Improving the Productivity of Pakistan's Irrigation: the Importance of Management Choices.

(draft 10 October 1999)

Jacob W. Kijne

Abstract

Pakistan is used as an illustration of the effect of water scarcity on the productivity of irrigated agriculture. Productivity is diminished by the accumulation of salts in the soil. Management alternatives to improve the situation are described. In many areas the only feasible solution is to gradually decrease the acreage of crops that require large amounts of water, such as sugarcane and rice. The productivity of irrigated agriculture is found to depend on the political will to make changes and set up a regulatory system to enforce new rules, as well as a significant attitudinal change on the part of the farmers involved.

INTRODUCTION

Water is a major input in agricultural production, especially in arid and semi-arid regions, where irrigation is required for the production of food and cash crops. Current competition for water from urbanisation and industrialisation makes it an urgent matter to consider how agricultural production can be increased while using less water than before. The world's irrigated area per capita has decreased from a peak of 48 ha/1000 people in the late 1970's to 45 ha/1000 people in 1989, with further decreases since because of population growth exceeding the rate of growth of irrigated area. Without irrigation, the present area under cultivation in the world would only meet the minimum food needs of less than half of the world's present population as traditional agriculture is estimated to need 0.6 ha of arable land to meet the per capita minimum dietary requirements (Ghassemi et al., 1995). The technological innovations that made it possible to provide enough food included the introduction of high yielding varieties of seeds, and high inputs of water, fertilisers and pesticides. However, there is concern that for a variety of reasons, yields from irrigated lands in the tropics have stagnated or declined. The case of stagnating yields from the rice-wheat production system in the Indian sub-continent is well documented (see for example, Abrol and Gill, 1993).

In many parts of the world water is already a scarce resource. Since irrigation waters contain dissolved salts, it is not just a matter of the quantity of water for agriculture but also its quality that must be considered. Salts applied to the soil with the irrigation water tend to accumulate in the soil, in the drainage water and also in the groundwater. When drainage water is re-used for irrigation and when pumped groundwater is used for irrigation even more salts are applied to the soil to the detriment of crop yields. Thus knowledge of crop response to salinity in the soil and in the irrigation water is an important element in the evaluation of irrigation management practices.

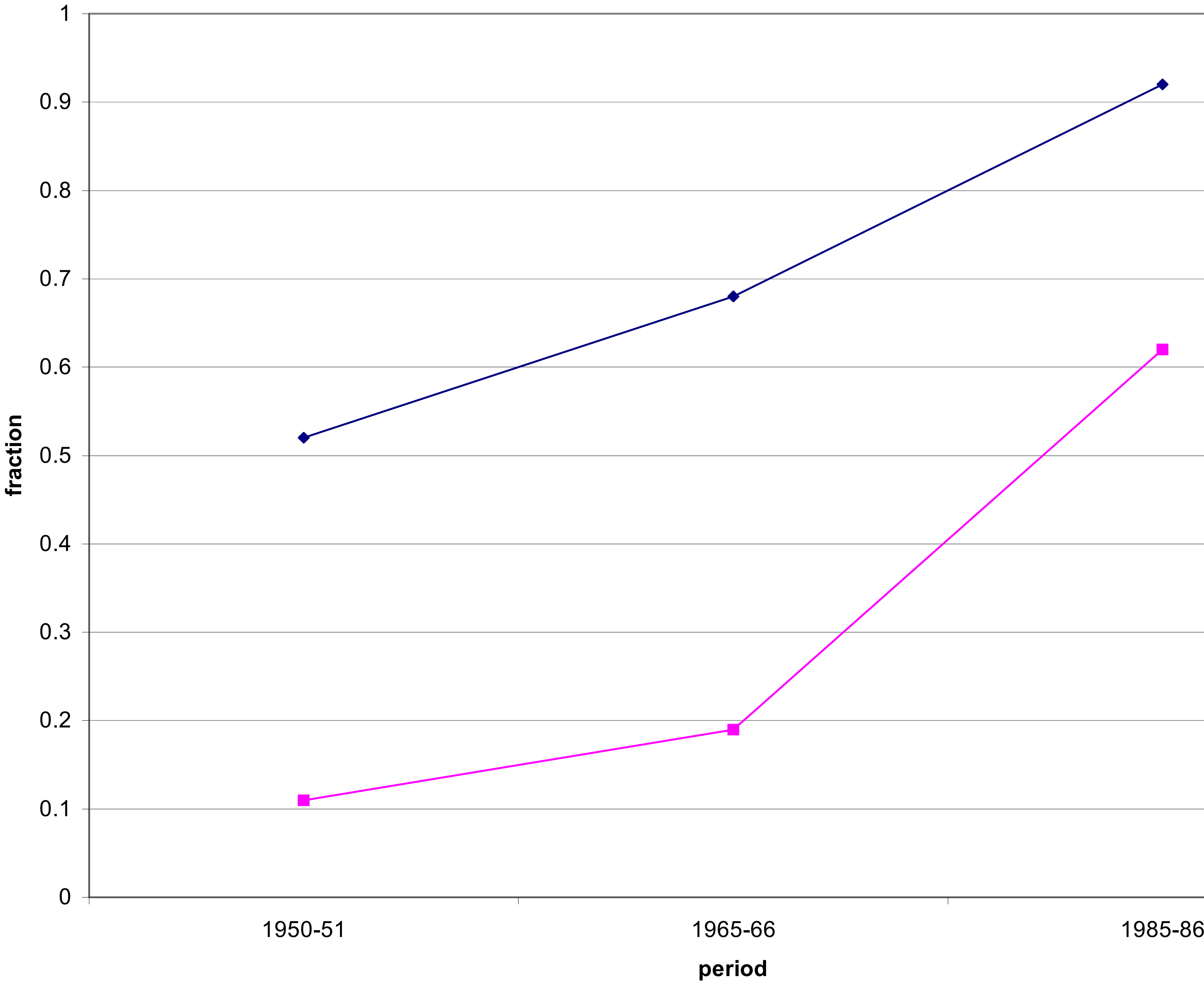
The availability of water for agriculture is threatened by competition from domestic and industrial requirements. About 70% of the total withdrawals of water in the world are for irrigated agriculture and the figure, although not precisely known, is expected to be even higher, on the order of 90%, for many developing countries. Seckler and de Silva (1996) have developed an indicator of relative water scarcity based on a country's water supply and demand for irrigated agriculture. From their analysis it appears that accounting for seasonal differences in supply is essential when assessing whether a country is water-short, e.g., in India over 70% of the total supply occurs in the three monsoon months of June, July and August, when most of it floods out to the sea. Moreover, country-wide data ignore regional differences in water supply and withdrawal within a country. The tentative conclusion is that many countries do not have a surplus of irrigation water, i.e., they do not have sufficient annual water withdrawal to irrigate their potential gross irrigated area even at a high basin irrigation efficiency[1] of 80%. Whatever indicator is used, more than half of the world's population lives in countries with varying degrees of water scarcity.

With the advent of high-yielding wheat and rice varieties, the production of these crops in both Indian and Pakistan Punjab has more than tripled from 1975 to 1987. The irrigated area with wheat and rice has also grown both in absolute and relative terms. Figure 1 shows the increase in the fraction of the irrigated land under wheat during the winter season (*rabi*) and rice during the monsoon summer season (*kharif*) (from data reported by Singh and Paroda, 1993). A similar increase took place in Pakistan with the result that pressure on available water resources in the Indian sub-continent has increased greatly.

---

[1] Basin irrigation efficiency includes all re-use of drainage water and is considerably higher than system irrigation efficiency, if drainage flow from one system is used for irrigation again downstream in another system. Basin-wide irrigation efficiency for the Nile basin in Egypt has been calculated to be about 90% (Keller and Keller, 1995).

Figure 1. Fraction of irrigated land under wheat and rice



Water requirements for paddy cultivation vary and depend largely on soil type. The average requirement under the conditions of Pakistan's Punjab is considered to be around 1600 mm, which includes water needed for land preparation, intentional drainage and deep percolation (Bhatti and Kijne, 1992). However, the mean irrigation application was found to be around 1300 mm from measurements on a fairly large number of farms, which means that the average yield is only 0.14 kg rice per m^3 water diverted from the source (i.e., canal or groundwater). It has been shown that considerable amounts of water can be 'saved'[2] by reducing the period of continuous flooding without adverse effect on the yield (e.g., Narang and Singh, 1988). One of the reasons for continuous flooding is to control weeds. Reducing the period of continuous flooding would probably lead to greater use of agrochemicals for weed control. And not all percolation or flooding water is wasted as rice is sometimes grown as a reclamation crop. Deep percolation during rice cultivation helps to leach the salts from the root zone and restores a more favourable salt level for the subsequent crop.

---

[2] saved between inverted commas, because a reduction in water diverted from the source does not mean that less water is consumed by the crop through transpiration. A shorter duration of flooding may indeed save water that would otherwise have been evaporated from the ponded surface.

The objective of this paper is to examine whether the productivity of irrigated agriculture in water-scarce environments can be improved by better irrigation management. The main focus in this paper is on Pakistan, but similar conditions exist in other dry countries including the western states of India.

Methodology

This paper is largely based on data collected in Pakistan's Punjab by IIMI's country programme in collaboration with its national research partners. Much attention will be given to the importance of water quality in the analysis of irrigated agricultural productivity, which in Pakistan depends increasingly on the quality of pumped groundwater. Frequent reference is made to several IIMI publications which report in depth on the incidence and significance of salinity, especially in Pakistan's Punjab. Site selection and research methodology are described in detail in those papers. The location of the irrigation systems in Punjab which were studied in detail is shown in Kijne and Kuper, 1995.

Salinity and Waterlogging

Two issues threaten the sustainability of irrigated agriculture: water shortage and salinity. The two are linked in several ways. Irrigated agriculture concentrates salts because water is taken up by the crop and salts are left behind in the root zone. Proper management must ensure that the salt is concentrated outside the root zone, and away from future water supplies for irrigation, domestic or industrial use. Hence water is required to transport salt from the root zone, in addition to consumptive requirements of the crop, and also land is required to store the salt. Water shortage also prevents remedial action on land already adversely affected by salinity.

Salinization often occurs naturally, not only as a consequence of poor irrigation practice. Part of the Indian subcontinent including the Indus Plain was formed from sediments transported by rivers into a shallow sea. The receding sea left salts behind in the soil profile. Whether the salinity of the aquifer is also a remnant of this ancient sea is disputed. Isotopic evidence as presented by Sajjad et al. (1993) indicates that salinity of the groundwater is mainly due to transport of salts from the soil profile by infiltrating fresh water. Application of fertiliser and irrigation continue to add salts to the system. Each year, irrigation with good quality river water adds 1 to 2 tons of salt per ha (e.g., an annual application of 800 mm of water with a salinity of 200 mg/L adds 1.6 T/ha). The obvious solution to prevent this accumulation of salt in the soil profile is to apply more water than can be taken up by the crops and leach the salts out of the root zone. Unless there is an adequate drainage system, this practice leads to rising watertables and waterlogged conditions. High watertables actually increase the salt transport into the root zone because of capillary rise from the watertable.

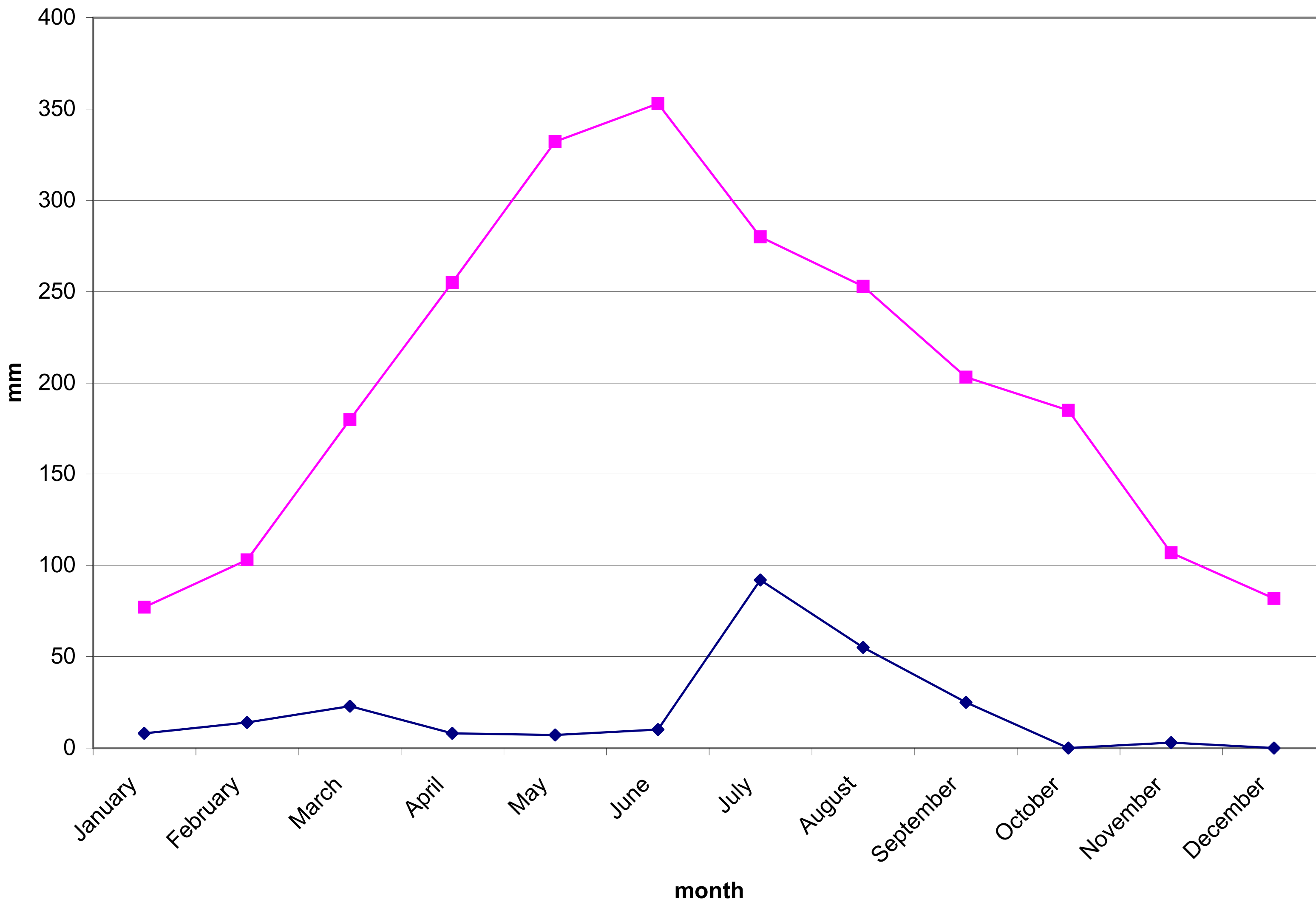
Managing the water and salt balances of irrigated agriculture well has proved to be difficult. It is not only a matter of minimising the amount of water required to transport salt from the root zone, but also minimising the land area required to store the salt temporarily or permanently. Although human-induced salinity problems can develop swiftly, solutions can be very time consuming and expensive. Installation of sub-surface drainage, the most common physical solution in many countries, costs between $1500 and $3000 per ha.

The global extent of salt-affected lands is considerable. However, there is wide divergence in the figures reported by different institutions. E.g., estimates for India range from 7 to 26 Mha, or between 17 and 60% of the irrigated land. For Pakistan the most likely figure is some 40%, Israel 13%, Australia 20%, China 15%, Iraq 50% and for Egypt 30% of the irrigated land (Gleick, 1993 and Ghassemi et al., 1995). Human-induced (or secondary) salinization occurs in large and small irrigation schemes alike: in recent years many farmers have been abandoning their rice fields in Sahelian irrigation schemes due to the incidence of salinity. The countries affected by secondary salinization are predominantly but not exclusively located in arid and semi-arid regions. Other activities, such as land clearing and replacement of native trees with shallow-rooted crops contributed to the development of so-called dryland salinity. This has been well documented for areas in Australia, the USA, Canada and Thailand, among others. Salinization also occurs when crops are irrigated with pumped groundwater of marginal or poor quality, and as a result of sea-water intrusion when watertables have been lowered by mining of groundwater in coastal areas, as has occurred for example in Bangladesh and in the State of Gujarat in India.

Pakistan

Pakistan is ranked fifth in the world on the basis of irrigated area with 16.2 million ha (Postel, 1993). According to UN estimates (1998), the medium expected population growth rate over the next 30 years is 2.2% per annum; the low rate is 2% per year. Cereal consumption grew by an average 2.7 % per year during 1985-95. The past trend in cereal yield per ha is an increase of only 1.5% per year (IWMI's Podium Programme, 1999). The average annual canal withdrawal of the Indus basin in Pakistan is estimated to be about 129 billion m^3 (or km^3). Annual usable groundwater, defined as water of a salinity level of less than 1000 mg/L, is only about 29 billion m^3, which is about half the average annual recharge to the aquifers which underlie the Indus plains. The mean monthly potential evaporation and rainfall for one of the research sites (Fordwah/Eastern Sadiqia) are shown in Figure 2. The data are thirty year averages obtained from the Punjab Meteorological Department for the nearest weather station. The dominant crops in the research areas are cotton or rice in kharif and wheat during rabi.

Figure 2. Mean monthly rainfall and potential evaporation



The first experiments with tubewells for watertable control took place in the 1950s and was followed by the implementation of large-scale Salinity Control and Reclamation Projects (SCARP's) in the 1960s. Over the past 30 years, more than 12,500 public tubewells have been installed in various SCARP project areas. The primary objective of these projects was to combat waterlogging and associated salinity. A secondary objective, however, became supplementing canal water with pumped groundwater for irrigation, usually discharging directly into the existing watercourse network, when canal discharges became increasingly unreliable. Unreliability of canal irrigation is illustrated in Figures 3 and 4. Figure 3 shows the water distribution equity[3] of a representative distributary canal at low and normal discharge. The design discharge of the distributary is 4.7 m^3/s, and its gross command area 16400 ha.

---

[3] Equity in distribution was intended as equity in sharing a seasonal shortfall of canal water; it should not be taken to mean that everyone received an equal share of the canal water per unit land. In the past, so-called leaching shoots (additional allocations of canal water to leach salts from affected fields) were authorised by the Irrigation Department staff. This inequitable allocation made good sense as some lands are more affected by salinity than others. Unfortunately, this practice has all but stopped because powerful farmers succeed in claiming unauthorised additional discharges, e.g. to irrigate their orchards

The delivery performance ratio, plotted on the y-axis of Figure 3, is the ratio of actual discharge to the design discharge at a given location and time. Supplies to tail outlets are typically far less than those to head- and middle-reach outlets. One of the most persistent problems of the irrigation systems in Pakistan's Punjab occurs at farm level. Farmers cannot be sure there will be water in the watercourse when their turn comes to have the full flow in the watercourse. This is illustrated in Figure 4 where the number of missed turns is plotted for a watercourse in the head reach of a distributary during the kharif season of 1994. Each week farmers dependent on water from this watercourse missed between 15 and 95 turns, and consequently could not irrigate or had to revert to tubewell water. Conjunctive use of canal water and groundwater has thus become essential for irrigated agriculture throughout much of the Indus Basin.

Figure 3. Pir Mahal Distry: equity

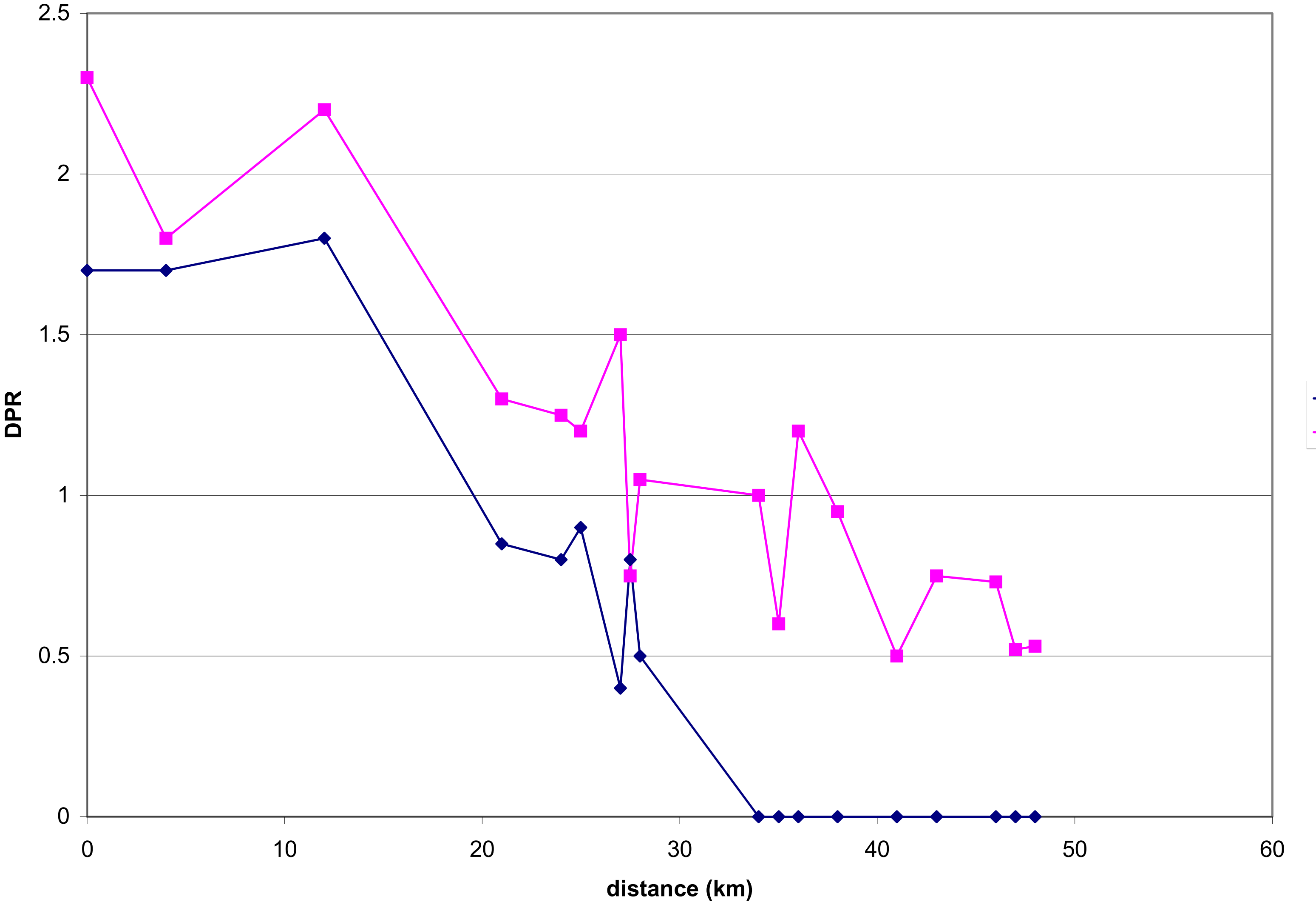
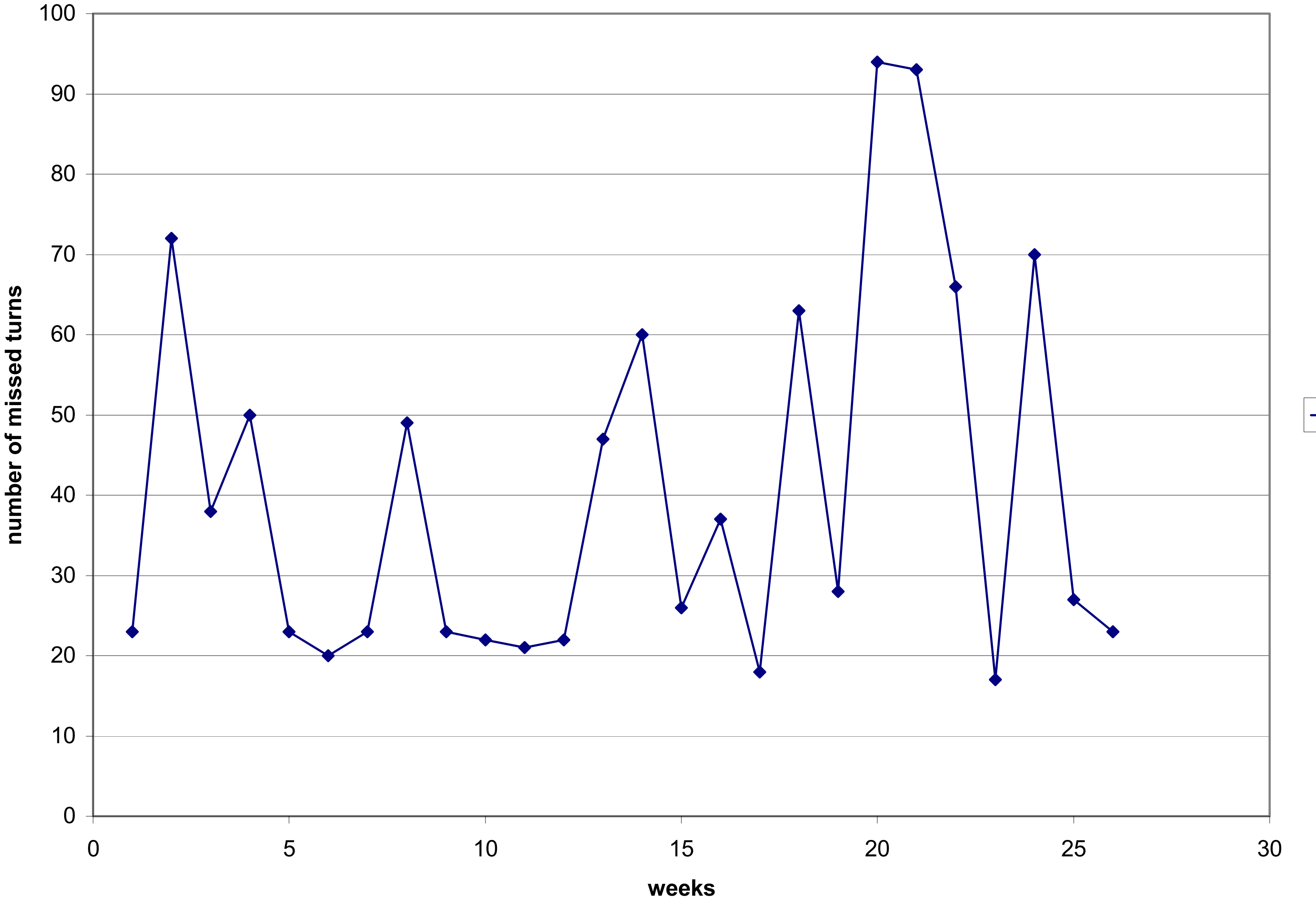


Figure 4. Missed turns in watercourse



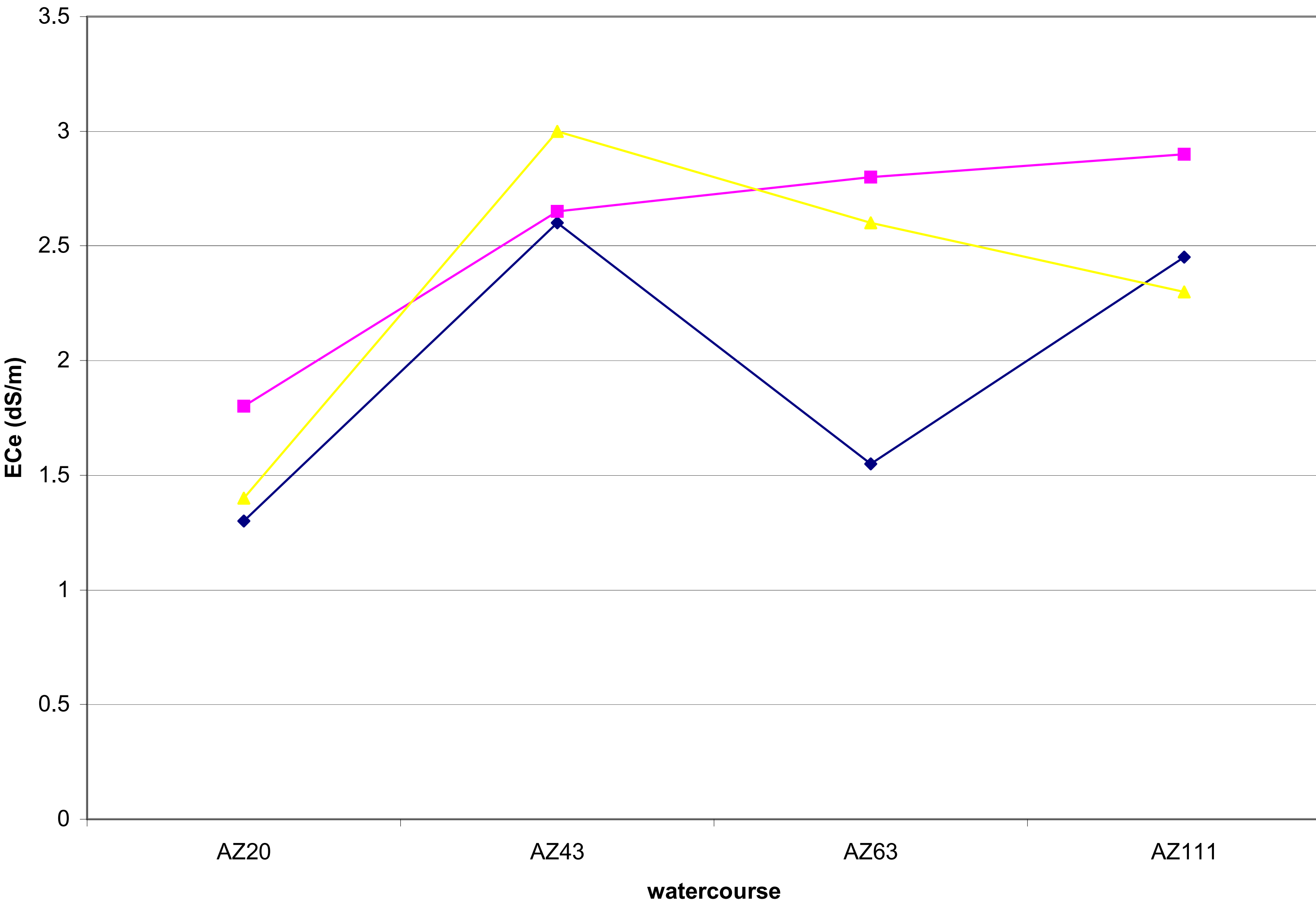
Groundwater quality in the Indus Basin varies in quality in a rather complicated way, depending as it does on the extent of the recharge. The occurrence of recharge is largely governed by topography, old and existing river beds, rainfall and irrigation practices. The general pattern is for the groundwater quality to decrease going downstream in the Indus valley. The best quality is found in the north-eastern part of the country where the rainfall is highest. Fresh groundwater is also found close to the river beds of the Indus and its tributaries, and poor quality groundwater in the central parts of the interfluvial regions. Locally, the spatial variability in quality of pumped groundwater is greater than this general picture would make one think. Even tubewells in close proximity are known to yield different quality waters, partly depending on the depth from which they are pumping. Since the early 1960s, groundwater development has been exponential, especially in Punjab, through private tubewells, of which according to the latest estimates there are about 500,000 in all of Pakistan. A national survey undertaken in 1991 shows that at that time about 46 billion m^3 of groundwater was used in the Indus Basin for irrigation, of which 85% comes from private tubewells (NESPAK/SGI, 1991). This exceeds the annual usable groundwater recharge by more than 50%. Clearly, a non-sustainable situation.

By reducing waterlogging, as was done in large parts of Punjab where groundwater was pumped to lower watertables, it was hoped that also the problem of salinity had largely been solved. This is not the case. Firstly, large quantities of salts were present in the soils before the inception of the Indus Basin Irrigation System. An extensive survey of soil profiles in the Indus basin carried out before the introduction of private tubewells, classified nearly one quarter of the soils as saline-alkaline, 3.5% as alkaline and 10.7% as saline (Ghassemi et al., ibid.). Secondly, pumped groundwater contains far more salts than canal water. When irrigation depends to a large extent on water of marginal quality, each year vast quantities of salts are left behind in the root zone after the water has evaporated or been transpired by the crops. Leaching fractions (the amount of water applied to the fields in excess of the crop water requirement) are usually not sufficient to leach these salts out of the root zone.
The significance of conjunctive use of canal supplies and pumped groundwater for irrigation in Pakistan can be judged from the fact that cropping intensities in the Punjab now commonly exceed 125%, with high values in some watercourse command areas of as much as 190% (IIMI, unpublished data). These canal commands were designed in the late 19th century with the expectation of annual cropping intensities ranging from 50% to 75%, two-thirds of which were to occur in rabi and one-third in kharif. The actual amount of irrigation water available at tertiary (watercourse) level has now increased from 2.5 mm/day to about 6 mm/day, especially in head reaches of canals where supplies are at design level or higher.

All groundwater in the Punjab contains sodium (Na), but in varying amounts. Whether Na from the percolating water will be retained in the top layers of the soil profile or leached to greater depths depends on many factors, including evapotranspiration, the dissolution and precipitation of salts, mineral weathering and organic matter decomposition. There may be a loss of calcium (Ca) and magnesium (Mg) from solution owing to the precipitation of Ca and Mg carbonates, or a gain of these ions in solution from the dissolution of the earth carbonates, processes which in turn are governed by relative concentrations of these salts, CO_2 pressure and pH in the root zone (Rhoades and Loveday, 1990). It is now generally recognised that the presence of Na causes sealing of the soil surface, lowers the basic infiltration rate and reduces the saturated permeability of the soils, even of light textured soils, and at lower values of the Sodium Adsorption ratio (SAR) than was previously assumed (Sumner, 1993).

In many distributary command areas, not only canal supply but also tubewell water quality decreases from head to tail. This decrease in water quality manifests itself in higher salt contents in the soil profile. Two measures are used to quantify the amount of water: the profile electrical conductivity (ECe), measured in the saturation extract of soil samples, higher values indicating a higher soluble salt content, and the Sodium Adsorption Ratio (SAR), a measure of the extent to which the soluble salts consist of sodium salts. Figure 5 shows the deteriorating quality, expressed as ECe of soil samples collected in land irrigated by a series of watercourses off-taking from one of the sample distributary canals going from head to tail in the command area. Three times series are presented in the figure.

Figure 5. ECe of land irrigated by four watercourses



This trend was found to be affected, among other things, by the distance from recharge areas, such as link canals, river arms, etc., and by the fraction of irrigation water derived from pumped groundwater (Kijne and Vander Velde, 1992). The chemical composition of the original groundwater also plays a major role in the spatial variability of pumped groundwater. Where shallow hand pumps and deeper tubewells were close together, it has been found that in about half the cases the salt gradient, expected to be towards greater salt concentrations at greater depths, had been reversed. The aquifer is known to have clay lenses and vertical mixing is apparently restricted. Hence two processes seem to be operating simultaneously: upconing of more saline water from greater depth in the aquifer due to localised extraction of groundwater by pumping, and recycling of increasingly saline water that percolated from the root zone back to the top of the aquifer. One would expect general deterioration of groundwater to occur over time under these conditions. It has indeed been reported that tubewell water pumped from the shallow fresh water zone overlying saline 'native' groundwater, i.e. undisturbed groundwater from before the introduction of irrigation, has become more saline with time (Hafeez et al., 1986). Also many of the deep tubewells have been shut down at the request of farmers because of the poor quality of the pumped water. In sum, the increasing dependence of irrigated agriculture on pumped groundwater and the attendant increase in cropping intensity carry with it the danger of degradation of the soil and water resources and therefore the risk that the production system itself can no longer be sustained at the present level.

DISCUSSION

Water and Salt balances

The description of irrigated agriculture in Pakistan points up the importance of two issues that threaten the productivity of irrigated agriculture: water shortage and salinity. Salinization of irrigated lands is reasonably well understood and preventive and remedial measures are generally well known (see e.g., Rhoades and Loveday, 1990, Van Hoorn and van Alphen, 1994). However, salinization, and particularly enrichment with sodium, is an insidious process whose early symptoms are often ignored. Moreover, general solutions are not readily available. Canal irrigation doesn't necessarily lead to waterlogging, but under some conditions it does. Irrigation with tubewell water doesn't necessarily lead to depletion of the groundwater resource, but under some conditions it does. Careful monitoring of salt and water balances in irrigated areas would help to provide a scientific basis for deciding on the need and urgency of remedial actions, especially if done at field or farm level, system level, and also at river basin level.

The water balance approach has often been used at field level for the determination of the contribution from a shallow watertable to the water supply of an irrigated crop (e.g. Ragab and Amer, 1986). These studies, though important in understanding water uptake by crops, do not by themselves provide insight in what needs to be done to sustain agricultural productivity. Measuring the components of the water balance is easier than evaluating the salt balance. Reliable data on the components of the water and salt balances at various levels in the system are usually not collected when changes in irrigation practice and management are considered, although these changes - if implemented – could have considerable impact on the water and salinity relationships. The interactions between the various sources of water (rainfall, canal water and pumped groundwater) and the salt contents of each of these are complex. A number of reasonable, simplifying assumptions can be made in order to establish water and salinity balances of entire irrigation systems or sub-systems, such as distributary command areas. Studying these water and salinity balances is informative with respect to the potential impact of continuing current irrigation and agronomic practices on the agricultural productivity (Kijne, 1996).

Information on the various aspects of water and salt movement in the system needs to be known or estimated for the calculation of water and salt balances. In systems or command areas where groundwater and surface water are used conjunctively, the percentage of water going to groundwater from seepage from canals, watercourses, drains and in the fields is an extremely important figure. It usually cannot be known through an independent assessment and needs to be stipulated for the first round of calculations. Knowing rainfall, crop water requirements and the irrigation allocation from canal supplies makes it possible to determine the seepage losses and groundwater pumping through an reiterative process. IIMI (Kijne,1996) used a salt balance model that regards the root zone as one layer with a homogeneous distribution of water and salt (Van Hoorn and van Alphen, 1994). Several assumptions have to be made and this approach does not take into account the type of salts in the root zone or in the irrigation water. The latter is unfortunate, as it is well known (e.g., So and Aylmore, 1993), that the sodium component of the total salinity is of particular importance because of its adverse effect on the soil structural stability under irrigated conditions.

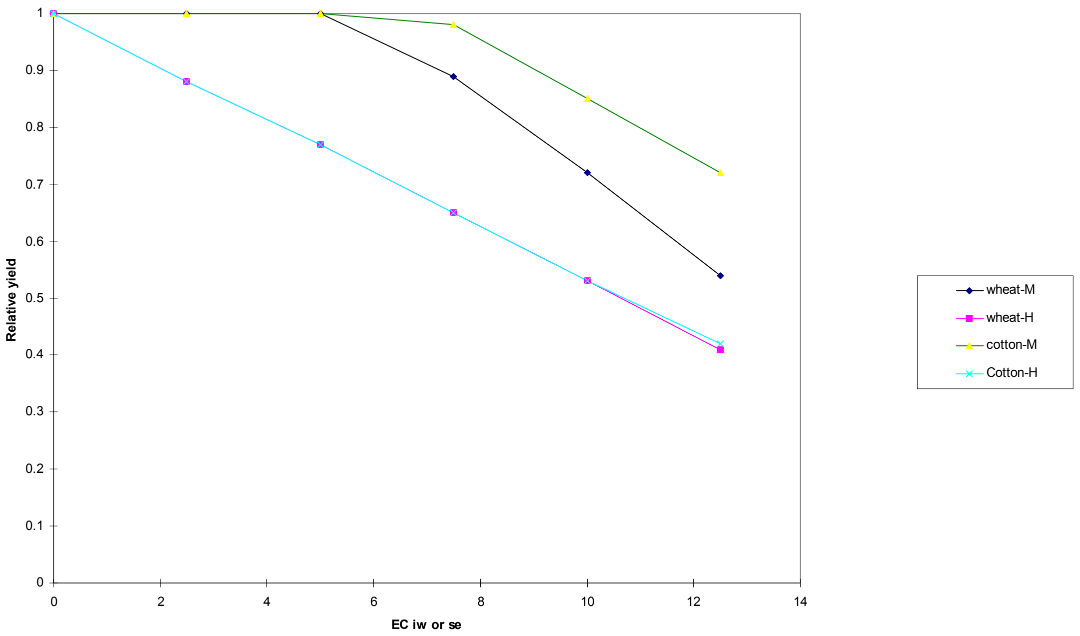
Analysis of water and salt balances of three irrigated areas in Pakistan showed that at one site over-irrigation took place with the inherent hazard of waterlogging, and that at the other sites more salts were added to the root zone than were removed, if current irrigation practices were to continue (Kijne, 1996). At those sites where salts are accumulating less tubewell water should be used, which is only feasible if crop intensities are drastically reduced (in the order of 25% to 45% less). The implication for one of these sites, one with predominantly a rice-wheat farming system is that less rice should be grown during kharif season. The analysis for the last site indicates that the salt balance is reasonably well maintained, better in kharif than in rabi as more canal water is available during kharif. Nevertheless, continued use of irrigation water from about one quarter of the tubewells in the command area would lead to local salt accumulation in the root zone. There is thus a need for a dynamic management approach which recognises the spatial differences of soil and water resources.

Economic impact of saline irrigation water

Several economists have developed models for optimal management of pollutants, such as salts, in irrigation water. The models attempt to weigh the costs of the damage caused by salinity against the costs of reducing the damaging discharge of pollutants. This is particularly applicable to situations where re-use of drainage water is practised on a large scale, as in Egypt. Policy options with respect to irrigation water quality in Egypt are the varying degrees to which drainage water is mixed with fresh Nile water to dilute the salts (Hussain, et al., 1995, Keller and Keller, 1995). Nile water is in limited supply and has an opportunity cost that must be balanced against gains from dilution. Hussain et al. (1995) assessed the economic damages from salinity by estimating the change in net income resulting from salinity. Net income tends to decline as crops yields are lowered. Income is also affected by the response of farmers to increasingly saline irrigation water, for example by growing more salt-tolerant crops that yield better but may be less profitable. The adoption of different irrigation technologies, such as drip and sprinkle irrigation, can lead for some crops to higher yields with less irrigation water, thereby reducing the need for re-use of poor quality drainage water. The introduction of different irrigation technologies is an option, although an expensive one, for farmers in some farming systems. A crucial element in the assessment of economic damages from salinity is reliable knowledge of yield response to salinity of the irrigation water, and its impact on net income.

Hussain et al. (1995), noting that data on salinity response at farm level are non existent in Egypt, succeeded in constructing salinity damage curves from yield response under experimental conditions. The salinity damage curves are for wheat, cotton, rice, berseem, broadbeans, soybeans, sugarbeet and flax grown in the cultivated area of the Nile Delta. Of all these crops cotton and wheat are the most salt tolerant, and the net financial and economic returns are higher for these crops even under increased levels of salinity. As reproduced in Figure 6, the reduction in yield was found to occur at lower values of EC of the saturation extract than predicted by the well-known salt tolerance data of Maas (1990). The production curves of Maas (1990) have EC of the soil saturation extract as independent variable, while for the curves of Hussain et al. (1995) it is the EC of the irrigation water. However, the more important difference between the two sets of curves is at which value of EC the yield starts to decline, which determines whether yield is expected to be suppressed under conditions of relative low salinity. Salt tolerance is influenced by other factors, such as differences between cultivars, evaporative demand (e.g. temperature and humidity), soil conditions and cultural practices, and hence differences between measured and predicted values are expected (e.g. Francois and Maas, 1993).

Figure 6. Yield reduction as predicted by Maas (1990) and measured by Hussain et al. (1995).



Tyagi (1994) set out to calculate the effectiveness of salinity mitigating measures, by comparing the expected benefits from reducing groundwater discharge and increasing groundwater pumping for the control of shallow watertables. Although details of the derivation are not given in the paper, Tyagi presents a curve of the agricultural production losses as function of groundwater salinity. This curve shows that loss in production only occurs when groundwater salinity exceeds 2 dS/m.

Dinar and Zilberman (1991) developed an economic model to assess irrigation technology choice for the production of cotton and tomatoes on the west side of the San Joaquin Valley, California. The economic conditions of California differ so much from those in developing countries that the conclusions of Dinar and Zilberman's study are perhaps not relevant for other countries. Nevertheless, their study is a fascinating example of what can be done if the right data are available. They argue convincingly that modern technologies (sprinkler, low energy precise application -LEPA, and drip) reduce the impact of land quality differences on yield, on applied water, and - of particular importance in the San Joaquin Valley - drainage production. Reduction in water quality (up to EC = 4dS/m) resulted in higher water use and reduced yields, especially with furrow irrigation. For furrow irrigation, the losses due to lower water quality became considerable as soil quality declined. Dinar and Zilberman (ibid.) also point out that the changes in one input-quality indicator are not independent of the level of other input-quality indicators: for a given technology, an increase in land quality is likely to have a stronger impact on optimal profits when water quality is poor. In summary, the attractiveness of modern irrigation technologies increased substantially when water quality is poor.

Management Options

Several types of management interventions are presented in Table 1. They have been categorised as engineering, agronomic, policy and management options. However, the distinction between them is not water tight. Often before engineering or agronomic options can be implemented, certain policy decisions need to be made. Nevertheless, for clarity of presentation, we will discuss the options in terms of these various types.

The first category, engineering options, includes interventions aimed at enhancing the supply of good quality water and the removal of poor quality water. Dam construction, with its environmental and social implications, is not popular with donors, nor with environmental action groups in the countries in need of more water. Moreover, the high costs associated with the construction of water storage facilities in countries, such as Pakistan, where the easier and less costly sites have all been used, requires priority setting at government level. The options aimed at the removal of poor quality water include construction of drainage facilities, and improved maintenance of existing (natural) drains; alternative disposal of drainage effluent, industrial and urban waste such that it does not contaminate water supplies; and rehabilitation of irrigation canals to enhance the reliability and quantity of supplies (e.g., improve the hydraulic performance of irrigation canals through de-silting[4]). The implementation of any of these engineering options (whose benefits mature slowly) depends, just like the construction of storage facilities, on strong governmental support both in terms of incentives and sanctions as well as on economic prioritising. Often there is no immediate prospect of enhancing the supply of good quality water to the system and/or of reducing the amount of poor quality water that remains in the system

The agronomic options presuppose that scarcity of water and salinity are here to stay and that one has to learn how to live with them. One of the key agronomic options consists of crop diversification. Different crops have different evapotranspiration patterns and lead to different rates of recharge of the groundwater. In areas with rising watertables, planting sufficient trees can reduce or even reverse this trend. Varieties and species with higher salt tolerance can be planted to replace those that yield less when the salt content of the available irrigation water increases, for example when more of the irrigation supplies are drawn from pumped groundwater. Of course, this option is only feasible if there is a market for these crops and framers who grow them can make a decent living. Fodder crops that have successfully been introduced on salt affected land in the Indian subcontinent include kallar grass (Leptochloa fusca) and sesbania (Sesbania aculeata). Improving soil fertility by addition of organic matter through green manuring can also help to restore a more favourable root zone environment. Other agronomic interventions that can be exercised at farm level include precision land levelling to remove high spots in fields, such that a thinner layer of water would cover the entire field. Experience in the Murray-Darling Basin has shown that laser levelling of the land can greatly improve net salt accumulation in the root zone (private communication by Dr. S.A. Prathapar, September 1996).

Perhaps the last agronomic option a government would be prepared to support is to reduce deliberately the area that is cropped each season to match demands for good quality water with available supplies. This could be done by reducing crop intensities, while maintaining the total command areas, through the introduction of periodic fallow. Rotation of canal supplies and restricting the use of pumped groundwater are the instruments to achieve it. It can also be done by closing off parts of command areas, with the result that those areas would depend completely on tubewell water, and would most likely continue to degrade. The socio-economic and political implications are huge. The government may have to stimulate alternative sources of employment in rural areas to provide acceptable livelihoods for the rural population affected by these changes.

Other policy options available to governments in order to change current agronomic and irrigation practices include water and power pricing, issuing transferable water entitlements, subsidising gypsum for reclamation of sodic soils[5], and better co-ordinate the activities of various ministries and departments dealing with water and power supplies[6]. Increasing

---

[4] Computer modelling prior to de-silting is recommended to assess the likely effect of the exercise in terms of improved equity of distribution of the irrigation water and evaluate the costs and benefits of the desilting operation (see, e.g., Murray-Rust and Vander Velde, 1993)

[5] The application of gypsum is more widely practised in India than in Pakistan, partly because of subsidies and better distribution in India. One drawback of wide-spread use of gypsum would be enhanced deterioration of shallow groundwater as soluble salts are leached.

[6] For example, irrigation and drainage responsibilities in Pakistan's Punjab are not co-ordinated at field level, only at the level of the office of the Chief Engineer, probably overseeing around 1 million ha. Also co-ordination between power and water supplies in rural areas is lacking, with the result that power cuts occur when farmers need to use their electrically powered tubewells to water their crops. Another example is the well known lack of co-ordination between Departments of Agriculture and Irrigation.

charges for water would tend to reduce application per unit area and hence exacerbate the problem of salinity.

Institutional options that come to mind include the introduction of management information systems (decision support systems) to improve operation and maintenance of irrigation canals. These information systems require that data on water supplies and demands throughout the system, and the breakdown of infrastructure (e.g., breaches) are available and quickly communicated to the decision centre. Traditionally much of this type of information was communicated in Pakistan through the telegraph, which has since been allowed to break down and is no longer in use. Current communication techniques and computer modelling allow vast improvements to be made over the present decision support system which consists mainly of messages sent (if at all) by bicycle. Another important institutional option is the involvement of the water users in the management of the natural resources water and soil. Many governments, often spurred on by the World Bank, are moving towards greater involvement of farmers in the management of (parts of) irrigation systems.

In the following paragraph, we consider how these options can help in improving the productivity of irrigated agriculture in Pakistan.

Management choices and productivity

Attempts were made during the ‘sixties and ‘seventies to improve farmers’ practices through USAID-supported On-Farm-Water-Management projects. Gradually the aim of these on-farm activities, including the so-called Command Water Management projects, became limited to the lining of watercourses. It should now be realised that where canal water and groundwater are used conjunctively for irrigation, on-farm water ‘savings’ are not equal to reductions in consumptive use of water; at most they have the potential to reduce the supply of water diverted from the source. The analysis of the water-and salt balance clearly suggests the necessity of reducing the irrigated area where canal water is insufficient to maintain the salt balance and the quality of the tubewell water is such that continuous use would lead to further soil and water degradation. These various options, i.e., selectively reducing the area under rice and sugarcane, reducing the total area that can be irrigated, and introducing different crops, are not easily implemented.

A number of irrigation management improvements for the control of salinity were proposed by Kuper (1997) for one of IIMI’s research sites in Pakistan’s Punjab, comprising a command area of 75,000 ha. The proposed changes in irrigation management aim to enhance the supply of canal water to the most salt-affected lands. They included modification of some forty outlets from two secondary canals, desilting part of one of the secondary canals, installation of gates in ten minor secondary canals, and improving the communication between gate operators. The costs of these modifications were estimated (Kijne, 1998). The benefits that would accrue from implementing the changes were calculated for the two main marketable crops (wheat and cotton, which are grown on two-thirds and over half of the irrigated area during rabi and kharif, respectively) using crop response functions to water quantity and water quality based on field data collected in India (Panda et al., 1996) and Egypt (Hussain et al. 1995, mentioned above).

The resulting benefit-cost ratio is about 0.5 when the benefits are based on world market prices of wheat and cotton, and even less when local prices for these crops were used. The proposed management interventions can apparently not be justified with current, low yield levels of irrigated wheat and cotton. The economics for the implementation of the proposed interventions improves when higher value crops or less salt-tolerant ones are grown. An important caveat arises from the likelihood that farmers benefiting from additional supplies of canal water will probably substitute only part of the tubewell water they presently use, and expand the irrigated area with the remainder. If those farmers who will receive less canal water after introduction of the management changes compensate for their loss by pumping more groundwater, the long-term effect of the changes will be continued salinization over a larger area than without the change. Of considerable concern on the benefit side is also the fact that the risk of future sodication of irrigated land is insufficiently accounted for. Kuper (1997) has shown that as a result of the management interventions the area with the highest risk of sodication is reduced but the area with a lower risk is increased. The upshot is therefore a more equal sodicity risk for the entire command area, which is not necessarily a good thing. The calculated yield increases did not account for these changes in behaviour with respect to groundwater use, which probably means that the benefits of the changes were over-estimated.

It has been argued that if the reliability of canal supplies were to be improved, more farmers in the head reaches would grow rice and sugarcane at the expense of farmers at the tail end. This is indeed likely to happen unless the farmers on a watercourse realise that it is in the long-term interest of them all to spread the scarce, good quality canal water over the entire watercourse command area. Crop diversification, and the gradual introduction of more salt-tolerant crops should go hand in hand with a reduction in the area under rice and sugarcane.

The present knowledge of the change processes that occur when changes are made in the allocation and distribution of canal water is obviously insufficient. The above considerations, however, point already to the inevitable conclusion that the management interventions, proposed by Kuper (1997) are hard to justify with present cropping patterns and yield levels. And even less so when they have the side effect of spreading the salts and especially the sodium salts more evenly over the land. The long term effects of management changes on the productivity of irrigated agriculture are of critical importance. If the good quality canal water, a limited resource, is spread equally over a large area, yields of all but the most salt-tolerant crops will be reduced to below their maximum levels. The choice then becomes one of equality versus productivity, equality in terms of access to canal water but also to the hazards of salinity and sodicity, and productivity as the increased yield potential on the non-saline part of the land. Continuing irrigation with a mixture of groundwater and canal water, of equal, marginal quality for everyone, brings with it the hazard of spreading salts, including the sodium salts, to ever larger areas.

Pakistan has produced a series of plans for agricultural and irrigation development over the years, e.g. development of public tubewells to combat waterlogging; initiating a private tubewell promotion scheme to meet an unforeseen demand for extra irrigation water; watercourse improvement programs when donors became interested in reducing seepage losses. The latest cliché is “demand-based irrigation” (Bandaragoda, 1994, and Merrey, 1997); this concept refers to a system that provides water flexibly in time and amount according to demands specified by the irrigators themselves. Without exception these plans have failed to achieve the desired results. Those projects related to infrastructure development and increasing water supply have received priority, while the more important institutional development and cost-recovery issues have not received strong research or policy support. According to Bandaragoda (ibid.) lack of clear policy direction is one major reason. Another reason is the failure to obtain full participation of all parties, for example the provinces. This is well illustrated by the protracted debate on the construction of the Kalabagh dam. Considering the reduced storage capacity of the reservoirs of the Tarbela and Mangla dams due to the accumulation of silt, the need for one new large storage reservoir or several smaller ones is apparent to ensure adequate water supplies in the future.. These problems, compounded by the continuing fragmentation among sectors, reflect the failure to achieve a cohesive and comprehensive research-based policy over time.

Recently, however, institutional reforms have been introduced through the transformation of the provincial irrigation departments into financially autonomous Provincial Irrigation and Drainage Authorities. Also irrigation management has been decentralised with the creation of area water boards at the level of the distributary canal command area. Farmers are represented in the water boards. However, it is questionable whether these institutional changes will suffice to strengthen the notion that it is in the common interest to preserve the natural resources for the benefit of tomorrow’s farmers and city dwellers alike. Consideration has been given also to water markets as a means to improve performance and productivity of irrigated agriculture. Strosser (1997) has studied the potential for water markets based on data and information gathered in one of IIMI’s research areas. He found that the potential for reallocation of canal water in terms of increased farm gross income is highest within and between tertiary units (i.e. areas served by a watercourse), rather than at higher levels of the irrigation system. The impact of such reallocations is expected to be higher when the timing and amount of canal water transactions are kept flexible, rather than fixed in rigid operational rules. At present small water markets operate at tertiary level, particularly for pumped tubewell water. However, the market is distorted as the price of tubewell water exceeds that of canal water, although its quality is generally less. This distortion results from the implicit subsidy of canal water, whereas the cost of traded tubewell water is more likely commensurate with its production cost.

Concluding remarks

In view of the spatial variability of the extent of the water-related problems, a flexible management approach is called for. How can this flexibility be attained, if the institutional changes currently under way are unlikely to bring it about? Experience elsewhere indicates that strict adherence to a set of site-specific regulations of allowable recharge to the groundwater and maintenance of an acceptable salt balance in irrigated areas is probably necessary to sustain and enhance the productivity of irrigated agriculture. In the Murrumbidgee Valley of Australia, for example, acceptable levels of recharge to the groundwater and of environmental damage have been stipulated for each farm. Farmers have been informed about the consequences of various cropping patterns in terms of recharge and salt accumulation. They can thus make well informed choices about the crops to be grown and the cropping intensities but *within* a strict set of rules. Excess recharge to the groundwater and/or excess salt accumulation are penalised through a tiered pricing structure of the irrigation water (private communication by Dr. S.A. Prathapar, 1996).

Local control in regulating water use has also been attempted in Nebraska, where the rate of groundwater withdrawal from the Ogalalla aquifer is much more than the rate of recharge. Also, residues of agro-chemicals, i.e. fertilisers and pesticides, have led to increased levels of nitrogen and other chemicals in the local water supplies. These problems reflect the inability of the existing institutional structure to regulate the use of ‘common pool’ resources. Peterson et al. (1993) argue convincingly that in the case of the Nebraska irrigators, recourse to the judicial system has been critical in overcoming local resistance to change in the *status quo* property rights. Regulations on the amount of water farmers are authorised to use as well as on the application of nitrogen fertiliser have been put into place. For the most part, these regulations have been developed by local agencies run by the farmers themselves. However, the effectiveness of the local governmental institutions charged with implementing these policies, in managing groundwater resources depends critically on institutions at the state and federal levels. These examples show that co-ordination in regulation and enforcement is necessary, involving farmer organisations as well as state and federal institutions. An adequate monitoring system and the willingness to comply to the rules for the long term benefit of all are necessary. It will not be easy to introduce this type of regulation in Pakistan’s Punjab where social control in rural areas is nowhere as well developed as in Australia and the USA, and where the compliance to rules and regulations in society at large is weak at best. Unfortunately, high levels of illiteracy among farmers compound the issue.

It is difficult to say whether these irrigation systems in Pakistan will remain productive considering the demands that are placed on them. The soil and water resources are at risk of degradation, the competition for water between agriculture, industry and domestic use is likely to increase, and there is an increasing demand for reliable water supplies in order to produce food and fibre for the present and future population. Topics such as food security rather than food self-sufficiency, and re-allocation of scarce good quality water are hardly discussed as they are probably not part of the ‘sanctioned discourse’ (Allan, 1999). Likewise, one may wonder whether Pakistan, both at the level of the water users and of society at large, has the ‘social adaptive capacity’ (Turton, 1999) to deal with the problems that are now arising as a result of population growth and water scarcity.

REFERENCES

Abrol, I.P. and M.S. Gill, 1993. Sustainability of rice-wheat production systems in India, in *Regional Expert Consultation on the Sustainability of the Rice-Wheat Production in Asia.* FAO, RAPA, Bangkok, FAO, Rome.

Allan, J.A., 1999. Global systems ameliorate local droughts: water, food and trade. MEWREW Occasional Paper 10, SOAS University of London, London, UK

Bandaragoda, D.J., 1994. *Institutional strengthening activities in Pakistan's program: Concepts, methods and results leading to a medium term strategy.* IIMI Internal Program Review, 7-10 November 1994, Colombo, Sri Lanka.

Bhatti, M.A. and J.W. Kijne, 1992. Irrigation management potential of paddy/rice production in Punjab in Pakistan, in *Soil and Water Engineering for Paddy Field Management: Proceedings Intern. Workshop, AIT, Bangkok, 1992,* AIT, Bangkok, Thailand, pp. 355-366.

Dinar, A. and D. Zilberman, 1991. The economics of resource-conservation, pollution-reduction technology selection: The case of irrigation water. Resource Energy 13:323-348.

Francois, L.E. and E.V. Maas, 1994. Crop response and management on salt-affected soils. In Handbook of Plant and Crop Stress, ed. M. Pessarakli, pp. 149-18. Marcel Dekker Inc. New York, N.Y., USA.

Ghassemi, F., A.J. Jakeman, and H.A. Nix,1995. *Salinization of land and water resources: human causes, management and case studies*. CABI/ Univ. New South Wales Press Ltd.

Gleick, P.H., 1993. *Water in Crisis. A guide to the world's fresh water resources*. Pacific Institute for Studies in Development, Environment, and Security. Stockholm Environmental Institute, Oxford University Press.

Hafeez, A., Z.A. Piracha, and N. Ahmed, 1986. *Multi-strainer tubewells for skimming top layer of fresh water underlain by saline aquifer,* Mona Reclamation Experiment Project, WAPDA, Bhalwal. Report no 152.

Hoorn, J.W. van, and J.G. van Alphen,1994. Salinity control, in *Drainage Principles and Applications*, 2nd ED., Ritzema, H.P. Ed., ILRI Publication 16, Wageningen.

Hussain, et al. 1995. Strategic research program: Drainage re-use and economic impacts of salinity in Egypt's irrigation waters. Working Paper Series No. 8-4. Ministry of Public Works and Water Resources, Cairo, Egypt.

Keller, A. A. and J. Keller, 1995. *Effective efficiency: a water use efficiency concept for allocating freshwater resources*, Centre for Economic Policy Studies, Winrock International, Arlington, Virginia.

Kijne, J.W., 1996. *Water and Salinity Balances for Irrigated Agriculture in Pakistan*, Research Report, International Irrigation Management Institute, Colombo, Sri Lanka.

Kijne, J.W., 1998. Yield response to moderately saline irrigation water: implications for feasibility of management changes in irrigation systems for salinity control. *Journal of Applied Irrigation Science* 33(2): 261-277.

Kijne, J.W. and M. Kuper, 1995. Salinity and sodicity in Pakistan's Punjab: a threat to sustainability of irrigated agriculture? Water Resources Development 11 (1): 73-86.

Kijne, J.W. and E.J. Vander Velde, 1992. Salinity in Punjab watercourse commands and irrigation system operations, in *Advancement of IIMI's Research 1989-1991*, International Irrigation Management Institute, Colombo, Sri Lanka.

Kuper, M. 1997. Irrigation management strategies for improved salinity and sodicity control. Ph.D. Thesis, Wageningen Agricultural University, The Netherlands.

Maas, E.V. 1990. Crop salt tolerance. In: Agricultural salinity assessment and management, ed. K.K. Tanji. New York, USA: American Society of Civil Engineers.

Merrey, D.J. 1997. Expanding the frontiers of irrigation management research: results of research and development at the International Irrigation Management Institute, 1984 to 1995. IIMI, Colombo, Sri Lanka, 217 p.

Murray-Rust, D.H., and E.J. Vander Velde, 1993. Conjunctive use of canal water and groundwater in Punjab, Pakistan: management and policy options, in *Advancements in IIMI's Research 1992*. International Irrigation Management Institute, Colombo, Sri Lanka.

Narangh, R.S. and N. Singh, 1988. Water management studies in rice. *Intern. Rice Research Letter.* 13(4), p. 43.

NESPAK-SGI, 1991. *Contribution of private tubewells in the development of water potential*. Final Report, Planning and Development Division, Ministry of Planning and Development, Islamabad, Government of Pakistan.

Panda, S.N., S.D. Khepar and M.P. Kaushal, 1996. Interseasonal irrigation system planning for waterlogged sodic soils. ASCE J. Irrigation and Drainage Engineering 122:135-144.

Peterson, E.W.F., J.D. Aiken, and B.B. Johnson, 1993. Property rights and groundwater in Nebraska. *Agriculture and Human Values.* 10(4), pp. 41-49.

Postel, S., 1993. Water and Agriculture, in *Water in Crisis. A guide to the world's fresh water resources,* Gleick, P.H., Ed., Pacific Institute for Studies in Development, Environment, and Security. Stockholm Environmental Institute. Oxford University Press.

Ragab, R.A. and F.Amer, 1986. Estimating watertable contribution to the water supply of maize. *Agric. Water Management.* 11, pp. 221-230.

Rhoades, J.D. and J. Loveday, 1990. Salinity in irrigated agriculture, in *Irrigation of Agricultural Crops*, Monograph 30, American Society of Agronomy, Madison, WI, USA.

Sajjad, M.I., S.D.Hussain, M.A.Tasneem, M.A.Ahmad. W.Akram, and I.H.Khan, 1993. Isotopic evidence of the source of groundwater salinity in the Indus basin, Pakistan. *The Science of the Total Environment*. 129(3), pp. 311-318.

Seckler, D. and R. de Silva, 1996. *The IIMI Indicator of International Water Scarcity*, Research Report, International Irrigation Management Institute, Colombo, Sri Lanka.

So, H.B. and A.G. Aylmore, 1993. How do sodic soils behave? The effect of sodicity on soil physical behaviour. *Australian Journal of Soil Research.* 31, pp. 761-77.

Strosser, P., 1997. Analyzing alternative policy instruments for the irrigation sector: An assessment of the potential for water market development in the Chishtian Sub-division. Ph.D. Thesis, Wageningen Agricultural University, The Netherlands.

Sumner, M.E., 1993. Sodic soils: new perspectives. *Australian Journal of Soil Research.* 31: 683-750.

Turton, A.R., 1999. Water scarcity and social adaptive capacity. MEWREW Occasional Paper 9, SOAS University of London, London, UK.

Tyagi, N.K. 1994. Cost effectiveness of salinity mitigating measures. Paper prepared for IFPRI/ICAR Workshop on Agricultural Growth in India, May 1994, New Delhi, India. Unpublished.

TABLES

Table 1. Various management options and interventions

Category	Options
Engineering	construct additional storage facilities (dams and reservoirs) improve maintenance of irrigation infrastructure conserve water in catchment, and rain in irrigated areas construct drainage facilities improve maintenance of existing (incl. natural) drains reuse waste and drain water, and find alternative ways to dispose drainage effluent, industrial and municipal waste water
Agronomic	grow different crops, i.e. less water demanding, or more drought and salt tolerant ones reduce irrigated area (use more water per unit land) on-farm watercourse improvement and precision land levelling
Policy	introduce water and power pricing to make water more expensive introduce transferable water entitlements provide incentives for land reclamation, e.g. subsidising gypsum
Institutional	improve the operation of existing irrigation and drainage infrastructure through introduction of management information systems, etc. enhance farmers’ involvement in management and maintenance of irrigation and drainage facilities