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Research Report

Water and Salinity Balances for Irrigated Agriculture in Pakistan

Jacob W. Kijne

International Irrigation Management Institute

Research Reports

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Summary

Water and salt balances are calculated for three irrigated areas in Pakistan, which differ in water availability, amounts of water pumped for irrigation from groundwater, and salt content of the irrigation water. One of the sample areas is the Chasma Right Bank Canal (CRBC) command area in the North-West Frontier Province and the other two are in the Punjab, in the command areas of the Gugera Branch Canal and the Fordwah/Eastern Sadiqia Irrigation System.

The input data for the water and salt balances were obtained from actual field measurements and observations over a number of years in sample watercourses in the irrigation systems. Some simplifications were made in the input values because of considerable spatial and temporal variations in several of the input parameters. A sensitivity analysis was carried out to identify the most critical input parameters. Results indicate that the net flow to groundwater in the Punjab sites is much less during *kharif* (summer or monsoon season) than during *rabi* (winter).

It is concluded from the analysis that current irrigation and agronomic practices are not sustainable. In the CRBC site, considerable groundwater recharge occurs, which in the absence of groundwater pumping leads to rising water tables, waterlogging, and salinity. At present, while the second and third stages of the project are still being developed, farmers in the area of the first stage receive more water than the crops require. The only feasible solution appears to be to limit the irrigation supply to farmers and to reduce the area under rice. In the sample irrigation areas of the Punjab, groundwater is mined, water tables drop, and salt continues to be added to the root zone because of the relatively high proportion of irrigation water derived from pumped groundwater. If the current high crop intensities are maintained, further degradation of land and water resources is inevitable. Additional studies, including regional groundwater flow modeling, are required to predict the rate of expected soil degradation.

Water and Salinity Balances for Irrigated Agriculture in Pakistan

Jacob W. Kijne

Introduction

The value of information that can be obtained from an analysis of the water and salinity balances of an irrigation system is frequently underrated. When planners consider changes in irrigation practices and management that could have considerable impact on water and salinity relationships, they seldom give sufficient attention to collecting reliable data on the components of the water and salt balances. Although the various sources of water (rainfall, canal water, and pumped groundwater), with their differing salt contents, interact in complex ways, some reasonable, simplifying assumptions can be made to establish the water and salinity balances of entire irrigation systems or distributary command areas. Analysis of these water and salinity balances will yield useful information about the potential impact of current irrigation and agronomic practices on the continued sustainability of irrigated agriculture in the system.

Recent overviews of the various methods and models for determining water and salt balances in irrigated agriculture have been given by de Ridder and Boonstra (1994) and van Hoorn and van Alphen (1994). It is obvious from these reviews that the data requirement for the more sophisticated methods exceeds the data available in most developing countries, particularly when canal water and pumped groundwater with different water qualities are used conjunctively for the irrigation of crops.

The water balance approach has often been used to determine the contribution a shallow water table makes to the water supply of an irrigated crop (e.g., Ragab and Amer 1986; Chiew and McMahon 1991). Working at the University of Alexandria, Egypt, Ragab and Amer (1986) described two independent methods for determining the water supply through capillary rise to maize at a field research station that is underlain by a shallow but fluctuating water table. For an average water table depth of some 30 centimeters below the root zone, capillary rise contributed more than 4 mm / day from the fourth day after an irrigation until the next irrigation for part of the growing season (40 days after planting until harvest). Extensive areas in Egypt have shallow water tables resulting from inadequate drainage and poor irrigation practices.

The situation in large parts of Pakistan's Punjab was similar until deep tube wells were introduced for vertical drainage under the Salinity Control and Rehabilitation projects (SCARPs) in the 1960s. Over the past 30 years, more than 12,500 public tube wells have been installed in various SCARP tube well areas. The primary objective of these projects was to combat waterlogging and associated salinity. A secondary objective, however, became supplementing the scarce surface water supplies for irrigation with pumped groundwater, which is usually discharged directly into the existing watercourse network. Since the early 1960s, groundwater development through private tube wells has grown exponentially, especially in Punjab. According to the latest estimates, Pakistan has more than 300,000 private tube wells. A national survey undertaken in 1991 claimed that about 46 billion cubic meters of groundwater are used for irrigation in the Indus Basin, of which 85 percent comes from private tube wells (NESPAK-SGI 1991). The total groundwater extraction would then exceed the annual usable groundwater by more than 50 percent. As a result of this groundwater extraction, water tables have declined beyond the range over which salinization due to capillary action can be expected (Kijne and Vander Velde 1992). Despite the drop in water tables, salinity continues to present a threat to the sustainability of irrigated agriculture in Punjab because of recycling of large quantities of poor quality groundwater from the top of the underlying aquifers and the relatively high sodium contents of the water (e.g., Kijne and Kuper 1995).

The present paper describes the calculation of somewhat simplified water and salinity balances for three regions of Pakistan that differ widely in water availability and the salt contents of the irrigation water. The conclusions that can be drawn from these calculated water and salinity balances of the sample sites in Pakistan are not new. However, similar quantitative evidence has not previously been presented. By changing the input values of groundwater pumping and cropping intensity in the water balance calculations, it is possible to show by how much both parameters need to be altered to achieve sustainable irrigation and agronomic practices. A corollary is that it is essential to analyze first the water and salinity balances under current practice before proposals are made that imply changes to the soil water balance and hence to the salt balance regime.

Methods

The water balance approach followed in this paper has been described by Perry (1996). It consists of a vertical water balance that takes into account two sources of water (surface-delivered supplies and rainfall) and four uses or outflows (crop evapotranspiration, nonbeneficial evaporation and transpiration, drainage runoff, and net flows to groundwater). These elements are linked through seepage from channels and irrigated fields; the disposition of rainfall among runoff, infiltration, and evapotranspiration; and two modes of internal reuse (pumping from groundwater and pumping from drains).

As input data, the model requires the area under consideration, its cropping intensity, the surface water supplies, and the effective rainfall (i.e., used by the crop) over the period considered, e.g., a season. The outcome of seasonal balances can later be combined into an annual balance. A single large irrigation system may be taken, but where deliveries, cropping patterns, and groundwater use vary within the system, it may be better to disaggregate the project into smaller, more homogeneous command areas.

Information needs to be available (or reasonable guesses need to be made) about

- the percentage of canal inflow that is lost to escapes
- the percentage of canal inflow lost to seepage in canals
- the percentage of inflows from canals lost to seepage in watercourses
- the field application efficiency, i.e., the percentage of field deliveries from watercourses used by the crop
- the field losses going to drains

- the percentage of all losses (except runoff) going to nonbeneficial evapotranspiration

- the percentage of rainfall on nonirrigated areas that is evaporated

- the percentage of the noneffective rain that goes to drains

- the percentage of water that goes to the groundwater and is recovered through pumping

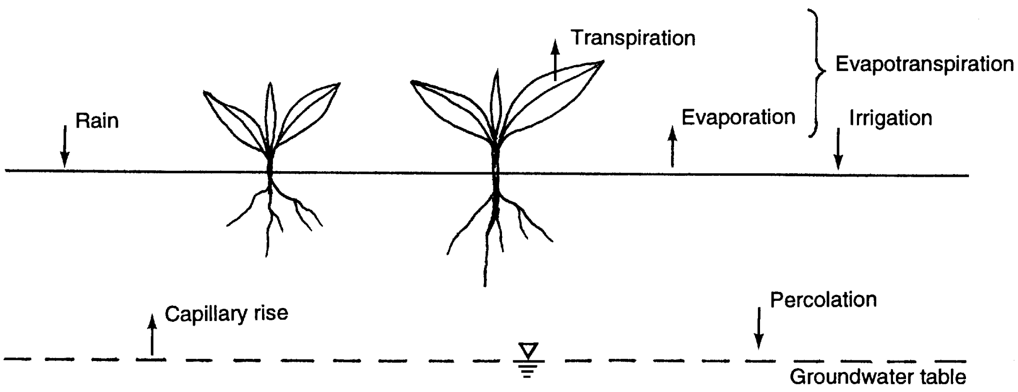
- the percentage of water that goes to drains and is recovered through pumping

- the efficiency with which pumped groundwater is used by the crop (which may be higher than the field efficiency of surface deliveries because it is generally a more expensive source of irrigation water, which farmers may be expected to apply more carefully)

In systems or command areas where groundwater and surface water are used conjunctively, the percentage of water going to groundwater through seepage from canals, watercourses, drains, and fields is an extremely important figure. It usually cannot be determined through an independent assessment and needs to be stipulated for the first round of calculations. If the water balance calculations lead to unrealistic estimates of the irrigation allocation from canal supplies, rainfall, and pumped groundwater, changes need to be made in the values used for the seepage losses and in the estimated groundwater pumping until the figures agree with known irrigation practices. In other words, crop water requirements need to be known or be evaluated through CROPWAT, the FAO approach to the calculation of crop evapotranspiration (Doorenbos and Pruitt 1977), and some idea about the ratio of irrigation supplies from canal water and pumped groundwater is necessary.

The salinity balance used in this paper follows the approach described by van Hoorn and van Alphen (1994) and is schematically presented in figure 1. The model regards the root zone as one layer with a homogeneous distribution of water and salt. The salts are assumed to be highly soluble and not to precipitate because of saturation of the soil solution. The amounts of salts supplied by rainfall and fertilizers or exported by crops are not considered in the calculations. But where accurate information on fertilizer application and efficiency of uptake is available, the amounts of salts

FIGURE 1.
Components of the water balance, each of which has its own salt content.



added to the system from fertilizers could be easily included. The maximum salt concentration in the root zone is limited by the salt tolerance of the crops and the expected yield reduction resulting from irrigation with brackish water. For most commercial crops, these relations are well documented (e.g., Maas 1990). It is also assumed that the irrigation water is thoroughly mixed with the soil water in the root zone and, hence, that the salt concentration of the soil water at field capacity equals the salt concentration of the water that percolates from the root zone. Because downward movement of water and the dissolved salt generally takes place at water contents near field capacity, we assume that the quantity of salt in the root zone at the beginning of the considered time period is dissolved in an amount of water corresponding to the water content at field capacity (W_{fc}) over the depth of the root zone. Salinity, rather than being measured in terms of concentration (meq/l), which is difficult to carry out in the field, is measured as the electrical conductivity (expressed as decisiemens per meter) of the saturated soil paste (EC_e), which can be assessed in the field by commercially available probes. Because for most soils (with the exception of sand and loamy sand), the water content of the saturated soil paste is about twice that at field capacity, EC_e equals 0.5 EC_{fc}.

From the salt balance, it follows that the net deep percolation, R, can be calculated as

$$R = (E - P)\ \{EC_i/(EC_{fc} - EC_i)\},$$

where E is evapotranspiration, P is precipitation, and EC_i and EC_{fc} are the electrical conductivities of the irrigation water and the soil water at field capacity, respectively. Making use of the fact that the leaching fraction, defined as the ratio of R to irrigation supply, I (both expressed in millimeters), is also equal to the ratio EC_i / $2EC_e$, the equation expressing the increase in salinity, Z, over the time period is given by

$$dZ = (I{*}EC_i - R{*}Z/W_{fc})\ /\ \{1 + (R/2W_{fc})\},$$

where EC_i is the weighted average electrical conductivity of the various components of the irrigation supply during the time period considered. If the salt concentrations are expressed as their electrical conductivities, the units for Z, the quantity of salt in the soil water contained in the root zone, become (dS/m)*mm rather than the more usual meq/m^2.

It should be noted that this approach does not take into account the type of salts encountered in the root zone or the soil water. As has been observed elsewhere (e.g., So and Aylmore 1993; Crescimanno, Iovino, and Provenzano 1995), the sodium content of the total salinity is of particular importance because of its effect on the soil structural stability under irrigated conditions.

Sample Sites

Upper and Lower Gugera Branch Canal

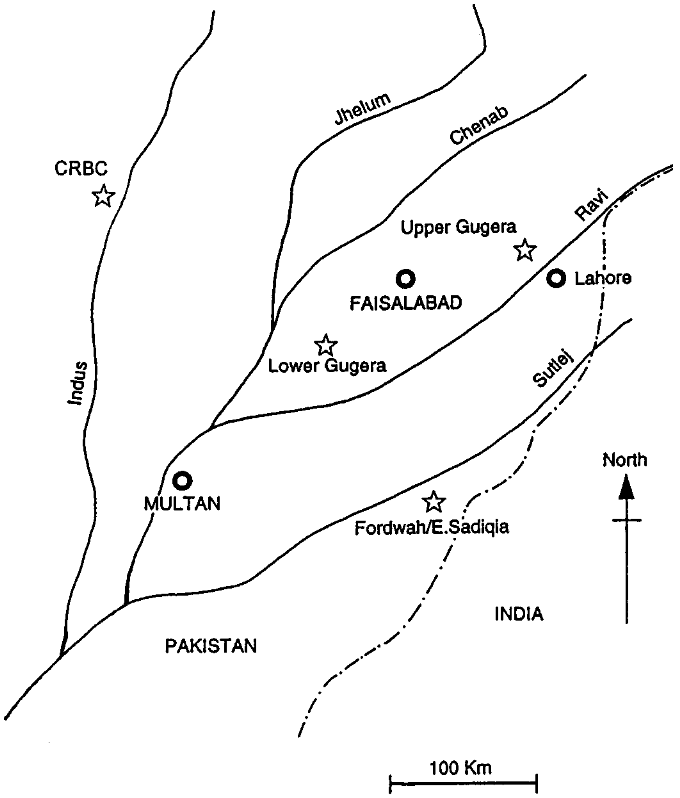
The sample area includes the command areas of two large, fairly typical distributaries in the Lower Chenab Canal System (LCC), which is the largest single canal system in Punjab Province, with a culturable command area (CCA) of about 1.2 million hectares. One of the distributaries is in the command area of the Upper Gugera Branch, and the other more than 200 kilometers downstream in the command area of the Lower Gugera Branch. Mananwala Distributary off-takes from the Upper Gugera Branch in the Farooqabad Subdivision, Upper Gugera Division, about 68 kilometers downstream from the Khanki Barrage, the headworks of the LCC System. Pir Mahal Distributary off-takes from the Lower Gugera Branch at

Bhagat Head Regulator in the Bhagat Subdivision, Lower Gugera Division (figure 2). In both subdivisions, SCARP tube wells were installed more than 15 years ago to control waterlogging. Since the early 1960s when the SCARPs were initiated, private tube well development in these areas has been extensive. Densities now commonly exceed seven wells per 100 hectares. Because the characteristics of the water and salt balance are quite similar in the two distributary command areas, they have been grouped together for this analysis and taken to represent irrigated agriculture in much of the LCC System.

The Mananwala Distributary is 45 kilometers long and its design discharge is 5.2 m^3/s. It supplies 125 outlets, either directly or from three minors, and serves a culturable command area (CCA) of 27,064 hectares. The average sanctioned discharge of its outlets is 30 l/s. The distributary was designed for two levels of cropping intensity. Those outlets serving 50 percent intensity command areas have a design water allocation of 1 l/s per 7.5 hectares; other outlets command 75 percent intensity service areas with water allocations of 1 l/s per 5 hectares.

The Pir Mahal Distributary is 47.5 kilometers long and has a design discharge of 4.67 m^3/s for a CCA of 14,891 hectares. It directly supplies 50 outlets, and 40 others off-take from its four minors. The average sanctioned discharge of these outlets is 35 l/s. The distributary was designed as a 75 percent intensity channel, with a seasonal cropping ratio of *kharif* (mid-April to mid-October) to *rabi* (mid-October to mid-April) seasons as 1:2 in its service area. In the commands of Pir Mahal and Mananwala, water tables today are at a depth of 3 to 8 meters.

FIGURE 2.
Location of irrigation systems, Punjab. Adapted from Kijne and Kuper 1995.



The Mananwala Distributary is located in the Punjab rice-wheat agroecological zone. Rice, especially the high value basmati variety, is the predominant crop during kharif wherever irrigation water is sufficient, and wheat is the principal crop in rabi. Pir Mahal Distributary is in the transition area between this rice-wheat region and Punjab's cotton-wheat agroecological zone further to the southwest. Here, cotton is more frequently the main kharif crop, though rice is also grown; wheat predominates in rabi (Bhutta and Vander Velde 1992).

In both distributary service areas, sugarcane, various kinds of fodder, seasonal fruits, oilseeds, and vegetables are also grown for cash income and domestic consumption. Thus, overall, the irrigated agriculture system in these two study areas is characterized both by a diversity of crops grown and by large areas planted to key crops in Pakistan's agriculture economy.

Fordwah/Eastern Sadiqia System

The second sample area is in the Fordwah/Eastern Sadiqia command, located in the southeast of the Punjab. It is confined by the Sutlej River in the northwest, the Indian Border in the east, and by the Cholistan Desert in the southeast. It commands a gross area of 301,000 hectares, out of which the culturable command area is 232,000 hectares. The irrigation system receives its water from the Sutlej at the left abutment of Suleimanki Headworks.

The climate is semiarid, with annual evaporation (2,400 mm) far in excess of annual rainfall (260 mm). The area is part of the cotton-wheat agroecological zone of the Punjab, with cotton, rice, and forage crops dominating in kharif and wheat and forage crops in rabi. In the Fordwah Division almost a quarter of the area is cropped with rice during kharif, mainly in the alluvial areas of the Sutlej. In contrast, the Eastern Sadiqia Division, which does not form part of the riparian tract, has almost no rice (5%).

Part of the Fordwah/Eastern Sadiqia Irrigation System, combining perennial and nonperennial canals in its command, was chosen for the study. A distinct hydraulic subunit, Chishtian Subdivision, was selected, starting at 65 kilometers along the Fordwah Branch (off-taking from Fordwah Canal) and going down to the tail at 112 kilometers; it includes the 14 off-taking distributaries. The total length of this stretch of main canal commands a total CCA of 67,597 hectares. The design discharge of the Fordwah Branch where it enters the study area is 33 m^3/s (Kuper and Strosser 1992).

The CRBC Irrigation Project

The Chasma Right Bank Canal Project (CRBC) will create a major perennial surface irrigation system that, once completed, will cover a gross command area of about 280,000 hectares on the right bank of the Indus River in Central Pakistan. The main source of irrigation water for the system is the Indus at the Chasma Barrage, which was commissioned in 1982. Additional water is obtained from the Kabul River. The main canal is 285 kilometers long with a CCA of 230,675 hectares. Sixty percent of the CCA is in the North-West Frontier and 40 percent in the Punjab. The main canal and the distributaries are being constructed in three stages: Stage 1 runs for 79 kilometers and covers a CCA of 55,455 hectares; Stage 2 is 37 kilometers long with a CCA of 36,240 hectares; Stage 3 is 142 kilometers long with a CCA of 137,835 hectares. The average water allowance for the entire system is 0.6 l/s per hectare. A significant feature of the system is that it has been designed so that water can be delivered to the watercourses on a demand basis rather than on rotation as in the older systems of Pakistan. This, of course, assumes adherence to the cropping pattern set in the planning stage. The design cropping pattern for rabi includes 45 percent of the cultivated area under wheat, 15 percent under sugarcane, 10 percent under fodder, and 5 percent under gram. The actual figures for IIMI's sample areas were 57 percent wheat, 8 percent sugarcane, 7 percent fodder, and 10 percent gram. For kharif the planned cropping pattern is 2 percent rice (the actual figure is 26%), 15 percent sugarcane (actual 10%), 10 percent fodder (actual 7%), and 10 percent each maize and cotton (hardly any land was under these two crops). In particular, the much larger-than-planned area under rice has consequences for the water demands (Garces-Restrepo, Bandaragoda, and Strosser 1994).

Construction of the first stage had been completed when the system became operational in early 1987. It contains the old Paharpur Irrigation System, which was remodeled to permit greater canal discharges. The full capacity of the main canal is 138 m^3/s, which is to be distributed through 49 distributaries and four link canals. This full capacity is unlikely to be utilized before the end of the century when Stages 2 and 3 should be completed.

Results

The input data for the water balance are presented in table 1. They are based on direct observations and measurements or are best estimates made by IIMI field research staff during the course of several years of field studies in the sample command areas. The Chasma Right Bank Canal site uses no pumped groundwater, only canal water, whereas the other two sites use both canal and groundwater conjunctively, but in different amounts. The values of the *operational losses* are estimates of the proportion of the canal inflows that were surplused to escapes. These losses are assumed to occur only at distributary or main canal level. The *canal and watercourse seepage* losses given in the table are best estimates of the proportion of flows entering the channels lost through seepage, based on actual measurements of inflow and outflow with current meters or flumes over a stretch of the canal or watercourse. The differences between the CRBC site and the other two sites result from the heavier soils found in the command area of CRBC. The *field application efficiency of pumped groundwater* was assumed to be somewhat higher than for canal water because farmers are likely to better control pumped deliveries for which they have to pay fuel costs, pump maintenance and depreciation (or cash to the owner of the pump) than canal supplies for which they pay very little. This point is discussed again later.

Irrigation going to runoff is the proportion of field losses that goes to the drains. It is higher in the CRBC command, where the farmers practiced a “refusal” system, than in the other two sites. *Drain seepage* is the proportion of flows in drains that is lost to seepage and could be recovered by pumping. *Losses to nonbeneficial evapotranspiration* include evaporation from wetted soil and fallow land and from transpiration by trees, weeds, etc. The proportion of rainfall going to runoff is separately specified to allow differentiation between storm runoff, associated with high intensity rainfall, and rainfall that

TABLE 1.
Input data for water balance calculations for the Chasma Right Bank Canal (CRBC), the Fordwah Branch Canal, and the Gugera Branch Canal, for kharif and rabi seasons.

	CRBC		Fordwah		Gugera	
Parameter	kharif	rabi	kharif	rabi	kharif	rabi
Study area (ha)	19,905	19,905	67,597	67,597	27,064	27,064
Cropping intensity (%)	50	90	70	55	70	85
Canal inflow (000 m^3)	123,295	145,053	389,000	115,600	68,475	80,559
Operational losses (%)	5	35	5	5	5	5
Canal seepage (%)	10	10	25	25	25	25
Watercourse seepage (%)	15	15	30	30	30	30
Field efficiency (surface) (%)	80	80	80	80	80	80
Irrigation to runoff (%)	30	30	20	20	20	20
Drain seepage (%)	10	10	30	30	30	30
Losses to nonbeneficial ET (%)	30	30	30	30	30	30
Rainfall (mm)	150	100	125	54	350	150
Effective rain (irrigated) (%)	80	80	80	80	80	80
Effective rain (unirrigated) (%)	50	50	50	50	50	50
Rain to runoff (%)	40	40	40	40	40	40
Pump recovery (groundwater) (%)	0	0	140	160	200	90
Pump recovery (drains) (%)	15	10	5	5	5	5
Field efficiency (pump) (%)	90	90	90	90	90	90

leads to groundwater recharge. These last four parameters are best estimates. *Pump recovery* is specified as the proportion of water going to groundwater that is recovered for irrigation. Its value can be more or less than 100 percent depending on whether more or less water is pumped from the groundwater than is recharged to it. The value of pump recovery calculated from the water balance analysis, which is now as high as 200 percent (i.e., twice groundwater recharge) for the kharif season in the Gugera site, is an important parameter for assessing the sustainability of current irrigation practices and needs to agree with known rise or drop in water tables.

Input for the calculation of the salt balances included the water supplies from canals, groundwater, and rainfall for crop use, obtained from the water balance analysis, and their salt contents (electrical conductivities). The electrical conductivity (EC) of the canal water was taken as 0.2 dS/m, and the mean EC of the pumped groundwater was obtained from measured values of water quality of tube wells in the sample areas. For the calculations of the salt balance, the EC of pumped groundwater was assumed to be 2.5 dS/m, ignoring the large variations in water quality that often occur even from pumps in close proximity. The salinity in the soil water at the beginning of the irrigation season was assumed to correspond to an EC of the saturation extract of 6 dS/m. The water stored in the root zone at field capacity was taken from water retention curves for the dominant soil type in the sample area and the estimated root depth (e.g., 300 mm for the light textured soils of the Fordwah/Eastern Sadiqia site).

Selected results from the calculated water balances (all sites) and salt balances (excluding CRBC, where without groundwater pumping, salinity is not yet a problem) are given in table 2. The amount of water used by the crops for evapotranspiration is calculated from the water balance, and the calculated values in table 2 should match the weighted average for the current cropping pattern as calculated by means of CROPWAT. If not, the choice of input values in table 1 needs to be amended to achieve a close match. In table 2, three components of water used for crop evapotranspiration are listed, i.e., derived from surface supplies, rainfall, and groundwater pumping. A fourth component (which in these sample sites is small in comparison with the other components) is water obtained from pumping from drains. The figure given for the net flow to (positive) or from (negative) the groundwater reservoir is the balance of losses from surface supplies and rain going to the groundwater and pumping from groundwater (for the Gugera and Fordwah sites). The leaching fraction is defined as the proportion of total water entering the soil profile that

TABLE 2.
Selected values of water and salinity balances in Chasma Right Bank Canal (CRBC), the Fordwah Branch Canal, and the Gugera Branch Canal, for kharif and rabi seasons.

	Crop use (mm) from			Total	Non-	Net flow to	Leaching	EC (dS/m)	
Season	Surface water	Rainfall	Groundwater pumping	crop use[a] (mm)	beneficial ET (mm)	groundwater (mm)	fraction (%)	Irrigation water avg	Change in soil water
				CRBC					
Kharif	716	120	–	855	89	207	11	–	–
Rabi	303	80	–	409	69	160	10	–	–
				Fordwah					
Kharif	322	100	487	912	122	–256	10.1	1.53	0.4
Rabi	122	43	228	394	41	–157	9.8	1.65	0.3
				Gugera					
Kharif	142	280	473	897	74	–353	12.8	1.93	0.4
Rabi	137	120	139	397	62	–10	14.1	1.3	–0.2

[a] Includes pumping from drains.

goes to groundwater. The calculation ignores seepage from canals, watercourses, and drains, which is localized and does not contribute to leaching of accumulated salts from the root zone.

Two calculated values of the salt balance are included in the tables for the Gugera and Fordwah sample sites:

1. The average weighted electrical conductivity of the irrigation water, as proxy for its salinity, and based on the relative proportions of the surface supplies, with low electrical conductivity, and pumped groundwater with a higher EC value, in the total irrigation supplies.

2. The change in electrical conductivity of the soil water that occurred over the season as a result of applying the specified amounts and quality of irrigation water with the specified leaching fraction.

For both sites in the Punjab, the net flow to groundwater is much less (i.e., more negative) for kharif than for rabi. Correspondingly, salt accumulation in the soil is greater in kharif than in rabi.

Sensitivity Analysis

An analysis was carried out on the water balance to assess how sensitive the conclusions are to the assumed input values. The results are summarized in table 3 for the Fordwah/Eastern Sadiqia site. Large changes occur in the allocation of surface supplies to crop use when the input values for watercourse seepage or field efficiency for surface water are changed. An even stronger effect on the allocation of groundwater pumping to crop use results from changes in these two variables and also from changes in the input values for canal seepage, losses to nonbeneficial evapotranspiration, and pump recovery. As the allocations from surface supplies decrease and allocations from pumped water increase, the ratio between the two soon becomes unrealistic. For this particular example, it is known from field measurements that pumped groundwater constitutes about one-half to two-thirds of the total irrigation supplies during kharif (Kuper and Kijne 1993).

The effect of changes in input values on the salt balance is small. The calculated leaching fraction is not affected by a relative

TABLE 3.
Sensitivity analysis for the Fordwah/Eastern Sadiqia site.

Parameter	Change in assumed input values	Change (%) Crop use	From surface	From groundwater
Operational losses	0 to 10%	–6	–10	–4
Canal seepage	15 to 25%	–2	–10	21
Watercourse seepage	30 to 20%	2	12	–24
Field efficiency (surface)	80 to 70%	–3.5	–13	18
Irrigation to runoff	20 to 30%	–0.7	0	–4
Drain seepage	10 to 20%	0.4	0	3
Losses to nonbeneficial ET	30 to 40%	–3	0	–15
Effective rain (irrigated)	80 to 70%	–1.5	0	6
Pump recovery (groundwater)	100 to 90%	–2	0	–11
Pump recovery (drains)	15 to 5%	–0.5	0	0
Field efficiency (pump)	90 to 80%	–1	0	–5

change in allocations from surface water and groundwater supplies so long as the field efficiencies for surface water and groundwater supplies remain the same. Only a decrease in field efficiency for either or both of the water sources causes the leaching fraction to increase. The ultimate effect of it all on the change in salinity in the root zone is small, however, because more groundwater, which brings more salt into the root zone, is required to match the crop water use.

Discussion

The choice of input values as given in table 1 is crucial for the actual values of the various components of the water and salt balance. The sensitivity analysis has shown which factors are the most important to get right. These are canal seepage, watercourse seepage, and field efficiency for the surface supplies. The values of canal seepage and watercourse seepage are based on actual field measurements in the sample areas by IIMI field staff or collaborating studies by staff of the Punjab Irrigation Department. Admittedly, these are spot observations as no attempts were made to cover entire command areas, which is beyond the scope of IIMI's field work. There is a fairly large body of data on seepage losses in Pakistan's irrigation canals and watercourses (e.g., Bhutta et al. 1992 and the studies referred to in their paper). Characteristic of all these measurements is the large spatial variability due to, among other things, variations in soil type and whether the major canals were built in cut or fill. A systematic attempt to quantify the determining factors of seepage losses has not been made until now.

The input values of the seepage losses for the calculation of the water balance are given as a percentage of the canal or watercourse inflow. This is a simplification because the losses depend on the wetted area of the channel. It is well known that the losses can increase more than proportionally when a canal is run at full capacity if the portion of the canal banks that is submerged at full flow is weak and full of rodent holes. For example, the seepage loss reported by Bhutta et al. (1992) for the Lower Gugera Branch canal is 0.33 $m^3/day/m^2$, which means that it probably ranges from 7 to 15 percent of the discharge, depending on the flow conditions.

The field application efficiencies of 80 percent for the surface supplies and 90 percent for the pumped supplies may seem high. It should be realized that the fields are small—often less than one-quarter hectare—bunded, and leveled. Many of the larger fields have in recent years been leveled with laser equipment. The bunds around the fields are generally well maintained and overtop only during intense monsoon rains, when farmers may deliberately break the bunds to remove excess water from the fields.[1] The difference between field efficiencies for surface water and groundwater supplies presumably reflects the greater care farmers take with the more expensive source of water. It is doubtful whether the difference is always as much as 10 percent, particularly when groundwater supplies are mixed with canal supplies flowing in the same watercourse. Consistent differences in field efficiency between kharif and rabi were not recorded, although they may have been expected on the basis of differences in relative water supply between the two seasons.

The input values are the best available at this time. The calculated water and salt balances are consistent with field observations of the relative proportions of applied surface water and groundwater and with the changes in water table depth and root zone salinity. However, it should be noted that the

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[1] The frequency with which the bunds overtop or are broken is not known. Frequent field visits seem to indicate that this happens only a few times during the monsoon season. Not all bunds overflow at the same time nor do all farmers take the same action. The effect on the salt balance of water spilling from the fields has not been assessed.

input values contain simplifications about observed spatial and temporal variabilities, not only in seepage losses as was mentioned above, but also in the field applications. It is known from field observations that farmers seem to favor certain fields over others. Some fields may receive only canal water or groundwater if there is a difference in distance between source and location of the field. This may be a matter of convenience, but farmers also deliberately apply more water to some fields in an attempt to leach salts from the root zone (Kuper and van Waijjen 1993). Variations also occur between watercourse command areas. For example, the cropping intensity of the Fordwah/Eastern Sadiqia site during kharif is given in table 1 as 70 percent. During kharif 1994, the cropping intensity in each of two of the key sample watercourse command areas, Fordwah 14R and 46R, was 100 percent. Nevertheless, we have kept the value for the calculations at 70 percent as we feel this value is currently more representative for the larger command area. It is conceivable that cropping intensities are still increasing in the area, but there is no firm evidence for this.

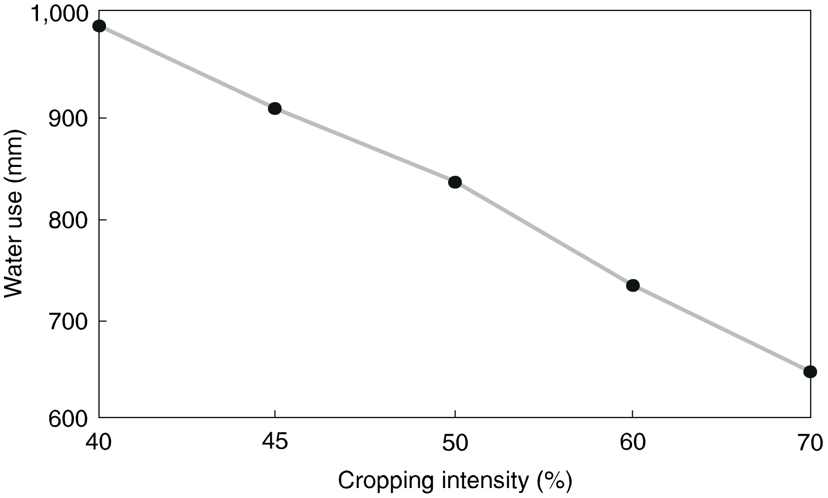
Large spatial variation also existed in the electrical conductivity of soil water. For example, for soil samples taken in June 1995 in the command area of Watercourse Azim 111 in the Fordwah/Eastern Sadiqia sample area, EC_e over the depth interval of 0 to 30 centimeters was 2.12 dS/m (with coefficient of variation of 0.35); for 45 to 90 centimeters depth, EC_e was 3.70 dS/m (CV 0.49); and for 120 to 200 centimeters depth, EC_e was 1.5 dS/m (CV 0.56). Hence, simplifying assumptions were necessary to carry out the calculations of water balance and salt balance. In general, however, when there was some doubt about which value to choose, the more conservative was taken to avoid exaggerating the conclusions that can be drawn for the three sample areas.

In the CRBC command area, groundwater recharge is considerable and, in the absence of groundwater pumping, it is bound to lead to waterlogging and salinity due to capillary rise from high water tables. The Irrigation Department of the North-West Frontier Province recognizes the danger. Currently, farmers in the completed part of the CRBC system (Stage 1) receive more canal supplies than is intended in the design and than they will be receiving when all three stages of the project are in operation. The results presented here indicate that a harmful rise of the water table is likely to occur before the two later stages are finished. Moreover, farmers are becoming accustomed to receiving higher-than-design supplies of canal water, which they currently put to use by growing rice on far more land than was intended. There seems to be no other solution other than to limit water supplies to farmers, thus reducing the area under rice. For hydraulic reasons, the main canal needs to flow at near the full supply level to reduce the hazard of siltation; it is therefore imperative that more of the canal flow escape back to the river rather than being applied on the fields. The natural drainage in the CRBC command area is unlikely to be adequate to handle the required leaching volume and the losses that will occur under even the best of water management. However, if the measures suggested here are not taken soon, subsurface drainage will have to be provided within the next few years to sustain the agricultural productivity of the land.

The situation in the sample areas in Punjab is completely different but equally unsustainable. Here overexploitation of groundwater of marginal quality leads to a lowering in water tables combined with increasing salinity of the soil profile. Again, these hazards are known and generally acknowledged by the irrigation agencies, but they have rarely been expressed in such quantitative terms before.

If the water balance is calculated for the situation in which the groundwater pumping is equal to groundwater recharge, i.e., a pump recovery of 100 percent for the kharif season at the Gugera site rather than the

FIGURE 3.
Crop water use and cropping intensity at the Gugera site in kharif.



present 200 percent (table 1), the cropping intensity needs to be reduced to 45 percent to make about 900 millimeters of water available (figure 3); the crop requires 897 millimeters (table 2). As demonstrated in figure 3, which shows the relation between cropping intensity and water available for evapotranspiration by the crop for a 100 percent pump recovery, the lower the cropping intensity, the higher the irrigation supply available for crop use. The relation is not linear because of the fixed contribution from rainfall to the crop water requirements and the difference in field efficiency of surface water and groundwater supplies. For this situation of 100 percent pump recovery and 45 percent cropping intensity, the corresponding values of the salt balance are an average weighted salinity of the irrigation supplies of 1.62 dS/m and a change in electrical conductivity of the soil water, surely a more sustainable situation. Hence, the electrical conductivity in the root zone under this regime remains at 6 dS/m, the value assumed at the beginning of the irrigation season. A sudden change from the existing cropping intensity to this recommended cropping intensity, combined with groundwater pumping, would at first lower the salt content in the root zone. Thereafter, the salt content may be expected to increase again as the entire recharge to the groundwater continues to be recovered for irrigation. The rate at which the increase would occur is hard to predict. It depends on pumping depth and the mixing processes that take place in the top of the aquifer.[2]

Assumed in the calculation of the salt balance is that salinity of the soil water at the beginning of the season corresponds to an electrical conductivity of the saturation extract (EC_e) of 6 dS/m (corresponding to 12 dS/m at field capacity), which for most crops is the critical limit of soil water salinity. Beyond that, unacceptably large yield depressions of some 40 to 60 percent would occur (van Hoorn and van Alphen 1994). Even at an EC_e value of 4 dS/m, many crops show a yield depression of 20 to 25 percent. For present kharif irrigation practices, assuming a salinity level (EC_e) of 4 dS/m at the start of the season leads to an increase in salinity of 0.9 dS/m, compared with 0.4 dS/m for an initial salinity of 6 dS/m. In all cases, the calculated change in salinity during the season is greater if the salinity level at the start of the season is assumed at the lower level.

Current irrigation and agronomic practices *during rabi* at the Gugera site are sustain-

[2] Inverse salt gradients in the aquifer underlying the command area of the Upper Gugera Branch Canal have been observed in roughly half the cases where such comparisons could be made (i.e., water pumped from a shallow tube well has a higher salt content than water from a nearby deep tube well).

able as the change in electrical conductivity of the soil water is negative (–0.2 dS / m), and extraction from groundwater is in balance with recharge (net flow of –10 mm during the season) (table 1). The conclusion then is that the current *annual* cropping intensity of 155 percent is not sustainable and needs to be reduced to about 130 percent.

It should be remarked that in the command areas of the Upper and Lower Gugera Branch Canal, water tables are now 3 to 8 meters deep and appear to change less over time than would be expected from the above calculations of the water balance of the irrigated areas. The primary source of groundwater recharge in IIMI's research sites in the Upper Gugera command area is seepage from the Upper Gugera Branch Canal itself, which carries about 180 m^3/s in this reach, and the Qadirabad-Balloki Link Canal, which carries around 540 m^3/s (Greenman, Swarzenski, and Bennett 1967). Both flow parallel and close to the head reach of the distributaries (Mananwala and Lagar) in which the data were collected. This flow pattern accounts for the reported gradient in water tables and groundwater quality from the head reach to the tails in the command areas of the distributaries that flow more or less perpendicular to these two canals (Kijne and Vander Velde 1992). Recharge to groundwater in the area of the research sites in the command of the Lower Gugera Branch Canal is in large measure from the Ravi River, which flows as close as 2 kilometers from parts of the downstream half of one of the sample distributary canals in this area (Pir Mahal Distributary). The hydraulic gradient for a water table depth of 8 meters over a distance of 2 kilometers is small, and therefore the impact of local recharge can only be limited in spite of the fairly large horizontal transmissibility of the aquifer (Greenman, Swar-zenski, and Bennett 1967).

The water balance calculations presented here do not take into account lateral groundwater flow from sources of good quality water that affect the hydrological conditions of the command areas. Notwithstanding the possible local importance of lateral recharge phenomena, the results of the vertical water and salinity balances should not be discarded easily. The bulk of the 27,000 hectares of the command area of the Mananwala Distributary and of the nearly 15,000 hectares of the Pir Mahal Distributary is probably affected only by the vertical recharge phenomena occurring throughout the command area. In fact, it is reasonable to expect that calculated balances are representative for a large part of the Lower Chenab Irrigation System, excepting pockets with high water tables in the proximity of persistent seepage areas near major canals. A thorough analysis of the entire hydrological situation, though desirable, is far beyond what IIMI's research can undertake.

A similar analysis of the water balance of the Fordwah / Eastern Sadiqia site shows that the cropping intensity should be reduced from the current 70 percent during kharif to 48 percent to have adequate irrigation supplies for crop use while not exceeding 100 percent pump recovery. The corresponding salt balance values are an average weighted electrical conductivity of the irrigation supply of 1.34 dS / m and a change in electrical conductivity of +0.1 dS / m. For rabi, these values are a cropping intensity of 45 percent, average weighted EC of the irrigation supplies of 1.37 dS / m, and a change in EC of soil water of +0.1 dS / m. In other words, to obtain sustainability in this irrigation system, the annual cropping intensity needs to be reduced from the present 130 percent to only 93 percent. Alternatively, a different cropping pattern with a reduced area under water-demanding crops such as rice and sugarcane could be maintained on a larger area (hence a higher cropping intensity) with a reduced supply per unit of land. The relation between the two is shown in figure 3. For example, if the weighted crop water use for a different cropping pattern during kharif on the Gugera site is only 720 millimeters, which is 80 percent of the current demand, a cropping intensity of about 60 percent would be acceptable.

In conclusion, the analysis indicates that at all three sites current irrigation and agronomic practices should not be continued for much longer. In the command area of the Chasma Right Bank Canal, continuation will lead to waterlogging and concurrent salinity by capillary rise, and in the command areas of the Gugera and Fordwah/Eastern Sadiqia systems current practices are bound to lead to lowering of water tables and degradation of soil and water resources. Management solutions are reducing the area cropped in each of the two seasons, changing cropping patterns so that smaller areas are under crops with high water consumption, or a combination of the two.

Admittedly, the models used in the analysis have not been validated. Supporting data have been presented in papers referred to herein, but that does not constitute a validation of the model. Other studies have indicated that detailed water balance studies, which are used with success for irrigated agriculture, have failed to predict evapotranspiration accurately under conditions where plants suffer seasonal water stress and cover is sparse (see, for example, Gee and Hillel 1988). Under those circumstances, recharge, when estimated as a residual in the water balance model, may be in error by an equal order of magnitude. Therefore, additional studies should be undertaken, including regional groundwater flow modeling, to ascertain the rate of soil degradation and hence the degree to which current irrigation practices cannot be sustained.

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