Irrigation and Drainage Systems 8: 201–231, 1994

irrigation canals | conjunctive use | groundwater | irrigation policy
tubewells | soil salinity | water quality
Pakistan | Punjab

Conjunctive use of canal and groundwater in Punjab, Pakistan: management and policy options

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Accepted 5 April 1994

Key words: conjunctive use, cropping patterns, groundwater, management issues, Pakistan, private tubewells, public tubewells, relative water supply, research issues, soil salinity, sustainability, water quality

Abstract. Data from 41 watercourses commands in Pakistan show that, as expected, farmers in head end reaches of canals receive more canal water than those in tail end reaches. Contrary to conventional wisdom, however, these head end farmers also use more groundwater than those at the tail end. Overall, groundwater plays a more important role in irrigation than surface water, ranging from 65% dependence on pumped water in head end areas to over 90% in tail end areas. This means that groundwater is no longer supplemental to canal water, but is an integral part of the irrigated agricultural environment. However, the cropping choices of farmers appear to reflect the amount of good quality canal water they receive: head end farmers are able to grow more high value basmati rice in the summer and more vegetables in the winter, leaving tail enders *to* rely on less valuable crops such as fodder and wheat.

Tail end areas are not only deprived of their fair share of surface water: they have to pump proportionately more groundwater which shows decreasing quality towards the tail. Typically, head end areas have groundwater with EC values of less than 1.0 dS/m, rising to over 2.0 dS/m in tail end areas. When the quality of both surface and groundwater used by farmers is examined, only the top 40% of the distributary gets water of adequate quality, the next 40% get below average quality, while the tail 20% of farmers irrigate with water that is classified as saline.

Because of higher dependence on more expensive groundwater tail enders use less water per unit area, thereby reducing the leaching requirement. The result is a clear increase in soil salinity from head to tail along distributary canals, and there is some evidence of land abandonment in tail end watercourses due to excess salinity.

The implications of these results are far reaching. Government policy includes plans to divert significant quantities of fresh canal water to areas underlain by saline groundwater on the basis that farmers already have adapted to pumping fresh groundwater. The results reported suggest that if this policy were implemented, there is a risk that over-dependence on fresh groundwater could lead to an intensification of the rate of soil salinization and deterioration of quality in areas currently classified as fresh groundwater zones.

At present, the location and utilization of privately owned shallow tubewells is not monitored, and thus it is not possible for government agencies to determine just how much water of different qualities is being used. Further, canal water deliveries, public deep well monitoring, watercourse monitoring programs, soil salinity measurements, and agricultural performance monitoring are all scattered among different agencies and organizations, making the task of effective conjunctive management of surface and groundwater even more difficult.

Conventional wisdom: 'Groundwater in Pakistan ... where it exists within the canal system ... is used to supplement surface water supplies to meet peaks in demand.' (WAPDA, 1990)

1. Objectives

This paper has two main objectives:

- to identify current trends in conjunctive use of canal and groundwater, and their implications for sustainability of current levels of agricultural performance;
- to identify future research needs and management options that will be required for sustaining irrigated agriculture in Pakistan into the future.

A special focus of the study was to utilize as far as possible the existing data sets collected by IIMI to determine what research directions might be appropriate in any continued investigation into conjunctive use of surface and groundwater in Pakistan.

This approach was adopted primarily for two reasons. Firstly, data collection in the field is expensive, and there is a considerable opportunity cost in using existing data sets. Secondly, field data collection is time consuming, and there frequently is pressure to produce output more rapidly than is normally possible with a more traditional approach to field investigation and research. At the same time, the approach which has been used has some limitations, and these must be understood in any effort to place this study into an appropriate perspective.

The first limitation is that most of the existing data sets were not collected for the specific purpose of understanding conjunctive use; rather, they were usually generated for other purposes. Thus, the data available from each site were not necessarily compatible, nor was the same range of data always collected in the same manner. A second constraint was that the data collection programs of other research projects did not necessarily cover the complete range of variables that would be desirable for this study. Hence, there is a general absence of any economic information, a lack of data on farmer practices in sharing water at the watercourse level, and an absence of surveys of farmer perceptions about the relative utility of surface and groundwater supplies and the cropping choices that result from those perceptions. Lastly, the data are not fully representative of the range of surface and groundwater conditions found in the Punjab; they refer primarily to areas where there is good to medium quality groundwater according to the classification scheme used in Pakistan, and reasonable but not optimal surface water deliveries.

The data utilized in this paper result from the salinity and groundwater studies undertaken by Kijne, Vander Velde and Johnson, (Kijne & Vander

Velde 1992; R. Johnson 1991; Vander Velde & Johnson 1992), the surface water studies undertaken by Vander Velde, Murray-Rust and Bhutta (Murray-Rust 1988; Murray-Rust et al. 1992; Vander Velde 1991; Vander Velde & Bhutta 1992a, 1992b), and the study on late irrigation of wheat done by Bhatti and Wolf (Bhatti et al. 1988, 1989). All of those studies were supported by funding provided by the Government of The Netherlands and/or USAID.

2. The role of groundwater in Pakistan

Although modest relative to the average annual canal withdrawals of about 129 billion cubic meters, annual useable groundwater recharge in the Indus Basin is estimated to be about 29 billion cubic meters, or slightly over half of the average annual recharge to the aquifers which underlie the Indus plains.’ As shown in Table 1, agriculture in Punjab Province has access to the largest portions of both surface water and groundwater.

Table I. Pakistan: average annual canal withdrawal & usable groundwater recharge.

Province	Canal withdrawals		Usable recharge’	
	(billion m3)	(MAF)	(billion m3)	(MAF)
NWFP	1.5	6.1	1.5	1.2
Punjab	66.4	53.8	24.1	19.5
Sindh/Balochistan	55.2	44.8	3.3	2.7

* Salinity < 1500 mg/l

Source: WAPDA, 1990. pp 3–4 & 3–33.

Conjunctive use of canal and groundwater has become the lifeblood of irrigated agriculture throughout much of the Indus Basin. Following the first experiments with tubewells for water table control in the 1950s and the subsequent implementation of the large scale public sector Salinity Control and Reclamation Projects (SCARP) in the 1960s, there has been a virtual exponential growth in groundwater development, especially in Punjab. The significance of the expanded role of groundwater in Pakistan’s irrigated agriculture can be readily grasped from a simple, straightforward comparison of the design expectations of the original canal system with current reality.

From the first phase of coordinated canal designs in the late 19th century, areas served by perennial systems in Pakistan were expected to have an annual cropping intensities ranging from 50% to 75%, two-thirds of which was to occur in the winter (*rabi*) and one-third in the summer (*kharif*). In other words,

a,

for half the year it was intended that no more than one-half of a canal command would be irrigated, while in the other half merely one-sixth to one-fourth of the service area would be planted to irrigated crops. Although some farmers could and do achieve higher cropping intensities than this using surface water alone, rarely are they able to exceed 100% for the year, and that usually is achieved at the expense of farmers in tail end commands who get little or no canal water at all for much of the year.

With extensive groundwater exploitation, however, cropping intensities in Punjab canal commands now commonly exceed 125%, increasing to over 150% in some watercourse commands. For more limited extents of canal service areas, groundwater sustains permanent crops, and the intensive cultivation of fruits and vegetables or other shorter duration high value crops that can be harvested two or three times in a year. For large areas of the province, however, there is mounting evidence that as a result of current levels of groundwater pumping water tables have dropped so far that opportunities for further increases may be severely limited (NESPAK-SGI, 1991).

Most groundwater exploitation in Pakistan is done in the context of conjunctive use with surface water. Irrigated agriculture using only groundwater is limited to mainly three situations: gaps in the canal systems of the Indus Basin where surface water has not been made available, small systems outside the Indus Basin, and in the tail reaches of canal commands that have lost access to surface water through inequitable distribution of canal water supplies. The vast bulk of the most productive areas of the Indus Basin, and Punjab in particular, are those where there is conjunctive use of canal water and good to medium quality groundwater. Only where groundwater is highly saline is there a reliance on canal water deliveries for sustaining irrigated agriculture.

To understand the dynamics of the current situation, it is useful to briefly review the way in which groundwater development has occurred in Pakistan over the past thirty years.

3. Understanding conjunctive use

Virtually all of the surface irrigation systems in Pakistan's Punjab were developed within the framework of the North India Canal Act of 1873. This act institutionalized the concept that water allocations would be insufficient to meet the full potential crop water demand over all of the area developed with irrigation facilities. During the following decades a method of sharing water by time also emerged and became codified. This system, known as *warabandi*, was developed in order to allocate a scarce resource as equally as possible between as many farmers as possible and to simplify subsequent administrative requirements. In practice there are two distinct types of warabandi – either sanctioned by the Irrigation Department (so called *pucca)*, or non-sanctioned by government but locally agreed upon (*kaccha*) – with each also characterized by different sharing arrangements and cycles. However, all warabandis have in common the basic characteristic of a fixed time for and share in irrigation on a timetable that is known to every farmer served by the same watercourse.

3.1 Conditions prevailing before groundwater exploitation

When groundwater is not available, farmers have to make decisions on the area to be irrigated during each warabandi turn: some crops might be irrigated every turn, others only once every two or three turns. Although there are some opportunities for buying and selling water out of turn these are likely to be limited because all farmers face the same potential water deficit. Farmers are only likely to sell part of their turn if they have cultivated less than their full potential, or if the potential profit from selling water appears especially attractive.

Historically, through dug wells to which primitive water lifting devices were subsequently added, or later still, animal power was harnessed (e.g., the Persian wheel), a very small amount of groundwater development had occurred in parts of the Indus Basin. This was generally restricted to such locales as riverine terraces where water tables were favorable, and even with the advent of the Persian wheel, well irrigation remained slow, costly and limited in command area.

3.2 Public deep tubewell development: 1950-1980

Modern groundwater development in the Indus Basin occurred primarily through publicly financed and operated deep tubewells. These tubewells were invariably electric powered, with multi-stage turbine pumps in the bore itself, and designed to deliver about 85 l/sec.

In Pakistan Punjab several experimental attempts by government were underway in the 1950s to use deep tubewells either to reduce water tables in waterlogged areas or to increase supplies of water for irrigation. By the early 1960s Pakistan had embarked upon a large scale program of deep tubewell development, the SCARPs, primarily to combat widespread waterlogging and associated salinity. Over the past 30 years, more than 12,500 public tubewells have been installed nationally through various SCARP projects. An important, initially secondary, objective of this program was surface water supplementation by public wells, usually discharging directly into the existing watercourse network, where groundwater was classified as suitable for agriculture.[2]

The resulting conjunctive use of canal water and groundwater did not change the basic approach to irrigation through a time-based roster of turns, the warabandi. Rather than providing greater flexibility in access to water, the primary effect of the public tubewell was to augment the discharge in the watercourse.

Public tubewells, notably those pumping water defined as fit for irrigation use in SCARP schemes, are supposed to operate according to schedules developed by the Irrigation Department. The schedules are intended to conform to broad guidelines concerning the target percentage of annual capacity and the time of day of operation. For various reasons both guidelines and operating schedules have ceased to have much relevance to actual public tubewell operations (S. Johnson 1982).

The institutional setting is sufficiently complex that it has become difficult to achieve much coordination. The SCARP wells were installed by WAPDA and operations are controlled by an Irrigation Department division that is independent of the divisions that handle canal operations and drainage. The actual operation of the public tubewell is under the (now nominal) control of an operator, a low level irrigation department employee in the tubewell operations unit, whose job is to turn the tubewell on and off according to schedule, including the requisite four hour 'rest' period, to keep the equipment functioning as well as possible, and to maintain a logbook of well operations. Tubewell maintenance and repair is carried out by a separate maintenance unit within each tubewell division. In theory there was no role for farmers to play in public tubewell O & M; in practice farmers have become the operators of most public wells as well as active in organizing their maintenance.

Not all farmers benefitted equally from this type of groundwater development; real equity in access to water pumped by public tubewells can only occur when they are located at the head of the watercourse. Often, public tubewells are located elsewhere within a watercourse command area so that only those farmers downstream of it are able to benefit. Additionally, some tubewells serve parts of two or more watercourse commands; in other cases, siphons carry part of the tubewell discharge across distributaries; and other wells serve areas both outside the canal command and within it. Hence, local arrangements for accessing public tubewell water often are relatively complex. In certain instances, some farmers may have both a canal water warabandi and a separate tubewell water warabandi, while others have a single turn that mixes tubewell and canal water, and still others have a tubewell turn but remain outside of the canal water warabandi.

3.3 Private shallow tubewell growth: 1970–today

There is no doubt that with the development of the SCARP tubewells for irrigation purposes growing numbers of Pakistani farmers became accustomed to and increasingly desired greater access to groundwater to supplement their surface water deliveries. With the development of less expensive diesel engines and centrifugal pumps, modern shallow tubewell technology emerged as a viable option for groundwater exploitation.

Beginning in the 1970s, assisted by government programs that encouraged private tubewell development, the entire groundwater exploitation situation changed again (R. Johnson 1989). Individual farmers found it relatively easy to invest in small pump and engine sets capable of delivering 15–30l/sec. With the equipment sited on the surface rather than sunk in the well, the borehole drilling costs are modest and maintenance of both pump and motor comparatively easy.

More than 300,000 private tubewells are installed in Pakistan today, and many Punjab farmers now have access to three distinct sources of water for irrigation: canal water according to the original warabandi, groundwater from deep public tubewells according to the local schedule followed, and groundwater from privately owned and operated shallow tubewells. Where these conditions exist, farmers generally have access to irrigation more or less at any time they want. They can more easily trade water, either through buying and selling or on some other basis; and they can move water across previously impermeable watercourse command boundaries. In short, large parts of the Punjab irrigation system have become a complex conjunctive management environment.

4. Conjunctive use: substitution or complementary use?

A critical aspect of conjunctive use which must be thoroughly understood is that *groundwater and surface water are not necessarily equally exchangeable.* This situation only occurs when their price is essentially the same and where water quality does not threaten yield or soil deterioration. Where there are price or quality differences, then farmers have to make tradeoffs between the sources of water.

In one typical conjunctive use scenario, such as that examined in IIMI’s program in Indonesia, groundwater is used to supplement shortfalls in surface water supplies. Tail end farmers may, albeit at additional cost, attain cropping intensities at or close to those of head end farmers who have more than sufficient surface water. Pumping will occur during periods of peak demand to ensure crops do not suffer drought, but the entire groundwater irrigation system in this situation is supplemental to the surface system. During the wet season, there is no pumping and it is usual to find pumping only for short periods during the dry season.

By contrast, in Pakistan groundwater use commonly is not to meet temporary shortfalls in supply. Groundwater often constitutes a high percentage of total water used conjunctively in irrigated agriculture in many canal commands, and the agricultural pattern is completely dependent upon being able to pump for extended periods of time.

4.1 Conventional wisdom about conjunctive use in Pakistan

Early in **1991,** Pakistan's four provinces finally reached agreement on the apportionment of the water resources of the Indus River system (Badruddin **1991).** This accord and the extensive Water Sector Investment Planning Study (WAPDA **1990)** which preceded it have placed Pakistan's groundwater resources more firmly in perspective on the national resource map. While for many years the contribution of groundwater to irrigated agriculture went largely unrecognized in terms of overall water resources planning, it is now acknowledged as being of considerable importance. However, the perceptions which have developed about how it is used still require examination.

The conventional wisdom in Pakistan is that farmers use groundwater primarily to supplement water received from the canal system – except, of course, in those areas outside of canal command – and it is likely that this perception was largely shaped by the SCARP experience.[3] This view is rather neatly reinforced by further rationalizing that although it is unfortunate canals no longer deliver water equitably along their length, everything comes out alright in the end because farmers instead can and do use groundwater, mostly derived from canal system losses, to make up the deficit.[4] True, it is acknowledged, this places some additional financial burden on farmers in areas with poorer supplies of surface water because of the costs of its extraction, but that is or will be off-set, at least to society at large, through increased overall water use efficiencies.

A second, still evolving perception in some quarters in Punjab is that there even are possibilities to 'save' surface water because of high current levels of groundwater use in fresh groundwater areas. It is thought that this can be achieved through an extensive program of canal lining, with water saved by a subsequent slight reduction in allocations to lined channels because of reduced seepage losses. The quantum of water thus saved will off-set surface supplies 'lost' in the **1991** apportionment accord with the further possibility that more water then can be directed to areas where groundwater is saline.

In some contrast with these two inter-related views is the insight emerging in IIMI that even where farmers rely heavily on groundwater for agriculture, their decision making remains strongly influenced by their relative access to surface water. There are two sets of reasons that underpin this line of argument. The first is that surface water in Pakistan is of superior quality and, in practical terms, it is nearly free. The second is that surface water supplies are relatively more predictable than is groundwater; they are not subject to sudden termination by mechanical breakdown or power failure. In short, a little good quality surface water goes a long way in helping farmers decide what to grow, when to grow it, and how much of it to grow.

A major objective of this study, therefore, has been to determine whether or not such relationships exist between water source and cropping decisions made by farmers. If they do, then there should be a marked spatial dimension to groundwater utilization and agricultural patterns that is closely related to relative location within the distributary canal system.

The policy implications of such findings are important. If farmers freely substitute groundwater for surface water, then a policy to redistribute surface water within and between canal commands to mitigate and manage salinity could be pursued without any serious impact on cropping. On the other hand, if farmers continue to make decisions based upon their access to canal supplies, then it is likely that there will be significant cropping pattern changes in response to surface water redistribution.

Somewhat surprisingly there has been little effort to date in Pakistan to determine which of these scenarios is more likely to be true. Thus, it is useful to look at two aspects of groundwater exploitation that may be reasons for farmers to use water differently than suggested by conventional wisdom.

4.2 Groundwater quality and reliability

In this context, there seem to be two key areas in a farmer's irrigation decision-making matrix where information and a capacity to use it effectively are critical: ***water quality*** differences between available surface water and groundwater, and ***total water availability*** in the period of peak demand in each season.

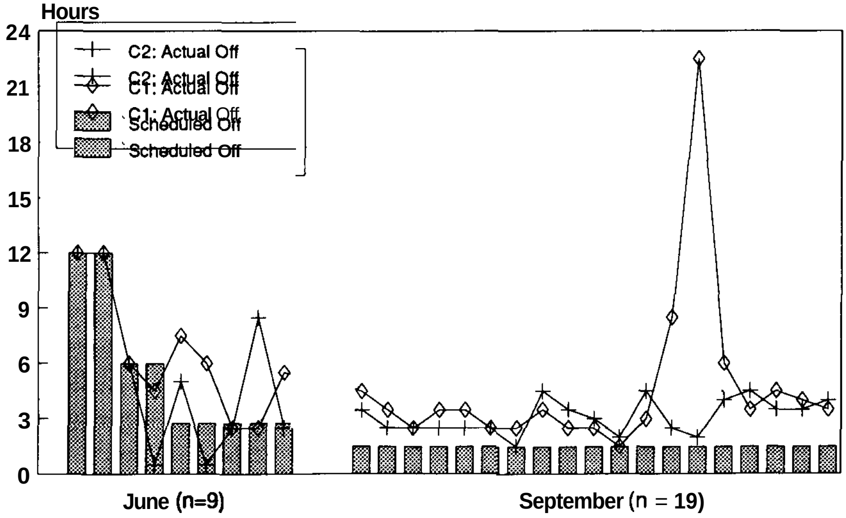
Water quality

In water quality terms, it is readily apparent that surface water and groundwater supplies are not simply exchangeable. It makes a great difference in basic cropping choices whether the bulk of available irrigation water will be fresh or saline. Some crops are particularly sensitive to salinity, and thus cannot be productively cultivated if only poor quality irrigation water is available. Therefore, in conjunctive use environments where surface water is of good quality but relatively less abundant, and groundwater is of poorer quality but relatively more abundant, most farmers are likely to seek to mix groundwater with as much surface water as possible to maximize their irrigated area. This in turn implies that the availability of greater quantities of surface water also favors a greater use of groundwater, an additive rather than a simple substitution relationship of one for the other. If this is so, then total irrigation water use trends should reflect general surface water trends, rather than being essentially neutral to location as would be the case if groundwater were simply being used as a substitute for canal water.

Reliability

The second factor, water availability, is probably directly related to reliability. Surface water supplies, particularly in the head reaches of canals, are highly reliable in the sense that water almost always comes. There are differences in volume delivered on a day to day basis, and these can be quite large, but there is a strongly positive relationship between discharge received one day and the probable discharge delivered the next. This means that both short term and long term decision-making is comparatively straightforward, and cropping decisions in areas where only surface water is available seem comparatively easy to predict and explain.

Pump-based irrigation requires a different assessment of reliability. When a tubewell – whether deep or shallow – is operating, the discharge is nearly uniform. Uncertainty tends to come in the time of operation. One concern is mechanical reliability: a tubewell and pump set can break, so that no more water is available until the equipment is repaired. In the case of a major breakdown in a deep tubewell, such as the burn out of electric motor windings or repairs to the turbine in the bore itself, it is not uncommon for farmers to immediately abandon part of their crop. For shallow tubewells, repairs are easier



Feeder C2 = Head & Middle Watercourses
Feeder C1 = Tail Watercourses

Fig. 1. **Lagar disty command electric supply loadshedding operations in Kharif, 1989**

– though not necessarily easy – to get done, but the owner usually requires cash in hand or a willingness to incur debt to get the repairs done quickly.

The second source of groundwater unreliability is tubewell power supply. Virtually all public tubewells and approximately 15%–20% of private tubewells are electrically powered.[5] Unfortunately, electricity in Pakistan continues to be a highly variable commodity, both in terms of supply and voltage. Power cuts – scheduled and unscheduled – have been and remain common for the rural feeder lines that supply tubewells in both months of greatest irrigation demand and during periods when crop water needs are low.[6]

Electric power operations data for several weeks during the 1989 kharif season for the two feeder lines that serve 25 of the 30 watercourse commands of Lagar distributary illustrate the problem faced by farmers using electric tubewells to pump groundwater (Fig. 1). On average, those feeders were off two to three times more hours than scheduled throughout the period covered by these data; moreover, stoppage of power supply occurred two or three times daily. Field measurements of private electric tubewells recently undertaken by Pakistan's National Energy Conservation Centre (ENERCON) have revealed that line voltages commonly deviate +/– 50 volts from the standard, while phase to phase differences frequently exceed 5%. Both conditions contribute to high rates of electric motor burnout and consequent frequent costly repairs.

Nevertheless, electric power remains attractive because it can be obtained at relatively low cost, often at a flat rate regardless of consumption and sometimes cheaper still by tapping transmission lines or bypassing meters through an accommodation or arrangement with power agency staff. The ease of electric tubewell operation also may be a factor. While it is true that diesel power is inherently more reliable than WAPDA-supplied electricity, it requires immediate, up-front payment, plus fuel transportation from a limited number of supply points and storage in reasonable quantity at site. Tubewells operated by tractor power take-offs play an important role, too. Although cheap to install relative to either diesel or electric tubewells, they tend to be a less favored source of groundwater because of their higher operating costs.

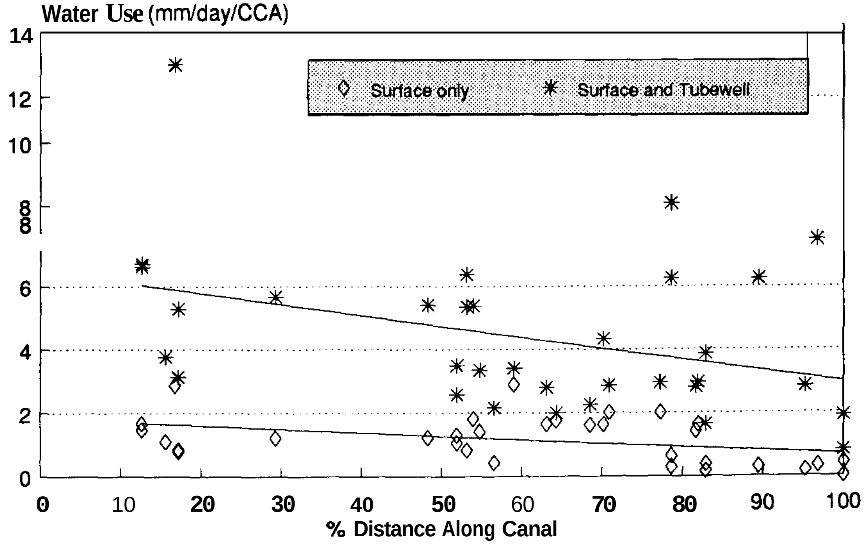
In the context of such uncertainties, it is reasonable to hypothesize that access to surface water of good quality and relatively high dependability is likely to influence farmer cropping decisions more fundamentally than access to larger volumes, but poorer quality groundwater obtained through equipment or power source of dubious reliability. These hypotheses are now examined in light of available data.

5. Observed trends of groundwater use and agricultural patterns

The data collected by IIMI over the past four years from 41 watercourses in four distributary canal commands in the LCC system provide several insights into conjunctive use of surface and groundwater. Water supply and water quality data were standardized by defining locations in terms of percentage distance along the canal from head to tail; crop data were standardized in terms of proportions of watercourse CCA (Culturable Command Area), the overall area of each watercourse ***irrigable by the surface system.*** Surface water and groundwater volumes were determined based upon measurements at the outlet and at the tubewell discharge pipe, respectively; they were not adjusted for within watercourse and farm conveyance losses and application efficiencies. The data have been analyzed from two dimensions: the apparent perception of farmers about likely availability of water that affects the overall pattern of irrigated agriculture, and farmers' short-term water use response in an environment where there is ample opportunity to pump groundwater to complement surface water supplies.

5.1 Broad patterns of irrigated agriculture

In an effort to determine the extent to which farmers are guided by or respond to the availability of different types of water, data were analyzed with respect to relative location along the distributary. In the following statements, water deliveries are assessed in respect of the Cultivable Command Area (CCA), the area in hectares of each watercourse that is designed to receive irrigation water at some time. Actual water utilization figures can, of course, be increased by



excludes rainfall

Fig. **2. Actual irrigation water utilized watercourse level** reducing the area irrigated by reducing cropping intensity or irrigation intensity. The following broad trends emerged from subsequent analyses:

- Surface water deliveries to outlets decline along canals from approximately 2 mm/day near the head to about 0.5 mm/day at the tail (Fig. **2).** The rate of decline of surface water deliveries is significantly related to watercourse location along the distributary at the 5% level, although there is a great deal of variability. When analyzed for individual canals the decline in access to surface water shows a much greater association with percent distance along the canal.
- Total groundwater use also declines along canals from about **4.5** mm/day at the head to about **2.5** mm/day in the tail end watercourses. This relationship, however, is not statistically significant.
- Total water use expressed in terms of the overall irrigable area declines from head to tail of the canal. This relationship is statistically significant at the *5%* level.

This means that the percentage of groundwater in farmers' total irrigation water increases along the canal, from roughly ***65%*** at the head to ***85%*** at the tail. Accompanying the decline in access to surface water and an increased dependence upon groundwater is a dramatic decline in groundwater quality from distributary head to tail:

- Average electrical conductivity (EC) for each watercourse increases from about 0.9 dS/m at the head to **2.1** dS/m at the tail (Fig. **3).** These figures

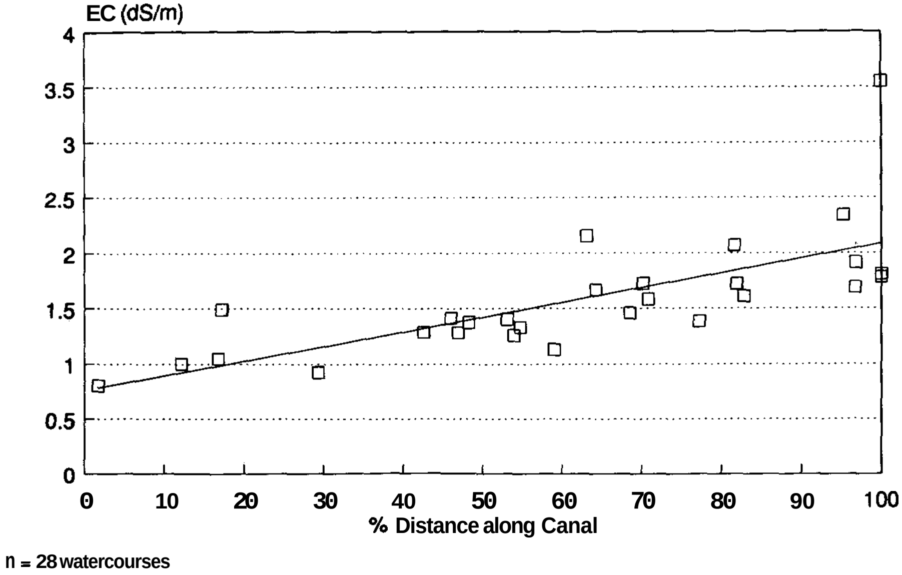
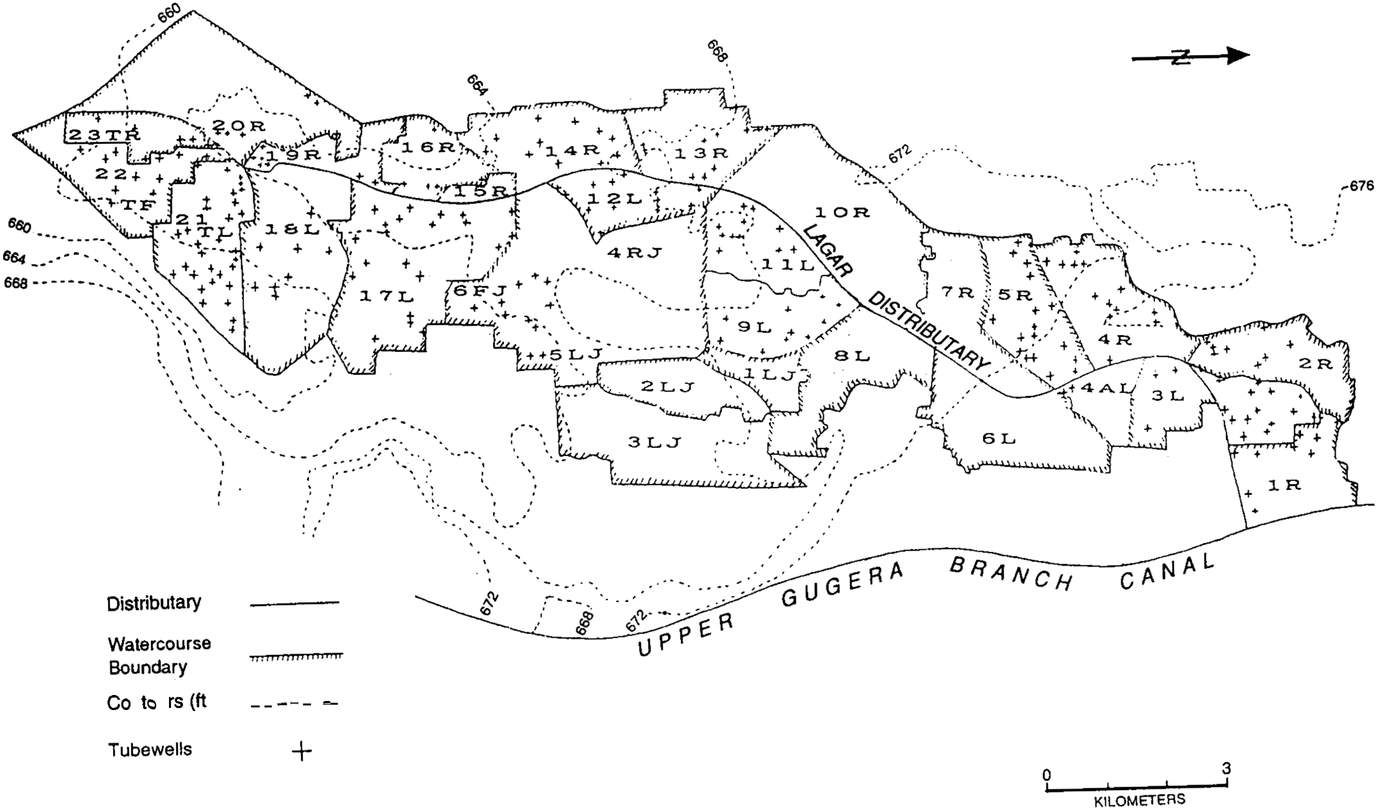


Fig. **3. Average tubewell water quality for watercourses**



Note: Incomplete data for the following watercourses:

Fig. 4. Lagar distributary command location of tubewells

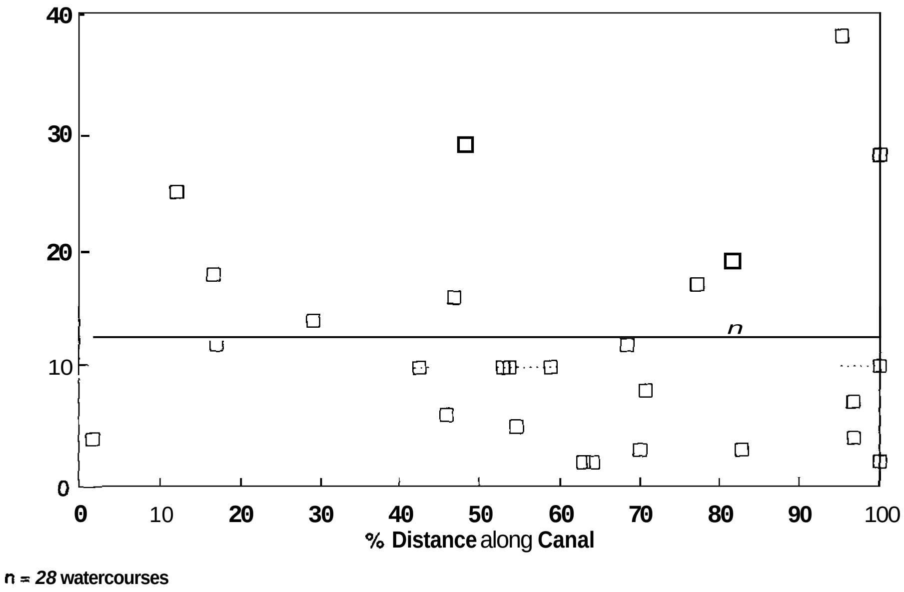


Fig. 5. **Number** of **tubewells per watercourse**

are based upon water quality measurements from all tubewells in each watercourse, typically in the range of 10 to 30 wells. Thus many farmers are using groundwater much worse in quality (up to 4.0 dS/m, a salinity level that severely affects much crop production).

- Sodium Absorption Ratio (SAR) increases in exactly the same pattern, from 2 at the head to about 14 in tail watercourses.

Both water quality measures show the same rate and direction of change within canal commands, at levels of significance exceeding 1%, and the relationship is persistent despite the wide geographical spread of the data.

Despite these two factors – decreased water use and declining water quality – there is no apparent relationship between canal location and density of tubewell installation. For Lagar distributary, for example, where a complete tubewell census was taken, there is no visual indication of a spatial pattern of tubewell installation (Fig. 4), and this observation is borne out by data from several different watercourses in other canal commands (Fig. 5).

Despite these trends, there are significant differences in water utilization rates between watercourses, and from one time of year to another. The range of conditions is illustrated for three watercourses in Lagar distributary command: a head end watercourse (2R) that has design levels of surface water supplies and high rates of groundwater use, a watercourse near the middle (9L) that has adequate surface water but highly seasonal pump utilization, and the

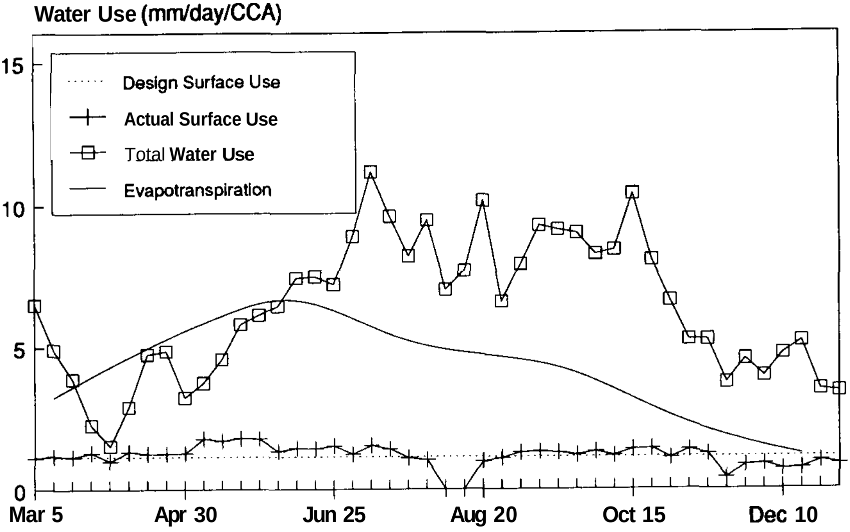


Fig. 6. Surface and tubewell water use watercourse 02R, Lagar, 1989

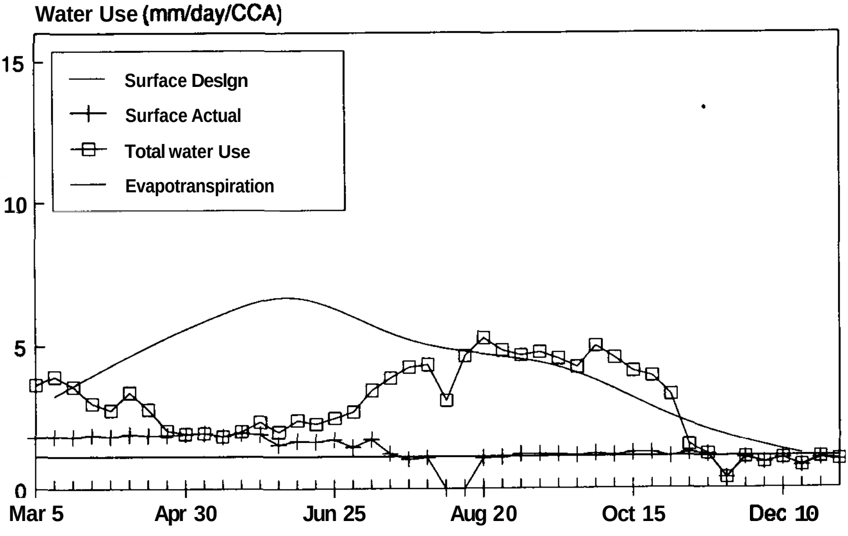


Fig. 7. Surface and tubewell water use watercourse 09L, Lagar, 1989

tail (21TL and 22TF combined) which has marginal surface water deliveries and, at least in the summer, is completely dependent on groundwater for agriculture (Figs. 6, 7 and 8).

The agricultural consequences of these conditions are clear and consistent across the two study areas in the resulting summer and winter cropping patterns

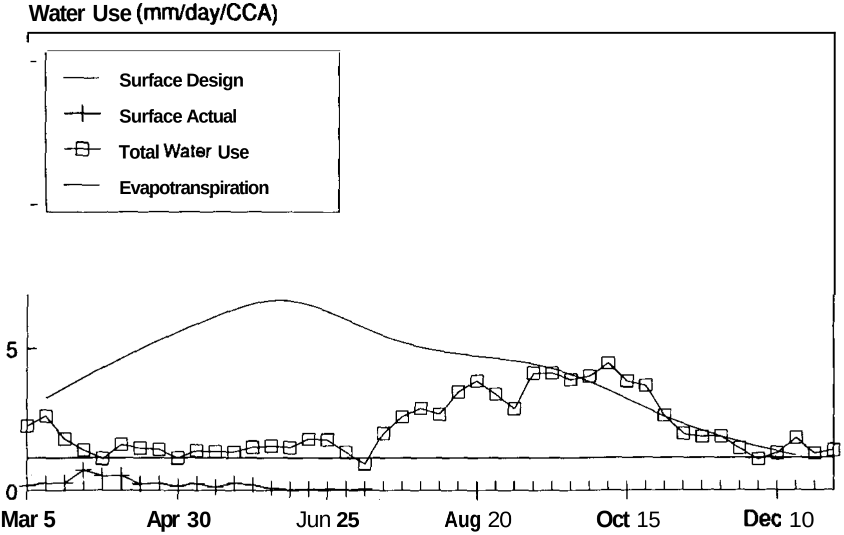


Fig. 8. Surface and tubewell water use tail watercourses (21 & 22), Lagar, 1989

and are readily explained by important differences in conjunctive use between the two seasons.

Summer cropping patterns

The summer season in Pakistan is hot, frequently humid in the middle months, and thus ideal for growing rice. In some locales, cotton is a major acreage competitor, but the study areas do not cover any of Pakistan's main cotton growing regions. Based upon Fig. 9, the following observations can be made:

- Cropping intensities (the percentage CCA cropped) drop from 80% in head-end watercourses to about 60% at the tail. This change is clearly mirrored in the decline in total irrigation water use from the head (6.5 mm/day/ha CCA) to the tail (3 mm/ha CCA/day), on average, from July 1 to September 30.
- Cropping patterns reflect the change in overall irrigation water supply: the area under rice drops from nearly 40% of the CCA in head-end watercourses to about 20% at the tail. A similar relationship is observed for other commercially important crops: cotton declines from 13% to 9%, sugarcane from 12% to 7%, and even orchards show a slight decline, from 3% to 1%. Farmers partially compensate by growing more fodder, which increases from 14% to 20% of tail watercourse CCA.

There is no evidence in the data that kharif cropping patterns are spatially neutral. They parallel trends in surface water deliveries to watercourses and downstream declines in groundwater quality, thus strongly supporting the

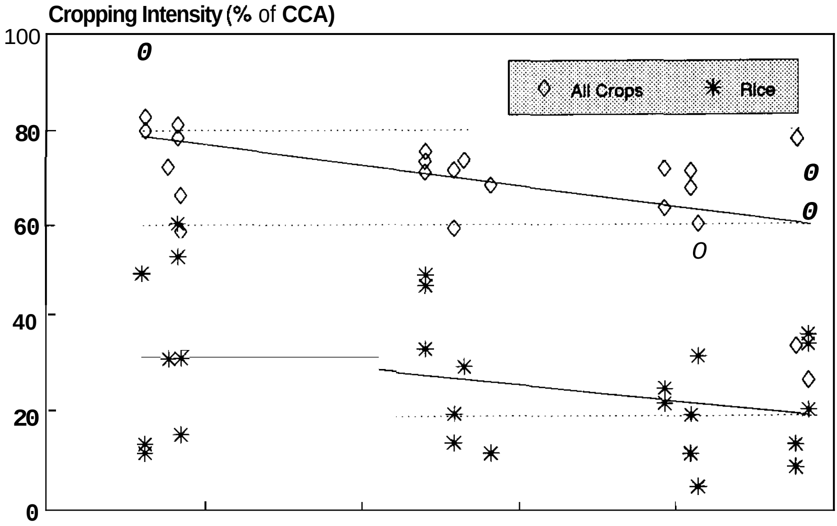


Fig. 9. **Summer (kharif) cropping** intensity

hypothesis of continuing influence of surface water availability on cropping patterns. It is obviously very expensive to cultivate rice using only pumped water, particularly when evapotranspiration is close to 7 mm/day. This helps to explain the huge increase in canal water theft between June and August, a phenomenon which decreases as evapotranspiration decreases.

Winter cropping patterns

The situation in winter is completely different, reflecting the changed balance between water availability and demand. The main observations are (Fig. 10):

- Cropping intensities show no relationship to location along the canal (they actually increase marginally down the canal), and are very high, averaging 85% of CCA.
- The area planted to wheat increases dramatically downstream the distributary, from 50% of CCA at the head, to 70% at the tail, a relationship that is statistically significant at the 5% level.
- Sugarcane and orchards show the same trend as in the summer, because they are annual or perennial crops; there is a marginal decline in both from head to tail watercourses, and in total they occupy about 12% of CCA.
- The balance cropped area is made up with fodder and vegetables. Vegetables are high value, but also highly vulnerable to salinity, thus farmers who must use much poorer quality groundwater normally will not grow vegetables.

The pattern found in winter is readily explained by water availability in rela-

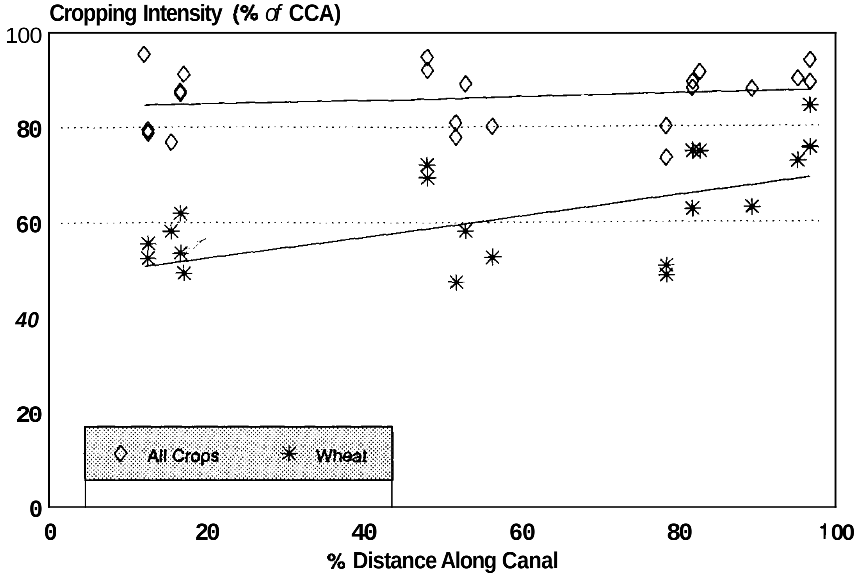


Fig. 10. **Winter** (rabi) **cropping intensity**

tion to demand. Surface water delivery rates at the tail-end are more or less at design (1.2–1.7 mm/day), which approximates evapotranspiration. Groundwater use, therefore, is significantly less than in the summer, both in terms of total amount and percentage used. **As** evapotranspiration increases during the later part of the wheat season, pumping of groundwater also increases, indicating that some measure of late irrigation is practiced in response to actual crop water requirements.

Only in areas where groundwater quality is reasonable and market access favorable is groundwater likely to be pumped in large quantities in periods of relatively low evapotranspiration because these locations are advantageous for intensive vegetable cultivation. Indeed, in such locales land too high for surface irrigation, gross command but not **CCA,** often has been brought under cultivation by groundwater development.

5.2 Water use per irrigated area

The data indicate that once farmers have made basic decisions about area to be cropped and the range of crops to be grown, they then use water relatively efficiently. This is demonstrated by actual water utilization rates for the peak period in kharif, July to September. In head-end watercourses, the average total irrigation water use is about *6.5* mm/ha/day (surface 2.0 mm/ha/day and tubewell water at **4.5** mm/ha/day), with a cropping intensity of 80%. This means that the rate of irrigation water delivery is around 8 mm/ha/day for ***actual*** cultivated areas, compared to an evapotranspiration rate averaging 4.85 mm/day. If the average crop water requirement is more or less equal to evapotranspiration during the summer months, and an additional requirement of ***5*** mm/ha/day is included for seepage and percolation in areas planted to rice, total water requirement is about *7.5* mm/ha/day.

These figures provide the basis for calculating the relative water supply (RWS) that indicates the degree of over-irrigation or under-irrigation by farmers. Relative Water Supply, as defined by Levine (1982) is expressed as:

$$\text{Relative Water Supply} = \frac{\text{irrigation} + \text{effective rainfall}}{\text{evapotranspiration} + \text{seepage} + \text{percolation}}$$

Assuming no effective rainfall, therefore, the overall relative water supply for irrigated areas is about 1.07, indicating that farmers are not pumping appreciably more water than they need (Fig. 11) to meet overall crop water requirements.

Using similar estimates of crop coefficients and seepage and percolation rates for tail-end watercourses, the total water requirements for actually irrigated areas are about 6.5 mm/ha/day. ***Actual*** irrigation water deliveries to the cropped area are nearly the same (6.0 mm/ha/day tubewell and 1.0 mm/ha/day canal water) as in head-end areas, so that relative water supplies are again close to 1.0.

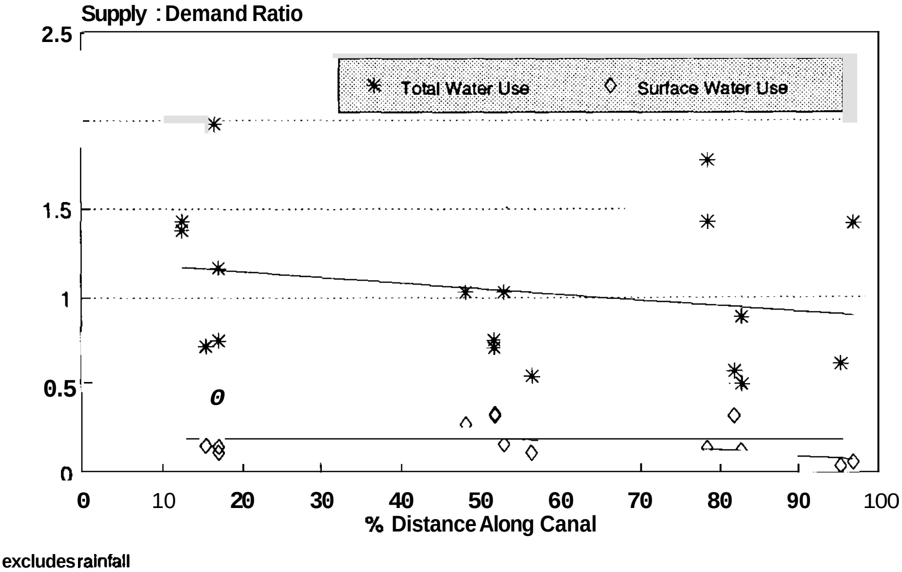
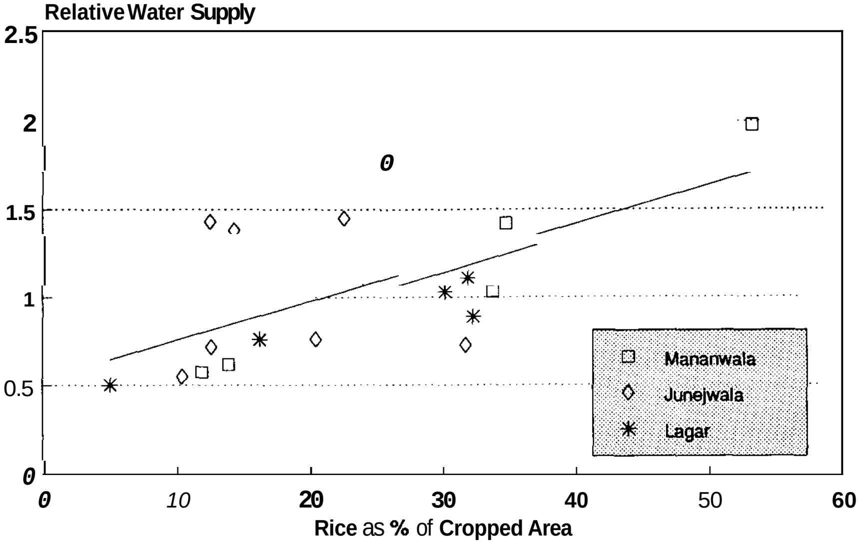


Fig. 11. **Irrigation water use watercourse level supply & demand**



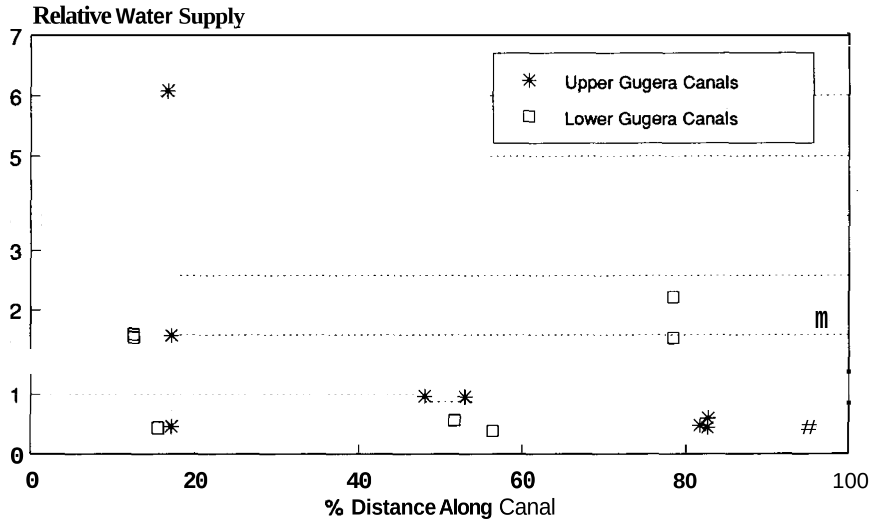
excludes rainfall

Fig. 12. Irrigation water use and rice cultivation

Effective rainfall during this period averages 4 mm/day, so that total water supply for the irrigated area is 12mm/ha/day. With demand at about 7.5 mm/ha/day, relative water supply then increases to 1.5. However, rainfall is uncertain even during this season, and rice often must be planted before the main rains have become established. Because rice is an important component of the cropping pattern in all of the sample areas, and because rice yields drop rapidly if there is drought-induced stress, it is logical for the decision on how much rice to plant to be based on the expected availability of dependable surface water and tubewell supplies rather than guessing on likely rainfall in the months ahead.

The importance of rice in the cropping system is seen by analyzing irrigation water use in the summer months (Fig. 12). When more than 30% of the cropped area is under rice, relative water supplies increase from more than 1.0 up to nearly 2.0 when rice exceeds 50% of the cropped area. Conversely, as rice declines in importance, relative water supply also drops. This relationship strongly suggests that farmers are fully conscious of the different water requirements of rice and other crops. If the relative water supply for rice drops much below 1.0 at the field level, yields will decline rapidly, but for most other crops when relative water supply is less than 1.0, yields decline more or less in proportion to the degree of crop stress.

If the assumption is made that rice is normally given sufficient water to avoid stress (i.e., at a relative water supply of 1.0, or 10 mm/day in the study area),



excluding rainfall
assumes 10 mm/day for rice

Fig. 13. Irrigation water **supply** for non-rice crops

the relative water supply for all other crops also can be calculated. The results, expressed here in relation to distance, suggest that despite the high proportion of groundwater use, relative water supplies in tail end areas are about 0.5, rising as expected to about 1.0 at the head (Fig. 13).[7]

The very close values of kharif season relative water supply found for watercourses from head and tail in all sample canals strongly suggests that throughout these areas farmers are using groundwater conjunctively to meet crop water requirements with some precision. However, it is important to also include a leaching requirement in the calculation if secondary salinization is to be avoided, even more so in the tail reaches of distributaries.

Groundwater EC in tail-end watercourses averages 2 dS/m and exceeds 3 dS/m in many wells; under these conditions the leaching requirement is quite high. An application of 2.5 mm/ha/day of water with an average EC of 2 dS/m means that the total amount of salt applied at the soil surface is very high. A daily water volume of 25 cu m per hectare with a dissolved salt load of 1250 ppm means that approximately **32** kg of salt is applied per hectare per day. Given actual relative water supply values found for these areas, it is not surprising then that secondary soil salinity is building up rapidly there, and it is only with adequate rainfall that any significant leaching likely is occurring.

6. Interpreting the findings

The overwhelming conclusion from these results is that farmer kharif season cropping choices, in terms of both total area cultivated and the crop-mix, are closely linked with the relative location of their watercourses along the distributary. There appear to be two possible explanations for this:

- Farmers are influenced in their cropping decisions by the deterioration in groundwater quality downstream within canal commands, and relatedly along watercourses.
- Farmers are influenced by relative access to good quality surface water rather than by the ready availability of groundwater when making crop choices.

In reality, it may not be possible *to* differentiate which of these two explanations is operative for most farmers. However, it seems clear that the phenomena of secondary salinization is closely linked to the process of irrigation subsequently being practiced by these farmers in the LCC system. Furthermore, if the data presented here are reasonably representative of water use rates elsewhere in Pakistan Punjab, then it is probable that the high percentage use of poor quality groundwater in tail-end watercourses is a major, if not primary, contributor to the rise in secondary soil salinity towards the tails of distributaries.

In summer, especially early summer, evapotranspiration rates are extremely high. If plants use most of the available water for growth then the residual moisture in the soil inevitably will have a higher salt content than that of the irrigation water being applied. Because groundwater quality and water use are higher in head-end areas, however, the development of secondary salinity there will have been less than has been the case in the tail-end areas in the past two to three decades of groundwater exploitation.

Just how farmers could be so sensitive to the relatively gradual decrease in groundwater quality along each canal remains a puzzle. It is true, of course, that when salinity has reached a certain level it is possible to detect its presence without sophisticated equipment: soils may show salt residues on the surface, or tubewell water tastes brackish. Before that point is reached, however, salinity may be affecting both crops and soils, but in a more insidious, less obvious manner.

If the conclusions that (1) a primary cause of decreasing groundwater quality downstream in distributary commands is the greater proportion of its use relative to surface water to meet irrigation requirements, and **(2)** that secondary salinity is largely a consequence of present conjunctive irrigation practices characterized by high water use efficiencies are correct, the implications for sustainable irrigated agriculture in Pakistan's Punjab are ominous.

Two sets of options are proposed below that may guide policy makers towards determining what course to take in the future in efforts to sustain irrigated agriculture in Pakistan. They are divided into shorter term and longer term options.

Short term options

The short term options all revolve round the principle of redistribution of existing water supplies in efforts to minimize the current trends towards increasing groundwater and soil salinity. They are based upon the various policy options included in the national Water Sector Investment Planning Study referred to in Section 4.1, above.

- ***Present trend:*** farmers in watercourses in the upper half of distributaries continue to capture greater percentages of surface water to maintain their current cropping patterns; in lower reach watercourse commands, increases in salinity and decreases in kharif cropping intensitites continue and farmers become poorer.

Realistically, given the research findings reported herein, it is difficult to conceptualize approaches to the problem that would reduce the overall potential for increased salinization. For example, events following efforts to reallocate surface water within a distributary canal command with both a significant decline in groundwater quality and increasing secondary soil salinity from head to tail might well look like this:

- ***Intervention:*** deliver less water to canal head-end watercourses and redirect flows to tail-end outlets; water distribution equity is restored in the canal and/or reverse inequity is established.
- ***Probable response:*** head-end farmers refuse to accept a lower percentage share of good quality surface water and do not switch to using more groundwater.
- ***Likely result:*** no change in irrigation water supply conditions in downstream watercourse commands; continued increase in secondary salinization and groundwater quality deterioration.

Head-end farmers already exploit locational advantage to appropriate as much surface water as they can in the periods of peak demand and they also have a high density of tubewells which are not used to full capacity. There is no particular reason why they should willingly agree to a reduction in their favorite irrigation water source and their profitable agricultural system. On the other hand, let us suppose head-end farmers respond by accepting such a management intervention; then:

- ***Possible response:*** head-end farmers forego Iocational advantage, accept less surface water and increase their groundwater pumping rates to those found in tail-end areas.
- ***Likely result:*** cropping patterns in downstream watercourse commands change to become more like those in distributary head reach areas as do

relative water supply conditions; processes of secondary salinization and groundwater quality deterioration continue at a slower rate downstream, but increase in upstream locations.

Shifting to greater groundwater use in areas where EC values are still relatively low, < 1.2dS/m, may appear intuitively attractive, but if the proportion of groundwater used here increases from 60%–70% to the **85%** currently found in tail end areas, it is probable that soil and groundwater EC levels also will begin to rise in these locations.

Alternatively, let us briefly consider an intervention where more, higher quality surface water is made available through an intra- or inter-system reallocation of supplies. The following sequence of events may occur:

- ***Intervention:*** increase surface water supplies to an entire distributary command so that middle and tail-enders can get an increase over currently sanctioned allocations.
- ***Likely response:*** farmers throughout the command attempt to increase summer cropping intensities and grow more rice by pumping more groundwater to match surface water quantities now available.
- ***Probable result:*** farmers in head end areas may attempt to capture still more water at the expense of middle and tail watercourses; there may be an amelioration of the rate of salinization in tail end areas of favored distributary commands; canals that have 'lost' fresh water will likely experience more rapid increases in salinity because of increased groundwater use.

In some respects this second option is the classic zero-sum game: every area that benefits from obtaining more surface water can only do so at the explicit expense of areas which now have less surface water. The benefits in the short run may look favorable, but the long run implications are still ominous.

Long term options

However, over the long term, none of the above scenarios may work. The central issue here is the ratio of surface water and groundwater conjunctive use in irrigated agriculture identified in this research. On average, it is about **2:5** throughout the distributary command, resulting in an average irrigation water EC of 1.4dS/m. This value exceeds the current international FAO-based standard that sets the upper limit for 'good' quality irrigation water at EC 0.7 ds/m, but it is within the safe upper limit of WAPDA's guidelines, based upon 1954 standards.

To bring that average water quality condition down to 1.0 dS/m, still about 40% higher than the FAO maximum value, a canal-tubewell water conjunctive use ratio of 3:4 would be required. Assuming no change in the total volume of irrigation water used in the command area, this means that the volume of canal water would have to be increased by more than **50%** and the volume of pumped groundwater reduced by more than **20%** of ***current volumes.*** The present physical condition of Punjab's distributary canals precludes any possibility of accommodating a 50+% increase in discharges without frequent, massive breaching, even assuming enough farmers could be convinced to reduce groundwater pumping by the required amount, also no mean management feat!*

Increasing the volume of canal water also would require additional surface storage. Efforts over the past decade to construct new storage reservoirs, such as Kalabagh Dam, have been deadlocked because of seemingly unresolvable differences between the provinces.

An alternative, and one that in reality is already occurring in parts of Punjab, is to reduce the irrigated area. There is a trend to a loss of tail-end land either by abandonment or reduced frequency of cultivation. From a technical and agronomic perspective it is probably rational to allow this to happen, to concentrate higher quality water into a smaller area and allow those areas to prosper through adoption of better agricultural practices. Whether there is the political and social will to allow this to happen, of course, is another matter.

In short, there is no single, 'magic bullet' solution in sight to the problem of sustaining a productive irrigated agriculture posed by secondary salinization and groundwater quality in the current conjunctive use environment of large, agriculturally important areas of Punjab. What is very clear, however, is that present conditions in that environment are dynamic and the direction of change is not encouraging.

7. Research issues and management implications

The research results discussed in this paper are necessarily based upon a limited sample, and data from just 41 watercourse commands out of the more than 89,000 that exist nation-wide is probably not statistically significant. Nevertheless, the trends that have been identified are sufficiently consistent between spatially separate locales to provide grounds for genuine concern. These trends point to several important management and research issues in the area of conjunctive irrigation, certainly for Punjab and perhaps elsewhere in Pakistan.

7.1 Research issues

Areas where further research is likely to produce results and insights that will be useful in developing suitable management responses and institutional changes include:

- Determining realistic critical limits for surface:groundwater ratios at different water qualities for a range of Indus Basin physical environments. Field verification of those values is necessary, spatially and over time, as are corresponding relative water supply targets. The relationship of the resulting parameters to values of current farmer irrigation water use over a similar environmental range will be needed to design extension service interventions that facilitate necessary changes.

- Development **of** a model that is able to predict salinity changes over time in relation to different intensities of groundwater use for different surface and groundwater qualities. Such a model is essential for decision support for aquifer management for long term sustainability; it could help evaluate the impact of periodic, but not permanent, reallocations of water around the system to facilitate leaching for salinity management.
- The factors that affect farmer cropping choices in conjunctive-based irrigated agriculture need more thorough analysis. In this paper, that has been done only in the context of water quality and location; other economic, social and physical factors may be important as well, and evaluation of perceptual variables would be desirable, too. The application of GIS would be advantageous here because of indications of a close relationship between cropping choice and geographical location within the canal command.

Until some of these issues are explored further, it is hard to see how the appropriate management actions can be taken.

7.2 Management issues

From the perspective of managing conjunctive irrigation to mitigate those processes that may threaten the sustainability of Pakistan's irrigated agriculture, there are three primary needs to be addressed: understanding current trends in the conjunctive use of canal water and groundwater, organizing for changes in management of government inputs into the sector, and policy review and planning. Each is briefly addressed below.

Understanding current trends in conjunctive use

IIMI's research has indicated that there are large gaps in the conventional understanding of conjunctive use in Pakistan. It also is clear that the national capacity to bridge these gaps is weak. A major reason for this is the virtual absence of any coordinated data collection program for relevant variables within national and/or provincial organizations. **To** illustrate this point, consider the following types of essential data that are collected; the processes do not coincide geographically or temporally, nor have the resulting data ever been assembled into a single location in Pakistan:

- ***Surface water data*** is collected by the Irrigation Departments or by WAPDA's Watercourse Monitoring and Evaluation Directorate and Alluvial Channels Observation Project;

- ***Public tubewell data*** is available with WAPDA's SCARP Monitoring Organization, the Irrigation Research Institute, and the tubewell operations units of the Irrigation Departments;
- ***Cropping data*** is collected through the Agricultural Census, the Irrigation Department's assessments for water charges, and the activities of the Agriculture Department's On-Farm Water Management Directorate;
- ***Yield data*** **is** collected by the Agriculture Department's Crop Reporting Service and through the Agricultural Census, but is not referenced to hydraulic location, only to civil divisions;
- ***Private tubewell data*** remains largely outside the purview of any public agency, even though such wells now account for more than half of all water irrigation used in much of the Indus Basin.

Thus, while the Punjab Irrigation Department continues to perceive 'the irrigation system' primarily as a canal system, while responsibility for public sector groundwater operations remains organized and implemented essentially independent of surface system operations, and while private sector groundwater operations are completely unmonitored, it is not surprising that the threat to the sustainability of irrigated agriculture based upon present patterns of conjunctive use is largely unrecognized and less understood. When a national research institution, such as WAPDA's SCARP Monitoring Organization, restricts its monitoring and applied research activities to public sector tubewell groundwater operations independent of spatially coincident surface irrigation systems and private sector groundwater development, while using water quality standards long out-of-date, it is unlikely that its work will have more than limited utility in defining the problem or in the development of solutions.

Clearly, arresting the processes of resource deterioration in the present conjunctive use environment requires both provincial and national water and agricultural sector agencies and research institutions to recognize and respond to the present ***realities*** of Pakistan's irrigated agriculture with coordinated, cooperative and effective actions. The need is not new, of course, but in the context of increasing constraints on development resources and the highest rate of population growth in Asia, neither has it been more urgent.

Changes in management of government inputs

A similar lack of overall coordination and effective collaboration occurs within the line agencies responsible for providing water and other services to farmers in areas of conjunctive use. The Irrigation Department persists with its surface, tubewell and drainage divisions having completely uncoordinated boundaries; WAPDA's supply of electricity is unrelated to agricultural needs and its rural grids crosscut canal commands; divisional boundaries within Agriculture Departments rarely coincide with those of any of the hydrological units used in the Irrigation Departments. The On-Farm Water Management Directorate plans and implements its interventions in watercourse commands without knowledge of PID canal operations or of private tubewell development, while its sister organization, the Agriculture Extension Directorate, is ignored by all of the foregoing, perhaps because it remains incapable of effectively advising farmers on any important aspect of irrigated agriculture. **So** long as this situation prevails, the odds that changes, say, in water supply intended to alleviate the negative impacts of salinity will be met with any improvement in overall conditions are very long indeed.

Pakistan's public agencies and supporting research institutions must begin shedding this 'historical baggage,' reorganize internally and establish functional, working linkages with one another. This seems an essential prerequisite for any effective use of better information and knowledge to design and implement appropriate, coordinated, management-focused responses to the conjunctive use problems identified in this paper. Admittedly, how that will be achieved in the current environment of belief that change is impossible, a widespread lack of will among senior professional staff, increasingly frequent political interference, declining professional standards among junior professional staff, and a growing institutional malaise that borders on paralysis is by no means clear.

Policy implications

Amelioration of the trend toward a declining sustainability of Pakistan's irrigated agriculture ultimately comes back to the policy environment in which other necessary actions will have to be taken. The cries for institution realignment and more performance-oriented management by government agencies at field level have been heard before, sometimes for long periods, and yet nothing really happens. Until there is a genuine commitment at the national level to implement policies and allocate resources that will positively stimulate these changes, it is unlikely they will materialize.

Acknowledgements

The authors would like to thank the tireless efforts of the field staff of IIMI Pakistan in undertaking the fieldwork involved in collecting hydraulic, agricultural, tubewell and salinity data under very difficult conditions. We also thank the Punjab Irrigation Department and WAPDA for access to information and data.

Notes

1. Useable recharge is defined by WAPDA as groundwater of a salinity level less than 1500mg/l. To this total, another 6.7 billion cubic meters of annual groundwater recharge exceeding that salinity parameter, but remaining less than 3000 mg/l, could be added. These salinity

parameters, used by WAPDA to define 'fresh' and 'marginal' water quality, are equivalent to 2.3 dS/m and 4.7 dS/m, respectively. For most authorities, however, the more generous definition of useable recharge would be qualified by various caveats regarding its use in irrigated agriculture.

2. Over 11,000 SCARP tubewells are classified as pumping fresh groundwater (WAPDA 1988).
3. 'The main incentive necessary for (private groundwater development) appears to be the farmer's demand for more water which cannot be fulfilled by other means ...' (WAPDA 1990: 3–37).
4. '(Fresh groundwater) does, however, offer considerable potential for supplementary supplies when surface supplies are short' (WAPDA 1990: 9–9).
5. A total of 1212 private tubewells have been identified in the nearly 50 watercourse commands surveyed by IIMI field staff in the **LCC,** Fordwah and Eastern Sadqia canal commands by mid-1992. Of this total, 16% were electric powered, 49% diesel powered (either high speed or low speed engines) and 35% were operated by tractor power take-off. These figures contrast sharply with the data reported by NESPAK-SGI in their recent Pakistan-wide study of private tubewells; there 39% of all Punjab tubewells and 45% of all wells in Pakistan are identified as electric powered. No mention is made in this study, however, of tractor powered tubewells. NESPAK-SGI. 1991. Final Report, Annex I. pp. 9–11.
6. Officially, loadshedding ended in Pakistan in mid-1991. However, frequent, often extended disruptions in power supplies continue, especially for rural electric grids. They occur during both the annual canal closure period, traditionally the month of January in the cool rabi season, when hydro-power generation is purposely reduced in order to minimize non-multi-use water releases from Pakistan's few reservoirs, and in the hot kharif season months when peak crop evapotranspiration rates directly compete with urban dwellers' refrigeration and air conditioning requirements.
7. The authors are grateful to Gil Levine for his insights into thehse of relative water supply in understanding farmer irrigation practices in this context.
8. Additions to full supply discharges have been simulated using a flow model, *IIMI Rajbah I*, for known distributary channel physical conditions. The certain consequence of a 20% increase over present full supply levels is breaching at any of innumerable locations in the upper half of the channel.

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