Salinisation in irrigated agriculture in Pakistan: mistaken predictions

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Abstract

This paper revisits data and information that was collected through field studies by the International Irrigation Management Institute (IIMI) in Pakistan in the early 1990s. Analysis of available data led in 1996 to the publication of an IIMI research report (Kijne, 1996) whose main conclusion was that current cropping intensities and groundwater usage in Pakistan’s irrigated agriculture were not sustainable. Ten years on there is no evidence that this prediction came true and the paper questions why those predictions were wrong. Based on more recent field data and information, the water and salt balances for one of the experimental sites are recalculated.

Reasons for the mistaken predictions include: lack of understanding of farmers’ reactions to signs of salinity in their fields, insufficient knowledge of the actual groundwater usage and underestimating the leaching fractions. The difficulty in accurately determining the actual leaching fraction from easily measurable field parameters affects the prediction of salt accumulation in the soil. The conclusion that current practices are all right is conditional on maintaining sufficient downward fluxes in the soil profile. The paper ends with some general reflections on predictions for the future.

Keywords: Farmers’ practices; Groundwater flow; Leaching; Salt accumulation; Sustainability; Water balance

1. Introduction

“From the viewpoint of natural science, a disquieting aspect of computer-based modeling is the gap between the model and the real-world events” (Philip, 1991)

From its inception, the Pakistan programme of the International Irrigation Management Institute (IIMI) has been involved in quantifying the incidence and severity of salt accumulation in irrigated agriculture. However, the accuracies of the estimates have not been checked against farmers’ reaction to signs of salinity in their fields, insufficient knowledge of the actual groundwater usage and underestimating the leaching fractions. The difficulty in accurately determining the actual leaching fraction from easily measurable field parameters affects the prediction of salt accumulation in the soil. The conclusion that current practices are all right is conditional on maintaining sufficient downward fluxes in the soil profile. The paper ends with some general reflections on predictions for the future.

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1 The Institute, which has its headquarters in Colombo, Sri Lanka, changed its name in 1998 to the International Water Management Institute (IWMI).

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areas, particularly in Pakistan’s Punjab (e.g. Vander Velde & Murray-Rust, 1992; Kijne, 1996, hereafter called Pak96\(^2\)). In 1996, the present author wrote “the value of information that can be obtained from an analysis of the water and salinity balances of an irrigation system is frequently underrated”. He noted however that irrigation managers and planners seldom gave sufficient attention to collecting reliable data on the components of the water and salt balances.

Pak96 described the calculation of simplified water and salinity balances for three regions of Pakistan that differed widely in water availability, especially in the relative portions of canal water and pumped groundwater and the resulting salt content of the irrigation water. The paper concluded that based on current irrigation input, water quality and cropping patterns, present-day irrigation and agronomic practices were not sustainable and large areas of irrigated land would go out of production in another ten years or so. Overexploitation of groundwater of marginal quality was expected to lead to lowering of water tables and increased salinity in the soil profile for the two sites in Punjab, while in the sample site in North West Frontier Province excessive irrigation was expected to lead to water-logging.

It is now about ten years since the original data for Pak96 and related papers (e.g. Kijne & Vander Velde, 1992; Kijne & Kuper, 1995) were collected. The objective of this paper is to examine whether or not the predictions regarding the build-up of salinity levels in Pakistan’s Punjab were realised, what was wrong with the modelling or with the data on which the predictions were based.

Total cereal production in Pakistan shows an annual increase of about 3.2% per year over the last 30 years with no obvious break in the trend during the last ten years. Likewise, arable land area increased at a rate of about 3.5% per year, but irrigated land area at only just over 1% per year over the last 30 years. The average wheat yield was 2,305 kg/ha in 1999–2001 up by 29% since 1989–91, or 2.6% per year. In recent years, some 85% of the total wheat production took place on irrigated lands. It appears that the overall wheat yield and the irrigated wheat yield have steadily increased at about the same rate (see also Hussain et al., 2004); yet, average wheat yields in Pakistan (and also in India) are the lowest among major wheat producing developing countries. At the same time, average meat production over the last ten years has gone up by 3% and average annual fertiliser use by 46% (all data from WRI, 2003 and FAO, 2003). Obviously, these data do not suggest that agricultural production became unsustainable during the last ten years. This paper aims to identify why our predictions about the lack of sustainability of the farming practices in one of the study areas were wrong.

2. Methodology

The water balance approach that was followed in Pak96 was described by Perry (1996). It consists of vertical water balances that take into account two sources of water (surface-delivered water and rainfall) and four outflows (crop evapotranspiration, non-beneficial evaporation and transpiration, surface 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 the two modes of internal reuse (pumping from groundwater and pumping from drains). The salt balance considers the salinity levels of the various flows included in the water balance. The study was carried out for areas with water tables below 2 m.

\(^2\) Most of these studies were summarised and reviewed by Merrey (1997).
As input data, the water and salt balances require details of the area under consideration, its cropping intensity, the surface water supplies and their quality and the effective rainfall over the period considered. Additional data or information are needed about the percentage of canal inflow that is lost to escapes and to seepage within the canals and watercourses, the percentage of field deliveries actually used by the crop, the percentage of field losses going to drains and of all losses going to non-beneficial evapotranspiration, and the percentage of water that seeps into groundwater and drains and is then recovered through pumping. It was considered that the field application efficiency of pumped groundwater may be higher than that of canal deliveries as groundwater is usually more expensive than canal water and farmers could apply it more carefully. It was realised at the time that for those areas where canal water and groundwater were used conjunctively, the percentage of water going to groundwater through seepage from canals, watercourses, drains and fields is a very important parameter. This was confirmed by a sensitivity analysis for one of the sample sites of the effect of input value changes on the relative allocation of canal water and pumped groundwater. As percolation losses cannot easily be assessed independently, Pak96 assumed its values for the first round of calculations and later adjusted them if the water balance calculations led to unrealistic estimates of the irrigation allocation from canal supplies, rainfall and pumped groundwater until the allocation figures agreed with known irrigation practices.

The salt balance analysis of Pak96 followed the approach described by van Hoorn & van Alphen (1994). The model regards the root-zone as one layer with a homogeneous distribution of water and salts. The salts are assumed to be highly soluble and not to precipitate because of saturation of the soil solution. The amount of salts applied in rainfall and fertilisers or exported by crops is not considered in the calculations. 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 at field capacity equals the salt concentration of the water that percolates from the root-zone. As was pointed out at the time, this approach did not take into account the type of salts encountered in the root-zone or the soil water. This omission is especially important when sodium salts are the predominant salts because of their effects on the soil structural stability under irrigated conditions. The above-mentioned sensitivity analysis indicated that the effect of input value changes on the salt balance was rather small. As long as the field application efficiencies for canal water and pumped groundwater remained the same, the calculated leaching fraction was not much affected by a relative change in allocations of canal water and groundwater supplies.

3. Salinity assessment in waterlogged and saline area: review of some relevant studies

In a World Bank sponsored study, IIMI-Pakistan and the Mona Reclamation Experimental Project collaborated in assessing the benefits associated with lowering the water table and preventing the recurrence of waterlogging and salinity in the Fordwah-Eastern Sadiqia (FES) Irrigation and Drainage Project (Kahlown et al., 1998). This study was carried out in the same irrigation system as one of the sample areas in Pak96, except that the project area for this later study was entirely situated in the saline zone in an area with high water tables. There were no tubewells in any of the watercourse commands included in the study by Kahlown et al. (1998). Its primary objective was to evaluate the impact of water logging and salinity on crop yields and to develop methodologies for improving agricultural productivity in the study area.

The data of this study show that wheat and cotton received up to five irrigations, depending on the depth of the water table, for a total irrigation supply of 375 mm; rice up to 13 irrigations with a total application of
1,300 mm, and sugarcane 12 irrigations and 1,200 mm. All of these irrigation applications far exceed the values reported for the other part of the FES area. No wonder, the area is characterised by extensive water logging and salinity. Large seasonal fluctuations in temperature and rainfall are typical for the area, while canal irrigation supplies are found to be variable and inequitable. The authors estimated that the adverse effect of soil sodium content sodicity could reduce yields of wheat, rice and sugarcane by about 30–40% and cotton yields by some 10%. In addition, lack of adequate drainage reduces the yield potentials by a further 10–20% depending on the depth of the water table. Cereal yield levels reported for the area were all less than 1,000 kg/ha and hence much lower than the national average. The authors suggest that installation of sub-surface drains could alleviate much of these yield reductions.

Molden et al. (2001) applied a water accounting procedure to four sub-basins in Asia to assess whether irrigated agriculture could possibly get by with less water. One of the sub-basins is Chishtian in Pakistan, which is in the same irrigation system as the Fordwah branch canal command area of Pak963. The authors use a water balance approach and classify different outflow components into water accounting categories. The reported water accounting data, also presented in diagrams which show the various flow components, are based on the 1993/94 seasons of rabi and kharif, winter and summer/monsoon seasons, respectively. At Chishtian, more water is used in evapotranspiration than the gross inflow from canal water and rainfall. The additional water depletion beyond gross inflow is derived from groundwater. The authors say, “Based on only a one-year analysis, we are unsure whether or not this is an extreme case of overdraft, but certainly if this imbalance in inflow and outflow persists, the water use patterns are not sustainable.” They conclude that there is little or no scope for reducing the depletion through water-saving measures such as recycling water or improving application efficiency. Reference is made to their paper for more details of the study. In the context of this paper, the additional data and information they present on groundwater use, cropping intensities and non-process, beneficial depletion (water used for home gardens and forests) are of interest.

Of even more relevance is the paper by Ahmad et al. (2002), which made use of a more sophisticated physically based numerical model, Soil–Water–Atmosphere–Plant (SWAP), to compute soil water content and vertical soil water fluxes in the unsaturated zone for the cotton–wheat and rice–wheat cropping systems of Punjab, Pakistan. This model4 had been calibrated and verified with in situ measurements of soil moisture content and evapotranspiration fluxes measured by means of the Bowen ratio surface energy balance technique. With knowledge of the soil hydraulic parameters, SWAP was applied to assess recharge and capillary rise for most irrigated field conditions. The authors present detailed time–depth profiles of the sub-soil water fluxes to capture their spatial and temporal variability.

The results obtained under the conditions that prevail in irrigated agriculture in Pakistan’s Punjab indicate that deep percolation cannot always be estimated from root-zone water balances. The percolation flux varies significantly with time and across the unsaturated zone, and the flux direction can reverse at a greater depth. The water flux leaving the root-zone at 2.0 m depth cannot be considered as the deep percolation rate. The model study predicted an annual gross recharge of about 230 mm for the cotton–wheat areas and of nearly 390 mm for the rice–wheat areas, with some 80% of the recharge occurring during the rice-growing season (kharif). The net recharge which takes account of

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3 The distinct hydraulic sub-unit, Chishtian subdivision, which was selected is part of the Fordwah/Eastern Sadiqia Irrigation System, located in the southeast of the Punjab (see page 8 in Kijne, 1996).

4 There are several other soil–water balance approaches to quantify groundwater flows in the literature. A recent one is discussed by Kendy et al. (2003) with respect to irrigated land in the North China Plain.
the capillary rise from the water table was calculated to be 175 mm in the cotton–wheat areas and 300 mm in the rice–wheat areas. Current pumping practices lower the water table indicating that lateral inflow and the net recharge (175 mm) in the cotton–wheat areas cannot compensate for the annual groundwater extraction of about 270 mm. In the rice–wheat areas there is an even greater discrepancy between current pumping of over 800 mm and the net recharge of about 300 mm. The authors conclude that considerable reduction in groundwater extraction (for example, reducing pumping in the rice–wheat areas to about one-third of its current value) is needed to make these irrigation practices sustainable.

In a study by Qureshi et al. (2002), field data on groundwater use were collected in four watercourse command areas of the rice–wheat area of Pakistan’s Punjab. These data were used in a water balance approach to develop a relationship from which groundwater use could be estimated without the need to monitor tubewell discharges or operating hours. The authors assumed that groundwater extraction could be obtained after all other water balance components were either calculated or estimated. These other components include surface drainage outflow, which could be monitored in the drains, and field percolation rates, which the authors expect to be of importance only in rice production and which they suggest could be derived from the literature. However, the data presented (their Table 3) indicate that in each of the four watercourse command areas, and for both seasons the estimated groundwater being pumped, exceeded evapotranspiration, sometimes by as much as 100%, which was confirmed in the field observations of tubewell operations. Combined with canal supplies and rainfall, the water applications must have given rise to considerable downward fluxes from the irrigated fields.

4. Results of recalculation of water and salt balance for the Chishtian subdivision

The input values used in Pak96 and the other earlier studies were the best available at the time, but we realised that some of them were no more than best guesses. Taking into account the data and information mentioned above (Molden et al., 2001; Ahmad et al., 2002), the water and salt balances for the Chishtian subdivision, which are representative of large command areas in Pakistan’s Punjab, were recalculated. The main differences in input data were as follows:

- Long-term average values of rainfall and evapotranspiration were used rather than values for one specific year.
- The percentage of field losses that goes to the drains was lowered from 20 to 10%.
- The percentage that seeps from the drains was increased from 30 to 50%.
- Evaporation from wet soil and transpiration from trees etc. (non-beneficial evapotranspiration) were decreased from 30 to 20%.
- The proportion of seepage going to groundwater that is recovered for irrigation is reduced to 67 from 140%.
- The field application efficiency of groundwater was lowered from 90 to 80%, the same as the field application efficiency of applied canal water.

The most important changes in input data for the recalculation of the water and salt balances are the last two. In retrospect, a recovery rate of seepage in excess of 100% was wrong. The net groundwater flux needs to agree with a known rise or drop in water tables and that was not the case. In fact, this agreement only needs to be approximate, as lateral flow from outside the study area could mask a small difference between pumping rate and seepage rate. Lateral flows are not quantified in any of these water
balance studies. The model with the input data we used at the time tended to overestimate the amount of pumped groundwater and underestimate the canal flows.

With respect to the last-mentioned change in input data, there was no evidence for our earlier assumption that farmers would apply pumped groundwater to their field with more care than canal water, which would have justified a higher value of the field application efficiency for groundwater than canal water.

In Table 1, the recalculated values of selected parameters of the water and salt balances for the Chishtian sub-division are compared with the original data (Table 2 in Pak96, page 10). The values in the last column of the table refer to the change in soil water salinity, expressed in dS/m.

5. Discussion

5.1. Recalculated parameters of the water and salt balance

The groundwater component of the irrigation supply, at just under 40% in both seasons, is far more realistic than in the data presented in 1996. The calculated net flow to the groundwater of 4 mm during rabi and 88 mm during the kharif season is consistent with the absence of marked changes in water table levels in the command area.

Whereas in the earlier calculations soil water salinity appeared to increase slightly over time, the recalculated values indicate a slight decrease in soil water salinity. Either way, the changes are small and do not point to a rapid decrease in soil water quality. Two components of the set of input data, that is, the pump recovery rate of water that seeps to the groundwater and the seepage rates from canals and watercourses, are still no more than best estimates, which ignore their inherent temporal and spatial variability. Changing the pump recovery rate from 67 to 90%, or reducing canal and watercourse seepage rates to around 20% does not change the overall picture with respect to net groundwater flow or leaching fraction. There remains a significant difference between the revised data on the net groundwater flow in Table 1 and the data reported by Ahmad et al. (2002). The latter authors, as mentioned earlier, calculated an annual net groundwater recharge of around 175 mm in the cotton–wheat producing areas and 300 mm in the rice–wheat areas, whereas the revised annual net groundwater recharge for the Chishtian area is less than 100 mm. The study areas and the seasons of observation are not the same, so this could reflect genuine differences in farming practices and soil characteristics.

The most difficult parameter to measure in the field is actual groundwater pumping. Ahmad (2002) compared several methods and concluded that the specific yield method for assessing groundwater withdrawal, based on vertical movement of the water table which ignores all lateral flow, yielded an estimate of groundwater withdrawal which is less (by 65%) than the estimated net groundwater use according to the geo-information method.

Attempts have also been made to calculate the amounts of water pumped from the hours of pump operation. Of course, this method gives gross groundwater withdrawal values. This was first attempted as part of IIMI’s research in Pakistan by Johnson (1990) (see also Vander Velde & Johnson, 1992). Johnson found that farmers were very reluctant to record actual pumping hours, fearing the information would be

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5 This was pointed out by Ir.E.G. van Waijjen in a personal communication in April 1996, when Research Report 6 had already been printed. I am glad to acknowledge his contributions to our understanding of the complexity of water and salt balances at field level.
used for taxing purposes. Probably for the same reason, some farmers did not allow him to install automatic vibration meters on the pump engines to assess pumping hours. In spite of these difficulties, Johnson deduced that in one of the distribution command areas of his study, average annual private tubewells, were utilised for around 12% of the time with large variations between the different types of power source. Electrically powered pumps operated on average 27% of the time, which is 3.5 times as much as the diesel pumps and ten times as much as the tractor-driven pumps. Private tubewells (with the exception of tractor-driven pumps) that pump good to marginal quality groundwater are reported to work at least 33% more intensively than those installed in areas with poor quality groundwater. Johnson (1990) also reported that the average annual utilisation rate of 11 public tubewells located in the command areas of his study was 64% in 1988/89, based on the number of hours that each well was operational with electric power available. Public tubewells provided, on average, 43% of all irrigation water available to farmers during rabi and nearly 30% of irrigation supplies available in kharif. Average utilisation factors of around 20% as used by Pakistan’s Water and Power Development Authority (see NESPAC-SGI, 1991) ignore all these differences and clearly give no insight in net groundwater use.

5.2. Changes in soil salinity

The change in profile salinity depends on the electrical conductivity of the irrigation water (EC in Table 1) and the leaching fraction. Simulation studies reported in Kijne & Vander Velde (1992) indicated that salinity in the soil profile varied much and increased about as often as it decreased. The highest increase was found for sugarcane on silt loam soils. Often, irrigation practices differ within watercourse command areas with the tail ends receiving far less water than the head reaches of canal commands and farmers in the tail reaches of watercourse commands tend to apply relatively more tubewell water than those in head reaches. It has been observed that in general groundwater quality deteriorates towards the middle and tail reaches (e.g. Kijne & Vander Velde, 1992; Hussain et al., 2003). The latter authors reported that the inequity in water distribution was greater in the study area in Pakistan than in the one in India. The estimated Gini-coefficients are 0.29 and 0.42, respectively for the sites in India and Pakistan. Hussain et al. (2003) also point out that inequity for the tail-end watercourses of

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Table 1. Selected values of water and salt balances in Chishtian sub-division as calculated in 1996 and 2004.

<table>
<thead>
<tr>
<th>Season</th>
<th>Canal (mm)</th>
<th>Rain (mm)</th>
<th>Pumping (mm)</th>
<th>Total crop use (mm)</th>
<th>Non-beneficial ET (mm)</th>
<th>Net flow to groundwater (mm)</th>
<th>Leaching fraction (%)</th>
<th>EC Irrigation water (dS/m)</th>
<th>ΔEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>kharif</td>
<td>322</td>
<td>100</td>
<td>490</td>
<td>912</td>
<td>122</td>
<td>−256</td>
<td>10</td>
<td>1.53</td>
<td>0.4</td>
</tr>
<tr>
<td>rabi</td>
<td>122</td>
<td>43</td>
<td>229</td>
<td>394</td>
<td>41</td>
<td>−157</td>
<td>10</td>
<td>1.65</td>
<td>0.3</td>
</tr>
<tr>
<td>2004</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>kharif</td>
<td>315</td>
<td>98</td>
<td>257</td>
<td>670</td>
<td>97</td>
<td>88</td>
<td>18</td>
<td>1.23</td>
<td>−0.5</td>
</tr>
<tr>
<td>rabi</td>
<td>167</td>
<td>65</td>
<td>149</td>
<td>381</td>
<td>44</td>
<td>4</td>
<td>18</td>
<td>1.28</td>
<td>−0.3</td>
</tr>
</tbody>
</table>

6 The larger the Gini coefficient (between 0 and 1), the greater the inequity in water distribution.
distribution commands is greater than for head-end watercourses. Less reliable water distribution, coupled with poorer quality groundwater, leads inevitably to lower yields in tail reaches.

How long it would take for soil salinity to build up, for example in tail ends of canal commands, or for it to be considerably reduced under current irrigation practices, has rarely been addressed. Models are not suitable for making such predictions, as some adverse effects of long-term irrigation with saline water, for example degradation of soil structure and reduction of hydraulic conductivity, are not considered. Kijne & Vander Velde (1992: 171) wrote “it is reasonable to assume that so long as the soil structure is not affected, the build-up of profile salinity is reversible and reclamation should not take much longer than it took the salts initially to accumulate in the profile. However where clay migration in the profile has led to compacted layers and sharply decreased hydraulic conductivities, the reversal process will be very slow”.

Sharma & Tyagi (2004), who have studied the long-term effects of irrigation with saline drainage water in India, emphasise that in saline irrigation, site-specific management practices have to be followed depending on the water quality, soil conditions, crops and climatic conditions. They observed that above-average monsoon rains help to maintain the salt balance in the root-zone over the long run. A slight decrease in hydraulic conductivity after monsoon leaching, Sharma & Tyagi (2004) opine, will not be a problem during the irrigation season if the negative effects of a high sodium adsorption ratio (SAR) of drainage water are offset by the high salinity of the drainage water. They observed only slight variations in water-dispersible clay after six years of irrigation with drainage water indicating little structural soil deterioration. The issue was also addressed by Emdad et al. (2004), for irrigated agriculture in Spain, who distinguish between chemical and physical causes of soil structural breakdown as revealed by hardpans and lower infiltration rates.

5.3. Farmers’ responses to poor quality irrigation water

There are few systematic studies of how farmers deal with salinity in their fields, but early observations of farmers’ responses to the adverse effects of poor quality water supplies and secondary salinity were recorded by Johnson (1990). In one of the watercourse commands areas of his study, higher proportions of cropped areas were under rice and sugarcane and smaller areas under vegetables and orchards in holdings irrigated with tubewell waters of more than 1 dS/m. This finding and other field observations since then confirm that farmers are aware of the harmful effects of prolonged irrigation with poor quality tubewell water and choose to plant the more water-demanding or salt-tolerant crops when the irrigation water is of relatively low quality. Farmers are in all probability aware of salinity problems when white efflorescence or dark deposits appear on the soil surface as a result of, respectively, precipitation of salts and the dispersion of organic matter. Farmers undoubtedly also notice the presence of surface crusts and hard layers when they plough the land, and as evidenced by reduced germination rates, which are indications of sodicity. All of these signs appear when salinity or sodicity is already significantly affecting crop yields. From the changed cropping patterns it appears, however, that farmers had already taken remedial measures at an earlier stage of the insidious process of salinisation.

Farmers are known to abandon salt-affected fields in response to water shortage. These fields then often serve as sinks for salts through lateral flows from adjacent fields that are irrigated and cropped. It has also been observed that farmers scrape off the saline top layer of their fields and continue to cultivate the field at a lower level. Whether farmers take other measures, such as laser-levelling of their fields and
the application of gypsum, in response to salinity depends on whether they can afford it, in view of the expected benefits and costs.

Irrigation managers in Pakistan often maintain that farmers within canal command areas use groundwater primarily to supplement canal water and that canal water could be “saved” in areas with high groundwater use where groundwater quality is suitable for irrigation. However, Murray-Rust & Vander Velde (1993) are of the opinion that even where farmers rely heavily on groundwater for agriculture, their decision making remains strongly influenced by their relative access to surface water. They argue that this is so because canal water is of good quality and available to farmers at little or no cost and that canal water supplies are relatively more predictable than groundwater, as pumps are subject to sudden breakdown and power outages.

Their data, collected in a number of sample watercourse commands, indicate that once farmers have decided how much of the land is to be cropped and which crops are to be grown, they use water relatively efficiently. They found both in the head and tail reaches of watercourses that the relative irrigation supply (i.e. the ratio of irrigation supply over water demand, where demand consists of crop water requirements and likely percolation losses) is close to 1. But the proportion of irrigation water pumped from groundwater is far greater in tail reaches than in head reaches, indicating that farmers are not pumping more water than they need. If rainfall were included in the relative water supply, the ratio would increase to about 1.5. However, rainfall is uncertain even during the *kharif* season when farmers grow rice. Because farmers usually want to plant their rice before the main monsoon rains start, they have to depend initially on irrigation water supplies. Since water demands of rice exceed those of other summer crops, the relative water supplies in sample canals increased according to the relative area under rice, suggesting that farmers were fully aware of the different crop water requirements. There are also indications that farmers are sensitive to the gradual decrease in groundwater quality going from head to tail reaches along many of the canal commands, an effect that was referred to earlier.

Some farmers in the study areas are known to have increased the frequency of irrigation and added pumped groundwater to the canal supplies such that the salinity of the irrigation water remains below 1.15 dS/m (Kijne et al., 1988). Increasing irrigation frequency without reducing the overall salt concentration of the irrigation water is controversial as it could exacerbate the problem by bringing the salts in the profile closer to the soil surface where they would have a greater effect on plant growth. The complexity of the relationship between crop yield and the proportion of groundwater in the total irrigation supply is nicely illustrated by Hussain et al. (2003: 20–21) in a series of figures for wheat grown in their study areas in India and Pakistan where irrigation supplies consist of various proportions of canal water and groundwater. The graphs depicting the relationship between wheat yield and groundwater percentage in the irrigation supply show only a weak negative correlation, that is, a small decrease in yield with increase in groundwater percentage with large variability in the data points.

### 5.4. Leaching fractions

Owing to a combination of factors, yields in farmers’ fields tend to be lower than predicted on the basis of yields obtained under more controlled conditions (see for example, Warrick, 1989; Howell et al., 1990). Contributing factors appear to include at least the spatial variability of soil structure and fertility, of water application rates, soil salinity and plant density and the temporal variability in sensitivity of crops to drought and salt stresses. The accuracy with which yields can be predicted is relevant in the assessment of leaching requirements.
Dinar et al. (1991) derived yield response functions relating yield to seasonal amount of irrigation water, its average salt concentration and the average soil salinity at the beginning of the season. A major conclusion from this study is that a direct relation between yield and average seasonal salinity does not apply to conditions where several factors are interrelated. For example, when salinity of the soil and the applied water is high and the amount of applied water is not sufficient, average soil salinity itself will not explain yield reduction. One should have relationships between water quantity, water quality, yield, soil salinity and drainage volumes. The quantity of drainage water, however, is likely to increase as more water is applied, with higher initial salinity levels of the root-zone and with higher salt concentration in the irrigation water. This behaviour implies that increased salinity of the irrigation water results in smaller or fewer plants with decreased evapotranspiration rates and, hence, in more deep percolation for a given irrigation application. The relation between soil and water salinity as governed by leaching is a dynamic one, subject to feedback mechanisms between growth of the crop and leaching of salts, which is not captured in the most common threshold salinity-response functions (Dinar et al., 1991). The situation is compounded by the variability in measured values of the electrical conductivity of soil-saturation extracts. The coefficient of variation of the EC of soil moisture at saturation is about 50% (e.g. Kijne, 2003 and references therein).

The ratio of root-zone salinity to irrigation-water salinity is very sensitive to changes in the leaching amount at leaching fractions (LF) below 0.1. The implication is that a small change in the leaching amount can make a large difference to root-zone salinity. This ratio of root-zone salinity to irrigation-water salinity is less sensitive to changes in the leaching amount at LF values between 0.1 and 0.4, which are most common (e.g. Molden et al., 1998; Singh et al., 2003). Hence, in this range of LF values, root-zone salinity increases approximately linearly with the salinity of the applied water. Therefore, difficulties in the accurate determination of the components of the water balance and hence LF, from readily available field data, are bound to affect predictions of salt accumulation in the soil.

5.5. Mistaken predictions

When Cohen (2002) analysed forecasting errors of past demographic projections, he concluded that the further trends were extrapolated into the future, the lower the accuracy of the forecasts was and that for short-term projections (5–10 years), simple models were at least as good as more complicated ones. But perhaps even more relevant to salinisation projections (and others, such as for water scarcity) is his observation that forecasters generally underestimate both the uncertainty of their predictions and the instability of the underlying assumptions on which those forecast are based.

In case of the Pak96 paper, the possible reaction of farmers to the first signs of salt accumulation or sodicity in the soil was a source of uncertainty. Perhaps we should have been more aware of it as some of the studies on farmers’ responses to poor quality irrigation water referred to earlier were carried out at the same time as the data collection which led to the Pak96 paper. In any case, the farmers’ response was not taken into account and the prognoses of salt accumulation on the basis of the water and salt balances led to the mistaken prediction that current irrigation and agronomic practices in much of Pakistan’s Punjab were not sustainable. It was thought that if the practice of deriving a high proportion of irrigation water from pumped groundwater was continued, soil salinisation would follow inevitably. The solution was expected to come from forced reduction of cropping intensities. It now appears that irrigation and agronomic practices give rise to a fairly stable plant environment in which seasonal downward fluxes in the soil prevent harmful salinity levels from occurring. The corollary is that crop yields are not at their
maximum level but are yet sustainable. This conclusion, like the one in Pak96, is a generalisation that ignores the large spatial variability in practices and yields, caused by inequity in land and water resources (e.g. tail-end effects mentioned before) and differences in farmers’ skills. The latter are hardly ever quantified. An exception is the recent paper by Lorite et al. (2004) who explicitly refer to considerable variation in irrigation practices among farmers in an irrigation system in southern Spain.

Another serious deficiency of the water and salt balances used in Pak96 is the uncertainty associated with groundwater movement both laterally and vertically. Pakistan’s Punjab is underlain by a deep unconfined aquifer with large buffering capacity that could lead to long travelling times (in the order of centuries perhaps rather than decades) for salts contained in the percolating water before they show up in the groundwater that is pumped up through tubewells. If this is correct, the predictions may only be mistaken in terms of the timeframe and the inevitable long-term effects of current practices are still to show up. However, there is considerable evidence that salts in the seepage water are recycled only through the top of the aquifer and picked up quickly again in the pumped groundwater. Most of the tubewells are pumping from the shallow groundwater. In other words, the buffering capacity of the aquifer goes largely unused. Data are not available to decide in favour of one or the other possibility and much more extensive groundwater modelling is needed.

Although often not stated explicitly, the purpose of projections could also be to influence policies affecting the future rather than to forecast the future. Depending on how people respond to projections, the very fact that a responsible agency has projected a certain outcome may itself affect outcomes. For example, telling farmers that groundwater tables will continue to fall might change their behaviour with respect to groundwater use, thus perhaps averting a future shortage.

Feedback loops of information provide the theoretical basis for the observation that an open system can “learn” to organise and steer itself by reacting to new environmental challenges (Schmidt-Gernig, 2002). A system should be able to enhance its problem-solving capacity if information about its own past performance is reintroduced into the system in order to control future conduct. As Schmidt-Gernig (2002) points out, not everyone is equally convinced of this presumed ability of organisations or systems to effect a sort of cybernetic self-transformation. The scope and extent of social and cultural change processes could be under- or overestimated, which constitutes a significant weakness of future studies in general.

Influencing water management policies was one of the main aims of IIMI’s research programme in Pakistan, especially those policies under the jurisdiction of the Provincial Irrigation Departments (e.g. Bandaragoda, 1999). However, to claim that the predictions in Pak96 were intended for policy makers would be incorrect. Nevertheless, before the water and salt balance studies were started, the Punjab Irrigation Department staff were by and large of the opinion that restoring the canal irrigation infrastructure to its design dimensions would suffice to bring adequate canal water to tail end farmers and eliminate the inequity in water distribution and allocation. At that time, irrigation engineers and water managers did not realise the relative importance of the groundwater contribution and its potential hazard in terms of salt accumulation. Sharing data and information, such as those in Pak96, with Irrigation Department staff and with the staff of the Ministry of Water Resources undoubtedly contributed to a better understanding of the vulnerability of Pakistan’s irrigated agriculture in a time of increasing water scarcity. Ideally, projections to guide policy decisions should be put in economic terms, spelling out the costs when the projection is right and nothing is done, the consequences if the projection is right and policies are changed, as well as what would happen if the projection is wrong and policies are changed (Freeman, 2003). Pak96 did not live up to that ideal, as economic data on which to base such consequences of the various options were not available.
The notion that current irrigation and agronomic practices appear to be sustainable for now should not lead to complacency. For one thing, there is much spatial and temporal variability in water management within and between the irrigation systems. Hence, the question of long-term sustainability has certainly not yet been answered satisfactorily. Rather the spatial and temporal variability in rainfall, water management and crops makes any answer to this question worryingly uncertain. The same is true for much of irrigated agriculture in northern India (e.g. Kumar, 2003). Nonetheless, several sets of data are important when considering sustainability of irrigated agriculture in Pakistan: the country’s population growth rate is 2.4%, total wheat production appears to have levelled off (Hussain et al., 2004), 100% of its renewable water resources are withdrawn and 97% of this is for agriculture7 (WRI, 2003; World Bank, 2003). When these data are considered together, it seems to confirm present day conventional wisdom, that is, that the greatest threat will probably come from the need to reduce the amount of water allocated to agriculture.

6. Conclusions and policy implications

Predictions made in 1996, based on the study of water and salt balances in several irrigations systems in Pakistan, avowed that irrigation and agronomic practices were not sustainable. These predictions were mistaken, at least for the relatively short term of one decade. The water and salt balance data and information available at the time were incomplete and the model was inadequate to capture the complexity of water flows into and out of the root-zone. The feedback mechanisms that occur when soil salinity starts to affect plant growth were also inadequate. Apart from the shortcomings of the model itself, important limitations included lack of understanding of farmers’ responses to early signs of salt accumulation in their fields, unreliability of groundwater usage data and underestimating leaching fractions. As mentioned, the latter resulted from the complicated interaction between evapotranspiration as governed by crop establishment and downward water fluxes in the soil profile. The difficulty in accurately determining the components of the water balance and hence the actual leaching fraction from easily measurable field parameters was underestimated. This affected the prediction of salt accumulation in the soil.

Recalculation of the water and salt balances for one of the sample areas in Punjab led to the conclusion that current irrigation and agronomic practices appear to maintain a relatively sound environment for crop production. The validity of this general statement is site specific and many exceptions can be found in sites where groundwater overdraft and salt accumulation occur, especially in the tail reaches of command areas, as well as of water-logging in poorly drained areas. Whether continuing with current irrigation and agronomic practices is acceptable hinges on the maintenance of a downward flux of water in the soil profile to prevent salt accumulation in the root-zone. Some may consider this downward flux to be wasteful, but it is in fact essential for the sustainability of irrigated agriculture under these conditions. Monitoring changes in water table levels, the quality of the pumped groundwater and the trends in crop yields is essential in order to recognise the first signs of reduced sustainability of current practices. However, the emphasis of research has now unfortunately shifted away from the collection of field data to more model studies. The notion that we could make predictions about the future on the basis of inadequate data, information and models, should give pause for reflection to any researcher considering making such predictions.

7 Comparable figures for India are: population growth rate of 1.5%, withdrawal of the renewable water resource 32% and 92% of this for agriculture.
This paper identified a few general weaknesses for future studies, which could, for instance, be relevant to the present rash of predictions about water scarcity. The decisive weakness of many prognoses about the future appears to lie in the social and cultural change whose scope and extent are at best estimated because researchers usually do not know enough about how affected people will react to changes in their environment. In addition, there is considerable uncertainty about the stability of the core assumptions of the models which form the basis of the predictions. A critical analysis of the underlying assumptions is not often made. And finally, the worthwhile purpose of projections may not be to forecast the future but to influence policies designed to affect the future. Looking back, it would have been better if in 1996 we had not posited that current practices were unsustainable but had used the data and information to suggest policy changes and incentives that could have helped farmers in sustaining their water and land resources.

References


