6 Water Productivity under Saline Conditions

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Abstract

The opportunity for increasing water productivity under saline conditions is contingent on the determination and accurate implementation of the leaching requirement needed to prevent unnecessary percolation below the root zone. The leaching fraction of the applied irrigation water percolates through the root zone to maintain soil salinity at an acceptable level. Crop water use (evapotranspiration) and leaching requirement (LR) together constitute the beneficial depletion of the water resource. Evapotranspiration and leaching are linked through the yield–water-production function. The more the crop growth is affected by salinity, the lower the evapotranspiration and the higher the leaching fraction of the applied irrigation water.

Crops differ in their tolerance for salinity. Under controlled conditions, crops have salinity threshold values below which crop yields are not affected. However, evidence is presented that under field conditions, where plants are subjected to periodic and simultaneous water and salt stress and to non-uniform water application, yields are lowered by salt concentrations below the assumed threshold values. In addition, rather than having one specific seasonal crop salt tolerance (threshold value), crops react differently depending on the timing of the imposed salinity stress.

Irrigation water that is consumed by evapotranspiration leaves the remaining water more concentrated with salts. The leaching requirement increases with the salinity of the water supply and the sensitivity of the crop for salinity. This chapter illustrates how uncertainty about LR, resulting in part from uncertainty about yield–salinity relations, imposes constraints on the possible improvement of water productivity under saline conditions. The chapter points out implications for the successful production of crops with a mixture of saline water and good-quality irrigation water (e.g. conjunctive use of groundwater and canal water).

Introduction

Saline water has been successfully used to grow crops. Saline water can be mixed with better-quality water prior to application, or the two types of water may be applied intermittently. Sensitivity may vary during the growing season, but crops apparently respond to the weighted mean water salinity regardless of the blending method (Letey, 1993). An example of a crop often irrigated with saline water is cotton. Even when irrigated with water of relatively high salinity, the yield of cotton is nearly as much as when irrigated with good-quality water. Cotton is considered a salt-tolerant crop. More sensi-

 Water Productivity in Agriculture: Limits and Opportunities for Improvement (eds J.W. Kijne, R. Barker and D. Molden)

tive crops can also be irrigated with relatively saline water, but they are likely to yield less than when irrigated with good-quality water. Equally high yields, as with the application of non-saline water, can often be obtained by applying more of the saline water. As the salinity of irrigation water increases, its effective quantity decreases (Letey, 1993). The degree by which the quantity is diminished depends on the crop to be grown and the relative yield to be achieved. This relationship is expressed in crop–water–salinity functions.

During the last 100 years, many experiments have been carried out to determine the salt tolerance of crops. Maas and Hoffman (1977) carried out a comprehensive analysis of salt-tolerance data, which was updated by Maas (1990). Based on this analysis, Maas and Hoffman (1977) concluded that crop yield as a function of the average root-zone salinity could be described reasonably well by a piecewise linear response function characterized by a salinity threshold value below which the yield is unaffected by soil salinity and above which yield decreases linearly with salinity. This relationship is found to be variety-specific, and it may also depend on the unique soil conditions, evaporative demand and water-management conditions (van Genuchten and Gupta, 1993).

The threshold–slope model of Maas and Hoffman (1977) has been used widely in a variety of applications in research and water management. Nevertheless, other salinity response functions have been found equally successful in describing the observed data on crop salt tolerance (e.g. van Genuchten and Hoffman, 1984; Dinar *et al.*, 1991). One of the problems with the threshold–slope model in describing experimental data is the rather poor definition of the salinity threshold value for data sets that are poorly defined or erratic or have limited observations. An example of such data is presented in Fig. 6.1 for wheat grown in the Fordwah–Eastern Sadiqia Project of Pakistan – from data reported by Kahlown *et al*. (1998). The relationship between yield and salinity of the applied irrigation water is even more difficult to ascertain, as illustrated in Fig. 6.2, also from Kahlown *et al.* (1998).

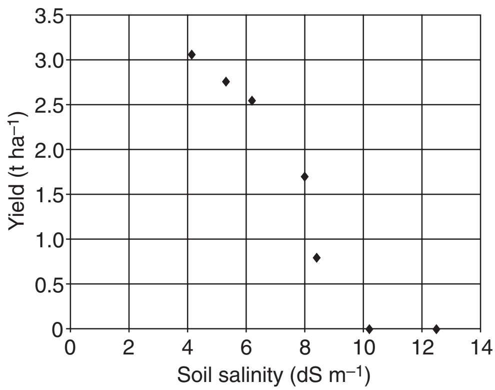

Fig. 6.1. Yield as a function of soil salinity (from Kahlown *et al.*, 1998).

A smooth S-shaped response function, as proposed by van Genuchten and Hoffman (1984), describes the various reported data sets at least as well (see also van Genuchten and Gupta, 1993). The equation for the S-shaped curve is:

$$Y/Y_m = 1/[1 + (c/c_{50})^p] \tag{6.1}$$

In this equation, Y is the yield, Ym yield under non-saline conditions, c is average root-zone salinity, c_{50} is the soil salinity at which the yield is reduced by 50% and p is an empirical constant. The curve shown in Fig. 6.3 is for wheat with an average value of p = 3 and c_{50} = 23.9 dS m^{-1}. Van Genuchten and Gupta (1993) reported that the value of p in Equation 6.1 is close to 3 for most crops.

Based on lysimeter studies in California, Dinar *et al*. (1991) derived quadratic yield response functions relating yield to the 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 is likely to increase as more

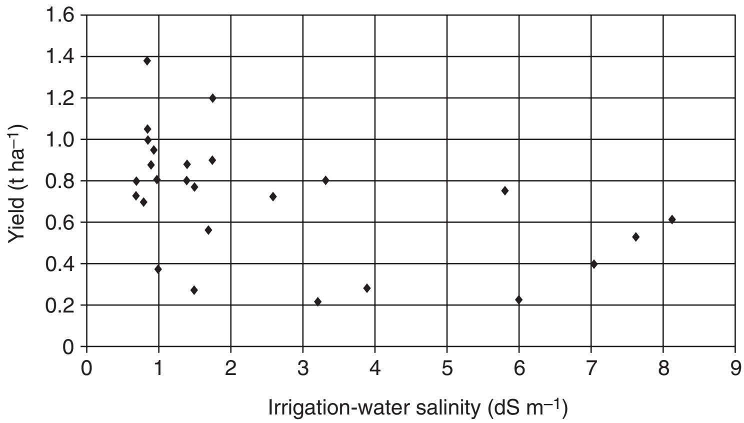

Fig. 6.2. Yield as a function of irrigation-water salinity (from Kahlown *et al.*, 1998).

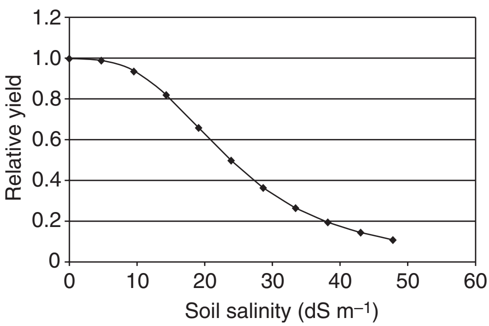

Fig. 6.3. Salt-response function for wheat, according to van Genuchten and Hoffman (1984).

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 greater deep percolation for a given irrigation application.

When the salinity is mainly the result of sodium salts, the structure of the soil will be adversely affected. High values of the exchangeable sodium percentage (ESP) in the soil can cause the hydraulic parameters, such as percolation rate and infiltration rate, to change significantly. The potential hazard of reduced water infiltration is partly related to the intensity and timing of rainfall. Rainwater has a very low salinity. When it infiltrates the soil, the salinity of surface soil can decrease rapidly, but the soil may remain at almost the same ESP. As a result, the potential of dispersion by rainfall is especially high if the ESP of the soil is high. Rainfall also contributes dispersive energy because of its impact on the soil (Kijne *et al.*, 1998). So far, these effects of sodicity have not been incorporated in any of the salt-response functions. It is to be expected that, with sodic soils, reduced plant growth and, hence, reduced evapotranspiration will not lead to increased percolation for a given irrigation application. Percolation into sodic soils may be so slow that most of the irrigation water will runoff without leaching salts from the root zone.

Apart from the S-shaped relation between yield and soil salinity (Equation 6.1), quadratic yield functions were developed by Dinar *et al.* (1991), quadratic, log–log and linear functions by Datta *et al.* (1998) and a linear function by Lamsal *et al.* (1999). None of these functions show a threshold salinity below which yield is unaffected by salinity. There is now considerable evidence from field observations that yield starts to decline at much lower values of soil salinity than predicted by the threshold–slope functions of Maas and Hoffman (1977). For example, Hussain (1995) reported field data that illustrated this earlier response, and Katerji *et al.* (2000) confirmed this effect in their lysimeter experiments in Bari, Italy. Shalhevet (1994), in a seminal paper on the use of marginal water for crop production, observed that under conditions of high evaporative demand the salinity response function may change so that the threshold salinity decreases and the slope increases, rendering the crop more sensitive to salt. Tyagi (2001) reported a set of empirical relations between relative yield, the amount of water applied as a fraction of pan-evaporation and the salinity of the applied water. These relations were developed at the Central Soil Salinity Research Institute, Karnal, India, for five crops, including wheat, cotton and maize. The curvilinear relations reflect the local conditions and show a gradual decline in yield with an increase in salinity of the irrigation water.

The effect of salinity on yield differs depending on the timing of the salt stress, another factor not considered in salt-response functions. Zeng *et al*. (2001) and Francois *et al*. (1994) reported the importance of timing of salt stress on yield components for rice and wheat, respectively. Shalhevet (1994) hypothesized that the duration of salinization is more significant than sensitivity at a critical growth stage. Zeng *et al*. (2001) argued that this hypothesis can only be tested when the salt-stress periods during the various well-defined growth stages are of equal length, which is the way they designed their experiments. Hence, at least for rice, they repudiated the hypothesis.

In general, yields in farmers' fields tend to be lower for a combination of factors than those predicted on the basis of yields obtained under more controlled conditions (see, for example, Warrick, 1989; Howell *et al*., 1990; Kijne, 1998). Contributing factors appear to include at least the following: spatial variability of soil structure and fertility, water-application rates, soil salinity, plant density and 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. Leaching is a non-productive but beneficial water use. Without maintaining an acceptable salt balance in the root zone, it would not be possible to continue to grow crops in many irrigated areas of the world. But how much water should be allocated to leaching? Guerra *et al*. (1998) report data for seepage and percolation in rice-fields ranging from 1–5 mm day^{-1} in puddled clay soils to as high as 24–29 mm day^{-1} in lighter-textured soils. Seepage occurs in irrigation canals but percolation occurs over the whole area planted with rice. The reported range of values implies that percolation from rice-fields can vary from the same order of magnitude as evapotranspiration up to about eight times as much. The latter is surely excessive in terms of salinity control. In this chapter, the focus will be on leaching requirements for non-rice crops.

In most definitions of irrigation efficiency and water productivity, no allowance is made for leaching as beneficial use of irrigation water (Seckler *et al*., Chapter 3, this volume). Water-productivity values vary with the geographical scale, as Keller and Keller (1995) illustrated for the Nile valley. A major cause of this variation is the fact that runoff or drainage from one field may be reused on another. However, because of its higher salt content, drainage water is inevitably of lower quality than the applied irrigation water. Even runoff will be degraded if it picks up disease organisms, agricultural chemicals or salt (Solomon and Davidoff, 1999).

Reuse of drainage water (including seepage from canals and percolation from fields) between parts of an irrigation system or within an entire river basin complicates the distinction between consumptive and non-consumptive beneficial use of water (Molden *et al*., Chapter 1, this volume). To correctly determine the potential for reuse of drainage flows, it is necessary to account for all components of the salt and water balances at the different geographical scales and to know the leaching requirements for the crops to be grown.

High water tables are often associated with irrigated agriculture. They provide a source of water for plant growth through capillary rise of water into the root zone. Substantial contributions from shallow groundwater to crop water requirements have been reported in the literature (e.g. Grismer and Gates, 1991; Letey, 1993). However, when this shallow groundwater is saline, the harmful effects caused by the salt accumulation in the root zone probably outweigh the potential benefits of the groundwater as a source of water for plant production. Usually, the only option for sustaining agricultural production on fields underlain by shallow saline groundwater is to install a subsurface drainage system.

Thorburn *et al.* (1995), studying the uptake of saline groundwater by eucalyptus forests in part of the flood-plains of the Murray River in South Australia, showed that groundwater depth and salinity are the main controls on the uptake of groundwater, while soil properties appear to have a lesser effect. Model studies indicated that uptake of saline groundwater would result in complete salinization of the soil profile within 4 to 30 years at the sites studied, unless salts were leached from the soil by rainfall or floodwaters. However, a relatively small amount of leaching may be sufficient to allow groundwater uptake to continue. Thus groundwater, even when saline, may be an important source of water to salt-tolerant plants and trees in arid and semi-arid areas.

Grismer and Gates (1991) carried out a stochastic simulation study for a salinity-affected area underlain by a shallow water table, representative of conditions in the western San Joaquin valley of California. The model analyses the effects of irrigation–drainage management on water-table depth, salinity, crop yield and net economic returns to the farmer over a 20-year planning period. They found that cotton farming on salinity-affected soils subject to shallow saline groundwater is economically optimal if the application efficiency is 75−80%, which may be attainable with well-managed surface irrigation, and a subsurface drainage system is capable of removing 79−93% of the downward flux. The study illustrates the need to approach management strategies on irrigation and drainage together, from a regional perspective.

Research Data

The data for this chapter were collected at the International Water Management Institute (IWMI)'s research sites in irrigation systems in the Indus River basin of Pakistan between 1988 and 1995. The salt problem of the Indus is formidable. Smedema (2000) reported that the average salt influx by the Indus river water, taken at the rim stations, is estimated at 33 million t, while the outflow to the sea contains only 16.4 million t. Hence, the average annual addition of salts to the land and the groundwater amounts to some 16.6 million t. Most of this accumulation takes place in the Punjab. This is in sharp contrast to Egypt, where a large portion of the irrigated land is underlain by subsurface drains that take the drainage water back to the river. The salts do not stay in the Nile basin but are discharged into the Mediterranean Sea. During part of the year, the salt content in the lower Indus is much lower than in the lower Nile (in the Nile delta) and more salt disposal into the Indus could be accepted. However, during critically low flow periods, such disposals would not be possible. The only option during such periods would be to store the drainage water temporarily for release during high flood periods. Extending the left bank outfall drain, now operating in Sindh, into the Punjab may provide a more permanent (but quite expensive) solution than the present inadequate number of evaporation ponds.

Much of the drainage water from agricultural land in Pakistan's Punjab is being reused, either from surface drains or pumped up from shallow groundwater. The leached salts are therefore returned to the land rather than disposed of to the sea. IWMI's research sites in the Indus basin, the data-collection methodology and data analyses were described by Kijne (1996), Kuper and Kijne (1996) and Kuper (1997).

Specifically, information on the quantity and quality of applied irrigation water at the study sites in Punjab, Pakistan, is obtained from Kijne (1996). The electrical conductivity (EC, i.e. the standard measure of salinity) of canal water was 0.2 dS m^{-1} in most of the experimental sites. The EC of pumped groundwater was obtained from measured values of water quality of tube wells in the sample areas. For the calculations of the salt balance of the study sites, Kijne (1996) used 2.5 dS m^{-1} as a representative value for the salinity of pumped groundwater, ignoring the large variations in water quality that often occur even from pumps close to one another. Average values of the leaching fraction (LF) (the fraction of the infiltrated applied water that passes below the root zone) for the three irrigation systems reported in these studies were between 10 and 15% (Kijne, 1996, Table 2).

Data on LFs for four irrigated fields in the Fordwah–Eastern Sadiqia irrigation system, Chistian subdivision, Punjab, studied in considerable detail, are obtained from Kuper (1997). The latter set of data is summarized in Table 6.1.

ECe is the electrical conductivity of soil water at saturation, the usual parameter for measuring soil salinity in the profile. The value in the third column refers to the linearly averaged electrical conductivity of soil water in the profile down to 1 m. No leaching for field 2 (last column of the table) indicates that there may have been capillary flow from the water table (water table was at 2 m depth).

The spatial and temporal variability of soil salinity is large. Values in columns 4, 5 and 6 give some indication of the vertical spatial variability. Soil salinity increases when the soil dries out between irrigations or in rainfall events, and it varies greatly between upper and lower layers of the root zone. It is generally accepted that plants respond to the average salinity in the root zone and vary their water uptake in the growing season depending on relative values of the osmotic potential in the root zone.

The excessive leaching in field 1 (leaching fraction of 0.65) is blamed on a combination of poor water management by the farmer and the light-textured soil with high permeability. Leaching in the other fields is inadequate for maintaining an average root-zone salinity equivalent to an ECe value of 2 dS m^{-1}. The attainable yield level under these low leaching conditions is less than the maximum.

Leaching Requirement

When more water is applied than is taken up by the plant roots, water flows out of the root zone and carries soluble substances, such as salts and agrochemicals, with it. During this process of downward flow (percolation), soil salinity in the root zone increases with depth. In planning the desired leaching requirement (LR), it is commonly assumed that EC values of the soil extract at the lower root-zone boundary corresponding to 25–50% yield reduction are still acceptable. The weighted average EC value for the entire root zone (weighted according to root distribution) would be much less than at the lower root-zone boundary and the corresponding yield reduction for plants growing in this soil would be less than 25–50%. Such yield reductions are assumed to be economically viable (Smedema and Rycroft, 1988).

The rate of downward flow and leaching varies with the soil water content. It is highest during the first couple of days after irrigation, when the soil water content is still above or near field capacity. Thereafter, leaching continues at a much reduced rate. In many soils, the soil solution at field capacity is about twice as concentrated as when the soil is saturated (shortly after irrigation). When the soil dries out further between irrigations, the soil solution becomes even more concentrated.

Table 6.1. Salinity and leaching fractions in four experimental fields, Chistian subdivision, Punjab, Pakistan (from Kuper, 1997).

	Soil type	ECe (dS m^{-1})	Lowest ECe (dS m^{-1})	Highest ECe (dS m^{-1})	90 cm depth	LF
Field 1	Loamy sand	0.75	0.5	0.8	0.75	0.65
Field 2	Sandy loam	1.75	0.5	2.8	1.8	Nil
Field 3	Loam	2.5	1.3	4.2	2.5	0.07
Field 4	Silt loam	4.75	1.5	8.0	6.0	0.01

Not all downward flow is equally effective in leaching salts from the root zone. The most effective leaching occurs when water moves through the soil mass, rather than through cracks between aggregates. Water moving through cracks and wormholes has been called preferential flow. How much of the percolation occurs as preferential flow depends on the structure and texture of soil and is difficult to determine. As a result, the leaching efficiency of the percolating water is also difficult to assess. In cracking clay soils, initially as much as three-quarters of the applied water may flow through the cracks. Once the soil swells up with moisture, cracks close and the leaching efficiency increases (Smedema and Rycroft, 1988).

In its simplest form, for steady-state conditions, the relation between the LR and the amounts of irrigation and drainage water and their EC reduces to:

$$LR = D_d/D_a = EC_a/EC_d \tag{6.2}$$

where D is depth of water (subscript a for applied water; subscript d for drained water) and EC is the corresponding electrical conductivity. Equation 6.2 states that the amount of salt added in the irrigation water must equal the amount drained to maintain the salt balance. If the actual LF is less than the requirement, salt will accumulate (Hoffman, 1990).

The relationship between the salinity of the applied water, the LF and the resulting soil salinity is an important one. It would be easier to estimate expected yields if it were possible to unambiguously predict the soil salinity likely to result from irrigation applications of known salinity and a specified LF. Table 6.2 presents various relationships between LF and the dimensionless ratio of the average weighted root-zone salinity (Cs) and the average salinity of applied water (Ca).

The values in the table are based on steady-state conditions. However, the relationship between soil and water salinity as governed by leaching is a dynamic one, subject to feedback mechanisms between growth of the crop (hence, evapotranspiration) and leaching of salts (see Dinar *et al.* (1991), referred to earlier). In all cases the salinity-tolerance data are from threshold salinity-response functions. In addition, the leaching equations ignore the effect of sodium salts on the soil structure. The variations among the data in the table are due to the site specificity of the relationship between root-zone salinity and salinity of applied water for any given leaching fraction. A contributing factor is the variability in measured values of the EC of soil-saturation extracts. The coefficient of variation of the EC of soil moisture at saturation is about 50% (Kijne, 1996) (see also Datta *et al.* (1998) and Tedeschi *et al.* (2001), who give similar values).

The various analyses that resulted in the data in Table 6.2 indicate that the ratio of root-zone salinity to irrigation-water salinity is very sensitive to changes in the leaching amount at LF below 0.1. The implication is that a small change in the leaching amount can make a large difference in 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. Hence, in this range of LF values, root-zone salinity increases about linearly with the salinity of the applied water. Therefore, difficulties in the accurate determination of

Table 6.2. Relationships between leaching fraction and ratio of soil salinity over applied water salinity.

LF	Cs/Ca (Pratt and Suarez, 1990)	Cs/Ca (Rhoades, 1982)	Cs/Ca (Hoffman and van Genuchten, 1983)	Cs/Ca (Prendergast, 1993)
0.05	3	7	4	10.5
0.1	2	5	2.6	5.5
0.2	1.25	3	1.4	3
0.3	1	2.5	1.3	2.15
0.4	0.83	2.35	1	1.75

LF from field data can affect the fit of the leaching equations. The study by Prendergast (1993), in particular, emphasizes the need for local data of the salt- and water-balance parameters.

The leaching equation of Hoffman and van Genuchten (1983) uses a root water-uptake function that is exponential with depth and incorporates some empirical coefficients that can be adjusted according to the local conditions. Of the relations reported in Table 6.2, Hoffman and van Genuchten is probably most commonly used in modelling studies where a relationship between leaching and root-zone salinity is required. It is plotted in Fig. 6.4.

Analysis of Data

Leaching water, as was pointed out before, is a beneficial, non-consumptive use of applied irrigation water. Its benefit is in the removal of salt from the root zone. If a portion of the drainage and runoff water is reused elsewhere in the irrigation system, part of their salt load is reapplied, rather than being removed, and the benefit of the drainage and runoff water is reduced. Solomon and Davidoff (1999) have presented analytical expressions relating irrigation-performance parameters for an irrigation system (called a unit) and its subunits (e.g. watercourse command areas (WCAs)) when drainage water and runoff from one subunit are reused on another. The performance parameters considered are the irrigation consumptive-use coefficient, which is defined as the ratio of irrigation water going to consumptive uses over irrigation water applied, and irrigation efficiency (IE) is defined as irrigation water beneficially used over irrigation water applied. The numerator of IE includes beneficial consumptive use (evapotranspiration), beneficial runoff and beneficial drainage water.

Rather than following this analytical analysis, perhaps the same point can be made by the following simplified example. A series of WCAs of an irrigation system, characteristic of conditions in Pakistan's Punjab, apply a blend of canal water and some drainage water from the upstream command area. The EC of the blend applied to the first WCA is 1.35 dS m^{-1}. All WCAs require 100 units inflow to meet their consumptive-use demand (crop evapotranspiration). According to the relationships of Fig. 6.4, the LR is 0.2 to maintain the root-zone salinity at a level corresponding to an EC of 2 dS m^{-1}. Hence, rather than an inflow of 100 units, $100/(1 - \text{LR}) = 125$ units of water need to be applied. The EC of the drainage water issuing from this first WCA is assumed to be 2.5 dS m^{-1}.

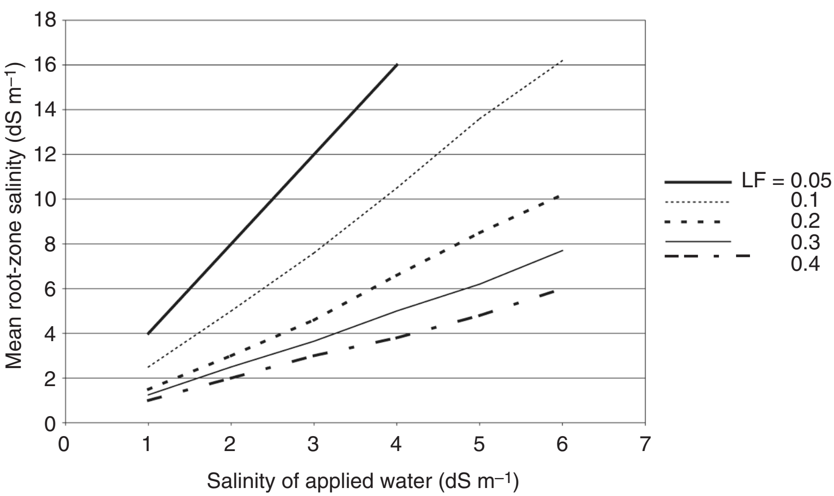

Fig. 6.4. Root-zone salinity as a function of salinity of the applied water and the leaching fraction (Hoffman and van Genuchten, 1983).

In the first example, plotted in Fig. 6.5, the next WCA in line applies a blend consisting of 60% canal water and 40% drainage water from the upstream WCA. The second WCA has as its source of irrigation water a blend of water with an EC of 1.35 dS m^{-1} for the irrigation-water component and an EC of 2.5 dS m^{-1} for the drainage component, resulting in an EC of 1.8 dS m^{-1}. Its LR is 35% and the required inflow is 154 units of water. The drainage water from this second WCA has an EC equal to 2.7 dS m^{-1}. This procedure is repeated for four WCAs. The characteristic values for the fourth WCA are an inflow salinity of 2.5 dS m^{-1}, LR of 45%, inflow of 180 units and drainage salinity of 3.3 dS m^{-1}.

The WCAs of the second example, plotted in Fig. 6.6, take only 10% of their applied water from the upstream drainage flow and 90% from the irrigation supply. In this case, the characteristic values for the fourth WCA are an inflow salinity of 1.74 dS m^{-1}, LR of 36%, inflow of 156 units and drainage salinity of 3.3 dS m^{-1}. The salinization of the water supply is slower when less water is taken from the more saline source. However, the trends are the same: more and more water from the 'good' source needs to be applied to the crop to maintain the root-zone salinity at an acceptable level.

Field 3 in Table 6.1 referred to a farmer's field where the LF was only 0.07. For a water demand of 100 units, this small amount of leaching would bring the inflow to 108 units and, with an EC of 1.35 dS m^{-1}, as in our example, the average EC of the root-zone moisture would be about 10 dS m^{-1}. This level of root-zone salinity would lead to significant production losses of even salt-tolerant crops.

Reuse of drainage flow from another WCA is very common in Pakistan's Punjab. Percolation from one WCA flows to the groundwater and is pumped up by tube wells for reuse elsewhere in the system. In many systems, pumped groundwater makes up between one-half and two-thirds of the irrigation water.

Keller and Keller (1995) used a different method to calculate the leaching requirement:

$$LR = ECa/(5ECe - ECa) \qquad (6.3)$$

where ECa is the EC of the irrigation water and ECe is the EC of the soil-saturation extract for a given crop and a tolerable degree of yield reduction. They assumed an allowable ECe of 1.5 dS m^{-1}. The use of this equation leads to LR values that are almost identical to those obtained in the manner described above.

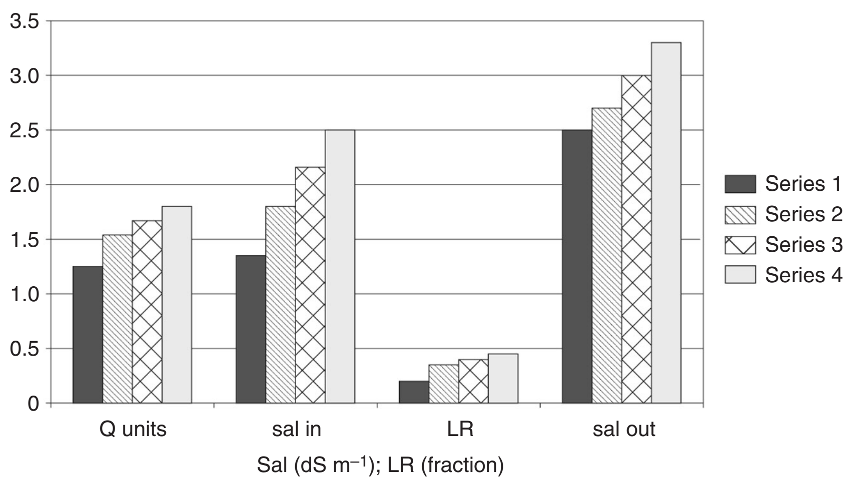

Fig. 6.5. Inflow volume (Q in multiples of 100 units), salinity of inflow and outflow (dS m^{-1}), and leaching requirement (fraction) for four successive reuse cycles, with 40% drainage water blended in.

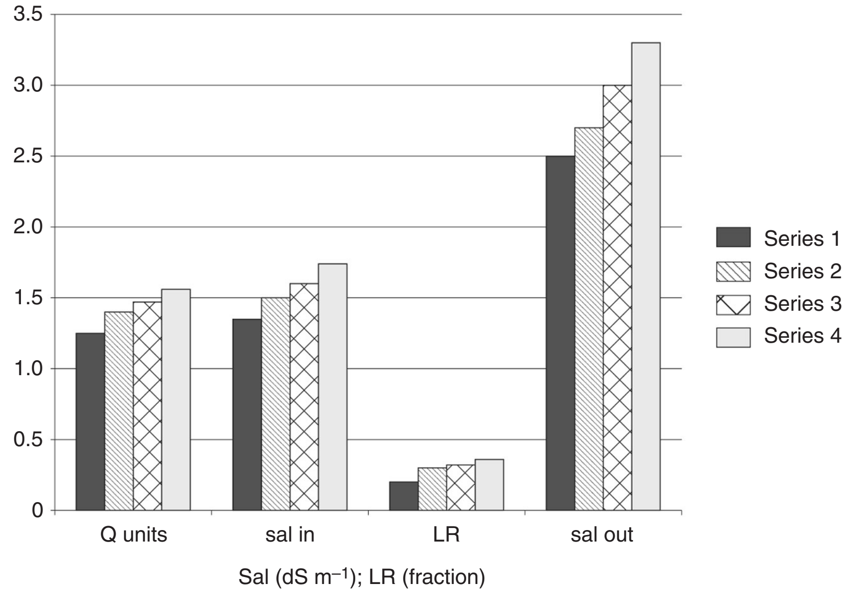

Fig. 6.6. Inflow volume (Q in multiples of 100 units), salinity of inflow and outflow (dS m^{-1}), and leaching requirement (fraction) for four successive reuse cycles, with 10% drainage water blended in.

Discussion

Several factors contributing to the present uncertainty about LRs have been mentioned. The most important ones derive from the inherent complexity of the dynamic plant–soil–water system in terms of its reaction to variations in water quality. Current salt-response functions and leaching equations are valid for static conditions, whereas the system itself is a dynamic one, with seasonal changes in the quality of the applied water, especially where rainfall meets a large part of the crop water demand during one or part of one growing season. Feedback mechanisms in this dynamic system are poorly understood and have rarely been quantified. One example of such a mechanism is the increase in downward flow when crop evapotranspiration declines as a result of salt stress on the crop. Rather than one specific crop, cropping sequences should be considered (see the examples given by Tyagi, Chapter 5, this volume). If the reported threshold values for salt tolerance are too high for most field situations, LR values would be higher than calculated. The effect of this difference is probably small in view of the overall uncertainty in the calculation of leaching requirements. Depth of water table may vary throughout a season or from one season to another, and hence the potential contribution to the evaporative demand of the crop through capillary flow varies as well. The effect of irrigation water rich in sodium salts (alkaline water) on crop production and soil structure is not considered.

Accurate determination of LRs is obviously not easy. Does it matter? It appears that under most conditions more than enough water is applied to the fields to meet the LR. Or, in other words, those low LFs reported in Table 6.2 must surely be exceptions rather than the rule. One gets that impression when considering the values of the relative water supply (the ratio of irrigation supply plus rainfall over water demand) and the relative irrigation supply (irrigation supply over demand) for 26 irrigation systems reported by Molden *et al*. (1998). Relative water supply values varied between 0.8 and 4.0 and half of the systems had values greater than 2.0. The reported variation in relative irrigation supply was between

0.41 and 4.81, while 22 of the 26 systems had values in excess of 1.5. The relative irrigation supply should be near 1 when irrigation supplies tightly fit the gap between demand and rainfall. System-wide values of these two parameters, however, do not tell us where the excess water is applied. In many irrigation systems, subsystems served by a distributary canal in the head reach of a system receive more water per unit land than those located in tail reaches of the same system. This same variation in water distribution is repeated at lower levels of the systems, i.e. between head and tail WCAs within a distributary command area and between farms located in head and tail reaches within the same WCA. The worst salinization often occurs in those tail areas.

A more equitable distribution of water within irrigation systems and better knowledge of LRs would contribute to greater water productivity (yield per unit of water beneficially used for evapotranspiration and leaching of salts) than that presently occurring in many irrigation systems. A condition for such an improvement is more extensive monitoring of the amounts of water and salts applied to and drained from irrigation systems as a whole and especially from their subunits. The data collection should cover all aspects of the water and salt balances at the different levels of irrigation systems. Salemi *et al*. (2000) and Droogers *et al*. (2001) give examples of insights that come from modelling of the water and salt balances in respect of the relation between water application, its salinity and the resulting water productivity for different water application and salinity conditions. The effect of water quality on the attainable water productivity is apparent without explicit knowledge of the LR.

Water productivity in rice cultivation has not been considered in this chapter. Paddy rice is often grown as an ameliorative crop. The high rates of percolation from the fields help reduce the salinity of the root zone for subsequent crops. A drawback of this approach is that rice is often grown on unsuitable light-textured soils that are poorly puddled at the start of the season, leading to excessive percolation rates and rising water tables. Water productivity as low as 0.14 kg m^{-3} of water applied to the rice-fields has been recorded in Pakistan's Punjab. This uncontrolled leaching wastes water.

Kotb *et al*. (2000) describe rice cultivation in salt-affected lands of the northern Nile delta in Egypt. They illustrate that the use of rice paddies to control salinity is faced with a number of constraints, such as periodic water shortages and salinity of supply water, which consists of a blend of fresh water and drainage water. Diversified cropping in the same subsurface drainage system compounds the problems, as rice and the other crops in the cropping system vary in their irrigation and drainage requirements. The authors propose that, to alleviate the problems of water shortage, the rice-cultivation area needs to be reduced by 50% and that rice cultivation in the delta should be consolidated to monitor its extent and to have uniform drainage requirements. Kotb *et al*. (2000) recommend rice cultivation only in saline soils of the delta but perceive that enforcement of such a policy may be difficult to achieve. In addition, long-term changes in the salinity of the delta water resulting from increased drainage-water reuse are not clearly known.

This example is typical in two respects. In many developing countries, the long-term productivity impacts of using saline and sodic irrigation water are unknown and the enforcement of policy measures that would lead to greater equity of distribution is doubtful, at best. A set of measures suggested by Kuper (1997) for a specific command area in Pakistan's Punjab included diversion of good-quality canal water from head to tail reaches to improve the blend of irrigation water available in the tail reaches and thereby curtailing further salinization. The consequence of this measure was that less canal water would be available to head-end farmers, who may object to this measure and compensate for their perceived shortage by pumping more groundwater and hence increasing the likelihood of salinization in the head reaches. The suggested measures were probably not economically viable or enforceable. Because of the current low levels of yield, the expected slight improvements in yield did not raise the economic returns in tail reaches by much (Kijne, 1998).

Unfortunately, few data are available on the economics of salinity-control measures. One complicating factor in the calculation of benefit/cost ratios is that the potential yield level under non-saline conditions is not well known. Yield levels between 4 and 7 t ha^{-1} for wheat and rice irrigated with canal water in India's Punjab (e.g. Tyagi, Chapter 5, this volume, Tables 5.2 and 5.3) are lower than the maximum irrigated yields attained elsewhere when all growth factors are closer to their optimal value.

This chapter has shown that the potential exists for improved water productivity by better-managed leaching practices but is not easily realized. Better knowledge is needed about the magnitude and interaction of the various components of the water and salt balances under field conditions and their changes over time. Those studies are expensive and time-consuming. Modelling studies, such as those discussed by Salemi *et al*. (2000) and Droogers *et al*. (2001), will contribute to our understanding, but they need to be validated in the field. In addition, it should be realized that the recommendations arising from such studies are probably difficult to implement. Reallocation of water supplies to achieve greater equity in access to and quality of water for farmers in different parts of irrigation systems requires greater management inputs and control. Using good-quality water only for high-value crops and poor-quality water for fodder crops and trees is politically unacceptable in a country like Pakistan, where the introduction of such measures would lead to greater poverty and unemployment for those farmers left with the saline groundwater. Reducing cropping intensities or changing cropping patterns to ensure adequate leaching applications is also likely to increase the gap between relatively rich and poor farmers.

In the long term, the installation of subsurface drains in a substantial portion of Pakistan's Punjab and the disposal of saline effluent into salt sinks and ultimately into the sea may be unavoidable. The investments required for this type of work are huge. The recent gradual decline in multilateral infrastructural investments in agriculture gives no reason to think that improved drainage will happen soon. In the meantime, yield levels and water productivity will remain lower than necessary.

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