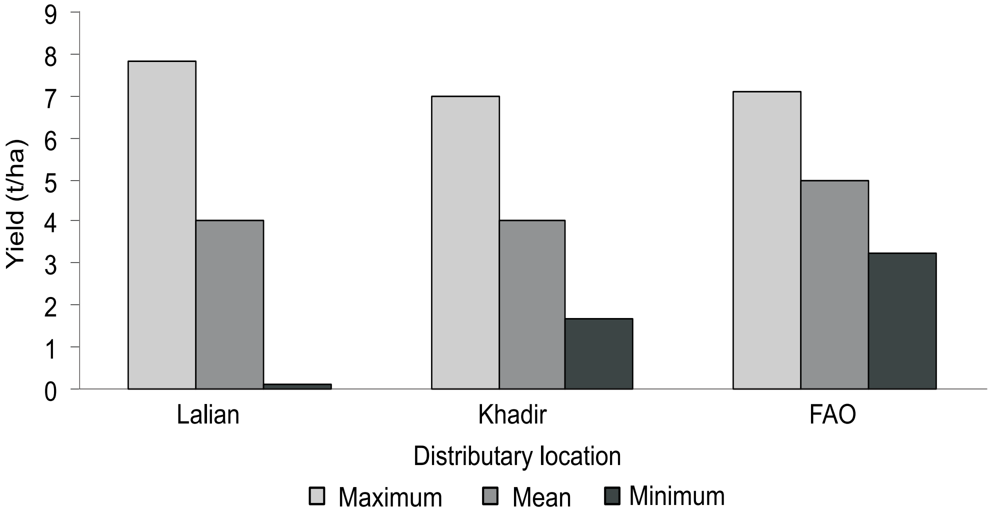
Note: Based on crop cutting experiment in the study areas, 2000-2001.

FIGURE 7.
Yield variation across distributaries in BCS- India, 2000-2001.



Note: Based on crop cutting experiment in the study areas, 2000-2001.
Maximum = 5.73, Minimum = 2.96
Overall average = 4.48, standard deviation = 0.54

FIGURE 8.
Yield variation across distributaries in LJCS-Pakistan, 2000-2001.



Source: Based on crop cutting experiment in the study areas, 2000-2001.
Maximum = 7.82, Minimum = 0.12
Overall average = 4.11, Standard deviation = 1.35

Khadir distributary in LJCS-Pakistan where yields in tail ends are higher than those in head and middle reaches, basically reflecting the availability and use of good-quality groundwater). However, yield differences across watercourses are much higher than those within watercourses, particularly for BCS-India.

Overall, the coefficient of variation (CV) of average wheat yields is higher for distributaries in LJCS-Pakistan (33 percent) than those in BCS-India (12 percent). In BCS-India, CV of yields is the same across the two distributaries, and intra-water course CV is generally less than that at the distributary level. In LJCS-Pakistan, there is a difference in CV of yields across the two distributaries (37 percent for Lalian and 27 percent for Khadir) and it varies significantly within and across watercourses (see appendix table A1 for details on CV of wheat yields). This finding has an important research and policy implication as to what should be the unit of analysis and what type of efforts should be directed where.

Inputs Used in Wheat Production

It is clear from data that there are significant yield differences within and across watercourses, suggesting that the productivity/yield differences/gaps exists both at watercourse as well as distributory levels. What are the key factors influencing these locational differences in crop productivity?

The productivity of wheat depends on a range of factors, including: (1) land and water related factors (such as farm/watercourse location, quality of land, source of water, quality and quantity of water, timing of water application, etc.); (2) climatic factors (rainfall, temperature, sunshine, frost, etc.,); (3) agronomic factors including

TABLE 2.
Average wheat yield (t/ha) of different watercourses in India and Pakistan, 2000-2001.

BCS-India						
Location	Batta			Rohera		
(Distributary/ watercourse)	Head	Middle	Tail	Head	Middle	Tail
Head	4.81	4.73	4.42	4.92	4.83	4.28
Middle	4.56	4.42	4.22	4.89	4.79	3.98
Tail	4.35	4.31	3.72	4.91	4.67	3.55
Average	4.57	4.49	4.12	4.91	4.76	4.04
LJCS-Pakistan						
	Lalian			Khadir		
Head	5.18	4.02	2.96	4.56	3.00	4.51
Middle	4.92	3.31	3.01	3.32	3.51	4.57
Tail	4.79	4.5	3.59	4.22	3.62	4.69
Average	4.95	3.92	3.19	4.03	3.37	4.59

Note: Based on crop cutting experiment in the study areas, 2000-2001.

quality, quantity, and timing of input application (seed, fertilizers, weedicides, labor, etc.,); (4) socioeconomic factors (farmers education level and experience in farming, farm size, tenancy terms, land fragmentation, availability of credit); and (5) farm management factors (adoption of modern production technology, farm planning and management practices, etc.).

Some of these factors may be interrelated and the effect of some of these may be much smaller than that of others, we focus here on the major factors influencing wheat productivity.

As mentioned earlier, soils of the study areas in both locations are loamy. In BCS-India, average soil EC across six water courses varies from 1.85 dS/m to 5.63 dS/m. Generally, soils are of lower quality in Batta (with an average EC of 3.83 dS/m) compared to those in Rohera (with an average EC of 2.86 dS/m). There are significant locational variations within the distributaries in both BCS-India and LJCS-Pakistan, with land quality generally deteriorating towards tail-end locations. For LJCS-Pakistan, the land-quality index based on farmers perceptions on quality of their lands also suggests similar trends. Average EC and pH for Batta tail end and Lalian tail end (two areas of relatively poorer quality soils), are 5.63 dS/m and 8.25 dS/m and 3.15 dS/m and 8.34 dS/m, respectively.

Along with canal (surface) water, groundwater is commonly used in the study areas in both countries. The overall groundwater proportion in the total water use per hectare is higher in BCS-India than in LJCS-Pakistan. In general, groundwater use is high where canal water is in short supply. Groundwater use is much higher in Rohera in BCS-India and Khadir in LJCS-Pakistan, contributing on average around 90 percent of total water use at the farm level compared to Batta (73%) and Lalian (55%). However, there are significant variations in water use from the two sources across various reaches of the canal systems. In both the study areas, groundwater use is much higher in tail-end reaches as compared to that in head and middle reaches where canal water supply is relatively higher.

The location of farms/watercourses is directly related to the use of both surface water and groundwater. The head and middle reaches receive more canal water as compared to tail ends in both BCS-India and LJCS-Pakistan. This is indicated by canal-water flow measurements at the outlet level for each of the selected watercourses (given in appendix figures A4 to A16)[9] and the amount of canal water applied at the field level.[10] Average canal water applied for wheat in BCS-India is 550 m^3/ha compared to 980 m^3/ha in LJCS-Pakistan. Canal-water use is higher in Batta (BCS-India) and Lalian (LJCS-Pakistan), averaging at 816 m^3/ha and 1458 m^3/ha respectively compared to Rohera (285 m^3/ha) and Khadir (465 m^3/ha). Data on outlet-level discharges and farm/field-level water supplies suggest that there are wide locational variations in canal-water supplies, and hence unequal distribution of water to farmers across reaches of distributaries in both BCS-India and LJCS-Pakistan.

Overall inequity in canal-water distribution is higher in the study area in LJCS-Pakistan than in the study area in BCS-India, as shown in the Lorenz curve in figure 9. The estimated Gini coefficients[11] for BCS-India and LJC-Pakistan are 0.29 and 0.42 respectively. Gini coefficients are higher for distributaries where per hectare canal-water supply is relatively less (Rohera, BCS-India and Khadir, LJCS-Pakistan). Except for the Batta head watercourse in BCS-India, Gini coefficients for tail-end watercourses are higher than their respective head-end watercourses. In general, inequity in canal-water distribution prevails both within watercourses and across watercourses along distributaries.[12]

The quality of canal water is generally good for irrigation in both BCS-India and LJCS-Pakistan, with EC levels of 0.22, 0.24, 0.25 and 0.27 dS/m for Lalian, Batta, Rohera and Khadir, respectively. However, groundwater EC levels for BCS-India are much higher than for LJCS-Pakistan, averaging at 3.39 dS/m and 1.13 dS/m, respectively. Therefore, overall groundwater salinity levels are relatively higher in the study area in BCS-India than in LJCS-Pakistan. However, groundwater salinity levels and its overall quality varies significantly across distributaries. Groundwater is more saline in Batta and Lalian (the two distrubutaries presently receiving relatively more canal water) as compared to that in Rohera and Khadir. Groundwater quality varies significantly across head, middle and tail reaches of the distributaries. In general, groundwater quality deteriorates towards middle and tail reaches, except for Khadir in LJCS-Pakistan where groundwater salinity levels decrease towards middle and tail reaches. Unfortunately, high saline groundwater reaches are the ones receiving less canal water. Thus, the present strategy of canal-water allocation at the distributary level, i.e., more canal water to areas of high saline groundwater, Batta and Lalian, compared to areas of relatively less saline groundwater areas, Rohera and Khadir, makes sense. However, the main problem lies within a distributary, where reaches with saline groundwater are receiving less canal water. Tail reaches of Batta and Lalian are the worst areas (table 1 and 3).

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[9] Outlet discharge measurements were taken on a daily basis. All outlets were calibrated in order to develop a separate "coefficient of discharge (cd)" for each outlet (if a change in outlet occurs, the outlets are re-calibrated in order to estimate the new cd value). White marks were put and readings were taken with the help of a staff rod and level set. By taking the values of the breadth of outlet (B) and the height of outlet (Y), daily discharge value was estimated.

[10] For LJCS-Pakistan, field level water applications were measured with flumes throughout the season for all 218 plots.

[11] Gini coefficient is based on the Lorenz curve and is a commonly used measure of inequity. The value of Gini coefficient ranges between 0 and 1. A zero value shows a completely equal distribution (Lorenz curve is located on the 45 degree line so that the area between the 45 line and Lorenz curve is zero). The greater the value of Gini, the greater the degree of inequity in distribution.

[12] We also used Head-Tail equity ratio, which is another measure of inequity. The results indicate that the Head-Tail equity ratio for average per hectare canal-water use in selected distributaries in BCS-India and LJCS-Pakistan is 1.72:1 and 3.90:1 respectively. These results further suggest that head-tail inequities in LJCS-Pakistan are much greater than in BCS-India. Details on estimates of Gini coefficients and Head-tail equity ratios for within and across watercourse reaches are given in appendix table A3.

FIGURE 9.
Canal-water distribution of sample farms in India and Pakistan, 2000-2001.

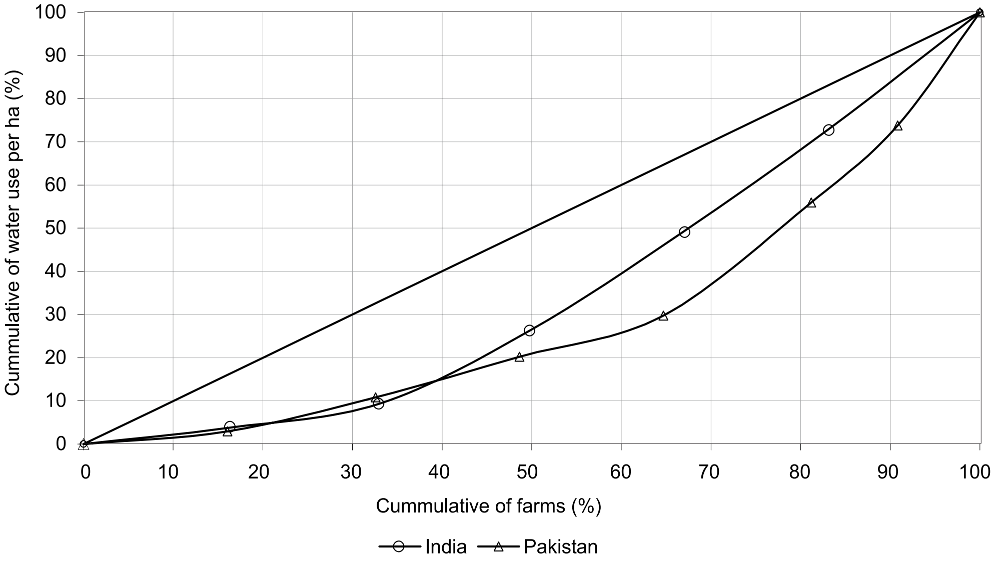

TABLE 3.
Water usage for wheat production in BCS-India and LJCS-Pakistan.

Outlet/distributory/ minor	No. of canal irrigations	Total no. of irrigations	Amount of tubewell water applied (m^3)	Amount of canal-water applied (m^3)	Amount of total water applied (m^3)	Tubewell water as a percentage of total water applied
BCS-India						
Batta head	1.1	4.3	1,829	849	2,678	68
Batta middle	1.0	4.1	2,219	897	3,116	71
Batta tail	1.1	4.5	2,545	700	3,245	78
Rohera head	0.7	4.3	2,194	584	2,778	79
Rohera middle	0.4	4.4	3,011	148	3,159	95
Rohera tail	0.2	5.0	3,225	109	3,334	96
Batta all	1.1	4.3	2,197	816	3,013	73
Rohera all	0.4	4.6	2,806	282	3,088	91
All	0.8	4.4	2,500	550	3,050	82
LJCS-Pakistan						
Lalian head	2.1	4.4	1,845	1,500	3,345	55
Lalian middle	2.5	3.8	1,304	2,745	4,049	32
Lalian tail	1.5	4.6	2,146	345	2,491	86
Khadir head	1.5	4.4	2,704	606	3,311	82
Khadir middle	1.3	4.7	3,591	600	4,191	86
Khadir tail	1.3	5.4	5,088	187	5,275	96
Lalian all	2.0	4.2	1,758	1,458	3,185	55
Khadir all	1.9	4.8	3,794	465	4,259	89
All	1.9	4.5	2,748	980	3,702	74

Figures 10 to 13 show yields obtained by farmers using various proportions of groundwater in total per-hectare water application. In general, with adequate, reliable, timely and good-quality groundwater, yields can be expected to be higher than that with canal water. In Khadir in LJCS-Pakistan, the quality of groundwater is good. Increasing the proportion of good groundwater in the total water applied resulted in improved wheat yields in this distributory. On the other hand, in the three remaining distributaries, use of saline groundwater has a negative impact on wheat yields. The overall significance of impacts of groundwater use and its quality are quantified in the yield function developed in the next section.

In LJCS-Pakistan, no significant fluctuations in the depth of groundwater tables were observed during the crop season in both distributaries. Data on groundwater depth measurements during the period from October 2000 to July 2001 suggests that the water tables fall only slightly from December through to March and then begin to rise again to original levels. In BCS-India, the water table declined in the Batta head reach. On the other hand, the water table in the Batta tail reach has risen from 5.46 m to 4.37 m. In the Rohera head and tail reaches the average water table has decreased from 4.72 m to 5.54 m and 4.51 m to 4.91 m, respectively.

Table 4 gives data on average quantities of key non-water inputs used for wheat production. Overall seed use per hectare in LJCS-Pakistan is higher than in BCS-India. This may be because most farmers in LJCS-Pakistan use older seed varieties (mostly from their home storage) as compared to those in BCS-India. The number of ploughings is the same across irrigation systems in both countries. However, there are significant differences in the use of NPK per hectare (expressed in terms of kg of element) across the two countries. Average NPK use per hectare in BCS-India is substantially higher (at 222 kg/ha) than that in LJCS-Pakistan (146 kg/ha). Most farmers in BCS-India have applied NPK in line with recommended amounts, and there is not much variation across and within distributaries. On the other hand, NPK use in LJCS-Pakistan is lower on most farms than the recommended levels for medium soil fertility levels (the recommended amount of NPK is 253 kg/ha). There are significant differences in quantities of NPK used across farms and watercourses. NPK application rate is higher in Khadir (148 kg/ha) compared to Lalian (145 kg/ha). For LJCS-Pakistan, NPK and yield show a strong positive relationship, yields increasing with increasing amounts of NPK applications. Given the complementary relationship between NPK and water, average NPK use is higher on farms and watercourses where water supplies are also higher and vice versa. Also, NPK use is directly related to reliability of water supplies. Farmers using greater percentage of good-quality groundwater also use higher amounts of fertilizers and vice versa. The least amount of NPK use is found on farms in Lalian tail-end reaches (89 kg/ha) where groundwater is of poorer quality, canal-water supplies are the least, and consequently yields are low. Other factors that may influence yields include quantity of weedicides, wheat seed variety and sowing time.

FIGURE 10.
Effect of groundwater use on wheat yields in Batta, BCS-India.

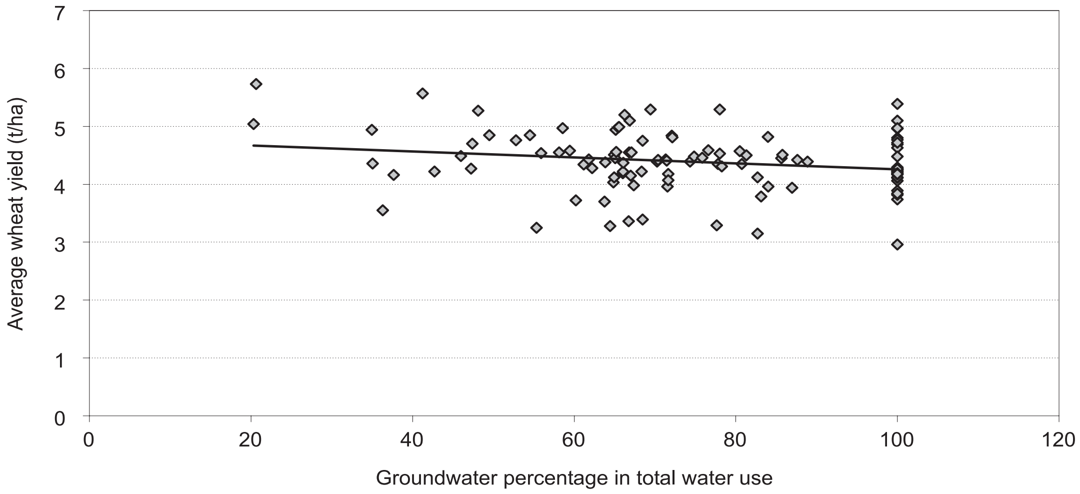

FIGURE 11.
Effect of groundwater use on wheat yields in Rohera, BCS-India.

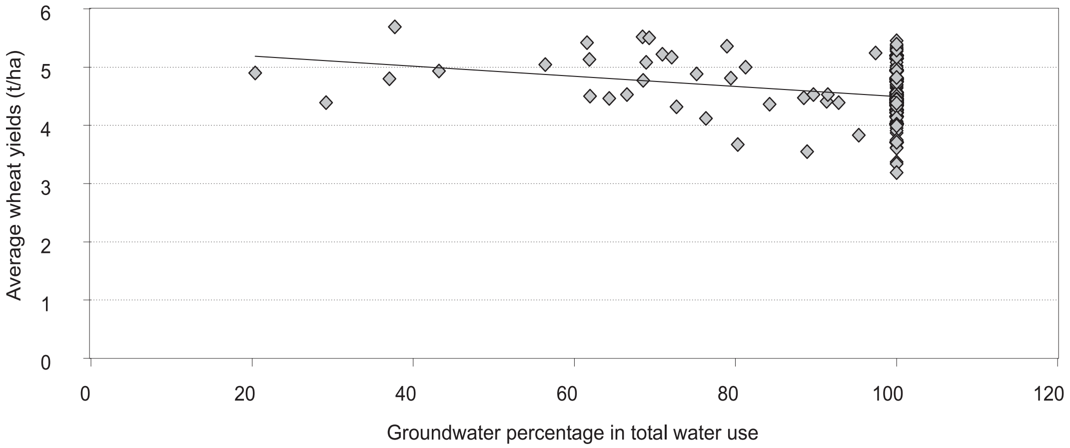

FIGURE 12.
Effect of groundwater quality on wheat yields in Lalian, LJCS-Pakistan.

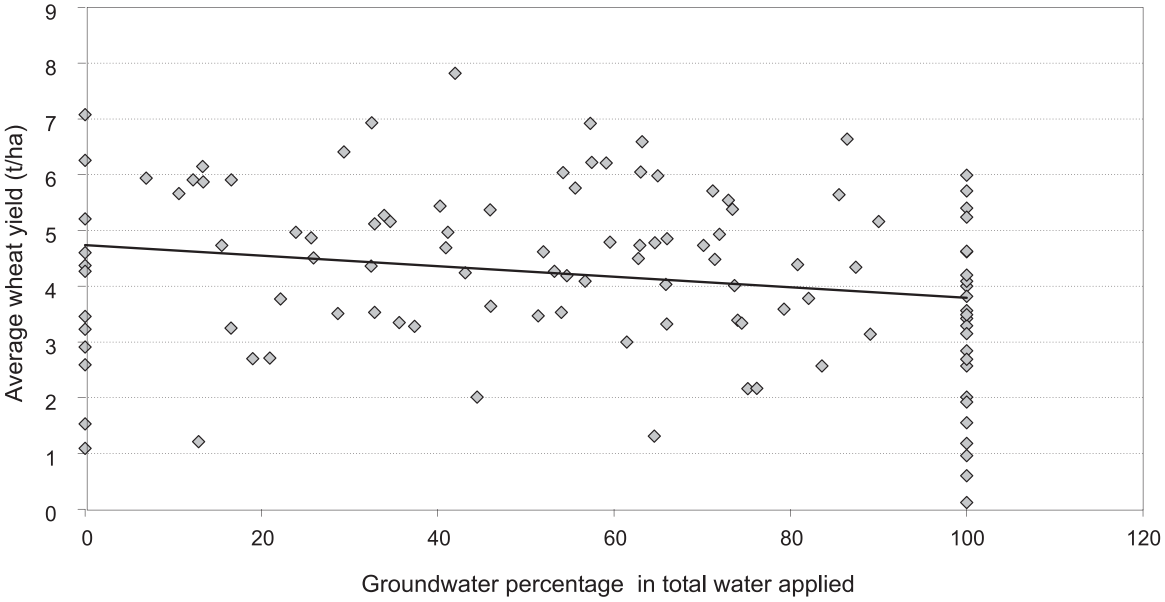

FIGURE 13.
Effect of groundwater quality on wheat yields in Khadir, LJCS-Pakistan.

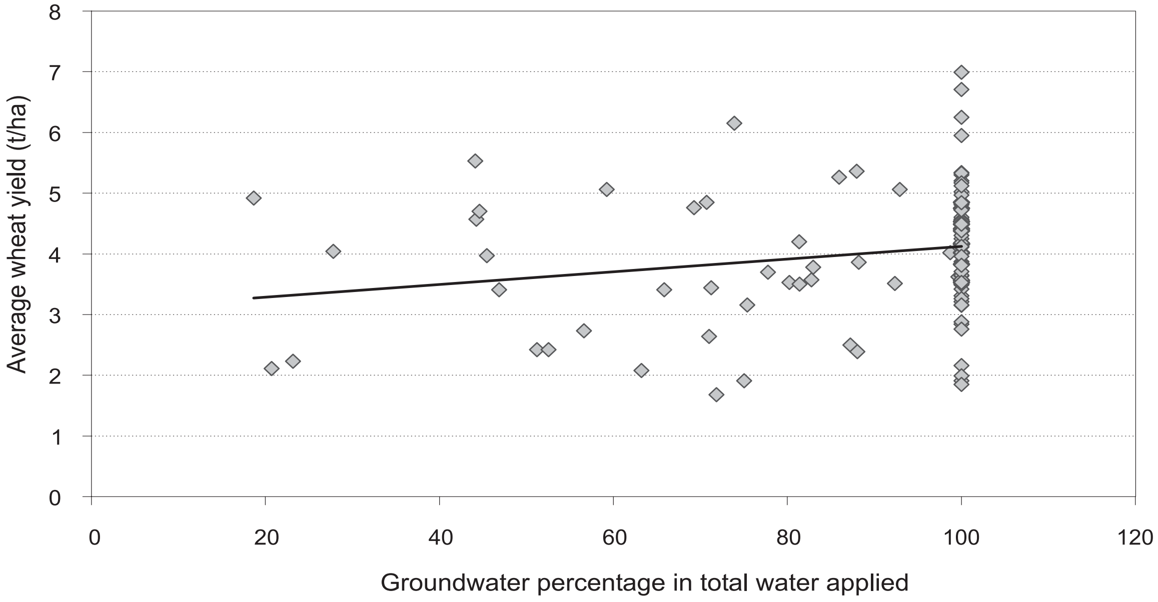

TABLE 4.
Average quantities of non-water inputs (per hectare).

Outlet/distributory/ minor	Seed (kg/ha)	NPK (kg/ha)	No. of ploughings
BCS India			
Batta head	100	248	3.6
Batta middle	108	229	3.7
Batta tail	99	193	3.9
Rohera head	109	199	4.0
Rohera middle	106	202	3.6
Rohera tail	124	244	4.4
Batta all	102	223	3.7
Rohera all	113	215	4.0
All	108	219	3.9
LJCS Pakistan			
Lalian head	116	169	3.5
Lalian middle	126	196	3.8
Lalian tail	124	89	2.9
Khadir head	130	155	5.7
Khadir middle	131	139	3.2
Khadir tail	127	153	4.6
Lalian all	123	144	3.5
Khadir all	130	149	4.5
All	126	147	3.9

Yield Function Analysis

The yield function analysis was carried out to identify and estimate the combined effects of various factors of production with a view to assessing their importance in influencing wheat yields. The yield function is a formal representation of a set of hypotheses that the identified production factors influence yields and that their effects on yields are of varying magnitude. The analysis was undertaken for an entire sample for BCS-India and LJCS-Pakistan separately. The yield function was specified using a range of variables, including those discussed earlier, and estimated with a set of functional forms including linear, log-linear, log-log (Cobb-Douglas) and quadratic. The popular econometric and statistical criteria, such as predictive power of the equation, consistency and plausibility of estimated coefficients, algebraic signs and numerical magnitudes and their statistical significance, were used to select the functional form that had the best fit for the given data set. The following yield functions for BCS-India and LJCS-Pakistan were finally estimated with a set of independent variables as given below.

BCS-India

$$Y_i = \alpha_0 + \alpha_1 D_{m\,i} + \alpha_2 D_{ti} + \alpha_3 V_i + \alpha_4 S_i + \alpha_5 F_i + \alpha_6 W_i + \alpha_7 WD_i + \alpha_8 NW_i + \alpha_9 T_i + \alpha_{10} ECTW_i + U_i \qquad (1)$$

LJCS-Pakistan

$$Y_i = \alpha_0 + \alpha_1 Dm_i + \alpha_2 D_{t\,i} + \alpha_3 V_i + \alpha_4 S_i + \alpha_5 F_i + \alpha_6 W_i + \alpha_7 W^2{}_i + \alpha_8 NW_i + \alpha_9 T_i + \alpha_{10} ECTW_i + U_i \qquad (2)$$

Where:

Y = Wheat output/yield in tons per hectare

D_m = Dummy for middle location of farmers on the distributary (D_m = 1 if the location is middle, D_m = 0 otherwise)

D_t = Dummy for tail location of farmers on the distributary (D_t = 1 if the location is tail, D_t = 0 otherwise)

V = Dummy for Variety (for LJCS-Pakistan V =1 if variety is MH97, V= 0 otherwise; and for BCS-India V=1 if variety is WH-542 and PBW-343, V= 0 otherwise; these are relatively newer varieties)

S = Sowing week (for LJCS-Pakistan first actual sowing week is from 16-22 Oct 2000; for BCS-India first actual sowing week is from 1-7 November); Delay in sowing is hypothesized to negatively affect yields.

F = Quantity of fertilizers - NPK in kilograms/ha

W = Quantity of total irrigation water applied (m^3/ha.)

WD = Weedicides use as a fraction of recommended dosage

NW = Number of irrigations or waterings to wheat during the entire growing season

T = For LJCS-Pakistan, time gap between pre-sowing and first post-sowing; for BCS-India time gap between second and third irrigation/watering;[13]

$ECTW$ = ECTW measures the amount of salts in the total water applied (groundwater (%) times EC of groundwater (dS/m) divided by total water)

α_s = coefficients to be estimated

i = denotes farm

U = error term

Each estimated coefficient measures absolute change in wheat yield per unit change in one factor holding the others constant. The location of farms along the canal system enters the yield function as a shift variable—measuring the absolute differences in yields between middle-end and tail-end farmers, and the farmers located at the head reaches. Location dummies capture the influence of location specific factors other than those included in the yield function (particularly, soil salinity, land quality and rainfall). The coefficients of dummy variables for middle and tail locations, α_1, α_2, respectively, measure the net contribution to yield of middle and tail locations of the farms relative to head-end farms. The coefficient of the dummy variable for seed, α_3 measures the net contribution of improved seed varieties relative to all other seed varieties.

The results of the estimated equations are presented in table 5. In a wide range of factors

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[13] In the estimation process, we also tried time gaps between irrigations other than these.

that could possibly affect wheat yields, location, seed variety, quantity of irrigation water and fertilizers for LJCS-Pakistan, quantity of weedicides (for BCS-India) number and timing of irrigation/waterings and quality of groundwater were found to be significant in influencing wheat yields. While the coefficients of determination of the estimated equations are low for both equations, it is acceptable given the type of data being used in estimations (cross-sectional). Means and standard deviations of all dependent and independent variables are given in appendix table 2.

The values of the variance inflation factors (VIF) test indicates the absence of the multicollinearity problem among independent variables[14] in both equations. The standard errors of the coefficients are low, which are reflected in higher t-statistics, with all the estimated coefficients being significant (except for quantity and timing of water and fertilizer applied in the case of BCS-India). In short, the results of the estimated equation suggest that the specified set of variables significantly affect (positively/negatively) wheat yields. The coefficients of location dummies indicate that wheat yields in middle and tail locations are lower than those at head ends by 0.11 t/ha and 0.44 t/ha respectively for BCS-India and 0.70 t/ha and 0.53 t/ha respectively for LJCS-Pakistan. For LJCS-Pakistan, lower coefficients for tail indicates the dominant effect of relatively good-quality groundwater on yields at Khadir. However, the magnitude of the effect of other factors on yields varies significantly across locations—as indicated by marginal productivities, calculated based on the above coefficients using appropriate units (table 6).

In BCS-India, marginal productivity of seed varieties WH-542 and PBW-343, which are relatively newer varieties, is higher than that of other varieties such as HD-2329 and HD-2009 with WH-542 and PBW-343 contributing additional 97 kg/ha to average wheat yields. However, marginal

TABLE 5.
Estimated coefficients and their significance.

	BCS-India			LJCS-Pakistan		
Variable	Coefficient	t-value	VIF	Coefficient	t-value	VIF
Constant	4.456	11.08		3.583	5.74	
D_m	-0.1058	-1.08	2.48	-0.701	-3.66	1.61
D_t	-0.4384	-3.65	3.81	-0.526	-2.58	1.77
V	0.2028	2.71	1.18	1.696	5.01	1.27
S	-0.105	-2.87	1.43	-0.121	-3.31	1.14
F	-0.000745	-1.43	1.25	0.00292	2.25	1.35
W	0.0000013	0.02	2.10	0.000538	2.32	27.48
W^2	-	-	-	-0.0000000445	-1.87	25.19
WD	0.183	2.07	1.12	-	-	-
NW	0.047938	0.59	2.14	0.183	2.35	2.03
T	0.004385	1.01	1.41	-0.0777	-3.37	1.14
ECTW	-0.058609	-2.93	2.06	-0.364	-2.28	1.39
R^2	0.44			0.40		
N	216			218		

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[14] VIF greater than 5 for any independent variable, except squared variables, indicates the problem of multicollinirity, i.e., that the variable is collinear with one or more of the other independent variables in the equation (Gujarati 1995).

TABLE 6.
Marginal productivities of factors of production.

Factor	BCS-India	LJCS-Pakistan
	Marginal productivity (kg/ha)	Marginal productivity (kg/ha)
Wheat seed variety (MH97 for Pakistan, and WH-542 and PBW-343 for India)*	97	995
Sowing delay by week	-105	- 121
NPK quantity in kg per 10 kg unit	-7	29
Irrigation water (m^3) per 100 m^3	0.13	24
Number of irrigations/waterings	48	183
Time gap between irrigations/waterings (for Pakistan, time gap between pre-sowing and first post-sowing; for India time gap between second and third irrigation/watering) (week)	4	-78
Percent of groundwater in total water applied times present level of average EC of groundwater—at 100 percent groundwater use level.	-199	-411

*Marginal productivities are just the coefficients in the regression, so for variety in India it is 0.2 ton per hectare, while in Pakistan it is 1.696 ton per hectare (as given in table 5). However, if we account for impacts of location specific factors (i.e. combining the impacts of locational factors and impacts of varieties), marginal productivity of MH97 (LJCS-Pakistan) would be 1696 kg/ha at head, 995 kg/ha at the middle and 1521 kg/ha at the tail reaches. In BCS-India, marginal productivity of WH-542 and PBW-343 would be 202 kg/ha at the head, 97 kg/ha at the middle and –236 kg/ha at the tail (because of the negative locational effect of it is greater than the positive effect of variety). Figures in the table are combined locational and variety impacts at the middle water courses.

productivity of newer seed varieties in LJCS-Pakistan is substantially higher than that in BCS-India. Marginal productivity of MH 97, which is a relatively newer variety, is much higher than that of other varieties such as Inqulab, Pak–81 and others. The results indicate that replacing Inqulab and other varieties with MH 97 contributes 995 kg/ha to average wheat yields (after accounting for locational factors). Sowing time also significantly affects yields. A one week delay in sowing, from 1 November reduces wheat yield by 105 kg/ha in BCS-India. A similar effect was observed for LJCS-Pakistan, where a one week delay in sowing from appropriate sowing dates (i.e., if sowing is done after first week of December),[15] reduces wheat yield by 121 kg/ha.

Fertilizer use has positive impacts on yields in BCS-Pakistan—10 kg of NPK increases yield by 29 kg/ha.[16] Like fertilizers, the marginal productivity of irrigation water is also positive—100 m^3 of water contributes 24 kg/ha to yields.[17] However, in the case of BCS-India, marginal

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[15] The recommended sowing dates for Inqulab and MH 97 are 10 Nov-15 Dec and 25 Oct-30 Nov, respectively (Government of Punjab 2000).

[16] Since the fertilizer use on most farms is lower, the fertilizer response to yield is positive linearly. The squared term used for the NPK variable was insignificant, although it carried a negative sign.

[17] Marginal productivity of water is calculated using coefficients on both W and W^2.

productivity of fertilizers is negative, indicating that there is some scope to reduce the amounts of fertilizer use. Marginal productivity of irrigation water in BCS-India is very low, estimated at 0.13 kg/ha, indicating average yields obtained are closer to the highest point on the yield water curve (and that farmers are applying water fairly in line with crop water requirements). Therefore, there is not much scope to increase yields by further increasing the quantity of irrigation water per hectare. However, the total quantity of water per hectare now supplied over one season when given in more frequent waterings positively influences yields, with each additional watering increasing yield by 48 kg/ha and 183 kg/ha for sample farms in BCS-India and LJCS-Pakistan,[18] respectively. Period after crop emergence is critical for crop growth, and prolonged delays in watering influences crop yields negatively[19] in the case of LJCS-Pakistan. A one-week delay in first post-sowing watering, from the appropriate period, reduces wheat yields by 78 kg/ha. In the case of weedicides, with application of recommended doses, there is a considerable increase in yields of 183 kg/ha in BCS-India. Only 11, 20 and 2.5 percent of sample farmers have applied 60, 80 and 110 percent of the recommended dosage of weedicides in their fields, respectively, while 7 percent of sample farmers have not applied any weedicides at all.

In addition to timeliness, quality of water is also an important factor influencing yields. At the present level of groundwater EC (dS/m), use of only groundwater (i.e., 100 percent groundwater with no canal water) reduces wheat yields on average by 199 kg/ha and 411 kg/ha in BCS-India and LJCS-Pakistan respectively. Although the average EC level in BCS-India is relatively higher, negative effects on yields is low than in LJCS-Pakistan. This is because overall water use in BCS-India is high in reaches where EC levels are also high, but the opposite situation prevails in LJCS-Pakistan (especially in Lalian tail ends where per hectare water use is the lowest, even lower than the crop water requirements, and groundwater salinity levels are highest than in other reaches, and the negative effect of poor quality groundwater is highest at -622 kg/ha). Overall, yield response to groundwater use and its quality varies across locations in the distributaries. It is clear from the above discussion that seed variety (in LJCS-Pakistan), correct dosage of weedicides application in BCS-India and quality of groundwater (in both BCS-India and LJCS-Pakistan) are the three most important factors influencing wheat yields.

As noted above, the marginal productivity of irrigation water is much lower in BCS-India than in LJCS-Pakistan. However, while average productivity of consumed water is fairly the same, average productivity of diverted water is much higher in BCS-India than in LJCS-Pakistan (table 7).

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[18] In Pakistani Punjab, the general recommendation for wheat is three to five waterings, depending on climatic conditions and groundwater table depths (Government of Punjab 2000).

[19] The Pakistani Punjab Agriculture Department recommends that for wheat, watering after sowing be done within 20-25 days if it is sown after cotton, maize or sugarcane, and within 30-40 days if it is sown after rice.

TABLE 7.
Average productivity of water.

Outlet/distributory/ minor	Average land productivity/yield (kg/ha)	Average productivity of consumed water (kg/m^3)	Average productivity of total water applied (kg/m^3)
BCS-India			
Batta head	4,569	1.38	1.71
Batta middle	4,485	1.36	1.44
Batta tail	4,119	1.25	1.27
Rohera head	4,908	1.49	1.77
Rohera middle	4,761	1.44	1.51
Rohera tail	4,043	1.23	1.21
Batta all	4,391	1.33	1.46
Rohera-all	4,576	1.39	1.48
All	4,483	1.36	1.47
LJCS-Pakistan			
Lalian head	4,946	1.60	1.48
Lalian middle	3,917	1.29	0.97
Lalian tail	3,188	1.08	1.28
Khadir head	4,033	1.31	1.22
Khadir middle	3,372	1.10	0.80
Khadir tail	4,590	1.62	0.87
Lalian all	4,206	1.39	1.32
Khadir all	3,998	1.34	0.94
All	4,106	1.37	1.11

Economics of Wheat Production

Profitability of crop production depends on crop yields, output price and cost of production (table 8). As discussed earlier, average yields in BCS-India are higher than those in LJCS-Pakistan. However, there are significant locational variations in yields across distributaries. In BCS-India, average yields are lower towards middle and tail locations. A similar pattern is observed for distributaries in LJCS-Pakistan, except for Khadir tail ends where yields are even higher than those at the head reach (mainly because of good quality groundwater use).

While average yields in BCS-India are higher, average cost of production (COP) is also high (US$269 per hectare) as compared to that in LJCS-Pakistan (US$229 per hectare). Higher gross value of production (GVP) for BCS-India (US$574 per hectare) contributes to overall higher gross margins(GM) (US$306 per hectare) compared to that in LJCS-Pakistan where both GVP (US$480) and GM (US$251) are relatively lower. However, these are significant differences in GM across locations in all four distributaries. In BCS-India, GM are lower in tail ends of both the distributaries. However, in LJCS-Pakistan GM are the lowest in Lalian tail and Khadir middle reaches. Overall, GM are lowest in locations or reaches where groundwater is of poorer quality.

TABLE 8.
Profitability of wheat production (US$/ha).

Outlet/distributory/ minor	Price of wheat (US$/t)	Gross value of product (GVP) in (US$/ha)	Cost of production (COP) (US$/ha)	Gross margins (GM) (US$/ha)	Ratio of GM to COP
BCS-India					
Batta head	126	574	254	320	1.26
Batta middle	143	639	271	369	1.36
Batta tail	122	505	226	279	1.24
Rohera head	124	610	263	347	1.32
Rohera middle	122	583	297	286	0.96
Rohera tail	132	533	301	232	0.77
Batta all	130	573	250	323	1.29
Rohera all	126	576	287	289	1.01
All	128	574	269	306	1.14
LJCS-Pakistan					
Lalian head	119	589	252	337	1.34
Lalian middle	116	454	228	227	1.00
Lalian tail	116	374	163	211	1.29
Khadir head	107	433	231	202	0.88
Khadir middle	115	388	220	168	0.76
Khadir tail	118	541	284	257	0.90
Lalian all	119	503	214	289	1.35
Khadir all	113	454	245	209	0.85
All	116	480	229	251	1.10

Notes: 1. Cost of production, which is variable cost of production, includes all cash and non-cash expenses incurred on production inputs and activities, including cost of hired labor and imputed value of family labor, but excludes land rent. Equipment depreciation and other fixed costs are not included. The cost of hired labor was imputed by multiplying the amount of hired labor by average rate of hiring during the season.

2. GVP= yield multiplied by price

3. Gross Margins = GVP minus variable cost of production

Table 9 shows various components of the cost of production. In both BCS-India and LJCS-Pakistan, cost of irrigation water and fertilizers are the two key components of the total cost of production. In BCS-India, fertilizers and irrigation constitute around 19 and 17 percent respectively, where as in LJCS-Pakistan these two inputs constitute around 22 percent and 24 percent, respectively, to the total cost of production. While the cost of other components remains fairly similar across various reaches, cost of irrigation and fertilizers varies significantly in both BCS-India and LJCS-Pakistan. Per-hectare cost of irrigation in BCS-India is lower (US$46) than in LJCS-Pakistan (US$56). Cost of canal irrigation is substantially less than the cost of groundwater in both countries, averaging at US$3.2/ha for BCS-India and US$4.5 per hectare for LJCS-Pakistan.[20]

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[20] The canal-water charge (or abiana) is paid by farmers for all crops on farm together at the end of the cropping season. The assessment of water charge is undertaken by a revenue department official based on cropping intensity and crop conditions. The average water charge for the entire sample of 218 farms is Rs 262 per hectare. This figure is high because some of the farmers on Khadir middle reported paying over Rs 700 per hectare (as the water charges paid also include charges paid for water from public tubewells, and illegal charges by Patwari as reported by farmers). Excluding these cases, the average canal-water charge is around Rs 200 per hectare.

In general, cost of irrigation water and of fertilizer is directly related to the use of groundwater, which in turn influences crop yields and overall profitability. Use of good-quality groundwater increases yields (due to its reliability) more than canal water, but it results in increased cost of production. However, the poorer quality groundwater not only reduces yields, it increases the cost of production, resulting in reduced profitability. Canal water on the other hand, though relatively less reliable, has positive effects on yields and at the present rate of water charges, is much cheaper than groundwater. Under these conditions, promoting groundwater use in locations where its quality is good and reallocating canal water to poorer quality groundwater irrigation systems is an important innovation for increasing productivity and profitability for farmers and the total value of production.

TABLE 9.
Components of cost of production (US$/ha).

Outlet/distributory/ minor	Cost of land preparation	Cost of seed	Cost of NPK	Cost of weedicides	Cost of labor	Cost of groundwater irrigation	Cost of canal irrigation	Total cost of irrigation	Cost of harvesting and threshing	Cost of marketing*
BCS-India										
Batta head	36.2	18.8	56.5	30.3	20.8	31.4	3.2	34.6	42.7	11.7
Batta middle	34.4	18.0	53.0	33.7	20.5	38.1	3.2	41.2	52.4	14.5
Batta tail	36.9	16.2	46.6	18.4	14.0	43.7	3.2	46.8	36.2	8.2
Rohera head	38.6	17.7	46.3	32.5	20.5	37.6	3.2	40.8	57.5	6.4
Rohera middle	35.5	20.1	46.4	23.4	26.1	51.7	3.2	54.8	78.1	9.4
Rohera tail	47.3	20.0	56.3	33.7	21.3	55.3	3.2	58.5	51.1	8.6
Batta all	35.8	17.7	52.1	27.5	18.4	37.7	3.2	40.9	43.8	11.5
Rohera all	40.4	19.3	49.6	29.8	22.6	48.1	3.2	51.3	62.2	8.1
All	38.1	18.5	50.8	28.6	20.5	42.9	3.2	46.1	53.0	9.8
LJCS-Pakistan										
Lalian head	35.7	20.6	55.3	15.3	15.5	54.1	3.0	54.0	32.4	33.2
Lalian middle	30.8	19.1	65.8	30.2	12.9	37.1	3.8	31.6	28.0	30.4
Lalian tail	25.2	15.9	27.8	.	13.1	32.9	3.0	35.9	33.8	16.6
Khadir head	49.5	18.0	51.7	16.0	11.6	48.4	3.4	51.7	27.8	21.2
Khadir middle	28.7	18.6	47.3	.	15.9	47.9	11.4	59.3	31.0	19.5
Khadir tail	36.7	18.8	54.1	8.4	13.3	104.0	2.5	106.5	33.5	22.9
Lalian all	32.1	18.8	47.7	19.9	13.6	41.7	3.3	40.5	30.7	28.7
Khadir all	38.3	18.5	51.0	12.2	13.6	66.7	5.8	72.5	30.7	21.2
All	35.1	18.7	49.3	19.4	13.6	54.5	4.5	55.9	30.7	25.1

*Marketing cost excludes labor cost for BCS-India but is included for LJCS-Pakistan.

Improving Productivity—Closing the Productivity Gap

This study identifies several factors influencing land and water productivity of wheat. The results suggest that there is significant scope to improve land and water productivity and profitability of wheat in the western Indo-Gangetic plains of India and Pakistan. From a policy view point, this can be done by:

1. Improving agronomic/farm management practices through:

   a) Promoting the use of improved/newer varieties of seed wheat, such as MH 97 in Pakistan, and WH 542 and PBW 343 (especially where soils and groundwater are of relatively good quality) . In LJCS-Pakistan, improved seed variety alone has the potential to increase wheat yields by about 1 t/ha. In BCS-India, applying the recommended dosage of weedicides alone increases wheat yields by about 0.2 t/ha.

   b) Providing/enhancing the role of extension services to farmers for dissemination of up-to-date knowledge on appropriate sowing dates, and quantities and timing of application of inputs, particularly irrigation water.

2. Improving water management practices.

   While improved farm management practices remain important, there is also potential to increase productivity and profitability of wheat by improving water management practices at the canal-system level. Much needed improvements at this level include:

   a) Improving on timing of water delivery. As indicated earlier, in LJCS-Pakistan a one week delay (from appropriate dates) in the first post-sowing watering reduces wheat yields by 78 kg/ha. This loss can be turned into gains by improving timing of water deliveries, and this can be done by setting delivery targets and schedules by location in line with agronomic factors such as dates of crop sowing. In the case of BCS-India, however, the gap between the second and third irrigation is found to have a positive impact on wheat yields, although this impact is small (4 kg/ha).

   b). Increasing overall canal-water supplies at the farm level. While marginal productivity of water is very low for BCS-India, it is positive and higher for LJCS-Pakistan, with each additional 100 m^3 of water producing 24 kg/ha more wheat. Therefore, there is some scope to increase yields in Pakistan with additional water. However, in a physically water-short environment as in Pakistan, it would be unrealistic to expect significant increases in additional canal-water supplies at the system level. Considering the constraint on total available water supplies, options to increase farm-level water supplies are to reduce distribution losses through improved maintenance of distribution infrastructure, and to reallocate canal water by accounting for groundwater quality. At the watercourse level, efforts should be directed towards improving maintenance of infrastructure and reducing losses, while at the distributary level efforts should be on improving maintenance and operational management for effective reallocation of water across watercourses.

   c). Considering the inter- and intra-system locational variations (and inequities) in canal-water supplies and quality of groundwater, the other option to increase farm-level water supplies for increased productivity and profitability of wheat, is to reallocate canal water within and across distributaries and to encourage the use of groundwater (to sustainable levels) in locations where it is of relatively good quality. However, since reallocation of canal water could influence productivity and profitability of wheat, it would be justified only if overall economic and social gains from such a reallocation are higher than from the present situation. In the next section, we analyze the socioeconomic impacts of canal-water reallocation and present scenarios and strategies for canal-water reallocation.

Impact of Canal-water Reallocation

Here we analyze the impacts of the conjunctive use of canal water and groundwater on wheat productivity and profitability in BCS-India and LJCS-Pakistan by using the yield functions estimated in equations 1 and 2. In this analysis, we assume that all other factors including total quantity of water applied and the price of wheat remain at current levels across various canal reaches; only the source of water or combination or proportions of water from the two sources changes. In order to generate various scenarios, we use the following equation:

$$\hat{GM}_L = (P_L * \hat{Y}_L) - COP_L \qquad (3)$$

where:

$\hat{GM}_L$ is the estimated gross margins (US$/ha)

Y_L is predicted wheat yield in t/ha

P_L is the price of wheat; COP_L is the cost of production (US$/ha)

L is for farm location (head=1, middle=2 and tail=3).

The predicted wheat yields were obtained using average values of independent variables in equations 1 and 2. The following scenarios were generated using information on predicted yields, current average values of various factors, current wheat prices and estimated changes in cost of production resulting from changes in water use from two sources.

Scenario 0 : Base level (at present levels of groundwater and canal-water use at all reaches)
Scenario 1 : 0% groundwater with 100% canal-water at all reaches
Scenario 2: 50 % groundwater and 50% canal-water at all reaches
Scenario 3:100% groundwater with 0% canal-water at all reaches
Scenario 4 (BCS-India): at 10% canal-water with 90% groundwater in head reaches
20% canal-water with 80% groundwater in middle reaches
30% canal-water with 70% ground water in tail reaches
Scenario 4 (LJCS-Pakistan):at 50% of canal-water use each in head, middle and tail reaches of Lalian (with 50% groundwater); 10% canal water (and 90% groundwater) use each at head, middle and tail reaches of Khadir.[21]

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[21] Under this scenario, total water use per hectare remains at current levels, canal-water is reallocated so that total canal-water use is equal to the currently available supplies. However, total groundwater use is changed, with increased use in areas of good quality groundwater and vice versa. Also, canal water is reallocated so that there is an equity in distribution of available supplies across head, middle and tail reaches.

The results are presented in tables 10 to 13. It is clear that the highest yields are obtained with exclusive canal-water use, and that yields are the lowest with exclusive groundwater use (scenario 1 and scenario 3, respectively). Overall, aggregate yields increase with decreasing use of poor-quality groundwater. With canal-water reallocations, yield increases are highest in tail ends than in other reaches.

Similarly, highest gross margins are achieved in scenario 1 in all reaches reflecting the combined positive effects of higher yields and lower cost of production (i.e., mainly because of lower cost of canal-water). Gross margins are lowest under scenario 3 in all reaches, again reflecting the combined effects of lower yields and significantly higher cost of production (i.e., due to high cost of pumping groundwater). Similarly, total production and value of production (computed for 216 ha for BCS-India and 377 ha for LJCS-Pakistan) are highest under scenario 1 and lowest under scenario 3.

Scenario 1 and 2 are attractive both for India as well as Pakistan, but not achievable due to limits on availability of canal-water supplies, whereas scenario 3 presents the worst option. The reallocation option and conjunctive use of surface and groundwater (scenario 4) results in overall gains in both BCS-India and LJCS-Pakistan. In BCS-India, average yields and production increase from the base level by 0.01 t/ha and 4 t, respectively. Gross margins and total value of production increase from the base level by US$2 per hectare and US$463. In LJCS-Pakistan, average yields and production increase from the base level by 0.04 t/ha and 15 t, respectively. Gross margins and total value of production increase from the base level by US$5 per hectare and US$2,110.

However, the impact of reallocation (under scenario 4) varies across distributaries and locations within distributaries. In Batta, gross margins decreased by US$3 per hectare at the distributary level, with decreases occurring at head and middle reaches. However, tail ends gained by US$7 per hectare. In Rohera, overall gains of US$6 per hectare were achieved at the distributary level with only a small change at

TABLE 10.

Impact of canal-water reallocation on average wheat yields (t/ha) and gross margins (US$/ha) of sample farms on each of the selected watercourses in LJCS-Pakistan.

Item/scenario	Lalian head	Lalian middle	Lalian tail	Khadir head	Khadir middle	Khadir tail	Lalian	Khadir	All
Wheat Yield									
Scenario 0	4.82	4.43	3.47	4.29	3.73	4.42	4.24	4.15	4.19
Scenario 1	5.03	4.56	4.02	4.60	4.05	4.70	4.53	4.45	4.49
Scenario 2	4.83	4.44	3.70	4.41	3.87	4.55	4.33	4.28	4.30
Scenario 3	4.64	4.32	3.39	4.22	3.68	4.41	4.12	4.10	4.11
Scenario 4	**4.83**	**4.44**	**3.70**	**4.25**	**3.73**	**4.44**	**4.33**	**4.14**	**4.23**
Gross margins (US$/ha)									
Scenario 0	325	294	243	230	215	239	290	229	260
Scenario 1	398	336	331	306	265	362	360	312	339
Scenario 2	332	282	280	260	236	298	304	265	287
Scenario 3	**265**	**227**	**230**	**213**	**207**	**234**	**247**	**218**	**234**

TABLE 11.
Impact of canal-water reallocation on total wheat production (t) and total value of production (US$) of all the sample farms on each of the selected watercourses in LJCS-Pakistan.

Item/scenario	Lalian head	Lalian middle	Lalian tail	Khadir head	Khadir middle	Khadir tail	Lalian	Khadir	All
Total production (t)									
Scenario 0	176	198	225	235	103	331	932	652	1,582
Scenario 1	184	204	260	252	112	352	998	700	1,695
Scenario 2	177	199	240	241	107	341	952	672	1,623
Scenario 3	170	194	220	231	102	330	906	645	1,550
Scenario 4	**177**	**199**	**240**	**233**	**103**	**332**	**952**	**652**	**1,597**
Total value (US$)									
Scenario 0	11,913	13,190	15,746	12,605	5,951	17,926	63,737	35,984	97,932
Scenario 1	14,588	15,053	21,440	16,760	7,323	27,104	79,240	49,119	12,8014
Scenario 2	12,149	12,622	18,162	14,220	6,527	22,326	66,762	41,676	108,223
Scenario 3	9,709	10,192	14,884	11,680	5,730	17,549	54,285	34,233	88,432
Scenario 4	**12,149**	**12,622**	**18,162**	**12,188**	**5,953**	**18,600**	**66,284**	**35,975**	**100,042**

TABLE 12.
Impact of canal-water reallocation on average wheat yields (t/ha) and gross margins (US$/ha) of sample farms on each of the selected watercourses in BCS-India.

Item/scenario	Batta head	Batta middle	Batta tail	Rohera head	Rohera middle	Rohera tail	Batta	Rohera	All
Wheat yield									
Scenario 0	4.63	4.53	4.40	4.83	4.81	4.38	4.52	4.67	4.60
Scenario 1	4.68	4.71	4.67	4.90	4.94	4.67	4.69	4.84	4.76
Scenario 2	4.64	4.59	4.50	4.86	4.87	4.53	4.58	4.75	4.66
Scenario 3	4.60	4.46	4.33	4.82	4.80	4.40	4.47	4.67	4.57
Scenario 4	**4.61**	**4.51**	**4.43**	**4.83**	**4.83**	**4.48**	**4.52**	**4.71**	**4.61**
Gross margins (US$/ha)									
Scenario 0	332	380	312	342	294	282	341	307	324
Scenario 1	366	435	378	381	303	358	393	366	375
Scenario 2	341	397	336	357	298	320	358	335	344
Scenario 3	317	358	294	332	293	283	323	303	313
Scenario 4	**321**	**374**	**319**	**337**	**295**	**305**	**338**	**313**	**326**

Table 13.

Impact of canal-water reallocation on total wheat production (t) and total value of production (US$) of all the sample farms on each of the selected watercourses in BCS-India.

Item/scenario	Batta head	Batta middle	Batta tail	Rohera head	Rohera middle	Rohera tail	Batta	Rohera	All
Scenario 0	176	198	225	235	103	331	932	652	1,582
Total production (t)									
Scenario 0	167	163	158	174	173	158	488	505	993
Scenario 1	169	170	168	176	178	168	506	522	1028
Scenario 2	167	165	162	175	175	163	494	513	1008
Scenario 3	166	161	156	173	173	158	482	505	987
Scenario 4	**166**	**162**	**159**	**174**	**174**	**161**	**488**	**509**	**997**
Total value (US$)									
Scenario 0	11,938	13,685	11,230	12,310	10,594	10,139	36,815	33,205	69,910
Scenario 1	13,163	15,669	13,618	13,726	10,895	12,884	42,415	39,534	81,052
Scenario 2	12,279	14,285	12,106	12,839	10,724	11,532	38,642	36,143	74,371
Scenario 3	11,394	12,901	10,594	11,952	10,552	10,179	34,869	32,752	67,690
Scenario 4	**11,571**	**13,455**	**11,501**	**12,129**	**10,621**	**10,991**	**36,516**	**33,792**	**70,373**

head (slight decrease) and middle reaches (slight increase), but significant gains were achieved at the tail ends (gross margins increasing by US$23 per hectare). In Lalian, overall gross margins increased by US$11 per hectare. All three reaches gained in yields and overall production, but middle reaches lost in gross margins (by US$12 per hectare). Tail-ends received much of the gains, where gross margins increased by US$37 per hectare. In Khadir, there were almost no changes in yields and gross margins at the distrubutory level. There were loses of US$7 per hectare at the head reach, no change at the middle but the tail gained US$9 per hectare.

As discussed earlier, Khadir in LJCS-Pakistan and Rohera in BCS-India are extremely canal-water-short environments, where groundwater accounts for over 90 percent of the total water use per hectare. While more canal-water use at the tails ends will increase overall benefits, no significant gains can be expected by reallocating current water supplies across the three reaches. On the other hand, the proportion of canal-water use per hectare in Batta in BCS-India and Lalian in LJCS-Pakistan is higher, relative to the other two distributaries. Canal-water reallocations in these distributaries will have a significant impact on gains from crop production across the three reaches. From this analysis, we conclude the following:

1. In all of the four systems, the share of groundwater per hectare is very high, and it varies across systems and locations within the system.
2. Where groundwater quality varies across reaches in the system, aggregate gains in yields and overall profitability of crop production can be increased by promoting conjunctive use of canal water and groundwater through canal-water reallocations.

3. However, in systems where canal water is in extreme short supply (as in Khadir and Rohera), no significant gains in aggregate yields and crop profitability can be expected through canal-water reallocations—even if there are significant inequities in canal-water distribution across reaches.

4. In systems, where canal water constitutes a significant proportion of total water use per hectare, as in Lalian, significant gains in aggregate yields and overall crop profitability can be achieved through canal-water reallocations to reaches where groundwater is of poorer quality, and particularly so in situations of significant head-tail inequities. Under such situations, canal-water reallocation would be helpful in achieving not only efficiency and equity of water distribution but also sustainability of resource use—the three pillars of sustainable development.

Summary, Conclusions and Policy Implications

This study was conducted to understand causes of differences in land and water productivity of wheat across farms and reaches of the selected irrigation systems in BCS-India and LJCS-Pakistan. Six watercourses on head, middle and tail reaches of two distributaries in each country were selected for detailed field-level data collection. Data on various wheat production activities, and input use including irrigation water use from both canal and groundwater sources, were collected for 216 farms in BCS-India and 218 farms in LJCS-Pakistan, on a daily basis throughout the rabi season (from October 2000 to May 2001). The study analyzed the impacts of both land-water and non-land-water factors on productivity of wheat in the selected irrigation systems in India and Pakistan. Key findings of the study are summarized below.

- Average wheat yields in the studied irrigation systems are higher in India (4.48 t/ha) than in Pakistan (4.11 t/ha). However, the magnitude of yield difference is not as high as is generally perceived.

- There are significant differences in yields across farms and locations in selected irrigation systems in both countries, with yields ranging from 2.96 t/ha to 5.73 t/ha for BCS-India, and 0.12 t/ha to 7.82 t/ha for LJCS-Pakistan. The overall yield gap across farms is much wider in LJCS-Pakistan than in BCS-India.

- Wheat yield differences are much higher across watercourses within a distributary than across distributaries.

- There is significant variation in total water (both surface and groundwater) applied to wheat. In BCS-India, per hectare water use varies from 746 m^3 to 4,322 m^3 averaging at 3,050 m^3 against crop water requirements of 3,300 m^3. In LJCS-Pakistan, per hectare water use varies from 570 m^3 to 9,134 m^3 averaging at 3,702 m^3 against crop water requirements of 3,009 m^3.

- There is a significant inequity in distribution of canal water in both BCS-India and LJCS-Pakistan, with tail reaches receiving less canal water than head and middle reaches. However, inequities in canal-water distribution are higher in LJCS-Pakistan than in BCS-India. Gini coefficients for canal-water distribution across watercourses are 0.29 and 0.42 for India and Pakistan, respectively. Groundwater use is, obviously, higher in reaches receiving less canal-water supplies and vice versa.

- Average productivity of consumed water is similar for both countries, i.e., 1.36 kg/m^3 and 1.37 kg/m^3, for BCS-India and LJCS-Pakistan, respectively. However, average productivity of diverted water is higher for BCS-India (1.47 kg/m^3) than for LJCS-Pakistan (1.11 kg/m^3).

- In both BCS-India and LJCS-Pakistan, average land productivity/yields are lower in locations and reaches where groundwater is of relatively poorer quality.

- Overall, quality of groundwater is relatively poorer in selected irrigation systems in India than in Pakistan.

- In both countries, more canal water is supplied to distributaries where groundwater is more saline (Batta and Lalian) as compared to those where groundwater is less saline (Rohera and Khadir), which is appropriate. However, groundwater quality varies significantly across reaches within a distributary. In general, groundwater quality deteriorates towards middle and tail reaches (except for Khadir in Pakistan where groundwater is less saline in the tail ends). These saline groundwater reaches presently receive less canal water, and productivity of wheat is low in these reaches. Thus, intra-distributary canal-water allocation is an important issue in relation to productivity of wheat.

- The locational unevenness in distribution of canal water, quality of groundwater and level of input use leads to significant variations in productivity of wheat, which have financial implications for wheat growers across locations.

The results of the estimated yield functions suggest that in addition to location specific factors such as soil salinity, land quality and rainfall, factors such as seed variety, application of recommended doses of weedicides, planting dates, irrigation application dates and groundwater quality are important contributory factors to yield differences. Promoting on-farm agronomic practices such as newer seed varieties, and dissemination of knowledge on planting dates and timings and application rates of inputs, especially water and fertilizers and proper dosage of weedicides are important for reducing yield gaps. Existing yield gaps can be closed by reducing the time delay in sowing from the recommended dates, replacing Inqulab with MH 97 and other newer varieties in LJCS-Pakistan and WH-542 and PBW-343 in BCS-India and applying the recommended quantities of fertilizers at the right time (at the time of sowing, with first or second irrigation), and proper application of recommended dosage of weeicides in BCS-India.

In addition, improvements in water management practices at the system level will also contribute to increased yields and overall profitability of wheat production. Improving on timings of canal-water deliveries and adopting an effective canal-water allocation strategy will result in overall socioeconomic gains in wheat production. Surface-water reallocations will be mainly effective in situations where it provides a considerable proportion of total water use per hectare. The results of the study suggest that poor groundwater quality leading to accumulation of salts is one of the key factors influencing wheat yields, and that groundwater quality varies significantly across reaches in command areas of the systems.

The study presents alternative scenarios on impacts of water use from two sources on the socioeconomics of wheat production. Wheat production is found to be highly profitable with exclusive canal-water use and least profitable with the exclusive use of poor-quality groundwater. Findings suggest that overall gains from wheat production will increase if canal water is reallocated so that more canal water is supplied to canal reaches where groundwater is of poorer quality. Accounting for the constraints on availability of total canal-water supplies and locational variations in quality of groundwater, the study concludes that: (1) where groundwater quality varies across reaches in the system, aggregate gains in yields and overall profitability of crop production can be increased by promoting conjunctive use of canal water and groundwater through canal-water reallocations; (2) however, in systems where canal water is in extreme short supply (as in Khadir and Rohera), no significant gains in aggregate yields and crop profitability can be expected through such reallocations—even if there are significant inequities in canal-water distribution across reaches; and (3) in systems, where canal water provides a considerable proportion of total water use per hectare, as in Lalian, significant gains in aggregate yields and overall crop profitability can be achieved through canal-water reallocations to reaches where groundwater is of poorer quality, and particularly so in situations of significant head-tail inequities. Under such situations, canal-water reallocation would be helpful in achieving not only efficiency and equity of canal-water distribution but also sustainability of resource use—the three pillars of sustainable development.

The policy implication of these findings is that, under conditions of canal-water scarcity and locational variations in quality of groundwater, conjunctive use and joint management of surface water and groundwater is essential to increase overall gains from crop production.

The strength of this study lies in bringing out the fact that conjunctive use and reallocation of canal water within a distributary or minor can contribute to closing yield gaps and increasing the overall profitability of crop production. However, the findings of the study could be strengthened by incorporating quantitative relationships between surface water and groundwater of differing qualities existing in various locations of the Indo-Gangetic plains. The study could be extended over a larger area using Remote Sensing and GIS combined with some additional field-level data.

Literature Cited

Ahmed, B.; and M. A. Chaudhry. 1996. *Productivity differential between Paksiatn and Indian Punjabs: An analysis.* Faisalabad, Pakistan: Agricultural and Social Sciences Research Center, Faculty of Agricultural Economics and Rural Sociology, University of Agriculture, Faisalabad, Pakistan.

Altaf, Z. 1994. *Rice-wheat systems in Pakistan: The sustainability questions*. Paper presented in Expert consultation on Sustainability of the Rice-Wheat Production Systems in Different Agro-Ecological Settings in Asia organized by RAPA in Bangkok. RAPA publication: 1994/11. pp197-203.

Aslam, M. 1998. *Improved water management practices for the rice-wheat cropping systems in Sindh province, pakistan*. Report No. R-70-1a. Lahore, Pakistan: International Irrigation Management Institute. 96p.

Bureau of Statistics. 1999. *Punjab development statistics.* Lahore, Pakistan: Bureau of Statistics, Government of the Punjab, Lahore, Pakistan.

Chaudhary, T. N.; B. K. Bhatnagar. 1980. Wheat root distribution, water extraction pattern and grain yield as influenced by time and rate of irrigation. *Agricultural Water Management* 3: 115-24.

Doorenbos, J.; A. Kassam; H. Benvelsen; C. I. M. Bransheid; V. Plusje; J. M. G. A. Smith; M. Uittenbogaard; G. O. Wal; and H. K. V. D. Wal. 1979. *Yield response to water*. FAO Irrigation and Drainage Paper. Rome, Italy: Food and Agriculture Organization of the United Nations. pp 164-170.

Gujarati, N.; and Damodar. 1995. *Basic econometrics, third edition*. N.P.: Mcgraw-Hill International Editions.

Minhas, P. S.; O. P. Sharma; and S. G. Patil. Eds. 1998. *25 years of Research on Management of Salt-affect Soils and Use of Saline Water in Agriculture.* Karnal, India: CSSRI. pp.150-170.

Misra, A.; and N. K. Tyagi. 1988. Improving canal water deliveries with auxiliary storage*. Journal of Irrigation and Drainage Engineering* 114: 535-45.

Molden, D.; R. Sakthivadevel; and Z. Habib. 2001. *Basin level use and productivity of water: Examples from South Asia*. Research Report 49. Colombo, Sri Lanka: International Water Management Institute.

Mudasser, M.; and I. Hussain; and M. Aslam. Unpublished. Constraints to wheat productivity in Pakistan: A review of literature. Colombo, Sri Lanka: International Water Management Institute.

Nagarajan, S. 1998. Perspective on wheat demand and research . In *Wheat Research Needs Beyond 2000,* ed., S. Nagarajan, G. Singh, and B. S. Tyagi. Karnal, India: Directorate of Wheat Research. pp 13-28.

Narayanamurthy. S. G.; and C. J. Perry. 1997. *Farmer response to rationed and uncertain irrigation supplies*. Research Report 24. Colombo, Sri Lanka: International Water Management Institute.

Pintus, F. 1997. *Impact of irrigation, salinity and cultural practices on wheat yields in southeastern Punjab, Pakistan*. Report No. R-30. Lahore, Pakistan: International Irrigation Management Insstitute. 70 p.

Rehman, M. S. U. 1986. Contribution of main factors of production on the yield of wheat. MSc. thesis. Department of Agricultural Economics, University of Agriculture, Faisalabad, Pakistan. 42 p.

Siddiq, A. 1994. Sustainability of Indus basin: Impact of tertiary salinity/sodicity on wheat productivity, damage assessment and future public policy. Ph.D thesis. Graduate College, University of Illinois at Urbana-Champaign, U.S.A.

Timsina, J.; D. J. Connor. 2001. Productivity and management of rice-wheat cropping systems: Issues and challenges. *Field crops research* 69(2001) 93-132.

Tyagi N. K; and D. K. Sharma. Unpublished. Improving wheat productivity in Indo-Gangetic Plains: Constraints and technological options: Colombo, Sri Lanka: A review of literature. International Water Management Institute.

Appendix

TABLE A1.

Coefficient of variation of wheat yields in BCS-India and LJCS-Pakistan.

Outlet/distributory/ minor	Coefficient of variation
BCS-India	
Batta head	0.11
Batta middle	0.07
Batta tail	0.13
Rohera head	0.09
Rohera middle	0.08
Rohera tail	0.10
Batta all	0.12
Rohera all	0.12
All	0.12
LJCS-Pakistan	
Lalian head	0.20
Lalian middle	0.44
Lalian tail	0.47
Khadir head	0.25
Khadir middle	0.29
Khadir tail	0.20
Lalian all	0.37
Khadir all	0.27
All	0.33

TABLE A2.

Mean and standard deviation of factors.

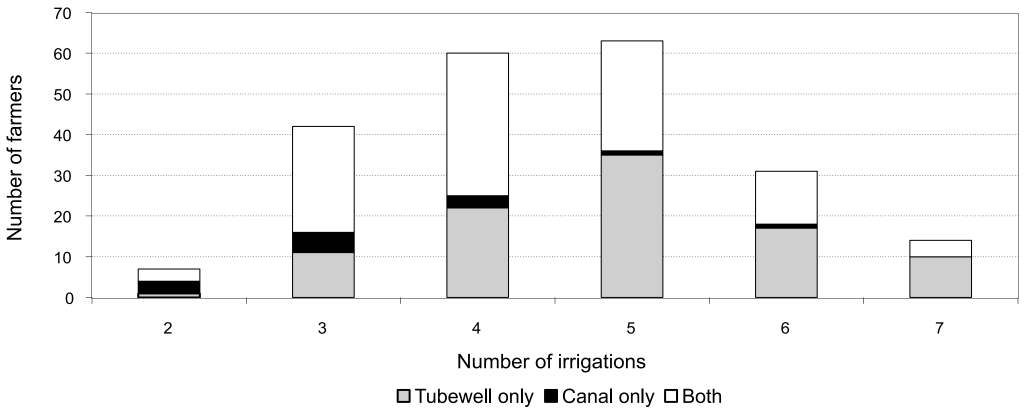
Factor	V	S	F	W	WD	NW	T	ECTW
BCS-India								
Mean	0.232	13.423	313.174	3,083.48	2.286	4.459	25.211	2.723
Standard Deviation	0.423	6.864	63.274	522.76	0.349	0.530	7.947	2.086
LJCS-Pakistan								
Mean	0.061	6.822	140.480	3,724.84	-	4.579	7.154	0.807
Standard Deviation	0.239	2.113	64.401	1,624.46	-	1.315	3.331	0.533

V = seed variety (MH 97 for Pakistan, and WH-542 and PBW-343 for India); S = sowing week (for Pakistan week 1 is Oct 16-22, for India week 1 is Nov 1-7); F = fertilizers (NPK); W = amount of water applied; NW = number of waterings; WD = weedicides (gm); T = time gap (for Pakistan, time gap between pre-sowing and first post-sowing; for India, time gap between second and third irrigation/watering); and ECTW = percentage of groundwater in total water use multiplied by the EC of groundwater.

TABLE A3.
Gini coefficients and head-tail equity ratios for canal-water use in sample farms in BCS-India and LJCS-Pakistan.

Outlet/distributory/ minor	Gini coefficient	Head-tail equity ratio
BCS-India		
Batta head	0.55	2.07
Batta middle	0.10	1.34
Batta tail	0.29	1.11
Rohera head	0.63	3.41
Rohera middle	0.78	11.46
Rohera tail	0.80	
Batta all	0.36	1.21
Rohera all	0.75	4.64
Across all watercourses	0.29	1.72
LJCS-Pakistan		
Lalian head	0.29	1.47
Lalian middle	0.20	0.67
Lalian tail	0.60	3.61
Khadir head	0.71	1.00
Khadir middle	0.62	1.17
Khadir tail	0.89	14.23
Lalian all	0.44	4.35
Khadir all	0.74	3.24
Across all watercourses	0.42	3.90

FIGURE A1.
Number of farmers and wheat irrigations by type, in LJCS-Pakistan.



Note: Based on field-level data 2000-2001.

FIGURE A2.
Average wheat yield and number of irrigations in LJCS-Pakistan.

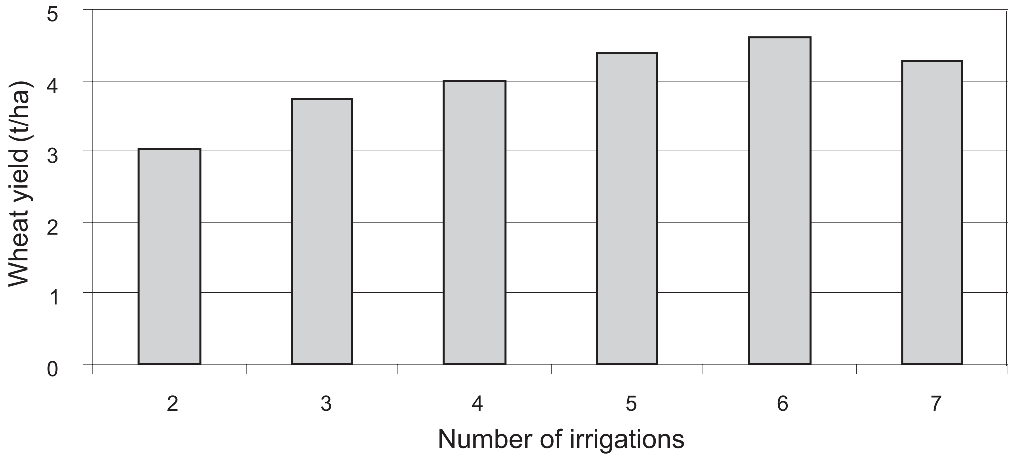


FIGURE A3.
Average wheat yield and number of irrigations in BCS-India.

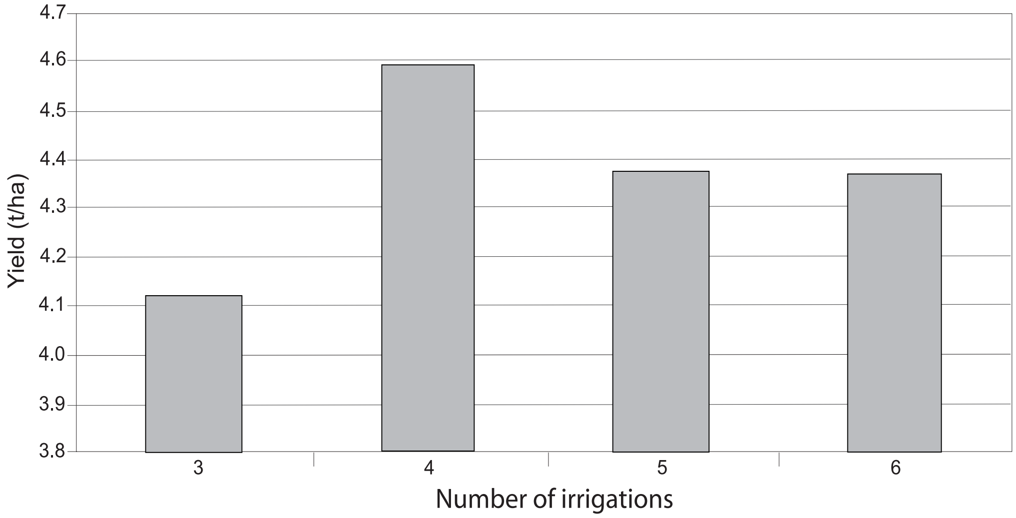
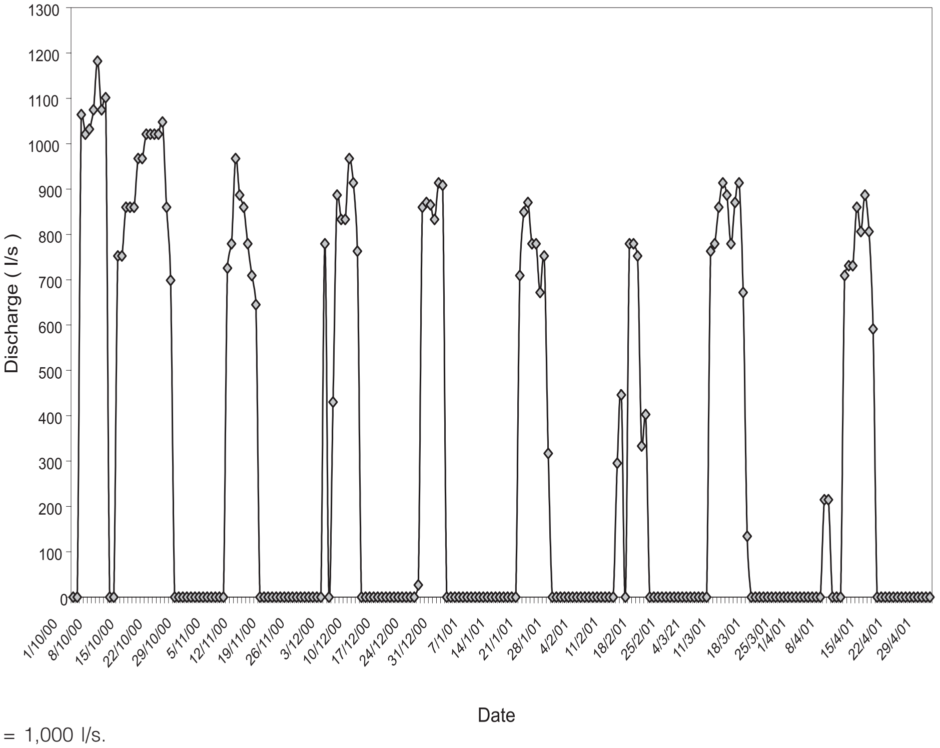
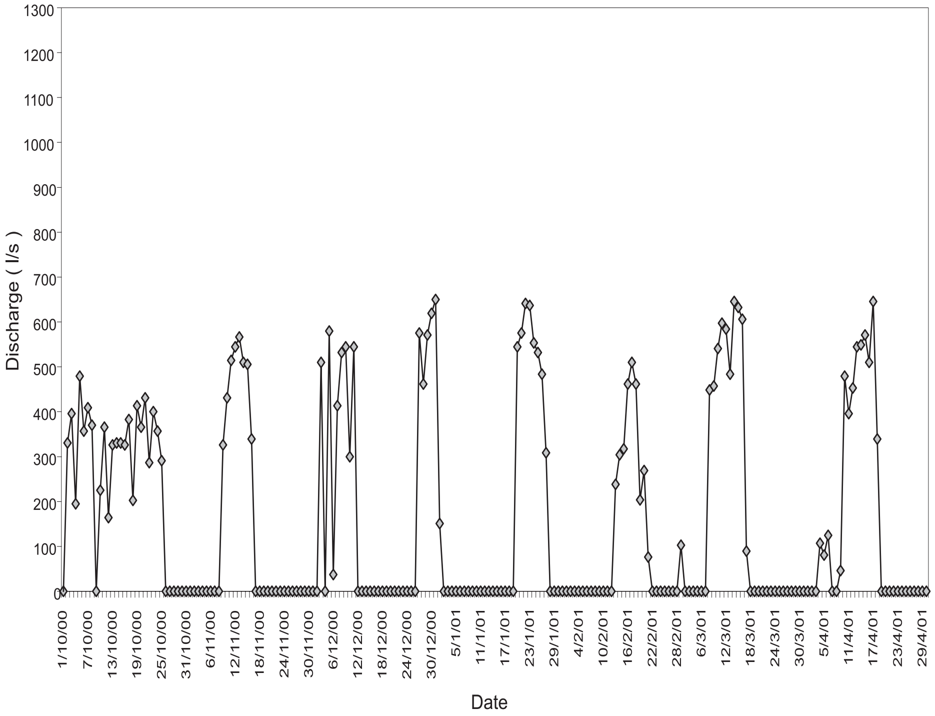


FIGURE A4.
Daily flow measurements at Batta head outlet, BCS-India.



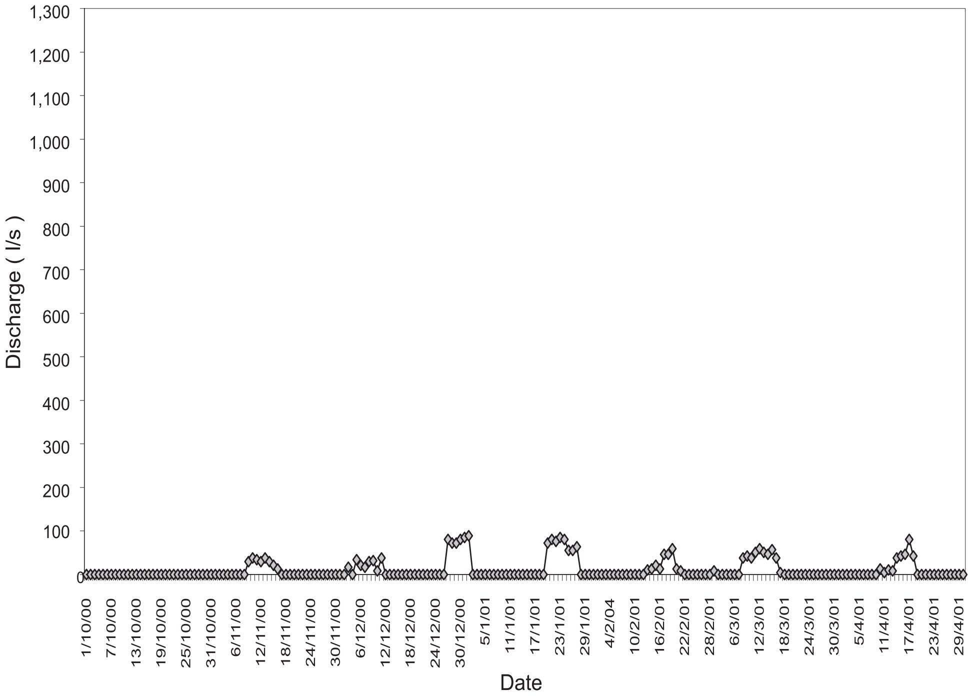
Note: 1 m^3/s = 1,000 l/s.

FIGURE A5.
Daily flow measurement at Batta middle outlet, BCS-India.



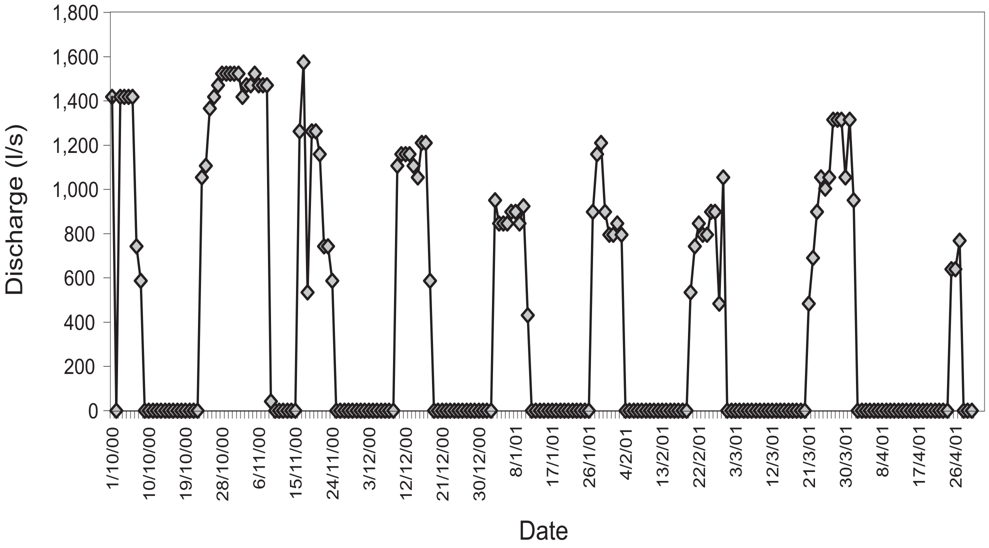
Note: 1 m^3/s = 1,000 l/s.

FIGURE A6.
Daily flow measurement at Batta tail outlet, BCS-India.



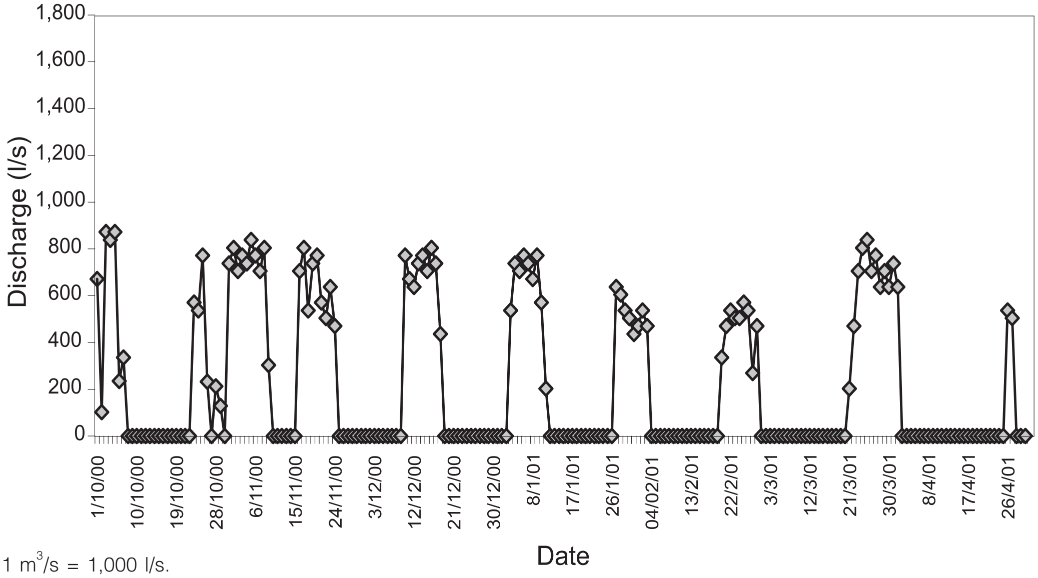
Note: 1 m^3/s = 1,000 l/s.

FIGURES A7.
Daily flow measurement at Rohera head outlet, BCS-India.



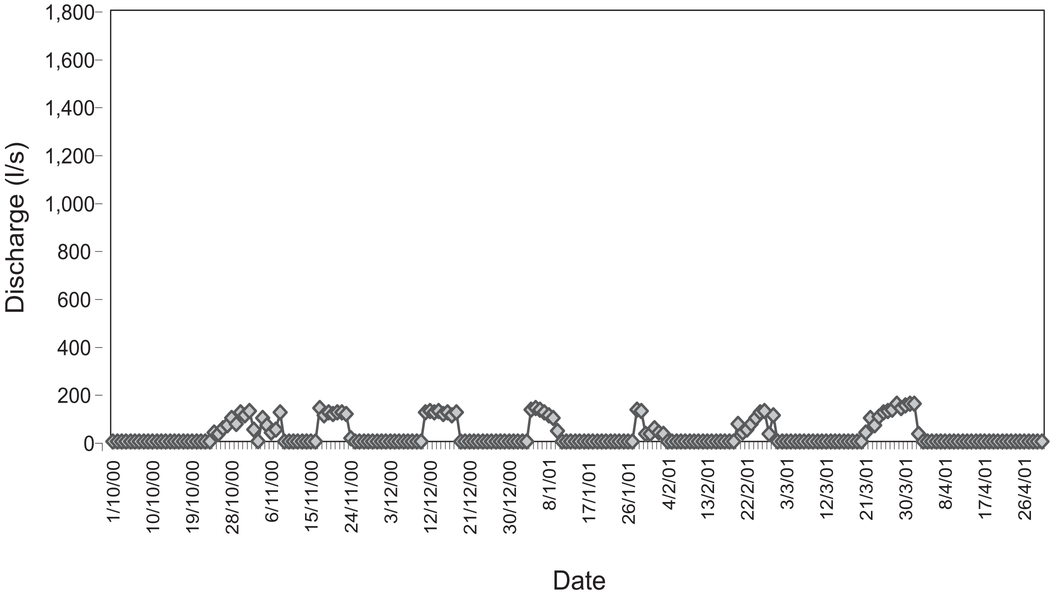
Note: 1 m^3/s = 1,000 l/s.

FIGURE A8.
Daily flow measurement at Rohera middle outlet, BCS-India.



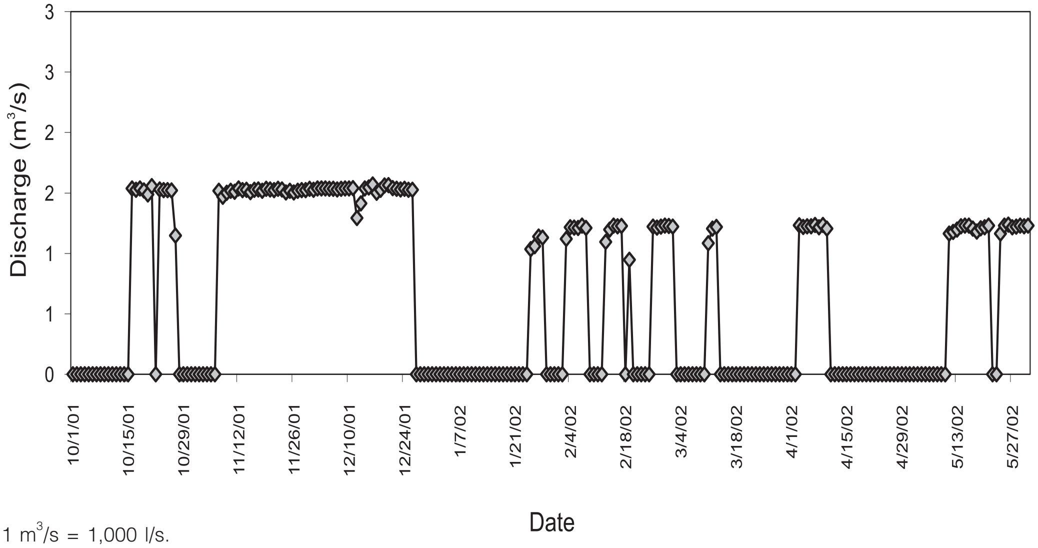
Note: 1 m^3/s = 1,000 l/s.

FIGURE A9.
Daily flow measurement at Rohera tail outlet, BCS-India.



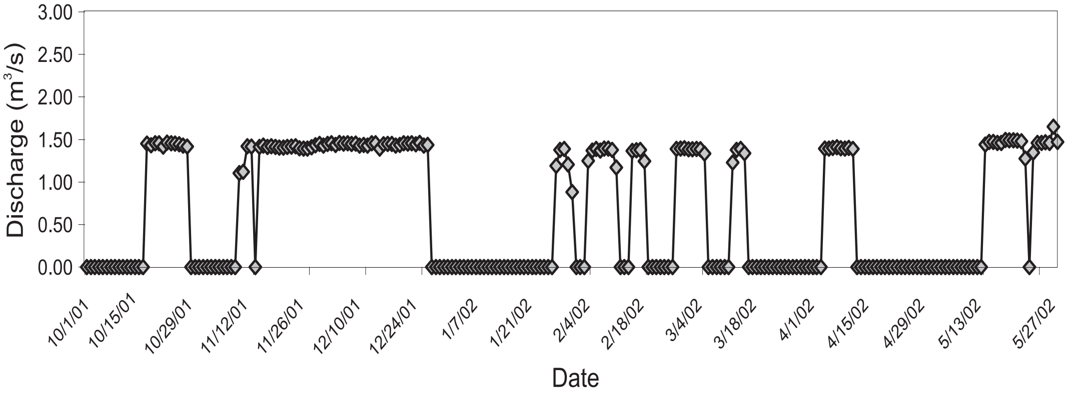
Note: 1 m^3/s = 1,000 l/s.

FIGURE A10.
Daily flow measurement at Lalian head outlet, LJCS-Pakistan.



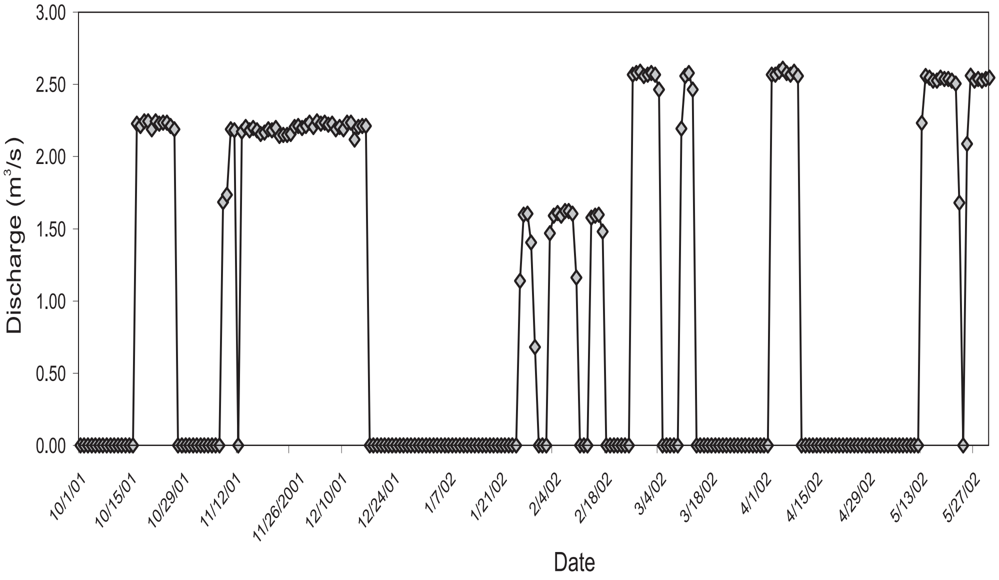
Note: 1 m^3/s = 1,000 l/s.

FIGURE A11.
Daily flow measurement at Lalian middle outlet, LJCS-Pakistan.



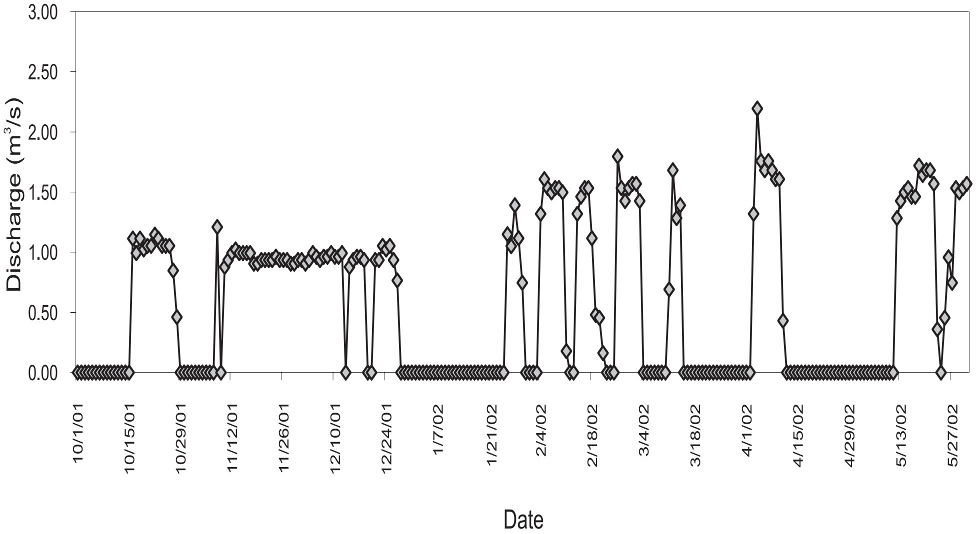
Note: 1 m^3/s = 1,000 l/s.

FIGURE A12.
Daily flow measurement at Lalian middle (FAO) outlet, LJCS-Pakistan.



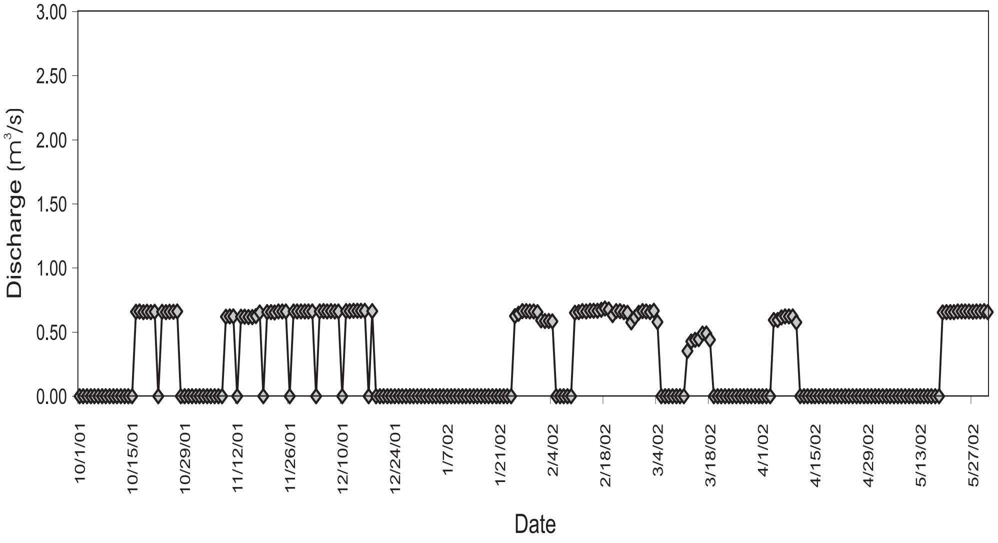
Note: 1 m^3/s = 1,000 l/s.

FIGURE A13.
Daily flow measurement at Lalian tail outlet, LJCS-Pakistan.



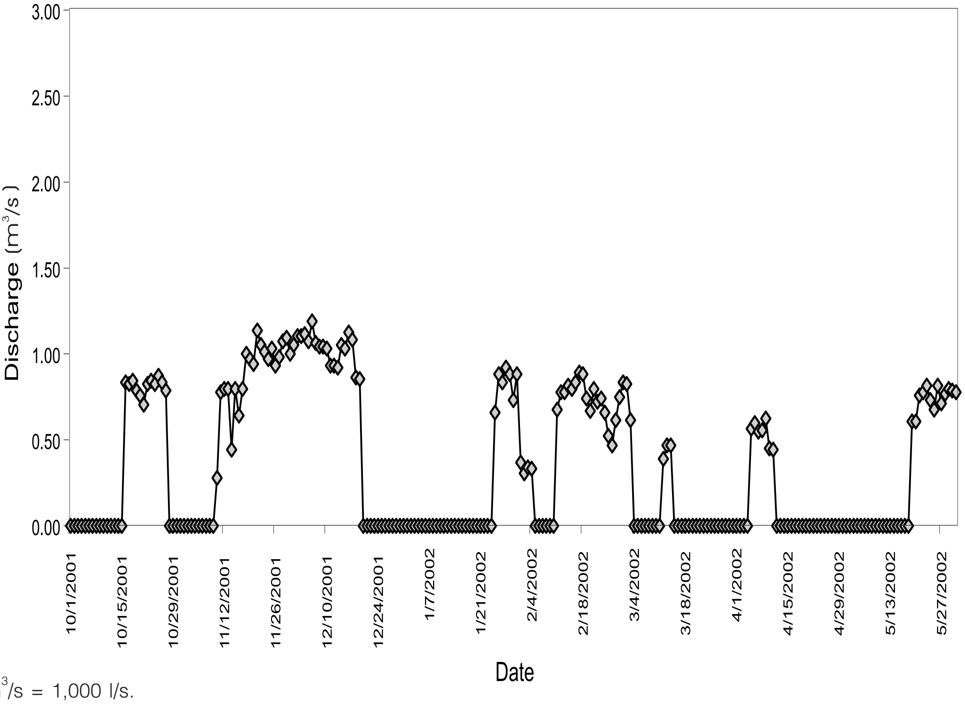
Note: 1 m^3/s = 1,000 l/s.

FIGURE A14.
Daily flow measurement at Khadir head outlet, LJCS-Pakistan.



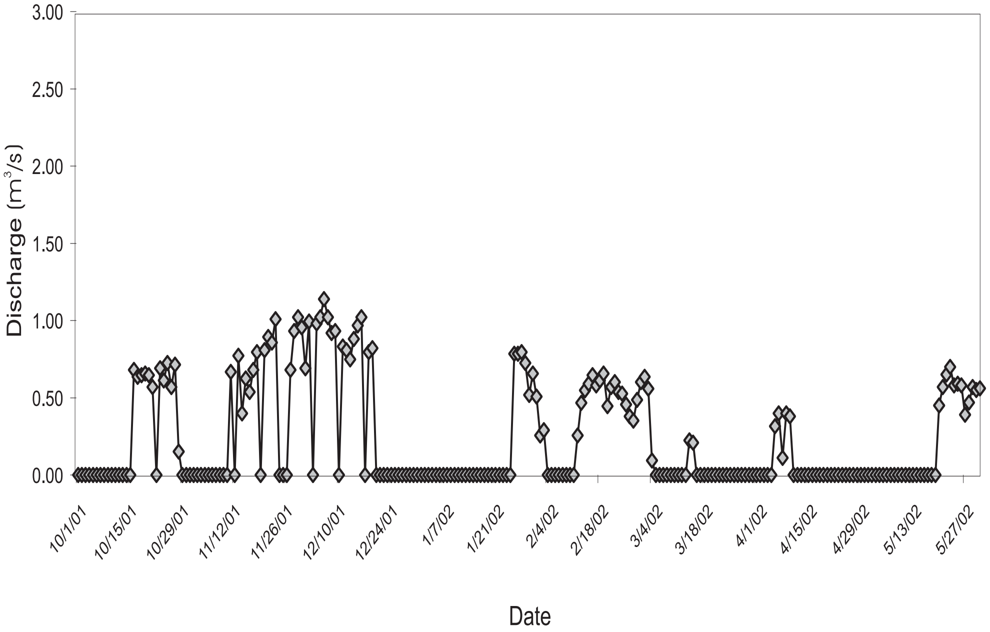
Note: 1 m^3/s = 1,000 l/s.

FIGURE A15.
Daily flow measurement at Khadir middle outlet, LJCS-Pakistan.



Note: 1 m^3/s = 1,000 l/s.

FIGURE A16.
Daily flow measurement at Khadir tail outlet, LJCS-Pakistan.



Note: 1 m^3/s = 1,000 l/s.

Research Reports

53. *Estimating Productivity of Water at Different Spatial Scales Using Simulation Modeling.* Peter Droogers, and Geoff Kite, 2001.

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58. *Fundamentals of Smallholder Irrigation: The Structured System Concept.* B. Albinson and C. J. Perry. 2002.

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64. *The Use of Untreated Wastewater in Peri-Urban Agriculture in Pakistan: Risks and Opportunities.* Jeroen H. J. Ensink, Wim van der Hoek, Yutaka Matsuno, Sarfraz Munir and M. Rizwan Aslam. 2002.

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