RESEARCH
REPORT

97

Strategies to Mitigate Secondary Salinization in the Indus Basin of Pakistan: A Selective Review

M. Aslam and S.A. Prathapar

International Water Management Institute

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International Water Management Institute
P O Box 2075, Colombo, Sri Lanka

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The authors: M. Aslam is a Water Resources Consultant at the Pakistan Council of Research in Water Resources, Regional Office, Lahore, Pakistan (m_aslam62@yahoo.com); S. A. Prathapar is a Associate Professor and the Head at the Department of Soils, Water and Agricultural Engineering, College of Agricultural and Marine Sciences, Sultan Qaboos University, Al Khod, PC 123, Oman (saprathapar@yahoo.com).

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Cover photograph by IWMI Pakistan Field Staff shows a salinized land in southern Punjab of Pakistan.

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Contents

Abbreviations

ACIAR	Australian Centre for International Agricultural Research
AWB	Area Water Board
BCM	Billion Cubic Meters
CV	Coefficient of Variation
DLR	Directorate of Reclamation
ECe	Electrical Conductivity of Soil Saturation Paste extract
FESS	Fordwah Eastern Sadiquia South
FO	Farmers Organization
GIS	Geographical Information System
IBIS	Indus Basin Irrigation System
LBOD	Left Bank Outfall Drain
Mha	Million hectares
NDP	National Drainage Program
OFWM	On-Farm Water Management
O & M	Operation and Maintenance
PIDA	Provincial Irrigation and Drainage Authority
Ppm	Parts per millions
PRs	Pakistan Rupees
SAR	Sodium Adsorption Ratio
SCARP	Salinity Control and Reclamation Project
SD	Standard Deviation
SIC	Simulation of Irrigation Canals
SMO	SCARP Monitoring Organization
TDS	Total Dissolved Solids
TV	Television
WAPDA	Water and Power Development Authority

SUMMARY

The Indus Basin Irrigation System (IBIS) of Pakistan serves an area of 16 million hectares (Mha) and distributes 172 billion cubic meters (BCM) of river water per year. With the introduction of IBIS, groundwater levels rose at a rate of 15 to 75 cm per year. The capillary up-flow from shallow water tables and evapotranspiration concentrate the salt, which salanizes the soil and water. In areas where river water is unavailable and groundwater of marginal quality is used for irrigation, evapotranspiration leads to sodicity. Estimates of losses due to salinization are 28,000 to 40,000 ha of land and about US$230 million (PRs 14,000 million) of revenue per year. An area of about 2 Mha is estimated to be salinized at present.

In response, researchers, policymakers, agency personnel and farmers in Pakistan have continuously devised strategies to mitigate secondary salinization. These can be categorized into on-farm and off-farm strategies. On-farm strategies include: (a) improved irrigation practices; (b) deficit irrigation; (c) change in land use; (d) agroforestry and biological-drainage; (e) mechanical cultivation; (f) use of chemical amendments; (g) use of skimming wells for irrigation water; and (h) conjunctive water use. Off-farm strategies include: (a) participatory irrigation system management; (b) improving reliability of canal water; (c) selective maintenance of irrigation and drainage infrastructure; (d) revision of water allocation rules currently in place; and (e) drainage measures at sub-regional and regional levels.

This report discusses the nature and causes of secondary salinization, reviews strategies developed and tested within IBIS to mitigate salinization, and identifies areas requiring further investigation.

Strategies to Mitigate Secondary Salinization in the Indus Basin of Pakistan: A Selective Review

M. Aslam and S. A. Prathapar

Introduction

Salts are present naturally in land and water. When the concentration of salts in land or water exceeds the limits beyond which they are unsuitable for productive, aesthetic or environmental needs of a society, they are considered salinized. Land and water resources may be naturally saline (primary salinity), or their salt concentration may increase due to human intervention (secondary salinity). Irrigated agriculture is a major human activity, which often leads to secondary salinization of land and water resources in arid and semi-arid conditions.

The Indus River and its tributaries, Kabul, Jhelum, Chenab, Ravi and Sutlej Rivers, originate in the Karakoram, Hindukush and the Himalayan regions along the north and northeastern borders of Pakistan (figure 1). The Indus Basin Irrigation System (IBIS) of Pakistan, home to more than 140 million people, is the largest contiguous irrigation system in the world. The waters of the Indus Basin Rivers are diverted through reservoirs and barrages into the main canals, which distribute water through a network of branch canals. The irrigation network comprises 3 reservoirs, 15 barrages and 45 main canals (figure 2).

Within IBIS, approximately 16 million hectares of land receives 172 BCM of high-quality (150–200 Ppm TDS) river water per year. If it were to be distributed uniformly across the Indus Basin, the net result would be an addition of 2,150 tons of salt per hectare per year. Unless this salt is removed from the root zone, salinization is inevitable.

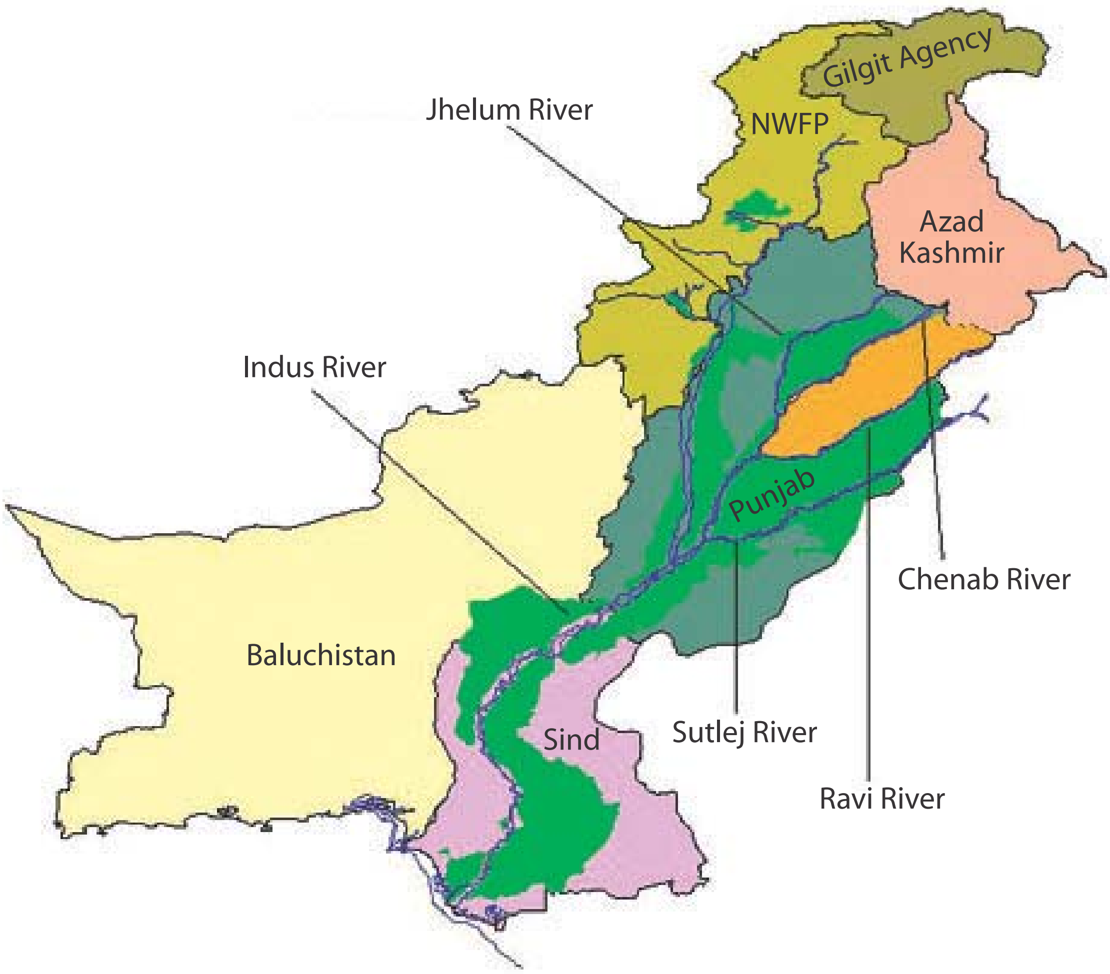
Salinization in IBIS is due to two significantly different processes: (i) is by shallow saline water tables; and (ii) is due to irrigation with marginal-quality groundwater.

Water-Table-Induced Salinization

In areas where the water table is hydraulically linked to bare soil evaporation or crop evaporation, water from the water table moves to meet the partial or total evaporative demand. When water is lost to the atmosphere as vapor, salts are left behind in the root zone, salinizing the root zone. The rate of water-table-induced salinization depends on:

- atmospheric factors such as the evaporation demand and rainfall (intensity, amount and frequency);
- soil factors such as texture, structure and its geologic origin;
- water table factors such as depth and water quality; and

FIGURE 1.
Rivers and tributaries within the Indus Basin of Pakistan.



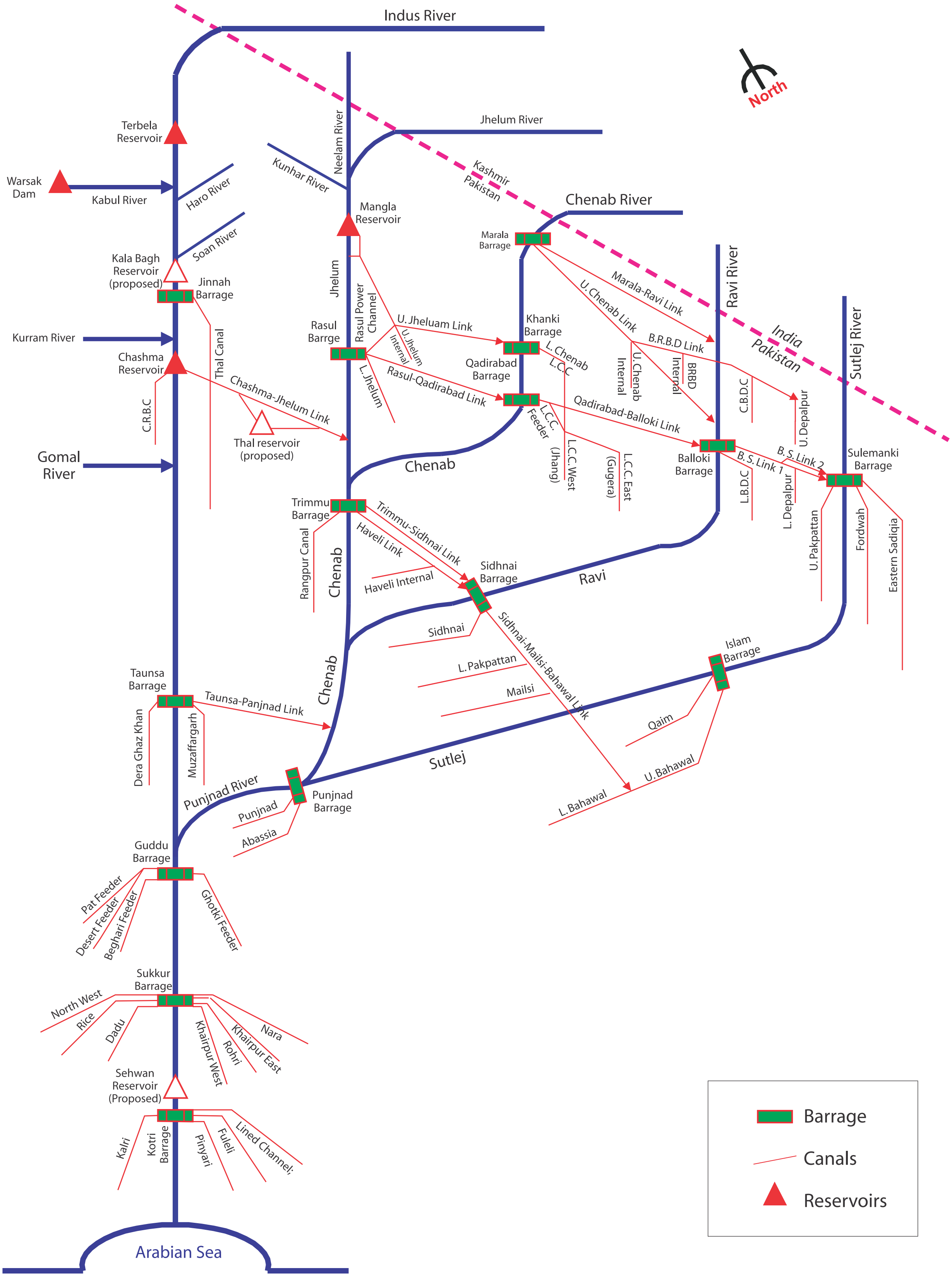
∉ management factors such as crops grown and irrigation practices (intensity and amount).

Interactions among these factors are complex, and have been modeled (Prathapar et al. 1992; Robbins et al. 1995; Prathapar et al. 1996). Although it would be difficult to prioritize factors influencing water-table-induced salinization, it is reasonable to conclude that a shallow water table is a key factor, because several studies confirm the link between water-table-rise and water-table-induced salinization in the IBIS (Kuper 1997; Rehman and Rehman 1998; Aslam et al. 1999; Ejaz and Ahmad 1999).

Water-Table-Rise in the IBIS

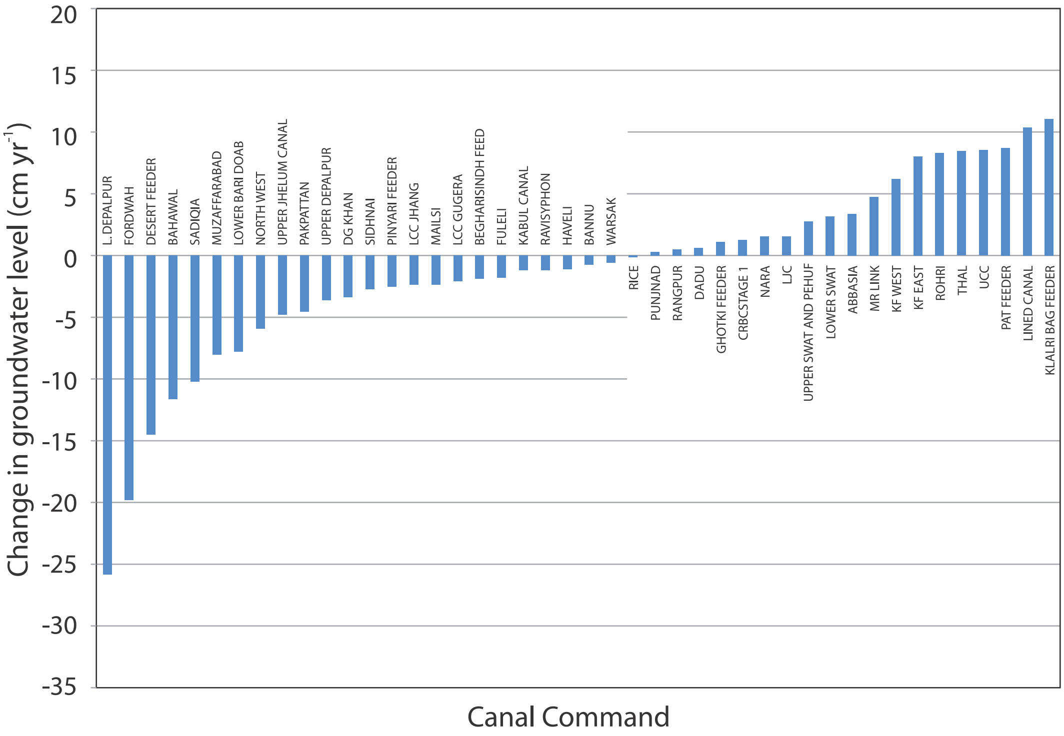
Irrigation has disturbed the hydrologic equilibrium between recharge and discharge of groundwater within the Indus Basin. In addition to seepage from canals, distributaries and watercourses; deep percolation from irrigated lands have increased natural recharge rates. As a result, groundwater levels have risen at a rate of 15 to 75 cm per year. In Punjab, groundwater levels have risen by 20 to 30 meters in the middle of the *doabs* (land between two rivers). However, the rate of groundwater level rise has receded in recent years. The average annual change in groundwater level between 1990 and 1996 within various canal commands is presented in figure 3

FIGURE 2.
Reservoirs, barrages and main canals in the Indus Basin Irrigation System (IBIS).



Source: Khan 1999

FIGURE 3.
Annual change in groundwater level of IBIS canal commands, 1990–1996.



Source: SCARP Monitoring Organization (SMO) 1996

(SCARP Monitoring Organization, SMO, unpublished data). It shows that in most canal commands, the annual change is within ± 10 cm.

The percentage of area with shallow water tables within the IBIS since 1978, is presented in table 1. Table 1 data show that standard deviations are smaller than the mean, resulting in low coefficients of variations. The percentage area with a depth less than 1.5 m has a higher coefficient of variation (CV) than the other depth categories (1.5–3.0 m and > 3.0 m). While having low CVs for all three depth categories, in general, a relatively large CV is attributed to the <1.5 m category. The information presented in figure 3 support the proposition that depth to the water table across the IBIS has arrived at a dynamic equilibrium, varying only in response to annual climatic variations.

Inefficient on-farm and off-farm management of irrigation water has contributed to a water-table-rise in the IBIS. This is confirmed by Mills (1989), who

TABLE 1.
Percentage of land area of the IBIS with shallow water tables during April–June.

Year	Land area (%) at a depth of:			Total
	< 1.5 m	1.5 –3.0 m	> 3.0 m	
1978	11.9	39.5	48.6	100.0
1982	13.5	43.2	43.3	100.0
1986	13.0	41.0	46.0	100.0
1988	9.0	38.2	52.8	100.0
1990	13.2	36.2	50.6	100.0
1992	18.3	32.6	49.1	100.0
1993	16.2	35.7	48.1	100.0
1994	12.0	36.0	52.0	100.0
1995	12.3	36.9	50.8	100.0
1996	10.4	40.1	49.5	100.0
1997	17.2	33.2	49.6	100.0
1998	14.7	36.6	48.7	100.0
Mean	13.5	37.4	49.1	100.0
SD	2.7	3.1	2.6	
CV	0.2	0.1	0.1	

Source: Bhutta and Chaudhry 1999

Note: SD = standard deviation; CV = coefficient of variation.

concluded that conveyance losses from the water distribution system and deep percolation losses from croplands contribute more to a water-table-rise than rainfall.

Irrigation Water Off-Farm

An unreliable and often inadequate supply of water at the farm gate (farm gate means the point [farm inlet] where irrigation water enters the farm for crop use), in conjunction with inadequate on-farm water management practices, has contributed to a water-table-rise in the IBIS. In the IBIS, *warabandi* (means "turns" (*wahr*) which are "fixed" (*bandi*)) is practiced as a river water allocation method. By design, warabandi is a rotational method for the equitable allocation of the available water, with irrigation turns fixed according to a time roster specifying the day, time, and duration of supply to each irrigator. Warabandi provides a continuous rotation of the water supply in which, one complete cycle of rotation, generally, lasts 7 days. The duration of supply to each farmer is in proportion to the size of the farmer's landholding. A small allocation of extra time is given to certain farmers who need to be compensated for conveyance time. Nevertheless, no compensation is specifically made for seepage losses in the distribution network (Bandaragoda 1998).

However, in practice, due to several socio-technical factors, distribution of irrigation water is often inequitable and unreliable. Jacobs and Schoonderwaldt (1992) found that in Punjab, there are large diurnal fluctuations in the inflow to the Fordwah Branch canal, which causes fluctuations in water levels along the canal and in the distributaries originating from it. Van der Velde (1990), Bhutta and Van der Velde (1992), Munir et al. (1999), and Skogerboe et al. (1999a) documented inequity and unreliability in water distribution along several distributaries. Van der Velde (1990) also observed outlet tampering and water theft in the upper reaches of distributaries. Khan et al. (1999) reported a high degree of discharge variability at the head of watercourses, with 32 to 65 percent conveyance losses in the unlined watercourses. All of this combined resulted in tremendous inequity at the farm gate. Bhatti (1990) and Bhatti and Kijne (1992) reported that actual irrigation supplies received at the farm gate were insufficient and unreliable. A study by the Directorate of Land Reclamation (DLR) of the Punjab Irrigation Department found that, reclamation shoots (pipe outlets to provide additional water for leaching to reclaim salt-affected lands) are, generally, provided in the head reaches of the channels, which had an adverse impact on equity of water supply at the tail reaches. (Bandaragoda and Rehman 1994).

Irrigation Water On-Farm

Long irrigation events in unleveled, bunded units of land result in poor water uniformity and over-irrigation. Pintus (1997) reported that:
(a) best crop yields are not obtained with the highest quantities of water; and, (b) tubewell owners tend to over-irrigate more than those who rely on canal water. Studies within the IBIS indicate that 13 to18 cm water is applied during each irrigation event, which is considerably higher than the average consumptive use between two irrigation events (approximately 8 cm). On several occasions, it was observed that irrigation efficiencies ranged between 23 percent and 70 percent (Clyma et al. 1975; Bhatti 1990; Kijne and Vander Velde 1990; Bhatti and Kijne 1992; Kalwij 1997; Sarwar and Shafique 1997). It was also found that, in many farms, total amount of irrigation water applied to a crop was far less than its total consumptive use requirement. Alberts and Kalwij (1999) and Kalwij et al. (1999) found that canal water supplies are meeting less than 60 percent of a crop's consumptive needs in parts of the IBIS. These deficits are partially rectified by utilizing the groundwater capillary up-flow from the water table. This practice, however, causes root-zone salinization.

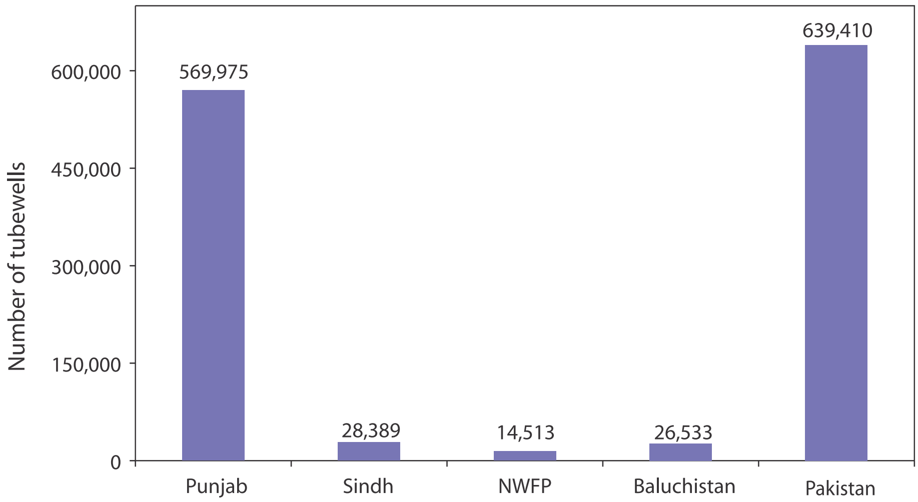
Marginal-Quality-Water-Induced Sodicity

Inadequate and unreliable canal water supplies (especially at the tail end of distributaries and water courses) and change in cropping patterns from low-delta-crops to high-delta-crops have made farmers' depend on marginal-quality water for irrigation. Depending on the circumstances, groundwater meets 10 to 90 percent of the irrigation requirements (Mills 1989; Kijne and Van der Velde 1990; Asghar et al. 1992; Kijne and Kuper 1995; Blaauw and Heinsbroek 1990; Bhatti and Kijne 1992; Murray-Rust and Vander Velde 1992; Kijne and Vander Velde 1990; Malik and Strosser 1993; Strosser and Kuper 1994).

The principal locations where fresh groundwater is available are the Peshawar Valley and the Punjab Province. The highest number of wells is in the Punjab Province (figure 4, Shafique et al. 2004). In the Punjab Province, particularly in Rechna Doab's large tracts of land, groundwater pumping has lowered the water table levels during the late 1970s and early 1980s. Furthermore, pumping brackish groundwater at some locations has accelerated the process of secondary salinization (Kijne and Kuper 1995).

Kuper (1997) reported that irrigation with groundwater, which is rich in sodium and bicarbonates leads to the sodification of the soil. Farmers indicate that the adverse effects of poor-quality irrigation water are felt by them quite rapidly. After two to three irrigations with such water, a surface crust develops. In addition to such a development, there is a likelihood of hard layers occurring in the soil within an irrigation season. Van Dam and Aslam (1997), and Aslam and van Dam (1998) modeled the conjunctive use of canal water and groundwater of relatively high sodium content and found that a loam soil could become sodic within a short period of 3 years. Their views were confirmed by Condom (1997), who used a geo-chemical model in conjunction with a solute transfer model, and provided evidence of such a rapid sodification of soil taking place.

FIGURE 4.
Private well development in Pakistan.



Source: Shafique et al. 2004

Managing Secondary Salinization in the IBIS

On-Farm Management Strategies

Pakistani farmers apply a wide range of measures to mitigate salinity. These measures are mostly related to water management, crop choice, cultural practices and the application of chemical and biotic amendments. The choice of measure depends largely on farm characteristics and the experience of the farmer and fellow farmers. The common practices adopted by farmers in the IBIS are summarized below.

Improved Irrigation Practices

Although techniques such as laser leveling, furrow irrigation, corrugated basins, sprinkler irrigation and drip-irrigation had been introduced in the IBIS, only a few large landowners have adopted them. Most farmers are aware of the advantages of improved irrigation practices, but lack of exposure to and familiarity with such practices, along with existing constraints (labor, equipment, etc.), make them hesitant in trying them (Berkhout et al. 1997). Among several improved irrigation practices evaluated, the bed-and-furrow method is probably the most appropriate one for most farmers within the IBIS. Alberts and Kalwij (1999) reported that, on average, 17 percent less water was applied per irrigation event to the bed-and-furrow fields compared to the basin fields. Comparing the first four irrigation events, water applied to bed-and-furrow fields was 12 to 41 percent less than that of basin fields. Kalwij et al. (1999) reported that use of the bed-and-furrow irrigation method in conjunction with precision laser leveling showed a better irrigation performance. The total duration of irrigation, total depth of water applied and average depth of water applied per irrigation event were reduced by about 45, 54 and 32 percent, respectively. Such reductions while increasing irrigation efficiency, decreases water-table-induced salinization.

Deficit Irrigation

Deficit irrigation refers to deliberate under-irrigation of a crop when compared to its evaporative and leaching needs. As a result, farmers are forced to utilize stored soil-water from the rains or pre-season irrigation and capillary up-flow from the water table to water their crops. This recommended concept by Rehman and Rehman (1998) was modeled by Prathapar and Qureshi (1999a). The modeling study showed that in areas where water tables are shallow, irrigation requirements could be reduced to 80 percent of the total crop evapotranspiration without reducing crop yields. It also showed that root-zone salinity would not increase due to monsoon rains and that drainage volume would be reduced because of the lower water tables (Prathapar and Qureshi 1999a).

Change in Crop Selection

Kijne and Vander Velde (1990) found that farmers respond to secondary salinization by changing cropping patterns. They tend to grow more of salt-tolerant and low-water-consuming crops in saline areas. Ahmad (1992) reported that farmers, assisted by government agencies, reclaimed about 16,000 hectares of extremely salinized and sodic soil within a period of 6–8 years by leaching, irrigating with canal water and adopting a crop rotation of jantar-rice-berseem-wheat.

Agroforestry and Biological-Drainage

Water table control using deep-rooted plants and trees with a high evapotranspiration demand is known as “biological-drainage.” This method has been successful in many areas where shallow groundwater salinity is less than 2,000 $\mu S\ cm^{-1}$. There is a general tendency to plant trees in abandoned saline areas. Nevertheless, this practice usually has been unproductive. Plantations in marginal lands, however, have proven to be effective and productive.

Eucalyptus camaldulensis, *Atriples lentformis*, *Acasia nilotica*, and *Acacia ampliceps* are species that offer a great potential to work as bio-pumps (Hafeez and Basharat 2003; Ansari et al. 1998; Khanzada et al. 1998; Qureshi and Barrett-Lennard 1998; Tanwar 1998; ACIAR 1997). Four-year old *Acasia nilotica trees* can consume 1,400 to 2,000 mm of brackish groundwater annually, thereby acting as a biological pump. Eucalyptus can use 1,000 to 1,200 mm saline groundwater per year. While high water tables are lowered appreciably by these species, drainage needs too are reduced considerably. Though the capacity of these species to extract shallow groundwater is a valuable means of controlling water tables, it requires careful planning. Qureshi and Barret-Leonard (1998) estimate that gross returns from agroforestry and biological-drainage vary between US$406 (PRs 24,700) per hectare of acacia and US$657 (PRs 40,000) per hectare of eucalyptus.

Mechanical Reclamation

Since evaporation from the water table deposits salt on the soil surface, breaking the hydraulic connectivity of capillary up-flow by cultivating abandoned soil prior to and in between monsoon rains would lead to the reclamation of saline soil. In this strategy, monsoon rains provide leaching, while cultivation breaks up the hydraulic connectivity. This was numerically demonstrated by Prathapar and Qureshi (1999b). Subsequent field trials confirm results of the modeling study (Prathapar et al. 2005a).

Broadcasting Soil Amendments

Application of chemical amendments such as gypsum, calcium chloride dehydrate, sulfuric acid, hydrochloric acid and farmyard manure can reclaim sodic soil in the IBIS. Soil amendments are usually broadcast across the field, and plowed in. Thus, treatment is limited to surface layers and the quantity of amendment needed is high.

Gypsum Slotting

Reclamation of sodic soil requires an increase in the infiltration rates, so that water can flow through the soil matrix and leach the sodium ions. Short-term increases in the infiltration rate can be achieved mechanically by plowing. However, medium- to long-term solutions require the replacement of sodium by divalent (calcium or magnesium) ions. Therefore, an ideal solution to reclaiming sodic soils requires a combination of mechanical and chemical measures.

Prathapar et al. (2005b) demonstrated that the “slotting technique” developed by Jayawardene et al. (1994) to improve the drainable porosity of soil can be applied to reclaim sodic soil within the IBIS. With slotting, the soil is disturbed to the required working depth in narrow, parallel and vertical bands leaving the rest of the soil undisturbed. These narrow bands (slots) are about 10 to15 cm wide, 50 cm deep and spaced 1 to 2 m apart. The loosened soil is mixed with gypsum. Row-crops are planted along these slots. While soil-loosening is confined to the narrow bands of soil, the beneficial effects of slotting can be extended to the entire expanse of soil. The canopy of the crop planted in the slot will create a microclimate and add organic matter to the inter-slot area. The roots too will extend beyond the slots and extract additional soil-water and create a hospitable environment for soil-microorganisms, which in turn will improve soil health.

Fractional Wells

In the IBIS, the term “fractional well” is used to refer to a well with a discharge rate of less than 30 l/s. Fractional wells are particularly expedient for pumping shallow groundwater of reasonable salinity, which overlies more saline groundwater at deeper depths, for irrigation purposes. If the pump discharge rate is increased, there is a greater likelihood of the deeper saline groundwater being moved upward into the well. Improved well-design and better operating strategies were evaluated by

Asghar et al. (2002), to ensure that the wells are operated in a manner, which would not subject the fresh water layer to be neither mined nor degraded significantly in quality. They concluded that in an unconfined aquifer of 15 to 18 m saturated thickness, a fractional well can be installed and operated successfully with a 60 to 70 percent penetration ratio, and at a discharge rate of 10 to18 l/s for 8 to 24 hours.

Conjunctive Water Use

In the IBIS, about 8.4 MAF of public tubewell water and about 37 MAF of private tubewell water (in the fresh groundwater areas) are being used directly or in conjunctive (blending/cyclic) form for irrigation by Pakistani farmers. The poor quality of groundwater constrains its recycling and reuse as a means of crop irrigation, without proper management practices. Continuous recycling and reuse of saline-sodic groundwater causes an imbalance in the salt balance of an irrigation system, in general, and in the crop root zone, in particular (secondary salinization). Furthermore, it deteriorates the quality of fresh groundwater.

In different parts of the Indus Basin, several studies have been conducted on the use of saline-sodic tubewell water for crop production. These studies revealed that direct use of saline-sodic tubewell water cannot be made for crop production without having a proper soil, water and crop management system in place. Under these conditions, frequent light irrigations, use of chemical amendments (gypsum, H_2SO_4, etc.), along with adequate leaching, growing salt-tolerant and moderately salt-tolerant crops in proper cropping sequence are essential requisites, if saline-sodic tubewell water is to be used for irrigation on a sustainable long-term basis (Haider and Farooqi 1972a; Haider and Farooqi 1972b; Haider et al. 1973; Chaudhry et al.1985; Chaudhry et al.1987; Javaid and Channa 1990; Chaudhry et al. 1992; Ghafoor et al.1996; Qadir et al. 1996; Rashid et al. 1997; Ghafoor et al.1998; Ahmed et al. 1998).

Conjunctive use of good-quality and bad-quality waters through blending or cyclic application could be practiced to minimize the adverse effects of poor-quality waters on land and water resources. A blending strategy is useful under the conditions when fresh and saline water qualities are such that the mixed water would have less salinity than the threshold salinity of a given crop. In other cases, cyclic use practice is more beneficial for sustained use of saline tubewell water, provided sufficient rainfall or better-quality water is applied to maintain a favorable salt balance in the soil. Also, a cyclic water management strategy has great value in dual crop rotation, which includes salt-sensitive and salt-tolerant crops. In a cyclic water management strategy, salt-sensitive crops are irrigated with better-quality water and salt-tolerant crops such as cotton, sugar beet and wheat are irrigated with more saline-sodic tubewell water. For salt-tolerant crops, the switch to saline-sodic tubewell water is usually made after seedling establishment; pre-plant irrigation and initial irrigation are done with canal water. For the Indus Basin, the effectiveness of the cyclic use of canal and tubewell water, along with a heavy pre-sowing irrigation with canal water was confirmed by different studies, where blending of canal and tubewell water proved less effective in keeping ECe (Electrical conductivity of soil saturation paste extract) and SAR (Sodium adsorption ratio) levels low than alternate irrigations (Javaid and Channa 1991; Rafique and Chaudhry 1993; Khoso et al.1994; Sidhu et al. 1996; Mahmood et al. 1999).

Off-Farm Irrigation Water Management Strategies

Participatory Irrigation Management

Environmentally sustainable agriculture in the IBIS requires farmer-friendly institutions. During mid-1997, each of the Provincial Assemblies in Pakistan passed a Provincial Irrigation and

Drainage Authority (PIDA) Act. These Acts envisage transforming each of the Provincial Irrigation Departments to a semi-autonomous PIDA. An effective combination of the Provincial Irrigation Drainage Authority (PIDA), an Area Water Board (AWB) for each canal command, and a Farmers Organization (FO) for each distributary in a canal command area could significantly improve the equity and reliability of canal water supplies (Skogerboe and Bandaragoda 1998).

Improved Canal Operation

First, and probably the most cost-effective measure for improving canal operations would be the installation of a good and reliable communications network with gate operators who are able to communicate with one another, so as to stabilize canal water levels more effectively and reduce discharge fluctuations. The intent is to improve the accuracy of the hydraulic data collected and have this data quickly transmitted with the use of improved communications facilities. Improvement in hydraulic operations would effectively reduce the discharge variability in the system. Thus, enabling farmers to irrigate their fields more effectively (Skogerboe et al. 1999b).

Second, periodic field calibration of headwork, bifurcations, crosses and head regulators along with *moghas* (watercourse outlets) for discharge measurement and control should become standard operating procedures (van Essen and van der Feltz 1992; Jacobs and Schoonderwaldt 1992; Aslam 1994; Kuper 1997; Skogerboe and Bandaragoda 1998).

A pilot trial based on these principles, called “Irrigation Management Information System (IMIS),” was carried out successfully at the Chistian Subdivision within the IBIS (Riviere 1993; Aslam 1994). Furthermore, benefits of improved canal management had been demonstrated by using the two hydraulic models, RAJBAH and SIC (Simulation of Irrigation Canals) — (Habib and Kuper 1998).

Desiltation

Desiltation of canals on an annual basis has improved the equity and reliability of water delivery, especially at the tail ends (Vander Velde 1990; Bhutta and Vander Velde 1992; Murray-Rust et al. 1992; Vander Velde and Murray-Rust 1992; Kuper and Kijne 1992).

Canal Lining

Although lining results in canal water savings (Skogerboe et al. 1999c), other studies show that it is not that effective in improving the hydraulic performance of a canal (Murray-Rust and Vander Velde 1993). They recommend lining only in areas where there is saline groundwater and seepage rates are very high. These recommendations have been adopted in the national “On-Farm Water Course Lining Program,” which is presently being implemented in all four provinces. The estimated cost of the program is US$1.1 billion.

Watercourse Lining

Watercourse conveyance losses are as high as 30 percent (Khan et al. 1999). These losses were recognized in the 1970s and resulted in the creation of provincial On-Farm Water Management (OFWM) Directorates. By the mid-1990s, approximately 30 percent of the watercourses in the IBIS had been lined. Watercourse lining still remains a viable alternative, along with reconstruction of earthen watercourses.

Reconstruction of Earthen Watercourses

At the time of implementing the “On-Farm Water Management Development Project,” in each of the four provinces in Pakistan, namely Punjab, Sindh, Balochistan and the North West Frontier, under the auspices of the OFWM Directorates of Provincial Agriculture Departments, the main focus was on organizing the farmers in a watercourse command area to reconstruct their earthen watercourse to reduce the conveyance losses. The program allowed only 10 percent of the watercourse to be lined with brick and mortar. For its (the program) implementation village areas were preferred for social and health reasons. Lining at the head of the watercourse was preferred as it permitted more water to flow downstream and benefit more people at the tail reaches. It also secured the support of head-reach farmers.

Selective Maintenance

A selective maintenance intervention is more cost-effective when compared to other interventions such as major desilting or lining programs. Irrigation departments could implement a selective maintenance program by effectively using their limited financial resources for maintenance and repair (Murray-Rust et al. 1992; Vander Velde and Murray-Rust 1992).

Revision of Water Allocations

Water allocation may be revised on the basis of cropping patterns and/or the level of salinity in the groundwater. Canal water allocated to areas with saline groundwater may be increased to prevent pumping of poor-quality groundwater, while it may be decreased in areas with good-quality groundwater. Kuper (1997) reported that it is technically feasible to reallocate canal water resources. Applying this method in an area of 14,000 ha, it was shown that the area threatened by sodicity could be reduced by 40 percent. However, Kijne (1998) calculated that the cost of reallocation exceeded the expected benefits, considering the relatively low yields and low market value of the harvested crops. Another disadvantage is that farmers in the head reaches would pump more groundwater to compensate for the loss of canal water, which would result in an increase of the salinity level in the head reaches. Studies undertaken in the 14 canal commands of the Sindh Province disclosed that some adjustments in the water allocations, along with modifications in cropping patterns, could reduce groundwater recharge, thereby lower the groundwater levels (Skogerboe and Bandaragoda 1998).

Off-Farm Drainage Management Strategies

Salinity Control and Reclamation Projects (SCARPs)

The Water and Power Development Authority of Pakistan (WAPDA) has completed 57 Salinity Control and Reclamation Projects (SCARPs) at a total cost of US$435 (PRs 26.48 billion) covering a gross area of 7.81 million hectares. Under SCARPs, more than 20,000 wells have been installed and an area of 0.22 million hectares has been tile-drained. The effect of drainage measures on the groundwater table of some SCARPs is given in table 2. The data presented in table 2 show that waterlogging has been generally controlled.

Left Bank Outfall Drain Project

In the Sindh Province, extensive tracts of croplands are underlain with saline groundwater, which is unsuitable for irrigation and, as such, a different approach had been adopted in irrigating the land. The Left Bank Outfall Drain (LBOD) providing drainage for an area of 500,000 ha in the districts of Nawabshah, Sanghar and Mirpurkhas was completed recently at a cost of US$1.0 billion. The main feature of LBOD is a" Spinal Drain," which connects the drainage network to the sea through a "Tidal Link," and provides an outfall for saline effluent to the Arabian Sea. This is the only outfall to the sea in

TABLE 2.
Impact of SCARPs on waterlogging (area in '000 ha).

SCARP	Total Project Area	Pre-Project		Post-Project			
				1987	1988	1989	1998
		Year	Area*	Area*	Area*	Area*	Area*
I	493	1961	66.4	10.5	2.0	6.9	1.2
II	667	1964	73.2	47.4	8.0	34.0	32.0
III	461	1969	189.9	106.0	69.0	119.4	119.0
Khairpur	154	1960	45.7	68.1	32.8	52.4	32.5
N. Rohri	278	1966	30.6	10.8	17.2	15.6	27.2
Drainage IV	143	1985	42.9	-	-	-	32.9

Source: Bhutta and Chaudhry 1999
Note: * waterlogged area

Pakistan besides the Indus River. The other features include drainage wells, interceptor drains, scavenger wells, tile drains and surface drains. There is a possibility that such an integrated scheme may be draining more water than necessary to provide water table control. This fear was confirmed by a modeling study (Ejaz 1998), which showed that if all drainage facilities operate continuously as planned, water tables will drop below the critical depth necessary to provide salinity and waterlogging control. It also showed that pump operating hours could be reduced by 30 percent without compromising waterlogging and salinity control.

Fordwah Eastern Sadiquia South (FESS) Irrigation and Drainage Project

In Fordwah Eastern Sadiquia South (FESS), where a minimum of 67 percent of the area is affected by waterlogging, the government implemented an integrated irrigation and drainage development project to control waterlogging and salinity. It included the lining of canals, installation of interceptor drains and the extension of surface drainage infrastructure.

Evaporation Ponds

Drainage effluent from the Salinity Control and Reclamation Project VI (SCARP-VI) and the Fordwah Eastern Sadiqia South (FESS) Irrigation and Drainage Project, both located in the southern Punjab of Pakistan, is disposed into evaporation ponds. In SCARP-VI area, drainage effluent generated by 514 drainage tubewells (with discharge rates in the range of 0.043 to 0.085 m^3/s) is disposed into the evaporation pond of 13,360 ha area through a network of 444 km of surface drains (Bhutta et al. 2004). Similarly, drainage effluent from the FESS Irrigation and Drainage Project area is disposed into an evaporation pond of 6,400 ha area (Javed et al. 2000).

National Drainage Program (NDP)

To control waterlogging and salinity, a number of drainage projects have been implemented. The performance of these projects has been below par, mainly because of deficiencies in policy and institutional matters, inadequate O&M of completed drainage facilities and the undertaking of too many new projects at one time. To overcome these shortcomings and to reappraise the existing situation, the National Drainage Program (NDP) was launched with the following two main objectives: (i) minimizing the drainage surplus; and (ii) facilitating eventual evacuation of the saline drainage effluent from the Indus Basin to the Arabian Sea.

The scope of work undertaken by the NDP and its continuance for 25 years is summarized in table 3.

Discussion

Irrigated agriculture is an industry, which provides food more efficiently than rain-fed agriculture. All industries produce waste; so does irrigated agriculture. Its (irrigated agriculture) waste and the salt has to be managed like in any other waste. Those who produce waste material cannot manage all of them, because depending on the potency of the waste matter, specialists and high technologies will be required to manage it effectively and efficiently. Farmers alone cannot solve salinity problems in the IBIS. There are measures that farmers can adopt, but management of voluminous drainage of high-salt concentrations certainly requires government interventions.

While waterlogging requires solutions covering large areas, salinity problems are frequently "patchy," and require solutions suited to individual farms or sometimes only to certain fields of a farm. In general, Pakistani farmers are aware of the adverse effects of salinity and have the capacity to manage field-level salinity by modifying their farming and irrigation management practices. However, their ability to mitigate sodicity, which requires the knowledge of chemical amendments, water quality and leaching, appears limited.

To mitigate salinity at the farm level, it is necessary for farmers to know: (i) when to irrigate; (ii) how to irrigate; and, (iii) how long to irrigate. Under *warabandi*, when to irrigate is not an option to a farmer. However, since a considerable fraction of all irrigated area is now supplied with groundwater of varying quality, timing and the volume of groundwater are directly managed by the farmer and may offer scope for improvement of soil health. A farmer irrigates whenever his/her turn is on. Being

TABLE 3.
Major activities undertaken by the National Drainage Program.

Remodeling/Extension of existing surface drains	10,000 km
Rehabilitation/Replacement of saline groundwater wells	1,150 nos.
Installation of pipe drains in new areas	100,000 ha
Lining of watercourses in saline groundwater areas	1,050 nos.
Construction of interceptor drains	400 km
Reclamation of waterlogged-areas through biological drainage	16,000 ha
Transfer of tubewells installed in fresh groundwater areas to farmers	1,500 nos.
Rehabilitation and modernization of canal command in pilot areas	One in each province
Mobile pump stations	310 nos.

Source: Bhutta and Chaudhry 1999

aware of the unreliable nature of the supply of water, farmers tend to overirrigate when water is received. In order to avoid overirrigation, measures need to be adopted to ensure the reliability of water supplies.

How long to irrigate a field within a farm is an option provided to the farmer, but to determine the period of irrigation, the farmer should be aware of the extent of soil water depletion since the last irrigation. Unfortunately, most of the time he does not have this information. In the end, farmers irrigate when they get water, based on visual observation of crop and soil conditions. There is a need for an irrigation advisory service, conducted through mass media (TV and print) informing irrigation requirements to farmers. This kind of service is provided to the farmers in the Murrumbidgee Irrigation Area, in Australia, where daily and weekly evaporative demand is conveyed to the farmers via evening news bulletins and local newspapers.

Collective efforts for improved operation and maintenance (O&M) at tertiary- and secondary-canal levels require formation of farmers' organizations (farmers' institutions). Pilot efforts are underway in the IBIS to organize farmers who are being served by distributaries. In several cases, joint management agreements have been entered into between Area Water Boards and Farmer Organizations. Though good progress is being made, more time is required to establish whether or not institutional reforms would result in improved canal operations.

At the system level, irrigation departments need to ensure equitable and reliable water distribution, especially for areas where canal water is inadequate, and for areas where groundwater is unsuitable for irrigation. Significant improvement in canal operations would reduce the demand for well water, particularly when the well water is of marginal quality, reducing salinity and sodicity problems.

Many criticize irrigated agriculture for causing salinity without accepting the catastrophic consequences of curtailing it in a country like Pakistan. The critics should recognize that salinization will continue as long as irrigation takes place, and the fact, that as long as there is a need for food irrigation will continue. The challenges for salinity managers within the IBIS are enormous, and require a continuous input of human and financial resources. There is no choice but to continue working towards effective salinity control. All options have to be considered, because there is no single solution for the problem.
All cost-effective, partial solutions must be considered and implemented.

Irrespective of any amount of goodwill and the adoption of best management practices among farmers and system operators, the Government of Pakistan needs to recognize that land and water resources are limited and will remain scarce. Salinity control measures may improve land and water productivity, but not indefinitely, and there is a limit to what extent land and water productivity can be improved.
At that limit, labor productivity—income to the farmer—may not be above the poverty line.
This will result in reduced investments at the farm level to mitigate salinity, and finally threaten environmental sustainability of the IBIS and the food security of Pakistan. The government needs to explore and invest in strategies to reduce the reliance of Pakistanis on irrigated agriculture for poverty alleviation.

Areas for Future Research

Salinity management is central to the future of Pakistan's agriculture, hence merits considerable further effort and research now and in the future as well.

Despite the execution of many research and investigations programs, there is still a need to:

- Develop a rapid and inexpensive methodology and apply it consistently to monitor the impact of salinity control measures on the rate of salinization. Soil salinity surveys over the years have resulted in data, which are inconsistent and possibly unreliable. The methodology should be based on analysis and improvement of this existing data, using remote sensing and GIS tools. The analysis should be made with reference to conditions prevailing in the 1960s and detailed in WAPDA's national survey reports of the time. An understanding of the trajectory of salinization (both mitigation and degradation) should be understood in terms of the interventions carried out in the intervening years.
- Develop effective conjunctive water management strategies at the primary, the secondary and the tertiary canal command levels. At the primary canal level, strategies need to be worked out to take advantage of groundwater storage in wet years and private groundwater pumping in the fresh groundwater zones.
- Conduct benefit-cost analyses of various management interventions to find technologically and financially feasible measures for improving the management of irrigation systems.
- Identify strategies that would improve the rate of adoption of salinity control measures at the farm level, the tertiary level, the secondary level, the primary level and the system level.
- Evaluate and establish improved institutional arrangements governing conjunctive use and interprovincial water allocations in the light of the results of the activities listed above.

Conclusions

Secondary salinization in the Indus Basin of Pakistan is associated with the shallow groundwater table and use of marginal- to poor-quality groundwater for irrigation. The on-farm and off-farm salinity mitigation measures based on preventive and curative approaches are adopted within the Indus Basin. The preventive salinity measures compared to curative measures pay rich dividends at a much less cost and effort. To meet the challenges for salinity managers within the IBIS, require significant input of human and financial resources. There is no choice but to continue working towards salinity control. All options must be considered as there is no single solution for the problem of salinity control.

The improved management of irrigation systems, along with improved irrigation management practices at the farm and conjunctive management of surface and groundwater, offer great potential for mitigation of the secondary salinization in the Indus Basin. This reflects a dire need to devise cost-effective management interventions to the improved irrigation systems management. In addition, technically and economically effective and sustainable conjunctive water management strategies must be developed at the primary, the secondary and the tertiary canal command levels, along with improved institutional arrangements to regulate all aspects of conjunctive water use and interprovincial water allocations.

However, salinity control measures adopted by farmers and irrigation system operators may only improve land and water productivity up to a certain limit at which point, labor productivity—income to the farmer—may not be above the poverty line. This will result in reduced investments at the farm level to mitigate salinity and, finally, threaten environmental sustainability of the IBIS, in particular, and the food security of Pakistan, in general. The Government of Pakistan, therefore, needs to explore and invest in strategies to reduce the level of reliance on irrigated agriculture for poverty alleviation.

Finally, despite extensive research in salinity management strategies, knowledge gaps still exist. To bridge those gaps, there is a need to: (i) develop a rapid and inexpensive methodology using remote sensing and GIS tools, and apply it consistently to monitor the impact of salinity control measures on the rate of salinization; (ii) develop effective conjunctive water management strategies at the primary, the secondary and the tertiary canal command levels; (iii) conduct benefit-cost analyses of various management interventions to find technologically and financially feasible measures for improving the management of irrigation systems; (iv) identify strategies that would improve the rate of adoption of salinity control measures at the farm level, the tertiary level, the secondary level, the primary level and the system level; and, (v) evaluate and establish improved institutional arrangements governing conjunctive use and interprovincial water allocations.

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Postal Address
P O Box 2075
Colombo
Sri Lanka

Location
127, Sunil Mawatha
Pelawatta
Battaramulla
Sri Lanka

Telephone
+94-11-2787404

Fax
+94-11-2786854

E-mail
iwmi@cgiar.org

Website
http://www.iwmi.org

International Water Management Institute

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