RESEARCH
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108

Water Saving Technologies: Myths and Realities Revealed in Pakistan's Rice-Wheat Systems

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Contents

Acronyms and Abbreviations

ACIAR	Australian Centre for International Agricultural Research
CGIAR	Consultative Group on International Agricultural Research
CIMMYT	International Maize and Wheat Improvement Center
CPWF	CGIAR Challenge Program on Water and Food
IREC	Irrigation Research & Extension Committee
IWMI	International Water Management Institute
LBOD	Left Bank Outfall Drain
LCC	Lower Chenab Canal
NSL	Natural Surface Level
OFWM	On-Farm Water Management
PARC	Pakistan Agricultural Research Council
RCT	Resource Conservation Technology
RWC	Rice-Wheat Consortium
SCARP	Salinity Control and Reclamation Program
SMO	SCARP Monitoring Organization
UCC	Upper Chenab Canal
WAPDA	Water and Power Development Authority

Summary

Water scarcity is an increasing concern in Pakistan. Partially in response, the government and international organizations are encouraging the use of 'Resource Conservation Technologies' (RCTs) by farmers to reduce water use while maintaining or increasing production. While RCTs such as zero tilled wheat and laser leveling are being increasingly adopted in Pakistan's rice-wheat and sugarcane-wheat cropping systems, there has been little assessment there or elsewhere of the actual impact of RCTs on the nature and magnitude of water savings at the field, irrigation system and basin scales. This study uses both farmer surveys and physical measurements to understand the impact RCTs have had on water use and water savings in the irrigated Rice-Wheat Zone of Pakistan's Punjab province. The findings show that RCTs do indeed result in reduced water applications at the field scale. However, these field scale savings do not necessarily translate into reductions in overall water use for two reasons. First, some of the water 'saved' would have percolated into the groundwater table from where it would later be reused by farmers through pumping. Second, the increased crop water productivity for medium and large scale farms made possible by RCTs has made water use more profitable and hence *increased* water demand and groundwater depletion through expansion in cropped area. These findings provide insights into the conditions under which RCTs in Pakistan, or similar technologies elsewhere, can result in 'real' water savings - that is, decreases in water depleted per unit of crop output. At the same time, they provide a warning that even when technologies decrease applications per unit of crop output, in other words increase irrigation water productivity, they may not decrease actual water use unless institutional arrangements are in place to limit demand - a challenging undertaking in any environment.

Water Saving Technologies: Myths and Realities Revealed in Pakistan's Rice-Wheat Systems

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Introduction

Ensuring food and livelihood security for growing populations is one of the major global challenges (Seckler et al. 1998). Over the last 50 years, a major factor in meeting this challenge has been the expansion of irrigated area. In future years, the irrigation expansion option will be increasingly difficult to pursue, both because many river basins have already been developed to their maximum capacity and because of the growing competition for existing water supplies for domestic, industrial and environmental purposes. In such a scenario, one promising alternative is to seek strategies to increase crop yields whilst using similar or even reduced water resources, i.e., improving water productivity (Molden 1997).

The global challenge of increasing food production, while using less water is exemplified in the case of Pakistan. The population there has increased by over 25 percent in just the last 10 years and continues to expand much faster than global averages. While factors such as salinization and waterlogging as well as labor and financial constraints compound the problem, a key issue in efforts to keep food production rising with population is the lack of additional sources of water for agricultural use. In response to the water challenge, as well as other concerns including low farm income, various Resource Conservation Technologies (RCTs) are being developed and promoted by national and international organizations, in particular for rice and wheat which together make up 90 percent of the country's total food grain production. These technologies include zero tillage, direct seeding, parachute transplanting, bed planting, laser land leveling and crop residue management (PARC-RWC 2003). While two primary impacts from these technologies are expected to be water savings and increased crop production, they are also hoped to variously address a range of other issues including emerging labor shortages, poverty reduction and environmental sustainability. Among the technologies, zero tillage and laser land leveling are to date the most widely adopted in Pakistan, with use centered on the Punjab and other rice-wheat cropping systems (Hobbs and Gupta 2003).

In terms of water use, recent performance evaluation studies have documented that these Resource Conservation Technologies (RCTs) can be successful in improving field scale irrigation efficiency (Gupta et al. 2002; Humphreys et al. 2005), resulting in savings in water application. However, whether or not improved irrigation efficiency translates to 'real' water savings depends on the hydrologic interactions between the field and farm, the irrigation system and the entire river basin. In fact, the water saving impacts of RCTs beyond the field level are not well understood and documented. It is possible that real water savings are much lower than what might be assumed when field level calculations are extrapolated to broader scales, because of water recycling and the conjunctive use of surface and groundwater in many, particularly rice based, cropping systems (Ahmad et al. 2002; Humphreys et al. 2005; Tuong et al. 2005).

This paper evaluates the reasons for RCT adoption and the resulting water saving impacts of the main RCTs being developed and promoted in the Rice-Wheat Zone of Pakistan's Indus Basin, the center of the country's food grain production system. The analysis provides a systematic tracking of the various water balance components at field, farm and higher scales of the irrigation system. The fate of water saved at the field level is explored by studying farmers' response to saved water and its linkage with the system level water balance. The study also discusses the conditions under which field level water savings could be translated into real water savings at the irrigation system and basin scales in the context of rice-wheat cropping systems in Indus Basin of Pakistan and for similar basins elsewhere. Finally, general conditions and generic policy recommendations for achieving the dual goals of increased food production and real water savings under new interventions are described.

Study Area

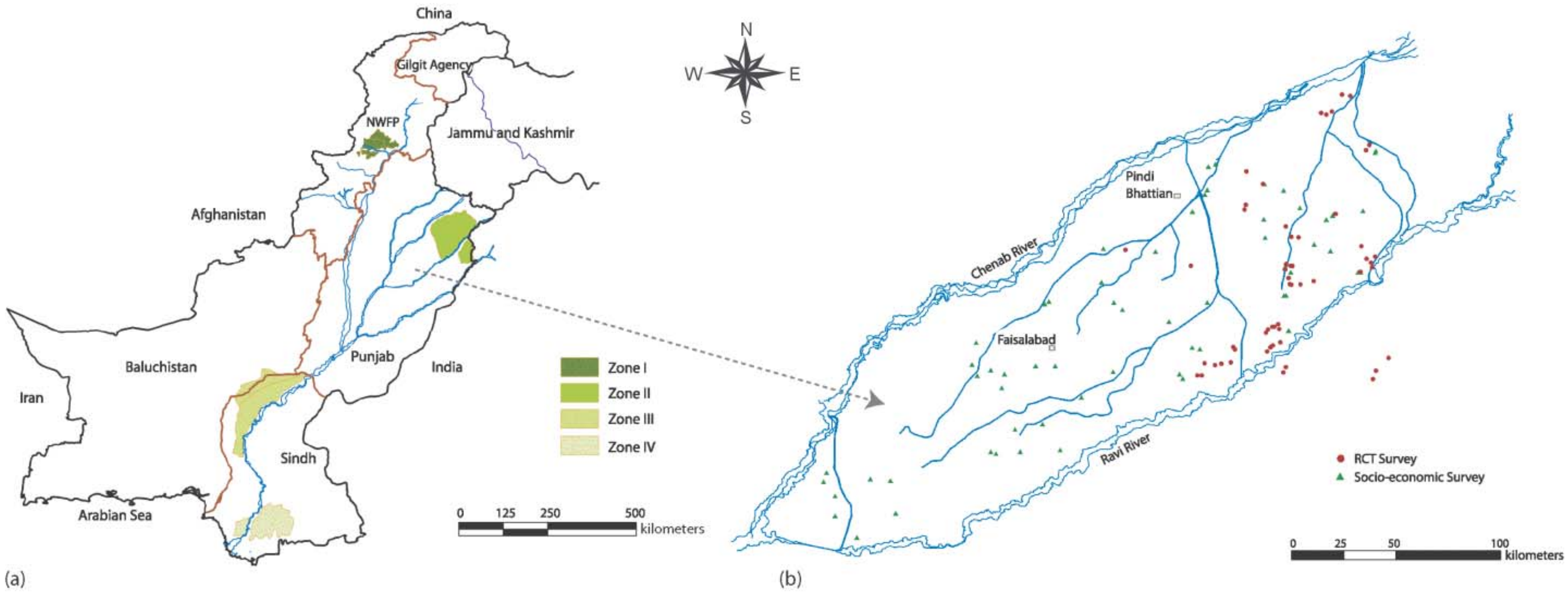
The Indus Basin contains approximately 16 million of Pakistan's 22 million hectares (ha) of cultivated land and the vast majority of the country's irrigated area. Within the basin, rice-wheat production systems account for about 14 percent of the area and form a core base for national food grain output. As shown in figure 1a, rice-wheat areas have been categorized into four main zones based on climate, land and water use: the Northern Zone (Zone I), the Punjab Rice-Wheat Zone (Zone II), the Upper Sindh Zone (Zone III) and the Lower Sindh Zone (Zone IV).

The Punjab Rice-Wheat Zone, in particular, was chosen for examination in this study for three primary reasons. First, it was a focal point of the Rice-Wheat Consortium, a collaborative group established to examine the possible roles of RCTs in Pakistan and similar regions in India, Nepal and Bangladesh. Second, it largely falls within Rechna Doab (the area between the Ravi and Chenab tributaries of the Indus), an IWMI benchmark 'basin' (figure 1b) and thus considerable background work and technical study has already been done on its hydrology and production systems. Finally, as explained in more detail later, the nature of its conjunctive (surface and groundwater) agricultural water use system highlights the concepts and issues in understanding water savings across scales. Maps representing the irrigation network, groundwater quality, administrative districts, irrigation administrative units and soils of Rechna Doab are provided in Annexes 1 to 5.

The climate in the Punjab Rice-Wheat Zone is semi-arid and typical of the low-lying interior of the northwest Indian sub-continent. Summers are long and hot, lasting from April through September, with maximum temperatures ranging from 21°C to 49°C. Winter lasts from December through February, with maximum daytime temperatures of up to 27°C sometimes falling below zero at night. Average annual rainfall is approximately 400 millimeters (mm), about 75 percent of which falls during the June to September monsoon.

The prevailing temperature and rainfall patterns govern two distinct cropping seasons. Water intensive rice is grown during the monsoonal summer *(kharif)* season while wheat is produced in the drier winter *(rabi)* season. Both crops together have been estimated to require 970 mm of water for evapotranspiration per year, 640 mm for rice and 330 mm for wheat (Ullah et al. 2001). However, the actual evapotranspiration of all crops except rice is generally lower than the potential requirement (Ahmad et al. 2002; Jehangir et al. 2007). The reasons for this include deliberate under-irrigation of wheat to reduce pumping costs, restricted *rabi* water supply from canals and erratic and untimely surface irrigation

FIGURE 1.
Rice-wheat cropping zones in Indus Basin of Pakistan and location of sample farms surveyed in and near Rechna Doab, the Punjab, Pakistan.



delivery. In saline areas, farmers also restrict groundwater supply to minimize salinity effects on crops, even when it is their only source of supply.

However, the amount of water applied to grow rice is significantly higher than crop water requirement (ET_p). Rice is grown in continuously flooded conditions with ponding depths of 50-75 mm for most of the growing season maintained by 15 to 25 irrigations. Thus, total water application ranges from 1200 to 1600 mm over a 100-150 day growing period, ignoring the relatively small amount of water required for seedling nursery. The water applied for puddling (to minimize deep percolation) varies from 100 to 200 mm and a further 100 mm may be needed to complete land preparation prior to transplanting.

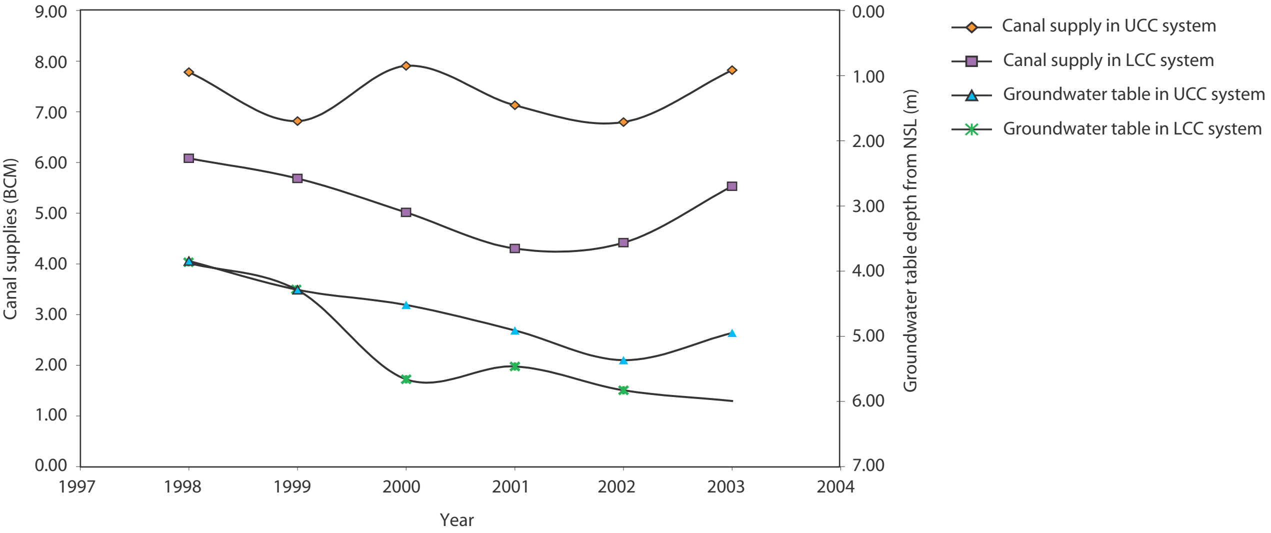
As the total crop water requirement for the rice-wheat rotation is more than double the annual rainfall, it is obvious that irrigation is essential. It has been provided in the first instance through a network of irrigation canals, developed mainly over the last 140 years, which draws water from the Indus River and its tributaries (Annex 2). The original design objective of the irrigation development was to spread limited water over a large area, at a cropping intensity of approximately 65 percent, to protect against crop failure, prevent famine, and generate employment and revenue. Before the introduction of surface irrigation systems, the groundwater table was about 30 meters (m) below ground level in Punjab Province and about 12-15 meters deep in Sindh province. The only sources of groundwater recharge were rivers, seasonal floods and rainfall, and a steady natural hydrological balance was maintained between the rivers and the groundwater table.

However, massive and widespread surface water irrigation development in the nineteenth and twentieth centuries altered the natural hydrological balance due to increased recharge from earthen canals and irrigated fields. Over the years, persistent seepage from this huge gravity flow system has gradually raised the groundwater table. By the middle of last century, at some locations, the groundwater had risen to the surface or very close to the root zone, causing waterlogging and secondary salinity which badly affected agricultural productivity. While describing these negative impacts of irrigation development in the Indus, the scientific literature has tended to neglect the massive and beneficial freshwater recharge and storage that occurred in the highly permeable unconfined aquifer of Indus Basin system. As a result, surface supplies are augmented by groundwater irrigation, initially developed by the government as part of a vertical drainage programme (SCARP), starting in the 1960s and greatly increased by private sector investment over the ensuing 25 years. With additional irrigation supplies from groundwater, cropping intensities have increased to 150 percent in some areas over the last two to three decades, and groundwater has become a key input in agricultural production.

From 1999 through 2003, Pakistan experienced its lowest water availability on record due to a combination of low rainfall and unusually low snowfall in the Himalayas. Most surface flows are sourced from spring and summer snowmelt, and water deliveries in the Punjab were as low as 40 percent of long term average value. As a result, groundwater took on an even more important role. However, this rapid increase in use of groundwater over the last two decades, combined with lower than average recharge, has resulted in declining groundwater levels, as shown by canal supply and groundwater table trends in the two main canal systems irrigating Rice-Wheat Zone of the Punjab (figure 2). This has occurred despite the fact that over-pumping is clearly constrained by fuel price as most tubewells are powered by diesel motors (Qureshi et al. 2003).

A key factor in groundwater use within the rice-wheat system is recycling. Ahmad (2002) has shown that, due to deep percolation, a significant fraction of the volume pumped is recycled many times in the rice season. In such systems, net groundwater use is much less than that pumped or applied (Ahmad et al. 2005). In the Punjab, rice is generally grown where groundwater quality is good, but in the Sindh, where rice-wheat systems are also common, groundwater quality is uniformly poor (see Annex 1). The relationship between groundwater quality and the study findings are discussed further below.

FIGURE 2.
Changes in average water table depth and variation in canal flows for the Upper Chenab Canal (UCC) and Lower Chenab Canal (LCC) system of Rechna Doab. Locations provided in Annex 2.



Sources: Groundwater elevation (SMO-WAPDA); Canal Flows (Punjab Irrigation Department)

Water Scarcity and Resource Conservation Technologies

The rice-wheat system regime has served as a key source for Pakistan's ever growing food demand over the last 50 years. However, the ability to further expand or intensify production is severely constrained by available water supplies. In response, both the government and international organizations have emphasized developing and disseminating technologies to reduce agricultural water use and increase production, while at the same time addressing growing labor shortages, reducing rural poverty and ensuring environmental sustainability (Hobbs and Gupta 2003; PARC-RWC 2003).

The generic set of improved farm-scale technologies is known as *'Resource Conservation Technologies'* (RCT). RCTs have been developed with multiple objectives – to enable more timely sowing and save on land preparation costs (e.g., zero tillage); to improve irrigation uniformity, crop establishment and field drainage (e.g., laser leveling); or to do both (e.g., planting of rice and wheat on permanent beds). Photographs of major RCTs being promoted in Pakistan are given in Annex 6.

Globally there has been considerable interest in and uptake of RCTs, and their economic value has been demonstrated in multiple studies. For example, adoption levels of zero tillage and mulching in rainfed agriculture have increased from 1 percent in 1985 to 37 percent in 2003 in northern New South Wales in Australia (Vere 2005). Wheat producers' surplus in the adopting region on northwest China was $1.10 billion compared to a net loss of $358 million for other wheat growers, and similar results are demonstrated for maize (ibid.). RCTs have been shown to control herbicide resistant Phalaris minor in the Punjab in India, with a corresponding increase in wheat yields from 1.5 tonnes per hectare (t/ha) in the early 1990s to between 4 and 5 t/ha post 2000, estimated to be worth $1.8 billion to India over a 30 year period (ACIAR 2005).

The value to farmers of some RCTs is demonstrated by their rapid and widespread adoption in the Indian Punjab and Haryana (Hobbs and Gupta 2003). In Pakistan, it has been estimated that *zero tillage* has been adopted on about 0.4 million hectares and *laser leveling* on about 0.2 million hectares (Ahmed and Gill 2004) after the initial introduction in the 1980s. In Rechna Doab, the percentage of planted area now under RCTs (12%) is somewhat higher than the percentage of farmers using the technologies, since larger farmers are disproportionately more likely to adopt. Reasons are explored later but involve levels of mechanization, labor availability and fallow land. More detailed statistics are given in Annex 7, which show that average adoption is highest in the rice-wheat area, but that adoption can vary by irrigation subdivision from 0 to 35 percent.

A number of evaluations have suggested that these technologies can reduce the amount of water applied (e.g., Gupta et al. 2002). Work conducted in China and Pakistan, in collaboration with CIMMYT and ACIAR, respectively, has shown reduced water applications of between 32 and 37 percent in wheat-maize systems (Fahong et al. 2005; Hassan et al. 2005). In the Pakistan study site, located in Northwest Frontier Province, maize yields increased 32 percent when compared to traditional planting on the flat beds (Hassan et al. 2005). The RWC has shown water savings of 30 percent due to the adoption of zero tillage in rice-wheat systems (Hobbs and Gupta 2003). In contrast, bed planting in rice-wheat systems in Australia has proved more variable, with improved and depressed rice (Borell et al. 1997) and wheat yields and water use under different circumstances (ibid.) (Beecher et al. 2006).

Water Savings and Net Water Use: Field and Basin Perspectives

In the studies mentioned above, reductions in field level water application have been equated with water savings, but it remains an open question, and an objective of this paper, to determine whether water is in fact saved at a larger scale. Thus, much of the remainder of this paper attempts to answer the question:

> *“Are there quantifiable real water savings associated with RCTs that would allow water to be transferred somewhere else than the immediate locale, for other users and purposes?”*

To answer this question requires an understanding of the various components of the water balance at field and system scales. As shown in figure 3, a cropped field can receive water from rainfall, irrigation with canal and ground water, and in some cases from capillary rise from high groundwater tables. For a farmer, the water received in the field would ideally be used as transpiration to support crop growth, since other outcomes such as, evaporation from bare soils and ponded water, transpiration by weeds, percolation to the groundwater table and runoff to surface drains, do not contribute to food and fodder production. From the *field perspective,* it is clear that water savings can occur by reducing any of these sources of loss (though it should be remembered that water, especially in rice production, also plays important non-transpiration roles in maintaining anaerobic conditions and suppressing weeds).

To understand water savings beyond the field scale, it is essential to understand the flow paths and final destinations of percolation and surface runoff, often considered as ‘losses’. Deep percolation and surface runoff can take two paths: one is into fresh groundwater aquifers or surface water bodies, the other is into saline or other sinks - bodies

FIGURE 3.
Water balance components in the Punjab Rice-Wheat system, Pakistan.

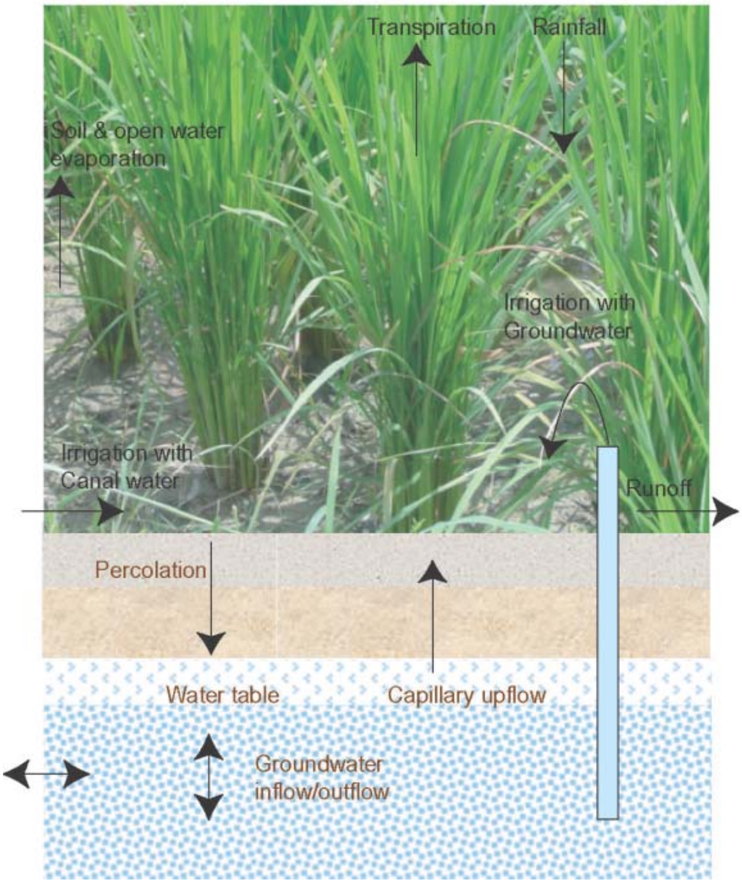
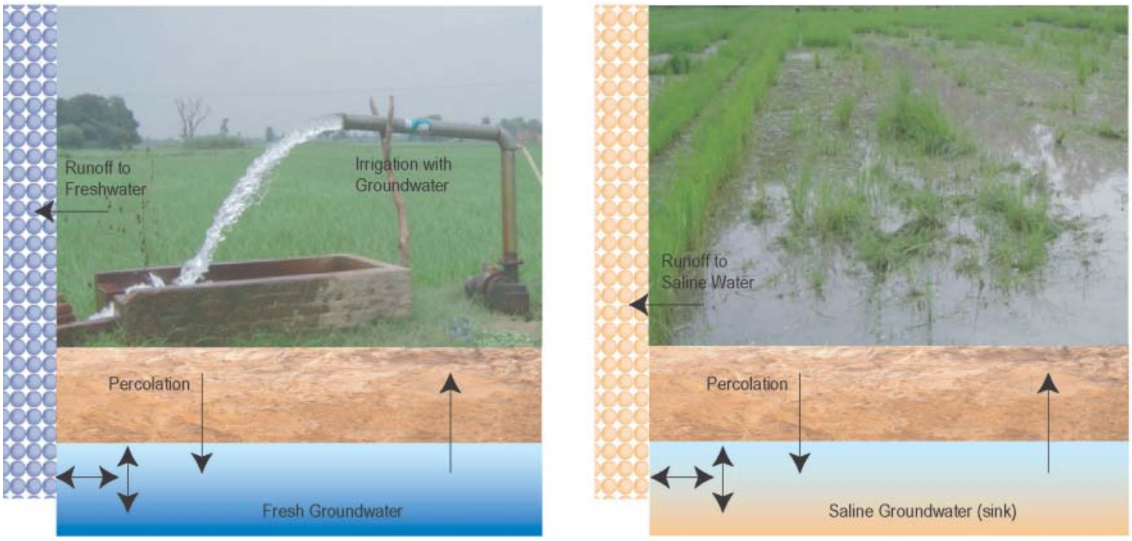


FIGURE 4.
The interaction between recharge and abstraction of saline and fresh groundwater.



of water so degraded or saline that further use is not possible without treatment (such as saline aquifers and the sea). As stylized in figure 4, the extent to which 'true' or 'real' water savings can be gained from reduced field scale applications depends on whether percolation and surface runoff flow (1) to sources where they can be pumped or otherwise reused by the same or 'downstream' farmers, or (2) to degraded sinks. Groundwater recharge and recycling processes are described more technically with application to the study area in Ahmad (2002). A second aspect of water savings resulting from new technologies is the impact on farmers' production choices and how those in turn impact on larger (e.g., system and basin) scale water balances. These issues are addressed in further detail below.

Data and Methods

IWMI has been working as part of the RWC in India and Pakistan to better quantify water use and land and water productivity of the rice-wheat system and the impact of various RCTs. Simultaneously, IWMI has been working on the issue of scale in water use and productivity. This study provides a crossing point for the two efforts and uses both new data, and data and concepts developed from the previous work, to examine the role of water savings from RCTs across scales.

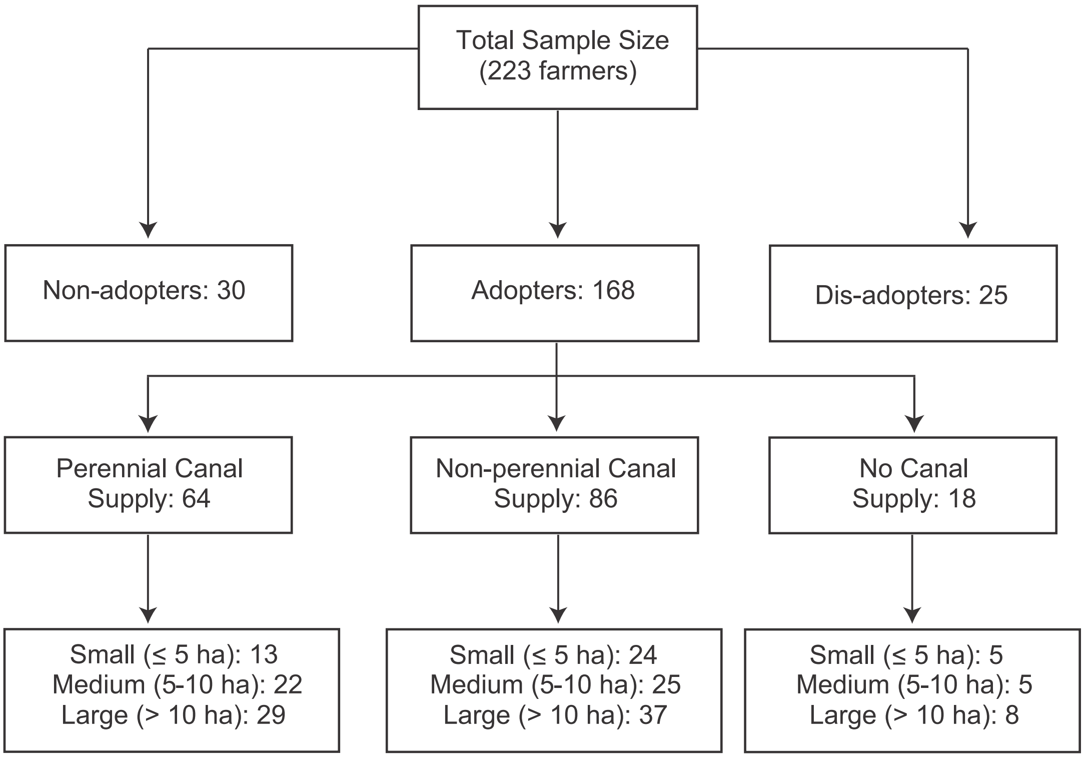
In this study, technical measurements and understanding of the water balance components were derived from (a) earlier field experiments on water use and productivity, and (b) detailed water balance studies by Ahmad (2002). However, since it is difficult to directly measure water balance components in detail at large scales, we also undertook a survey of 168 RCT adopters in 2004 in the rice-wheat area of Punjab (referred to hereafter as the RCT Survey, figure 1(b)) to determine their perceptions of water savings and other impacts of RCTs and how they responded to those impacts in terms of farming systems and water use. Data from these two efforts were supplemented by information from a second Socio-Economic Survey of 360 farmers throughout Rechna Doab (figure 1(b)), conducted in early 2004 (referred to hereafter as the SE Survey).

For the RCT Survey, a group of 223 adopters, dis-adopters and non-adopters were sampled from June through December 2004. Respondents were chosen using a stratified random sampling approach based on farm size (Annex 8) and irrigation system type of all recorded adopters identified by the On-Farm Water Management Unit of the Department of Agriculture, the Punjab and from the results of the SE Survey. Additional farmers (non-adopters) were randomly selected within the same sample areas. The distribution of sampled farmers with respect to RCT adoption, irrigation system and farm size is presented in figure 5. In this context, large farmers have more than 10 ha, medium farmers have between 5 and 10 ha and small farmers have less than 5 ha (see also Annex 8).

The survey was designed to gain insights into questions related to RCT adoption and water savings including:

- the main factors influencing RCT adoption and diffusion;
- field scale impacts of RCTs on water use, crop yields and income, cropping patterns, cropping intensity and estimated evapotranspiration;
- farm level impacts of RCTs on water use, including changes in canal water and groundwater use, and the use of any field scale water 'savings'; and
- system level impacts of RCTs on overall crop yields, land use, irrigation water use, water distribution and allocation.

FIGURE 5.
Distribution of the RCT survey respondents with respect to adoption status, surface irrigation system, and farm size.



Survey Results

The basic characteristics of the RCT Survey respondents are presented in detail in Annex 9. The farmers in the study area have an average farming experience of 25 years and an average age of 45 years. Twenty-eight percent have no formal education and cannot read and write, whereas 30 percent have completed 10 years of schooling and 5 percent have graduated from colleges or attended higher education in universities. About 95 percent of the farmers own land (60% own all of their farmed land and 35% own and rent land) and 5 percent cultivate land only as tenants. The main soil types are clay and clay loam and the majority of the adopters possess both types, although the rice-wheat rotation is practiced on other soils as well (Annex 5). The average farm size is 17 ha, with adopter farmers having slightly higher than average holdings than non-adopters and dis-adopters.

Land Use and Irrigation

Approximately 15 percent of the farmers reported that they have 0.5 to 15 ha of “culturable waste” area - agricultural land that has not been cultivated for the last three years. The two main reasons for not cultivating this land were:

1. scarcity of irrigation water (50% of responses); and
2. soil salinity (35% of responses).

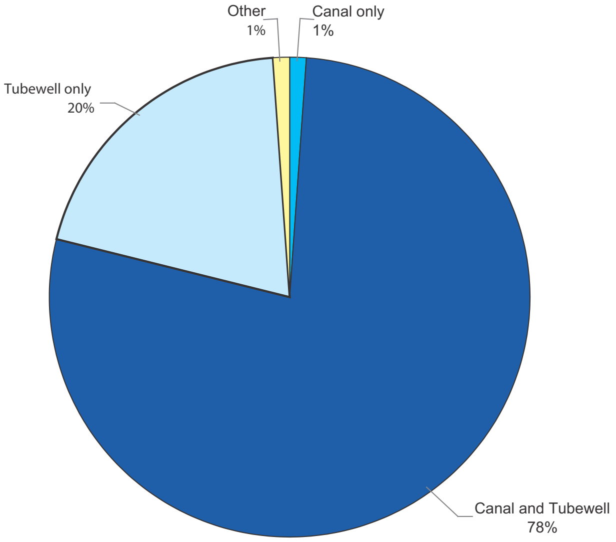
In fact soil salinity problems are also related to water scarcity. Salinity is one of the main soil problems in the study area and remains a threat to the sustainability of irrigated agriculture there and throughout the Indus Basin of Pakistan. Salinity hazards can be categorized into two types: *primary (i.e., fossil) salinity* and *secondary salinity*. Fossil salinity is related to natural salts present during soil formation (Smedema 2000). Secondary salinization is a complex problem. In some areas, secondary salinization is linked to a shallow phreatic surface whereas in other parts, it is a consequence of irrigation with marginal and brackish groundwater, particularly where fresh canal water is insufficient. Very few farmers reported the problem of waterlogging, as water tables have fallen in the area, due to the recent decline in surface water availability and continued groundwater abstraction. This represents a very considerable, and largely undocumented, change from conditions prevailing in the 1960s and 1970s. After gypsum application (36%), the use of flood irrigation and long-term ponding of water are the most common ways in which farmers attempt to control salinity (and sodicity), although other methods are used including application of sulfuric acid and planting salt tolerant trees and grasses.

Freshwater availability from the canal system has been erratic and poor, especially in the last 4-5 years. The majority of the farmers (about 75%) in the study area report that they do not receive their allocated share of canal water. The farmers attribute this poor performance to the following reasons:

1. low discharge rates;
2. location of farm in the tail reaches of tertiary (watercourses) or secondary (distributary) canals;
3. frequent canal breaches due to poor maintenance and/or water theft;
4. reduced time allocation; and
5. conveyance losses.

Farmers have responded to canal water scarcity by pumping more and more groundwater. As a result, virtually all farmers report using groundwater, with 78 percent using the resource in conjunction with surface supplies and 20 percent using only groundwater, as shown in figure 6. Furthermore, the major share of all irrigation water now comes from groundwater sources, with farmers reporting about 60-70 percent of the volume of water they apply to fields as groundwater. At the same time, the increased exploitation of groundwater has negatively impacted on the system level water balance with 70 percent of farmers reporting a declining trend in groundwater tables while only 1 percent reported rises.

FIGURE 6.
Source of irrigation in Rice-Wheat Zone of the Punjab, Pakistan.



Source: IWMI RCT survey 2004

RCT Adoption

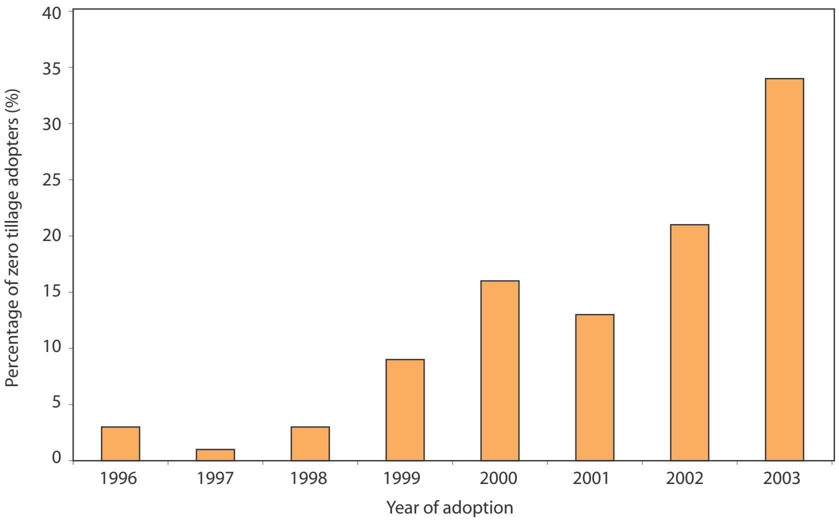
The overall adoption rates for the main RCTs are estimated from the 2004 Socio-economic Survey of the whole of Rechna Doab, and set the context for the analysis of adoption within the Rice-Wheat Zone. This estimate immediately reveals a considerable increase in adoption of zero tillage between 2000 and 2003 (figure 7). The trend in adoption of laser leveling has been similar, though at lower absolute levels. Clearly the two technologies show an important and growing change in the region's farming systems. It should be noted that both these technologies are primarily for use in wheat, not rice, production. The survey indicated that other RCTs have not been widely adopted.

Within the Doab, technologies and rates of adoption vary by farming system. Zero tillage is mostly used in the Upper Doab where rice-wheat systems dominate (figure 8). Laser leveling is practiced more in the Middle and Lower Doab where sugarcane-wheat and more mixed cropping systems are found and where surface water is scarcest and groundwater more saline. Other technologies are not yet widely adopted as these are still under development or not profitable to farmers - reasons for non-adoption are discussed in detail later in this report.

Farmers indicated that their two primary reasons for adopting the technologies were to (a) increase profitability (97% of adopters' respondents), and (b) cope with water scarcity (87% of respondents). While not possible to discern from the survey questions, coping with water scarcity is also related to profitability because it is strongly linked with productivity and the cost of pumping. Farmers also reported increasing shortages of labor due to migration to cities as a major reason for adopting zero tillage. Figure 9 illustrates farmers' perceptions of the impacts of the two most used RCTs on field level agricultural input use. Both laser leveling and zero tillage resulted in substantial savings in labor, fuel and water, though the relative impact of each varied with technology. Impacts on fertilizer and herbicide use were relatively small.

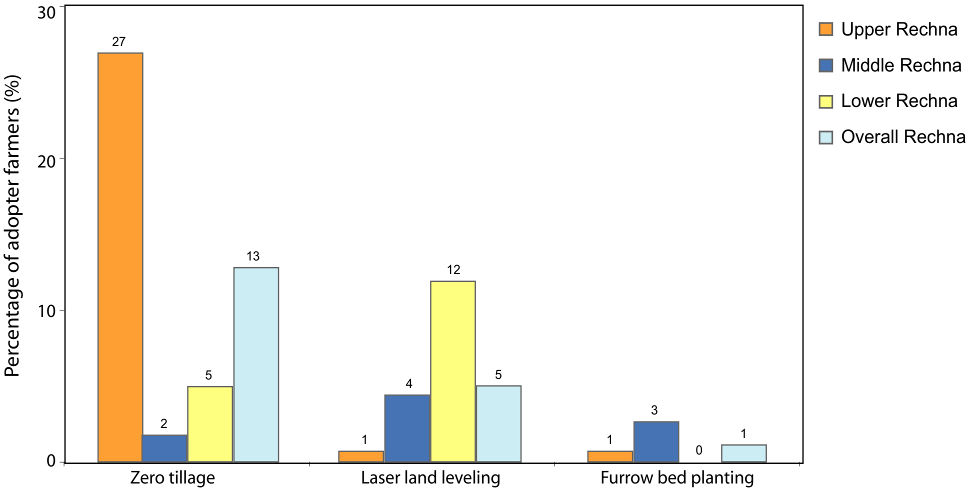
In the rice-wheat area, a delay in planting is one of the main factors that reduces wheat yield. Farmers prefer to grow late maturing, high-priced basmati rice varieties, which are mostly transplanted in July and harvested in November. Wheat planting is further delayed as the heavy soils of the area cannot be tilled immediately after rice

FIGURE 7.
Temporal trend in the adoption of zero tillage technology (wheat) in the Rice-Wheat Zone of the Punjab, Pakistan.



Source: IWMI RCT survey 2004

FIGURE 8.
Adoption of resource conservation technologies in Rechna Doab, the Punjab, Pakistan (2003-2004).

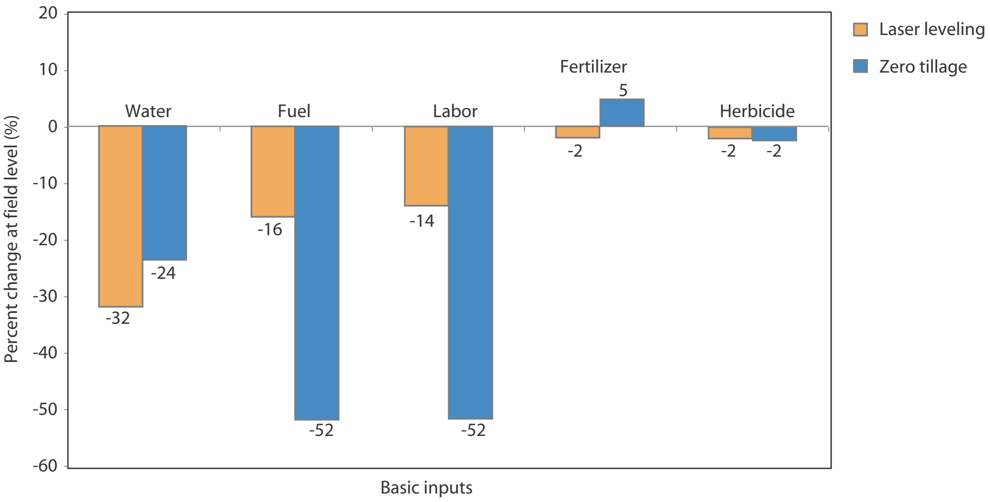


Source: IWMI Socio economic survey 2004

harvest due to excessive residual moisture from the rice crop. Wheat yield declines by 1-1.5 percent per day delay in planting after 21 November, in conditions similar to those of rice-wheat area of the Punjab Pakistan (Aslam et al. 1993; Ortiz-Monasterio et al. 1994; Hobbs et al. 1997).

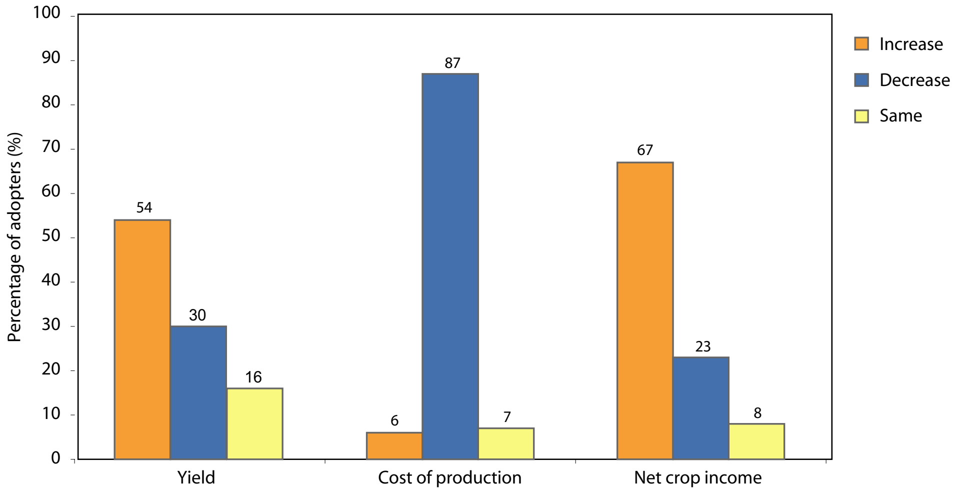
The impacts of RCTs on wheat yield were varied, with about 54 percent of farmers reporting an increase, 30 percent a decrease and 16 percent no change for zero tillage (figure 10a). The comparative numbers for laser leveling were 96, 0, and 4 percent (figure 10b) respectively. Because of the decrease in input use shown above, almost all farmers reported a decrease in production costs (87% for zero tillage and 88% for laser leveling). With generally increased yields

FIGURE 9.
Farmers' responses on the impact of laser leveling and zero tillage on field level water application and other inputs.



Source: IWMI RCT survey 2004

FIGURE 10a.
Impact of zero tillage on wheat yield, cost of production and net crop income.

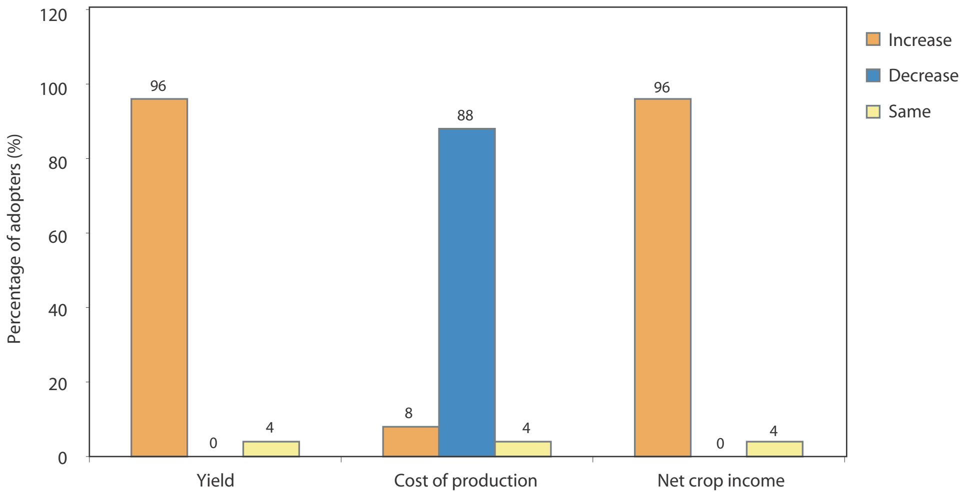


Source: IWMI RCT survey 2004

and decreased costs, net crop income rose for the majority of farmers (figures 10a and 10b), providing an obvious explanation of the increasing adoption and popularity of the two technologies. These findings are consistent with those of Jehangir et al. (2007) for zero tillage as summarized in figure 11.

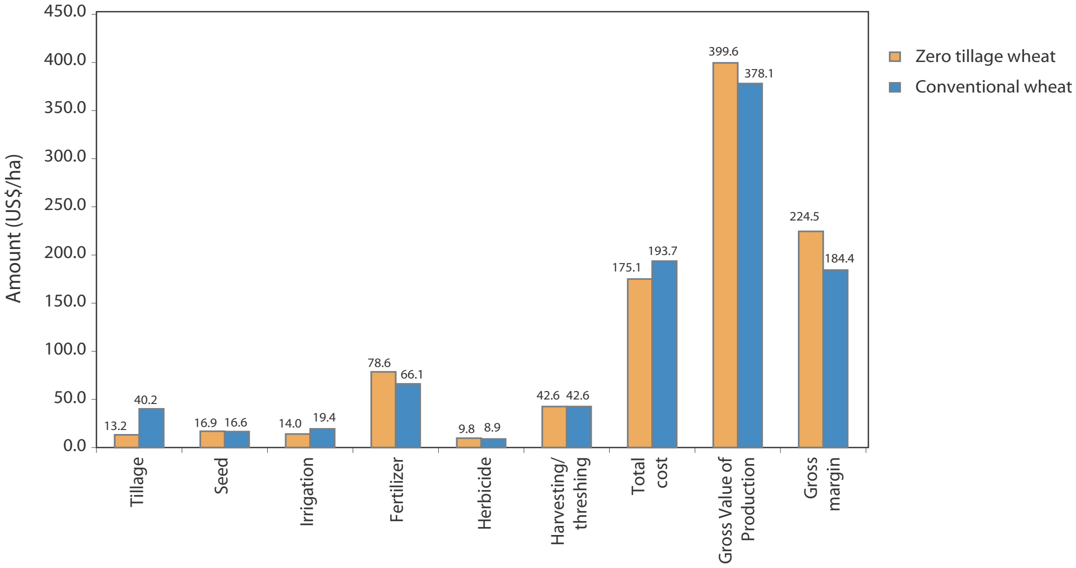
While the popularity of the two technologies can be explained by their contributions to increased farm profitability, farmers also report substantial reductions in water applications as shown in figure 9. The reduced irrigation depth usually results from saving one pre-sowing irrigation *(Rouni)* from an average of four

FIGURE 10b.
Impact of laser leveling on yield, cost of production and net crop income.



Source: IWMI RCT survey 2004

FIGURE 11.
Comparison of zero tillage and conventional wheat for production cost and income in Rechna Doab, in Rabi, 2002-2003.



Source: Jehangir et al. 2007

irrigations applied to conventionally cultivated wheat in the study area. Most farmers also reported shorter irrigation times per unit of land under zero tillage compared to conventionally tilled soils with an average reduction of 2.5 hours per event (from 7.5 to 5 hours) for one hectare of land. Shorter application times are attributed to higher advance rates of water in no till compared with tilled soils, especially for the first irrigation. However, a few farmers also reported similar or even increased application amounts under zero tillage and/or stated that more frequent irrigation was required, hence increasing the total irrigation depth.

Impacts of RCT Adoption on Savings in Water Application, Water Use and Productivity

It is clear that the reasons for the adoption of RCTs in Rechna Doab are due to a combination of reduced costs (mainly labor and tillage) and increased yields for wheat. *Thus far, there is almost no impact of RCT adoption in rice culture.* Savings in water application are also evident at the field level, contributing to lower wheat production costs, but also raise the possibility of intensification on farms that have excess land compared to water availability. In this section, the farmer responses and reasons for their adoption behavior are set in the context of the whole Rechna Doab, using the IWMI RCT and SE surveys and results of previous field experimentation by IWMI in 2001-2003 (Jehangir et al. 2007; Ahmad 2002).

Field scale water use and productivity

Wheat is a minor water user (actual evapotranspiration of 390 mm) compared to rice (actual evapotranspiration 660 mm), but the adoption and benefits of RCTs in Pakistan have mainly been related to wheat. Wheat evapotranspiration is roughly the same as the applied water (irrigation plus rain of 377 mm), and accounts for about 80 percent of total water supply when soil moisture is carried over from rice (58 mm) and net soil moisture depletion (37 mm) are taken into account (table 1, total water supply = 433 mm).

By contrast the total water supply in rice is 1020 mm compared to actual evapotranspiration of only 660 mm. Ahmad (2002) showed convincingly that most of the water required to maintain ponding on relatively light soils was simply recycled by deep percolation and re-pumping from groundwater. Thus, although field irrigation efficiency is low, the actual depletion of water is only the sum of the evaporated and transpired components, and the groundwater return flow is reused (many times). Ahmad et al. (2004) also demonstrated that evaporation during the land preparation and subsequent crop growth periods after transplanting amounted to 60 percent (388 mm) of total evapotranspiration, and rice transpired only about 40 percent (272 mm of 660 mm). Therefore, there are significant potential water savings to be made by adjusting the time of planting and minimizing evaporation losses.

In the Rice-Wheat Zone of the Punjab, deep percolation contributes to the fresh groundwater aquifer, and this water becomes part of the broader scale irrigation supply as it is pumped from tubewells. The water stored in the root zone at the end of the rice season contributes to the needs of the wheat crop that follows. Deep percolation from the rice fields in this region should not be considered as a real loss as it is recycled and reused under multiple use cycles of groundwater abstraction (Keller et al. 1996; Seckler 1996; Ahmad et al. 2002, 2005). Other recent studies have shown that the water productivity of rice based systems is not low when studied at irrigation system or higher scales (Hafeez 2003; Matsuno et al. 2003; Renault and Montginoul 2003). The analysis indicates that evaluation of the water balance and water productivity of rice requires an annual perspective, an understanding of the whole cropping system and the extent of recycling and reuse of water within it.

Both, the SE Survey of the whole Rechna Doab and the RCT Adoption Survey, show that other RCTs, such as bed planting, are barely used (figure 8). The reasons for this can be briefly explained by the results of on-farm field

TABLE 1.
Measured water balance of a rice-wheat field: an example from the Rice-Wheat Zone of the Punjab, Pakistan, 2000-2001.

Water balance components	Rice season (mm)	Wheat season (mm)	Annual [rice-wheat] (mm)
Precipitation	320	34	354
Irrigation with canal water	182	0	182
Irrigation with tubewell water	468	343	811
Actual evapotranspiration	660	390	1050
Upward flux in root zone	50	19	69
Downward flux from root zone	302	43	345
Change in root zone storage	58	-37	21

Source: after Ahmad et al. 2002

trials conducted by IWMI from 2001 to 2003, which showed that yields of both rice and wheat in bed planting systems are lower than in conventional or zero tillage systems. Similarly, the yields of direct seeded rice are lower than for conventional transplanting (table 2). The trials were performed on full-size farmers' fields at three locations in the head, mid and tail of a watercourse. The beds were freshly made each year, and rice was direct seeded into 'dry' soil using modified direct drill to sow normal seed. These findings complement work reported by Kukal et al. (2005) that relative yield declined on permanent beds over time.

The technology package for these RCTs is clearly still under development in the Punjab, and the yield loss in direct seeding of rice and bed systems has been attributed to:

- weed infestation in direct seeded and bed planted rice;
- lack of precision in sowing depth, resulting in poor seed germination and low crop density in direct seeded rice;
- loss of net cropped area due to the relatively high proportion of furrow area to bed area;
- lack of farmer experience with agronomy and water management in bed planting systems; and
- lack of reliability, equity and adequacy of canal water supplies, resulting in poor crop establishment.

Irrigation water savings with zero tillage in wheat are modest in comparison with traditional practices. On the other hand, irrigation water savings in rice are significant (some 30-40%), but they are derived from the recycled water component, and do not reduce actual evapotranspiration. Surprisingly, higher evaporation from direct seeded fields increases net water depletion by roughly 150 mm due to a longer crop season (about 30 days).

In this experimental study, the difference in irrigation input between zero tillage and conventional methods was small compared with what farmers usually report (including the RCT

TABLE 2.
Comparison of water balance and water productivity of various resource conservation technologies (RCTs) in Rice-Wheat Zone, Rechna Doab.

RCTs	Rain mm	Irrigation mm	Gross inflow mm	ET_c mm	Yield kg/ha	WP_{y_Ig} kg/m^3	WP_{y_ETc} kg/m^3
RCTs for Rice							
Direct seeding on flat fields	198±84	966±209	1164±212	695±40	2878±1357	0.25±0.14	0.40±0.19
Direct seeding on beds	198±86	920±208	1118±232	695±44	2850±1170	0.26±0.15	0.41±0.16
Transplanting on beds	183±84	1200±317	1383±310	539±74	3124±854	0.23±0.09	0.56±0.15
Traditional transplanting	183±80	1384±273	1567±268	544±46	3910±1039	0.25±0.08	0.72±0.20
RCTs for Wheat							
Zero tillage	106±76	176±84	281±65	416±37	4322±849	1.62±0.52	1.03±0.22
2 row beds	106±76	148±81	254±60	415±37	3260±1180	1.33±0.47	0.77±0.30
3 row beds	106±76	160±80	265±46	415±33	3316±890	1.24±0.37	0.80±0.23
Traditional practices	106±76	185±77	291±76	416±35	4131±503	1.53±0.48	0.99±0.13

Source: Field experiments for water use and productivity conducted under RWC project at selected farmers' fields during 2001-2003 (See also Jehangir et al. 2007)

Notes: WP_{y_Ig} refers to water productivity in terms of yield per unit of gross inflows
WP_{y_ETc} refers to yield per unit of potential crop evapotranspiration
kg/ha – kilograms per hectare
kg/m^3 - kilograms per cubic meter

Adoption Survey) and what other studies have presented (Gupta et al. 2002; Hobbs and Gupta 2003). It is possible that more timely sowing of the conventional wheat treatment at the same time as the RCT treatments allowed better use of conserved soil moisture for the wheat, which does not normally occur in field conditions when conventional sowing is delayed.

Field to Farm Scale

In this section, we explain how the improvements in irrigation efficiency with adoption of RCTs actually contribute to increased water use, rather than result in net savings at farm and system levels. According to farmer responses, there is a significant increase in cropping intensity on medium and large farms following the adoption of zero tillage and laser leveling, as shown in figure 12. There is only a marginal increase in cropping intensity by small farmers, because in general they already cultivate all available area and are not constrained by labor or water availability. In contrast, water and, to a lesser extent, labor limit the area sown by medium and larger farmers. The reductions in field level water applications, mainly surface supply, derived from RCTs allow them to expand the wheat area, which then requires greater groundwater abstraction to maintain the crop, once planted.

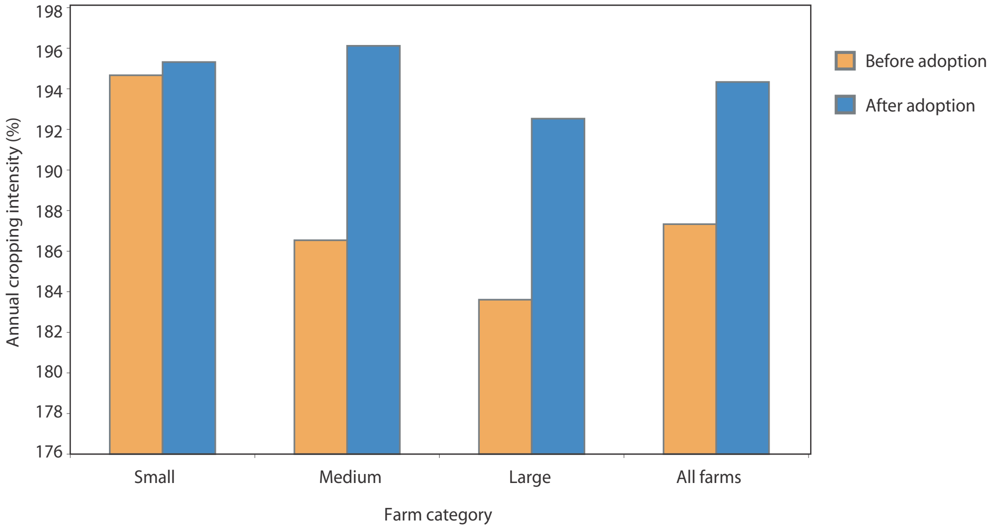
The implications for water use are shown in table 3, based on potential crop evapotranspiration elaborated on earlier in this report. On average this implies a small but significant increase (8% for large farmers, 5% for medium farmers and less than 1% for small farmers) in net water use, which will further contribute to stress on the groundwater system.

Some farmers reported higher infiltration rates under zero tilled soils, and that rainwater

TABLE 3.
Changes in total evapotranspiration at the farm scale as influenced by RCT adoption and resulting increase in cropping intensity in the rice-wheat zone of the Punjab, Pakistan.

Average farm size under each category (ha)	Change in potential crop evapotranspiration (%)		
	Rabi	Kharif	Annual
2.83 *(small)*	1.5	-1.1	0.2
7.69 *(medium)*	5.0	3.7	5.0
33.18 *(large)*	7.7	5.0	8.1

FIGURE 12.
Impact of RCT adoption on cropping intensity in the Rice-Wheat Zone of the Punjab, Pakistan



is more effectively captured, which is especially beneficial in clayey and salt affected soils as it contributes to leaching. Farmers' observations of increased infiltration rate under zero tillage suggest that further studies are needed to quantify the contribution of rainfall to crop water demand. More effective use of rainfall (with lower evaporation losses due to high infiltration) could result in greater groundwater recharge, lowered groundwater pumping, or increased yields with no change in groundwater use (where wheat is currently under-irrigated), depending on farmer response. More systematic measurements of water balance components at farm to system scales are needed to study the changes in recharge to groundwater, surface water runoff, water depletion and soil moisture storage in the root zone arising from RCT adoption. This poses serious experimental challenges, but ones that can be addressed with sophisticated instrumentation, chemical/ isotope tracing techniques and hydrological modeling.

Farmers use all the available **canal** water, because it is of good quality and considerably cheaper than pumped groundwater (farmers' annual costs for canal water and groundwater use in Rechna Doab are estimated as US$7 and US$100 per hectare (US$/ha), respectively). Because of this, canal water and rainfall play critical roles in leaching salts from the root zone, whereas groundwater use augments salinity, especially in the lower reaches of the canal systems and of the Doab.

Currently, the overwhelming majority of farmers rely on conjunctive water supply, using groundwater, even of poor quality, to make up for inadequate volume, frequency and timing of canal water. Farmers reporting an increase, decrease or no change in the amount of groundwater irrigation after RCT adoption were 13, 54 and 33 percent, respectively. The increase in groundwater use was mostly reported by large farmers which will increase pressure on groundwater resources, as large farmers, although a minority in number, own about half of the farmland in Rechna Doab (Annex 8). In the long run with reversion to more normal precipitation in Indus Basin, canal water supplies can be expected to be roughly double those from the drought/low rainfall years of 1999-2003, and there will be less pressure on groundwater and more good quality water will be available. However, longer term reductions in snowmelt and Himalayan ice-pack are already evident, and are projected to worsen with global climate change, so long term surface water availability is also projected to decline and drought periods become more frequent and severe.

The increase in tubewell irrigation intensity occurs mainly on large and medium farms, where more area has been brought under cultivation or the cropping pattern has changed as a result of adoption of RCTs. In contrast, most of the smaller farmers reported a decrease in groundwater pumpage, which could be attributed to increased efficiency of canal water use with similar land use intensity/pattern, and without the ability to reuse the savings. Since the volumetric change in total irrigation water use was not measured in this study, it is only possible to estimate the implications and consequences of these changes.

Farmers' strategies and balance of water use will change, but it is very likely that once they have realized that they can establish larger areas through more efficient irrigation management in wheat, then the tendency for more generally increased groundwater use will continue.

At a farm scale, the adoption of beds or direct seeding of **rice** will only take place if (1) the yield penalties can be reduced; and (2) the costs of managing weeds (and using bed planters and other machinery) reduced to levels that result in higher gross margins. This is particularly true for medium and large scale farmers, who are commercial producers. Even if these technologies are adopted, savings to farmers will be in the form of reduced pumping costs, not in depleted water and, even at farm scale, there will be no net realizable savings in water use. It is possible, that reduction in pumping and reduced pumping costs could also encourage some farmers to plant more rice if they have excess land, as has been seen with wheat.

If attractive technologies can also be developed that minimize actual evaporation losses between land preparation and the establishment of full vegetative cover of rice then it will, in theory, be possible to make real savings in water use. Given the experience so far, it would also be reasonable to conclude that such savings would be used on farm to plant larger areas of rice on medium and large properties, as has happened with wheat. The implications for increased groundwater use from this would be more significant than at present.

Farm to System Scale

At irrigation system and basin scales, the net effect of irrigation water savings in wheat by smaller farmers and the counterbalancing increase of groundwater for wheat by medium and larger farmers, depends on the differential adoption rates of the technologies, and the relative proportions of land area in each category.

At the moment, adoption rates of zero tillage and laser leveling are highest by medium and larger scale farmers who have better access to the required machinery, more to gain from increased efficiency and better management, and who occupy, overall, about 50 percent of the cultivated area. Therefore, the net increase in water use from the medium and large scale farmers will outweigh the net savings on small farms, and result in further net increases in groundwater use. The expected change in crop evapotranspiration across the sampled distribution of farm size in Rechna Doab is given in figure 13 to illustrate this point.

The net increase in annual crop water depletion at Doab level is estimated (see table 4), given current adoption rates, an assumed ceiling on adoption, and estimates of incremental land area that can be sown. Since these changes are relatively small, it is difficult to monitor them with any precision, especially given the inter-annual variations in water availability and use in a complex system like Rechna Doab. Nevertheless, these scenarios provide useful information on system/basin level impacts. It is important to note that most of these increases in evapotranspiration are achieved by a reduction in groundwater recharge and that this may aggravate the decline of the groundwater table in rice-wheat systems and also reduce groundwater availability

FIGURE 13.
Impact of RCT adoption on farm level potential crop water requirements in the Rice-Wheat Zone of the Punjab, Pakistan.

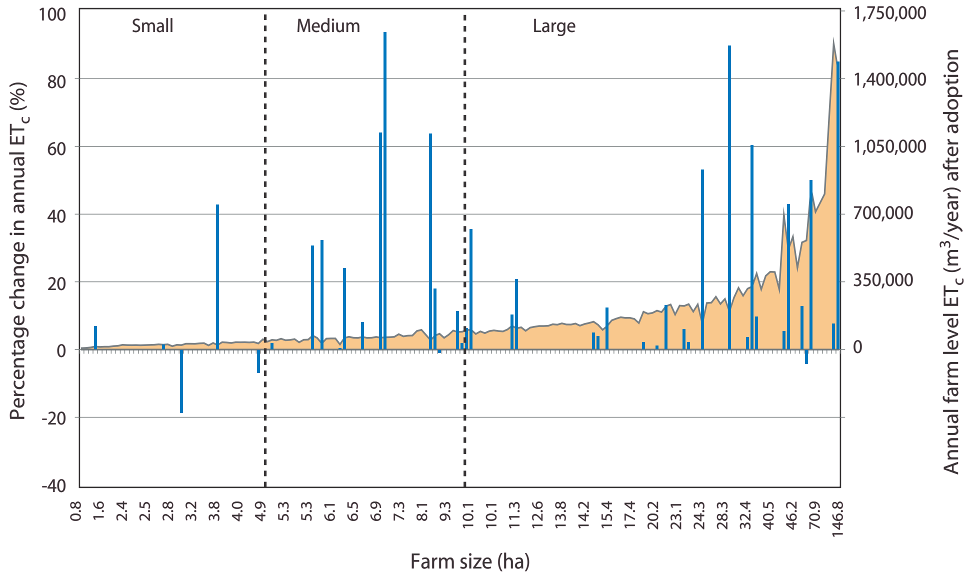


TABLE 4.
Anticipated changes in the volume of crop water use in Rechna Doab, as a result of the increased RCT adoption.

Domain of analysis	Farm area (“000” ha)	Adoption rate %	Net increase in crop water use (10^6 m^3)	%
Base Scenario: Increased crop water use under current level of RCT adoption				
Rice-Wheat Zone	1,440	28	252	1.8
Rechna Doab	2,594	18	291	1.2
Scenario 1: Maximum increase in RCT adoption of 20%, assuming similar trends in differential adoption rates (of 57% on large farms), changes in cropping pattern and an increase in cropping intensity of 7%.				
Rice-Wheat Zone	1,440	48	431	3.2
Rechna Doab	2,594	38	615	2.5
Scenario 2: Maximum increase in RCT adoption of 40%, otherwise as scenario 1				
Rice-Wheat Zone	1,440	68	611	4.5
Rechna Doab	2,594	58	939	3.8
Scenario 3: Maximum increase in RCT adoption of 60%, otherwise as scenario 1				
Rice-Wheat Zone	1,440	88	791	5.8
Rechna Doab	2,594	78	1262	5.1

Note: Adoption rate is based on IWMI socio-economic survey and includes zero tillage and laser leveling RCTs only

to ‘downstream’ users. Without increases in surface supplies or other institutional arrangements to limit water use in the near future, this may result in a negative water balance at a system scale and pose a serious threat to the sustainability of irrigated agriculture.

Discussion

The discussion refers to the context and water-related implications of the adoption of RCTs in three situations: to (1) the Mid-Indus Basin, as represented by the Punjab, (2) the Lower Indus Basin as represented by the Sindh, and (3) in more generic relation to semi-arid, water scarce basins.

The main policy implications hinge on the role and nature of groundwater irrigation. Since the early 1980s, private development of groundwater irrigation has proved, in the Punjab, to be dramatically more successful in reducing waterlogging and lowering the groundwater table than earlier attempts to use pumped drainage, starting with the Salinity Control and Reclamation Program (SCARP) projects in the 1960s. The most extensive development and pumping of groundwater is in the freshwater zones, such as Middle and Upper Rechna Doab, the location of the rice-wheat systems of the Punjab. The present success of salinity mitigation and land reclamation (usually by farmers) in the Punjab is a yet undocumented story. Although there is considerable pumping of poorer quality groundwater in more downstream zones, such as Lower and Inner Rechna Doab, gradients between saline groundwater and freshwater zones are developing. The long term danger to the sustainable use of groundwater is the potential mixing and degradation of the fresh groundwater zones from the saline ones.

The situation in the lower basin, in the Sindh, provides a stark contrast with widespread high and very saline water tables, largely due to over-application of canal water and ineffective drainage, in part due to very low land surface gradients to the sea. Many public funded SCARP (reclamation) wells are no longer operational, and some problems persist with the operation of the arterial Left Bank Outfall Drain (LBOD).

In the Punjab, the recent low allocations of canal water (as little as 40% of long term average supply), due to low snowfall and rainfall in the Upper Indus Basin, have contributed to lowered water tables, through (1) lower recharge from surface irrigation from fields and the channel network, and (2) increased groundwater abstraction in all zones. In the longer term, water tables may rise again, and the gradients between saline and fresh areas may decrease and stabilize.

The main incentive for large and medium scale farmers to adopt RCTs lies in the increased profitability of wheat production in the Rice-Wheat Zone, due to a combination of reduced costs and increased yield through better timeliness of sowing. The success of this technology, and the small realizable water savings at field level allow expansion of the winter wheat area, requiring further abstraction of groundwater to support the additional crop through to harvest. Potentially, there could be greater groundwater abstraction in winter on up to 50 percent of the rice-wheat area (depending on final levels of adoption), with implications for a long term increase in the risk of groundwater mixing and degradation, as estimated in the previous section. However, adoption of RCTs may be only one of many reasons that farmers will continue to increase use of groundwater in the Punjab.

The main policy lever constraining over-exploitation of the groundwater is the maintenance of full cost recovery pricing for energy to constrain groundwater use within economically viable limits. To date, this has largely been the case in Pakistan, where the majority of irrigation tubewells are diesel powered, and pumping depths do not require excessive energy inputs. Careful oversight of the energy-irrigation nexus in Pakistan will be an important factor in the sustainability of groundwater use and in the management of salinity at a basin scale.

Almost any technology that minimizes groundwater recharge ought to be attractive to farmers and policymakers in the Sindh, where water tables are high and saline over extensive areas. Groundwater use is much less common because of the high salinity of the water table, and drainage will continue to rely on public-sector drainage wells coupled to extensive surface drainage networks. Normally, disposal of salt is the overriding problem in arid-zone irrigated agriculture, but the Left Bank Outfall Drain (LBOD) allows disposal of saline effluent directly to the sea – at least in theory, as there are considerable operational difficulties at present, including seepage induced salinization of areas adjacent to the main channel and problems with the outfall structure and gates. Rice areas in the Sindh maintain good soil and water quality through application of large quantities of surface water, generating a continuous flux that leaches the soils, but this contributes strongly to regional groundwater rise and larger scale salinization in non-rice areas.

In the Sindh, broad adoption of zero tillage would help to reduce net accession of groundwater, and the incentives for its adoption by larger and medium scale farmers are self driven, as explained earlier. Small farmers still face capital barriers to the adoption of zero tillage, due to the price and availability of direct seeding machinery and tractors. Rental markets could be further stimulated to ensure cost-effective and timely supply of direct seeding equipment, but alternatively, smaller scale and cheaper equipment, such as that being produced in the Haryana and the Punjab in India, could be an attractive alternative for the smaller farmer, in both the Punjab and the Sindh.

Laser leveling has long been promoted in Pakistan, with very low levels of adoption without subsidized government assistance until recently. This research shows that even in the Punjab, real interest in laser leveling has been stimulated probably because of the reduction in irrigation times, and the better uniformity of application, both of which assume greater importance when canal supplies are limited and groundwater quality is poor. Evidence for this is the greater level of adoption in the sugarcane-wheat system in the Lower Rechna Doab, where recently farmers have been relying increasingly on groundwater, despite its poorer quality.

To date, adoption rates of zero tillage and laser leveling in the Sindh have not been surveyed and assessed in the same detail, nor the farm size distribution and the locations of rice-wheat and other production systems. This is certainly a task that should be undertaken. Farmers' understanding of water savings, resulting from laser leveling, and their appreciation of other benefits such as better and more uniform leaching, would pave the way for broader adoption. If there are no direct production benefits evident, then, in the interests of long term sustainability, it may be prudent to scale up the extent of laser leveling and use well-targeted subsidies to encourage its more widespread adoption, as is being done in the Punjab, Pakistan. In the rice areas of the Sindh, reductions in total water application will have a net positive benefit on lowering and stabilizing water tables. RCTs such as bed planting, if they can be made to perform as well or better than traditional transplanting, offer the possibility of significant reductions in total water application, mainly through reduced ponding, seepage and evaporation losses. A salt balance analysis will also be necessary to understand the effects on leaching and salt accumulation of reducing water fluxes through rice paddies in the Sindh.

Salinity has a much larger negative effect on water productivity than the incremental addition of irrigation water, or higher use of nitrogen fertilizer. As groundwater degrades, water productivity of all crops will steadily decrease, and ultimately the aquifers in the Punjab could become too saline for agricultural use, as has already happened in the Sindh and in significant parts of the Murray-Darling Basin in Australia (Khan 2004).

Options to replace one crop with another need to be carefully evaluated, even if the policy levers to do this are often limited by the dictates of the market. However, in Australia, rice cropping is zoned and prohibited in areas where there is high groundwater recharge as a result of ponding water on porous soils (Humphreys et al. 1994). In Pakistan, replacing rice with cotton may lead to a reduction in net irrigation application, but would lead to more water depletion as cotton has higher seasonal evapotranspiration than rice, particularly the transpiration component (Ahmad et al. 2004; Jalota and Arora 2002). However, replacing rice with cotton may be a good option for areas where seepage and percolation go to sinks (e.g., saline groundwater), but it is necessary to assess the biophysical environment, market and other factors conducive for replacement of one crop with another.

Conjunctive water management is the key to Pakistan's agricultural future, and understanding of the impacts of surface and groundwater use on salinity in the long term is required. Water allocation policy should explicitly account for future effects on salinity, water productivity and the sustainability of groundwater use. Although there has been considerable monitoring of groundwater depth and quality, much of the data have not been evaluated and a good understanding of surface-groundwater interaction has not yet been achieved. This can be done through scenario modeling that links surface and groundwater allocation and use, but the modeling must also be able to include and explain the impacts of interventions (SCARPs, private groundwater abstraction) on water table levels and salinity since WAPDA's baseline survey in the early 1960s. The modeling framework also has to take into account key factors elaborated in this research report:

1. the proportions and extents of canal and groundwater use;
2. the efficiency and equity of surface water allocation and distribution within and across systems;
3. the extents of and connections between saline and fresh groundwater areas and their connections to the surface supply system - via rivers, irrigation and drainage canals, regional and on-farm;

4. farm structure: the size and distribution of large, medium and small farms and their differential impacts on surface and groundwater use;
5. the fit and nature of technologies, such as RCTs, to these farms and farming systems, including: effectiveness and performance of the technology; incentives for its adoption; capital and operational requirements;
6. the balance of upstream and downstream development and surface water allocation over the full range of natural hydrologic variability;
7. understanding of where technologies and allocation policy result in real water savings at field, farm, system and basin scale through understanding what happens to water delivered on farm – whether it is transpired, evaporated, recycled over and over again, or lost to a sink, such as saline groundwater; and
8. social issues, for example, the influence of large, wealthy landholders on distribution of water and the distribution of RCT benefits among various farm size categories, etc.

The lesson that field level water savings from RCTs translate into net increases in total water use at system scale (on the rational economic basis that the more productive an activity is, the more of it a producer wants to do) is highly instructive. The implications for the Indus Basin, outlined above, are more generally applicable to many arid basins where surface and groundwater are conjunctively used, and where salinity imposes a delicate balance on the long term sustainability of the agricultural system.

The overriding message of this research is that water savings on farm that lead to more productive enterprises will tend to be reused somehow, and may even stimulate greater total water use. The main factor governing this in Pakistan is farm size: in situations where small farmers are the majority, small net water savings may not be able to be reused on farm, and the cumulative saving may result in system level water savings. Alternatively, the savings could allow better placed large farmers or other downstream users a more secure and generous water supply. In countries like Australia, water rights are allocated to each individual farmer and as bulk allocations to an irrigation system, stock and domestic water supply or rural town (Humphreys and Robinson 2003). In such situations, it is up to the right-holder what happens to unused water allocation – it can be traded, used for intensification, as in the Punjab example, or simply left in the system – either as carry over storage to another year or as spill through the dams or as in-stream flow. A key question that is rarely addressed in the rhetoric on water savings is, *"who is the beneficiary of real water savings"* when they exist.

One of the lessons of this work is that the fate of real water savings is a very variable outcome, and one that pushes for more explicit recognition and allocation of water rights to farmers, irrigation systems and other users in developing countries such as Pakistan. Even then, there are multiple possible outcomes, it will be important that the allocation and maintenance of environmental flows does not rely on notional water savings, but instead are explicitly specified (e.g., amount, pattern, location and quality). The multiple incentives to save water and the factors governing security of supply will in the end drive the adoption of water saving technologies, and policymakers need to be aware of the likely outcomes.

Recently, to address the issue of growing water scarcity, the Government of Pakistan launched a massive *watercourse lining program.* The aim of this project is to save water by seepage reduction and to enhance agricultural production by further expansion/increase in cropping intensity. As suggested in this study, there is need of a broader scale perspective in the water conservation strategies embarked upon in Indus Basin of Pakistan and similar basins elsewhere. More comprehensive understanding and evaluation of impacts on water balance (and salinity) dynamics at larger hydrological domains and the possibilities of achieving real water savings needs to be incorporated in project planning and impact evaluation studies.

Conclusions

The study shows that farmers in the rice-wheat area of the Punjab, Pakistan, are adopting Resource Conservation Technologies (RCTs), specifically zero tilled wheat and laser leveling, that help to improve their livelihoods and reduce the costs of production. Improving water productivity and achieving real water savings remain secondary concerns, despite a gradual increase in water scarcity at the sub-basin or basin scales. Increasing use of fresh groundwater has helped farmers to remedy the scarcity of canal water, although declining groundwater tables have indicated the need for better conjunctive management of these two sources of water. The implications of this for sustainable groundwater use and salinity management are complex and multiple outcomes are possible, depending on the understanding of policymakers and their subsequent actions.

> *Counterintuitively, field level water savings due to the adoption of zero tillage and laser leveling in wheat production have contributed to increased net water use at system scale, due to field level savings being used to establish greater crop area on uncultivated land owned by medium and large scale farmers.*

Without doubt, net basin level water use has also increased, as evidenced by declining groundwater levels, but at this stage, it may not be significant in terms of the total water balance. This study provides a practical example of why system level approaches to water conservation are required to understand the differential impacts of interventions in the hydrologic cycle at different scales. The impacts of broader scale adoption of resource conserving technologies depend on many factors, especially the opportunity to reuse apparent savings at the farm level. Pakistan is perhaps unusual in the extent of its potentially irrigated area that is cultivated by medium and large scale farmers with unused fallow areas, but even without this, there are many other possibilities at the basin level to reuse water that has apparently been saved at field level.

Zero tillage technology for wheat cultivation and laser land leveling are being more widely adopted than beds and alternative crop establishment methods for rice, which are as yet immature and unprofitable options. The analysis indicates that both zero tillage and laser land leveling have positively contributed in increasing net income of the farmers, whereas other RCTs do not yet offer that possibility. Reduced recharge to groundwater and declining water tables suggest that more rigorous analysis of the trade-offs among various water balance components is required for proper impact evaluation and to identify the contribution of RCTs to sustainable management of water and land resources.

There is a need to devise suitable guidelines for making RCTs viable and managing the associated water savings and/or water productivity enhancement options across all scales of irrigated river basins. The opportunity of increasing economic benefits could be harnessed along with achieving real water savings, but these will not be realized at the basin scale without corresponding institutional development that involves better water accounting, more detailed and better balanced water allocation strategies, policies that promote balanced and wise conjunctive use of surface and groundwater, and social frameworks and policies which can implement those strategies. Strategies for developing and promoting resource conservation technologies should be based on the following four major thrusts:

1. optimizing water depletion by productive uses;
2. selecting technologies that are appropriate to the farming system and to the hydrologic outcomes at the basin level, based on better understanding of the factors involved;

3. improving overall management of the irrigation system; and
4. comprehensive water balance and water productivity assessment at field to higher scales of the river basin.

For the zero tillage and laser land leveling technologies in Indus Basin of Pakistan, real water savings and improvement in water productivity can be achieved by: (a) providing incentives to small farmers for technology adoption while limiting new groundwater use by medium and large scale farmers, (b) improving the performance of canal water supply systems and managing these systems in high water availability years to sustain good quality groundwater resources, (c) promoting evaporation reducing technologies on a priority basis in Rice-Wheat Zone located in upper parts of Indus Basin (Punjab) where groundwater quality is fresh and drainage is reused by downstream users, (d) targeting technologies that reduce accessions to saline groundwater and also minimize evaporation losses at the Rice-Wheat Zone in the lower part of the basin (Sindh), and (e) investing more on data collection, monitoring and case studies for detailed agro-hydrological, salinity and water productivity assessment for resource conservation technologies at different scales, from field, to farm, to system, and to basin.

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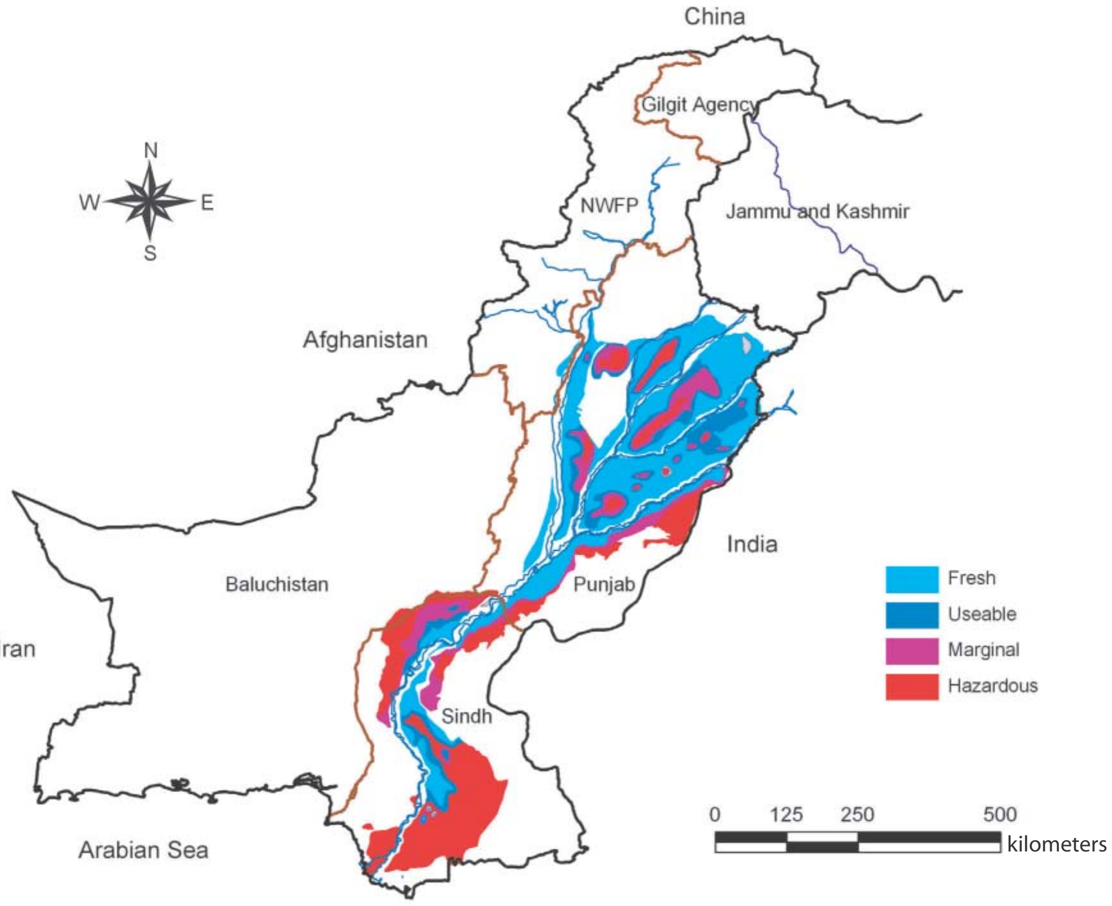
Annexes

Annex 1.

Spatial variation in groundwater quality across the Indus Basin of Pakistan.

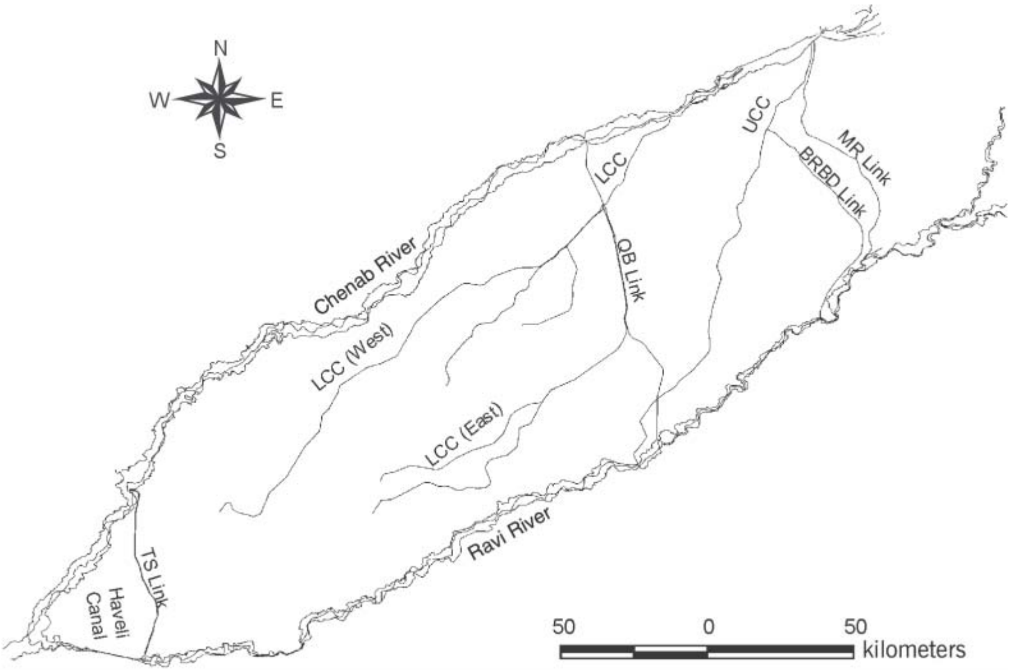
Classification Criteria Used by WAPDA:
[Fresh: Conductivity (25°C) <0.75 dS/m and SAR <6;
Useable: Conductivity (25°C) <1.50 dS/m and SAR 6-10,
Marginal: Conductivity (25°C) <1.50-3.00 dS/m and SAR 10-18;
Hazardous: Conductivity (25°C) >3.00 dS/m and SAR >18]



Data/Map Source: Water And Power Development Authority (WAPDA), Pakistan, 1977

Annex 2.

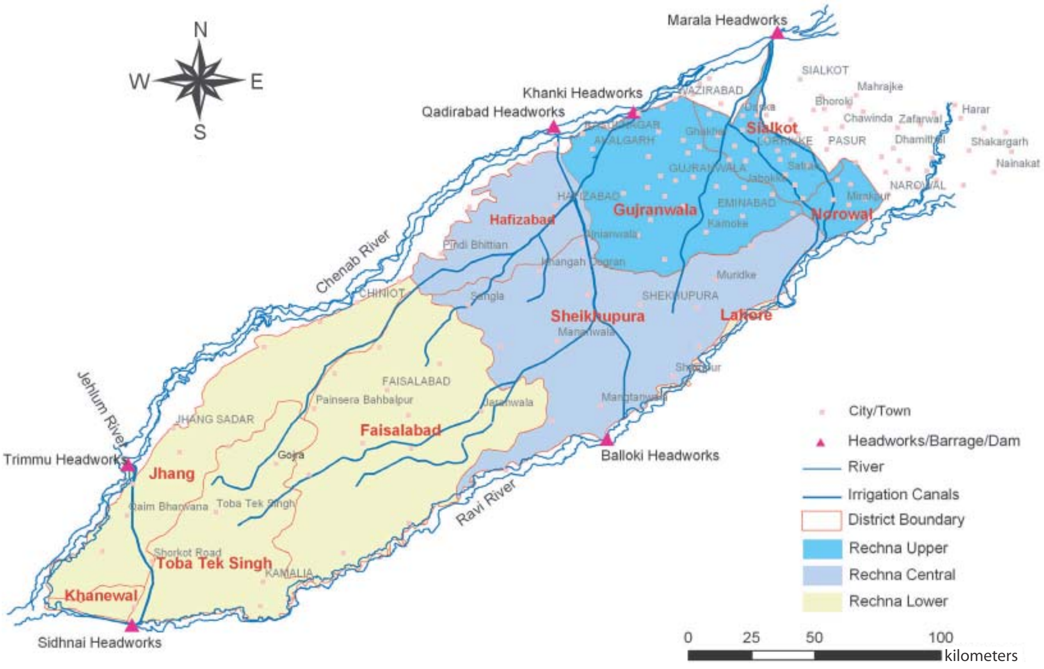
Irrigation network in Rechna Doab, Pakistan.



Note: Upper Chenab Canal (UCC), Bambanwala-Ravi-Bedian-Depalpur (BRBD) Link, Marala-Ravi (MR) Link, Qadirabad-Balluki (QB) Link, Lower Chenab Canal (LCC), Trimu-Sadhnai (TS) Link and Haveli canal. Upper Rechna Doab (served by MR Link, BRBD Link and UCC) is non-perennial system (little or no water supply in *rabi*)

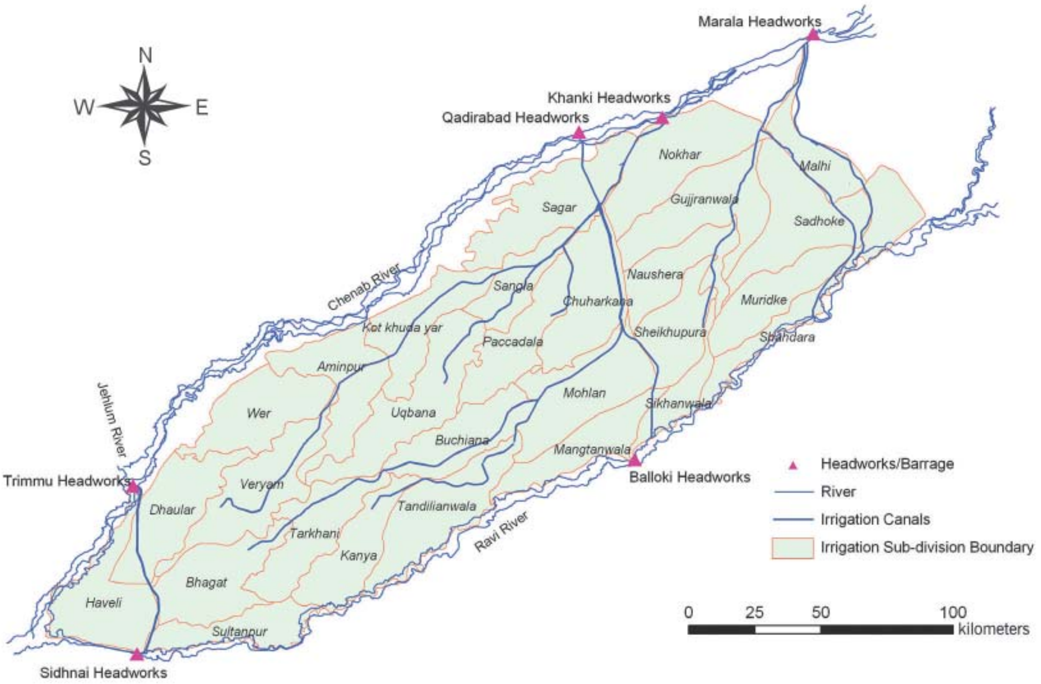
Annex 3.

District boundaries in Rechna Doab.



Annex 4.

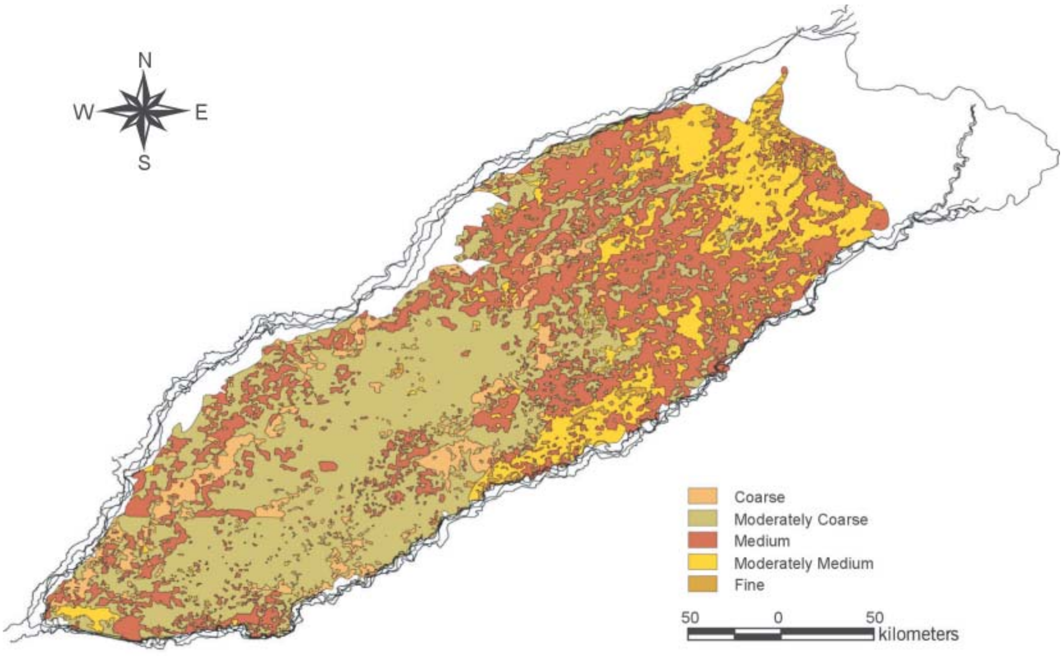
Irrigation Sub-divisions in Rechna Doab.



Note: A sub-division is the lowest administrative unit of the Irrigation departments in Pakistan

Annex 5.

Soil texture map of Rechna Doab.



Source: WAPDA 1981

Annex 6.

Key Resource Conservation Technologies (RCTs) being promoted in Pakistan.

a. Laser land leveling

b. Zero tillage

c. Bed planting

d. Direct seeded rice

Source: Photographs a and c: Mr. M. A. Gill, OFWM, Punjab, Pakistan
Photographs b and d: Dr. Riaz Ahmad Mann, PARC, Islamabad, Pakistan

Annex 7.

Statistics of RCT adoption (% cultivable area) in Irrigation Sub-divisions in Rechna Doab.

	RCT area	Laser land leveling	Zero tillage	Furrow-bed planting	Crop residue management
Malhi	-	-	-	-	-
Sadhoke	20	-	20	-	-
Shahdra	40	-	22	-	17
Muridke	11	-	11	-	-
Gujranwala	19	10	9	-	-
Nokhar	-	-	-	-	-
Noushera	35	-	35	-	-
Sheikhupura	27	-	27	-	-
Shikhanwala	0.5	-	0.5	-	-
Chuharkana	5	-	5	-	-
Sagar	-	-	-	-	-
Upper	**15**	**1**	**12**	**-**	**2**
Sangla	4	-	-	4	-
Mohlan	3	3	-	-	-
Mangtanwala	-	-	-	-	-
PaccaDalla	-	-	-	-	-
Buchiana	36	35	1	-	-
Uqbana	1	1	-	-	-
Kot Khuda Yar	16	3	-	13	-
Aminpur	16	-	16	-	-
Tandlianwala	-	-	-	-	-
Middle	**9**	**6**	**2**	**1**	**-**
Kanya	-	-	-	-	-
Tarkhani	-	-	-	-	-
Veryam	3	-	3	-	-
Wer	-	-	-	-	-
Sultanpur	-	-	-	-	-
Bhagat	7	7	-	-	-
Dhaular	33	28	5	-	-
Haveli	-	-	-	-	-
Lower	**10**	**9**	**1**	**-**	**-**
Overall	**12**	**4**	**6**	**0.4**	**0.8**

Source: IWMI Socio economic survey 2004

Annex 8.

Percentage distribution of small, medium and large farms with respect to farm area and farmers in district of Rechna Doab. Gujranwala, Hafizabad, Sialkot, Narowal and Sheikhupura districts falls under the Punjab rice-wheat zone.

District	Percent distribution based on farm area			Percent distribution of farmers		
	Small	Medium	Large	Small	Medium	Large
	≤5 ha	>5-10 ha	>10 ha	≤5 ha	>5-10 ha	>10 ha
Gujranwala	48	24	28	83	11	6
Hafizabad	45	24	31	80	13	7
Sialkot	72	15	13	95	4	1
Narowal	72	16	12	94	4	2
Sheikhupura	54	22	24	87	9	4
Faisalabad	73	18	9	93	6	1
T. T. Singh	60	22	18	89	8	3
Jhang	42	18	40	83	10	7

Source: District-wise farm size in Rechna Doab (Agricultural Census 2000, Punjab)

Annex 9.

Salient characteristics of the respondent farmers of rice-wheat zone of the Punjab, Pakistan.

Category	Adopter (N=168)	Dis-adopter (N=25)	Non-adopter (N=30)	Overall (N=223)
Mean age (years)	44	46	45	45
Occupation (%)				
Farming	80	56	80	77
Farming and employment	7	16	7	8
Farming and others	13	28	13	14
Farming experience (mean number of years)	25	25	24	25
Education (%)				
Illiterate (0 years of schooling)	29	32	23	28
Primary (5 years of schooling)	12	8	10	11
Middle (8 years of schooling)	16	12	7	14
Matric (10 years of schooling)	28	20	50	30
Intermediate (12 years of schooling)	11	20	10	12
Graduate & above (≥ 14 years of education)	4	8	--	5
Tenancy status (%)				
Owner	60	56	63	60
Owner-cum-tenant	35	36	33	35
Tenant	5	8	4	5
Mean farm size (ha)	18	16	13	17
Main soil type (%)				
Clay	44	44	30	42
Clay loam	29	24	30	28
Loam	17	24	23	19
Others	10	8	17	11
Soil problem (%)				
Salinity	40	20	40	38
Others	6	--	--	4
No problem	54	80	60	58

Note: N refers to the number of respondents

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