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SWIM Paper

How to Manage Salinity in Irrigated Lands: A Selective Review with Particular Reference to Irrigation in Developing Countries

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Contents

Acronyms

EC	electrical conductivity
ESP	exchangeable sodium percentage
HC	hydraulic conductivity
IR	infiltration rate
LF	leaching fraction
RA	residual alkalinity
RSC	residual sodium carbonate
SAR	sodium adsorption ratio
SSSA	Soil Science Society of America
TEC	total electrolyte concentration

CGIAR Centers

CIAT	Centro Internacional de Agricultura Tropical
CIFOR	Center for International Forestry Research
CIMMYT	Centro Internacional de Mejoramiento de Maize y Trigo
CIP	Centro Internacional de la Papa
ICARDA	International Center for Agricultural Research in the Dry Areas
ICLARM	International Center for Living Aquatic Resources Management
ICRAF	International Centre for Research in Agroforestry
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IFPRI	International Food Policy Research Institute
IIMI	International Irrigation Management Institute
IITA	International Institute of Tropical Agriculture
ILRI	International Livestock Research Institute
IPGRI	International Plant Genetic Resources Institute
IRRI	International Rice Research Institute
ISNAR	International Service for National Agricultural Research
WARDA	West Africa Rice Development Association

Glossary[1]

Acidity, total: the sum of the soil acidity that is neutralized by lime or a buffered salt solution to raise the pH to 7.0 and the aluminum and hydrogen that can be replaced from an acid soil by an unbuffered solution of salt such as KCl or NaCl.

Adsorption: the process by which atoms, molecules, or ions are taken up from soil solution or soil atmosphere and retained on the surfaces of solids by chemical or physical binding.

Alkali soil: a soil that contains sufficient sodium to interfere with the growth of most crop plants.

Alkaline soil: a soil with a pH value of > 7.0.

Alkalinity, soil: the degree or intensity of alkalinity in a soil, expressed by a value of >7.0 for the soil pH.

Cation exchange: the interchange between a cation in solution and another cation in the boundary layer between the solution and surface of negatively charged material such as clay or organic matter.

Cation exchange capacity: the sum of exchangeable bases plus total soil acidity at a specified pH (usually 7.0 or 8.0). It is usually expressed in centimoles of charge per kilogram of exchanger ($cmol_c$/kg), or millimoles of charge per kg of exchanger.

Electrical conductivity (EC): conductivity of electricity through water or an extract of soil. EC is commonly used to estimate the soluble salt content in solution.

Evapotranspiration: the combined loss of water from a given area, and during a specified period of time, by evaporation from the soil surface and transpiration from plants.

Exchangeable bases: charge sites on the surface of soil particles that can be readily replaced with a salt solution.

Exchangeable cation: a positively charged ion held on or near the surface of a solid particle by a negative surface and which may be replaced by other positively charged ions in the soil solution. It is usually expressed in centimoles or millimoles of charge per kg.

Exchangeable sodium percentage (ESP): the fraction of the cation exchange capacity of a soil occupied by sodium ions, expressed as a percentage.

Leaching: the removal of soluble materials from one zone in the soil to another via water movement in the profile.

Leaching fraction: the fraction of infiltrated water that percolates below the root zone.

Leaching requirement: the leaching fraction necessary to keep soil salinity, chloride, or sodium (the choice being that which is most demanding) from exceeding a tolerance level of the crop in question. It applies to steady state or long-term average conditions.

Preferential flow: the process whereby free water and its constituents move by preferred pathways through a porous medium (also called bypass flow).

Saline soil: a non-sodic soil containing sufficient soluble salts to adversely affect the growth of

[1]Extracted from *Soil Science Society of America 1997*.

most plants. The lower limit of saturation extract electrical conductivity of such soils is conveniently set at 4 dS/m (at 25° C). Actually, sensitive plants are affected at half this salinity and highly tolerant ones at about twice this salinity.

Salinity, soil: the amount of soluble salts in a soil, usually expressed through the electrical conductivity of a saturation extract.

Salinization: the process whereby soluble salts accumulate in the soil.

Salt balance: the quantity of soluble salts removed from an irrigated area in the drainage water minus that delivered in the irrigation water.

Saturation extract: the solution extracted from a soil at its saturation water content.

Sodic soil: a non-saline soil containing sufficient exchangeable sodium to adversely affect crop production and soil structure under most conditions of soil and plant type.

Sodication: the process whereby the exchangeable sodium content of a soil is increased.

Sodium adsorption ratio (SAR): a relation between soluble sodium and soluble divalent ions that can be used to predict the exchangeable sodium fraction of soil equilibrated with a given soil solution. It is defined as follows:

$$SAR = [Na]/[Ca + Mg]^{0.5},$$

where concentrations, denoted by brackets, are expressed in mmoles per liter.

Sodium adsorption ratio, adjusted: the sodium adsorption ratio of a water adjusted for the precipitation or dissolution of calcium, that is expected to occur where a water reacts with alkaline earth carbonates within a soil.

Abstract

This paper reviews the causes of irrigation-induced salinity, particularly in developing countries. It describes the underlying chemical and physical processes involved in soil and water degradation due to irrigation. The present state of knowledge and the contributions made by modeling these processes are presented. Areas of uncertainty in our current understanding are identified. Weaknesses in the knowledge base include the yield response to simultaneous under-irrigation and salt stress, the transport of salts during leaching, especially in the presence of preferential flow paths in the root zone, and the rates of soil and water degradation during salinization and sodication (i.e., the accumulation of sodium salts in the soil profile).

The paper discusses several remedial management actions, categorized as engineering, agronomic, policy-level and system-level interventions. Special attention is given to the regional management of saline effluent from irrigation systems, including options for its disposal. In a section on farmers' response to salinity, it is argued that the farmers should be provided with better information on the hazards of salinity and sodicity, but that a farmer's ability to prevent or mitigate the problem is closely linked to his or her financial status.

There is presently a large mismatch between the available knowledge and its application. The technical problems that have led to large-scale, irrigation-induced salinity are well known. They include, among others, poor on-farm water use efficiency, and inadequate standards of construction, operation, and maintenance of the irrigation and drainage facilities. Many of these technical problems, however, are the product of a host of government policies, such as those concerning water pricing, and the funding levels for maintenance and operation of the infrastructure. Remedial actions should address this web of technical, economic, political, and social factors, but are unlikely to lead to quick solutions. However, because of the need for sustained and enhanced food production, the prevention, mitigation, and reversal of further degradation of soil and water resources in irrigated agriculture is a first priority. Several broad areas for further research are presented in the final section of the paper. The output of the research is expected to enhance the understanding of what happens when current irrigation and agronomic practices are continued. These findings also provide the information that is necessary to give sound practical advice on the management of salinity to farmers and policy makers.

SWIM Papers

In an environment of growing scarcity and competition for water, increasing the productivity of water lies at the heart of the CGIAR goals of increasing agricultural productivity, protecting the environment, and alleviating poverty.

TAC designated IIMI, the lead CGIAR institute for research on irrigation and water management, as the convening center for the System-Wide Initiative on Water Management (SWIM). Improving water management requires dealing with a range of policy, institutional, and technical issues. For many of these issues to be addressed, no single center has the range of expertise required. IIMI focuses on the management of water at the system or basin level while the commodity centers are concerned with water at the farm and field plot levels. IFPRI focuses on policy issues related to water. As the NARS are becoming increasingly involved in water management issues related to crop production, there is strong complementarity between their work and many of the CGIAR centers that encourages strong collaborative research ties among CGIAR centers, NARS, and NGOs.

The initial publications in this series cover state-of-the-art and methodology papers that assisted the identification of the research and methodology gaps in the priority project areas of SWIM. The later papers will report on results of SWIM studies, including intersectoral water allocation in river basins, productivity of water, improved water utilization and on-farm water use efficiency, and multiple uses of water for agriculture. The papers are published and distributed both in hard copy and electronically. They may be copied freely and cited with due acknowledgment.

Randolph Barker
SWIM Coordinator

How to Manage Salinity in Irrigated Lands: A Selective Review with Particular Reference to Irrigation in Developing Countries

Jacob W. Kijne, S. A. Prathapar, M.C.S. Wopereis, and K.L. Sahrawat

Introduction

Salinity has been associated with irrigated agriculture since its early beginnings. One reason is that irrigation often exacerbates the effects of salinity, which occurs naturally because of weathering of saline parent material derived from sea water deposits or other sources. Salinity has thus been linked with the rise of groundwater tables resulting from excess irrigation and poor drainage in large-scale, perennial irrigation systems. The resulting shallow water tables bring salts to the upper layers of the soil profile. That salinity can also be induced by the use of pumped groundwater of marginal or poor quality has been realized only more recently. In these cases, the physical process underlying salinization is the absence of a downward soil water flux of sufficient magnitude to leach the salts from the root zone. Salinity can also result from sea water intrusion into coastal areas where the water tables have been lowered by the mining of groundwater, as has occurred, for example, in Bangladesh and the state of Gujarat in India.

One of the technical methods used for combating irrigation-induced salinity is the installation of expensive drainage systems. Examples of successful use of this technique are the installation, over the last 30 to 40 years, of pipe drainage in a large part of Egypt's irrigation system, and of vertical (tube-well) drainage in the Indian subcontinent. Recent research, including that by the International Irrigation Management Institute (IIMI), has focused on potential improvements in irrigation management at farm and system levels that would provide farmers and system managers with better tools to sustain irrigated agriculture without enhancing salinity levels in the root zones.

These efforts are important in view of the global extent of salt-affected lands. Although there is no general agreement on the definition of salt-affected land, which contributes to a wide divergence in the figures reported in the literature, the best estimates indicate that roughly one-third of the irrigated land in the major irrigation countries is already badly affected by salinity or is expected to become so in the near future. Present estimates for India range from 7 to 16 million hectares, or from 27 to 60 percent of the irrigated land. Estimates for other countries are: Pakistan 14 percent of the irrigated land, Israel 13 percent, Australia 20 percent, China 15 percent, Iraq 50 percent, and Egypt 30 percent (Gleick 1993, and Ghassemi et al. 1995).[2]

Irrigation-induced salinization occurs in large and small irrigation systems 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 (another word for human- or irriga-

[2]Some papers in the list of cited literature, which are especially useful for further reading on the topics of this paper, are briefly annotated.

tion-induced salinity) are predominantly but not exclusively located in arid and semiarid 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 in relatively humid countries such as the USA and Canada and in the drier parts of Thailand.

Need for Further Study

Much research on the diagnosis and improvement of saline and alkali soils has been carried out in the past; most noticeable is the work done by the United States Salinity Laboratory in Riverside, California (United States Salinity Laboratory Staff 1954). Why, one may ask, is there still a need for further studies on the impact of saline and sodic irrigation water on crop yields and soil degradation? The answer would be:

- First, water scarcity forces us to rethink water use in agriculture, in view of the competition for water from industry and urban users in developing countries. In many of these countries, agriculture is by far the biggest user of water, or, more precisely, most of the water that is withdrawn from natural water resources is applied to agriculture. Then, much of the recharge or drainage water from irrigation is of poorer quality than the water that was withdrawn. Leaching to maintain an acceptable salt balance in the root zone is often considered by nonspecialists as wasteful, especially as irrigation engineers and scientists appear to be in doubt about the required leaching rates and the efficiency of the leaching practice.
- Second, the scale at which salinity occurs worldwide, mentioned in an earlier paragraph, makes it an urgent problem in terms of food security for the rapidly growing populations of many developing countries. The prevention of the degradation of more land by the wrong combination of agronomic and irrigation practices should be the most important impact of new research endeavors. These efforts should be aimed at disseminating existing knowledge and at increasing our understanding of the underlying causes of salinity.
- Third, to address the economic and policy impacts of land degradation, reliable data and information on the rate of degradation and on the associated costs of prevention and reclamation are required. Models to predict the economic impacts of salinity control measures need information on the expected impacts of water scarcity and salinity on crop yields. All the information required is not available at present.
- Fourth, the irrigation community can no longer depend solely on the enhancement of scientific insight, generated in the developed countries, into the physical and chemical processes involved in salinization of soil and water resources. In the western world, the focus of research attention has largely shifted from salinity to other environmental problems. A case in point is the amount of research done in recent years on the selenium problem of the drainage water affecting the San Joaquin Valley in California. Sophisticated models that were developed have only limited application to salinity and sodicity

problems in developing countries because of a much smaller database in the latter. In other respects, work done, some of which is in developing countries, has not been continued long enough to ascertain the long-term effects of particular irrigation and agronomic practices. Unfortunately, studies were often carried out in soil columns or lysimeters in the laboratory, which are less costly than field studies but are often of very limited usefulness. Successful works in developing countries, for example, the salinity studies of the Central Soil Salinity Research Institute in Karnal, India, have not received the attention they deserve. Wider publication of these studies in international journals may help to disseminate the results, and should lead to assessment of their applicability in other agro-ecological zones.

These factors justify the urgent initiation of a research program that focuses on the impacts of and solutions to salinity problems in a wide range of developing countries. Such a research program should include applied, site-specific studies to identify actions for the prevention, mitigation, and reversal of resource degradation in irrigated agriculture. These studies need the participation of the affected farming communities, irrigation agencies, NGOs and policy makers. The research program should also intend to develop generic findings that have wider applicability. They will enhance the success rate of management interventions aimed at decreasing the rate of degradation of the natural resources of land and water in irrigated agriculture, or a reversal of this process altogether. A first step toward the development of the research program is to review the current state of knowledge regarding irrigation-induced salinity.

Problems

Saline soils contain sufficient soluble salts to adversely affect the growth of most plants. The lower limit of the saturation extract electrical conductivity of such soils is conveniently set at 4 dS/m (at 25^o C). Sensitive plants are affected at half this salinity and highly tolerant ones at about twice this salinity. Salinity reduces growth rates and yields and, in severe cases, causes total crop failure. Most major irrigation systems throughout the world suffer to some extent from the effects of salinity, but the economic loss as a result of salinity and sodicity has not been clearly established (Umali 1993).

The salt composition of the soil water affects the composition of cations on the exchange complex of the soil colloids. The total salinity level and exchangeable cation composition together influence soil permeability and soil tilth. With a predominance of sodium on the exchange complex and a low concentration of salts in the infiltrating water, the infiltration rate and permeability can be severely and, in some cases, irreversibly reduced. The immediate source of the salts in saline soils can be the parent material, irrigation water, shallow groundwater, or fertilizers and amendments applied to the soil. This salt load will gradually increase in the root zone over time with each irrigation, unless salt is removed through leaching (over-irrigation) and disposal (drainage). Leaching and drainage cause salt loading (pollution) of the water resource into which the effluent is discharged. The volume needing disposal can be reduced through improved irrigation management and reuse of drainage outflow for irrigation, but ultimately some disposal is necessary (Rhoades and Loveday 1990).

The reclamation of saline soils also requires leaching (with water of lower salinity) and drainage. The reclamation of sodic soils may, in addition to leaching, require the application of amendments to increase soil permeability and reduce the exchangeable sodium levels.

Technologies for the prevention, mitigation, and reclamation of saline soils exist and are well understood. The technical problems that have led to irrigation-induced salinity include poor on-farm water use efficiency; poor construction, operation and maintenance of irrigation canals causing excessive seepage losses; and inadequate or lack of drainage infrastructure or, if drainage facilities are present, their poor quality of construction, operation and maintenance. Umali (1993) has pointed out that these technical problems are the product of, among others, government policies with respect to water pricing, poor water management by irrigation agencies, ineffective project planning, inadequate extension services, and scarce financial resources of governments in many countries to undertake corrective measures. Remedial actions should address this web of technical, economic, political, and social factors, but they are unlikely to lead to quick solutions. However, delays in taking action will escalate the economic, social, and environmental damage and the cost of repairing such damage.

Chemical Processes Involved in Salinization

State of Knowledge

The total salt concentration and the proportion of sodium have long been recognized as the key parameters in the classification of a soil as either saline or sodic. The total salt concentration in soil solution is usually expressed as the electrical conductivity (EC) of the soil extract at saturation (in dS/m), and the sodium content as the sodium adsorption ratio (SAR) or the exchangeable sodium percentage (ESP) (see, for example, the review by van Hoorn and van Alphen 1994). The importance of anions in the soil solution during the process of soil degradation due to sodicity has also been recognized (see, for example, van Beek and van Breemen 1973, Rengasamy and Olsson 1993, Condom 1996, and Marlet 1996).

Two pathways of salinization (the general term for the accumulation of salts in the root zone and the associated chemical processes) can be distinguished: the neutral pathway and the alkaline pathway, often referred to as salinization and alkalinization, respectively. Both processes ultimately cause sodication (soil degradation associated with the presence of sodium ions in the soil solution), but at different rates. The Soil Science Society of America (SSSA) (1997) defines alkalinity as the degree of alkalinity in a soil, expressed by a value of more than 7 for the soil pH. The SSSA publications no longer use the term alkali soil, previously defined as a soil that contains sufficient sodium to interfere with the growth of most crop plants. The term is superseded by sodic soil, defined as a non-saline soil containing sufficient exchangeable sodium to adversely affect crop production and soil structure under most conditions of soil and plant type. The SAR value of the saturation extract of sodic soil is at least 13, according to the definition of SSSA (See the glossary, page v.).

The concept of residual sodium carbonate (RSC) is controversial. RSC is defined as the difference between the sum of carbonate and bicarbonate ions and the sum of calcium and magnesium ions, expressed as meq/l. RSC was introduced by the United States Salinity Laboratory Staff (1954) to take into account the precipitation of slightly soluble salts in the classification of irrigation waters. If RSC exceeded 2.5, the water was considered unsuitable for irrigation, and if it was below 1.25, the water was considered probably safe. This classification was tentative, and it appears that waters with RSC values higher than 2.5 could sometimes be used without adverse effects on soil structure. In American literature, RSC is no longer used, and it is superseded by the adjusted SAR (see below). Others, for example, van Hoorn and van Alphen (1994), although agreeing that the classification may not be correct, still consider the RSC value a useful warning signal for an expected increase in SAR of the soil solution, far greater than the normal increase proportional to the square root of the concentration factor. It is generally accepted that the sign and value of RSC alone cannot be used to appraise sodicity hazards. RSC has to be considered in conjunction with the buffer capacity of the soil, i.e., the soil's cation exchange capacity (the sum of the charge sites on the surface of soil particles that can be readily replaced with a salt solution), which is largely determined by the clay and organic matter contents of the soil.

In recent French literature (for example, Marlet 1996), residual alkalinity (RA), a more general term than RSC, has been identified as a particularly important parameter in the process of salinization. It is defined as the difference between the total anions, such as carbonate, bicarbonate, hydroxyl and sulphate ions, and the calcium and possibly magnesium ions in the soil solution. The concentration of these ions in solution depends on the solubility of certain calcium (Ca) and magnesium (Mg) containing minerals, which is, in turn, pH dependent. For most of the soils, alkalinity is mainly due to carbonate and bicarbonate ions. Between pH 6 and pH 10.3, the proportion of carbonates in the soil solution is negligible, which simplifies the concept of alkalinity in most soils to the presence of bicarbonate ions. The residual alkalinity on the basis of calcite and sepiolite (a magnesium containing fibrous clay mineral) considers only the presence of Ca and Mg, and is equal to RSC. Residual alkalinity can also be considered on the basis of calcite only, and is defined as the difference between carbonate and bicarbonate ions and Ca^{++}. If calcite, sepiolite and gypsum are all considered in the analysis of the geo-chemical processes, RA is expressed as the difference between carbonate, bicarbonate and sulphate ions and Ca^{++} and Mg^{++}.

In brief, the main characteristics of salinization are the following: If RA of the soil solution is negative, and many salts are present, the soil is saline. If Na^{+} is present in large amounts, it may eventually predominate on the exchange complex, and sodication would occur. However, when RA is negative, sodication is a slow process.

When RA is positive, precipitation of Ca and Mg causes a fast drop in Ca and Mg concentrations, and hence an increase in alkalinity. This is the process of alkalinization. When the soil solution becomes more concentrated due to evaporation and plant water uptake, sodium is soon the predominant ion in the soil solution and, through cation exchange, on the exchange complexes of the soil matrix. This is the process of sodication, which occurs rapidly when RA is positive. Once Na predominates on the exchange complex, the soil is sodic. This type of soil is unstable and becomes degraded: it loses its structure due to mechanical effects, such as the impact of rain drops and tillage, and the clay minerals disperse as a result of geo-chemical processes. Hence, the value of RA, particularly its sign, positive or negative, helps to distinguish the geo-chemical processes that are likely to occur.

The exchangeable sodium percentage (ESP), which is the degree to which the exchange complex of the soil is saturated with Na, is also an important parameter in the characterization of the degree of sodication. The ESP value is usually calculated from the sodium adsorption ratio (SAR), because determining the amount of Na adsorbed on the soil complex is time-consuming and rarely done in a routine manner. However, there are various procedures in use to determine SAR. A "practical" SAR is calculated from the total concentrations of the Na, Ca and Mg ions in the soil solution. Various ways of adjusting SAR to take account of the precipitation and dissolution of calcium minerals in the soil have been proposed and, currently, the adjustment proposed by Jurinak (1990) seems to be most widely accepted. In this method, the equilibrium Ca concentration in the root zone is calculated from the molar HCO_3/Ca ratio and the ionic strength of irrigation water by using the method given by Suarez (1982). Rengasamy and Olsson (1993) found that the "practical" SAR may underestimate sodicity in soils with alkaline pH. With respect to the relation between ESP and SAR, Manchanda (1993) has reported that for various cropping patterns in north India, none of the equations relating ESP with SAR gave a good estimate of ESP. For example, for wheat-fallow and wheat-rice cropping patterns, ESP buildup in the soil was best predicted by equating ESP with 1.5 SAR, as measured in the irrigation water. Also, Robbins (1984) reported deviations between calculated and measured values of ESP, when ESP was derived from SAR according to the original empirical equation suggested by the United States Salinity Laboratory (1954), especially in soil samples where the Na/K ratio was less than 4.

These contradictions can only be resolved by more field studies in which the chemical changes resulting from continuous irrigation with saline or sodic water are monitored and in which SAR and ESP, and all other relevant chemical parameters are measured.

Models

Attempts have been made to model various aspects of salinization and solute transport in soils, ranging from models to predict the major ion chemistry to irrigation system planning and management for waterlogged sodic soils. An example of a model to predict the major ion chemistry is the two-dimensional transport model, UNSATCHEM-2D, developed by the United States Salinity Laboratory in Riverside (Simunek and Suarez 1994). Panda et al. (1996) report on linear programming to find the optimum allocation of land and water resources based on a groundwater simulation model combined with crop water response functions. Undoubtedly, these studies have helped to identify discrepancies in the current knowledge and understanding of the processes involved, but it is beyond the scope of this paper to classify the various existing models (e.g., deterministic and stochastic) and to review them all (see, for example, the review in Lenselink and Jurriens 1993). Only a few of the most salient findings will be reported here.

The numerical model UNSATCHEM-2D simulates the main processes involved in salinization and sodication. These processes are: transient water flow in the saturated and unsaturated soil; convection-dispersion type transport of carbon dioxide, heat and solute; root growth and root water uptake; cation exchange of Ca, Mg, Na, and K; and kinetic precipitation and dissolution of calcite and dolomite. It therefore aims to integrate the various transport processes that occur during salinization. The model has indicated that the soil chemistry in the unsaturated zone is significantly influenced by changes in soil water content, temperature, and CO_2 concentration of the soil gas. Further complications arise from the temperature dependence of the precipitation and dissolution reactions. These studies are likely to enhance the understanding of the basic processes involved, but at present it is difficult to apply the model for the improvement of irrigation management of saline-sodic soils in developing countries due to the scarcity of data. The model falls into the category of scientific models, as defined by Passioura (1996). Passioura (1996), in a critical analysis of various modeling techniques, divides the models into two groups. The first comprises scientific models that aim to test theories and hypotheses, which describe "how the world works" and aspire to improve our understanding of the underlying processes. The second group contains the engineering models that are concerned with achieving particular practical outcomes by using set procedures that are typically based on a mixture of well-established theory and robust empirical relationships. This latter group of models aims to provide sound management advice to farmers and reliable predictions to policy makers.

Areas of Uncertainty

Weaknesses in the knowledge base can be identified from the work with UNSATCHEM and similar models such as LEACHM (Hutson and Wagenet 1992). They include uncertainty with respect to the yield response to water and salt inputs, and about the transport process during leaching. Both models ignore the possibility of preferential or bypass flow, in which part of the infiltrating water passes through large pores of the soil matrix and contributes only little to the leaching of salts from the root zone. We will return to these points in later sections of this paper.

The rate at which soil degradation occurs under various circumstances is still hard to predict. Van Dam and Aslam (1997) in a comparative study of UNSATCHEM and LEACHM models, applied both models to data from an area of conjunctive use of canal water and pumped groundwater of relatively high sodium content in Pakistan. They concluded that the root zone of a loam soil could be degraded by the application of sodic tube-well water in as little as 3 years.

Physical Processes Involved in Salinization

State of Knowledge

It was first demonstrated in the 1950s that the permeability of a soil column is a function of both the exchangeable sodium content relative to the other cations and the total electrolyte concentration (TEC) of the percolating solution. Basically, the higher the sodium concentration, expressed as SAR, and the lower the TEC of the percolating solution, the greater the reduction in hydraulic conductivity (HC). Quirk and Schofield (1955) proposed the concept of a threshold concentration, which is defined as the concentration required to maintain soil permeability at an acceptable level relative to that measured with a strong salt solution for any particular value of SAR. Soils exhibit a behavior that qualitatively corresponds with the threshold concept, but apparently each soil has its own unique threshold value as other soil properties, such as clay content and mineralogy of the clay fraction, organic matter content, and bulk density, which strongly influence the permeability of the soil.

Swelling and dispersion of clays have been proposed as the major mechanisms contributing to the reduction in HC as TEC is reduced. Clay dispersion, particularly, is very sensitive to changes in ESP. It has been argued that in heavy textured soils, the swelling of clays is the main cause of the reduction in HC, whereas in the lighter textured soils, clay dispersion and movement predominate, resulting in irreversible sealing of soil pores. When Na-affected soils are exposed to rainfall or irrigation water of low TEC, permeability is reduced because the ambient concentration in the soil solution is not sufficient to prevent swelling and clay dispersion. This is likely to occur in irrigated soils, where groundwater and nearly pure canal water are used intermittently to irrigate the lands. Sumner (1993) has suggested that parts of the clay fractions of soils that would not normally be considered to be sodic can be dispersed simply by the velocity of water of low TEC passing through the soil. He suggests that in sandy soils, these colloids can be moved over great distances, but that they get trapped where the pores become narrow, blocking the pores and consequently reducing HC. Hence Sumner's view that physical properties of a particular soil are a continuous function of Na saturation and TEC (expressed as electrical conductivity of the soil solution, EC), and are moderated by clay mineralogy, texture, and organic matter. The threshold value of ESP above which Na saturation becomes harmful was set in 1954 by the United States Salinity Laboratory as 15 percent. Recent studies have made it clear that a single value of ESP cannot be used as a threshold for all conditions, and that sometimes soil structure is adversely affected at much lower ESP values. For example, Condom (1996) found that some of the samples taken from crusted soils in Pakistan's Punjab exhibited quite low ESP values, and lower than ESP's of samples taken from non-crusted soils. Although the ESP values of the crusted soils showed considerable variability, the data show clearly that crusting can occur in soils of the sample area at ESPs below 4 percent. Nevertheless, for practical purposes, the threshold concept is still useful as a first indication of likely soil structural damage.

Thus, apart from swelling and dispersion of clay particles, slaking of soil aggregates is one of the main causes of soil degradation. Slaking is the disaggregation of soil particles into smaller units under the influence of mechanical forces, when the forces associated with osmotic swelling and air entrapment exceed the binding forces in the soil. Dispersion and slaking together lead to the formation of surface crusts[3] and hard layers in the soil profile, which hamper infiltration and water movement through the soil profile. In sodic soils, it also narrows the range of water contents over which water is readily available (the non-limiting water range; Jayawardane and Chan 1993). As soil clays are more readily dispersed under the influence of mechanical energy inputs (Sumner 1993), the infiltration rate (IR) is much more sensitive to increasing levels of Na than the hydraulic conductivity of the soil at greater depth. Oster and Schroer (1979), among others, have demonstrated that irrigation in which water with a SAR of about 20 was alternated with distilled water resulted in very low IR values (0.3 mm / hr). With mechanical disturbance due to falling raindrops, clay movement is possible at lower SAR values than would be required within a saturated soil column.

There is no generally agreed classification of the hazards of soil degradation due to sodicity. One categorization was presented by Rengasamy and Olsson (1993) from experiments on the effects of saline-sodic irrigation waters on soil properties of duplex red-brown earths (Alfisols) in Australia. The main point is that salt accumulation occurs in the red-brown earths when the EC of the irrigation water exceeds 0.2 dS / m, and the leaching fraction (LF), the ratio of net deep percolation below a specified depth and the amount of water applied at the top of the layer, is below 0.5: and sodication occurs when the SAR of the irrigation water exceeds 3, also when the LF is less than 0.5. Condom (1996), as was mentioned above, found that above an ESP of 4 percent there was a risk of soil degradation in an area of southern Punjab, Pakistan, where canal water and tube-well water were applied (conjunctive use) to fairly light textured soils. Both classifications reflect local conditions and are not intended to have general validity beyond the area for which they were defined.

In a review article on the use of poor quality water for irrigation, Oster (1994) presents the following table as the best available guideline for the use of water for irrigation:

When SAR of irrigation water or soil water is:	Potential problem on infiltration is unlikely if EC_e or EC_{iw} is:	Potential problem on hydraulic activity is likely if EC_e or EC_{iw} is:
0.0 – 3.0	> 0.7	< 0.3
3.1 – 6.0	> 1.0	< 0.4
6.1 – 12.0	> 2.0	< 0.5
12.1 – 20.0	> 3.0	< 1.0
20.1 – 40.0	> 5.0	< 3.0

Oster (1994) also warns that the effects of salinity and sodicity on hydraulic conductivity and infiltration rate are not predictable for specific soil / crop / tillage situations.

Gupta (1994), reviewing research findings of the last 25 years obtained at the Central Soil Salinity Research Institute, Karnal, India, used four categories of water quality for mapping the suitability of groundwater for irrigation on a large scale, i.e., for the whole of India. These categories are:

[3]Two types of surface crusts can be distinguished: those due to disaggregation of soil particles and those consisting of layers of fine particles that were deposited on the surface when covered by water ("deposited crust").

good water: EC<2 dS/m; SAR<10 meq/l

saline water: EC>2 dS/m; SAR<10 meq/l

high SAR saline water:
EC>4 dS/m; SAR>10 meq/l

alkali waters: both EC and SAR variable;
RSC>2.5.

These categories can be used as a first indication, since they were derived from many irrigation waters covering vast areas of irrigated lands. Gupta (1994) added that apart from the salinity aspects, groundwater may also have local pollution problems, such as excessive amounts of nitrate, fluoride, boron, magnesium or toxic heavy metals, or be contaminated due to human activities. These aspects were not considered in the assessment of water quality due to paucity of information, and point to the necessity to carefully consider the local conditions.

In recent years, one has become more aware of the fact that soil degradation can result from the use of tube-well water for irrigation. There are indications in some command areas in Pakistan, but not in others, that the quality of pumped groundwater tends to decrease toward the tail end of the systems (Kuper and Kijne 1996). This simple spatial pattern is clearly disturbed when there are obvious areas of groundwater recharge elsewhere in the command area; for example, areas in close proximity to river bends, link canals, or other main canals.

Leaching and drainage are the main mechanisms for the removal of salts from the root zone as the uptake of salts by field crops contributes only little to the removal of salts. It has been calculated that pasture and cereal crops can remove 0.1-0.5 metric ton of Na^+ per hectare per year from moderately saline soils, compared to up to 1 metric ton of Na^+ per hectare per year for halophytes, such as saltbush, from highly saline soils (Rengasamy and Olsson 1993). A moderately saline-sodic soil can contain about 2,000 metric tons of Na^+ per hectare, at a rooting depth of 1 meter.

Van Hoorn and van Alphen (1994) discuss in some detail the concept of leaching efficiency. The leaching fraction, LF, the ratio of the net deep percolation to the amount of irrigation water applied, is assumed to be identical to the ratio of the salt concentration in the irrigation water to that in the soil solution in the root zone at field capacity. This is true only if all irrigation water mixes completely with the soil water in the root zone:

$$LF = Vd/Vi = Ci/Cd \qquad (1)$$

where Vd is the seasonal depth of deep percolation, Vi is the seasonal depth of irrigation water, Ci is the mass salt concentration in irrigation water, and Cd is the concentration in the drainage water.

This equation is based on the simplified salt balance equation. The assumptions underlying it include steady state conditions, salt precipitation equal to salt dissolution, no upward movement of salts from the water table, and no seepage from outside the area.

The leaching efficiency is then defined as the fraction of irrigation water mixing with the soil solution. Field experiments have indicated that the leaching efficiency may range from 0.2 for clay soils to 0.6 for a silty loam soil. Van Hoorn and van Alphen (1994) compare the water and salt movement of a soil profile that is considered as one layer with the water and salt distribution of a four-layered soil profile, taking into account the water that passes through the large pores in the soil without leaching salts efficiently. They conclude that when a high leaching efficiency can be expected as, for example, under drip irrigation or careful surface irrigation on a coarse textured soil, the use of the one-layer concept will overestimate the leaching requirement (the leaching fraction required to maintain a specified electrical conductivity in the soil solution in the root zone). It may then be better to use the four-layer concept. However, for most practical purposes, the leaching requirement can be calculated by using the simple one-layer approach, with the understanding that in reality the salinity of the upper layers of the root zone will be somewhat lower than the average value, and the salinity of the lower part of the root zone somewhat higher.

Models

Uncertainty with respect to the leaching efficiency, especially on a regional scale, was considered by Gates and Grismer (1989) in their study on the preferred irrigation and drainage strategy of the San Joaquin valley in California, which is well known for the presence of toxic levels of selenium in the drainage water. The simulation model they discuss is, however, generally applicable to areas underlain by shallow saline groundwater tables for which the economic net benefit of various irrigation and drainage management practices need to be determined.

The concept of a preferential flow path or bypass flow in solute transport has received considerable attention in recent years. A complete review of the literature on this topic is beyond the scope of this paper. However, some interesting conclusions were drawn by Prendergast (1995) in his study of bypass flow and solute transport under irrigated pasture in Australia, which are relevant to the discussion on leaching efficiency. Prendergast found that bypass decreased and the penetration of tritium-labeled water decreased with increasing salinity, despite a greater leaching fraction under saline conditions. He attributed this effect to higher antecedent water content due to lower crop water use under saline conditions, which, in turn, resulted in less soil cracking and hence less bypass flow. The results of the simulation model and the measurements did not agree as the model assumed that bypass was of low salinity, whereas the experiment indicated that bypass contributed to leaching. In the next paragraph, we will consider various modeling attempts in more detail. Here, we can conclude that the topics of leaching efficiency and the prediction of water and salt movement in saline-sodic soils are complicated and deserves further study.

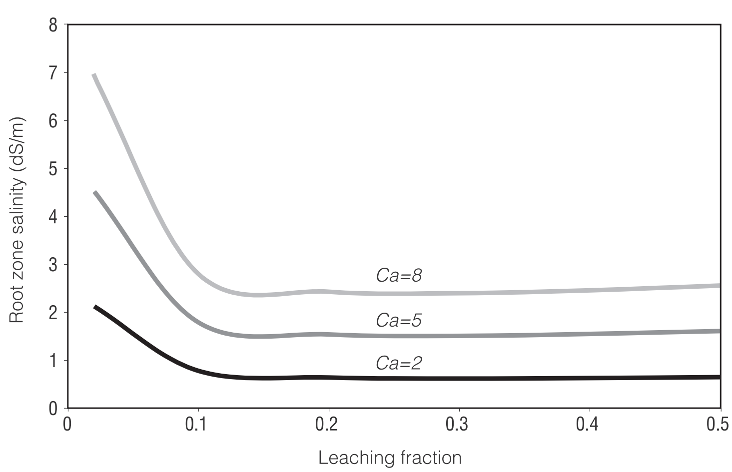
Prendergast et al. (1994a, 1994b) extended the steady state equations of earlier work (Prendergast 1993) by including the groundwater mass balance of an unconfined aquifer, to model conjunctive use of groundwater and surface water for the control of soil salinity. The model was applied to the Shepparton Irrigation Region in the Murray Basin, Australia. (For additional information on the salinity management of the Shepparton region, see Heuperman 1993.) The mass conservation of groundwater was introduced because water salinity in the conjunctive use model is determined by volume and salt content of the pumped groundwater. A semi-empirical leaching equation (Rhoades 1974) was used for the development of the conjunctive use model:

$$C_s = 0.5\, J^*C_i\, (1 + 1/LF) \qquad (2)$$

where C_s and C_i are the average concentrations of salts in the soil solution in the root zone and in the water applied to the crop, respectively, and J is an empirically determined coefficient, which Rhoades (1974) suggested to be about 0.8.

An interesting conclusion from these studies by Prendergast et al. is that root zone salinity, as affected by groundwater salinity, is insensitive to the actual leaching fraction for the common range of leaching fractions (0.1 to 0.4) encountered in field situations. This is shown in figure 1. As the model indicated that high induced leaching rates were unlikely to increase root zone salinity, lowering the water table in waterlogged areas could be achieved by using high pumping rates or more continuous pumping to increase the pumped water depth. The proviso in this approach is that the non-leaching recharge to the groundwater, which is the recharge that does not contribute to root zone leaching in the conjunctive use area (consisting of percolation losses from irrigation channels, flow through soil cracks, and upward movement from deeper layers of the aquifer), is not increased excessively. Whether this is the case depends on the local and regional hydrogeological characteristics of the irrigated area. The relations depicted in figure 1 are specific for the conditions of the study and have no general validity. For example, it should not be assumed that 10 percent leaching is normally sufficient for salt removal. There are many examples in the literature (Bower et al. 1969, Rengasamy and Olsson 1993) that show a much more gradual change is soil salinity with increasing LF.

FIGURE 1.
Insensitivity of root zone salinity to leaching fractions encountered in field situations.



The model calculations for conjunctive use in the Shepparton region indicated that the highest value of the average groundwater salinity at which no yield reduction occurred was 5 dS/m for a crop with a salinity threshold of 1.6 dS/m for leaching fractions between 0.15 and 0.5. A crop threshold salinity of 3.0 dS/m would be required for an average groundwater salinity of 10 dS/m. The contribution from pumped groundwater in the total irrigation supply (including rainfall) ranged from about 20 percent to 40 percent. This fraction was not constant as it depended on a variable leaching fraction, because mass conservation of groundwater demanded that the equivalent depth of pumped groundwater equals all recharge to the groundwater, such as leaching from irrigated fields and seepage from irrigation canals. In the Shepparton region, the rate of groundwater degradation caused by salts in the irrigation water and rainfall under good conjunctive water management was found to be as low as 0.02 dS/m per year for a situation in which the depth from the soil surface to the base of the aquifer is 10 m, and the annual infiltrated depth of surface water supplied for irrigation is 0.8 m.

Good salinity management of the groundwater resource implies that pumped groundwater is distributed over the entire area of influence of a groundwater pump, or at least a large part of it. When salts are exported from the conjunctive use area through disposal in a drainage system, the depth of exported groundwater must be less than the depth of groundwater recharge; otherwise the water table would drop and the steady state assumptions used for the derivation of the conjunctive use model are no longer valid. Pumping groundwater for irrigation in excess of recharge induces faster degradation of the groundwater. A similar conclusion was reached by Kijne (1996) in a water and salt balance study of irrigation areas with conjunctive use of groundwater and surface water in Punjab, Pakistan.

Kuper and Kijne (1996) compared the results of the water and salt balance study in Pakistan with earlier simulations with models of Hanks and coworkers (for example, Hanks 1983), and found considerable differences in computed average root zone salinity and leaching fractions. There was agreement that present management practices of conjunctive use of groundwater and surface water involved pumping rates greater than the recharge rate and that salt accumulation in the root zone was occurring. However, the differences precluded reliable estimation of the rate of soil degradation.

An alternative approach to the development of conjunctive management of groundwater and canal water in Pakistan's Punjab was taken by Afzal et al. (1992), who, using a linear programming model, optimized the use of different quality waters by alternate irrigations rather than by the blending of canal water and pumped tube-well water. The aim was to determine how much land can be cultivated with a variety of crops and how much groundwater should be applied to each of these. Although some of the advantages of intermittent irrigations with good and poor water are obvious (for example, no deterioration of the good quality water, and application of good quality water during sensitive growth stages: see Hamdy 1996), in many practical situations, infrastructural constraints preclude the option of alternative use of the different quality waters.

Areas of Uncertainty

From the above description of the adverse effects of sodium in soils and irrigation water it can be concluded that infiltration rates and the hydraulic conductivity of many irrigated soils are severely reduced. The extent to which soils are affected, however, is difficult to establish when benchmark data of unaffected soils are not available. Moreover, SAR values are often not measured. EC values can be approximated in the field (i.e., by electromagnetic induction measuring techniques) but there is no easily measurable proxy for the SAR value. For the determination of SAR, one remains dependent on laboratory determinations.

At present, the interdependence of the final infiltration rate of irrigation water into a soil and the SAR (or ESP) and EC of the top soil is not well established for a wide range of soils. Quantitatively predicting the effect of using different quality irrigation waters on the infiltration rate and hydraulic conductivity and, in general, on the rate of soil degradation in field situations is not possible. In the absence of more generic findings, it is necessary to evaluate the suitability of irrigation water for the specific conditions at the location where it is to be used (Suarez and Lebron 1993). Variables likely to affect this relation between soil degradation and water quality include the relative water supply (i.e., the degree of over-irrigation or applied leaching fraction), the cropping intensity, and cropping pattern. From a practical point of view, one is interested in a method of predicting the effects of using a particular kind of irrigation water if it involves a few parameters that can easily be measured in the field. If predictions can only be made on the basis of a large number of parameters, for example, including soil organic matter, free iron oxides, etc., its practical value would be small.

The leaching process is an important aspect of many different types of models with various objectives, but modeling the leaching process is no simple matter. Considerable progress has been made but no single model of the leaching process is appropriate for all purposes. As was pointed out before, considerable doubt still exists about the rate of soil and water degradation when fields are irrigated with water of marginal or poor quality. The need for further research is apparent, which should include systematic testing of existing models by someone other than the developer—presently a rather rare occurrence as noted by Addiscott and Wagenet (1985)—rather than the development of more models. The need to test existing models under a variety of conditions applies equally well to existing scientific models, i.e., those aiming to enhance understanding of the underlying geophysical processes, as well as to the "engineering types" that aim to find management solutions, such as the agro-hydrological model of van den Broek et al. (1994) and the models proposed by Prendergast and coworkers. The underlying assumptions of these latter models, especially with respect to the required mass balance of the groundwater, may not be satisfied under all practical situations (for example, with extensive pumping of groundwater), but it is expected that the model outcomes will point us in the right direction for finding improved salinity management practices. Research needs will be addressed in more detail in the final section of the paper.

Impact of Irrigation-Induced Salinity on Plant Growth

State of Knowledge

The effects of salts on plants have been reviewed many times in recent years. The *Handbook of Plant and Crop Stress* edited by Pessarakli (1993), and the paper on *Salinity Management in Irrigated Agriculture* by Tyagi (1996) are examples. It is not possible to do justice to the topic within the scope of this review. In general, three categories of salinity effects have been considered: general growth suppression, especially during germination, emergence and early seedling growth; growth suppression due to nutritional imbalance of essential ions; and growth suppression caused by ions of toxic nature. Often, these different effects are indistinguishable and, in fact, the primary cause of salinity damage is not known. Moreover, it is quite difficult to clearly distinguish between the effects of sodium as a toxic ion (mainly for trees), and its effect on the soil physical properties and hence indirectly on plant growth.

High concentrations of particular ions, for example, Na^+ and Cl^-, interfere with the uptake of other ions, leading to critical nutrient deficiencies, or have other toxic effects on plants. One example of many such studies on the specific response of a number of crops to high exchangeable sodium in the soil under field and greenhouse conditions is the study by Gupta and Sharma (1990). These studies are important for the establishment of genotypic differences for sodicity tolerance of, for instance, wheat and rice, but they need to be continued for several years under field conditions to monitor the long-term changes in soil structure and crop response arising from irrigation with saline or sodic water.

Tolerance to salinity depends on, among others, the type of crop, its variety and growth stage, the availability of water in the soil, soil structure, and the evaporative demand from the atmosphere. Maas and Hoffman (1977), and various updates of their work since then (for example, Maas 1990), have given the threshold values and yield loss per unit increase in salinity in excess of the threshold value for many field crops. Yield response functions have been reported for yield as a function of amount of water applied, but data on the combined effect of various depths of irrigation water and the quality of the water on crop yield are rare. Recently, Panda et al. (1996) have developed quadratic and square-root functions for eight field crops commonly grown in Punjab, India, based on limited experimental observations of crop yield as a function of EC of the irrigation water. The coefficients of the response functions were computed using the least-squares technique. It would be worthwhile to compare any other observations of yield response to water quantity and quality, for example, those developed by Dinar et al. (1993) in lysimeter experiments, with the calculated yields as obtained from these regression equations.

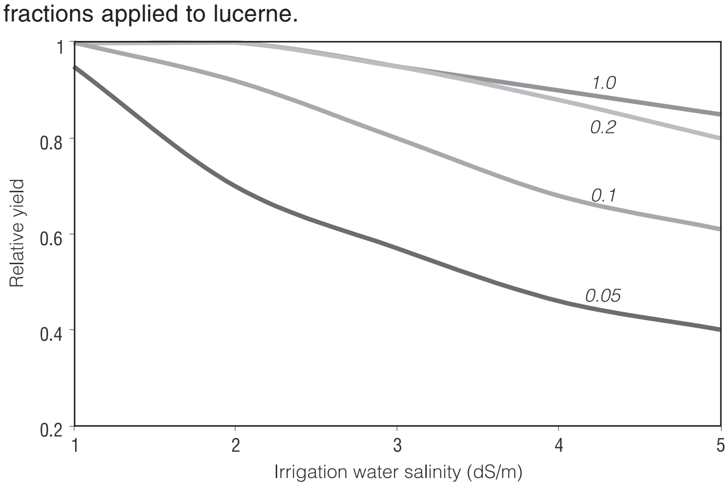
Apart from the direct effects of salts on plant growth, crop yields are also affected by the interaction between salinity and fertility. Most saline and sodic soils are low in fertility and crops growing on these soils suffer from suboptimal supplies of nitrogen (N) and need to be supplemented by chemical fertilizer. However, the conditions of the salt-affected soils do not favor efficient nitrogen use from sources such as urea because of nitrogen losses by ammonia volatilization. It has been suggested that for nitrogen management of rice on saline and sodic soils, substituting part of the mineral nitrogen by organic forms can improve nitrogen use efficiency (Ghai et al. 1988). Shalhevet (1994), in reviewing the relationship between the level of nitrogen application and salinity, found very few studies that report a response to higher levels of nitrogen fertilization at high salinity than are considered optimal levels under non-saline conditions. The most common type of response reported in the literature is that the addition of nitrogen results in the same relative yield increase at all levels of salinity, or that the response in relative yield is greater at low levels of salinity than at high levels.

Sodic soils in India have been reported by Gupta and Abrol (1990) to contain high amounts of available phosphorous (P), which is to be expected considering that the concentration of phosphorous in the soil solution is high at high pH levels, such as are found in sodic soils. Although the application of gypsum is expected to lower the level of extractable phosphorous in sodic soils, long-term field experiments at the Central Soil Salinity Research Institute, Karnal, India, have shown that after gypsum was applied to a typical sodic soil, there was no benefit from phosphorous and potassium (K) fertilizer application during the first six years of reclamation (Chhabra 1985). It has been known for years that crops grown on sodic soils with pH values around or above 8 are likely to respond to zinc (Zn) application, although the total zinc level in the soil may be high already. A complete review of plant nutrition on salt-affected soils is beyond the scope of this paper. However, the importance of plant nutrition in yield response on saline and sodic soils should be recognized.

Models

Yield response functions of water and salt were reviewed by Hoffman et al. (1990). The most significant advance since the development of the threshold-slope model of Maas and Hoffman (1977) is probably the numerical model for water and solute movement in and below the root zone by van Genuchten (1987). This model also includes a root extraction term. One of the persistent problems is how to account for the nonuniform distribution of salts in the root zone and across fields, a question that was addressed by Shalhevet (1994). He concluded that although current understanding of effective root zone salinity is incomplete, estimates of a mean salinity over the root zone would be satisfactory for all practical purposes. Shalhevet (1994) also discussed whether salt tolerance parameters, i.e., the threshold and slope values of Maas and Hoffman (1977), can be used under different conditions. Shalhevet pointed out that there are several factors that may affect the salinity response curve. One of these is a restricted water supply as the curves were based on ample water supply, i.e., heavy leaching. Prendergast (1993) calculated, from a simulation model, the effect of the salinity of irrigation water on the yields of perennial and annual pasture, lucerne and tomato, for the Shepparton Irrigation Region in the Murray Basin, Australia. The results of the simulation for three values of the leaching fraction (0.05, 0.1, and 0.2) applied to lucerne are shown in figure 2. Unfortunately, no independent field measure of yield response of these crops with various leaching fractions is available.

FIGURE 2.
Effect of salinity on yield: Results of simulation for 3 different leaching fractions applied to lucerne.



The yield response of rice to saline water has been reported for the Nile Delta in Egypt by El Guindy and Risseeuw (1987). Rice, when grown in paddy fields (lowland rice), is widely considered to be tolerant to salinity and alkalinity, although Maas and Hoffman (1977) put it (with a threshold value of 3 dS/m and a12% decrease in yield per dS/m increase in salinity) in the group of moderately sensitive field crops. Nevertheless, rice has been grown on saline and sodic soils as a reclamation crop. The submerged conditions required for optimal growth of the crop increase the partial pressure of carbon dioxide in the soil solution, which causes a decrease in pH and exchangeable sodium. The production and accumulation of carbon dioxide can be further enhanced by the application of organic matter. Rice is known to be sensitive to salts during the early seedling and initial reproductive stages, and its survival under saline conditions is most likely due to the over-irrigation that takes place under submerged conditions, which continues to push the salts out of the root zone.

Uncertainty about the simulation of water uptake by plant roots under irrigated field conditions is also a recurrent problem in modeling studies, and it has a direct bearing on the calculation of leaching fractions in soil layers. Recently, Monteith (1996), in a discussion of crop models, deplored the absence of data on the performance of crops over a wide range of environments, data that could be used for rigorous testing of the underlying hypotheses of existing crop models, especially with respect to the uptake of water and nutrients by roots in relation to their growth, anatomy, and activity.

It is not surprising then that Bresler and Hoffman (1986) concluded that irrigation management for soil salinity control cannot quantitatively be described by the simple steady state equation relating volumes and concentrations of irrigation and recharge water (equation 1 above), not even for the extreme case of near constant irrigation. A transient model they developed is more in agreement with measured field data. Verification of the various models (for example, by Cardon, Letey, and Minhas [1990], as quoted by Hoffman et al. [1990]) still indicates considerable variation between measured and predicted yields as the yields are influenced by the depth of irrigation water applied and its quality. Hoffman et al. (1990) conclude that

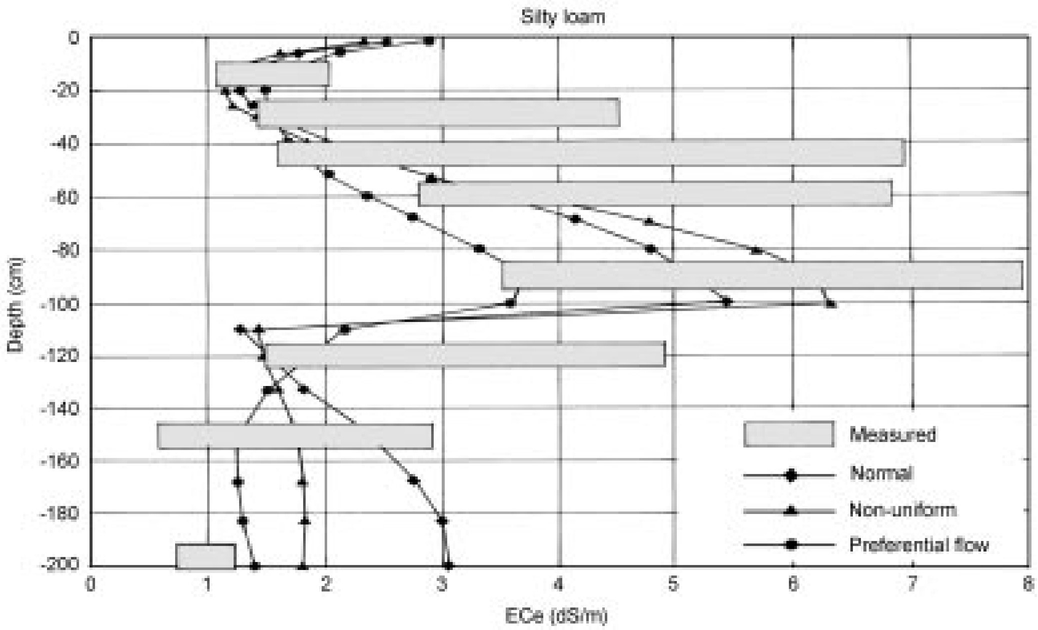
> a serious limitation [in determining optimum leaching requirements] is the lack of knowledge on how plants respond to salinity stress that varies with time and space. Our knowledge on solute transport, particularly in the presence of shallow, saline groundwater, on a field basis, is insufficient. Most of our present knowledge on the movement of water and salts is in the absence of a shallow water table.

The use of salt-tolerant trees, especially Eucalyptus varieties, in reclaiming saline areas by lowering the groundwater level, is important. In addition, other benefits of a tree crop, such as erosion control and provision of shade, shelter and timber, have been identified (van der Moezel et al. 1991). Bari and Schofield (1992) have reported the control of human-induced salinity through reforestation with Eucalyptus species in West Australia, where groundwater levels decreased in 10 years by 1.5 m under the forest, and increased by 1.8 m under nearby pasture land. Interestingly, groundwater salinity levels under the forest were reported to have decreased by 11 percent. It is desirable to have more data on the changes in the water and salt balance during the reclamation process.

Prendergast's (1993) model of crop yield response to irrigation water salinity, referred to above, quantifies the economic implications of management practices that increase the salinity of the irrigation water over time (for example, the disposal of saline drainage water into the irrigation supply). This study is important as it shows what can be achieved with a relatively simple deterministic model. The model can reduce the number of costly, local yield response experiments that would otherwise be required for different crops and soil types. It can also be used to determine the suitability of particular crops for an irrigation region if the salinity of the irrigation water is high. The specific set of problems associated with the use of high sodium waters is not addressed in this model.

Prendergast and coworkers, using the Maas and Hoffman (1977) approach, calculated crop water use and relative yield estimates for conjunctive use of groundwater and canal water, when the salt content of the root zone is more than the crop threshold value. More recently, the agro-hydrological model SWAP93 (van den Broek et al. 1994) was used by Smets et al. (Forthcoming) to assess the effects of various irrigation practices on salinization and crop transpiration for conditions similar to those in earlier studies. This model is far more sophisticated than the models that were used earlier, and hence requires more informa-

FIGURE 3.
A successful simulation of the salinity profile.



Note: ECe = electrical conductivity of the soil extract.

tion on soil and crop characteristics. Nevertheless, it was found that the model could be used successfully for Pakistan conditions, provided accurate data are available on crop factors, soil evaporation, rooting depth, and soil hydraulic characteristics. An example of the successful simulation of the salinity profile by Smets et al. (Forthcoming) is given in figure 3. One of the conclusions of the study is that because of shortage of water farmers tend to under-irrigate their crops. The model indicates that after a few years, salinization has reached an equilibrium and no further salt accumulation occurs, as the amount of salt added by irrigation equals the amount leached from the root zone. This equilibrium is reached earlier on sandy soils (after two years) than on loamy soils, and the resulting salinity is higher on the fine-textured soils. The relative transpiration by the crop is more affected by the amount of irrigation water applied than by its salt content. Again, sodicity of the irrigation water is not considered in the model.

Areas of Uncertainty

The yield response to simultaneously imposed under-irrigation and salt stress is still not well known. This, as was pointed out before, has implications for the modeling of salt and water balances of irrigated crops because of the importance of the water uptake function in these models. Yield response functions of water and salt should also be known for establishing the economic and political implications of current agronomic and irrigation practices. Further testing of integrated models, such as the agrohydrological SWAP93 model, under a wide range of conditions may help to fill this gap in our knowledge.

Remedial Management Actions

Categories of Potential Management Action

Several types of management interventions, collated from the literature, are presented in table 1. These possible actions aim to prevent, mitigate, or reverse soil and water degradation at various levels within irrigated agriculture. Some are applicable at field or farm level, others at system, regional, or subregional level. In table 1, the management interventions have been categorized as engineering, agronomic, policy, and management options (Kijne and Kuper 1997). The distinctions between the different categories, however, are 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. For possible remedial actions regarding salinity management for individual countries, see Ghassemi et al. 1995.

TABLE 1.
Various remedial options and interventions.

Category	Options
Engineering	Construct additional storage facilities for water (dams and reservoirs) and salts (evaporation ponds).
	Improve maintenance of irrigation infrastructure.
	Conserve water in catchment, and rain in irrigated areas.
	Construct drainage facilities.
	Improve maintenance of existing (including, natural) drains.
	Reuse waste and drain water, and find alternative ways to dispose drainage effluent, and industrial and municipal waste water.
	Prevent or reduce canal seepage, i.e., through lining.
Agronomic	Grow different crops or introduce different crop rotations, i.e., less-water demanding crops, more drought- and salt-tolerant ones.
	Irrigate according to reliable crop water requirement estimates (yield response functions) and leaching requirement calculations.
	Reduce irrigated area (use more water per unit land).
	On-farm watercourse improvement and precision land leveling
	Apply soil amendments, such as gypsum.
Policy	Introduce water and power pricing to make water more expensive.
	Introduce transferable water entitlements.
	Set limits for allowable groundwater recharge (amount and quality) and introduce penalties for exceeding these limits.
	Provide incentives for land reclamation, i.e., subsidizing gypsum.
Management	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.

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 or 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 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 (for example, in evaporation ponds, which will be discussed in more detail below); disposal of 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 (for example, the hydraulic performance of irrigation canals is improved through desilting[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 in economic prioritizing. Often, there is no immediate prospect of enhancing the supply of good quality water to the system or of reducing the amount of poor quality water that remains in the system.

The agronomic options aim to prevent or mitigate degradation of soil and water resources. Any one of these applied in areas where degradation is already present presupposes that scarcity of water and salinity will not be totally eliminated and that one has to learn how to live with them. One of the key agronomic options is crop diversification. Different crops have different evapotranspiration patterns and lead to different rates of recharge of the groundwater. In areas with rising water tables, 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 farmers 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). However, the economic factors should be considered, whether it would be economically more advantageous to obtain a somewhat lower yield of a good cash crop as a result of increased salinity than a full yield of a forage crop tolerant to salinity.

Improving soil fertility by the addition of organic matter through green manuring can help to restore a more favorable root zone environment. Other agronomic interventions that can be exercised at farm level include precision land leveling to remove high spots in fields, such that a thinner layer of water would cover the entire field. Experience in the Murray-Darling Basin in Australia has shown that laser leveling of the land can greatly improve net salt accumulation in the root zone.

Perhaps the last agronomic option a government would be prepared to support is to deliberately reduce 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

[4]Computer modeling prior to desilting 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, for example, Murray-Rust and Vander Velde 1993)

fallow. Rotation of canal supplies and restricting the use of pumped groundwater are the instruments to achieve it. Leaving fields fallow has the distinct disadvantage that they tend to accumulate salt through capillary rise from a shallow water table or through lateral flow from adjacent fields, which continue to be irrigated. Reducing crop intensity can also be done by closing off parts of command areas, with the result that these areas would depend completely on tube-well water and would most likely continue to degrade. The socioeconomic and political implications are huge. The government probably has 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 to change current agronomic and irrigation practices include water and power pricing, issuing transferable water entitlements, subsidizing gypsum for reclamation of sodic soils,[5] and better coordination of the activities of various ministries and departments dealing with water and power supplies.[6] Examples of successful introduction of penalties for exceeding agreed limits on quantity and quality of recharge to the groundwater, for example, by stipulating the area cropped under rice, can be found in Australia and parts of the United States. Increasing charges for water would tend to reduce application per unit area and hence exacerbate the problem of salinity.

Management options that come to mind include improving the management (operation and maintenance) of irrigation canals, for example, through the introduction of management information systems (decision support systems: see, for example, Tyagi et al. 1993). These information systems would require that data on water supplies and demands throughout the system, and the breakdown of infrastructure (i.e., breaches) are available and are quickly communicated to the decision center. Traditionally much of this information system was in place in a country such as Pakistan but has since been allowed to break down and is not in use any longer. Current communication techniques and computer modeling allow vast improvements to be made over the present decision support systems. Another important management option is to involve the irrigation community to a much greater extent in the management of the natural resources, water and soil, including their quality (salinity) aspects. Many governments, often spurred on by the World Bank, are moving toward greater involvement of farmers in the management of (parts of) irrigation systems.

[5]The application of gypsum is reported to be more widely practised in India than in Pakistan, partly because of subsidies and better distribution in India. One drawback of widespread 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 coordinated at field level but only at the level of the office of the Chief Engineer, probably overseeing around 1 million hectares. Also, coordination 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 tube wells to water the crops. Another example is the well-known lack of coordination between the departments of Agriculture and Irrigation.

Scale of Concern

Of the various management actions discussed above, the agronomic options are mainly applicable at field or farm level. That is the level where choices concerning the cropping pattern, the proportion of land left uncultivated, land leveling, and water applications are made. Some of the policy interventions attempt to make it possible for the farmers to make these choices in a rational manner.

Most of the engineering and management actions take place at system level, or at canal command area level, as in the large systems of, for example, the Indian subcontinent. Implementation of virtually all of these actions can take place only with the explicit approval of and funding by the relevant government agencies. Management improvements, such as participatory involvement of the farmers in system management and transfer of part of system management to the farmers, are rarely initiated at the level of the irrigation agency. Encouragement and incentives from policy makers are essential prerequisites.

All in all, this discussion of possible actions aimed at the prevention, mitigation, and reversal of soil and water degradation again illustrates the complexity of the issues and interrelations between agronomic, engineering, management, and policy aspects of the salinization process. The key to the solution, however, is the political will to give priority to and facilitate the various actions that intend to sustain the natural resources while maintaining or even increasing agricultural productivity.

Regional Saline Effluent Management

Leaching and drainage remove salts from the soil solution. What happens with the salt once it enters the drainage system is often ignored. Drainage water is regularly disposed of into rivers in the absence of other economically more attractive disposal options. This practice increases the salt load of the rivers and makes the river water less suitable for irrigation or other uses downstream. It is a challenge to keep the negative impact from the removal and disposal of excess salt from the root zone to a minimum. The volume of saline water needing disposal can be reduced by the right combination of agronomic and irrigation management practices, such as crop rotation, crop diversification, agroforestry, and pressurized irrigation systems. If proper drainage and recycling systems are designed and operated, drainage water can be used cyclically on crops of increasing salt tolerance until it becomes unsuitable for irrigation and has to be disposed of finally.

The process of salt removal requires water to transport salt. In arid and semiarid regions, provision of water to transport salt over long distances, for example, to the sea, is not always possible. Therefore, it is important in water-scarce environments to implement saline water disposal measures at subregional levels. Potential measures include outfalls or pipelines to seas, evaporation basins, aquifer storage, and desalinization.

The construction and operation of a separate drainage system to transport salt to the sea is an expensive proposition (the construction cost of the Left Bank Outfall Drain in Sindh, Pakistan is approximately one billion US dollars, to provide drainage for approximately 0.5 million hectares). Saline water can sometimes, under special geo-hydrological conditions, be disposed of into shallow or deep aquifers. Disposal of saline effluent in deep aquifers must be critically evaluated because hydraulic pressure and solute pulses move rapidly in confined aquifers, in ways that are hard to predict. Finally, desalination of drainage water is (still) very expensive, especially for high-salinity water.

As the other options are both expensive and applicable only under special conditions, evaporation basins have been installed in recent years in many countries. There are over 200 evaporation basins, ranging from 2 to 2,000 hectares in size, in the Murray-Darling Basin alone. They include constructed evaporation basins as well as natural depressions and salt lakes. Some of them are intended to hold saline water temporarily until released during high river flows, while others are expected to have operating lives of 50 to 150 years. Other countries, for example Pakistan, now include the construction and operation of evaporation basins in drainage projects (Mian and van Reemen 1991, Trewhella and Badruddin 1991).

The disposal of saline water into subregional evaporation basins was found to be cheaper than other options considered for the Murray-Darling Basin (Evans 1989), as illustrated in figure 4. Inferences from this study may be applicable to large water basins such as the Indus Basin. Many evaporation basins cost very little, as for example, when they are simply salinas or depressions in the landscape into which saline water flows by gravity.

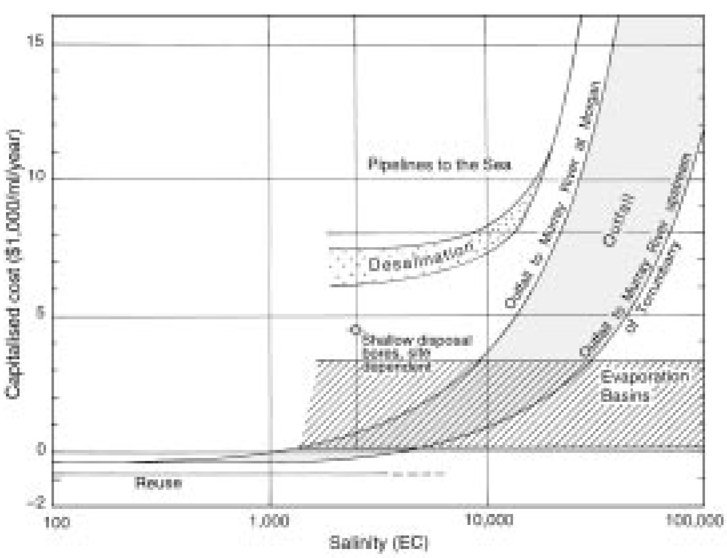
To sustain the use of an evaporation basin, inflow must equal outflow. The "outflow" processes include evaporation and leakage. Evaporation from a free water surface is governed by net solar radiation, air temperature, wind speed, humidity, solution (water) temperature, salinity, and color. Salinity is a key factor affecting evaporation but it is not a limiting one for salinity up to 60 dS/m (McCullough-Sanden 1987). The relationship between evaporation rate and salinity is curvilinear, but nearly linear at lower concentrations.

The two types of leakage—lateral aquifer recharge and deeper, predominantly vertical, aquifer recharge—cannot easily be distinguished. They can also be considered in terms of local and regional impacts. A groundwater "mound" is usually built up beneath a basin., which over time may cause leakage to a deeper aquifer, which then results in the transmission of a "hydraulic pulse" and a "solute pulse" through the aquifer to a lower hydraulic potential discharge location. The rate of movement of this dense fluid is hard to predict.

Mass balance-based estimates of leakage for several different basins yielded surprisingly similar data despite differences in soil texture of the basin bottom materials. Generally, leakage rates decreased dramatically following inundation, and varied seasonally about a steady-state leakage rate of a few millimeters per day after approximately two years of continuous inundation. The estimated leakage rates of evaporation basins are much less than those obtained for canals and recharge basins. Whether the seasonal variation in leakage rates is significant is not clear at present, but it appears that leakage rates are lower in winter than in summer (Grismer et al. 1993). Laboratory measurements of hydraulic conductivity as a function of pore water salinity, ranging from 0 to 120 dS/m, and SAR values ranging from 210 to 660, indicate that conductivity tends to decrease as salinity increases. The process is partially reversible when salinity of the percolating liquid is reduced.

More significant, however, is the degree of biological activity. In pores where biological activity was not artificially suppressed, hydraulic conductivity decreased irreversibly with time and with the volume of water that passed through the sample regardless of its salinity. Microbial activity within the pore structure appears to use the carbon-rich, saline water to produce polysaccharide compounds that clog the soil pores, which in the field eventually re-

FIGURE 4.
Relative costs of saline water disposal options in the Murray-Darling basin.



Source: Evans 1989.

sults in “bottom sealing.” McCullough-Sanden (1987) showed that leakage rates and basin water depth or groundwater depth were not correlated. Thus, variability in soil texture and the degree of microbial bottom sealing appear to be of greater significance in determining leakage rates. The addition of cyanobacteria or blue-green algae to basin water facilitates sealing of the bottom soils, reducing leakage to a minimum. There is some evidence that evaporation may be enhanced in basins having a green hue due to greater energy capture.

Design and Operation of Evaporation Basins

One of the common criticisms of evaporation basins is that they occupy large areas. However, in most cases, the land is already severely saline and virtually unproductive. The Wakool / Tullakool Subsurface Drainage Scheme in New South Wales, Australia protects an area of 30,000 hectares, and the evaporation basin covers 2,000 hectares, an evaporation basin to total area ratio of 1:15.

The environmental impact of evaporation basins is probably related to the circumference of the basin, in which case large evaporation basins would be better. However, the magnitude of the impact, for example on the groundwater resource, may be greater for bigger, deeper basins. Hence, the relative merits of bigger versus smaller basins need to be decided on the basis of the local conditions. A significant factor in local community acceptance of evaporation basins is the perceived benefit to the community. If the source of saline water needing disposal is far away from the disposal site, then little benefit is perceived by the local community and community acceptance may be poor (Evans 1989).

Areas of Uncertainty

The effects of decommissioning basins have not been considered until relatively recently. There is no doubt that some existing basins present a significant problem for the future. It is relatively simple to undertake measures (for example, interception bores) to stop any adverse effects. However, the economics of the measures would need to be considered for each individual basin. The site-specific environmental impacts need to be studied in relation to the size and depth of the basin, the geo-hydrological conditions, and the anticipated salt and water balances. A financial analysis is needed for various sites and design characteristics, which should consider other potential benefits such as aquaculture and brine or salt harvesting. Simulation models may enhance the effectiveness of various measures to contain lateral and vertical leakage from evaporation basins. These studies together will provide the information for policy makers regarding the relevance of evaporation basins, on a regional or subregional basis, in the Indus Basin and in other semiarid regions, where the disposal of excess salts presents an increasingly large problem.

Farmers' Response to Salinity

It has been said that an informed farmer can be successful on poor land and an uninformed farmer will not be successful on good land. As to drainage and salinity, it can be restated that the best farmer cannot be successful on lands of inadequate drainage and the worst farmer will have a disaster on good land. (Weeks and Levy 1985)

There are few systematic studies of how farmers deal with salinity and sodicity in irrigated agriculture, in spite of the long experience of many irrigation farmers in semiarid countries with these adverse effects of irrigation. A first attempt by IIMI in Pakistan to document farmers' practices related to the management of salinity showed that farmers often supplemented canal water with tube-well water and increased irrigation frequency and amount to mitigate the effects of salinity on crops (Kuper and van Waiijen 1993). By mixing canal water and tube-well water, farmers often succeeded in keeping the salinity of the irrigation water below an EC of 1.15 dS/m. Increasing the frequency of irrigation is usually not the best management practice: when irrigation water is applied more often, the peak salt concentration in the soil profile shifts upwards, and because salinity reduces evapotranspiration, the soil dries slower than under non-saline conditions (Shalhevet 1994). Other researchers, for instance Bras and Seo (1987), have also shown that controlling root zone salinity while irrigating with saline water is a balancing act: leaching the root zone before the irrigation season starts or irrigating intermittently with non-saline water is to be preferred.

Kielen (1996) found that a large group of farmers in Pakistan's Punjab is unable to reduce or prevent salinity and sodicity because of lack of funds (especially true for tenants) or because they are faced with shallow groundwater tables and totally inadequate canal supplies, circumstances which are outside their control. Farmers with better financial means are generally—not surprisingly—more inclined to take additional measures, such as the application of gypsum or laser-leveling of their fields. Many farmers, however, have no clear idea what they could do about salinity, especially when they have only recently been confronted with the problem as a result of increased cropping intensity and relatively greater use of poor quality tube-well water. Salinity is often judged by farmers on the basis of the white efflorescence due to precipitation of salts or of dark deposits on the soil surface resulting from the dispersion of organic matter, and the presence of surface crusts and hard layers as evidenced by reduced germination rates. Often farmers are well aware of the hazards involved in the use of tube-well water as they notice the soil becoming "bitter" or the surface crusted, both of which are effects of sodicity. There seems to be ample room for better extension services to inform farmers on what they could or should not do, especially in terms of crop choices and cropping intensities when salinity and sodicity are incipient problems.

Discussion

The state of knowledge regarding the incidence and causes of irrigation-induced soil and water degradation is impressive. Considerable advances were made during the last 10 to 15 years in understanding the physical processes of water and solute transfer in saturated and unsaturated soils, and in the chemical processes of soil degradation under the influence of excessive relative amounts of sodium in the soil solution. The factors that govern precipitation and dissolution of salts, or those influencing infiltration rates and permeability of the soil profile, are now much better understood. Also, our understanding of how the adverse conditions of insufficient irrigation and poor quality irrigation water change crop yields, has grown over the years. Moreover, it is now widely recognized that the prevention, mitigation, and reversal of irrigation-induced salinity are not just a matter of applying the right combination of technologies. It requires an array of measures many of which need to originate at the level of policy makers. But, in spite of these advances, in many if not most developing countries, the area adversely affected by salinity still increases faster than the rate at which affected land is being reclaimed. The mismatch between knowledge and its application is discouraging.

The reasons for this mismatch are many. The absence of an effective agricultural extension service with information on water and salt management is a key one at farmers' level. At system managers' level, it is often the lack of information about what happens elsewhere in the system, and the decision support the manager requires to make the right decision concerning water allocation and disposal. It could also be that the infrastructural constraints, for example, resulting from deferred maintenance, are such that the manager is incapable of taking "the right decision." But, perhaps most important at policy level, information may be lacking on how to prioritize scarce funds such that irrigated agriculture can be sustained and agricultural production enhanced. And, if the information is available, conflicting sector interests may preclude the allocation of sufficient funds and other resources to reverse the trend of soil and water degradation.

The economic impact of salinity has not been calculated with any degree of precision. Quantitative indications have mostly been limited to the amount of land affected or abandoned, often without considering the amount of land that had to some extent been reclaimed and taken back into production. Joshi and Jha (1991), as cited in Umali 1993, through a study of farm-level effects of irrigation-induced salinity in one irrigated area of India, found that the yields of rice and wheat on the degraded land were roughly half those on the unaffected land. Correspondingly, net incomes of the farmers in the salt-affected soils were only 10 to 20 percent of those on unaffected land. Economic analysis indicated that salinity accounts for as much as 72 percent of the difference in gross income between normal and salt-affected plots. An important conclusion was that farmers tend to revert to low-input traditional varieties and practices as soil conditions deteriorate.

Ghassemi et al. (1995) quote some estimates of damage to the economy of a few countries with irrigation-induced salinity. For Pakistan, they give the cost of damage as US$300 million per year for Punjab and North-West Frontier Provinces alone, based on estimates of Pakistan's Water and Power Development Authority. In Australia, it has been estimated that annual agricultural losses from salinization in the Murray-Darling Basin amount to more than US$200 million, and for the Colorado River Basin in California, the estimate is as high as US$750 million per year. Very limited research has been done to empirically quantify the economic impact of irrigation-induced salinity in developing countries. The development of the world's land and water resources for irrigation has taken huge investments in the past and continues to require large sums for annual maintenance and rehabilitation. Undoubtedly, reclamation of salt-affected land through the installation of drainage, and the prevention or mitigation of salinity damage through improved management at farm and system levels are also expensive. The costs of salinity and possible reclamation and preventive measures need to be compared with the expected production benefits resulting from the reclamation of affected lands and the prevention of land degradation, to ascertain what level of worldwide investments in land reclamation and prevention of salinity is economically justified. The challenge for policy makers and donors then is to weigh the costs of addressing short-term needs, which indeed are often very pressing in developing countries, against the long-term benefits that are likely to accrue from investments in reversing the present trend in land degradation due to irrigation-induced salinity.

The prevention and reversal of soil and water degradation resulting from irrigated agriculture depend on various actors working jointly. Researchers can play a role in convincing these actors that it is in their self-interest to collaborate. In the concluding section of this paper, the need for further research studies will be discussed, but here it should be noted that research and development, that is the application of available knowledge, are of equal importance in identifying practical solutions to the widespread adverse effects of irrigated agriculture. The urgency of the solution is apparent for anyone who has looked at current data of population growth and food production. One just cannot justify more irrigated land going waste because of salinity and sodicity when preventive measures can be taken. However, where the adverse effects of a harmful combination of agronomic and irrigation management practices may become apparent in 3 to 5 years, the time scale for the impact of most remedial actions is longer. Particularly, those actions that require the full policy support of governments (most of the engineering and management actions discussed above) have a fairly long gestation period: so much the more reason to start with what can be implemented now, as soon as possible.

Conclusions

Areas of uncertainty were identified in earlier sections. The two main concerns are the present inability to quantitatively predict the effects of using different quality irrigation waters on: (1) crop yields, and (2) the infiltration rate and hydraulic conductivity of the irrigated soils. In spite of a large body of site-specific studies, uncertainty about the effects and the rate of resource degradation persists. Research studies that plan to reduce this uncertainty are needed to reliably predict the changes that are likely to occur when lands are irrigated for a long time with saline or sodic waters. The research needs can be briefly summarized as follows:

1. There is a need to monitor the chemical and physical changes that occur at various depths in the root zone during irrigation under field conditions, i.e., conditions in which the crop is exposed to different water and salt stresses over time. This means monitoring changes over time in key chemical parameters, such as ESP and EC of the saturation extract, and physical characteristics, such as infiltration rate and the presence of soil crust.

2. Crop yield response needs to be determined for conditions of deficient irrigation supply with water of marginal or poor quality, i.e., when the crop is subjected to simultaneous water and salt stresses.

3. Leaching requirements, efficiency, and bypass flow need to be determined in the field under various crop, soil, and water quality conditions.

The outcome of the first study is needed for the determination of the hazard of soil degradation resulting from irrigation with poor quality water. Irrigation waters should be categorized using easily measurable parameters, in order to reach agreement on the classification of salinity and sodicity hazards of various types of irrigation water (including reused drainage water), or to determine the additional (site-specific) parameters that govern the use of various types of water for irrigation. If monitoring is continued for a sufficiently long time, it will enhance our understanding of soil degradation and hence of the sustainability of irrigated agriculture as presently practiced. The issue of scale and trends over time in water quality monitoring requires good statistical analyses, many of which are now available as computer programs (see, for example, Loftis et al. 1991). Agricultural land that is now irrigated with mainly sodic waters, or alternately with sodic water and good quality water, or with sodic water blended with various amounts of good quality canal water, should be included in the selection of research sites and conditions for these studies. With the magnitude of such monitoring programs, the need for representative sites and simple, practical methods for measuring salinity and sodicity in soil and water is obvious (Hoffman et al. 1990).

The second study called for above is needed to establish yield response functions of water and salt. These are needed in the development of quantitative models describing the quantity and quality of recharge to the groundwater from irrigation, which is a necessary step in the protection of the quantity and quality of our water resources. Yield response functions provide the necessary inputs in engineering-type simulation models that help to determine the economic suitability of crops in view of the quality and quantity of the irrigation water available in a region. They are also needed in benefit-cost analyses of reclamation when calculating the potential benefits of reclaiming salt-affected lands.

The third study deals specifically with the leaching of salts from the root zone and with quantifying the amount of recharge to groundwater. Information on salt and water balances under field conditions combined with records of the salinity changes in the root zone is of paramount importance in improving our understanding of leaching requirements and leaching efficiencies for different soil types. This, as was pointed out before, is increasingly urgent as competition for water increases the pressure on water use in agriculture when leaching is often seen by others as a wasteful practice. Moreover, improved understanding of leaching will also help to formulate water uptake relations, which can be used in modeling exercises. Combined with crop yield data, the information will help to develop yield response functions of irrigation depth and water quality that are relevant for the economic improvement of agronomic practices (cf. Prendergast 1993).

In short, the three types of research are needed to further enhance our understanding of the underlying processes; for example, the geo-chemical changes occurring in the soil during prolonged irrigation with saline and sodic water, the response of crops in terms of yields to these changes in the root zone, and the response of the soil itself as evidenced by changes in the water-holding capacity and water transmitting functions. The processes of leaching of salts and water uptake by plant roots are linked, because water that is not taken up by the crop, due to adverse effects of salinity or sodicity on the plant itself, will be recharged to soil layers below the root zone and ultimately to the groundwater. Both processes, leaching and water uptake, are components of the more complicated scientific models that aspire to enhance our understanding of these processes. However, they are also needed for the engineering-type models that will support sound practical advice on the management of salinity to farmers and policy makers alike.

Additional areas of research that were identified in the paper include the study of the environmental impacts of the disposal of saline effluent, especially concerning evaporation basins, and including the effectiveness of measures to constrain lateral and vertical leakage from the basins. The policy implications of salinity development and management in irrigated agriculture also form a separate but important area of research (see, for example, Dinar et al. 1993). The research should consider the livelihood of the farmers as it is affected by the incidence of salinity and sodicity along the lines of Kielen's (1996) study referred to above, but augmented by a thorough economic analysis.

Literature Cited

Addiscott, T.M. and R.J. Wagenet. 1985. Concepts of solute leaching in soils: A review of modeling approaches. *Journal of Soil Science* 36:411–419.

Afzal, J., D.H. Noble, and E.K. Weatherhead. 1992. Optimization model for alternate use of different quality irrigation waters. *Journal of Irrigation Drainage Engineering*, ASCE 118:218–228.

Bari, M.A. and N.J. Schofield. 1992. Lowering of a shallow, saline water table by extensive eucalyptus reforestation. *Journal of Hydrology* 133: 273–291.

Bower, C.A., G. Ogata, and J.M. Tucker. 1969. Root zone salt profiles and alfalfa growth as influenced by irrigation water salinity and leaching fraction. *Agronomy Journal* 61:783–785.

Bras, R.L. and D.J. Seo. 1987. Irrigation control in the presence of salinity: Extended linear quadratic approach. *Water Resources Research* 23:1153–1161.

Bresler, E. and G.J. Hoffman. 1986. Irrigation management for salinity control: Theories and tests. *Soil Science Society of America Proceedings* 50:1522–1559.

Chhabra, R. 1985. Crop response to phosphorus and potassium fertilization of a sodic soil. *Agronomy Journal* 77: 699–702.

Condom, N. 1996. *Salinisation, alcalinisation et sodisation sur un perimetre irrigue du Pakistan.* MSc. Thesis. International Irrigation Management Institute, Lahore, Pakistan and Centre de Cooperation Internationale en Recherche Agronomique pour le developpement, Montpellier, France.

Dinar, A., M. P. Aillery, and M.R. Moore. 1993. A dynamic model of soil salinity and drainage generation in irrigated agriculture: A framework for policy analysis. *Water Resources Research* 29:1527–1537.

This paper presents a dynamic model of irrigated agriculture that accounts for drainage generation and salinity accumulation. Yield response functions are based on lysimeter experiments. The model is applied to conditions in the San Joaquin Valley of California, and is characteristic of similar studies in the USA and Australia aimed at reducing drainage flows and salt accumulation in the root zone of crops: A good discussion of the required policy adjustments.

El Guindy, S.M. and I.A. Risseeuw. 1987. *Research on water management of rice fields in the Nile Delta, Egypt*. Publication 41. Wageningen, The Netherlands: International Institute for Land Reclamation and Improvement (ILRI).

Evans, R. S. 1989. Saline water disposal options. *Journal of Australian Geology and Geophysics* 11:167–185.

Gates. T.K. and M.E. Grismer. 1989. Irrigation and drainage strategies in salinity-affected regions. *Journal of Irrigation Drainage Engineering*, ASCE 115:255–284.

Ghai, S.K., D.L.N. Rao, and L. Batra. 1988. Nitrogen contribution to wetland rice by green manuring with Sesbania spp. in an alkaline soil. *Biology and Fertility of Soils* 6: 22–25.

Ghassemi, F., A.J. Jakeman, and H.A. Nix. 1995. *Salinisation of land and water resources: Human causes, management and case studies.* Canberra, Australia: Centre for Resource and Environmental Studies.

A rich source of information on the worldwide incidence of salinity as a result of irrigation. The paper contains sections on the management of salinity with special reference to engineering and policy options.

Gleick, P.H. 1993. *Water in crisis: A guide to the world's fresh water resources.* New York, USA: Oxford University Press.

Grismer, M.E., F. Karanjeh, and H. Bouwer. 1993. Evaporation pond hydrology in management of irrigation and drainage systems. In *Integrated Perspectives*, ed. R. G. Allen, pp.580–586. New York, USA: American Society of Civil Engineers.

Gupta, R.J. 1994. Groundwater quality for irrigation. In *Salinity management for sustainable agriculture*, eds. D.L.N. Rao, N.T. Singh, R.K. Gupta, and N.K. Tyagi, pp. 89–100. Karnal, India: Central Soil Salinity Research Institute.

Gupta, R.K. and I.P. Abrol. 1990. Salt-affected soils: Their reclamation and management for crop production. *Advances in Soil Science* 11: 223–288.

Gupta, S.K. and S.K. Sharma. 1990. Response of crops to high exchangeable sodium percentage. *Irrigation Science* 11:173–179.

Hamdy, A. 1996. Use and management of saline water for irrigation towards sustainable development. In *Sustainability of irrigated agriculture*, eds. L.S. Pereira, R.A. Feddes, J.R. Gilley, and B. Lesaffre, Proceedings of the NATO Advanced Research Workshop, Vimeiro, Portugal, 21–26 March 1994. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Hanks, R.J. 1983. Yield and water-use relationships: An overview. In *Limitations to efficient water use in crop production*, eds. H.M. Taylor, W.R. Jordan, and T.R. Sinclair. Madison, WI, USA: American Society of Agronomy.

Heuperman, A.F. 1993. Salinity management in the irrigation areas in northern Victoria, Australia, with special reference to biological management options. In *ICID, Fifteenth International Congress on Irrigation and Drainage, The Hague, Netherlands: Water Management in the Next Century: Transactions vol 1-G, Special Session-Irrigation and Drainage in Competition for Water.* New Delhi, India: International Commission on Irrigation and Drainage (ICID).

Hoffman, G.J., J.D. Rhoades, J. Letey, and F. Sheng. 1990. Salinity management. In *Management of Farm Irrigation Systems*, eds. G.J. Hoffman, T.A. Howell, and K.H. Solomon. New York, USA: American Society of Civil Engineers.

Hutson, J.L. and R.J. Wagenet. 1992. *LEACHM, Leaching estimation and chemistry model: A process-based model of water and solute movement, transformations, plant uptake and chemical reactions in the unsaturated zone*. Research Series 92–3. Ithaca, New York, USA: Department of Soil, Crop and Atmospheric Sciences, Cornell University.

Jayawardane, N.S. and K.Y. Chan. 1993. Physical properties of Australian soils. *Australian Journal of Soil Research* 32:13–44.

Jurinak, J.J. 1990. The chemistry of salt-affected soils and waters. In *Agricultural salinity assessment and management*, ed. K.K. Tanji. New York, USA: American Society of Civil Engineers.

Kielen, N.C. 1996. *Farmers' perceptions on salinity and sodicity*. Internal Report, International Irrigation Management Institute-Pakistan. Lahore, Pakistan: International Irrigation Management Institute.

Kijne, J.W. 1996. *Water and salinity balances for irrigated agriculture in Pakistan*. Research Paper 5. Colombo, Sri Lanka: International Irrigation Management Institute.

Kuper, M. and J.W. Kijne. 1996. *Advances in the understanding of the impact of irrigation management on salinity, sodicity and soil degradation in Pakistan*. Conference Proceedings, International Irrigation Management Institute-Pakistan. Lahore, Pakistan: International Irrigation Management Institute. Duplicated.

Kijne, J.W. and M. Kuper. 1997. Sustainable development and management of irrigated land in the tropics, especially the semi-arid tropical countries. In *Proceedings of the June 1996 Conference at Ohio State University on the sustainability of irrigated agriculture*, ed. R. Lal. Columbus, Ohio: Ohio State University Press.

Kuper, M. and E.W. van Waiijen. 1993. *Farmers' irrigation practices and their impact on soil salinity: Is salinity here to stay?* Paper presented at the Internal Program Review of the International Irrigation Management Institute, 1993. Colombo, Sri Lanka: International Irrigation Management Institute. Duplicated.

Lenselink, K.J. and M. Jurriens. 1993. *An inventory of irrigation software for microcomputers*. Wageningen ,The Netherlands: International Institute for Land Reclamation and Drainage.

Loftis, J.C., G.B. McBride, and J.C. Ellis. 1991. Considerations of scale in water quality monitoring and data analysis. *Water Resources Bulletin* 27:255–264.

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.

Maas, E.V. and G.J. Hoffman. 1977. Crop salt tolerance—current assessment. *Journal of Irrigation Drainage Division*, ASCE 103: 115–134.

Machanda, H.R. 1993. Long term use of sodic water in north India and the reliability of empirical equations for predicting their sodium hazard. In *Toward the rational use of high salinity tolerant plants*, eds. H. Leith and A. Al Masood, vol.2:433–438. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Marlet, S. 1996. Alcalinisation des sols de la vallee du fleuve Niger: modellisation des processes physiochimiques et evolution des sols sous irrigation. Doctoral Theses, Montpellier, France.

McCullough-Sandan, B. 1987. *Evaluation of seepage in an on-farm evaporation pond*. MSc. Thesis. Davis, California, USA: University of California.

Mian, M. A. and T. van Reemen. 1991. *Evaporation ponds for disposal of saline drainage effluent in Pakistan*. Lahore, Pakistan: Water and Power Development Authority.

Monteith, J.L. 1996. The quest for balance in crop modeling. *Agronomy Journal* 88:695–97.

Murray-Rust, D. and E.J. Vander Velde. 1993. Conjunctive use of canal and groundwater in Punjab,

Pakistan: Management and policy options. In *Advancements in IIMI's Research 1992*, pp, 161–188. Colombo, Sri Lanka: International Irrigation Management Institute.

Oster, J.D. 1994. Irrigation with poor quality water. *Agricultural Water Management* 25:271–297.

It is argued that because of increasing water scarcity the use of poor quality water will continue to increase. In most cases, only minor modifications of existing irrigation and agronomic practices are needed, but, in some situations, it will require major changes in the crops grown, the methods of water application, and the use of soil amendments. The paper looks at farmers' experiences and discusses specific examples of waters that caused problems with infiltration rates and soil tilth.

Oster, J.D. and F.W. Schroer. 1979. Infiltration as influenced by irrigation water quality. *Soil Science Society of America Proceedings* 43:444–447.

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

Passioura, J.B. 1996. Simulation models, science, snake oil, education or engineering. *Agronomy Journal* 88:690–694.

Pessarakli, M. (ed.). 1993. *Handbook of plant and crop stress.* New York, NY, USA: Marcel Dekker Inc.

Prendergast, J.B. 1993. A model of crop yield response to irrigation water salinity: Theory, testing and application. *Irrigation Science* 13:157–164.

Prendergast, J.B. 1995. Soil water bypass and solute transport under irrigated pasture. *Soil Science of America Journal* 59:1531–1539.

Prendergast, J.B., C.W. Rose and W.L. Hogarth. 1994a. A model for conjunctive use of groundwater and surface waters for control of irrigation salinity. *Irrigation Science* 14:167–175.

Prendergast, J.B., C.W. Rose and W.L. Hogarth. 1994b. Sustainability of conjunctive water use for salinity control in irrigation areas: Theory and application to the Shepparton region, Australia. *Irrigation Science* 14:177–187.

An interesting set of papers that illustrate the use of a steady state model in the analysis of conjunctive use of groundwater and canal water for salinity control. The data are from the Murray Basin in Victoria, Australia.

Quirk, J.P. and R.K. Schofield. 1955. The effect of electrolyte concentration on soil permeability. *Journal of Soil Science* 6:163–178.

Rengasamy, P. and K.A. Olsson. 1993. Irrigation and sodicity. *Australian Journal of Soil Research* 31:821–837

Rhoades, J.D. 1974. Drainage for salinity control. In *Drainage for Agriculture*, ed. J. van Schilfgaarde. Agronomy Monograph vol.17: 433–461. Madison, Wisconsin, USA: American Society of Agronomy.

Rhoades, J.D. and J. Loveday. 1990. Salinity in irrigated agriculture. In *Irrigation of Agricultural Crops*, eds. B.A. Steward and D.R. Nielsen, Agronomy Series number 30, pp. 1089–1142. Madison, Wisconsin, USA: American Society of Agronomy.

Robbins, C.W. 1984. Sodium adsorption ratio—exchangeable sodium percentage relationships in a high potassium saline-sodic soil. *Irrigation Science* 5:173–179.

Shalhevet, J. 1994. Using water of marginal quality for crop production: Major issues. *Agricultural Water Management* 25:233–269.

A review article with clearly articulated answers to a number of practical questions with respect to the use of poor quality water for crop production. Among others, it addresses issues of soil fertility, spatial distribution of salt, irrigation requirements and frequency, and leaching requirements.

Simunek, J. and D.L. Suarez. 1994. Two-dimensional transport model for variably saturated porous media with major ion chemistry. *Water Resources Research* 30:1115–1133.

Smets, S.M.P., M.Kuper, J.C. van Dam, and R.A. Feddes. Forthcoming. Salinization and crop transpiration of irrigated fields in Pakistan's Punjab. *Irrigation and Drainage Systems.*

Soil Science Society of America. 1997. *Glossary of soil science terms 1996.* Madison, WI, USA: Soil Science Society of America.

Suarez, D.L. 1982. Graphical calculation of ion concentrations in CaCO3 and / or gypsum soil solutions. *Journal of Environmental Quality* 11:302–308.

Suarez, D.L. and I. Lebron. 1993. Water quality criteria for irrigation with highly saline water. In *Toward the rational use of high salt tolerant plants*, eds. H. Leith and A. Al Masood, vol.2:389–397. Dordrecht, The Netherlands: Kluwer Academic Publishers.

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

An excellent overview of recent research results of the effects of sodium on soils. The effects of Na and solution concentration are discussed in relation to hydraulic conductivity, infiltration, crusting, runoff, erosion and hard-setting. The main conclusion is that the adverse effects of Na occur significantly down to very low levels far below those previously used to define sodic soils.

Trewhella, N. W. and M. Badruddin. 1991. *Evaporation ponds for disposal of saline drainage effluent in Pakistan*. Lahore, Pakistan: International Water and Salinity Research Institute.

Tyagi, N.K. 1996. Salinity management in irrigated agriculture. In *Sustainability of irrigated agriculture*, eds. L.S. Pereira, R.A. Feddes, J.R. Giley, and B. Lesaffre, pp. 345–358. Proceedings of the NATO Advanced Research Workshop, Vimeiro, Portugal, 21–26 March 1994. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Tyagi, N.K., K.C. Tyagi, N.N. Pillai, and L.S. Willardson. 1993. Decision support for irrigation system improvement in saline environment. *Agricultural Water Management* 23:285–301.

Umali, D.L. 1993. *Irrigation-induced salinity: A growing problem for development and the environment*. World Bank Technical Paper Number 215. Washington, D.C., USA: The World Bank.

The report reviews the extent of the salinity problem in several countries and examines the technical, economic, social, and institutional factors contributing to the onset of irrigation-induced salinity. It draws on various World Bank reports. It concludes that governments have to commit to the fostering of an economic environment that promotes efficient water resource use.

United States Salinity Laboratory Staff. 1954. *Diagnosis and improvement of saline and alkali soils*. Agricultural Handbook No. 60. Washington, D.C., USA: United States Department of Agriculture (USDA).

van Beek, C.G.E.M. and N. van Breemen. 1973. The alkalinity of alkali soils. *Journal of Soil Science* 24: 129–136.

van Dam, J.C. and M. Aslam. 1997. *Soil salinity and sodicity in relation to irrigation water quality, soil type and farmer management*. Internal Report. Lahore, Pakistan: International Irrigation Management Institute. Duplicated.

van den Broek, J.B., J.C. van Dam, J.A. Elbers, R.A. Feddes, J. Huygen, P. Kabat, and J.G. Wesselink. 1994. *SWAP 1993, input instructions manual*. Report 45, Department of Water Resources. Wageningen, The Netherlands: Wageningen Agricultural University.

van der Moezel, P.G., G.V.N. Pearce-Pinto, and D.T. Bell. 1991. Screening for salt and waterlogging tolerance in Eucalyptus and Melaleuca species. *Forest Ecology and Management* 40: 27–37.

van Genuchten, M.Th.. 1987. *A numerical model for water and solute movement in and below the root zone*. Research Report 121. Riverside, California, USA: United States Salinity Laboratory.

A widely quoted paper on the topic, which has become the present standard.

van Hoorn, J.W., and J.G. van Alphen. 1994. Salinity control. In *Drainage Principles and Applications*, 2nd Edition, ed. H.P. Ritzema. Publication 16. Wageningen, The Netherlands: International Institute for Land Reclamation and Drainage (ILRI).

A solid historical overview of the topic, especially insightful with respect to the salt balance of the root zone and leaching efficiency. The paper contains numerical examples of water and salt balances, with contribution due to capillary rise from shallow water tables.

Weeks, L.O., and T.E. Levy. 1985. Management solutions for salinity control in an irrigation district. In *Water and water policy in world food supplies*, ed. W.R. Jordan, pp. 153–157. Proceedings of the Conference, 16–30 May 1985. Texas, USA: Texas A&M University.

SWIM Papers

1. *Accounting for Water Use and Productivity.* David Molden, 1997.

2. *How to Manage Salinity in Irrigated Lands: A Selective Review with Particular Reference to Irrigation in Developing Countries.* Jacob W. Kijne, S.A. Prathapar, M.C.S. Wopereis, and K.L. Sahrawat, 1998.

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