16 Land and Water Productivity of Wheat in the Western Indo-Gangetic Plains of India and Pakistan: a Comparative Analysis

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Abstract

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). The average wheat yields generally reported in Bhakra (about 4 t ha^{-1}) are almost double the yield reported for Punjab (about 2 t ha^{-1}). These discussions have raised an important research question on why wheat yields vary so much under fairly similar agroclimatic, socio-economic and management conditions.

The purpose of this study is to analyse variations in wheat yields and to assess the range of factors affecting wheat yields and the profitability of wheat production in selected irrigation systems in India and Pakistan. The study attempts to identify constraints and opportunities for closing the existing yield gap. 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 (BCS) in the Kaithal irrigation circle in India and the Lower Jehlum canal system (LJCS) in the Chaj sub-basin in Pakistan. Six watercourses, one each on the head, middle and tail reaches of one distributary in each country, were selected for detailed field-level data collection.

Results show that the average wheat yield in the selected irrigation system in India is somewhat higher (4.48 t ha^{-1}) than that in the selected system in Pakistan (4.11 t ha^{-1}), but not by as much as is generally perceived. However, the overall yield gap across farms is much wider in the study area in LJCS-Pakistan than that in BCS-India. Wheat-yield differences are much higher across watercourses (i.e. at the distributary level) 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. Groundwater use, as expected, is higher in reaches receiving less canal water and vice versa. The average productivity of consumed water is similar for the selected systems in both countries, i.e. 1.36 kg m^{-3} in India and 1.37 kg m^{-3} in Pakistan. 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 the study areas of both countries, average land productivity is lower in locations where groundwater is of relatively poorer quality. The groundwater quality within a distributary deteriorates towards the middle and tail reaches (except for Khadir in LJCS-Pakistan, where groundwater is less saline in the tail ends), and these reaches currently receive less canal water. Thus, intradistributary canal-water allocation is an important issue in reducing the yield gap.

Using farm-level data, yield functions were estimated to analyse the effects of a range of production factors. Results show that, in addition to improved farm-management practices, such as adopting new varieties, avoiding sowing delays and improved input applications, the improvements in water-management practices at the system level will also contribute to increased wheat yields and overall profitability. Improving timings of canal-water deliveries and adopting an effective canal-water reallocating strategy will result in overall socio-economic gains.

In both BCS-India and LJCS-Pakistan, the profitability of wheat production decreases with the overall quality of the water used. The study presents alternative scenarios for the impacts of changes in the allocation of canal and groundwater on the socio-economics of wheat production. It is concluded that overall gains from wheat production can be increased by adopting effective reallocation of canal water at the distributary level. Many of the gains under the scenario will be in locations where groundwater is of poorer quality. The policy implication of this is that, under conditions of canal-water scarcity and variations in the quality of groundwater, joint management of canal water and groundwater is essential to increase overall gains from crop production. The study presents an example of 'institutional water scarcity' that could be addressed through effective institutions, leading to improved management of available surface-water and groundwater resources.

Introduction

Wheat production in both India and Pakistan has increased significantly over the past three decades, due to expansion in area sown to wheat, as well as yield improvements. Average wheat yields have increased at 3.21% annually in India (0.84 t ha^{-1} in 1961–1963 to 2.55 t ha^{-1} in 1996–1998) and 2.72% annually in Pakistan (0.82 t ha^{-1} in 1961–1963 to 2.10 t ha^{-1} in 1996–1998). The wheat area has increased by 1.9% annually in India and 1.53% annually in Pakistan over the same period. However, in the 1990s, the average yield growth in both countries has been slower than in the past (1.7% in India and 1.6% in Pakistan) with only slight year-to-year fluctuations. Deceleration in yield growth rate has caused concerns among policy makers and planners in both countries. Also, 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 in Bhakra (around 4 t ha^{-1}) almost double those in Punjab (around 2 t ha^{-1}). These discussions have raised an important research question on why wheat yields vary widely under fairly similar agroclimatic, socio-economic and management conditions.

The primary objective 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. The specific objectives are to:

- Analyse intercountry and intracountry variations in wheat yields in the selected irrigated agricultural systems in India and Pakistan.
- Analyse factors contributing to such variations.
- Identify constraints and opportunities and possible methods to reduce 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 a plethora of literature on analysing determinants of wheat yields in India and Pakistan. Tyagi and Sharma (2001) and Mudasser *et al.* (2001) give comprehensive reviews of the literature on determinants of wheat productivity in the India and Pakistan. Ahmed and Chaudhry (1996) discuss productivity differentials of the Indian and Pakistani Punjabs. Some of the specific studies at farm level in India include the degree of deficit irrigation and perceived reliability of canal-water supply (Narayanamoorthy and Perry, 1997), effects of irregularity and inadequacy of water supplies on wheat yields (Mishra and Tyagi, 1988), effects of delay in sowing on wheat productivity (Chaudhary and Bhatnagar, 1980; Rehman, 1986; Altaf, 1994; Nagarajan, 1998), decisions on the number of irrigations to be applied on the field and its relationship to groundwater availability (Pintus, 1997), number of irrigations and wheat yields (Aslam, 1998), effects of soil type and quality on wheat yields (Doorenbos *et al.*, 1979; Siddiq, 1994) and the effects of mixing of fresh water and saline/sodic waters on wheat yields (Minhas *et al.*, 1998).

Most past studies analysing determinants of wheat productivity have focused on soil, agronomic factors and water individually, with only a few attempting to analyse water-related factors at the system and farm levels in a more rigorous manner. This study takes a holistic approach by rigorously analysing a fairly comprehensive set of factors, including soil, agronomic and water-related factors (quantity, quality and timing of applications) and their influence on wheat yields in the selected irrigation systems in India and Pakistan. The analysis of factors is undertaken at both farm and irrigation system/subsystem levels. The study adds to the previous literature by developing a set of scenarios for improved water management and its socio-economic implications for farmers.

Study Locations

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

India

The Bhakra system was planned to serve the arid tracts of Punjab, Haryana and parts of Rajasthan. In Haryana, the Bhakra canal service is divided into five irrigation circles. One of them is the Kaithal circle, in which the study site is located. For the present study, two minors of the Kaithal irrigation circle, Batta minor (Sirsa branch) and Rohera minor (Habri branch), were selected.

The climate of the study area is semi-arid. The normal annual rainfall varies from 500 to 600 mm year^{-1}. The rainy season starts from 15 June and continues up to September and contributes about 70–80% of the total annual rainfall. The winter season starts from November and extends up to February. During this season, the temperature varies from 5°C to 20°C. Soils of the study area are light- to medium-textured, varying from sandy loam to clay loam, and are low in organic matter. The phosphorus content is medium but the potassium contents vary 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.

Pakistan

In Pakistan, the study was conducted in the Chaj Doab sub-basin of the Upper Indus basin. Chaj Doab is irrigated by both the Lower Jhelum canal and the Upper Jhelum canal. Two distributaries, namely, Lalian and Khadir, located in Laluwali and Khadir irrigation subdivisions, respectively, were selected for this study.

The climate of the study area is hot summers and cold winters. Summers start in late March, and May–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). Winters start from late October/early November and extend up to February. During this season the temperature varies from 6°C to 21°C. The winter season also receives part of the annual rainfall, in December (27 mm) and January (33 mm). The soils of Chaj Doab are mostly calcareous loamy soils.

Study Design, Methodology and Data

Two distributaries were selected in the BCS in India and in the LJCS in Pakistani Punjab, representing a relatively inadequate canal-water environment, practising conjunctive use of canal water and groundwater of differing quality and having large variations in farm-level wheat yields. For comparison purposes, a consistent study design and methodology were adopted for both locations.

Three watercourses, one each at the head, middle and tail ends, were selected from each selected distributary. The selection of watercourses along the distributary was based on the total length, command area and number of watercourses of the distributary. In Pakistan, one more watercourse was selected from the middle part of the Lalian distributary, where the Food and Agriculture Organization (FAO) is implementing demonstrative interventions on the effects of laser levelling and raised-bed–furrow cultivation practices on crop yields.

After considering the requirement for reliable statistical and econometric analyses and research manageability and logistics, a sample of 36 farms along each watercourse was selected. This includes 12 farms each on head, middle and tail ends of each watercourse. The total sample size was 216 farms in BCS-India and 218 in LJCS-Pakistan. A selected farm may have several field parcels. Yields between parcels may vary, due to possible differences in dates of planting and input. Considering these intrafarm yield differences, only one parcel 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 2000/01, i.e. from October 2000 through to 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 2000/01).
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-water and groundwater sources).

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

Characteristics of selected watercourses

Table 16.1 provides key characteristics of the selected watercourses in both locations.

From the point of view of comparability in size, both Lalian and Khadir in LJCS-Pakistan have a large gross command area (GCA) (20,000–26,000 ha) compared with Batta and Rohera in BCS-India (roughly 4000 ha). On the other hand, the GCAs of the selected watercourses in BCS-India and LJCS-Pakistan are of comparable sizes. The GCA of the selected watercourses varies from around 81 ha to 457 ha, with relatively higher GCAs of tail-end watercourses.

The water allowance per hectare at the watercourse level in the Indian system is more or less uniform (0.0017 $m^3\ s^{-1}$). On the other hand, water allowance per hectare in the LJCS-Pakistan system varies over a range from 0.0001 $m^3\ s^{-1}$ to 0.0002 $m^3\ s^{-1}$. Also, there is a distinct difference in water allowance between the two distributaries in LJCS-Pakistan. For Lalian, it is nearly twice that of Khadir.

Wheat-yield variations in the study area

Average wheat yields are higher in the study area in BCS-India (4.48 t ha^{-1}) than in the study area in LJCS-Pakistan (4.11 t ha^{-1}) (Fig. 16.1). However, these yield differences are not as high as is generally perceived (as discussed earlier). Yet the variations of wheat yield in the distributaries in Pakistan are higher (coefficient of variation (CV) = 33%) than the variations of wheat yields in India (CV = 12%).

In BCS-India, the CV of yields is the same across the two distributaries and the intra-watercourse CV is generally less than that at the distributary level. In LJCS-Pakistan, the CV of the yields differs between the two distributaries (37% for Lalian and 27% for

Table 16.1. General characteristics of selected watercourses.

Outlet/distributary	Gross command area (ha)	Design capacity ($m^3\ s^{-1}$)	Average discharge[a] ($m^3\ s^{-1}$)	Water allowance per ha ($m^3\ s^{-1}$)	Ground-water EC ($dS\ m^{-1}$)
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
Batta – all	3,669		–	–	3.81
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
Rohera – all	4,131		–	–	2.95
Batta and Rohera	–		–	–	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
Lalian – all	19,785	–	–	–	1.31
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
Khadir – all	25,859	–	–	–	0.95
All	–	–	–	–	1.13

[a]Measured in the field.

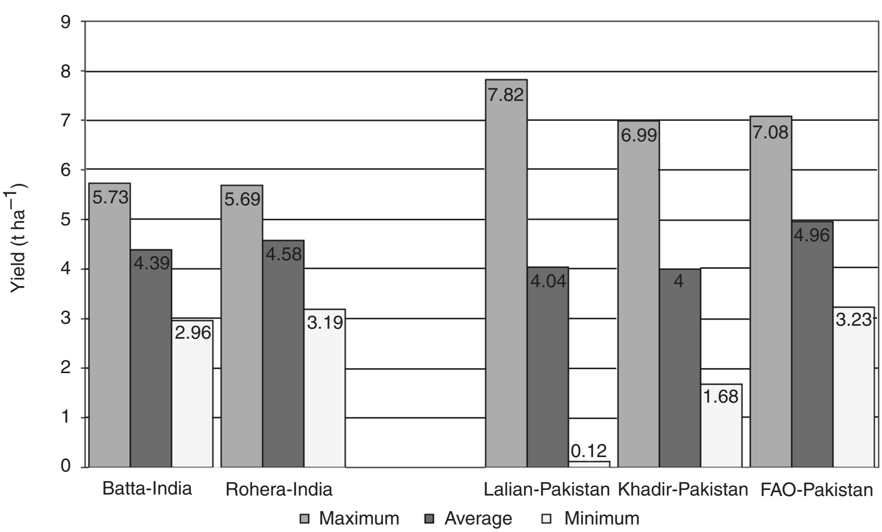

Fig. 16.1. Wheat-yield variations in the study areas of the Bhakra canal system in India and the Lower Jehlum canal system in Pakistan.

Khadir) and it varies significantly within and across watercourses. 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.

There are also 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 watercourses and decrease towards tail-reach watercourses in both locations, except for the Khadir distributary in LJCS-Pakistan. In the Khadir distributary, the yields in tail ends are higher than those in the head and middle reaches, basically reflecting the availability and use of good-quality groundwater (Table 16.2).

Factors Affecting Wheat Productivity

The above results indicate that there are significant yield differences within and across watercourses. What are the key factors that influence the crop-productivity differences between different locations?

The productivity of wheat depends on a range of factors, including land- and water-related factors (location of farms, quality of land, source of water, quality and quantity of water, timing of water application, etc.), climatic factors (rainfall, temperature, sunshine, wind, frost), agronomic factors (quality, quantity and timing of applications of inputs such as fertilizers, weedicides, labour, etc.), socio-economic factors (educational level, experience in farming, farm size, tenancy terms, land fragmentation, availability of credit, etc.) and farm-management factors (adoption of production technology, farm planning and management practices), etc. Some of these factors may be interrelated. The effects of some of these may be much smaller than those of others. We focus here on major factors influencing wheat productivity.

Soil quality

Soils of the study areas in both countries are loamy soils. In BCS-India, average soil electrical conductivity (EC) across six watercourses

Table 16.2. Average wheat yield (t ha^{-1}) of different watercourses in India and Pakistan, 2000/01 (based on crop-cutting experiment, 2000/01).

Location of watercourse	Location of watercourse			Location of watercourse		
	Head	Middle	Tail	Head	Middle	Tail
BCS-India		Batta			Rohera	
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
(CV)	(0.11)	(0.07)	(0.13)	(0.09)	(0.08)	(0.10)
Dist. average	4.39			4.58		
(CV)	(0.12)			(0.12)		
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
(CV)	(0.20)	(0.44)	(0.47)	(0.25)	(0.29)	(0.20)
Dist. average	4.04			4.00		
(CV)	(0.37)			(0.27)		

CV, coefficient of variation; Dist., distributary.

varies from 1.85 to 5.63 dS m^{-1}. The average soil quality of the watercourse command areas in Batta (average EC of 3.83 dS m^{-1}) is lower than that in Rohera (average EC of 2.86 dS m^{-1}). There are significant locational variations within the distributaries in both BCS-India and LJCS-Pakistan, with soil quality generally deteriorating towards tail-end locations. The average EC and pH for the tail ends of Batta and Lalian (two areas of relatively poorer-quality soils) are 5.63 dS m^{-1} and 8.25 and 3.15 dS m^{-1} and 8.34, respectively.

Water use

Both canal (surface) water and groundwater are used in most parts of the study areas of both countries. In general, groundwater use is high where canal water is in short supply. Overall, the proportion of groundwater use per hectare is higher in BCS-India than in LJCS-Pakistan (Table 16.3). Groundwater use is much higher in the Rohera distributary in BCS-India and the Khadir distributary in LJCS-Pakistan, contributing on average around 90% of total water use at the farm level, compared with Batta in BCS-India (73%) and Lalian in LJCS-Pakistan (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 the tail-end reaches than in the head and middle reaches, where canal-water supply is relatively higher.

The location of farms/watercourses is directly related with the use of both surface water and groundwater. The head and middle reaches receive more canal water than the tail ends in both BCS-India and LJCS-Pakistan. This is indicated by measurements of the canal-water flow at the outlet level for each of the selected watercourses and the amount of canal water applied at the field level. The average canal water applied for wheat in BCS-India is 550 m^3 ha^{-1} compared with 980 m^3 ha^{-1} in LJCS-Pakistan. Canal-water use is higher in Batta (BCS-India) and Lalian (LJCS-Pakistan), averaging 816 m^3 ha^{-1} and 1458 m^3 ha^{-1}, respectively, compared with Rohera (285 m^3 ha^{-1}) and Khadir (465 m^3 ha^{-1}). 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.

Inequity in canal-water distribution

Overall inequity in canal-water distribution is higher in the study area in LJCS-Pakistan than in the study area in BCS-India. The estimated Gini coefficients[1] for BCS-India and LJC-Pakistan are 0.29 and 0.42, respectively. Gini coefficients are higher for distributaries where canal-water supply per hectare is relatively less (Rohera – BCS-India; Khadir – LJCS-Pakistan). Except for the head end of the Batta 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.[2]

Water quality

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

[1] 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. The greater the value of Gini, the greater the degree of inequity in distribution.
[2] The head–tail equity ratio is another measure of inequity. The results indicate that the head–tail equity ratios for average per hectare canal-water use in selected distributaries are 1.72:1 and 3.90:1 in BCS-India and LJCS-Pakistan, respectively. These results further suggest that head–tail inequities in LJCS-Pakistan are much greater than in BCS-India.

Table 16.3. Water and other input use for wheat production in BCS-India and LJCS-Pakistan.

Outlet/dist./ minor	No. of canal irrigations	Total no. of irrigations	Amount of tube-well water applied (m^3)	Amount of canal water applied (m^3)	Amount of total water applied (m^3)	Tube-well water as % of total water applied	Seed (kg ha^{-1})	NPK (kg ha^{-1})	No. of ploughings
BCS-India									
Batta – head	1.1	4.3	1829	849	2678	68	100	248	3.6
Batta – middle	1.0	4.1	2219	897	3116	71	108	229	3.7
Batta – tail	1.1	4.5	2545	700	3245	78	99	193	3.9
Rohera – head	0.7	4.3	2194	584	2778	79	109	199	4.0
Rohera – middle	0.4	4.4	3011	148	3159	95	106	202	3.6
Rohera – tail	0.2	5.0	3225	109	3334	96	124	244	4.4
Batta – all	1.1	4.3	2197	816	3013	73	102	223	3.7
Rohera – all	0.4	4.6	2806	282	3088	91	113	215	4.0
All	0.8	4.4	2500	550	3050	82	108	219	3.9
LJCS-Pakistan									
Lalian – head	2.1	4.4	1845	1500	3345	55	116	169.4	3.5
Lalian – middle	2.5	3.8	1304	2745	4049	32	126	195.6	3.8
Lalian – tail	1.5	4.6	2146	345	2491	86	124	88.8	2.9
Khadir – head	1.5	4.4	2704	606	3311	82	130	154.7	5.7
Khadir – middle	1.3	4.7	3591	600	4191	86	131	139.2	3.2
Khadir – tail	1.3	5.4	5088	187	5275	96	127	153.2	4.6
Lalian – all	2.0	4.2	1758	1458	3185	55	123	144.5	3.5
Khadir – all	1.9	4.8	3794	465	4259	89	130	148.9	4.5
All	1.9	4.5	2748	980	3702	74	126	146.7	3.9

and 0.27 dS m^{-1} for Lalian, Batta, Rohera and Khadir, respectively. However, the quality of the groundwater is generally low in the study areas of both countries. The average EC level of groundwater for BCS-India (3.39 dS m^{-1}) is much higher than that for LJCS-Pakistan (1.13 dS m^{-1}). Therefore, overall groundwater salinity levels are relatively higher in the study area in BCS-India than that in LJCS-Pakistan.

The groundwater quality varies significantly across distributaries. Groundwater is more saline in Batta in BCS-India and Lalian in LJCS-Pakistan (the two distributaries currently receiving relatively more canal water) than that in Rohera in India and Khadir in Pakistan. Groundwater quality varies significantly across head, middle and tail reaches of the distributaries. In general, the groundwater quality deteriorates towards the middle and tail reaches, except for Khadir in LJCS-Pakistan, where the groundwater salinity levels decrease towards the middle and tail reaches. (The reason for the good quality of groundwater in Khadir tail ends is that it is closer to the Chenab River.) Highly 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 highly saline groundwater – Batta and Lalian – compared with areas of relatively less saline groundwater areas – Rohera and Khadir – makes sense. However, the main problem lies within a distributary where saline groundwater reaches are receiving less canal water. Tail reaches of Batta and Lalian are the worst-affected areas (Tables 16.1 and 16.3).

Fertilizer and other inputs

Table 16.3 provides data on average quantities of key non-water inputs used for wheat production.

Number of ploughings

The number of ploughings is the same across irrigation systems in both countries. On average, there are four ploughings in the study areas of both countries.

Seeds

Overall use of seed per hectare in LJCS-Pakistan (126 kg ha^{-1}) is higher than that in BCS-India (108 kg ha^{-1}). This may be because most farmers in LJCS-Pakistan use older seed varieties (mostly from the home storage) as compared with those in BCS-India.

Fertilizer

There is a significant difference in the use of NPK per hectare across the two countries. Average NPK use per hectare in BCS-India is substantially higher (222 kg ha^{-1}) than that in LJCS-Pakistan (146 kg ha^{-1}). 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^{-1}). In the study area of Pakistan, there are significant differences in quantities of NPK used across farms and watercourses. NPK application rate is higher in Khadir (148 kg ha^{-1}) compared with Lalian (145 kg ha^{-1}).

For LJCS-Pakistan, NPK and yield show a strong positive relationship, yields increasing with increasing amounts of NPK applications. Given the complementary relationships 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 a higher 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 ends (89 kg ha^{-1}), 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.

Water Use Versus Wheat Yield

Generally, with adequate, reliable/timely and good-quality groundwater, yields can be expected to be higher than those with canal water. This is true in Khadir in LJC-Pakistan, where the quality of groundwater is good. Increasing the proportion of good groundwater in total water applied resulted in improved wheat yields in this distributary. On the other hand, in the remaining three distributaries, the use of saline groundwater had a negative impact on wheat yields. The overall significance of impacts of groundwater use and its quality are quantified in the yield function developed below.

Yield-function analysis

The yield function estimates the effects of various factors of production on wheat yields. Separate analysis was undertaken for the samples of BCS-India and LJCS-Pakistan. 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:

$$Y_i = \alpha_0 + \alpha_1 D_{m\,i} + \alpha_2 D_{t\,i} + \alpha_3 V_i + \alpha_4 S_i + \alpha_5 F_i + \alpha_6 W_i + \alpha_7 WD_i + \alpha_8 NW_i + \alpha_9 T_i + \alpha_{10} ECTW_i + U_i \ldots \quad (16.1)$$

LJCS-Pakistan

$$Y_i = \alpha_0 + \alpha_1 D_{m\,i} + \alpha_2 D_{t\,i} + \alpha_3 V_i + \alpha_4 S_i + \alpha_5 F_i + \alpha_6 W_i + \alpha_7 W^2_i + \alpha_8 NW_i + \alpha_9 T_i + \alpha_{10} ECTW_i + U_i \ldots \quad (16.2)$$

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 16–22 October 2000; for BCS-India first actual sowing week is 1–7 November); delay in sowing is hypothesized to negatively affect yields.
- F = quantity of fertilizers – NPK – in kg ha^{-1};
- W = quantity of total irrigation water applied (m^3);
- 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;[3]
- $ECTW$ = percentage of groundwater in total water applied measured at field outlet (%), times electrical conductivity (*EC*) of groundwater (dS m^{-1});
- α_s = coefficients to be estimated;
- i = denotes farm;
- U = error term.

Estimated coefficients (α) measure absolute change in wheat yield per unit change in one factor, holding the others constant. 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 coefficient of the dummy variable for seed, α_3, measures the net contribution of improved seed vari-

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

eties relative to all other seed varieties. The results of the estimated equations are presented in Table 16.4.

Among the wide range of factors that could possibly affect wheat yields, the 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 are 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).

The coefficients of location dummies indicate that wheat yields on middle and tail locations are lower than those at the head ends by 0.11 t ha^{-1} and 0.44 t ha^{-1}, respectively, for BCS-India and 0.70 t ha^{-1} and 0.53 t ha^{-1}, respectively, for LJCS-Pakistan. For LJCS-Pakistan, the lower coefficient for the tail end 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 16.5).

In BCS-India new seed varieties (WH-542, PBW-343) contribute an additional 97 kg ha^{-1} to average wheat yields, while in LJCS-Pakistan a new variety (MH 97) contributes an additional 995 kg ha^{-1} to average wheat yields (after accounting for locational differences). A delay of 1 week in sowing reduces wheat yield by 105 kg ha^{-1} in BCS-India and by 121 kg ha^{-1} in LJCS in Pakistan. An additional 10 kg of NPK use would increase yield by 29 kg ha^{-1} in LJCS-Pakistan and decrease yield by 9 kg ha^{-1} in BCS-India, indicating the scope for reducing fertilizer use in average yields. A volume of 100 m^3 of more water contributes 24 kg ha^{-1} to yields in Pakistan, while only a marginal increase of 0.13 kg ha^{-1} is seen in BCS-India, indicating that average yields obtained are closer to the highest point on the yield–water curve (and that farmers are applying water fairly well 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.

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^{-1} and 183 kg

Table 16.4. Estimated coefficients and their significance.

	BCS-India		LJCS-Pakistan	
Variable	Coefficient	*t* value	Coefficient	*t* value
Constant	4.456	11.08	3.583	5.74
D_m	−0.1058	−1.08	−0.701	−3.66
D_t	−0.4384	−3.65	−0.526	−2.58
V	0.2028	2.71	1.696	5.01
S	−0.0146	−2.87	−0.121	−3.31
F	−0.000745	−1.43	0.00292	2.25
W	1.3 E-6	0.02	0.000538	2.32
W^2	–	–	−0.0000000445	−1.87
WD	0.183	2.07	–	–
NW	0.047938	0.59	0.183	2.35
T	0.004385	1.01	−0.0777	−3.37
ECTW	−0.058609	−2.93	−0.364	−2.28
R^2	0.44		0.40	
N	216		218	

E-6 = 0.0000013.

Table 16.5. Marginal productivities of factors of production.

Factor	BCS-India: marginal productivity (kg ha^{-1})	LJCS-Pakistan: marginal productivity (kg ha^{-1})
Wheat seed variety (MH 97 for Pakistan, and WH-542 and PBW-343 for India)[a]	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
Per cent of groundwater in total water applied times present level of average EC of groundwater, at 100% groundwater-use level	−199	−411

[a]Considering the locational factors, marginal productivity of MH 97 (LJCS-Pakistan) would be 1696 kg ha^{-1} at the head, 995 kg ha^{-1} at the middle and 1521 kg ha^{-1} at the tail reaches. In BCS-India, marginal productivity of WH-542 and PBW-343 would be 202 kg ha^{-1} at the head, 97 kg ha^{-1} at the middle and −236 kg ha^{-1} at the tail (because the negative locational effect is greater than the positive effect of variety).

ha^{-1} for sample farms in BCS-India and LJCS-Pakistan,[4] respectively. The period after crop emergence is critical for crop growth, and prolonged delays in watering influence crop yields negatively[5] in the case of LJCS-Pakistan. A delay of 1 week in the first post-sowing watering from the appropriate period reduces wheat yields by 78 kg ha^{-1}. In the case of weedicides, with the application of recommended doses, there is the considerable increase in yields of 183 kg ha^{-1} in BCS-India. Only 11%, 20% and 2.5% of sample farmers have applied 60%, 80% and 110% of the recommended dosage of weedicides in their fields, respectively, while 7% of the sample farmers have not applied any weedicides.

In addition to timeliness, quality of water is also an important factor influencing yields. At the present level of groundwater EC (dS m^{-1}), the use of only groundwater (i.e. 100% groundwater with no canal water) reduces wheat yields on average by 199 kg ha^{-1} and 411 kg ha^{-1} in BCS-India and LJCS-Pakistan, respectively. 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 weedicide application (in BCS-India) and the 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 the average productivity of consumed water is much the same, the average productivity of diverted water is much higher in BCS-India than in LJCS-Pakistan (Table 16.6).

Improving Wheat Productivity

This study identifies several factors influencing land and water productivity of wheat and indicates scope for improving land and water productivity and the profitability of

[4] In the Pakistani Punjab, the general recommendation for wheat is three to five waterings, depending on climatic conditions and groundwater-table depths (Government of Punjab, 2000).
[5] 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 sugar cane and within 30–40 days if it is sown after rice.

Table 16.6. Average productivity of water.

Outlet/ distributary/ minor	Average land productivity/ yield (kg ha^{-1})	Average productivity of consumed water (kg m^{-3})	Average productivity of total water applied (kg m^{-3})
BCS-India			
Batta – head	4569	1.38	1.71
Batta – middle	4485	1.36	1.44
Batta – tail	4119	1.25	1.27
Rohera – head	4908	1.49	1.77
Rohera – middle	4761	1.44	1.51
Rohera – tail	4043	1.23	1.21
Batta – all	4391	1.33	1.46
Rohera – all	4576	1.39	1.48
All	4483	1.36	1.47
LJCS-Pakistan			
Lalian – head	4946	1.60	1.48
Lalian – middle	3917	1.29	0.97
Lalian – tail	3188	1.08	1.28
Khadir – head	4033	1.31	1.22
Khadir – middle	3372	1.10	0.80
Khadir – tail	4590	1.62	0.87
Lalian – all	4206	1.39	1.32
Khadir – all	3998	1.34	0.94
All	4106	1.37	1.11

wheat production in general. From a policy point of view this could be:

- Improving agronomic/farm-management practices through: promoting new seed varieties (such as MH 97 in Pakistan and WH-542 and PBW-343 in India), 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.
- Improving water-management practices, including improving timeliness of water delivery, increasing canal-water supply, reallocating canal water within and across distributaries and encouraging the use of relatively good-quality groundwater wherever possible.

However, the reallocation option would be justified only if overall economic and social gains from such an exercise are higher than from the present situation. We have studied the socio-economic impacts of canal-water reallocation and present scenarios and strategies for canal-water reallocation.

Impact of Canal-water Reallocation

We analyse the impacts of the use of groundwater and canal water on wheat productivity and profitability in BCS-India and LJCS-Pakistan by using the yield functions estimated by Equations 16.1 and 16.2, respectively. 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 a combination of proportions of water from the two sources changes. In order to generate various scenarios, we estimate the gross margin of wheat production with the following equation:

$$\hat{GM}_L = (P_L \times \hat{Y}_L) - COP_L \qquad (16.3)$$

where, $\hat{GM}_L$ is the estimated gross margins (US\$ ha^{-1}); $\hat{Y}_L$ is predicted wheat yield in t ha^{-1}; P_L is the price of wheat; COP_L is the cost of production (US\$ ha^{-1}); and L (L = 1, 2 and 3) is for farm location (head, middle and tail). The predicted wheat yields are obtained using average values of independent variables in Equations 16.1 and 16.2.

We have generated several scenarios of canal-water reallocation and the results are presented in detail in Hussain *et al.* (2003). Only two scenarios are presented here (Tables 16.7 and 16.8). These would be the most likely scenarios out of all that were tried because of the inherent limitations in canal-water supplies:

- Scenario 0. Base level (at present levels of groundwater and canal-water use in all reaches).
- Scenario 1 (BCS-India) – 10% canal water with 90% groundwater in head reaches, 20% canal water with 80% groundwater in middle reaches and 30% canal water with 70% groundwater in tail reaches.
- Scenario 1 (LJCS-Pakistan) – 10% of canal-water use each in head, middle and tail reaches of Khadir (with 90% groundwater); 25% canal-water (and 75% groundwater) use each in the Lalian head and middle reaches; and 50% groundwater (and 50% canal water) in the Lalian tail reach.

The reallocation strategy (scenario 1) results in overall gains in both BCS-India and LJCS-Pakistan. In BCS-India, average yields and production increase from the base level by 0.12 t ha^{-1} and 26 t, respectively (Table 16.7). Gross margins and total value of production increase from the base level by US\$15 ha^{-1} and US\$3250. Highest gains are achieved on both the Batta and the Rohera tail reaches, with the Batta minor gaining US\$12 ha^{-1} and Rohera US\$17 ha^{-1}. There is only a marginal decrease in gross margins on the Batta head (US\$2 ha^{-1}).

In LJCS-Pakistan, average yields and production increase from the base level by 0.21 t ha^{-1} and 77 t, respectively. Gross margins and total value of production increase from the base level by US\$10 ha^{-1} and US\$3569 (Table 16.7). Average yields and total production increase across all reaches of both distributaries. However, gross margins and total value of production decrease marginally on the Lalian head and middle reaches, and the largest gains are achieved on the Lalian tail reaches (US\$35 ha^{-1}). Marginal losses on the head reaches can be avoided through influencing other factors, such as timeliness and reliability of irrigation supplies. Overall, the reallocation strategy presents a win–win situation. Murray-Rust and Vander Velde (1992) present a related discussion on the conjunctive water use and canal-water reallocation, and discuss the complexity in implementing reallocation of canal water and pumped groundwater between head- and tail-end farmers (in terms of farmers' acceptability of this option, particularly of those at the head ends of the systems).

Conclusions and Policy Implications

The study was conducted to understand the causes of differences in land and water productivity in wheat production across farms and reaches of selected irrigation systems in BCS-India and LJCS-Pakistan. These sites were selected because of similar agroclimatic characteristics and yet they were reported to have large variations in wheat yields. The study analysed the impacts of both land–water and non-land–water factors on productivity. Key findings of the study are summarized below.

- The hypothesis that significant gains in aggregate wheat yields can be obtained by improved water-management practices at the farm and irrigation-system levels was accepted for the irrigation systems selected for this study.
- The difference of average wheat yields in the studied irrigation systems in India (4.48 t ha^{-1}) and in Pakistan (4.11 t ha^{-1}) is not as high as generally perceived.
- There are significant differences in yields across farms and locations in selected irrigation systems in both countries, with much greater yield variations in LJCS-Pakistan than in BCS-India.
- The differences in wheat yield between watercourses are greater than between farms within a watercourse command area.

Table 16.7. Impact of canal-water reallocation on each of the selected watercourses – BCS-India.

Item/scenario	Batta – head	Batta – middle	Batta – tail	Batta	Rohera – head	Rohera – middle	Rohera – tail	Rohera	All
Wheat yield									
Scenario 0	4.63	4.53	4.40	4.52	4.83	4.81	4.38	4.67	4.60
Scenario 1	4.68	4.66	4.56	4.63	4.89	4.91	4.59	4.80	4.72
Total production (t)									
Scenario 0	167	163	158	488	174	173	158	505	993
Scenario 1	168	168	164	500	176	177	165	518	1,019
Total value (US$)									
Scenario 0	11,938	13,685	11,230	36,815	12,310	10,594	10,139	33,205	69,910
Scenario 1	11,862	14,219	12,092	38,146	12,425	10,987	11,503	34,959	73,163
Gross margins (US$ ha^{-1})									
Scenario 0	332	380	312	341	342	294	282	307	324
Scenario 1	330	395	336	353	345	305	320	324	339

Table 16.8. Impact of canal-water reallocation on each of the selected watercourses – LJCS-Pakistan.

Item/scenario	Lalian – head	Lalian – middle	Lalian – tail	Lalian	Khadir – head	Khadir – middle	Khadir – tail	Khadir	All
Wheat yield									
Scenario 0	4.82	4.43	3.47	4.24	4.29	3.73	4.42	4.15	4.19
Scenario 1	4.93	4.50	3.70	4.38	4.56	4.02	4.67	4.41	4.40
Total production (t)									
Scenario 0	176	198	225	932	235	103	331	652	1,582
Scenario 1	181	202	240	963	250	111	349	694	1,659
Total value (US$)									
Scenario 0	11,791	12,774	15,638	62,833	12,495	5,798	17,776	35,414	96,374
Scenario 1	11,550	11,712	17,894	63,304	13,167	6,632	19,489	40,674	99,943
Gross margins (US$ ha^{-1})									
Scenario 0	322	285	241	225	228	210	237	225	255
Scenario 1	315	261	276	259	241	240	260	259	265

- The total water applied varies significantly: an average of 3050 m^3 compared with crop water requirements of 3300 m^3 in BCS-India, and an average of 3702 m^3 compared with crop water requirements of 3009 m^3 in LJCS-Pakistan.
- There is significant inequity in distribution of canal water between tail reach versus head and middle reaches in both BCS-India and LJCS-Pakistan, with inequities much higher in LJCS-Pakistan than in BCS-India.
- The average productivity of consumed water is similar for both countries, i.e. 1.36 kg m^{-3} for BCS-India and 1.37 kg m^{-3} for LJCS-Pakistan. However, the average productivity of diverted water is higher for BCS-India (1.47 kg m^{-3}) than for LJCS-Pakistan (1.11 kg m^{-3}).
- The quality of groundwater is relatively poor in both locations and more so in BCS-India, while the average productivity per hectare is lower where groundwater is of poorer quality.
- In both countries, more canal water is supplied to distributaries where groundwater is more saline, and this is a rational strategy. However, groundwater quality varies significantly across reaches within a distributary. In general, groundwater quality deteriorates towards the middle and tail reaches. The reaches with saline groundwater currently receive less canal water, and the productivity of wheat is low in these reaches. Thus, intradistributary canal-water allocation is an important issue in relation to the profitability of wheat production.
- The locational differences in distribution of canal water, quality of groundwater and level of input use lead to significant variations in profitability of wheat production.

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 timing of water supplies and groundwater quality are important contributing factors in 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.

In addition, improvements in water-management practices at the system level will also contribute to increased yields and the overall profitability of wheat production. Improving on timings of canal-water deliveries and adopting an effective strategy for allocation of canal water will result in overall significant socio-economic gains in wheat production. 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. Wheat production is highly profitable with only canal-water use and least profitable with the sole use of poor-quality groundwater. As the results show, a reliable supply of good-quality water could indeed significantly increase wheat yields and enhance the profitability of wheat production in irrigated lands of the Indian subcontinent.

The chapter presents two scenarios on the impacts of water use from two sources on the socio-economics of wheat production. The results indicate that overall gains from wheat production will increase if canal water is reallocated such that more canal water is supplied to canal reaches where groundwater is of poorer quality. The reallocation strategy in scenario 1 would increase average gross margins by US$15 and US$10 in BCS-India and LJCS-Pakistan, respectively. Much of the gain from this reallocation will be achieved in tail reaches. The policy implication of these findings is that, under conditions of canal-water scarcity and locational variations in the quality of groundwater, joint management of canal water and groundwater is essential to increase overall gains from crop production. The study presents an example of ‘institutional water scarcity’ that could be addressed through enhancing existing institutions or developing institutional arrangements explicitly designed to effectively manage the available surface-water and groundwater resources holistically.

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