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Salinity Management for Sustainable Irrigation

*Integrating Science, Environment,
and Economics*

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*with an appendix by
E. Feinerman*

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Cover photograph: Salination in an irrigated field in Swift Current, Saskatchewan, Canada. Courtesy of Dr. Harold Steppuhn, Agriculture and Agri-Food Canada.

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Dedicated to the irrigators of arid lands who toil to feed humanity

Posing the Question: Is Irrigation Sustainable?

Irrigation is the supply of water to agricultural crops by artificial means, designed to permit farming in arid regions and to offset drought in semi-arid regions. Even in areas where total seasonal rainfall is adequate on average, it may be poorly distributed during the year and variable from year to year. Wherever traditional rain-fed farming is a high-risk enterprise owing to scarce or uncertain precipitation, irrigation can help to ensure stable production.

Irrigation has long played a key role in feeding expanding populations and is expected to play a still greater role in the future. It not only raises the yields of specific crops, but also prolongs the effective crop-growing period in areas with dry seasons, thus permitting multiple cropping (two, three, or even four, crops per year) where only a single crop could be grown otherwise. With the security provided by irrigation, additional inputs needed to intensify production further (pest control, fertilizers, improved varieties and better tillage) become economically feasible. Irrigation reduces the risk of these expensive inputs being wasted by crop failure resulting from lack of water.

Although irrigated land amounts to only some 17 percent of the world's cropland, it contributes well over 30 percent of the total agricultural production. That vital contribution is even greater in arid regions, where the supply of water by rainfall is least even as the demand for water imposed by the bright sun and the dry air is greatest.

The practice of irrigation consists of applying water to the part of the soil profile that serves as the root zone, for the immediate and subsequent use of the crop. Inevitably, however, irrigation also entails the addition of water-borne salts. Many arid-zone soils contain natural reserves of salts, which are also mobilized by irrigation. Underlying groundwater in such zones may further contribute salts to the root zone by capillary rise. Finally, the roots of crop plants typically extract water from the soil while leaving most of the salts behind, thus causing them to accumulate.

The problem is age-old. From its earliest inception in the Fertile Crescent, some six or more millennia ago, irrigated agriculture has induced processes of degradation that have threatened its sustainability (box 1). The artificial application of water to the land has ipso facto induced the self-destructive twin phenomena of waterlogging and salination (figure 1).

The same processes that evidently brought about the demise of ancient hydraulic civilizations, including those of the Tigris-Euphrates and the Indus river valleys, continue to plague irrigation districts today no less than in the past. Indeed, the problem extends far beyond the confines of the irrigated lands themselves, as it affects adjacent lands and water resources.

Processes occurring off-site (upstream as well as downstream of the irrigated area) strongly affect the sustainability of irrigation. For example, denudation of upland watersheds by forest clearing, cultivation, and overgrazing induces erosion and the consequent silting of reservoirs and canals, thereby reducing the water supply. The construction of reservoirs often causes the submergence of natural habi-

Box 1 Silt and salt in ancient Mesopotamia

Ancient Mesopotamia owed its prominence to its agricultural productivity. The soils of this alluvial valley are deep and fertile, the topography is level, the climate is warm, and water is provided by the twin rivers, Euphrates and Tigris. However, the diversion of river water onto the valley lands led to a series of interrelated problems.

The first problem was sedimentation. Early in history, the upland watersheds were deforested and overgrazed. The resulting erosion was conveyed by the rivers as suspended silt, which settled along the bottoms and sides of the rivers, thus raising their beds and banks above the adjacent plain. During periods of floods the rivers overflowed their banks, inundated large tracts of land, and tended to change course abruptly. The silt also settled in channels and clogged up the irrigation works.

The second and more severe problem was salt. Seepage from the rivers, the irrigation channels, and the flood-irrigated fields caused the water table to rise throughout southern Mesopotamia. Because all irrigation waters contain some salts, and because crop roots normally exclude salts while extracting soil moisture, the salts tended to accumulate in the soil and groundwater. And as the undrained water table rose it brought the salts back into the soil. The farmers of ancient Mesopotamia attempted to cope with the process of salination by periodically fallowing their land, and by replacing the salt-sensitive wheat with relatively salt-tolerant barley. However, the process proceeded inexorably. So the ancient hydraulic civilizations of Sumer, Akkad, Babylonia, and Assyria, each in turn, rose and then declined, as the center of population and culture shifted over the centuries from the lower to the central to the upper parts of the Tigris-Euphrates valley (Hillel, 1994).

tats as well as of valuable scenic and cultural sites. Concurrently, the downstream disposal of drainage from irrigated land tends to pollute aquifers, streams, estuaries, and lakes with salts, nutrients, and pesticides (box 2). Finally, the irrigation system itself may harbor and spread water-borne diseases, thus endangering public health. So the very future of irrigation is threatened by land degradation, as well as by dwindling water supplies and deteriorating water quality.

For some years now, even as great investments have been made in the development of new irrigation projects, the total area under irrigation has hardly expanded. That is because large tracts of irrigated land have degenerated to the point of being rendered uneconomic to cultivate, or—in extreme cases—have become totally sterile. The dilemma of land deterioration is not exclusive to the less-developed nations, where it has caused repeated occurrences of famine. It applies to an equal extent to such technologically advanced countries as Australia, the United States of America, and the central Asian regions of the former Soviet Union. So pervasive and inherent are the problems that

Figure 1   The process of waterlogging and salination
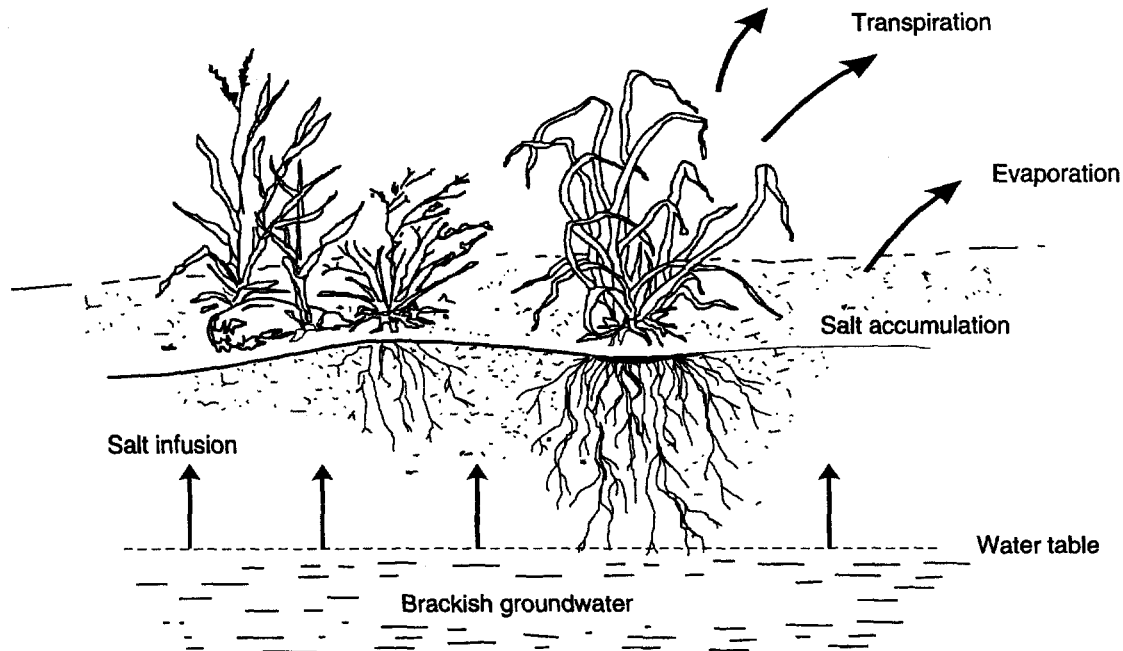
some critics doubt whether irrigation can be sustained in any one area for very long—and they have much evidence to support their pessimism. Herein, we examine the facts in search of a more positive approach, albeit one based on carefully conditional optimism.

The concept of sustainability, as pointed out by Letey (1994), is itself ambiguous. A dictionary definition is "being capable of remaining in existence, and of functioning, continuously and indefinitely." In the past, the extent of human knowledge was definitely too limited for people to foresee, let alone to forestall, the eventual consequences of the way they managed the environment. At present, we know a great deal about the processes involved, and we do have the technology to cope with problems formerly considered uncontrollable. Although our knowledge is still incomplete and much remains to be researched,

what we do know presents us with an opportunity and a challenge to avoid practices that are certain to cause degradation and to promote practices that are likely to maximize the probability of long-term success.

Is irrigation sustainable, and if so, how and under what conditions? That is the question that has impelled the writing of this manual. Given the diffuse and voluminous nature of the information available, the task at hand called for selecting and organizing the disparate facts into a unified exposition, combining physico-chemical, agronomic, environmental, and economic principles into practical recommendations. The ultimate aim of this and other such efforts must be to help ensure the long-term viability and productivity of irrigated agriculture in arid and semiarid regions around the world.

Box 2   How ancient Egypt escaped the scourge of salinity

In contrast to Mesopotamia, the civilization of Egypt thrived for several millennia. What explains the persistence of irrigated farming in Egypt in the face of its demise in Mesopotamia? The answer lies in the different soil and water regimes of the two lands. Neither clogging by silt nor poisoning by salt was as severe along the Nile as in the Tigris-Euphrates plain.

The silt of Egypt is brought by the Blue Nile from the volcanic highlands of Ethiopia, and it is mixed with the organic matter brought by the White Nile from its swampy sources. It was not so excessive as to choke the irrigation canals, yet was fertile enough to add nutrients to the fields and nourish their crops. Whereas in Mesopotamia the inundation usually comes in the spring, and summer evaporation tends to make the soil saline, the Nile rises in the late summer and crests in autumn. So in Egypt the inundation comes at a more favorable time: after the summer heat has killed the weeds and aerated the soil, just in time for the pre-winter planting.

The narrow floodplain of the Nile (except in the Delta) precluded the widespread rise of the water table. Over most of its length, the Nile lies below the level of the adjacent land. When the river crested and inundated the land, the seepage naturally raised the water table. As the river receded and its water level dropped, it pulled the water table down after it. The all-important annual pulsation of the river and the associated fluctuation of the water table under a free-draining floodplain created an automatically repeating self-flushing cycle by which the salts were leached from the irrigated land and carried away by the Nile itself (Hillel, 1994).

Unfortunately, the soil of Egypt—famous for its durability and productivity in ancient times—is now threatened with degradation. The Aswan High Dam (completed in 1970) has blocked the fertile silt that had formerly been delivered by the Nile. The river itself, now running clear of silt, has increased its erosivity and has been scouring its own banks. And along the estuaries of the Delta there is no more deposition, so the coast has been subject to progressive erosion and to intrusion of sea water (a process likely to worsen as global warming causes the sea level to rise). Finally, the artificial maintenance of a nearly constant water level in the river, necessary to allow year-round irrigation and successive cropping, has raised the water table. So Egypt is now subject to the maladies of waterlogging and salination (to which it had for so long seemed immune) and must invest in the installation of extensive groundwater drainage systems to prevent soil degradation.

CHAPTER 1

The Nature of Salinity

The term *salinity* refers to the presence in soil and water of various electrolytic mineral solutes in concentrations that are harmful to many agricultural crops. Most common among these solutes are the dissociated cations Na^+, K^+, Ca^{2+}, and Mg^{2+}; and the anions Cl^-, SO_4^{2-}, NO_3^-, HCO_3^-, and CO_3^{2-}. In addition, hypersaline waters may contain trace concentrations of the elements B, Se, Sr, Li, SiO, Rb, F, Mo, Mn, Ba, and Al, some of which may be toxic to plants and animals (Tanji, 1990).

Soil Salinity

The sources of salts causing soil salinity may reside in the soil itself, or in the subsoil. They may result, in the first instance, from the chemical decomposition (termed "weathering") of the minerals that constitute the rocks from which the soil is derived. Soils formed in arid regions, where rainfall is scanty, are especially likely to contain appreciable quantities of salts, simply because they have not been leached. In other instances, salts may be infused into the soil from brackish groundwater. This takes place especially where the subsoil contains salts that had accumulated over prior geologic eras. A rising water table may then mobilize such salts and convey them into the rooting zone of crops.

Some salts enter the soil with rainwater. Although the initial condensation of vapor produces pure water, the raindrops that form in clouds and fall earthward tend to pick up soluble constituents during their brief residence in the atmosphere. One such constituent is carbon dioxide, which dissolves in rainwater to form a dilute solution of carbonic acid. That acid, though relatively weak, reacts with minerals in dust, rocks and the soil, and causes certain minerals to dissolve more readily than they would otherwise, thus contributing indirectly to soil salinity. The acidity of rainwater increases significantly in industrialized regions where it mixes with emitted gases such as oxides of sulfur and nitrogen.

In addition, rainfall that occurs in coastal regions often mixes with sea spray, which may contribute appreciable quantities of salt to areas that extend some distance (in some cases, scores of kilometers) from the shore. Seawater also tends to intrude landward via tidal estuaries, as well as into groundwater aquifers due to overdraft. The latter process occurs where groundwater is extracted from wells in amounts greater than the annual recharge, thus causing the water table to fall and creating a pressure gradient that draws seawater into the subterranean aquifer.

Except along seacoasts, however, saline soils seldom occur in humid regions, thanks to the net downward percolation of water through the soil profile, brought about by the excess of rain-

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fall over evapo-transpiration. In arid regions, on the other hand, there may be periods of no net downward percolation and hence no effective leaching, so salts can—and often do—accumulate in the soil. Here the combined effect of meager rainfall, high evaporation, the presence of salt-bearing sediments, and—in places—the occurrence of shallow brackish groundwater gives rise to a group of soils known in classical pedology as *solonchaks*.

Less obvious than the appearance of naturally saline soils, but perhaps more insidious, is the inadvertent *induced salination* of originally productive soils, caused by human intervention. Irrigation waters generally contain appreciable quantities of salts (box 3). An accompanying calculation illustrates the potential contribution of even good-quality irrigation water to soil salination, if there is insufficient leaching. Hence irrigated soils, typically located in river valleys of the dry zone, are particularly vulnerable to the effect of rising groundwater due to inadequate drainage. Crop plants extract water from the soil while leaving most of the salt behind. Unless leached away (preferably continuously, but at least periodically) such salts must sooner or later begin to hinder crop growth. Additional anthropogenic sources of salts include applications of soil amendments (e.g., lime and gypsum), chemical fertilizers and pesticides, and such salt-containing organic materials as manure and sewage sludge.

Overall salinity is generally expressed in terms of the total dissolved solutes (TDS) in milligrams per liter (mg/l) of solution (roughly equivalent to parts per million, ppm), or in terms of the total solute concentration of cations (TSC) or of anions (TSA) in milliequivalents per liter (meq/l). Total salinity may also be characterized by measuring the electrical conductivity of the solution (EC), generally expressible in terms of deci-siemens per meter (dS/m, equivalent to the old units of milli-mhos per centimeter, mmho/cm).

Although no universally exact relationship exists between the total concentration of salts and the electrical conductivity of a solution, in practice TDS may be approximated by multiplying EC (dS/m) by a factor of 640 for dilute solutions. For highly concentrated solutions (in which ionization, affecting electrical conductivity, is somewhat suppressed), the factor increases to about 800. For solutions in the EC range of 0.1 to 5.0 dS/m, the total cation or anion concentration in terms of meq/l may be estimated by multiplying the value of EC by 10 (McNeal, 1980).

Quantitative criteria for diagnosing soil salinity were originally formulated by the U.S. Salinity Laboratory in its Handbook 60 (Richards, 1954), in terms of the electrical conductivity of the soil's "saturation extract"—i.e., the solution extracted from a soil sample that had been pre-saturated with water (box 4). Accordingly, a saline soil has been defined as having an EC greater than 4 dS/m. This value generally corresponds to about 40 meq/l of salt. In the case of a sodium chloride solution, this equals about 2400 mg/l (or parts per million).

Box 3   Potential contribution of irrigation water to soil salinity

As a rough calculation, let us assume that the harvested yield of a crop is about 10,000 kg of dry matter per hectare. At 3%, the salt contained in that harvest is 300 kg. Now compare that with the amount of salt applied in irrigation. Assuming a seasonal irrigation of 1,000 mm (equal to 10,000 cubic meters per hectare) with water of good quality, containing 300 mg/l (0.3 kg/m^3), the amount of salt added would total $0.3 \times 10,000 = 3,000$ kg per hectare. Thus, the amount of salt added with the irrigation water is roughly 10 times the amount of salt removed in the harvest. It appears, therefore, that under most agricultural conditions salt removal by crops is only a minor component of the overall salt balance.

Now consider the mass of salt added to crops in fertilizers. The nitrogen commonly applied to a crop such as maize amounts to about 250 kg/ha annually. Assume that this fertilizer is in the form of ammonium sulfate (21% nitrogen, 6% hydrogen, 73% sulfate), and that the nitrogen is entirely taken up by the crop. Then the amount of sulfate added would be $73 \times 250/21 = 870$ kg/ha. That is less than 30% of the amount of salt added in irrigation (calculated above). If the irrigation water contains twice as much salt (as it commonly does), then the sulfate added in the fertilizer would constitute about 15% of the salt load contributed by irrigation.

Box 4 Sampling the soil solution

Different water-to-soil volume ratios may be used to obtain a sample solution for characterizing the salt content of the soil. Early investigators used various ratios, such as 5:1 or 3:1 or 1:1 ratios. The results often differed, however, as the volume of water mixed with the soil was found to affect the degree of dissolution of mineral salts of varying solubility. To provide a uniform basis for comparison, therefore, a standard extraction method was sought. The method proposed for this purpose by the U.S. Salinity Laboratory (Richards, 1954) was the so-called *saturation ex-*

tract. It was based on the notion that each soil has a distinctive water content at saturation that is determined by its particular combination of interdependent physical attributes, such as texture, specific surface, clay content, and cation exchange capacity (Merrill et al., 1987). In practice, the method consists of mixing a sample of soil with a gradually increasing amount of distilled water until the sample becomes a saturated paste. The solution is then extracted by vacuum filtration and tested for salt content. Although higher water-to-soil ratios make extraction easier, amounts of water exceeding the saturation value are believed to be less representative of conditions likely to occur in the field.

The measurement of electrical conductivity is affected by the temperature of the solution, and it increases by about 2 percent per degree rise in temperature in the range of 15 to 35 Celsius. For purposes of comparison, EC data are referred to a standard temperature of 25 Celsius. The results obtained at higher or lower temperature are normalized by means of the following empirical relation:

$$EC(standard) = [1 - 0.02(T-25)]EC(measured)$$

The clay fraction in saline soils is generally well-flocculated. As the salts are leached, however, the flocs may tend to disperse and the soil aggregates to break down (or *slake*). This occurs especially where an appreciable concentration of sodium ions is adsorbed onto the clay particles. The tendency for flocs to disperse and for aggregates to slake and collapse results in the deterioration of soil structure by the clogging of large pores in the soil, and consequently in the reduction of soil permeability. This leads

to the associated phenomenon of *soil sodicity*, also known as *alkalinity*.

Soil Sodicity

Soil sodicity is a condition caused by the effect of sodium ions adsorbed onto the electrostatically charged clay particles. Colloidal clay particles generally exhibit a negative charge. When surrounded by an aqueous solution of electrolytic salts, such particles attract, or adsorb, cations, while repelling anions. So the concentration of cations in the vicinity of clay surfaces increases, while that of anions decreases. That inward attraction is countered by the tendency of the cations to diffuse toward the less-concentrated regions of the solution farther away from the particle surfaces. As a result, the adsorbed cations do not adhere rigidly to the solid surfaces (except in a completely dry soil), but tend to form a loose swarm in the hydration envelope surrounding each clay particle. The ions in that swarm are exchangeable, in the

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Box 5 Measuring the salt concentration

The earliest method for determining the concentration of dissolved salts in a solution was to evaporate a measured volume of the solution (pre-filtered to remove suspended solids) and to weigh the residue of salts. The result has traditionally been expressed in terms of the total dissolved salts (TDS), usually given as milligrams per liter (mg/l). A much more convenient method is to measure the electrical conductivity of the solution (being the reciprocal of the electrical resistivity). The capacity of a solution to

conduct an electrical current is proportional to the concentration of electrolytes (solutes that dissociate in water to form ions). It is measured in terms of reciprocal ohms, long designated as mhos. In the Systeme International d'Unites (known as SI units), mhos have been replaced by siemens (S). 1 dS/m = 1 mmho/cm, where mmho/cm (millimhos per centimeter) is the unit that had formerly been used (prior to the universal adoption of the SI system) for characterizing the electrical conductivity of solutions, and dS/m designates deciSiemens per meter (1 dS/m = 0.1 S/m).

Figure 2   Distribution of a monovalent vs. a divalent cation (Ca^{++} vs. Na^+) adsorbed to a negatively charged clay particle. The divalent cation is held more closely and strongly to the particle
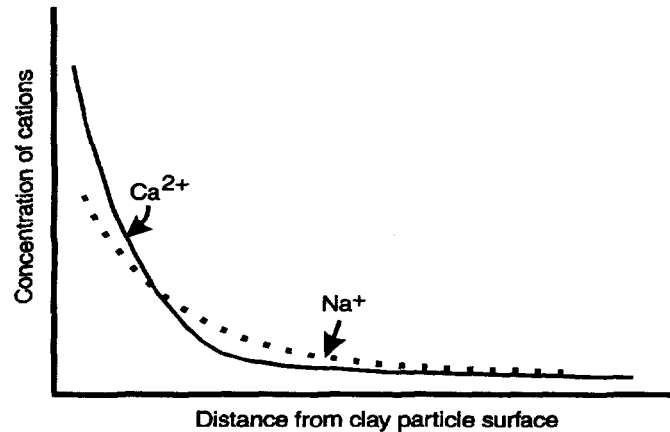
Source: Hillel (1998).

sense that they can be replaced by other cations whenever the composition of the ambient solution changes (Hillel, 1998).

Divalent cations, such as calcium and magnesium, are attracted to the clay surfaces more strongly than are monovalent cations such as sodium. If the swarm of adsorbed cations consists predominantly of divalent cations, it tends to be compressed (figure 2). Consequently, the particles can approach one another closely enough to clump together and to form flocs (a process called *flocculation*). Those flocs, in turn can associate in larger assemblages, called

aggregates. An aggregated soil typically contains large voids between adjacent aggregates, hence it tends to be porous and permeable.

The flocculation of clay particles is enhanced when the ambient solution is highly concentrated, i.e. when it is saline. In such conditions, the tendency of adsorbed cations to diffuse outwards is repressed (there being a weaker osmotic gradient between the region of adsorption close to the particles and the ambient solution farther from the particles). Hence swelling is reduced and the particles are drawn together so they can flocculate (figure 3).

Figure 3   Influence of ambient solution concentration ($n_1 > n_2$) on thickness of the ionic layer surrounding clay particles. Higher concentration compresses the layer, promoting flocculation
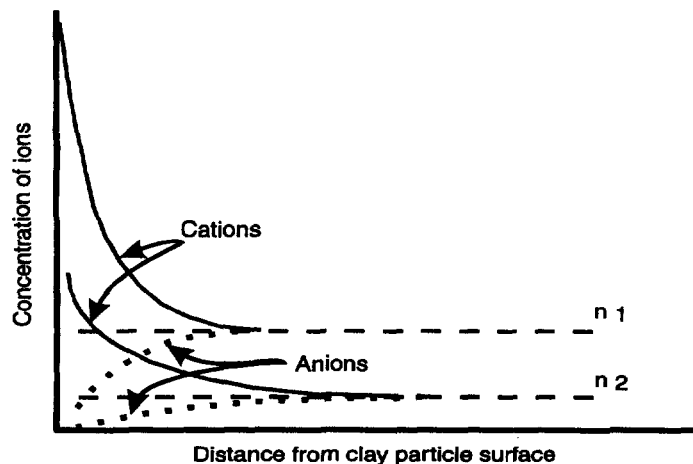
Source: Hillel (1998).

In contrast, if the ambient solution is dilute and many of the cations present are monovalent (e.g., when the sodium adsorption ratio is high), the swarm of adsorbed cations tends to diffuse farther away from the particle surfaces. This results in a thickening of the hydration envelope surrounding each particle, causing pronounced swelling and dispersion of the soil flocs. The process described, called *defloccu-lation*, destroys soil aggregates from within. As the aggregates collapse, the wide inter-aggregate voids are filled-in (clogged) by dispersed particles, and the soil's permeability diminishes markedly (figure 4). Infiltration and aeration are then restricted, and so are such vital plant functions as germination, seedling emergence, and root growth.

The swelling tendency is strongest in soils with a high content of smectitic clay (a type of active clay also known as montmorillonite), and when sodium ions constitute a sizable fraction of the cation exchange complex. In practice, the criterion for a "sodic soil" is an exchangeable sodium percentage (ESP) exceeding 15 percent of the total cation exchange capacity (box 6). This is a somewhat arbitrary criterion, since in many cases no sharp distinction is apparent at

a particular value of ESP between "sodic" and "nonsodic" soils.

In principle, soils may be saline without being sodic, and in other circumstances soils may be sodic without being saline. All too often, however, irrigated soils in arid regions can be both saline and sodic, i.e. when the EC exceeds 4 dS/m and ESP exceeds 15 percent. Such soils, when leached, tend to become strongly alkaline, with their pH value rising above 8.5.

Soil sodicity is especially notable for its effect on the soil surface, where it tends to form a relatively impermeable layer commonly known as a *surface seal*. When wet, the soil's top-layer becomes a slick and sticky mud; when dry, it hardens to form a tough crust with an irregular—roughly hexagonal—pattern of cracks. This dense surface condition not only reduces the entry of water and air into the soil but also forms a barrier to the emergence of germinating seedlings and to the penetration of their roots. As infiltration is inhibited, greater runoff, erosion, and silting of downstream water courses and reservoirs ensues.

Sodic soils (called *solonetz* by classical pedologists) may appear darkish, the coloration being due to the surface coating of dispersed

Figure 4   Hydraulic conductivity of a sandy loam as related to total salt concentration of the soil solution and to the soil's exchangeable sodium percentage (ESP)
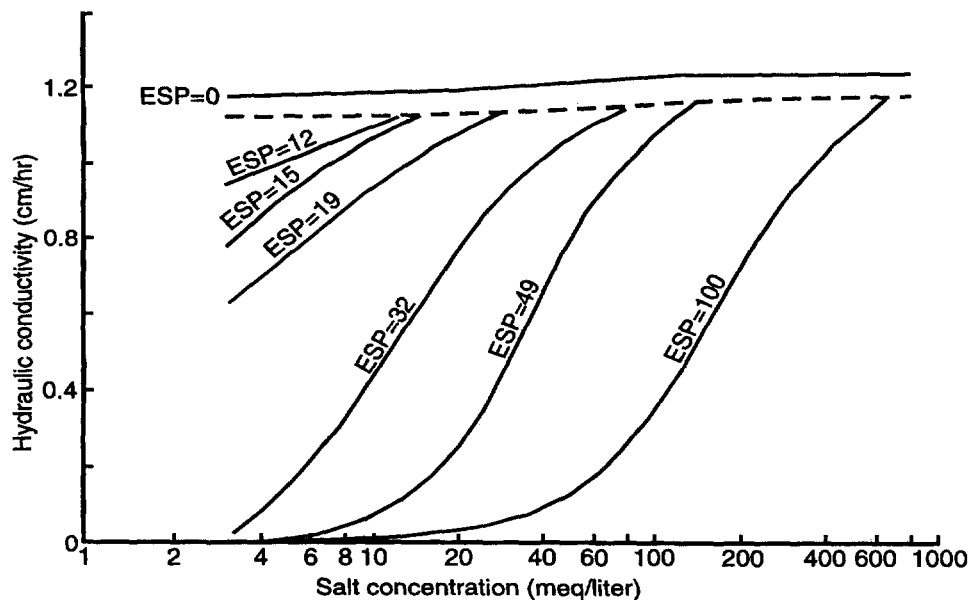
Source: After McNeal and Coleman (1966).

Box 6   Sodium adsorption ratio and exchangeable sodium percentage

A widely accepted index for characterizing the soil solution with respect to its likely influence on the exchangeable sodium percentage in the *sodium adsorption ratio* (SAR). It has also been used to assess the quality of irrigation water. SAR is defined as follows:

$$SAR = [Na^+]/\{([Ca^{2+}] + [Mg^{2+}])/2\}^{0.5}$$

In words, SAR is the ratio of the sodium ion concentration to the square root of the average concentration of the divalent calcium and magnesium ions. In this context, all concentrations are expressed in milliequivqalents per liter. SAR is thus an approximate expression for the relative activity of Na^+ ions in exchange reactions in soils. A high SAR, particularly at low concentrations of the soil solution, causes high ESP and is also likely to cause a decrease of soil permeability.

The relationship between ESP and SAR of the soil solution was measured on numerous soil samples in the Western states by the U.S. Salinity Laboratory and reported (Richards, 1954) to be

$$ESP = 100[-a + b(SAR)]/\{1 + [-a + b(SAR)]\}$$

where $a = 0.0126$ and $b = 0.01475$.

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organic matter. For that reason, sodic soils were long ago described as "black alkali"—in contrast with non-sodic saline soils that were described as "white alkali" because of the typical appearance of crystalline salts at the surface.

The Salt Balance

The *salt balance* is a summation of all salt inputs and outputs for a defined volume of soil during a specified period (box 7). If salts are conserved (that is to say, if they are neither generated nor decomposed chemically in the soil), then the difference between the total input and output must equal the change in salt content of the soil zone monitored. Accordingly, if total input exceeds total output then salt must be accumulating. The salt balance has been used as an indicator of salinity trends and of the need for salinity-control measures in large-scale irrigation projects as well as in single irrigated fields.

The following simple equation applies to the amount of salt in the liquid phase of the root zone per unit area of land:

$$[\rho_w(V_rc_r + V_ic_i + V_gc_g) + M_s + M_a] -$$
$$[M_p + M_c + \rho_wV_dc_d] = \Delta M_{sw}$$

Herein V_r is the volume of rainwater entering the soil with a salt concentration c_r, V_i the volume of irrigation with a concentration c_i, V_g the volume of groundwater with a concentration

c_g entering the root zone by capillary rise, V_d the volume of water drained from the soil with a concentration c_d; M_s and M_a are masses of salt dissolved from the soil and from agricultural inputs (fertilizers, soil amendments), respectively; M_p and M_c are mass of salt precipitated (or adsorbed) in situ and mass removed by the crop, respectively; ρ_w is density of water; and, finally, ΔM_{sw} is the change in mass of salt in the soil's liquid phase during the period considered. The actual quantitative magnitudes of all these terms vary from place to place and from time to time, depending on local conditions, climate, and management practices.

The composition of rain varies according to season, direction of wind, and proximity to possible sources of airborne salts such as seashores, volcanoes, dust-producing desert areas, and smoky or smoggy industrial centers. The annual deposit of salt in rainfall has been estimated to range from 10 to 20 kg/ha in continental interiors (Yaalon, 1963) to 100 to 200 kg/ha near seacoasts. Although seemingly small, the amount of salt delivered to the soil in rainfall may add up, over time, to a great deal of salt, which may be stored in the soil or subsoil. However, in irrigated areas the amount of salt contributed by irrigation water generally far exceeds that by rainfall.

Soils and subsoil layers in arid regions are relatively unweathered. The weathering of primary minerals and the dissolution of salts from newly irrigated soils may contribute significantly to soil salination and to the salt load of drainage waters. For example, irrigation with

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Box 7   Sample calculation of the salt balance

The following data were obtained in a field in an arid zone:

1. Rainfall occurred only in winter and amounted to 300 mm, with a total salt concentration of 40 ppm.
2. Capillary rise from saline groundwater in spring and autumn totaled 100 mm at a concentration of 1000 ppm.
3. Irrigation was applied during the summer season and amounted to 900 mm, with 400 ppm salts.
4. Drainage during the irrigation season amounted to 200 mm, with a soluble salt concentration of 800 ppm.

An additional increment 0.12 kg/m² of soluble salts was added in the form of fertilizers and soil amendments, of which 0.1 kg/m² was removed by the harvested crops.

Disregarding possible dissolution of soil minerals and the precipitation of salts within the soil, compute the annual salt balance. Is there a net accumulation or release of salts by the soil?

We begin with a slightly modified version of the salt balance equation of the root zone per unit of land area (note that in this formulation M_a includes M_g):

$$\Delta M_s = A_w(V_r c_r + V_i c_i + V_g c_g - V_d c_d) + M_a - M_c$$

Herein ΔM_s is the change in mass of salt in the root; A_w is the density of water; V_r, V_i, V_g, V_d are the volumes of rain, irrigation, groundwater rise, and drainage, respectively, with corresponding salt concentrations of c_r, c_i, c_g, c_d; and M_a, M_c are the masses of salts added agriculturally and removed by the crops, respectively.

Using 1 m² as the unit "field" area, calculating water volumes in terms of m³ and masses in terms of kg (water density being 1000 kg/m³), we can substitute the given quantities into the previous equation to obtain the change in mass content of salt in the soil:

$$DM_s = 10^3 kg/m^3 (0.3m)(40 \times 10^{-6}) + (0.1m$$
$$(1000 \times 10^{-6}) + (0.9m)(400 \times 10^{-6}) - (0.2m$$
$$(800 \times 10^{-6}) + 0.12 kg/m^2 - 0.1\ kg/m^2$$

$$DM_s = 0.322\ kg/m^2 yr$$

The root zone is accumulating salt at a rate of 3220 kg (3.22 metric tons) per hectare per year.

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water from California's Feather River, which has a low salt content of about 60 mg/l, results in considerably more salt in the drain water due to dissolution in the soil and subsoil than due to the salt content of the irrigation water (Rhoades et al., 1974).

Soils and subsoil strata of arid regions may also contain residues of salts deposited during earlier eons of time by drying lagoons or lakes, or by sea-spray. Such dormant "fossil" deposits may be mobilized when irrigation is begun, or when the water balance is otherwise altered so that excess water percolates into the pre-salinated subsoil. Such occurrences are well known in connection with the saline seeps of Australia and the northern Great Plains of the U.S.A. (box 8) (Hillel, 1991).

The concentration of the soil solution may in places reach such levels of salinity that certain species of salts (primarily calcium carbonate and calcium sulfate, but eventually even sodium chloride) actually begin to precipitate and become stored in the soil profile in lenses of crystalline salts. Consequently, the amount of salt leached below the root zone may be less

than the amount applied in the irrigation water. Internal salt deposition by precipitation can be a significant component of the salt balance when the leaching fraction is low. However, such salt deposits tend to be highly labile, so that when the amount of irrigation is increased the salts so stored can quickly redissolve.

Salt removal by agronomic crops is generally too low to contribute significantly to the maintenance of the salt balance of irrigated soils. For example, the average amount of salt contained in mature crops of alfalfa, barley, corn silage, sudangrass, and sweet clover grown in Texas' Rio Grande area was about 3.6 percent of the dry mass (Lyerly and Longenecker, 1962).

A simplified form of the salt balance equation in relation to the water balance equation was offered by Buras (1974) for a complete annual period. Assuming that the net change in total soil-water content from one year to the next is close to zero, and disregarding surface runoff, the water balance per unit area is:

$$V_i + V_r + V_g = V_{et} + V_d$$

Figure 5   Formation of a saline seep
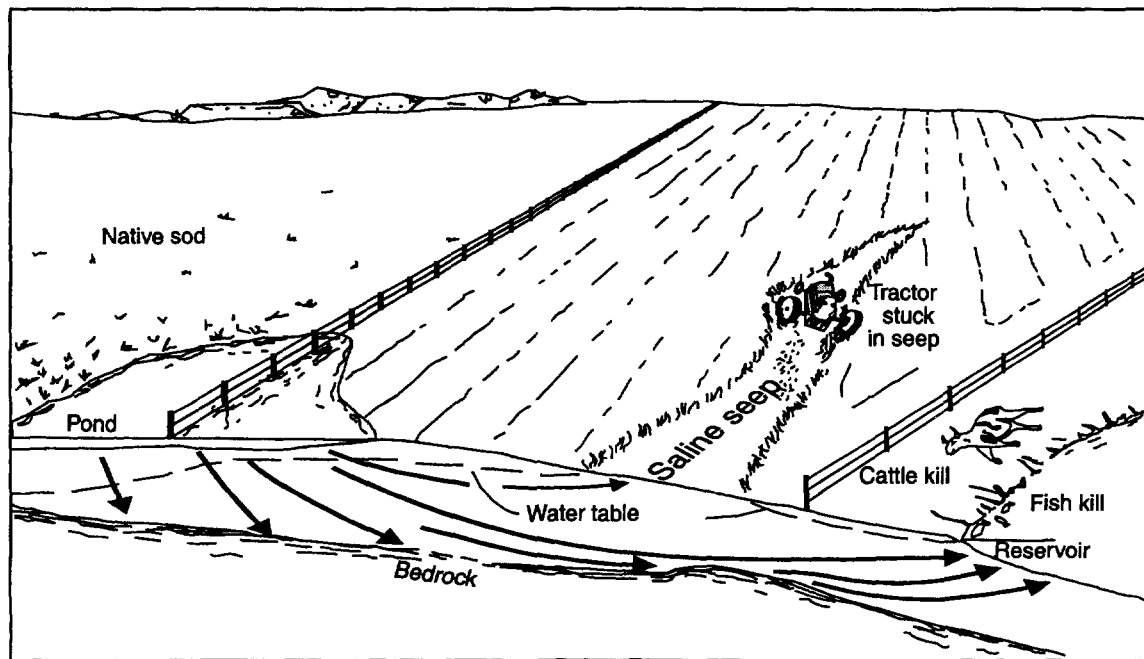
Source: Hillel (1991).

Here V_i, V_r, V_g, V_{et}, and V_d are total annual volumes of irrigation, atmospheric precipitation, capillary rise of groundwater, evapotranspiration, and drainage, respectively. Because evapotranspiration removes no salt and crops generally remove only a small amount, and if we disregard agricultural inputs and in situ precipitation and dissolution of salts, the salt balance corresponding to the above equation, assuming no accumulation, is

$$V_i c_i + V_r c_r = (V_d - V_g)\, c_d$$

Herein c_i, c_r, and c_d are the average concentrations of salt in the irrigation, rainfall, and drainage waters, respectively. If the water table is kept deep enough so that no substantial capillary rise into the root zone occurs, and since the salt content of atmospheric precipitation is usually small, the last equation further simplifies to:

$$V_i c_i = V_d c_d$$

Such an overall "black box" approach disregards the mechanisms and rates of salt and

water interactions in the root zone, as well as the changing pattern of salt distribution throughout the soil profile.

Most treatments of the salt balance have considered the relevant processes to be one-dimensional, i.e. vertical. In the case of furrow irrigation, however, where furrows alternate with ridges, salinity can vary laterally from the bottom of each furrow to the crest of each intervening ridge. As water spreads sideways from the furrows and rises up the ridges by capillary attraction, it carries along the salts dissolved in it, and as water is evaporated from the ridges the salts are deposited there (figure 6). The concentration of salts in the ridges of furrow irrigated fields is often high enough to inhibit seedling development during the subsequent season.

The pattern of salt distribution also varies laterally in the case of drip irrigation, where widely spaced emitters deliver water to separate points on the surface (or below the surface) of the soil, from each of which points the water spreads radially. An oft-observed phenomenon is the appearance of crystalline salts in the form

Box 8   Saline seeps in Australia and North America

Human management of the land may lead to unforeseen environmental consequences. A striking example is the saline seep phenomenon in Australia and North America. A few decades ago, Australian farmers were startled to notice that brine began to ooze out of low spots in their fields. Subsequent research revealed the phenomenon to be the delayed result of the extensive clearing of land carried out in southern Australia a century earlier.

Rains falling on land along the coasts of Australia mix with the sea spray, which forms by the splash of ocean waves against the shore and is wafted onto the land by the winds. Over eons of history, the brackish rains deposited a load of salt onto the soil. Native forests extracted moisture from the soil but left the salt behind. Slowly, the saline solution percolated beyond the root zone, gradually charging the subsoil with residual salts.

When European settlement of Australia began in the mid-1800s, the settlers cleared away the forest along the southeastern and southwestern edges of the continent. This changed the water regime. In the natural evergreen forest, part of the rain had been intercepted by the foliage and then evaporated without ever reaching the ground, and moisture extraction by the deep roots was continuous. The seasonal, shallow-rooted crops planted by the settlers ex-

tracted and evaporated less moisture. The increased fraction of rainfall that percolated downward eventually came to rest over an impervious stratum and formed a water table. That water also mobilized the salt that had accumulated in the subsoil in eons past. Gradually, the water table rose, and with it returned the ancient salt. All the while, the farmers and ranchers were oblivious to what was happening down below, so when the brine reached the surface and formed splotches of sterile soil, it came as a total surprise.

Saline seeps also occur in North America, both in the U.S and in the prairies of Canada. Tractors bog down or cut deep ruts in the low spots where the brine flows out. Here, the original vegetation was perennial grass, not trees, and the source of the salts was not sea spray but underlying deposits of marine shales, originating in an earlier geologic era. However, the process by which the seeps became manifest was similar in both continents: it resulted from human disruption of a preexisting equilibrium.

The saline seep problem can be remediated in many locations, but the task may well require time and considerable expense. Seasonal, shallow-rooted crops can be replaced with evergreen, perennial, deep-rooted vegetation capable of lowering the water table over the entire area contributing to the seeps, and drains can be installed within the seeps themselves to ensure the environmentally safe disposal of the emerging brine.

Figure 6   Salt accumulation patterns under furrow irrigation

Flat-top beds and irrigation practice

Salinity with sloping beds
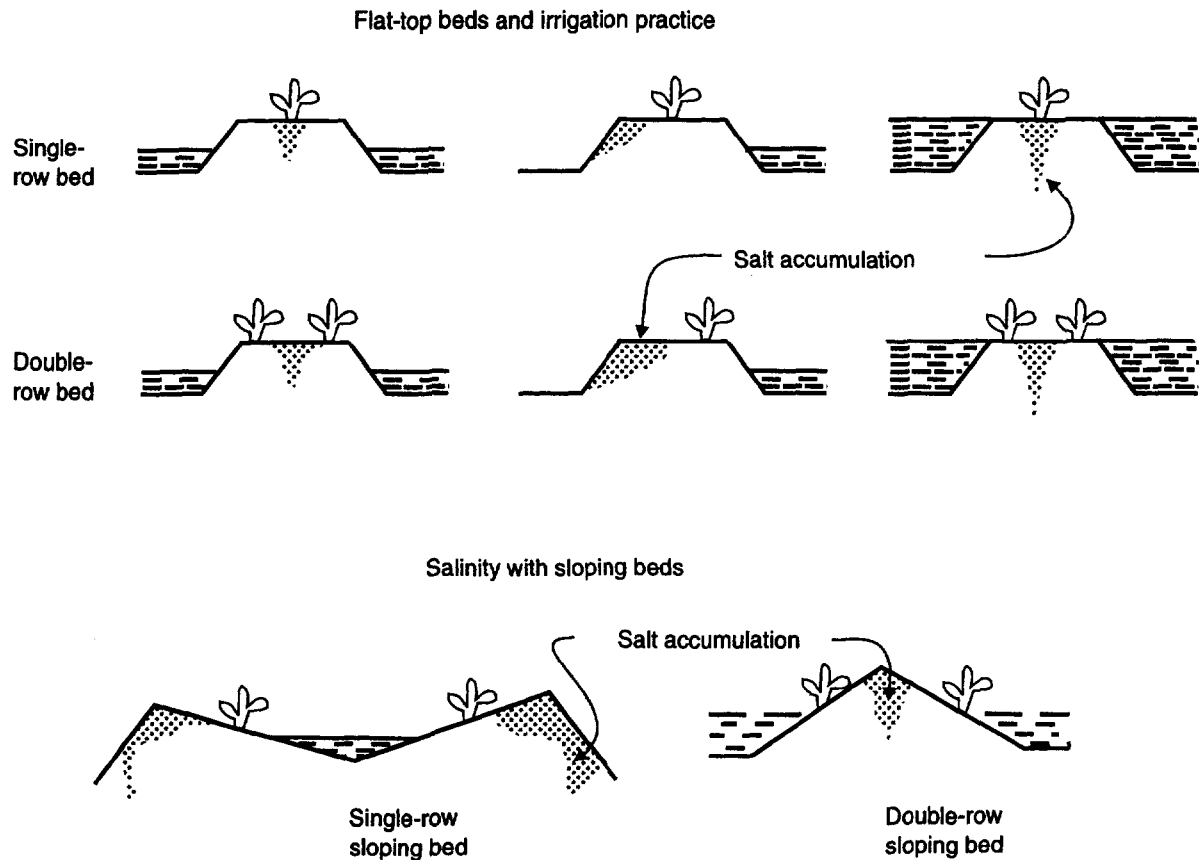
Source: Bernstein et al. (1955); Bernstein and Fireman (1957).

of rings around the perimeters of the wetted spots. As in the case of furrow irrigation, such localized accumulations of salt may affect the seedlings of a crop planted in a subsequent season, unless the rings of salt are leached away during the intervening period by rains or by sprinkling irrigation.

In any case, knowledge of the spatial distribution of salts in various zones of the soil may permit preferential planting where salts are least concentrated. End-of-season plowing and other modes of tillage tend to obliterate the localized salt concentrations and to redistribute the salts throughout the surface zone of the field.

Effects on Crops

Plants that are especially adapted to grow under saline conditions are called *halophytes*. Plants that are not so adapted, called *glycophytes*, generally exhibit symptoms of physiological stress when subjected to salinity. Most crop plants are of the latter category, though they vary from one another in the degree of their sensitivity. A condition of *stress* is such that prevents a plant from realizing its full potential for growth, development, and repro-

duction. In reality, there is no sharp dividing line between the occurrence or absence of stress. Rather, plant response to increasing salinity is a continuum, varying from no apparent stress to intense stress (figure 7). Hence there is no clear distinction between salt-tolerant and salt-intolerant crops. Even varieties or genotypes within a given species may differ significantly in their responses to various, or varying, levels of salinity.

Figure 7   Plant responses to salinity
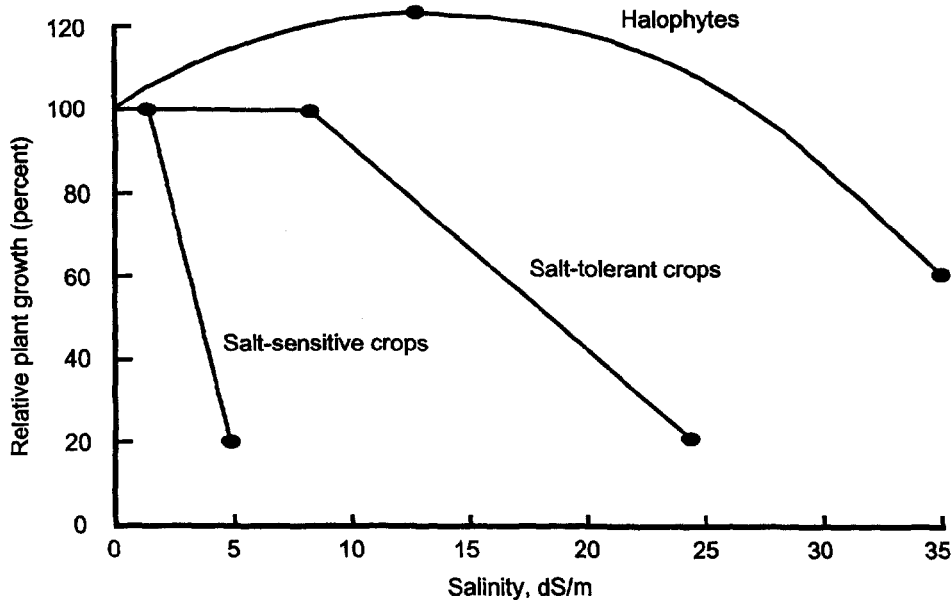
Halophytes increase yields at low concentrations; *salt-tolerant crops* reduce yields beyond a threshold; *salt-sensitive crops* suffer even at low salinity.

Source: NRC (1990).

Sensitivity to Salinity

Anatomical and physiological differences between halophytes and glycophytes reflect their variability in salt tolerance. In time, geneticists may find ways to implant salt tolerance attributes in crops that are at present salt-sensitive. Thus far, however, there do not seem to be any dramatic breakthroughs in plant breeding for salinity tolerance.

Among crops that are considered salt tolerant are barley, sugar beet, table beet, asparagus, spinach, tomato, cotton, and Bermuda grass. Among crops that are known to be sensitive (i.e., to have low tolerance) to salinity are radish, celery, beans, clovers, and nearly all fruit trees.

Salt concentration in the ambient solution (in the root zone) depresses the *energy potential* of water in the solution, thus requiring a greater exertion of energy by the plant to extract the water it requires. The plant does this by concentrating the internal solution of its cells by two mechanisms: absorption of salt from the medium or synthesis of organic solutes. This process, called "osmotic adjustment," requires the investment of additional metabolic energy, i.e. of photosynthates (Epstein, 1980), so as to lower the plant's own water potential further below that of the external solution from which it must draw water.

Highly salt-tolerant plants, or halophytes, tend to absorb salts from the medium and sequester it in the vacuoles, while organic compatible solutes serve the function of osmotic adjustment in the cytoplasm. As most crop plants (i.e., glycophytes) are salt-sensitive, they tend to exclude sodium and chloride from the shoots and, especially, the leaves. Hence they have to rely more heavily than do halophytes on the synthesis of organic osmolytes.

In extreme conditions of very high salinity, the external osmotic potential may be depressed below that of the cell water potential, thus resulting in the net outflow of water from the plant and in osmotic desiccation (a condition called *plasmolysis*). Even where conditions are not so extreme, salinity reduces the availability of water to the plant.

The salt sensitivity of a plant can be defined as the plant's capacity to endure the effects of excess salt in the medium of root growth (Maas,

1990). Implicit in this definition is the idea that a plant can withstand a certain concentration of salt without experiencing adverse effect. In fact, the sensitivity of a plant to salinity depends on a multiplicity of interacting factors and conditions, including the climate (temperature and potential evaporation), soil fertility (availability of nutrients) and soil physical conditions (porosity, aeration, and water regime). Plant sensitivity also varies with the physiological stage of crop development. Although a plant's capacity to tolerate salinity cannot be determined in absolute terms, the relative responses of various plants may be compared under definable conditions (figure 8).

Reliance on the mean seasonal salinity of the soil as a criterion may be misleading, as the soil solution typically fluctuates during the growing season. Even occasional or temporary increases of salinity that exceed a crop's tolerance limit may affect crops deleteriously, especially if they occur during sensitive stages of plant development.

The salt sensitivity of a crop may express itself in three developmental stages: germination, vegetative growth, and reproductive function. Some halophytes, whose vegetative growth is often stimulated by salinity, may not be salt-tolerant during germination. On the other hand, some salt-sensitive plants whose vegetative development is inhibited by salinity, may germinate readily in the presence of high concentrations of salt. If the plants do succeed in overcoming salinity during the germination and growth stages, some species of non-halophytes become more tolerant during reproductive development. However, no absolute rule prevails, as plants differ widely both in the degree and in the stage of their sensitivity to salinity.

Salt sensitivity changes during the growth cycle of a plant. Root growth is often less affected by salinity than shoot growth (Lauchli and Epstein, 1990), particularly when supplemental calcium is provided. In the shoot, decrease of leaf area is commonly observed in conditions of salinity, evidently a consequence of the osmotic effect on reduction of turgor. The salinity tolerance of many (but not all) plants increases as the plant matures (Maas, 1990; Pasternak, 1987).

Figure 8   Classification of crop tolerance to salinity
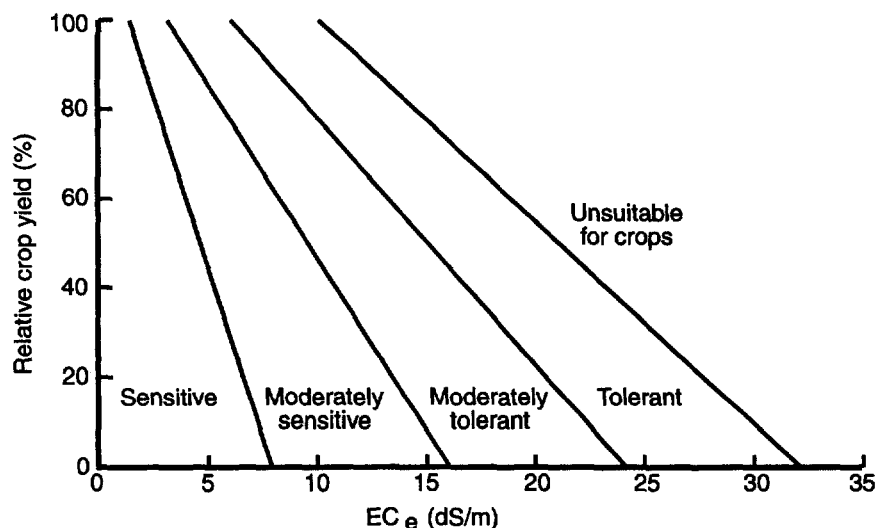
Source: After Maas (1990).

The terms *salinity tolerance* and *salinity resistance* are often used interchangeably. Another occasionally used term is *salt avoidance*. The appropriate term in each case depends on the plant's specific physiological response to salt stress. Tolerance implies that the plant is able to grow more or less normally in the presence of higher levels of salinity, though often at a diminished rate. Resistance implies that the plant can develop active biological mechanisms to counter the effects of salinity. Salt avoidance is the ability of plants to curtail or suspend activity so as to endure periods of salt stress, and to recover growth and development when conditions improve.

Of those various terms, tolerance is generally the most apt (Shannon and Noble, 1990). All responses to salinity depend in a complex way on the anatomical and physiological attributes of the plant. Since there is no single attribute that determines the capacity of a plant to survive or even thrive in a saline medium, the task of promoting tolerance is very difficult. The much easier approach in most cases is to prevent salinity from building up to harmful levels from the outset.

Plants suffer water stress sooner when osmotic pressure is high, and salinity can upset plant nutrition when an imbalance of certain essential nutrients occurs. As mentioned, sa-

line conditions force the plant to divert to increased maintenance some of the energy that it could otherwise invest in net growth. Salination of the root zone initially raises the rate of maintenance respiration in many species, but total respiration eventually falls along with reduced photosynthesis.

Many workers have employed the concept of "threshold salinity" to characterize the dependence of relative crop yield (Y_r) on salinity:

$$Y_r = 100 - b(EC_e - a)$$

where a is the salinity threshold expressed in dS/m; b is the slope expressed in percent change in yield per dS/m; and EC_e is the mean electrical conductivity of the root zone (usually measured using the saturated paste technique). This relationship implies a linear dependence of yield on soil salinity. Accordingly, farmers need know the levels of soil salinity that begin to reduce the yields of specific crops and by how much the yield of each crop is reduced at levels above its threshold.

Crop response to soil salinity may be described more accurately by means of a sigmoidal (rather than linear) relationship, such as offered by van Genuchten (1983):

$$Y_r = Y/[1 + (c/c_{50})^p]$$

where Y is the yield under non-saline conditions, c is the average salinity of the root zone, c_{50} is the salinity of the root zone that reduces yield by 50 percent, and p is an empirical constant. The usefulness of this relationship may be limited by its greater complexity and the difficulty of determining its parameters.

Specific Element Effects

Beyond the general effects of salinity on crops, there can also be specific ion effects (Lauchli and Epstein, 1990; Maas, 1990). High concentrations of one or another ion commonly associated with salinity may cause disorders in mineral nutrition (figure 9). For example, high sodium (Na) concentrations have been observed to interfere with plant uptake of such essential nutrient elements as potassium or calcium, and that is quite apart from its detrimental effect on the soil's physical properties. On the other hand, calcium at elevated concentrations often mitigates some of the adverse effects of moderate levels of salinity. However, certain elements, primarily chloride, may have specific toxic effects beyond interference with the uptake of nutrients. The element boron (B) is another example.

Sodium and chloride are particularly toxic to fruit crops and woody ornamentals. When the leaves of these plants accumulate more than about 0.5 percent chloride or 0.25 percent sodium on a dry weight basis, they tend to develop characteristic leaf injury symptoms.

Sodium, while not considered an essential element for most crops, may nonetheless be beneficial when present in concentrations below the threshold of salt tolerance. Above that threshold, sodium becomes harmful, especially for woody species. Tolerance to Na^+ varies widely among species and rootstocks. In the case of such crops as avocado, citrus, and stone-fruit trees, injury may occur at soil solution concentrations as low as 5 mmol/l. According to Bernstein et al. (1975), sodium is absorbed and retained for a time in the roots and lower trunk, but after some years the sapwood is converted to heartwood and the accumulated sodium ion is released. It is then transported up the canopy, where it may cause leaf scorch.

Chloride is an essential micronutrient for most crops, albeit in very small amounts. Even at higher concentrations, it is not particularly toxic, except to certain crops, e.g., soybeans. According to Parker et al., 1983, the decisive attribute appears to be the ability of plants to

Figure 9   Effects of salinity and sodicity on plants
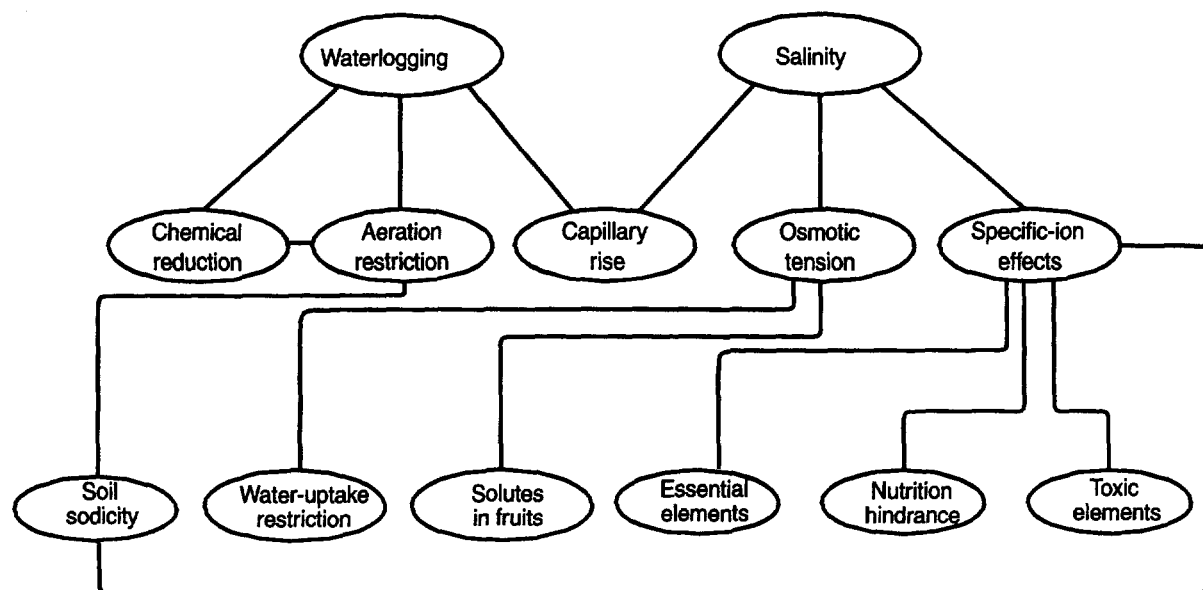
Source: Lauchi and Epstein (1990).

restrict the transport of Cl⁻ from the roots to the shoots. Many woody species are sensitive to Cl⁻ toxicity, though the degree of sensitivity varies among varieties and rootstocks (Maas, 1990).

Boron is an essential element for plants in minute concentrations, but becomes toxic at somewhat higher concentrations. For some plants, the threshold of toxicity may be as low as a few parts per million (ppm) in the ambient solution. Boron is toxic to many plants when it accumulates in susceptible tissue to reach concentrations exceeding about 0.1 mg/kg.

Symptoms of excess boron may include chlorotic and necrotic patterns of leaves, though some sensitive fruit crops may be suffer reduction of yield even without visible injury. The concentration of boron in leaves is normally in the range of 40 to 100 ppm of the dry mass, but may rise to 250 ppm where the soil approaches toxic levels. The concentration may even approach 1000 ppm in extreme conditions of boron toxicity.

Citrus and avocado are especially vulnerable to boron toxicity. The typical symptom is tip burn or marginal burn of mature leaves, accompanied by chlorosis (yellowing) of interveinal tissue. Stone fruits, apples, and pears are also sensitive to boron. Cotton, grapes, potatoes, beans, and peas, among other crops, exhibit marginal burning and cupping of the leaves as well as general restriction of leaf growth.

Maas (1990) provided a list of threshold tolerances for a large number of crops, based largely on the early work of Eaton (1944), as well as much more recent work by Bingham et al. (1985) and Francois (1988, 1989). The data provided do not apply equally to all situations, as boron tolerance (like salt tolerance in general) is known to vary with climate and soil conditions, as well as with the crop.

Bingham et al. (1985) demonstrated that yield reductions due to boron toxicity can be fitted to a two-parameter empirical relationship (Maas and Hoffman, 1977):

$$Y = 100 - m(x - A)$$

where Y is the relative yield, m is the reduction in yield per unit rise in boron concentra-

tion, A is the maximum concentration of B that does not reduce yield (threshold value), and x is the boron concentration in the soil solution.

The effect of boron on crop yield obviously depends on its concentration in the irrigation water, as well as on the physiological sensitivity (or tolerance) of the crop to this element. It also depends on the irrigation regime (particularly the volume and frequency of water application), inasmuch as that regime determines how high the concentration of boron (as well as of other solutes) is allowed to rise in the root zone above its level in the irrigation water. Ideally, the leaching fraction should be such as to prevent a significant rise in boron between successive irrigations (Bingham et al., 1985). Since boron is adsorbed onto and released from the surfaces of clay particles, soil solutions are somewhat buffered against rapid changes in boron concentration. In the long run, however, a steady-state is approached, as the amount of boron in the exchange complex equilibrates with the concentration of this element in the soil solution, which itself is influenced by the concentration of the irrigation water as well as the leaching fraction.

Toxic concentrations of boron occur mainly in arid regions. Although most surface waters do not generally contain excessive concentrations of boron, well waters occasionally do. Since different plant species and varieties vary in their response to boron, irrigation water that is unsuitable for particularly sensitive crops may be suitable for more tolerant ones.

The hazard of boron toxicity persists and may even worsen in recycled and desalted water. Desalination processes such as reverse osmosis may not eliminate traces of boron that might still be present in potentially harmful concentrations.

Selenium, the most studied trace element for its effects on wildlife, may cause damage at concentrations as low as 1 ppb. Its bioaccumulation has been found to cause birth deformities and deaths in several species of waterfowl at California's Kesterson Reservoir (Jacobs, 1989).

Ca, Mg, and K are the major cations required for plant nutrition. Fe, Mn, Zn, and Cu are also required, but in much smaller quantities. In sodic, non-saline soils, deficiencies of Ca and

Table 1   Relative salt tolerances of various crops

Grain crops		Electrical conductivity of saturated-soil extract		
Common name	Botanical name	Threshold dS/m	Slope % per dS/m	Tolerance rating[1]
Barley	Hordeum vulgare	8.0	5.0	T
Bean	Phaseolus vulgaris	1.0	19.0	S
Broad bean	Vicia faba	1.6	9.6	MS
Corn	Zea mays	1.7	12.0	MS
Cotton	Gossypium hirsutum	7.7	5.2	T
Cowpea	Vigna unguiculata	4.9	12.0	MT
Flax	Linum usitatissimum	1.7	12.0	MS
Millet, foxtail	Setaria italica			MS
Oats	Avena sativa			MT
Peanut	Arachis hypogaea	3.2	29.0	MS
Rice, paddy	Oryza sativa	3.0	12.0g	S
Rye	Secale cereale	11.4	10.8	T
Safflower	Carthamus tinctorius			MT
Sesame	Sesamum indicum			S
Sorghum	Sorghum bicolor	6.8	16.0	MT
Soybean	Glycine max	5.0	20.0	MT
Sugar beet	Beta vulgaris	7.0	5.9	T
Sugarcane	Saccharum officinarum	1.7	5.9	MS
Sunflower	Helianthus annuus			MS
Triticale	X Triticosecale	6.1	2.5	T
Wheat	Triticum aestivum	6.0	7.1	MT
Wheat (semi-dwarf)	T. aestivum	8.6	3.0	T
Wheat, durum	T. turgidum	5.9	3.8	T
Alfalfa	Medicago sativa	2.0	7.3	MS
Bermuda grass	Cynodon dactylon	6.9	6.4	T
Clover, alsike	Trifolium hybridum	1.5	5.7	MS
Clover, berseem	T. alexandrinum	1.5	5.7	MS
Clover, hubam	Melilotus alba			MT
Clover, ladino	Trifolium repens	1.5	12.0	MS
Clover, red	T. pratense	1.5	12.0	MS
Clover, strawberry	T. fragiferum	1.5	12.0	MS
Corn (forage)	Zea mays	1.8	7.4	MS
Cowpea (forage)	Vigna unguiculata	2.5	11.0	MS
Fescue, tall	Festuca elatior	3.9	5.3	MT
Foxtail, meadow	Alopecurus pratensis	1.5	9.6	MS
Harding grass	Phalaris tuberosa	4.6	7.6	MT
Love grass	Eragrostis sp.	2.0	8.4	MS
Orchard grass	Dactylis glomerata	1.5	6.2	MS
Ryegrass, perennial	Lolium perenne	5.6	7.6	MT
Sudan grass	Sorghum sudanense	2.8	4.3	MT
Timothy	Phleum pratense			MS
Trefoil, big	Lotus uliginosus	2.3	19.0	MS
Trefoil, narrowleaf	L. corniculatus	5.0	10.0	MT
Vetch, common	Vicia angustifolia	3.0	11.0	MS
Wheat (forage)	Triticum aestivum	4.5	2.6	MT
Wheat, durum (forage)	T. turgidum	2.1	2.5	MT
Wheat grass, standard crested	Agropyron sibiricum	3.5	4.0	MT
Wheat grass, fairway crested	A. cristatum	7.5	6.9	T
Artichoke	Helianthus tuberosus			MT
Asparagus	Asparagus officinalis	4.1	2.0	T
Bean	Phaseolus vulgaris	1.0	19.0	S

(Table continues on next page)

Table 1 *(continued)*

Grain crops		Electrical conductivity of saturated-soil extract		
Common name	*Botanical name*	*Threshold dS/m*	*Slope % per dS/m*	*Tolerance rating[1]*
Beat, red	Beta vulgaris	4.0	9.0	MT
Broccoli	Brassica oleracea botrytis	2.8	9.2	MS
Cabbage	B. oleracea capitata	1.8	9.7	MS
Carrot	Dacus carota	1.0	14.0	S
Celery	Apium graveolens	1.8	6.2	MS
Corn, sweet	Zea mays	1.7	12.0	MS
Cucumber	Cucumis sativus	2.5	13.0	MS
Eggplant	Solanum melongena esculentum	1.1	6.9	MS
Lettuce	Lactuca sativa	1.3	13.0	MS
Onion	Allium cepa	1.2	16.0	S
Pepper	Capsicum annum	1.5	14.0	MS
Potato	Solanum tuberosum	1.7	12.0	MS
Radish	Raphanus sativus	1.2	13.0	MS
Spinach	Spinacia oleracea	2.0	7.6	MS
Squash, scallop	Cucurbita pepo melopepo	3.2	16.0	MS
Squash, zucchini	C. pepo melopepo	4.7	9.4	MT
Strawberry	Fragaria sp.	1	33	S
Sweet potato	Ipomoea batatas	1.5	11	MS
Tomato	Lycopersicon lycopersicum	2.5	9.9	MS
Turnip	Brassica rapa	0.9	9	MS
Almond	Prunus duclis	1.5	19.0	S
Apple	Malus sylvestris			S
Apricot	Prunus armeniaca		24.0	S
Avocado	Persea americana	1.6		S
Blackberry	Rubus sp.		22.0	S
Boysenberry	Rubus ursinus	1.5	22.0	S
Cherry, sweet	Prunus avium	1.5		S
Date palm	Phoenix dactylifera		3.6	T
Fig	Ficus carica	4.0		MT*
Grape	Vitis sp.		9.6	MS
Grapefruit	Citrus paradisi	1.5	16.0	S
Guayule	Parthenium argentatum	1.8	13.0	T
Lemon	Citrus limon	15.0		S
Mango	Mangifera indica			S
Olive	Olea europaea			MT
Orange	Citrus sinensis		16.0	S
Papaya	Carica papaya	1.7		MT
Passion fruit	Passiflora edulis			S
Peach	Prunus Persica		21.0	S
Pear	Pyrus communis	1.7		S
Persimmon	Diospyros virginiana			S
Pineapple	Ananus Comosus			MT
Plum; Prune	Prunus domestica		18.0	S
Pomegranate	Punica granatum			MT
Pomelo	Citrus maxima			S
Raspberry	Rubus idaeus			S

[1] Ratings: S = Sensitive; T = Tolerant; M = Moderately.

Source: Selected from list compiled and referenced by Maas (1990).

Mg may occur, and the addition of these elements as fertilizers or soil amendments may be advisable.

A final consideration is the possible accumulation in plants of elements that may not be directly harmful to plants but that can be hazardous to consumers. Such "minor" elements as selenium and molybdenum may be toxic to humans and animals.[1] Toxic elements that are of particular concern are those that can concentrate as they move up the food chain, a process called *biomagnification* (Page et al., 1990).

Tabulated salt tolerances of various crops are listed in Table 1, based on the comprehensive listing provided by Maas (1990). The dependence of relative crop yield on electrical conductivity of the soil solution is shown schematically in Figure 8 for plants of various sensitivity or tolerance levels.

Note

1. Although selenium is essential to humans and animals in trace amounts, excessive amounts can cause toxicosis.

Irrigation Water

Water Quality

The quality of irrigation water affects soil salinity and sodicity, cation exchange, soil acidity or alkalinity, nutrient availability, clay dispersion and flocculation, and soil structure (the latter, in turn, affects soil-water relations as well as soil aeration). Clearly, therefore, the composition of irrigation water is an important determinant of crop growth and agricultural-drainage quality. To avoid the accumulation of salts to toxic levels, their inputs to the soil must not exceed the rate of their removal from the soil, or of their conversion to unavailable forms within it. The control of soil salinity must therefore include measures to control both the inputs and the outputs of salts.

Solutes are added to the soil solution in irrigation water infiltrated from above, in groundwater rising by capillarity from below, in the dissolution of salts initially present in solid form within the soil and subsoil. Removals of solutes from the soil include uptake by plants, downward transport by percolation and drainage (leaching), erosion of the soil surface by overland flow and by wind, precipitation or adsorption onto the solid phase and conversion to unavailable forms, and—for some substances—volatilization of gaseous compounds.

The hazard of plant stress and soil salination posed by irrigation water containing salts of varying composition and concentration depends on soil conditions, climatic conditions, crop species and variety, and the amount and frequency of the irrigation applied. In general, irrigation water of EC lower than 0.7 dS/m poses little or no danger to most crops, whereas EC values greater than 3.0 dS/m may restrict the growth of most crops (Ayers and Wescot, 1983).

The salinity of irrigation water is defined as the total sum of dissolved inorganic ions and molecules. The major components of salinity are the cations Ca, Mg, and Na; and the anions Cl, SO_4, and HCO_3. The potassium, nitrate, and phosphate ions, however important nutritionally, are usually minor components of soil salinity. In addition, certain constituents (such as boron) may have an important effect on crop growth even though their concentrations are usually too low to have any substantial effect on the soil's total salinity.

Irrigation waters of different sources, locations, and seasons vary greatly in quality. Some irrigation waters contain as little as 50, and others as much as 3,000 grams of salts per cubic meter. Since the volume of water applied in irrigation to a crop during its growing season commonly varies between 5,000 and 20,000 cubic meters per hectare, the salt input to a crop may thus range between 250 kg and as much as 60,000 kg per hectare. That is a very wide range indeed. Water quality categories based on total dissolved salts are given in Table 2.

Another important criterion of irrigation water quality is the sodium adsorption ratio (SAR) (figure 10). High alkalinity of irrigation water, manifested when the pH value is above 8.5, generally indicates the predominant presence of sodium ions in the solution, and poses a danger of soil sodification. Freshly pumped

Table 2   Classification of water quality according to total salt concentration

Designation	Total dissolved salts (ppm)	EC (dS/m)	Category
Fresh water	<500	<0.6	Drinking and irrigation
Slightly brackish	500-1,000	0.6-1.5	Irrigation
Brackish	1,000-2,000	1.5-3	Irrigation with caution
Moderately saline	2,000-5,000	3-8	Primary drainage
Saline	5,000-10,000	8-15	Secondary drainage and saline groundwater
Highly saline	10,000-35,000	15-45	Very saline groundwater
Brine	>35,000	>45	seawater

groundwater may have a high sodium adsorption ratio even if the pH is below 8.5, owing to the presence of dissolved CO_2 (which forms carbonic acid, $H^+ + HCO3^-$). Samples of such water should be aerated to allow the CO_2 to effervesce prior to measurement of the pH.

With high SAR water, irrigation by sprinkling will increase the soil's tendency to form a surface seal (crust) under the impact of the drops striking the bare soil. Flood irrigation may also cause the breakdown of soil aggregates by air slaking (Hillel, 1998). On the other hand, application of water by drip, at spaced points on the surface or below it, may lessen the physical disruption of soil structure that would otherwise take place under the influence of high SAR water.

High pH water may cause nutritional, as well as structural, problems. The addition of gypsum to the water or to the soil surface may help in both respects. The natural presence of calcite (calcium carbonate) in finely fragmented form in the soil may also help to mitigate the effect of high-sodicity irrigation water. Its dissolution by acidic rainwater, especially in the surface zone, tends to reduce SAR and to increase the electrolyte concentration. However, in soils that do not contain lime or gypsum, rainfall may even do more harm than good to soil structure. Where it is nearly pure (EC below 0.06 dS/m), rainwater reaching the surface leaches away the salts present there, and may cause spontaneous dispersion of clay, especially if its ESP is high.

Use of Brackish and Saline Water

Extensive studies have shown that, in certain circumstances, and with appropriate precau-

tions, available brackish water can be used safely, and even advantageously, for the irrigation of salt-tolerant crops. This is especially the case in arid regions with deep sandy soils, where drainage is unrestricted and there is little risk of either groundwater rise or of soil salination and sodification.

Various strategies have been proposed for the use of saline water, or for the reuse of brackish drainage water. One way is to use the water as is, directly, for irrigation. Another way is to alternate the applications of the brackish water with applications of better quality water, where such is available. A third way is to blend good-quality water with brackish water so as to extend the water supply, thus in effect gaining quantity at the expense quality. It appears that the optimal strategy depends on circumstances (e.g., how saline is the brackish water? How good is the quality of the nonsaline water? How tolerant are the crops to be grown? How sensitive is the soil? etc.). Therefore, no universal principle can be expected to apply equally in all cases. Sinai et al. (1988) provided a theory, design criteria for a network blending systems, and methods of automatically diluting saline water sources for irrigation. However, in the opinion of Grattan and Rhoades (1990), the cyclic strategy is generally preferable to the blending strategy, as it obviates the need for a blending facility and allows the soil to be flushed out more completely from time to time, as the need arises.

To evaluate reuse potential, standard water sampling techniques and analysis can be used (Chapman and Pratt, 1982). The most important water quality parameters are EC, SAR, and boron concentration, as well as the concentra-

Figure 10 Diagram for assessing salinity and sodicity hazards of irrigation water
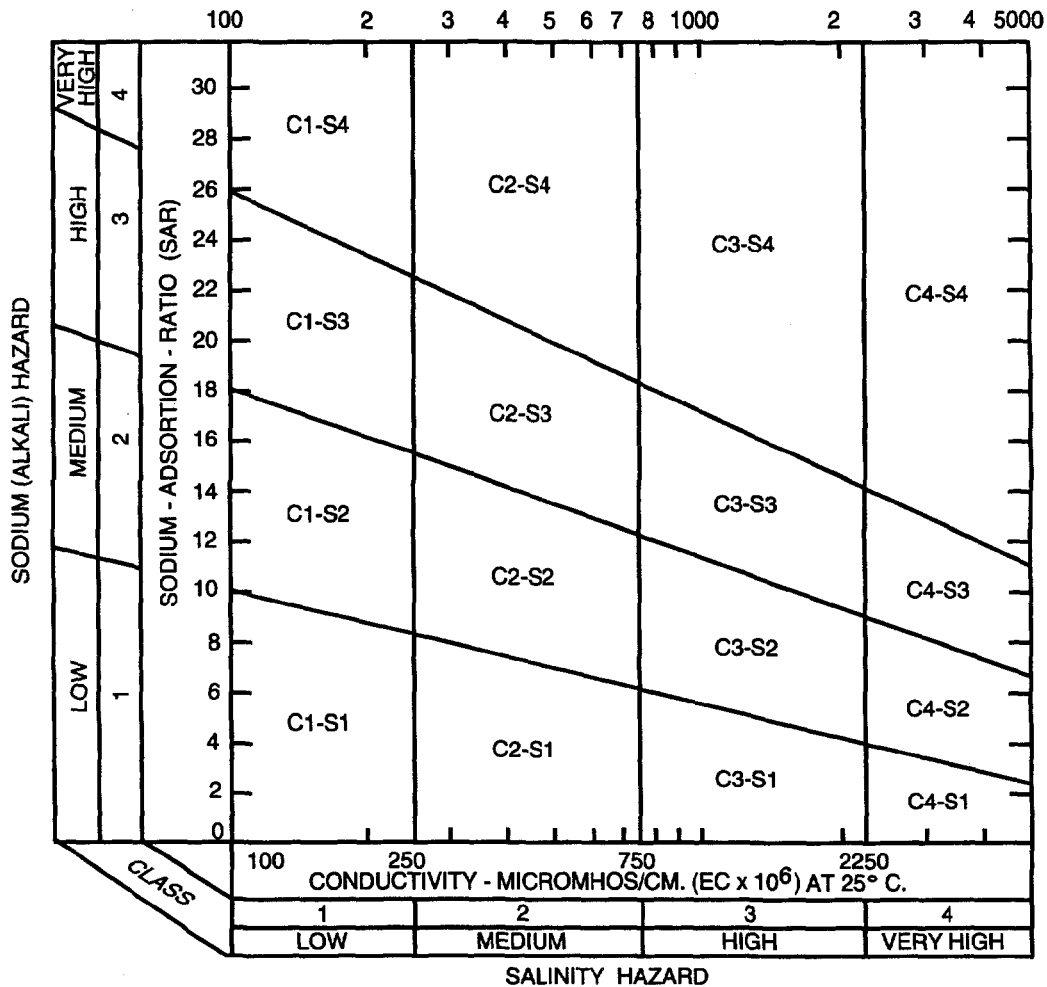
Source: Richards (1954).

tion of other potentially toxic elements. Irrigation water that contains more than 5 mg/l boron can be detrimental to many crops.

Irrigation water with EC of 4 dS/m was reported to improve the soluble solids content of relatively tolerant crops such as melons and tomatoes (Grattan et al., 1987), to raise the protein content of wheat and alfalfa, to increase the total digestible nutrients in alfalfa, and to improve the color and netting of cantaloupe (Rhoades et al., 1988). However, the use of brackish water for sprinkling irrigation may cause foliar injury. The degree of injury depends on the following factors: concentrations of ions in the water, sensitivity of the crop at various stages of growth, water stress of the plants prior to irrigation, and frequency of sprinkling. The potential damage also depends on the prevailing environmental conditions, including the temperature and relative humidity of the atmosphere, which affect the rate of evaporation. Sprinkling at night, when atmospheric temperature and evaporativity are relatively low, evidently reduces foliar absorption and injury (Pratt and Suarez, 1990).

The greater the rate of evapo-transpiration and the longer the interval between irrigations, the more concentrated the residual solution in the root zone and the more severe the salt stress imposed on the plants. Hence, when the irrigation water is brackish, a common management strategy is to increase the frequency of

irrigation so as to maintain a high level of water potential in the root zone. This strategy can help to prevent an excessive rise in the concentration of the soil solution toward the end of each interval between irrigations. Thanks to its ready adaptability to high frequency irrigation, drip irrigation beneath the canopy appears to be the most appropriate method to use with brackish water, especially as it avoids direct foliar exposure to saline water. In some soils, however, increasing irrigation frequency may also result in impedance of soil aeration and increased risk of root disease (Grattan and Rhoades, 1990).

The use of brackish water for irrigation may be environmentally beneficial in a larger sense. Intercepting drainage effluents before they are mixed back into the river and using them to irrigate certain crops in the agronomic rotation can help to reduce the salinity of river systems (Rhoades, 1984).

When the drainage water quality is so deteriorated that its potential for reuse is exhausted, this water can be discharged into evaporation ponds. Although ponds provide temporary relief, they cannot generally be sustained, because evaporation may result in the deposition of salts that contain hazardous levels of trace elements. In the latter case, strict precautions must be taken to prevent damage to wildlife, including aquatic birds. The problem is complicated by the fact that agricultural drainage waters may contain, in addition to the salt load, an appreciable concentration of pesticide residues, fertilizers, and toxic trace elements.

A technology that is often mentioned as a possible solution to the problem of water salinity is the process of desalination. It is used mainly to convert sea water and brackish water for direct human use, but in most cases has not yet been found to be economical for the irrigation of crops in the field. Of the various desalination methods, the one that seems most promising at present for the conversion of brackish water is *reverse osmosis*. It consists of forcing water under pressure through selective membranes, which permit the passage of water molecules but not of salts or suspended materials.

The problems associated with this technique of desalination (as well as with other techniques) are the high energy requirements, the frequent need to replace deteriorated membranes, the passage of boron through the membranes, and the need to dispose of the residual brine safely. Estimates of the costs of desalination by reverse osmosis vary from $0.50 per cubic meter to over $1.00, depending on the composition and concentration of the salts in the original solution, and on the costs of energy, brine disposal, and water conveyance. Alternative processes of desalination include distillation, freezing, and the use of ion exchange resins.

Drainage water may also be used in a system of agro-forestry. Salt-tolerant trees have the capacity to thrive when irrigated with brackish water, and also have the potential to lower the water table by the extraction and transpiration of water from deeper layers in the soil, thus to reduce the volume and expense of needed drainage in an area. Among the trees suitable for this type of agro-forestry are certain species of eucalyptus, acacia, casuarina, poplar, mesquite, Elderica pine (Lee, 1990), and tamarisk. The harvested wood may be used for fuel, for pulp, or for construction.

A publication issued by the U.S. National Research Council (1990) lists and describes scores of salt-tolerant plants, native to various saline areas, that may be capable of utilizing land and water unsuitable for conventional salt-sensitive crops (*glycophytes*). Some of the plants described can perhaps be grown with highly saline waters for the purpose of providing food, fodder, fuel, and other products. *Halophytes* (plants adapted naturally to growing in saline environments) can utilize saline water resources that are generally neglected and are usually considered impediments rather than opportunities for development. However, most undomesticated halophytes display poor agronomic qualities, such as wide variation in germination and maturation, tendencies to seed-shattering and lodging, as well as possible toxicities. The possibility of turning some of the many listed plants into economic crops is a worthy goal,

but will require much research in the coming decades.

Reuse of Wastewater

Decomposition in the soil is nature's way to recycle the organic products of terrestrial biological activity. As long as population density remained sparse, the waste products of human activity could be similarly accommodated. The growth of cities and of industries, however, produced quantities of solid and liquid wastes in excess of the soil's ability to reprocess in the immediate domain of human habitation. Some societies (notably, in China and other parts of Asia) continued to transport human wastes from cities to agricultural land for the purpose of fertilizing crops and replenishing soil nutrients. In many other places, the uncontrolled discharge of garbage and sewage ended up polluting streams and wells, to the detriment of the environment and public health.

With the advent of integrated sewerage systems in the cities of Europe at the beginning of the modern age, interest in land application increased (Shuval et al., 1986). A report issued in 1865 by the First Royal Commission on Sewage Disposal in England stated: "The right way to dispose of town sewage is to apply it continuously to the land and it is by such application that the pollution of rivers can be avoided." In 1868, Victor Hugo, in his "Les Miserables," expressed an even stronger opinion: "All the human and animal manure which the world loses... by discharge of sewage to rivers, if returned to the land instead of being thrown into the sea, would suffice to nourish the world."

In the late 19th and early 20th centuries, sewage-irrigated farms were widespread in the environs of many cities. In addition to the aims of preventing pollution of water supplies and of conserving nutrients for crops, there arose the impetus to utilize sewage as an additional water resource.

Subsequently, the growth of cities and their suburbs encroached upon the sewage farm areas and many of the early wastewater irrigation projects in Europe and America were abandoned. Concerns over the odor problem and over the transmission of disease from vegetable crops irrigated with raw sewage also contributed to the decline of sewage farming. Another disadvantage in some areas was that, following heavy rainstorms, runoff from sewage-irrigated fields periodically conveyed loads of pollutants into rivers and reservoirs. Many public health officials therefore came to believe that sewage farming was an unsanitary and hence undesirable practice of the past. The alternative was a sewage-treatment technology based on intensive centralized civil engineering systems in which the organic components of sewage could be digested and from which the "purified" fluid could be discharge more or less harmlessly to streams.

Still more recently, the pendulum seems to have swung back again. Interest has revived in the used of sewage as a resource rather than merely as a problem, based on more rational scientific principles than before. Research on the fate of pathogens and of various organic and inorganic components of wastewaters applied to the soil has shown that in many cases treated or even partially treated sewage can indeed be used safely and advantageously for irrigation, provided that necessary precautions are taken to prevent deleterious effects on public health as well as on soil quality. Guidelines have been formulated to allow wastewater irrigation to become a socially acceptable and sanitary practice. The trend has been led by the State of California and by the States of Israel, in both of which growing urbanization and industrialization increased the competitive demand (and hence the price) for scarce freshwater while simultaneously increasing the volume of generated wastewater.

Wastewater treatment standards such as those established by the California State Health Department apply strict criteria of bacterial counts (e.g., no more than 2.2 coliform/100 ml) and required the application of chemical disinfection (chlorination) for treated sewage water to be allowed for general use. Partially treated sewage should only be used for the irrigation of industrial crops such as cotton, or of tree-grown fruits that do not come in con-

Figure 11   Irrigation return-flow system
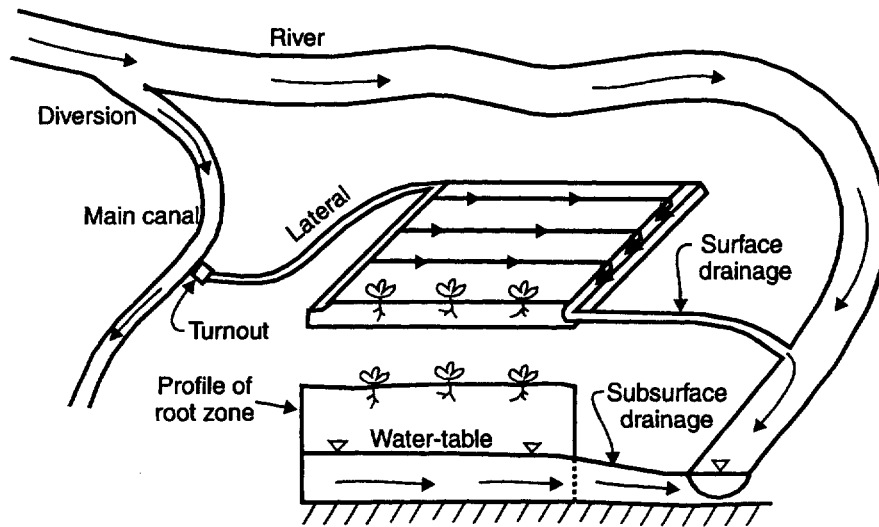
Source: Skogerboe and Walter (1981).

Figure 12   Drainage water reuse and disposal for an irrigation region
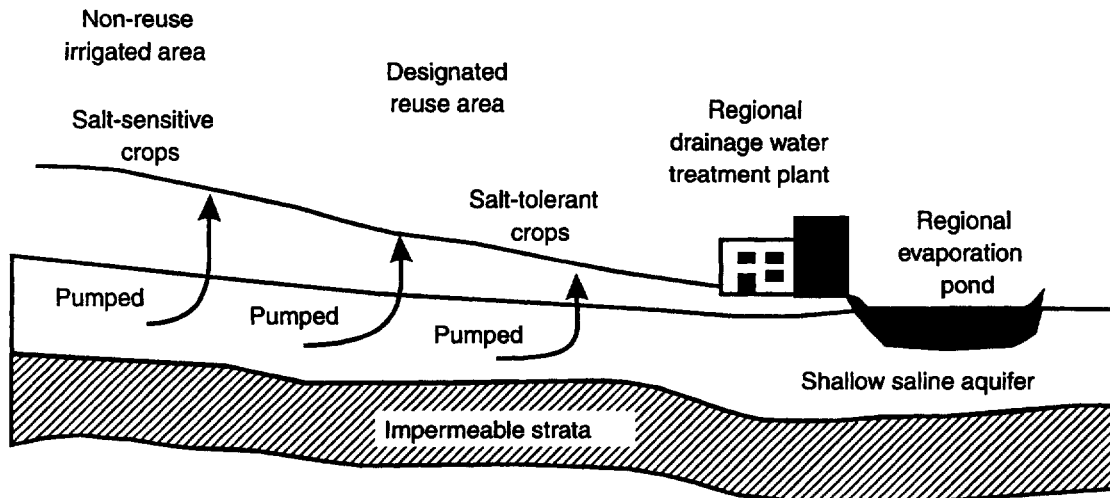
Source: Grattan and Rhoades (1990).

tact with the irrigation water, or— at most— for vegetable crops that are to be cooked before being consumed. Similar guidelines have been adopted elsewhere.

In Israel, some two-thirds of domestic sewage is currently being recycled for use in agriculture, and the projection is for reuse of some 80 percent in the foreseeable future. In fact, recycled sewage is expected to become the main source of water for irrigation. Wastewater irrigation has been shown to contribute significantly to soil fertility (especially to nitrogen, phosphorus and organic matter augmentation) in many areas, and to produce greater crop yields.

Wastewater irrigation is not always a blessing, however. In many places, the concentration of nitrates can be excessive, and to contribute to groundwater and surface-water contamination. Heavy metals and various other toxic materials can pose a problem. They tend to accumulate in the soil and thence to enter the biological food chain. Especially hazardous are industrial waste products that may be toxic as well as carcinogenic.

Wastewaters typically contain increased concentrations of soluble salts, and therefore pose the danger soil salination. Where salination is prevented by leaching, the salts tend to accumulate in the underlying aquifer and may contribute to the salinity of well waters. (Such is typically the case along the coastal plain of Israel.) The variable pH of the water applied to the soil may cause either acidification or alkalination, with consequent effects on soil structure and fertility. Finally, the materials suspended in sewage, if not readily decomposed, may cause clogging of soil pores (as well as of irrigation systems) and thereby reduce soil permeability to water and air. Naturally, some soils are more vulnerable than others.

Irrigation return flow, and drainage reuse and disposal systems are depicted schematically in figures 11 and 12.

CHAPTER 4

Waterlogging and Drainage

High Water-Table Conditions

The presence of a high water table can be either a blessing or a curse. The blessing occurs when, in periods of low rainfall or deficiency of water for irrigation, upward capillary flow from the water table augments the water supply to the roots. The curse occurs as the rising water brings up salts from below and thereby salinizes the root zone. In extreme cases, the latter phenomenon becomes manifested at the surface in the appearance of fine crystalline salt.

In the field, upward capillary rise and downward percolation may take place alternately during the year (Hoffman, 1990). Percolation occurs typically during the rainy and early irrigation seasons, when the water requirements of the crop are relatively low and the water supply from above is high. On the other hand, upward flow takes place later in the irrigation season, when water requirements are high and both rainfall and irrigation are restricted. Over the long term, a net downward flow of salt-bearing water through the root zone is essential to sustainable productivity.

If the water table remains at a constant depth and conditions at the surface remain constant as well, a steady-state flow regime tends to occur. The equation describing steady upward flow is (Hillel, 1998):

$$q = K(h)(dh/dz - 1)$$

where q is flux (equal to the evaporation rate under steady-state conditions), h suction head, K hydraulic conductivity, and z height above the water table. The equation shows that the upward flow stops (q = 0) when the suction profile is at equilibrium (dh/dz = 1). Integration should give the relation between depth and suction:

$$z = \int dh/[1 + q/K(h)]$$

To perform the integration, we must know the functional relation between K and h, that is, K(h).

A theoretical solution for this process was first offered by Gardner (1957) and validated experimentally by Gardner and Fireman (1958). Their work used an empirical relation between the soil's hydraulic conductivity K and its matric suction h of the form:

$$K = a/(b + h^n)$$

where a, b, and n are constants. For a saturated soil, the suction h is zero, so K assumes the value of a/b. For an unsaturated soil, K decreases as the suction increases. The exponential parameter n expresses the steepness of the decrease of K with increasing h, and is related to the soil's texture. In the case of a clayey soil, n was found to be about two; in a loam, about three; and in a sand, four or more.

Using this relationship, the flow equation can be solved to obtain suction distributions with height for different fluxes, as well as fluxes for different surface-suction values. The theoretical solution is shown graphically in figure 13 for a fine sandy loam with an n value of 3. The curves show that the steady rate of capillary rise and evaporation depends on the depth of the water table and on the suction at the soil

Figure 13   Steady upward flow and evaporation from a sandy loam (n = 3) as a function of the suction at the soil surface, with water table at various depths
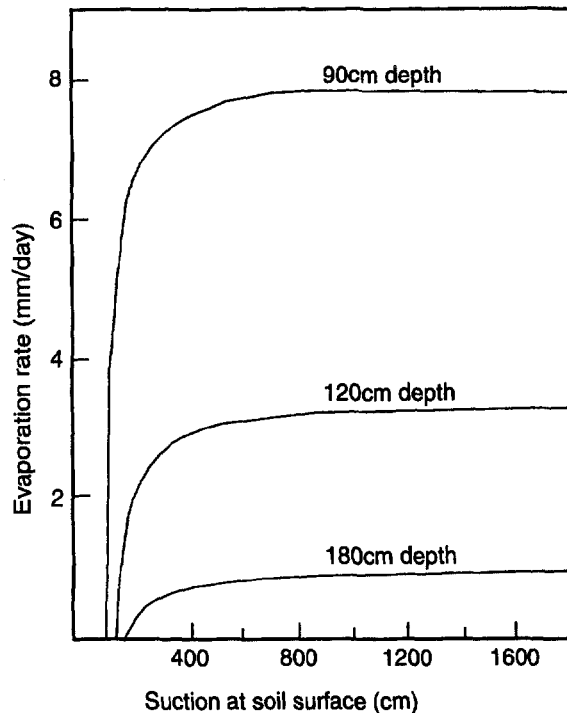
Suction at soil surface (cm)

surface. This suction is dictated largely by the external conditions. The greater the atmospheric evaporativity, the greater the suction at the soil surface on which the atmosphere is acting.

Increasing the suction at the surface, even to the extent of making it infinite, can increase the flux through the soil only up to an asymptotic maximal rate, which depends on the depth of the water table (figure 13). Even the driest and most evaporative atmosphere cannot steadily extract water from the surface any faster than the soil profile can transmit from the water table to that surface. The fact that the soil profile can limit the rate of evaporation is a useful feature of the unsaturated flow system. The maximal transmitting ability of the profile depends on the hydraulic conductivity of the soil in relation to suction, $K(h)$.

Disregarding the constant b of the preceding equation, we can obtain the function

$$q_{max} = Aa/d^n$$

where d is the depth of the water table below the soil surface, a and n are constants as above, A is a constant that depends on n, and q_{max} is the limiting (maximal) rate of water transmission from the water table to the evaporation zone at the surface.

The actual steady evaporation rate is determined either by the external evaporativity or by the water-transmitting properties of the soil, depending on which of the two is lower and therefore limiting. Where the water table is near the surface, the suction at the soil surface is low and the evaporation rate is dictated by external conditions. However, as the water table becomes deeper and as the suction at the soil surface increases, the evaporation rate approaches a limiting value regardless of how high external evaporativity may be.

The equation above suggests that the maximal evaporation rate decreases with water-table depth more steeply in coarse-textured soils (in which n is greater because conductivity falls off more markedly with increasing suction) than in clayey soils. Still, a sandy loam can evaporate water at an appreciable rate even when the water table is as deep as 1.8 m.

Subsequent findings of numerous workers have generally accorded with the theory described. Hadas and Hillel (1968), however, found that experimental soil columns deviated somewhat from predicted behavior, apparently owing to spontaneous changes of soil properties, particularly at the surface, during the course of the evaporation process.

Lowering the water table by drainage can decisively reduce the rate of capillary rise and evaporation, and hence also of salt accumulation. Drainage is a costly operation, however, and its is therefore necessary, ahead of time, to determine the optimal depth to which the water table should be lowered. Among the important considerations in this regard is the necessity to limit the rate of capillary rise to the surface. In the soil depicted in figure 13, for example, the maximal rate of profile transmission to the surface is 8 mm/day where the water-table depth is 0.9 m. Because potential evaporativity is seldom greater than this, it follows that a water-table rise above that depth

would not be likely to increase the evaporation rate substantially. On the other hand, a lowering of the water table to a depth of 1.8 m can reduce maximal evaporation to 1 mm/day. An additional lowering of the water table depth to 3.6 m will reduce the maximal evaporation rate to 0.12mm/day, while any further lowering of the water table can cause only a negligible reduction of evaporation and might in any case be prohibitively expensive to accomplish.

Comprehensive treatments of salt movement and accumulation as related to high water-table conditions and to drainage requirements can be found in van Schilfgaarde (1974), Bresler et al. (1982), Smedema and Rycroft (1983), Tanji (1990), and Hillel (1998). Their works confirm the importance of preventing water-table rise in all efforts to control salination. Soils with a shallow water table also tend to depress yields due to restricted soil aeration and inhibited root growth. Such findings, confirmed by field observations, have led to recommendations to install subsurface drainage systems at depths of 1.5 to 2.5 m, wherever groundwater conditions pose the hazards of waterlogging and salination. In examples cited by Hoffman (1990), subsurface drains spaced 20 m apart and placed 1.5 m deep in clay soil increased the yield of cotton and rice by 100 percent and of wheat and clover by 50 percent.

Subirrigation may be a dangerous practice in arid regions, where the irrigation water is brackish, owing to the tendency toward salt accumulation as a consequence of evaporation at the soil surface. A practice that may help to mitigate that tendency is the mulching of the soil surface to reduce the direct evaporation of soil moisture.

Groundwater Drainage

The term "drainage" can be used in a general sense to denote outflow of water from soil. More specifically, it can serve to describe the artificial removal of excess water, or the set of management practices designed to prevent the occurrence of excess water (Farr and Henderson, 1986). The removal of free water tending to accumulate over the soil surface by appropriately shaping the land is termed *surface drainage* and is outside the scope of our present discussion. Finally, *groundwater drainage* refers to the outflow or artificial removal of excess water from within the soil, generally by lowering the water table or by preventing its rise.

Soil saturation *per se* is not necessarily harmful to plants. The roots of various plants can, in fact, thrive in a saturated medium, provided it is free of toxic substances and contains sufficient oxygen to allow normal respiration. As is well known, plant roots must respire constantly, and most terrestrial plants are unable to transfer the required oxygen flux from their canopies to their roots. The problem is that water in a saturated soil seldom can provide sufficient oxygen for root respiration. Excess water in the soil tends to block soil pores and thus retard aeration and in effect strangulate the roots.

In *water-logged soils*, gas exchange with the atmosphere is restricted to the surface zone of the soil, while within the profile proper, oxygen may be almost totally absent and carbon dioxide may accumulate. Under anaerobic conditions, various substances are reduced from their normally oxidized states. Toxic concentrations of ferrous, sulfide, and manganous ions can develop. These, in combination with products of the anaerobic decomposition of organic matter (e.g., methane) can greatly inhibit plant growth. At the same time, nitrification is prevented, and various plant and root diseases (especially fungal) are more prevalent.

The occurrence of a high-water-table condition may not always be clearly evident at the very surface, which may be deceptively dry even while the soil is completely water-logged just below the surface zone. Where the effective rooting depth is thus restricted, plants may suffer not only from lack of oxygen in the soil, but also from lack of nutrients. If the water table drops periodically, shallow-rooted plants growing in water-logged soils may even, paradoxically, suffer from occasional lack of water, especially when the transpirational demand is very high.

High moisture conditions at or near the soil surface make the soil susceptible to compaction and puddling by animal and machinery traffic. Necessary operations (e.g., tillage, planting, spraying, and harvesting) are thwarted by poor *trafficability* (i.e., the ability of the ground to

support vehicular traffic and to provide the necessary traction for locomotion). Tractors are bogged down and cultivation tools are clogged by the soft, sticky, wet soil. Furthermore, the surface zone of a wet soil does not warm up readily at springtime, owing to greater thermal inertia and downward conduction, and to loss of latent heat by the higher evaporation rate. Consequently germination and early seedling growth are retarded.

Plant sensitivity to restricted drainage is itself affected by temperature. A rise in temperature is associated with a decrease in the solubility of oxygen in water and with an increase in the respiration rate of both plant roots and soil microorganisms. The damage caused by excessive soil moisture is therefore likely to be greater in a warm climate than in a cold one. Moreover, in a warm climate, the evaporation rate and, hence, the consequent hazard of salinity are likely to be greater than in a cool climate. The process of evaporation inevitably results in the deposition of salts at or near the soil surface, and these salts can be removed and prevented from accumulating only if the water table remains deep enough to permit leaching without subsequent resalination through capillary rise of the groundwater.

Numerous investigations of groundwater flow and drainage have resulted in a very extensive body of literature on this subject. Reference is made particularly to the books by Luthin (1957), van Schilfgaarde (1974), and Smedema and Rycroft (1983).

The artificial drainage of groundwater is generally carried out by means of *drains*, which may be ditches, pipes, or "mole channels," into which groundwater flows as a result of the hydraulic gradients existing in the soil. The drains themselves are made to direct the water, by gravity or by pumping, to the *drainage outlet*, which may be a stream, a lake, an evaporation pond, or the sea. In some places, drainage water may be recycled, or reused, for agricultural, industrial, or residential purposes. Because drainage water may contain potentially harmful concentrations of salts, fertilizer nutrients, pesticide residues, and various other toxic chemicals as well as biological pathogens, it is not enough to provide means to "get rid" of it; we must be concerned with the quality of the

water to be disposed of and with the long-term down-stream consequences of its disposal.

In principle, water will not flow out of the soil into a large cavity or drain spontaneously unless the pressure of soil water is greater than atmospheric. Drains must be located below the water table to draw water, and the water table cannot be lowered below the drains (figure 14). Hence the depth and spacing of drains is of crucial importance. Insufficient depth of placement will prevent a set of drains from lowering the water table to the extent necessary. Too great a depth might, on the other hand, lower the water table excessively, and thus deprive the plants of a possibly important source of water during drought periods.

Various equations, empirically or theoretically based, have been proposed for determining the desirable depths and spacings of drain pipes or ditches in different soil and groundwater conditions. Since field conditions are often complex and highly variable, these equations are generally based upon assumptions that idealize and simplify the flow system. The available equations are therefore approximations that should not be applied blindly. Rather, the assumptions must be examined in the light of all information obtainable concerning the circumstances at hand.

Among the most serious weaknesses of the approach described are the assumptions of an impervious layer at some definable shallow depth and the disregard of that portion of the total flow that occurs above the water-table (Bouwer, 1959). Corrections to account for that flow were described by van Schilfgaarde (1974).

Other equations, derived by alternative and in some cases more rigorous procedures, have been offered by, among others, Kirkham (1958), and the U.S. Bureau of Reclamation (Luthin, 1966). The ranges of depth and spacing generally used for the placement of drains in field practice are shown in table 3.

In Holland, the country with the most experience in drainage, common criteria for drainage are to provide for the removal of about 7 mm/day and to prevent a water-table rise above 0.5 m from the soil surface. In more arid regions, because of the greater evaporation rate and groundwater salinity, the water table must

Figure 14   Groundwater drainage (a) under steady flow conditions, and (b) under unsteady conditions resulting in a falling water table
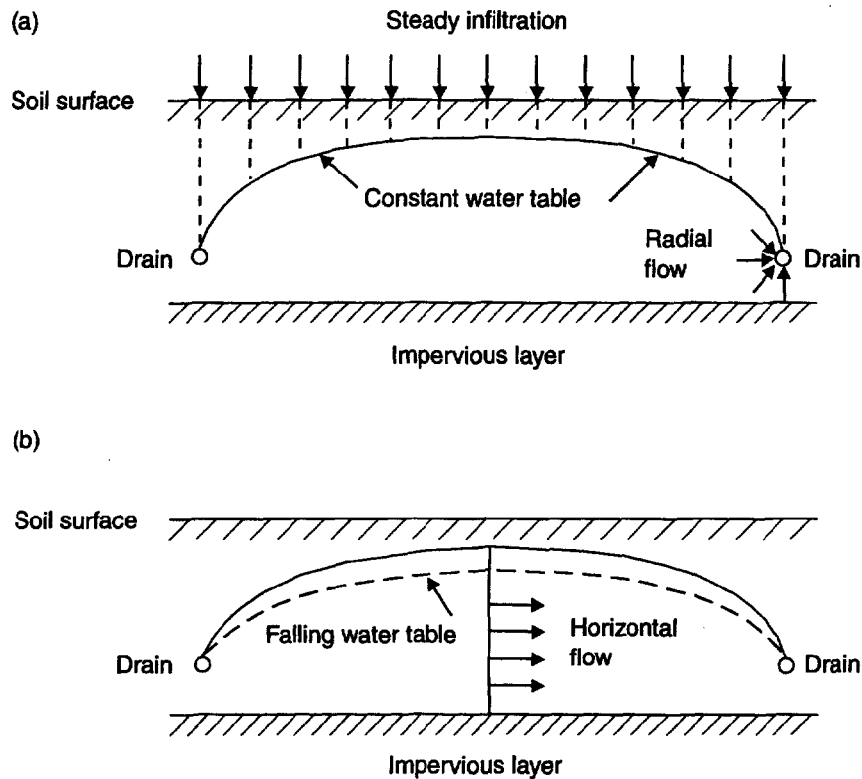
Source: Hillel (1998).

generally be kept very much deeper. In the Imperial Valley of California, for instance, the drain depth ranges from about 1.5 to 3 m and the desired water-table depth midway between drains is at least 1.20 m. For medium and fine-textured soils the depth should be greater still

Table 3   Prevalent depths and spacing of drainage pipes in different soil types

Soil type	Hydraulic conductivity (m/day)	Spacing of drains (m)	depth of drains (m)
Clay	1.5	10-20	1-1.5
Clay loam	1.5-5	15-25	1-1.5
Loam	5-20	20-35	1-1.5
Fine, sandy loam	20-65	30-40	1-1.5
Sandy loam	65-125	30-70	1-2
Peat	125-250	30-100	1-2

where the salinity risk is high. Since there is a practical limit to the depth of drain placement, it is the density of drain spacing that must be increased under such circumstances. By setting adjacent lines closer together, we can ensure that their drawdown curves will join at a lower midpoint level.

The disposal of salt-bearing drainage effluent poses a danger to rivers and groundwater. If the drainage water is returned to a river or an aquifer serving as a water source, or if the drainage is to be reused directly, its load of corrosive salts and other pollutants may affect downstream agriculture, households, water utilities, and industry. Where pesticides are applied to irrigated land, their residues can cause further damage to biotic communities, as well as to public health. The recent emphasis on modes of management that minimize chemical inputs may well help to lessen the problem

posed by the persistence of some of these chemicals in the environment.

Construction of evaporation ponds for disposal of drainage water generally requires the allocation of some 10 percent to 14 percent of the land area. This loss of land and the costs of construction make such ponds relatively unattractive. Care must also be taken to avoid leaks and consequent salination of the underlying ground water.

CHAPTER 5

Salinity Control

Leaching Processes

When irrigation is practiced in arid regions, particularly if the applied water contains an appreciable concentration of soluble salts, the twin processes of evaporation from the soil surface and transpiration by the plants tend to concentrate salts in the root zone box 9.

To prevent salt residues from accumulating during repeated irrigation-evapotranspiration cycles, the obvious remedy is to apply water in an amount greater than evapotranspiration, so as to deliberately cause a fraction of the water applied to flow through the root zone and flush away the excess salts. However, unless the water table is very deep, or lateral groundwater drainage is sufficiently rapid, the extra irriga-

tion can cause a progressive rise of the water table. And, once the water table comes within a meter or two of the soil surface, groundwater tends to seep upwards into the root zone by capillary action and thus to re-infuse the soil with salt between irrigations.

Here we face a dilemma similar to that of the proverbial frog in the frying pan: to escape being fried, the frog must leap; but in leaping the frog may fall into the fire and be burned. So the leap must be at just the right trajectory to escape both misfortunes. In our case, we must apply more water to leach out salts, but applying too much water may raise the water table and thus bring back the salt from below. Therefore, the amount of water applied must be optimized so as to allow leaching without

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Box 9 Models of root-zone salt concentration

Several recent models have been proposed to relate the concentration of drainage water to some clearly definable value of salinity that affects the crop directly. Hoffman and van Genuchten (1983) determined the linearly averaged, mean root-zone salinity by solving the appropriate equation for one-dimensional vertical flow of water through soil, assuming an exponential soil-water uptake function. The ratio of the linearly averaged concentration of the root zone (c) to the concentration of the irrigation water (c_i) is $c/c_i = 1/L + d/ZL + \ln[L + (1 - L) e^{-Z/d}$. Here L = leaching fraction, Z = depth of the root zone, and d = an empirical constant set to 0.2Z.

Hoffman (1990) provided an example of how to estimate the leaching requirement. Assume that tomatoes are to be grown in an arid region and irrigated by water with an EC of 3 dS/m, and that the salt-tolerance threshold of this crop is 2.5 dS/m. Assume that rainfall during the growing season is insignificant. From Figure 14, we see that the leaching requirement for these conditions equals 0.2. To calculate the salinity of the applied water when rainfall is significant, the following equation is used: $c_a d_a = c_r d_r + c_i d_i$. The variable c is salt content expressed in terms of electrical conductivity, and d is depth. The subscripts a, r, and i indicate applied, rain, and irrigation water, respectively. An iterative procedure must be used, since d_i is not known until L_r is known.

As an illustration, assume evapotranspiration d_e is 750 mm and rainfall d_r is 150 mm. Begin calculation by assuming that d_i is 900 mm and $c_r = 0$. Because $d_a = d_r + d_i$, then $c_a = c_i d_i /(d_r + d_i) = 3(900)/(150 + 900) = 2.6$. With $c_a = 2.6$, L_r for tomato is 0.18 and $d_i = d_e + d_t + d_d = 750 + 0.18 d_i$ or $d_i = 915$. This is sufficiently close to the assumed value of 900 that further iterations are unnecessary. With this rainfall, L_r for tomatoes is 0.18.

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water-table rise. The desired optimization can seldom be achieved and maintained in the long run without the installation of artificial ground-water drainage.

From the foregoing it should be obvious that any attempt to leach without adequate drainage is not merely doomed to fail but can indeed exacerbate the problem. However obvious, this principle is too often ignored in irrigation projects. In many areas where natural drainage is slow and artificial drainage is not provided, it becomes impossible to sustain irrigation in the long run, and the land must sooner or later be abandoned owing to progressive salination.

Box 10 Waterlogging and salination in the Indus River Basin

The Indus River Basin lies in Pakistan and parts of India, stretching from the foothills of the Western Himalayas to the Arabian Sea. Before region-wide irrigation was initiated, the groundwater table lay scores of meters deep and the aquifer was in hydrologic equilibrium.

When large-scale irrigation was introduced early in the twentieth century, an extensive water-distribution network was established (including storage reservoirs, barrages, canals, and numerous unlined watercourses) to form the largest irrigation district in the world, covering about 15 million hectares. The efficiency of the distribution system, however, is very low, with less than half the water diverted from the rivers actually reaching the farmers fields. The field irrigation efficiency is even lower—possibly about 30 percent. Since the natural groundwater drainage is inadequate and artificial drainage was not provided by the project, percolation from the canals coupled with over-irrigation led to a rapid rise of the water table.

Waterlogging occurred first in areas along the canals and later spread to contiguous areas. By 1960, the water table was within 3 meters of the soil surface under about half the canal command area, and within one meter of the surface over a tenth of the area, causing the salination of about 1 million hectares. By 1980, the groundwater rose to within less than 3 meters of the surface underneath 55 percent of the total irrigated area. Salination then affected an estimated 5 million hectares.

This alarming trend led the Pakistani government, with international assistance, to undertake construction of a regional drainage canal, and also to encourage private users to install tubewells to pump up water from the places where the groundwater is of good quality. Thanks to this program, the water table has ceased rising in large areas and is even being lowered in some. In other areas, however, the rise yet continues. The disposal of drainage is particularly expensive here because most of the irrigated areas in the Punjab lie a great distance from the sea, and the gradient of the land surface toward the sea is extremely small (less than 1:5,000). The problem of drainage and effluent disposal is common to both the Pakistani and the Indian sides of the Punjab, so the problem could best be resolved by a coordinated program of the two countries acting together.

Box 11   Sample calculation of the leaching requirement

Estimate the "leaching requirements" of a field subject to a seasonal evapotranspiration of 1000 mm, if the electric conductivity of the irrigation water is 0.1 S/m (equivalent to a salt concentration of about 650 ppm), and that of the drainage water is allowed to attain 0.4 S/m (about 2600 ppm salts). What would be the leaching requirement if the irrigation water were half as concentrated? And what if the drainage water were allowed to become twice as concentrated? Finally, what would be the electric conductivity of the drainage water if the amount of irrigation were 1500 mm ?

We use the equation:

$$d_i = [E_d/(E_d - E_i)]d_{et}$$

where d_i and d_{et} are the volumes of water per unit land area (in depth units) of irrigation and of evapotranspiration, and E_d and E_i are the electrical conductivities of the drainage and irrigation waters, respectively. Substituting the appropriate values, we get

$$d_i = [0.4/(0.4 - 0.1)] \ 1000 \text{ mm} = 1333 \text{ mm}$$

The "leaching water depth," $d_l = d_i - d_{et} = 1333 - 1000 = 333$ mm

If the irrigation water were half as concentrated ($E_i = 0.05$ S/m),

$$d_i = [0.4/(0.4 - 0.05)] \ 1000 \text{ mm} = 1143 \text{ mm}$$

Thus, the leaching depth would be only 143 mm, which is less than half the previously required leaching volume. If the drainage water were permitted to be twice as concentrated, i.e., if E_d were 0.8 S/m instead of 0.4, then

$$d_i = [0.8/(0.8 - 0.1)] \ 1000 \text{ mm} = 1143 \text{ mm}$$

In words: Doubling the allowable concentration of the drainage water is equivalent to halving the concentration of the applied irrigation water, in terms of its effect on reducing leaching requirements. If the depth of irrigation water applied were 1500 mm and its electric conductivity were 0.1 S/m, the electric conductivity of the drainage water would be

$$E_d = E_i/[1 - (d_{et}/d_i)]$$

which is obtained by simple transformation of the previous equation. Thus,

$$E_d = 0.1 \text{ S/m} / [1 - (1000/1500)] = 0.3 \text{ S/m}$$

Comment: Critics of the leaching requirement concept contend that it has little practical quantitative use in efficiently managing saline waters. It does not account for non-uniform irrigation, nor does it lead to the economically optimal level of irrigation.

This is happening at present in great and small river valleys from the Indus in Pakistan (box 9) to the Murray-Darling in Australia to the San Joaquin in California (box 10), to mention just a few.

Much attention has been devoted to the assessment of the optimal quantity of water that must be applied to cause leaching. Exaggerated leaching not only wastes water but also tends to remove essential nutrients and to cause waterlogging. The concept of "leaching requirement" was first developed by the U.S. Salinity Laboratory (Richards, 1954). It has been defined as the fraction of the irrigation water that must be percolated out of the bottom of the root zone in order to prevent average soil salinity from rising above some specifiable limit.

According to the standards developed there, the maximum concentration of the soil solution in the root zone, expressed in terms of electrical conductivity, should be kept below 4 dS/m for sensitive crops. Salt-tolerant crops such as beets, alfalfa, and cotton may give good yields at values up to 8 dS/m, whereas very tolerant crops like barley may give good yields at salinity values as high as 12 dS/m. The problem encountered in any attempt to apply such a simplistic criterion is that in the field (unlike in the case of plants grown in solution culture or in small containers of soil), the concentration of the soil solution varies greatly in space and time. In addition, the sensitivity of any crop to salinity depends on its stage of growth and on such variables as ambient temperature, atmospheric humidity, soil matric suction, nutrient availability, etc.

The leaching requirement depends on the salt concentration of the irrigation water, on the


Box 12   Drainage problems in California

Irrigation in the western section of the Central Valley of California is facing a crisis. To avoid salination, the area requires drainage. A mountain range prevents direct conveyance of effluent westward to the Pacific Ocean, so planners intended to direct drainage northward to San Francisco Bay. The first leg of the drainage canal was constructed and terminated at Kesterson Reservoir. This reservoir was to serve as a wildlife habitat and storage facility until the last leg of the drainage canal could be completed. However, the plan to terminate the canal in San Francisco Bay met opposition from Bay-area residents, who feared the bay's contamination by agricultural chemicals.

Just a few years later, biologists monitoring the Kesterson Reservoir noticed that young birds were deformed and died before reaching maturity. Other animals were similarly affected. The culprit was found to be selenium, an element that — ironically — is an essential nutrient in small amounts, but becomes toxic at higher concentrations. It originated in the sedimentary substrata underlying the region, and hence entered the groundwater and the effluent drained from it. The selenium discharged into the open reservoir became progressively concentrated as evaporation took place there. So the region's ag-

ricultural planners had to abandon the entire scheme. Now the district is left without an outlet for its drainage, and may be doomed to suffer the fate of other irrigated regions throughout history, unless some other solution is found (and it is likely to be expensive).

Irrigation in California is responsible for the continued existence of another body of water, the Salton Sea, located in the Imperial Valley near the Mexican border. Although repeatedly inundated in past ages, this basin was a dry depression in recent history. In 1904, the Colorado River breached the channel that was built to contain it, and flowed into that depression to form a new fresh-water lake. By 1907, the breach was repaired, and the new lake would normally have evaporated away. Contrary to expectations, the lake has remained, and even grown, since then. It is sustained by the collective agricultural drainage from the Imperial Valley, and sewage effluent from Mexicali. The Imperial Irrigation District is now one of the most intensively irrigated districts in America. The Salton Sea is also used for recreation and is an important wildlife habitat on the Pacific flyway, and is considered a permanent feature of the valley. However, the salinity of this landlocked lake, lacking any cleansing through-flow (its only outlet being the evaporative sink of the dry desert air) has increased steadily and is now greater than the salinity of ocean water.

California's Central Valley

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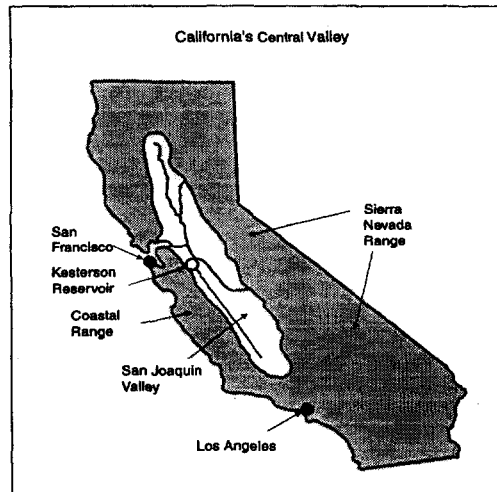
amount of water extracted from the soil by the crop, and on the salt tolerance of the crop, which determines the maximum allowable concentration of the soil solution in the root zone.

Assuming steady-state conditions of through-flow (thus disregarding short-term fluctuations in soil-moisture content, flux, and salinity), and furthermore assuming no appreciable dissolution or precipitation of salts in the soil and no significant removal of salts by the crop or capillary rise of salt-bearing water from below, we obtain the following simple equation,

$$V_d/V_i = c_i/c_d$$

in which V_d and V_i are the volumes of drainage and of irrigation, respectively, and c_d and c_i are the corresponding concentrations of salt. Water volumes are normally expressed per unit area of land as equivalent depths of water, and salt concentrations are generally measured and reported in terms of electrical conductivity. Because the volume of water drained is the difference between the volumes of irrigation and evapotranspiration, (i.e., $V_d = V_i - V_{et}$), we can transform the last equation as follows:

$$V_i = [c_d/(c_d - c_i)]V_{et}$$

This is equivalent to the formulation by Richards (1954),

$$d_i = [E_d/(E_d - E_i)]d_{et}$$

where d_i is the depth of irrigation, d_{et} the equivalent depth of "consumptive use" by the crop (evapotranspiration) and E_d and E_i are the electrical conductivities of the drainage and irrigation waters, respectively.

The leaching requirement equation implies that, by varying the fraction of applied water percolated through the root zone, it is possible to control the concentration of salts in the drainage water and hence to maintain the concentration of the soil solution in the main part of the root zone at some intermediate level between c_i and c_d. In the limit, as the volume of drainage approaches the volume of irrigation water applied (that is, when irrigation greatly exceeds evapotranspiration), the concentration of the drainage water approaches that of the irrigation water. In practice, irrigation managers aim for an optimal compromise between the needs of conserving water and of controlling salinity.

The leaching requirement concept disregards the distribution of salts within the root zone itself, as it is affected by the frequency and spatial variability of irrigation as well as by its quantity and water quality. In particular, the spatial and temporal variation of root-zone salinity is affected by the pattern and degree of soil moisture depletion between irrigations. The less frequent the irrigation regime, the greater the buildup of salt between successive irrigations. In some cases, the commonly recommended leaching fraction may not be sufficient to prevent the reduction of yield below its potential, especially if the climatically imposed evaporation rate is high and the irrigation water is brackish.

With modern methods of high-frequency irrigation (Rawlins and Raats, 1975; Hillel, 1987, 1997), it is possible to maintain the soil solution in the surface zone at a concentration essentially equal to that of the irrigation water. This zone can be deepened by increasing the volume of water applied. Beyond this zone the salt concentration of the soil solution increases with depth to a salinity level depending on the

leaching fraction (defined as V_d/V_i). High-frequency irrigation not only lowers the concentration of the soil solution in the upper zone (where most roots proliferate) but also minimizes the matric suction of soil moisture.

Gardner and Brooks (1956) developed a theory of leaching in which a distinction was made between relatively *immobile* (detained) and *mobile* salt, the latter moving with the velocity of the leaching front. They observed that in several soils about 1.4 pore volumes of water are needed to reduce salinity by 80 percent. They then opined that the flow process itself is responsible for the diffuse boundary between the soil solution and the leaching water as well as for the subsequent removal of the temporarily bypassed detained salt. Such behavior is generally related to the phenomenon of hydrodynamic dispersion (Bear, 1969; Hillel, 1998).

Control of salinity by leaching is accomplished most readily in permeable soils. A Coarse-textured soils (e.g., sandy soils) tend to be naturally permeable. On the other hand, fine-textured soils with a high content of clay are only permeable if they are well aggregated. Aggregation is disrupted in sodic soils. This is an import reason why every effort must be made to prevent soil sodification. In any case, when considering the optimal leaching fraction, a possible constraint must be taken into account, namely the limited permeability of the subsoil at the lower boundary of the root zone.

An interesting approach to the reclamation of saline-sodic soils having adequate drainage was first developed by Reeve and Bower (1960). They recommended using saline rather than good-quality water for the initial leaching of such soils. The higher concentration of salts in the applied water can help maintain the permeability of the soil and prevent the strong dispersion of clay. That undesirable dispersion often results when salts are removed abruptly by high-quality water without simultaneously replacing the high percentage of exchangeable sodium with divalent cations such as calcium. After the initial stage of leaching with saline water, the process can be continued with gradually improving quality of water until the soil is rendered free of excess salts with minimal damage to its physical structure.

Nielsen and Biggar (1961) suggested that leaching soils at a water content below saturation (e.g., under low-intensity sprinkling or intermittent ponding) can produce more efficient leaching than can be achieved by the then-standard method of continuous flooding (see box 16 for a summary of leaching methods). In a soil with macropores—cracks, wormholes, or decayed root channels—much of the water moves rapidly down those large passageways while bypassing the greater volume of the soil containing salt, so it is largely ineffective in leaching the micropores of the soil matrix. Under low-intensity sprinkling sprinkling, on the other hand, the soil never becomes saturated, so a greater portion of the applied water moves through the soil matrix, thus producing more efficient leaching per unit volume of water infiltrated. However, the processes of infiltration and unsaturated flow under low-intensity sprinkling are inherently slower and require much more time than saturated infiltration under ponding (figures 15 and 16).

Nonuniformity of irrigation is a complicating factor. If the leaching requirement is not met throughout in the field, soil salinity will prevail in spots, wherever leaching is insufficient. Whether to apply copious amounts of water to the entire field so as to ensure that the leaching requirement is met everywhere, or to accept some reduction in yield in parts of the field, must be determined from an economic analysis of costs and benefits. Such an analysis should take into account the danger that saline spots might recur (and perhaps even grow in extent and severity) from year to year.

One answer is to apply extra water preferentially to the spots that need it most, but such a strategy requires a flexible irrigation system that would allow controlled variability of water delivery. Although such a specialized irrigation system is likely to be expensive to install and operate, it may well be worthwhile in the long run.

Present irrigation practices in many areas are inefficient and result in excessive leaching. Such prevalent practices entail waste of water, energy, and nutrients; as well as deterioration of water quality and increased need for expensive drainage facilities.

The amount of water needed to achieve a satisfactory level of leaching depends not only on the quality of the water and the properties of the soil, but also on the method of irrigation. Under surface irrigation methods, the rate of water penetration (and hence the total depth

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Box 13 Summary of leaching methods

(1) Continuous ponding. This method is used in surface-irrigated areas, which are usually level or nearly level tracts of land with access to large volumes of water. In such locations, leaching by ponding is a relatively inexpensive and rapid process, especially where the soil is not highly permeable. However, the leaching efficiency of this method is lower than with alternative methods, especially when applied in saturated fields with tile or open drains (Talsma, 1967), and where much of the flow takes place through macropores. The rate of leaching is affected by the soil's permeability and by its initial salinity.

(2) Intermittent ponding. This method is suitable for fields with a deep water table or fields with tile drains, which increase the leaching efficiency by allowing the water table to draw down after each period of ponding (Talsma, 1967). Where the soil develops a surface seal (crust), intermittent ponding also enhances infiltration by allowing the crust to dry and crack during the intervals between successive pondings. However, the longer exposure of moist soil to the atmosphere also increases the amount of evaporation. Evaporative losses can be reduced by applying a mulch over the soil surface, and permeability may be improved in some locations by deep plowing prior to the leaching treatment, as well as by the incorporation of organic matter (e.g., by green manuring).

(3) Low-intensity sprinkling. This method can be used advantageously where the field is not necessarily level (as required for ponding), where the soil contains many macropores, as well as where the soil texture is coarse (sandy). It permits a high level of leaching efficiency (Nielsen et al., 1965), except under highly evaporative conditions (e.g., on hot, windy days). However, leaching under sprinkling is time-consuming, energy-consuming, and capital-intensive.

In the wake of leaching, the soil may be in rather poor physical condition and be deprived of nutrients (particularly nitrogen). Steps should then be taken to improve soil structure by the addition of such amendments as lime or gypsum, and to improve fertility by manuring and/or fertilizing.

Figure 15   Depth of water per unit depth of soil required to leach saline soil by continuous or intermittent ponding

Figure 16   Water content distribution during infiltration under flooding and under sprinkling at two intensities. Cumulative infiltration equals 80 mm
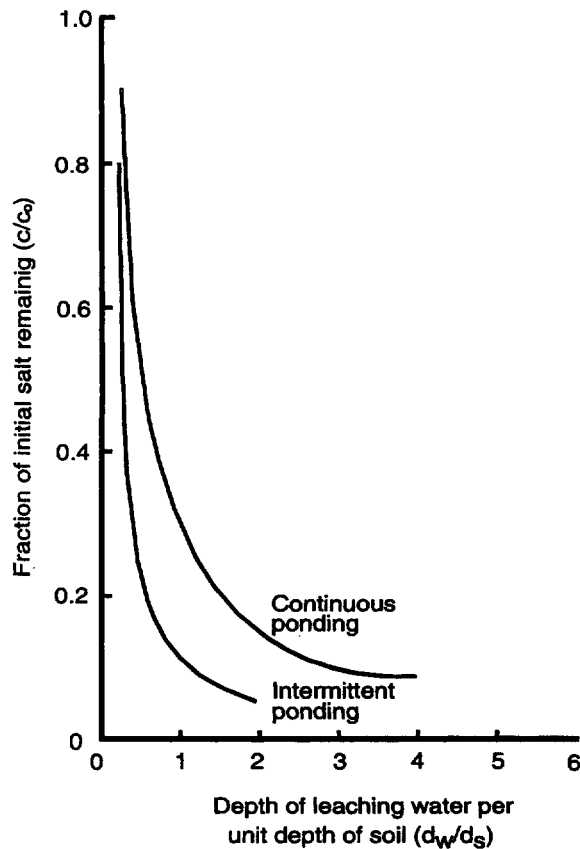
of penetration over a given period of time) varies in accordance with the inherent spatial variability of the soil. Sprinkler irrigation, if well adjusted, permits much greater uniformity of water distribution. Therefore, to achieve a minimal depth of water penetration and effective leaching everywhere in a field, the amount of water needed in surface irrigation (flood or furrow) is generally greater than in sprinkler irrigation. However, for sprinkling irrigation to be maximally efficient in leaching, the rate of application must not exceed the intake (infiltration) rate of the soil; otherwise, flooding ensues.

Under drip irrigation, unlike under sprinkler irrigation, the application of water is not uniform over the field, and the flow inside the

soil is three dimensional rather than entirely vertical. The rate of flow from each emitter and the spacing of the emitters, along with the properties of the soil and the spatial pattern of root-water uptake, combine to determine the directions and rates of salt movement in the soil. Although the soil volume directly under an emitter is leached frequently (or even continuously), salts do tend to accumulate over the periphery of the wetted volume of soil. Long-term use of drip irrigation may therefore result in irregularly distributed salt accumulations, such that may affect crops to be planted in subsequent years. Where annual rainfall is insufficient to leach out such accumulations, it may be necessary to use portable sprinkler systems

every few years to rid the topsoil of salts more effectively than is possible under drip irrigation alone.

The efficiency of leaching can be defined as the quantity of soluble salts leached per unit volume of water applied (Keren and Miyamoto, 1990). Another important consideration is the time required to effect leaching. The factors that determine the efficiency or rapidity of leaching include the initial salinity and water content of the soil, the volume of water applied, the mode of water application (whether by ponding or sprinkling), the presence or absence of macropores, the properties of the soil matrix (e.g., conductivity and hydrodynamic dispersivity) and its spatial variability, and the layout of the drainage system (box 14). When irrigating a crop, extra water need not be applied with every irrigation, but only when salinity approaches a hazardous level. This allows more efficient leaching with less water.

Based on field data from various sites around the world, Hoffman (1985) proposed the following empirical formula for salt transport efficiency under one-dimensional leaching:

$$c/c_o = k/(d/d_s)$$

where c = salt concentration in the leached soil, c_o = initial salt concentration in the soil, d = depth of leaching water applied, d_s = depth of the soil leached, and k = an empirical coefficient that ranges from 0.1 for a sandy loam to 0.3 for a clay under continuous ponding. Hoffman also reported that, under intermittent ponding with 5 to 15 cm of water per application, the empirical coefficient is about 0.1, i.e. nearly the same, for a range of soil textures. Oster and Rhodes (1973) reported a similar value of the coefficient for sprinkling irrigation of a silty clay. The above relationship applies after actual drainage has begun, or after d/d_s exceeds k. (That is to say, for a k value of 0.1 the formula applies after the depth of water infiltrated exceeds one-tenth of the depth of soil to be leached.) The leaching efficiency apparently decreases markedly if the process is continued after the d/d_s ratio exceeds 0.5 for a sandy loam and 0.75 for a clay loam or a clay (i.e., when more water is applied that strictly needed for maximal leaching efficiency).

Box 14 Factors determining flow rate to drains

Hydraulic conductivity of the soil, which may vary spatially if the soil is heterogeneous and may vary directionally if the soil is anisotropic. Generally, coarse-textured soils drain more readily than fine-textured ones, and well-aggregated soils drain faster than dispersed ones.

Configuration of the water table. The water table is seldom horizontal or of constant depth. Where the groundwater is confined, it may exhibit artesian pressures.

Depths of the drains relative to the groundwater table and to the soil surface, as well as the slopes of these drains and the elevation of their outlets.

Horizontal spacing between drains. The discharge per drain may become constant where the drains are spaced more than about 7 m apart. The drainage discharged from a field then becomes proportional to the number per unit area of drains installed. (Strictly speaking, this is true only in a homogeneous soil.)

Character of the drains. Open ditches allow a greater seepage surface than underground tubes, which are also more expensive. However, open ditches take up land and break the continuity of the field. They might scour and collapse, and allow the proliferation of weeds, pests, and disease-carrying vectors along their banks.

Inlet openings in the drain tubes. If segmented tubes are used, small gaps are left between the tube sections to allow inflow from the soil. If continuous tubes are used, they are perforated.

Envelope materials. Drainage tubes are commonly embedded in gravel to increase the seepage surface and therefore the discharge, and to prevent scouring or collapse of the soil at the inlets and possible clogging of the drains by penetration of loose soil material.

Diameters of the drains. These must be sufficient to convey the needed drainage discharge. Drainage tubes tend to clog within a few years owing to penetration of sediments and precipitation of salts (e.g., gypsum). Reduced iron and manganese may oxidize and precipitate in the drains, so the tubes must be flushed periodically.

Rate of groundwater recharge due to the excess of infiltration over evapotranspiration or to lateral flow from outside the field. When the rate of inflow by infiltration is equal to the rate of outflow by drainage, the water table remains constant, otherwise it may either rise or fall.

Still another factor in leaching is the effective depth of the water table (box 15). Leaching is more effective in well-drained soils with a deep water table than in an ill-drained soil with a shallow water table. However, in tile-drained or ditch-drained fields the water table is not at an even depth (being deepest at the drains and shallowest midway between adjacent drains). Hence the process of leaching is also two-dimensional (or three-dimensional), and therefore spatially uneven.

The pattern of leaching becomes even more complex if the soil itself is spatially variable. If, for example, a field consists sections that are

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Box 15 Predicting water-table height in a drained field

One of the most widely applied drainage equations is the classical one first derived by Hooghoudt (1937). It is designed to predict the height of the water table that will prevail under a given rainfall or irrigation regime when the hydraulic conductivity of the saturated soil and the depth and horizontal spacing of the drains are known. This equation, like others of its type, simplifies the real field situation, disregarding such factors as soil layering and the time-variable rate of evapotranspiration. It is based on the following assumptions:

(1) The soil is uniform and of constant hydraulic conductivity.
(2) The drains are parallel and equally spaced.
(3) The hydraulic gradient at each point is equal to the slope of the water table above that point .
(4) The flow of water in the soil obeys Darcy's law.
(5) An impervious layer exists at a finite depth below the drains.

(6) The supply of water from above is at a constant flux q.

The important criterion for evaluating the effectiveness of drainage is the maximal height of the water-table, which generally occurs at the midpoint between drains (where $x = \frac{1}{2}$ S). Accordingly, the maximum height H_{max} of the water-table "mound" is: $H_{max} = qS^2/8Kd_a$. The height of water-table rise between drains relates directly to the recharge flux and to the square of the distance between drains, and inversely to the hydraulic conductivity.

An equation describing the lowering of the water-table at the midpoint between drains, following an abrupt drop of the water-table at the drains, is known as the *Glover equation* (Smedema and Rycroft, 1983):

$$S^2 = (\pi^2 Kh_{i,ave} \, t/f_d) \ln(4H/\pi H)$$

wherein $h_{i,ave}$ is the average initial depth of the water-bearing stratum, f_d the drainable porosity, H_i the initial height of the midpoint water table above the drains, and H the height at any time t.

Illustration of terms used in the Hooghoudt equation
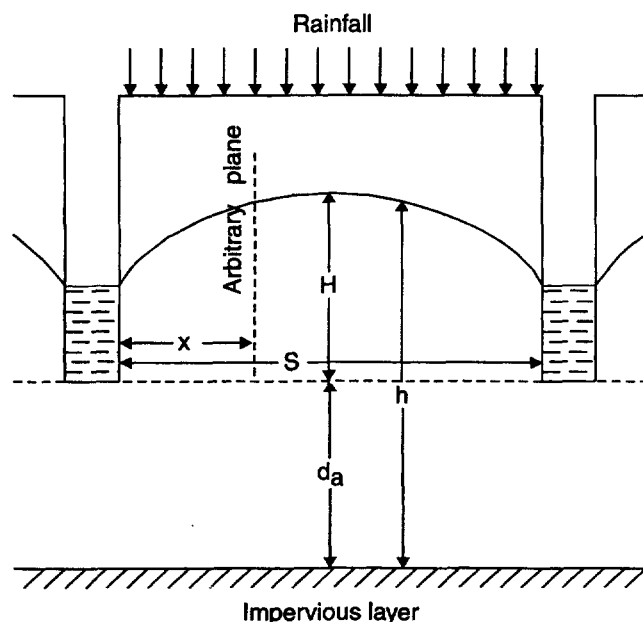
clay-rich and others that are sandy, the uniform application of sufficient water to leach the clayey sections will entail excessive percolation through the sandy sections. In some cases, it may be possible to divide the field into small sections that need different quantities of water, but that may not be practical in all cases.

Soil Amendments

The leaching process is enhanced if the applied water contains a sufficient concentration of electrolytes to reduce swelling and dispersion of clay. Where leaching occurs with water of very low salinity (such as seasonal rainwater), soil permeability can be enhanced by the surface application of a slowly soluble electrolyte source, preferably containing divalent or trivalent cations. Such materials, commonly known as *soil amendments*, can replace exchangeable sodium with flocculation-promoting cations (e.g., calcium or magnesium).

The most commonly considered soil amendments for the purpose of improving the structure of sodic soils and enhancing the infiltration of water are gypsum ($CaSO_4.2H_2O$) and calcium chloride dihydrate ($CaCl_2.2H_2O$). Gypsum is generally the preferred soil amendment, thanks to its ready availability in many places and to its relatively low cost. It may be derived from mines, or be available as a byproduct of the phosphate fertilizer industry (Keren and Miyamoto, 1990).

The solubility of pure gypsum is about 2.15 to 2.63 kg/m^3 (roughly 25 to 31 meq/l), depending somewhat on temperature. Applied gypsum dissolves in the soil solution until its solubility limit is reached, or until its supply is exhausted. When the soil solution is subject to evaporation (i.e., at the soil surface), gypsum may begin to precipitate before other salts of higher solubility (such as sodium chloride) do so.

The rate of dissolution of applied gypsum depends on its source and degree of granulation. Industrial gypsum generally dissolves more readily than mined gypsum, which typically contains impurities.

The amount of gypsum needed to replace the exchangeable sodium obviously depends on the initial exchangeable sodium percentage (ESP_i), the desired final percentage (ESP_f), the

soil's total cation exchange capacity (CEC), the soil's bulk density (BD), and the depth of the soil to be treated effectively (Z). Knowing these parameters, the amount of exchangeable sodium to be replaced (SR) can be calculated from

$$SR = k (Z)(BD)(CEC)(ESP_i - ESP_f)$$

where k is a constant depending on the dimensions (units) of the variables used. As formulated by Keren and Miyamoto (1990), $k = 10^4$.

The amount of gypsum needed to reclaim a sodium-affected soil (metric tons per hectare), referred to as the "gypsum requirement" (GR) is then obtained from

$$GR = 86.1 \times 10^{-6} SR$$

The relative concentration of Ca versus Na in the soil solution is generally higher in the deeper layers of the profile than at the surface, so Doering and Willis (1975) proposed a correction factor to account for this difference in the calculation of a soil's gypsum requirements. A recommendation commonly made to farmers in California, for example, is to apply gypsum every two to three years at the rate of 7 metric tons per hectare (Pehrson et al., 1985).

Surface spreading of gypsum may be more effective in rectifying sodium-induced crusting than mixing the material in the upper layer of the profile. Gypsum added to the surface of a sodic soil increases infiltrability both by raising the electrolyte concentration of the entering water and by reducing exchangeable sodium (Keren and Shaiberg, 1981).

A single treatment may not suffice to reclaim a strongly sodic soil. If so, the leaching process, accompanied by additions of soil amendments, should be repeated until the soil achieves a desired level of de-sodification as well as desalination.

Some arid-zone soils contain gypsum in amounts sufficient to protect the soil against sodification. This can be a positive factor. On the other hand, the presence of too much readily soluble gypsum in the soil may also be problematic. Dissolved gypsum in the soil solution adds to the osmotic stress imposed on the plant. Moreover, where the gypsum occurs in the form

of crystalline lenses inside the soil profile (as it does in some desert soils), the introduction of irrigation may cause the soil to subside (box 16). This subsidence can be so uneven as to turn a level field into an irregular jumble of depressions and hummocks, which affect the distribution of water and hence also of crop growth. This is what happened, for example, when irrigation was first introduced in certain desert areas of the Middle East (Hillel, 1990).

Saline soils often contain precipitated lime that, upon leaching, may dissolve to provide sufficient calcium to replace the initially adsorbed sodium (Jury et al., 1979). The rate of dissolution can be increased by various treatments designed to mobilize the soil's own calcium ions. Among the materials used for such purpose are sulfur, sulfuric acid, and iron and aluminum sulfates, which help to convert lime to gypsum (box 17).

If elemental sulfur is added to the soil in lieu of gypsum, it must be oxidized in situ to become effective (Miyamoto et al., 1975). Upon oxidation, it forms sulfuric acid, which then reacts with lime in the soil to produce gypsum. The application of S in powder form may be inconvenient because of the dust problem. This can be overcome by applying the material in granulated form, or in the form of an aqueous suspension containing 55 percent to 60 percent sulfur.

Other acidulants that must be oxidized are pyrites and polysulfides. The process of oxidation depends on soil microbes and on the conditions governing their activity. In any case, the process requires time, as its benefits occur gradually rather than immediately. The time required can be shortened by applying sulfuric acid, but this material is expensive and highly corrosive to pipes and other equipment, and its handling imposes strict safety precautions. However, the addition of acid tends to lower the soil's pH (which is often high in the soils of arid regions) and thereby to enhance the solubility of such nutrient elements as P, Zn, Mn, and Fe (Keren and Miyamoto, 1990).

Where acid waste products are available from mining and industrial activities, their use as soil amendments may provide a safe and efficient way to dispose of them (Miyamoto et al, 1975). However, such opportunities are not common.

Another possible soil amendment that can be effective in the treatment of sodium-affected soils is calcium chloride dihydrate, $CaCl_2.2H_2O$. Its use is generally restricted by its relatively high cost, unless it is locally available as an industrial waste product. Its effect is similar to that of gypsum. Being highly soluble, calcium chloride initially improves flocculation and water infiltration in clayey soils (Alperovitch and Shainberg, 1973). However, its high solubility also causes it to be leached rapidly from the soil profile. Therefore, a combination of calcium chloride and gypsum, where available and not too expensive, may be the ideal soil amendment (Prather et al., 1978).

Box 16 Native gypsum and soil subsidence

Native gypsum may be present in some soils of arid regions. In general, the presence of gypsum can help to protect the soil against sodification; however, in some locations it may lead to unforeseen problems. An example is what happened when irrigation was introduced in northeast Syria.

Syria is an arid country whose agricultural development depends greatly on irrigation. In 1974, engineers undertook to build a large dam on the Euphrates River, called the Tabqa Dam. It was intended to generate electricity and to permit the irrigation of some 400,000 hectares of land. The soil to be irrigated contained large amounts of native gypsum, in the form of crystalline lenses. When irrigation was begun, that gypsum tended to dissolve. Consequently, the land surface, which had been carefully leveled and formed into basins, subsided irregularly. A smooth area soon turned into a patchwork of hummocks and depressions that thwarted the effective distribution of water over the surface. Several of the canals collapsed due to seepage-induced subsidence. Moreover, the concentration of dissolved gypsum was so high in the root zone that it affected some crops adversely.

Some of these difficulties could have been avoided by prior soil testing, and some may be temporary. The situation may be rectifiable in time, by means of appropriate methods of water conveyance, irrigation, drainage, soil management, and crop selection.

Box 17 Solubility of lime and gypsum in the soil

Lime, consisting of the mineral calcite ($CaCO_3$), is a constituent of many arid-zone soils. It has a strong influence on the soil solution's chemical relations. The dissolution of calcite is represented by

$$CaCO_3 + CO_2 + H_2O == Ca^{2+} + 2HCO_3^-$$
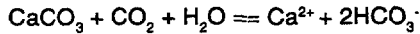
The presence of ions other than Ca^{2+} and HCO_3^- increases the ionic strength, which, in turn, decreases the ionic activity coefficients of Ca^{2+} and HCO_3^-. The solubility of $CaCO_3$ (otherwise quite low) is thereby increased.

Gypsum ($CaSO_4.2H_2O$) is another mineral often present in arid soils. It is moderately soluble, but tends to precipitate whenever its solubility is exceeded, e.g., when the irrigation water is high in sulfates (Jurinak, 1990). The dissolution reaction of gypsum is:

$$CaSO_4.2H_2O == Ca^{2+} + SO_4^{2-} + 2H_2O$$

Adding salts that contain ions such as Na^+, Mg^{2+}, Cl^-, and NO_3^- enhances the solubility of gypsum by the ionic strength effect. However, the presence of large amounts of other sulfates (Na_2SO_4, or $MgSO_4$ salts) reduces the solubility of gypsum. When its solubility is exceeded, gypsum tends to precipitate.

Gypsum's solubility is not affected materially by pH. In contrast, the solubility of lime is strongly pH-dependent. The addition of acid reduces the alkalinity of the solution and enhances the dissolution of $CaCO_3$. With increasing salinity, Na tends to predominate over Ca, because Na salts are more soluble than Ca salts. Whereas SO_4^{2-} may be prevalent in dilute solutions, Cl^- tends to dominate in saline waters (in which the solubility of $CaSO_4$ is exceeded so gypsum begins to precipitate).

Irrigation Practices

Crop growth under saline conditions is greatly influenced by the method of irrigation (see box 18 for an example from the Aral Sea). Flood irrigation is suitable for salinity control provided that the land is level. Furrow irrigation is more suitable for row crops where the slope of the land surface makes flooding impractical, but salts may accumulate in the ridges between the furrows.

Irrigation by sprinkling allows better control of the amount, rate, and distribution of water application. Potential disadvantages of sprinkling irrigation are soil crusting caused by drop impact, and damage to the crop when salt-containing water is intercepted and absorbed by the foliage.

Sprinkler-irrigated crops may suffer leaf-scorch or flower-scorch due to the direct deposition of brackish water, especially as the droplets evaporate and the salt residue remains in concentrated form on the sensitive plant surfaces. The sensitivity of a crop's aerial parts does not necessarily correlate with its sensitivity, or tolerance, toward salinity in the root zone. Sprinkling at night, when evaporation is minimal and the stomates are closed, can help to minimize the latter problem.

Subirrigation, a technique by which the water table is raised or maintained high enough to supply water to the root zone from below, can exacerbate the salinity problem by allowing water-borne salts to rise and to accumulate in the soil. To avoid this, the water table must be lowered from time to time so that the accumulated salts can be leached downward by rainfall or by the periodic application of additional irrigation water from above.

Of even greater importance is the frequency of irrigation. Under an infrequent irrigation regime, the matric and osmotic potential of soil moisture both diminish during the intervals between successive irrigations. Consequently, the crop experiences stress in the later stages of each inter-irrigation period. On the other hand, if irrigation is applied frequently, the concentration of salts in the soil solution is maintained at a level close to that of the applied water, and the progressive build-up of salinity in the root zone is prevented. This is why high-frequency drip irrigation has been found to enhance crop growth in conditions that would otherwise result in serious salinity stress and diminished yields (Hillel, 1997).

Drip irrigation, if properly designed and implemented, minimizes osmotic and matric stresses, as it maintains soil moisture at a high level continuously. Under drip irrigation, the salts are carried away from the points of water application toward the periphery of the wetted

Box 18   The shrinking and salination of the Aral Sea

An ecological debacle has occurred in the arid plains of central Asia, a part of the former Soviet Union, as a result of what had earlier seemed to be a shining success of large-scale irrigation development. With its warm, sunny climate, that region was a rich agricultural production center that yielded more than 33 percent of the USSR's fruit, 25 percent of its vegetables, 40 percent of its rice, and as much as 95 percent of its world-leading harvest of cotton.

To provide the water needed for irrigation, engineers diverted the flow of the region's two rivers, the Amu Darya and the Syr Darya, both of which flowed naturally into the Aral Sea. So much of the water was siphoned off that what was the world's fourth largest lake shrank to less than half its original size. The once-thriving fishing industry has been devastated, as fishing villages once located on the shore became stranded 30 to 80 kilometers inland. Moreover, the salinity of the water has risen dramatically.

Behind the receding waterline lie mudflats covered by fluffy salts, which are picked up by the swirl-ing continental winds and float in deadly dust clouds to destroy crops and poison land for hundreds of kilometers around. Compounding the damage of salinity are the residues of agricultural chemicals (fertilizers and pesticides), applied in huge overdoses in an effort to coax the greatest yields from the land in the shortest possible time. The chemicals have seeped into the groundwater and the surface streams, poisoning the only water supply available to the region's population.

Long-proposed schemes to divert the waters of Siberian rivers and to channel them south to the Aral Sea were abandoned after years of controversy over their costs and potential environmental impacts. The more practical approach is to improve the inefficient irrigation system by lining canals, laying pipes in place of open channels, applying water by means of sprinklers or drippers instead of by surface flooding, introducing volume-controlled sluices and valves, and altogether promoting greater efficiency in the distribution and utilization of irrigation water. Equally important is the selection of crops and agronomic methods to conserve water and prevent pollution.

The Aral Sea
1990
1965
0   100   200 km

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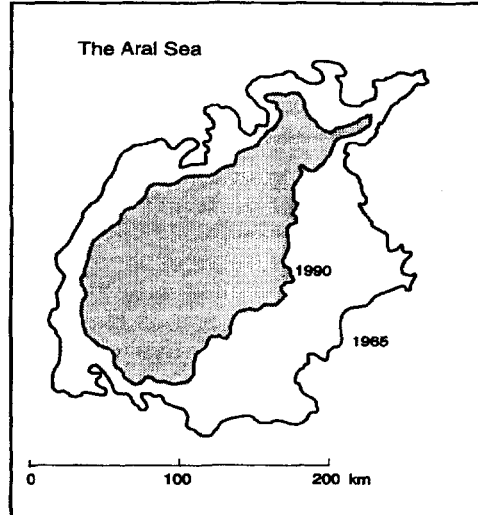
zone. Consequently, the salt content is lowest in the soil immediately below the drip emitters, and highest in the periphery of the wetted zones (a radial distance of, say, 20 - 40 cm from each emitter). Phene et al. (1986) designed a system of subsurface trickle irrigation, combined with fertilizer injection and automatic feedback, to control water application continuously. With such a system, those investigators were able to achieve exceptionally high yields of tomatoes while controlling the leaching fraction precisely.

In many cases, the major cause of waterlogging and salination, requiring expensive drainage works, is excessive irrigation, i.e., the application of volumes of water greater than needed to satisfy the evaporative demand and provide for leaching. Improving water application efficiency can substantially reduce the hazard of salination as well as the cost of drainage.

Ideally, water should be made available in the field on demand (rather than on an arbitrary fixed schedule), so as to allow frequent (or even continuous) irrigation at a rate sufficient to answer the needs of the growing crop and to maintain the root zone both moist and well aerated. Properly calibrated according to weather, soil, and crop conditions, this mode of irrigation can help to alleviate crop stress and to minimize drainage and pollution problems.

We can readily see that increasing irrigation efficiency can have a significant effect in reducing the load of salt that must be removed from the soil annually. The leaching fraction should be so adjusted as to remove the highly soluble salts (e.g., sodium chloride), while allowing the precipitation of the less soluble calcium carbon-

ate (calcite) and calcium sulfate (gypsum) to take place just below the root zone.

Irrigation water is hardly ever applied uniformly. Variable quantities of irrigation make for variable soil moisture regimes and therefore lead to variable rates of percolation and leaching. The spatial variability of these factors is compounded by the inherent heterogeneity of the soil itself. Consequently the yield of the crop tends to be distributed non-uniformly: some sections of the land may produce apparently healthy and vigorous plants while other sections exhibit stunted growth and perhaps even total crop failure.

Several investigators have studied the effects of irrigation non-uniformity on crop production (e.g., Zaslavsky and Buras, 1967; Seginer, 1978; Warrick and Gardner, 1983; Solomon, 1983; Letey, 1985; and Warrick and Yates, 1987).

In surface irrigation schemes, such as flood or furrow irrigation, the properties of the soil itself determine the spatial distribution of infiltration and soil moisture storage. With pressurized irrigation systems, such as low-intensity sprinkler or drip systems, the rate of water application can be adjusted so as to avoid surface ponding. The control of infiltration rate then shifts from the soil to the delivery system.

The scale of variation in space is also important. Depending on the extent of their root systems, plants tend to integrate the effects of small-scale non-uniformities in soil moisture conditions. Large perennial crops (such as fruit trees) with extensive roots can obviously do this better than small herbaceous plants (such as annual vegetables).

A major cause of high water table conditions in many locations is seepage from unlined (earthen) canals. Lining canals with impermeable materials, or at least compacting the canal walls and bottom, can help to lower permeability and thus reduce seepage. Seepage from channels has been successfully controlled by lining them with compacted earth, bentonite, concrete, and various types of membranes (such as rubber or plastic sheeting). For smaller canals and laterals, closed conduits (pipes) of concrete or plastic material such as polyvinyl chloride may be practical alternatives. Delivery of water in pipes has the effect of reducing evaporation as well as seepage, and permits pressurizing the water. It also protects water from surface contamination, and can be buried under the surface to save space and avoid the obstruction generally due to open channels.

Various other strategies have been proposed and tried in response to salinity. They include modifying crop selection and crop rotations, increasing the volume and frequency of irrigation, changing the method of water application, applying water of higher quality, installing subsurface drainage, reusing drainage water when its quality permits, and treating or disposing of drainage water when its quality is so degraded that it cannot be reused directly.

CHAPTER 6

Early Warning Systems

In most cases irrigation systems are organized and irrigation is begun long before drainage is installed. Indeed, an irrigation project can often function unimpeded for years, even decades, without artificial drainage. In some cases, the land is so well drained naturally that irrigation can thus be continued for a very long time. However, far more typically, the process of groundwater rise and salt accumulation proceeds inexorably, so that sooner or later (and much sooner in the case of naturally ill-drained river valleys where most irrigation development takes place) the provision of artificial drainage becomes essential.

Granted that a drainage system must be planned in advance at the very outset of an irrigation project, the crucial question is just when to begin implementing the difficult and expensive task of installing drainage. If installed too early, the drainage system may lie unused for some time and therefore be both unnecessary and uneconomical, and it may deteriorate in the interim before it comes into play. On the other hand, if installed after waterlogging and salination have advanced, it may be too late to maintain or even to restore productivity economically.

Need for Early Detection

All these considerations emphasize the importance of having an early warning system to indicate, before the problem becomes acute, that land degradation is incipient and that the need for drainage is imminent. Soil salinity is normally monitored by a combination of soil sampling, soil solution sampling by vacuum extraction, and various in situ devices that measure salinity. Depths of the water table can be monitored by means of observation wells.

Methods of Monitoring

Detection and diagnosis of salinity is difficult in the early stages of its occurrence. Visual inspection of crops provides obvious clues to salt stress only after the condition is well advanced. In fact, yields of various crops may be reduced significantly by salinity even when the plants show no visible symptoms. Box 19 provides a summary of early warning models.

Visual inspection of the soil surface to detect salinity may be misleading. For example, the white precipitation formed on the surface of furrow-irrigated or drip-irrigated soil may be due mainly to relatively harmless calcite (calcium carbonate) or gypsum (calcium sulfate) rather than to harmful salt (sodium chloride).

Only systematic and objective diagnostic tests, conducted repeatedly or—preferably monitored— continuously from the start of an irrigation project can provide timely warning of incipient salinity problems before they become severe, damaging, and prohibitively expensive to rectify.

Crop plants suffering salt stress eventually exhibit stunted growth, smaller leaves than normal, and a deep blue-green color (Rhoades, 1990). Such symptoms first occur in spots rather than uniformly over the entire field. Since factors other than salinity per se (e.g., water stress, disease, nutrient deficiencies, or misapplied

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Box 19   Summary of early warning methods

- *Planting salt-sensitive plants* at regular intervals (and especially at locations known to be prone to salination), to serve as indicators of increasing salt concentration in the soil.
- *Monitoring the soil profile* to detect changes in salinity, by soil sampling or, preferably, by embedding salt sensors in the soil to permit repeated measurements in the same locations. Possible changes in the exchangeable sodium percentage should also be detected. Mobile equipment is now available to monitor the spatial distribution of salinity in the top layer of the soil.
- *Monitoring the elevation of the water table* by means of regularly spaced observation wells to note the rate of groundwater rise and assess the danger of waterlogging the root zone.
- *Monitoring the salinity of the groundwater* by sampling the water via the observation wells or by using in situ electrical conductivity sensors.
- *Monitoring the pressure profile of the aquifer* by means of sets of piezometers inserted to various depths.

- *Assessing fractional areas infected with salinity,* preferably by using a non-destructive method such as infrared photography or some other mode of remote sensing.
- *Monitoring the quality of the irrigation water,* as it may vary over the irrigation season, including total salt concentration (TDS) as well as the sodium adsorption ratio (SAR).
- *Visual inspection of crops* to detect clues to the onset of salt stress (stunted growth, smaller leaves, deep blue-green color, scorching of leaf tips, etc.), followed by tissue analysis.
- *Visual inspection of the soil surface* to detect tell-tale signs of rising salts (appearance of salt crystals in the form of a fine powder).
- *Measuring the temperature of the crop canopy* in comparison with the ambient air temperature to detect the occurrence of salinity-induced moisture stress.
- *Applying modeling methods* to assess and predict the interactive processes of water and salt dynamics. The predictions of such models should be compared to independently obtained data from field measurements.

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pesticides) may produce similar symptoms, visually observed indications of apparent salinity should be checked by means of appropriate chemical analyses of soil, plant, and water samples.

One good way to help detect the early appearance of salinity is to place plants that are known to be particularly salt-sensitive at regularly spaced intervals throughout the irrigated area. Such interspersed detector plants may reveal early symptoms of physiological stress, and thus provide a timely warning of problems that are likely to exacerbate and become widespread if left uncontrolled. To confirm the apparent symptoms of the indicator plant or plants, one should take soil and groundwater samples from the affected sites, and compare their results with those of unaffected sites.

Salt-affected soils tend to be extremely variable in time and space. As the appearance and severity of salinity are unlikely to be distributed uniformly, efforts should be made to map out the spatial variability of salinity over the area of concern. This can best be done by setting a network of sampling and observation sites. At each site, soil and plant samples can

be collected periodically. Ideally, such sites should be equipped with permanently installed measuring devices, such as salt sensors, observation wells, and piezometers. Surface monitoring equipment is now available that can be used to "map" soil salinity without the need for permanently installed devices. Rhoades et al. (1997) developed a mobile salinity assessment vehicle with combined electromagnetic induction and four-electrode soil conductivity sensing systems. Such equipment, though expensive, can allow monitoring of extensive areas for early signs of soil salination.

The removal of excess salts from the root zone by percolation is only possible if the water table is deep enough to allow drainage and salt-leaching below the root zone. The required depth depends on soil texture, stratification, quality of the subsurface and of the irrigation waters, quantity and method of irrigation, and characteristics of the crop grown. There is generally cause for concern whenever the water table approaches to within 1.5-2 meters of the soil surface, if only during a part of the season. The position of the water table should be monitored carefully and regularly, by means of ob-

servation wells. Such wells may also be used to sample the groundwater for chemical analysis to determine the composition and concentration of salts in it. The observation wells should be cased with rigid plastic or metal tubes, to prevent the holes from caving in. The lower sections of the tubes should be perforated to allow free movement of groundwater into them.

A distinction must be made between observation wells and piezometers (figures 17 and

18   ). Both are vertical tubes of rigid plastic material or metal, inserted into the soil to a depth well below the water table. The difference is that an observation well is perforated to permit free inflow of groundwater along the length of the tube below the water table. In contrast, a piezometer is a similar tube that is not perforated, so its only opening is at the bottom. As such, a piezometer indicates the hydraulic head (or pressure) of the water at the bottom of the tube, rather than the position of the wa-

Figure 17   Observation wells to determine elevation of the water table
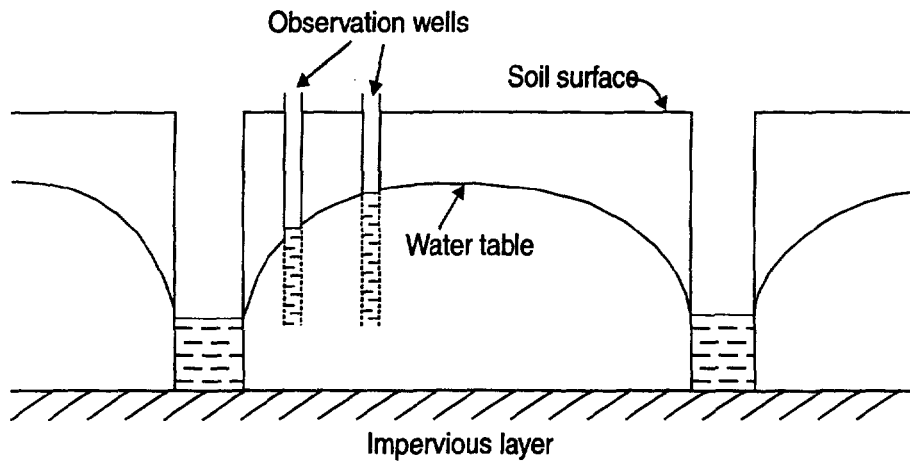
Source: Hillel (1998).

Figure 18   Set of piezometers to determine vertical pressure gradients under the water table. The condition illustrated suggests downward flow
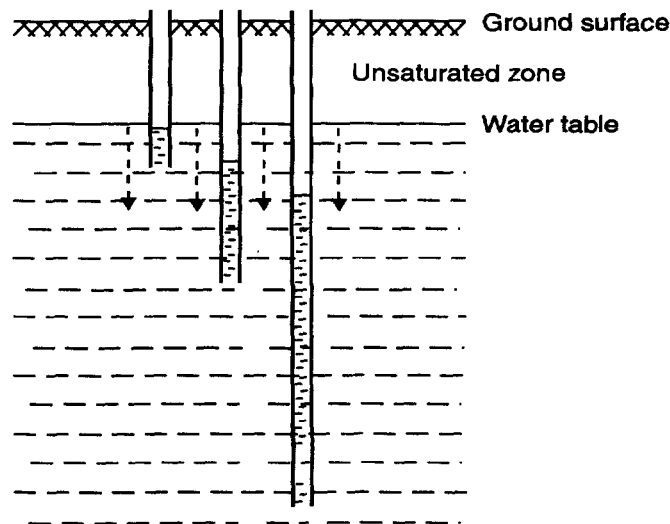
Source: Hillel (1998).

ter table. A set of several piezometers, inserted side-by-side to different depths, can indicate the vertical gradient of the hydraulic head below the water table. The direction and magnitude of that gradient is indicative of the tendency of the groundwater (and hence of the water table) to rise or fall.

The network of representative salinity monitoring points should be operated, using consistent procedures. Among the important measurements to be made are the electrical conductivity values of the irrigation water, of the soil, and of the underlying groundwater. Where the water table is high or appears to be rising, its elevation should be monitored. Special attention is to be paid to areas within an irrigation district that are most affected by salinity and are most in need of drainage.

Detailed procedures for sampling soil, water, and plants so as to monitor salinity were described by Hanson and Grattan (1990). Field and laboratory measurements of salinity were reviewed by Robbins and Wiegand (1990). Methods of measuring exchangeable cations and cation exchange capacity are described in Monograph No. 9 of the American Society of Agronomy (1986). The presence or absence of native lime and gypsum in the soil should also be considered when making management decisions regarding salt-affected soils. Procedures for determining the content of these minerals are specified in Nelson (1982) and in Monograph No. 9 of the American Society of Agronomy (1986).

Methods of tissue analysis to determine the salt content of plant parts are given in the book edited by Tanji (1990). In situ measurements of the hydraulic conductivity of the soil at saturation, such as the auger-hole method and alternative methods, were described by Amoozegar and Warrick (1986), and at unsaturation by Hillel et al. (1972).

Non-destructive methods for direct measurement in situ of soil salinity include: buried electrical conductivity sensors, electromagnetic induction sensors, and time domain reflectometric (TDR) systems. These methods (described by Robbins and Wiegand, 1990) measure total salt concentration in soils but not the concentration of specific ions.

The most commonly used are the electrical conductivity salinity sensors. They consist of a pair of corrosion-resistant electrodes embedded in a porous body of ceramic or glass that is buried in the soil at a given depth. (A series of such units can be buried at various depths to allow monitoring the entire soil profile.) As the porous units absorb and equilibrate with soil water, the electrodes sense the salinity of a representative sample of the soil solution in the surrounding soil. The electrodes are connected to recording monitors for continuous monitoring, or to manually operated meters for periodic readings. The units often contain thermistors to allow correction of the readings to account for variations in temperature. The units described must be recalibrated from time to time, lest the readings based on the original calibration deviate progressively from the real salinity status they are intended to monitor.

Time domain reflectometry is a fast-developing method that is used increasingly for simultaneously measuring volumetric wetness and bulk-soil electrical conductivity *in situ*, using parallel metal rods of a given length inserted into the soil. The measurement is based on the fact that the relative dielectric constant of the soil is primarily related to its water content, and that the propagation velocity of a voltage pulse along the transmission lines (the rods) is a function of the electrical conductivity of the soil. Dasberg and Dalton (1985) provided a detailed explanation of the method, in comparison with alternative methods.

The soil solution may be sampled in situ, even in the unsaturated zone. To do this, tubes tipped with thin-walled porous ceramic cups are inserted into the soil to various depths. Water samples may be extracted from the soil by applying suction in the tubes. In practice, however, such samples can only be obtained if the soil is quite wet, i.e., if the matric potential of soil moisture is above –30 kPa (-0.3 bar). Experience shows that at lower values of matric potential (greater values of suction) the soil solution generally moves toward and into the cups too slowly to permit sampling (Robbins and Wiegand, 1990). Such suction sampling tubes can be left in place for repeated samplings during the irrigation season.

Measurements should properly be made at fixed times following consecutive irrigations, since the effective soil volume sampled and the location from which the solution is extracted change as the water contained in soil pores of progressively smaller sizes drains or is taken up by plant roots.

Solutions extracted from sodic soils (pH greater than 8.5 and EC lower than 4 dS/m) are often dark in color owing to the dispersion of organic matter, which may interfere with certain analytical procedures (e.g., photometry). This problem can be overcome by adjusting the pH with an acid and by coagulating the suspended organic matter with an aluminum salt and then centrifuging and filtering it.

Remote sensing refers to procedures for measuring properties of an object from some distance, without direct contact. In practice, it consists of sensing the energy conveyed by radiation bands reflected or emitted by the object of interest. One method of remote sensing involves the use of aerial photography. In particular, infrared film can be used to detect salinity-induced plant stress. With this film, dark-green foliage appears bright red; light-green foliage pink; barren saline soil white; and non-saline soil gray, bluish-gray, or green. The color produced by clear water is a very dark-blue, whereas that produced by sediment-laden water is a lighter shade of blue. Thus, clusters of plants and patches of soil affected by salinity can often be identified quite readily.

Moreover, in some cases it may be possible to estimate fractional areas that are infected with salinity to different degrees of severity. As the relative degrees of salinity tend to vary from season to season and from one area to another (depending on such variables as precipitation, topography, soil stratification, groundwater configuration, and crop tolerance), repeated monitoring by means of infrared photography can be very useful in guiding management practices. This techniques can be applied on a regional scale.

Another useful technique for detecting plant water stress caused by soil salinity is the measurement of canopy and soil temperature, using infrared thermometry. Jackson (1982) showed that canopy temperature can be correlated with crop water stress, which is often one of the manifestations of soil salinity. Infrared thermometry can also be used to monitor saline seeps, since the temperature of a wet soil differs from that of a dry one. Infrared thermometers may be hand-held or flown across fields in transects. At midday, a dry soil surface can be more than 20 C warmer than the ambient, while the temperature of foliage is generally within 2 C of the air temperature. (The temperature of fully hydrated foliage is generally lower than that of the ambient atmosphere, whereas the temperature of water-stresssed plants tends to be higher.) A vertical view of surface temperature as it varies spatially in a field can help to map areas of crop stress, crop failure, and denudation due to salinity.

Spatial and temporal variabilities of both moisture and salinity greatly complicate the task of monitoring an irrigation system, and may call for specialized methods of sampling and analysis. Whereas standard methods of statistical analysis (such as regression and analysis of variance) require independence of observations, the techniques appropriate to time-series (e.g., autocorrelation) and space-series analysis (e.g., kriging) deal with interdependent data. Guitjens (1990) described methods of spatial analysis that are appropriate to the task of characterizing temporal and spatial variabilities of salinity.

Where possible, control measures should be applied preferentially to specifically affected locations, rather than indiscriminately to the whole area. For example, spots affected by sodicity should be given extra doses of soil amendments at the appropriate time. This spatially and temporally selected approach is likely to be more efficient than the common practice of treating a large area uniformly.

Irrigation water quality may remain fairly constant in time if the water is taken from large storage reservoirs. Contrariwise, it may vary during the irrigation season if the water is derived from small storage systems and stream diversions that have fluctuating flows, or that contain subsurface irrigation return flows (drainage waters) as well as spring flows. Recycled water (including treated sewage) also

tends to vary in quality over time. For this reason, representative water samples should be collected periodically and regularly throughout each season, and from one season to the next. Each water source should be tested for its salinity, sodium adsorption ratio, as well as the possible presence of toxic or pathogenic agents.

Analytical quantitative techniques and numerical computer models are available for predicting soil salinity, drainage amount and salinity, and crop response to water applications under various water management alternatives (Rhoades, 1990). Deterministic, or process-oriented, models can simulate the physical and chemical processes that take place as water moves through the soil profile. The processes include salt precipitation, mineral weathering, and cation exchange reactions. Stochastic models and optimization models may be used to predict problems that are likely to result from alternative irrigation practices in various conditions of soil, crop, and water quality. Economic models can be used to estimate the costs (in terms of increased expenditures and reduced income) of incurring salination versus the costs of preventing or remedying salination by various means. All models require periodic validation by comparison of predictions with the results of independent field-based measurements.

A very comprehensive and detailed description of electrical conductivity measurements applicable to the field monitoring and assessment of soil salinity has recently prepared by Rhoades, Chanduvi, and Lesch and issued by FAO (1999).

Scaling Up from the Field

Having described the fundamentals of irrigation-induced salinity and the possible ways to control it, we now come to evaluate its wider implications. In this chapter, we deal firstly with the relation between crop production and the quality as well as quantity and mode of water application on a broader scale. We then take up the larger-scale environmental, social, and institutional issues posed by salinity. Finally, we list policy options aimed at promoting the control of salinity in consideration of all the foregoing (box 20).

Crop-Water Production Functions

A way to evaluate the efficiency of crop production under irrigation is to consider the so-called *crop-water production functions*, which express the relation between the yield of a crop and the quantity of water applied to it or consumed by it. As originally formulated, these functions were used to analyze alternative irrigation management strategies, in the effort to devise economically optimal combinations of irrigation volumes and frequencies (Yaron et al., 1972). The concept has subsequently been applied to waters of different quality (Letey and Knapp, 1990).

The term has been used in a somewhat ambiguous way. Some authors have defined the crop-water production function as a relation between yield and the total amount of water applied, whereas others have defined it as a relation between yield and seasonal evapotranspiration (ET). If the volume of water applied is less than the potential evapotranspi-

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Box 20   Policies options to promote water conservation

1. *Ground and/or surface water taxes or effluent discharge taxes.* The optimal schedule of these taxes should be flexible and responsive to changing circumstances. These taxes (and especially the discharge tax) are difficult to administer since they require constant monitoring of water use and/or drainage at each farm.

2. *Direct quotas on surface and groundwater usage.* The major problems with non-tradable quotas is that they are usually economically inefficient and are subject to political pressures (e.g., users pressure the government to assign them higher quotas).

3. *A combination of taxes and quotas.* Since the development of salinity problems occurs over a considerable period of time, the regulation task becomes more complicated. Policies should provide the right mix of incentives and regulations with regard to the optimal timing of relevant activities (e.g., the appropriate time to install drainage outlets), their duration and evolution over time.

4. *Governmental subsidies of preferred technologies and of research and development activities.* Subsidies should be aimed at promoting the adoption of more efficient (but otherwise less profitable) and environmentally friendly irrigation and other conservation practices.

5. *Charges on contaminating technologies.* For example, furrow irrigation generates more drainage than drip irrigation. Therefore, charging users of furrow irrigation a higher lump-sum tax might help to promote the adoption of drip irrigation, if such a change is considered desirable.

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ration (PET), then - assuming no significant change of soil moisture storage from beginning of the growing season to its end—the volume of water may be roughly equal to ET. If, furthermore, the fraction of ET due to direct evaporation of soil moisture is negligible compared to crop transpiration, then the ratio of crop production, in terms of dry matter produced, to volume of water applied is in effect the reciprocal of the so-called "transpiration ratio." On the other hand, if the volume of water applied exceeds PET, then the excess of volume of water applied over PET must go to either augmenting soil moisture storage (end-of-season moisture being greater than start-of-season soil moisture) or to deep percolation beyond the root zone.

Some crop physiologists (e.g., de Wit, 1958) have long contended that, for a given crop and a given set of environmental conditions (meteorological and edaphic), dry-matter production is proportional to the volume of water transpired by the crop (or, rather, to the ratio of transpiration to potential transpiration). This implies that the transpiration ratio is constant, regardless of the amount of transpiration. The assumption that such a linear relation exists between crop production and evapotranspiration implies that evaporation from the soil is negligible, or that it is proportional to transpiration.

The standard economic definition of production function is the relation between inputs to a production process and the output of that process. More specifically, Letey and Knapp (1990) referred to CWPF as the maximum yield that can be obtained from a given level of seasonal water application.

A vast literature exists regarding crop-water production functions under nonsaline conditions (Vaux and Pruitt, 1983; Solomon, 1985). The concept has subsequently been applied to waters of different quality (Letey and Knapp, 1990). Analyses of production functions as influenced by salinity have been offered by Yaron et al. (1972), Feinerman et al. (1982), and Dinar and Zilberman (1991), among others.

The following type of empirical relationship has been reported for the relationship between crop yield and soil salinity (Pratt and Suarez, 1990):

$$\text{Yield} = 100 - B(E_C - A)$$

where A is the salinity concentration at which growth depression (threshold) starts, and B is the percent yield reduction per unit of E_C above the threshold level (Maas and Hoffman, 1977; Pratt and Suarez, 1990). (See Table 1.)

Bresler and Hanks (1969) combined a numerical model of water flow in unsaturated soil with a salt distribution model described by Bresler (1972) to compute the water and salt concentration in the soil as a function of time and depth. Nimah and Hanks (1973) then elaborated the model to include water extraction by a root system of given depth distribution. Childs and Hanks (1975) extended the same model to consider the effects of salinity on crop yield. Data from earlier studies (e.g., Shalhevet and Bernstein, 1968) were used to demonstrate a linear relationship between relative yield (Y/Y_{max}) and relative transpiration (T/T_{max}) when stress was caused by either salinity or limited soil moisture or by a combination of the two factors. Hanks (1984) admitted that the root extraction term used is rather crude, particularly regarding plant factors.

One of the main shortcomings of the early models was the omission of root growth as a process affecting the pattern of moisture extraction and movement in the soil profile and possibly enhancing the ability of plants to withstand or avoid both matric and osmotic stresses (Hillel, 1977; Huck and Hillel, 1983).

Even if total dry matter production is related linearly to ET, the same is not necessarily the case for a crop's marketable yield. In cotton, for example, the relation between marketable yield (lint) and dry matter production is evidently not linear. Letey (1991) modeled the crop-water production function of cotton using an empirical relationship between dry matter and lint production.

Crop-water production functions for non-uniform irrigation depend greatly on the distribution of infiltrated water over the field, as well as on the shape of the production function. Warrick and Yates (1987) analyzed the effects of irrigation uniformity or non-uniformity on crops with differing production functions. They showed that yields under non-uniform application are generally lower than yields un-

der uniform application for a given quantity of applied water. If the production function is linear, applying more water can help to mitigate the effects of non-uniformity. That is to say, higher yields can be obtained by applying more water, provided that the soil does not become waterlogged. However, if the production function is quadratic (i.e., if the yield vs. applied water curve rises to a maximum and then descends), applying more water may not help to overcome the effects of non-uniformity.

In many crop production models, yields are assumed to be proportional to relative transpiration, or:

$$Y/Y_p = T/T_p$$

where T is seasonal transpiration, T_p is the potential or maximal transpiration, Y is the actual yield, and Y_p is the potential yield obtained when transpiration is maximal.

As conditions of salinity develop, crop growth is stunted and transpiration is diminished. The economic yield appears to diminish in a commensurate manner with transpiration, in saline as it does in non-saline environments. However, the overall effect of salinity on crop production depends in a complex way on the soil and its fertility (nutrient balance and availability), the crop species and their sensitivities, and the irrigation regime. It also depends on the irrigator's expertise in achieving the needed leaching and on the degree of yield reduction that can be tolerated economically.

Social and Institutional Issues

The practice of irrigation is not simply a mechanical task of delivering water to, and draining water from, cropland. It is a human occupation and a social undertaking. No consideration of irrigation sustainability should fail to note that, ultimately, the success of the undertaking depends on the quality of human effort invested in it. An irrigation project is more than an enterprise producing crops; it is, primarily, a community of people with families needing to live healthy lives while working cooperatively and contributing to the food security of their nation.

Irrigation systems serve non-agricultural purposes as well: for domestic water needs, waste disposal, power generation, transportation, fishing and recreation. Fulfillment of these purposes often involves the coordination of resource allocation and utilization among various sectors and the resolution of issues of land and water rights.

Salinity control, especially as it pertains to drainage, cannot generally be achieved at the localized level of a single field or farm. Because the same groundwater table typically underlies an extensive area, deep percolation from one field may influence water table height and quality under adjacent fields. Hence the installation of drainage at any restricted location is likely to be futile. Rather, the drainage of all fields in an irrigated area must be planned and implemented simultaneously. Other practices, including pest control and disease prevention, must be similarly extensive and coordinated to be effective.

Indeed, irrigated agriculture must be considered a participatory social enterprise, not merely an individual activity, and its proper control to ensure sustainability requires comprehensive regional planning, installation, operation, maintenance, and regulation. Environmental as well as socioeconomic factors must be taken into account. The entire enterprise calls for the formation of appropriate legal and institutional frameworks, governed by wise and consistent institutional policy, along with the implementation of a program of training and public education. Underlying the technical tasks there must be an agrarian ethic that guides voluntary individual and collective behavior on the basis of a common understanding of the challenges and opportunities involved in sustainable development.

Quantifying the external costs of irrigation explicitly is an extremely important task. Irrigators normally do not bear the burden of these costs and therefore tend to ignore them, even to resist acknowledging them. But farmers and their children do bear some of the consequences indirectly. Other segments of society, as well as biotic communities, bear them now and will continue to bear them in the future.

The costs of cleaning up polluted water and habitats can be very significant. For example,

the estimated costs of cleaning up the Kesterson Wildlife Refuge (Wahl, 1986) exceed the value of the agricultural lands that caused the problem.

Another regional issue is the management of aquifers (as well as rivers). Aquifer overdraft occurs whenever water users pump out water from wells faster than natural recharge (in places, augmented by artificial recharge) can replenish it. When overdraft exhausts supplies, the agricultural economy of an entire region is literally undermined. Farmers in the southern High Plains region of Oklahoma and Texas, as one example, must pay more and more to pump water from greater depths, and these increased costs reduce the economic viability of irrigated agriculture there.

The availability of inexpensive irrigation water has long been a key condition of irrigation development. In the western states of the U.S., for example, water prices charged to irrigators have typically been one to two orders of magnitude less than the prices paid by municipal and industrial users. State water laws based on the appropriation doctrine of "first in time, first in right" have resulted in rights to irrigation water at virtually no cost other than conveyance to field headgates (Willey, 1990). Federal reclamation water contracts normally charge no interest to irrigators on the construction costs of water projects serving them. Similar policies may prevail in other countries as well.

Moreover, the cost of conserving water often exceeds the price paid by irrigators for the water. Hence irrigators have had little economic incentive to reduce their use of water. Also, the fees paid by them to discharge drainage and runoff have been too low to create an incentive to reduce pollution loads by improving management of on-farm irrigation. As the problems associated with water scarcity and pollution become ever more acute, the need for active policies to induce conservation of both quantity and quality of water will become inescapable. Incentive-based policies are in principle preferable to coercive penalty-based ones, though the latter may not be entirely avoidable.

Farmers generally will not voluntarily adopt procedures that diminish their net income, and will tend to resist the installation of drainage facilities, unless they are convinced that the temporary inconvenience and cost will be more than offset by the foreseeable future rise in tangible benefits. Economic aspects are treated more fully in the Appendix.

The sustainability of irrigation is a complex and comprehensive undertaking, requiring attention to much more than hydraulics, chemistry, and agronomy. A special combination of human, environmental, and economic factors exists in each irrigated region and must be recognized.

Policy Implications

Continued population growth and rising living standards are likely to require an increase of agricultural production in the coming decades. In this task, irrigation will play a decisive role. As farmers in semiarid and arid regions endeavor to expand and intensify production, they may utilize marginal soils as well as marginal water supplies, the latter including naturally brackish water resources and treated wastewater. Moreover, they may well need to rely on increasing amounts of chemical inputs, the residues of which will likely pose an ever greater threat to the environment. The increased load of salts and other potential pollutants added to soils and to groundwater may render the practice of irrigation, already tenuous in some regions, ultimately unsustainable.

Individual farmers caught in this trend and driven by the imperative to survive in the short run, may lack the knowledge, the ability, or even the incentive, to control or prevent the negative long-term environmental impacts of salination and other forms of degradation. The potentially disastrous consequences will ultimately be suffered by future generations, which—being yet unborn—cannot influence the decisions that will determine their fate (box 21). National governments and international aid and development agencies have a role to play in promoting the long-term welfare of societies and ecosystems.

Government policies can help to mitigate and—where possible—to remedy environmental damage already done, and to promote environmentally protective or beneficial practices on a regional basis. Where there are strong

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Box 21   Intergenerational Issues

Another important aspect of long-run management of water resources, under conditions of gradual deterioration in their quality, is related to intergenerational equity. Farm income and food security of future generations may suffer if the stock of groundwater and the water quality they inherit from the present generation decline. In other words, the actions of the current generation may impose negative costs on the next generations via inconsiderate depletion and contamination of groundwater. While negotiations between polluters and victims can of-

ten yield a socially optimal resource allocation, negotiations between the current and next generations are impossible.

Furthermore, water quality for generations yet unborn cannot depend solely upon intergenerational altruism at the individual level. In the absence of corrective actions, the damage to future water-users may be irreversible as salinized areas unsuitable for agriculture expand. Thus, governments of today have a responsibility to fulfill in regulating water usage to ensure adequate water quantity and quality, as well as sustainable food production and public health, in the long-run.

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vested interests, they may oppose the role of government. To build cooperation, agencies may create educational programs aimed at encouraging the adoption of more sustainable irrigation methods. Policy specialists may evaluate alternative measures including economic incentives (e.g., subsidies) for beneficial practices, as well as disincentives (e.g., regulations enforced by fines) to the continuance of deleterious practices. The effectiveness of such policies will be enhanced if they are implemented in consideration of social perceptions and cultural mores.

Government leadership is often essential in the planning and construction of large-scale drainage works, designed to prevent the waterlogging and salination of extensive districts and to treat, convey, utilize, or dispose of the effluent safely. A regional authority can enlist the financial and technical resources needed to

undertake such schemes that exceed the capability of local farmers and farmer associations.Determining the optimal mode of drainage and the most appropriate time for its installation calls for balancing disparate socioeconomic and environmental factors. Where the costs of effluent disposal are low, as in the proximity of a seacoast and in the absence of topographic or urban barriers, the early construction of a canal might be the most feasible option. In desert areas far from the sea, the availability of empty land may allow the disposal of effluent onto evaporation ponds with minimal danger to wildlife, or—better yet—into recharge basins underlain by saline aquifers. Where neither of these options is feasible or economical, measures will be called for to minimize the volume of drainage by means of stringent water conservation and improved water-use efficiency.

CONCLUSION

Irrigation is Sustainable—at a Cost

At the outset, we posed the crucial question regarding the fate of irrigation: Is it sustainable?

Waterlogging and salination, along with other degradation processes, have not only caused the collapse of irrigation-based societies in the past, but are indeed threatening the viability of irrigation at present. The problem is global in scope. Decimation of natural ecosystems, deterioration of soil productivity, depletion and pollution of water resources, and conflicts over dwindling supplies have become international problems closely linked with irrigation development.

Practical experience and scientific research provide an affirmative answer to the question. Irrigated agriculture can be sustained, albeit at a cost. The primary cost is effective salinity control, along with the prevention of upstream, on-site, and downstream environmental damage. Is society willing to bear the costs of ensuring the future sustainability of irrigation, even if that requires larger investments in the present? Stake-holders and policy-makers are likely to respond positively once the long-term biophysical processes and their socio-economic implications become abundantly clear.

Although there will be cases where the costs of continued irrigation (especially if severe damage has already occurred) may be prohibitive in practice, in most instances the cost is indeed well worth bearing. Investing in the maintenance of irrigation can result in improved economic and social well-being as well as in a healthier environment.

Irrigated agriculture must strive for a balance between the immediate need to maximize production here and now, and the ultimate need to ensure continued productivity in the future. It must also strive to achieve a harmonious interaction with the external environment, which includes both natural ecosystems and other human enterprises.

Developing and implementing an effective salinity control program requires an understanding of complex interrelationships with multiple causes, effects, and feedbacks, operating at different scales of space and time. Except at the most problematic locations, irrigation can be maintained, provided that water supplies of adequate quality can be assured, the salt balance and hence the productivity of the land can be maintained, the drainage effluent can be disposed of safely, and the economic returns can justify the costs.

Those requirements are conditioned on an effective program of monitoring and control. The program is made difficult—but not generally impossible—by the spatial and temporal variability of soil properties, plant growth, and weather conditions.

The *sine qua non* of ensuring the sustainability of irrigation is the timely installation and continuous operation of a drainage system to dispose safely of excess salts. All too often, drainage creates an off-site problem, beyond the on-site cost of installation and maintenance, since the discharge of briny effluent can degrade the quality of water along its downstream route. Where access to the open sea is feasible, solving the problem is likely to be easier than in closed basins or in areas far from the sea. In those cases, the disposal terminus (whether a lake or an aquifer) may eventually become un-

fit for future use. Hence the importance of reducing the volume and salinity of effluents.

Much can be achieved by improving the efficiency of water use. Modern irrigation technology offers us the opportunity to conserve water through reduced transport and application losses, coupled with increased efficiency of utilization.

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The problems posed by the practice of irrigation are real, and age-old. In former times, irrigators were largely unaware of, and in any case lacked the means to control, the processes of degradation engendered by the application of water to land in arid environments. Now we know much more about the dynamics of water and salts in the soil-plant-atmosphere continuum, and we have the techniques to prevent what could not be prevented in the past. We have the knowledge, the techniques, and—above all—the imperative.

Irrigated agriculture will not only survive, but indeed thrive *in the proper circumstances and with appropriate measures*. That statement is conditional: in some specific locations, inherently inefficient, self-destructive, and environmentally damaging operations will be forced to terminate. On the whole, however, irrigated agriculture should be able to adapt to the long-term requirements of sustainability, and to continue to help feed humanity, in the future even more than in the past.

Economic Aspects of Salinity Management

by E. Feinerman

conomists play an essential role in the water management arena. Economics is a discipline that provides rules for coordination of activities and choices, subject to defined objectives and constraints. To be effective in addressing water management problems, economists need know the physical and biological relationships involved and integrate them into an economic model. Therefore the best way to promote effective water management is via collaboration among economists and soil, water and plant scientists.

The purpose of this appendix is to describe the way economic analysis can contribute to understanding the complex relationships involved in irrigation management. Emphasis is placed on the economic, management, and policy aspects of irrigating with water of various qualities at field, farm and regional levels, as well as on the role of drainage in irrigation. Adequate drainage—natural or artificial—is imperative to maintain the irrigated land in equilibrium with the surrounding environment over time. The deviations of competitive outcomes from socially optimal ones and the policy instruments aimed at providing incentives for individual farmers to align their private self interests with societal environmental goals are also emphasized.

Representing Physical and Biological Relationships

In economic analyses, the physical and biological relationships are represented formally in mathematical terms, assuming an irrigation region with a fixed amount of productive land, say L hectares (ha), overlying a single-cell aquifer of groundwater and a large number of identical farmers, N, each owning $l=L/N$ ha of land. A schematic presentation of the irrigation district is depicted in Figure A1. The farmers rely on both surface water and ground water for irrigation, differing in quality, availability and cost. The quality (salinity level) of the surface water, denoted by q, is assumed to be stable over time. The quality of applied groundwater at time t, Q_t, may change over time.

The total quantities of surface and ground water applied at time t by a representative farmer are denoted by ws_t and wg_t cubic meters per ha, respectively. For simplicity, the amount of rainfall at time t is assumed stable at the value of R m³ per ha and is included in ws_t. Part of the irrigation water (as well as rainfall) applied to the fields percolates below the root zone to the groundwater aquifer. To further simplify the presentation, let us assume for a moment that the region's farmers grow a single crop. The crop's commercial yield at time t, denoted by Y_t tons/ha depends on a vector of non-water inputs, X_t (some of which, such as nitrogen fertilizer and insecticides, are potentially polluting); on conservation and management practices M_t (including the choice of irrigation technology, land leveling, etc.), and on the water content and salinity level of the soil solution at the root zone, sm_t and ss_t, respectively. Given the specific soil type, environmental conditions, and conservation practices, the latter two are functions of initial conditions, the quantity and quality of applied irrigation water, conservation practices, non water inputs, and G_t and Q_t—the stock (level) and the quality

Figure A1   Schematic representation of a water system at a regional level
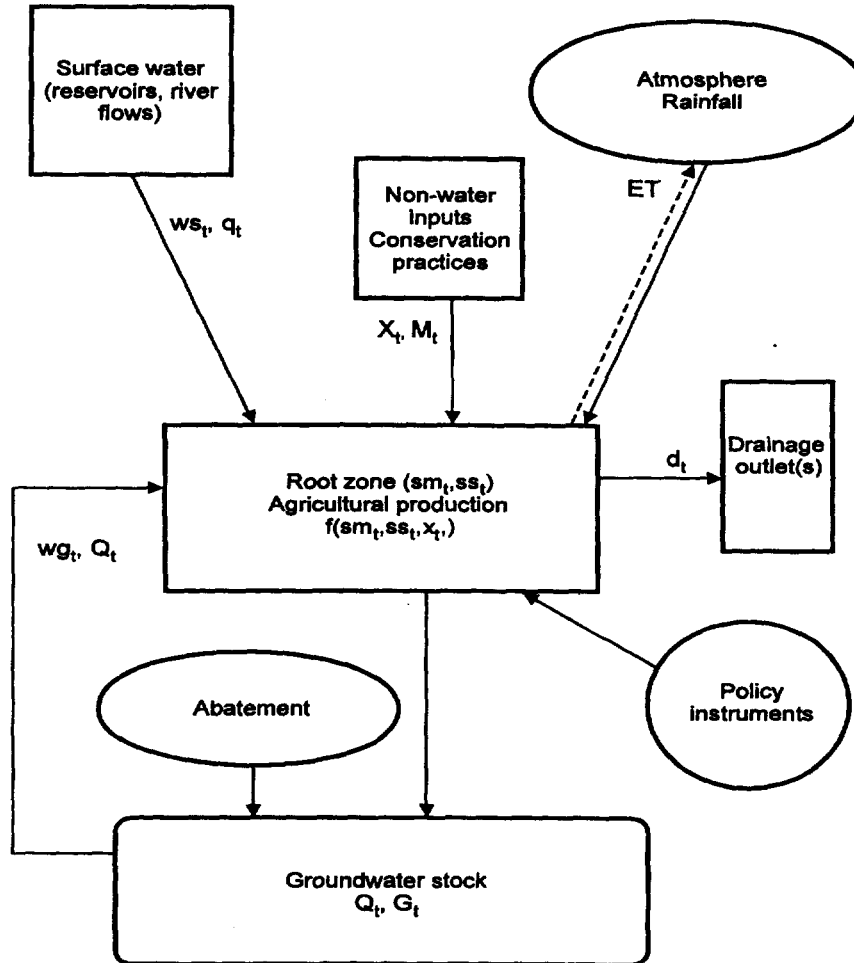
(salinity level) of groundwater at time t, respectively.

Schematically, the above relationships can be described in terms of the following implicit functions:

(1) $sm_t = f1 (sm_{t-1}, ws_{t+}wg_t, G_t, M_t)$

(2) $ss_t = f2(ss_{t-1}, (q)x(ws_t) + (Q_t)x(wg_t), Q_t, G_t M_t, X_t)$

(3) $Y_t = f (sm_t , ss_t , X_t)$

where f1, f2, and f denote implicit functional forms.

The first two functions represent the dynamics of soil moisture and soil salinity in the root-zone, respectively, and the last equation represents the production function. The level of root zone moisture is affected by G_t only in cases where the groundwater table comes close (within a meter or two) to the soil surface. Groundwater tends to seep upwards into the root zone by capillarity action and thus to re-infuse the soil with salts between irrigations. For that reason, soil salinity in the root zone might be affected by both G_t and Q_t.

Water-conservation practices (denoted here by M_t), especially the adoption of advanced irrigation technology, increase the efficiency with which the soil solution and salinity can be controlled. For example, with modern high-frequency irrigation, it is possible to maintain the soil solution in the surface zone at a concentration similar to that of irrigation water. This irrigation technology not only lowers the soil

solution concentration at the root zone (thus affecting ss_t), but also reduces the matric suction of soil moisture (affecting sm_t).

The sum $(q)x(ws_t) + (Q_t)x(wg_t)$ is the total amount of salts added to the top soil through irrigation. Note that non-water inputs, X_t, may affect yield directly and/or indirectly through their impacts on soil salinity. For example, the share of nitrogen fertilizers that is absorbed by the plant roots affects yield directly while the portion that is leached below the root zone may affect Q_t and as a result increase the level of ss_t (see equation 3).

The groundwater stock and its salt concentration evolve over time in response to groundwater withdrawals, deep percolation and drainage activities. Let α represents the share of the water applied for irrigation that percolates into the aquifer. The dynamics of the ground water stock can be described by the following mass balance equation

$$(4) \qquad G_t = G_{t-1} + L[ws_t - (1-)wg_t - d_t]$$

where d_t represents the volume of drainage (m^3/ha).

The change in groundwater quality is an outcome of complex hydrological processes and may be formulated implicitly by

$$(5) \qquad Q_t = Q_{t-1} + g\,[\alpha\,(q)x(ws_t) - (1-\alpha)$$
$$(Q_t)x(wg_t), X_t, G_t\,]$$

The function g increases in its first argument—the net amount of salts (in tons) washed into the aquifer with the irrigation water—as well as in its second argument (fertilizers, pesticides). However, it is expected to decrease in G_t: the same amount of salt changes the concentration of a small volume of water more than that of a large volume.

The temporal nature of the relevant physical relationships in the soil solution—equations (1) and (2)—and in the aquifer—equations (4) and (5)—implies that decisions made today concerning the control variables ws_t, wg_t, d_t, X_t, and M_t will have consequences in the future. As mentioned above, long-run economic analysis is made up of a series of short-run or single period processes, the initial conditions of which

are affected by the level of state variables (like G, Q, sm and ss) at the end of the immediately preceding period in each case. The decisions made in each short-run period affect immediate profits on the one hand, and the rates of change of state variables, and therefore the stream of future profits, on the other.

The biological relationships of our framework are implicitly embodied in the crop yield function (see equation 3). In order to focus on water management, let us assume for a moment that non water inputs (X_t) are fixed. In that case, Equation 3 may be viewed as a crop response function to soil moisture and salinity.

Review of Economic Analyses

Economic models may be classified according to: (a) the degree of aggregation in the single field-farm-region-nation hierarchy; (b) the temporal period of the simulation; (c) whether negative externalities (drainage, environmental pollution) exist and are taken into account; and (d) whether uncertainty is incorporated into the formal analyses (Yaron, 1981).

The distinction between a single field and higher levels of aggregation is obvious. As for the temporal dimension, two simulation periods can be distinguished:

a. A *"short-run"* analysis considers the soil-water-crop-environment system in the framework of a single period (commonly, a single irrigation season) with predetermined initial levels of the state variables. The decision-making process is based solely on "immediate profit" and ignores the effect of the state variables at the end of the season on subsequent seasons.

b. A *"long-run"* model takes into account the effects of the changes in the state variables over time. It is made up of a series of short-run processes, the initial conditions of which are affected by salt accumulation and water dynamics during previous periods. The decisions made in each short run affect immediate profits on the one hand, and the change of state variables, and therefore the stream of future profits, on the other.

Although externalities and drainage associated problems can be incorporated into both

short-run and long-run models, it is obvious that they are more meaningful in the long-run context. The externality problem is based on the possibility that return flow from irrigated crops of a specific farm may drain into surface water sources or groundwater aquifers that are utilized for irrigation by other farms or for human consumption. Drainage water generally contains considerably higher concentrations of dissolved salts and trace elements than the initially applied water.

Short-Run Analyses

1. **Single-Plot/Single-Crop.** A great deal of effort has been devoted to formulating the economic analysis of single-crop short-run irrigation. Most of these studies ignore the impacts of irrigation on groundwater aquifers and the environment, known in economic terms as "externalities." The core of the single-plot/single-crop short-run economic analysis can be schematically presented by the following optimization problem of a representative irrigator.

(6) $\underset{W,X,M}{\text{Maximize}}$ $\{\Pi = 1[P_Y \cdot f(sm,ss,X) - P_s w_s - Pgwg - C(X) - e((M)]\}$

Subject to:

(7) $sm = f1(sm_0, W,G,M)$

(8) $ss = f2(ss_0;(q) \cdot (ws) + (Q) \cdot (wg); Q,G,M,X)$

where:

Π	=	the irrigator's periodical (annual) profit function;
P_Y	=	income per unit of yield net of non-water variable costs directly related to yield;
W	=	(ws, wg) vector of quantities of applied surface and underground irrigation water;
P_s, P_g	=	the price per m³ of applied surface and groundwater, respectively;
sm_0, ss_0	=	initial soil moisture and soil salinity levels, respectively;
C(X)	=	the annual costs function of non-water inputs;

e(M) = the annual variable conservation cost function.

Yaron and Bresler (1970) developed a single-crop short-run optimization model aimed at determining (a) the least cost combination of water quantity and quality (salinity) in irrigation along a predetermined iso-soil-salinity curve, under given conditions of climate, soil and land use; and (b) the relative costs of water quantity and quality subject to restrictions on salt concentration in the soil solution. The levels of all non-water inputs as well as the level of conservation activities (including the irrigation system) were assumed to be predetermined. The model assumed the existence of a variety of water resources with different salinity levels and supply costs, and utilized Bresler's (1967) physical leaching model. An application of the model to the analysis of an irrigated citrus grove in northern Israel was presented.

Bresler and Yaron (1972) extended this study by including the effects of the time interval between successive irrigations and its associated soil-water content fluctuations on the plant's response to salinity and economically optimal quantities and qualities of applied water.

Yaron et al. (1980) presented an intraseasonal dynamic programming model for optimal pre-plant leaching and optimal scheduling of irrigation with waters of various salinity levels. The system underlying the model was characterized by two discrete state variables, soil salinity and soil moisture content, which were updated on a day-to-day basis during a single irrigation season. The results suggested that: (a) frequent applications of small quantities of water are preferable to applications of larger quantities at longer intervals; (b) under conditions of high salinity, the use of good quality irrigation water for leaching is generally justified at the beginning of the growing season; (c) under relatively low saline conditions it is worthwhile to extend irrigation over a longer period; and (d) at the highest salinity level referred to in the analysis irrigation is not economically worthwhile.

Additional economically oriented studies using the single-crop short-run framework have focused on the following topics:

a. The role of crop density. An investigation of the economic implications of plant density for irrigation water use under saline conditions was carried out by Feinerman, 1983. This analysis was motivated by the study of Francois (1982), who conducted a field plot study to determine the feasibility of increasing cotton density on highly saline soils and concluded that: "Although cotton is known to be one of the most salt-tolerant field crops, highly saline soils nevertheless can significantly reduce plant size... The smaller plant size leaves a significant space between plant canopies, which could support additional plants."

Based on these findings, Feinerman developed an economic framework for optimizing irrigation water quantities and qualities and crop densities, utilizing physical and biological relationships involved in irrigation with saline water. The analysis was applied to cotton data. It was assumed that the irrigator has at his disposal several sources of water, differing in quality and costs, which can be mixed. The analysis enables determination of the optimal combination of irrigation water quantity and quality, as well as of plant density for cotton. The results suggest that treating crop density as an endogenous decision variable (i.e., including it explicitly in the economic model) has a substantial impact on profits and on the optimal quantities and qualities of the applied water.

b. The role of infiltration uniformity. In irrigated agriculture, the unevenness with which water infiltrates the root zone is determined mainly by the spatial variability (non-uniformity) of irrigation water application, on the one hand, and on the variability of soil hydraulic properties, on the other (Warrick and Gardner 1983; Dagan and Bresler 1988). The yield of a given crop, grown during a specific season in a certain field and under certain management and cultivation conditions, is assumed to be directly dependent on the spatially variable water infiltration (Stern and Bresler 1983; Warrick and Yates 1987; Bresler and Laufer 1988). If water infiltration is non-uniform, there will be under-irrigated and over-irrigated areas and, assuming a concave crop-water response function, total yield per unit of land area

will be smaller as compared to conditions of uniform infiltration. Therefore, uniformity is considered desirable in yield production processes.

Feinerman et al. (1984) investigated the interactive effects of water salinity and infiltration uniformity on average crop yield (corn), optimal water application, and expected profits. Salt accumulation in the root zone was determined under both steady-state and transient conditions. The combined effects of salinity and non-uniformity determined crop yield as a function of the quantity and the quality of the irrigation water.

It was found that expected profit-maximizing water applications increase under conditions of increased irrigation water salinity, decreased uniformity of infiltration, and decreased water price. Decreasing uniformity of infiltration results in lower gross profits for all the salinity levels examined. The economically optimal water applications and expected profits were found to vary by a factor of three or more depending on water prices, salt concentrations, and uniformity of infiltration. Therefore, accurate determination of these variables is important for decision makers.

c. Biological and physical relationships. The biological responses of crop yield to soil salinity are not often well known to the farmer. In economic analyses, the physical and biological functions connected with the production process are sometimes represented as random variables in the production function. Since the exact values of the parameters of the response function may be unknown to the decision-maker, estimates are used, and a suboptimal solution often results. The deviation from the optimum solution may be measured by a loss function and the calculation of its expectation.

The estimates of the parameters are based on *a priori* information available to the decision maker. He may invest in acquiring additional information that will reduce the variances of these estimates and, hence, will improve his ability to choose a suitable strategy with resulting decrease of the expected loss (or, increase of the expected profits). The expected value of sample information is defined as the difference

between the reduction of the expected value of the loss function due to the additional information and the cost of its acquisition. The optimal number of observations to be acquired is the one that maximizes the expected value of sample information.

Feinerman and Yaron (1983a) have developed a method to estimate the expected profitability to farmers from acquiring additional information on the biological crop response function to soil salinity. Based on a switching regression technique to estimate a piecewise linear response function and on a short-run economic optimization model which includes a single-crop and a single saline water resource, they formulated a loss function and calculated the expected value of additional information and the optimal number of additional observations.

In another study, Feinerman and Vaux (1984) studied the impact of uncertain salt balances in irrigated fields with a hydroeconomic model that incorporates the effects of salinity. Uncertainty in two parameters that jointly determine root zone salinity was investigated. The results depended upon the way these parameters enter the mass-balance equation for soil salinity. It was shown that water has a risk-reducing marginal effect on output when growers are risk averse and, under certain conditions, when they are risk neutral. The effects of prices, water quality, and crop salt sensitivity on the conclusions were also analyzed and an empirical example was employed to illustrate the magnitude of the impacts. The findings suggested that research focused on the development of inexpensive means to measure soil moisture and salinity in the field has the potential to reduce the demand for water. Whether that potential can be realized economically depends, of course, on the cost of the research.

2. Farm-Level Analysis. Extending the single-crop analysis to the farm level commonly involves the consideration of several additional aspects: (a) choosing an optimal crop mix and irrigation treatment for each crop, taking into account yield reduction in response to salinity; (b) estimating the farm's salinity-induced income losses; (c) calculating rates of substitution

between water resources of various salinity levels; (d) evaluating the real cost to the farm of restricting water supply and/or salt outflow; and (e) considering externalities in the analysis. Short-run economic analyses of irrigation with water of varying salinity at the farm level include the works of Parkinson et al. (1970), Moore et al. (1974), Hanks and Andersen (1981), and Feinerman and Yaron (1983b).

A commonly used analytical framework is the linear programming model, the core of which can be schematically presented as follows (Yaron, 1984):

(9)   Maximize $f = C_1 Z_1 + C_2 Z_2 + C_3 Z_3$

subject to:

(10)
$$A_1 Z_1 \ b_1$$
$$A_2 Z_2 \ b_2$$
$$D_1 Z_1 + D_2 Z_2 + D_3 Z_3 \ b_3$$
$$Z_1, Z_2, Z_3 \ 0.$$

where Z_1 and Z_2 are vectors representing the activity levels of crops irrigated with "high" and "low" quality (saline) water, respectively; Z_3 is a vector of the activity of rainfed crops; C_1, C_2 and C_3 are vectors representing net income coefficients; b_1 and b_2 are vectors representing the restrictions on "high" and "low" quality water, respectively. The matrices A_1 and A_2 represent technological coefficients related to the water restrictions, and the matrices D_1, D_2 and D_3 represent technological coefficients related to restrictions other than water, the levels of which are represented by the vector b_3.

Parkinson et al. (1970) and Moore et al. (1974) utilized linear programming models to evaluate the costs and benefits of desalting saline water and the probable effects of various levels of water supply and quality on maximum farm returns to land and water. The analyses involved various soil types, irrigation treatments and water quality levels, taking into account yield reduction in response to soil salinity, and investigating adjustments in the relative share of crops in response to increasing salinity.

A comprehensive agro-economic model relating crop mixes and irrigation practices with

the salt content of the return flow was presented by Hanks and Andersen (1981). The physical relationships were comprehensively analyzed, with many relevant functional relationships regarded as endogenous to the model. The model was applied to a farm in Vernal, Utah. The real cost to the farm of restricting salt outflow was estimated and a concrete monetary expression of the externalities was included by calculating the relationship between farm income and salt outflow.

Feinerman and Yaron (1983b) formulated a deterministic short-run, as well as a stochastic long-run, linear programming model to analyze the complex relationships involved in irrigation with water of various salinity levels and optimizing its use within a single farm. The model was applied to a representative kibbutz farm (collective settlement) in the Negev desert. An irrigation season was defined as one year and was subdivided into two subseasons (spring-summer and autumn-winter). The farm has three water supply sources (varying in their quantities, salt concentrations and costs), which can be mixed, and five soil plots of different areas and initial soil salinity levels. Furthermore, the farm has four crop alternatives which are sensitive to soil salinity.

The ability to incorporate economic, physical and biological relationship (including mixing irrigation water from various sources, accumulation and leaching of salts in the soil, yield losses due to salinity, and net returns for each crop) into one system is the main advantage of the short-run model. This in turn leads to a better understanding of the economic significance of the various parameters, the optimal solution values, the shadow prices and the rates of substitution between the limited resources.

The analysis yields estimates of the marginal rate of substitution between water from the three sources during both subseasons needed to maintain a constant level of farm net income (table A1).

Note that for each subseason, the marginal rate of substitution increases proportionally with the gap between the salinity levels of the different water sources. The issue of substituting good quality water with relatively saline water in agriculture is relevant in many regions. The proper substitution quotas needed to compensate farmers for deteriorating irrigation water quality can be based on calculations similar to those in table A1.

3. Region-Level Analysis. The single-crop and farm-level economic analyses of irrigation with saline water provide information that is relevant to regional or catchment-basin analyses as well. Extending the analyses to a regional framework involves additional considerations associated with regional-level development costs and economies of scale, issues of externalities, sectorial preferences, regional cooperation, cost sharing and income transfers, and regulation of water quality. The various issues involved in a regional-level analysis have been investigated by Scherer (1977), Young and Leathers (1981), Howe and Young (1981), Quiggin (1988), and Yaron et al. (1990).

A simplified case of a regional setting in the short run is one in which several farms, each with limited land and fresh water, and a given cropping pattern, explore the use of an additional source of marginal water. To simplify the schematic presentation, the region is treated as a big farm with one objective function. The scheme of the regional problem is:

Table A1   Estimated marginal rate of substitution among waters from various sources

Autumn–Winter			Spring–Summer				Water Salinity Level
25	10	5	25	10	5		(meq Cl/l)
5.779	2.76	1.995	2.305	1.326	1.0	5	Spring-Summer
4.365	2.081	1.504	1.738	1.0	.754	10	
2.512	1.198	.866	1.0	.576	.434	25	
2.902	1.383	1.0	1.155	.665	.501	5	Autumn-Winter
2.098	1.0	.723	.835	.481	.362	10	
1.0	0.476	.345	.398	.229	.173	25	

(11)   Maximize

$$R = \Sigma_{i \in I} \Sigma_{j \in J_i} C_{ij} X_{ij} + \Sigma_{i \in I} \Sigma_{j \in J_i} C'_{ij} X'_{ij} - H$$

subject to:

$$\Sigma_{i \in I} \Sigma_{j \in J_i} A_{ij} X_{ij} \leq \Sigma_{i \in I} B_i$$

$$\Sigma_{i \in I} \Sigma_{j \in J_i} A'_{ij} X'_{ij} \leq W + \Sigma_{i \in I} B'_i$$

(12) $H = a + bW$

$W \leq \underline{W}$

$\Sigma_{i \in I} h_i = H$

where I is the number of farms in the region; J_i is the cropping pattern of the i-th farm; C_{ij} is the revenue per unit of land and X_{ij} the area irrigated with fresh water, of crop j on farm I; C'_{ij} is the revenue per unit of land and X'_{ij} is the area irrigated with marginal water of crop j on farm i. The total cost of the regional source of marginal water is represented by H; A_{ij} and A'_{ij} are fresh and marginal coefficients associated with crop j on farm i; B_i and B'_i are the restrictions on fresh and marginal water on farm i, respectively; W is the amount of water used from the marginal regional source; and is the constraint on this resource. The parameter a is the level of fixed cost associated with the regional resource and b is the per unit operational cost. Finally, h_i is farm i's share of the regional joint cost.

A solution to the regional problem (ignoring the existing institutions of water allotment, externalities and dynamic long-run considerations), allows transfer of water (fresh and marginal) between farms based on their marginal productivity, thereby enabling more efficient use of the limited resources. Although this approach is economically efficient, it might not be preferred by participants of a regional organization due to opposing political interests.

Dinar and Yaron (1986) developed and applied an optimization model aimed at analyzing regional cooperation in the treatment of municipal wastewater and the use of effluent in irrigation, subject to public health regulations. The decisions faced by the regional planners and farmers include: (a) capacity of the regional treatment plant; (b) wastewater treatment level; (c) allocation of the effluent to the farms in the region; (d) optimal cropping patterns; (e) cost allocation to the participants, and (f) level of government subsidies, if needed. The mathematical model was applied to the Ramla region in the coastal plain of Israel which includes one city—the source of the wastewater—and an agricultural periphery consisting of three farms. A game theory approach was utilized to compare cooperative and noncooperative solutions.

The results showed that comprehensive regional cooperation was possible only with a government subsidy of 50% of all costs. In this case, all of the city's wastewater was treated, and all the farms in the region used the effluent for irrigation. The city bore the increased treatment costs for the other participants, while the farms increased their gross income and were able to compensate the town. The comprehensive regional solution depends on the establishment of a redistribution system that is acceptable to all participants.

Yaron and Ratner (1990) investigated regional cooperation in irrigation water use, under conditions characterized by a general trend of increasing salinity. Income maximizing solutions for the region were derived and the related income distribution schemes were solved with the aid of cooperative game theory algorithms and shadow cost pricing. The analysis was applied to potential cooperation between three farms located in a small region in the Negev. A politically acceptable solution (based on game theory criteria) was derived with the aid of the Nash-Harsanyi model with no side payments (Table A2). Cooperation increases the region's income by $194,000 or by more than 8%.

Long-Run Analyses

A long-run model is composed of a series of short-run processes, the initial conditions of which are affected by the evolution of the state variables and the accumulation of knowledge and experience during the previous periods. The actions taken at any point of time have consequences for future periods. In long-run models, irrigation with saline water is often represented as a dynamic stochastic process. Salts are accumulated in the root zone during irrigation and are periodically leached by ex-

Table A2 Nash–Harsanyi solution for three farm cooperative with joint use of brackish water

	Farm			
	1	*2*	*3*	*Total*
Income* with no cooperation	946	769	605	2,320
% of regional income	41	33	26	100
Income generated in the cooperative solution	1,031	811	672	2,514
% of regional income	41	32	27	100
Incremental income	85	42	67	194
% of regional incremental income	43	22	35	100

*In thousand dollars.
Source: Author.

cess irrigation and/or rainfall, eventually reaching the groundwater. The major natural stochastic elements are rainfall and uncertainties regarding the physical and biological relationships involved.

1. Single-plot/single-crop and farm-level analyses. Long-run single-plot analyses of irrigation with saline water commonly utilize dynamic programming models, often within a stochastic Markov Chain framework, and concentrate on the steady state of the system. In these studies, crop yield responds to root-zone soil salinity, and the dynamics of soil salinity depend on irrigation quantity and/or quality. The objective is to choose the irrigation quantity and/or quality that maximizes the present value (or the expected present value) of net returns over a predetermined time horizon.

Yaron and Olian (1973) utilized a dynamic programming model in Markov chains for a long-run economic analysis of irrigation with saline water. They assumed a hydrological regime such that dry summer irrigation seasons alternate with winters of random rainfall. The model was applied to a citrus crop in the coastal plain of Israel over a 50-year period. The decision variables were restricted to quantities of water used for leaching at the end of the winter, before the summer irrigation season.

The results provided detailed information on optimal leaching policy in terms of the quantity to be used for each salinity level of the soil profile, quality of the leaching water, and quality of the irrigation water to be used during the following summer. The authors utilized the empirical results to estimate the value of water

quality. For example, for an initial salinity level of 5 meq Cl/l in the soil solution, the value of reducing the salinity of the irrigation water by one meq Cl/l is about $58 per hectare.

Bresler et al. (1983) utilized a long-run mixed-integer programming model to estimate the optimal salt concentration of the irrigation water using a stochastically prescribed nonuniform field as input and allowing soil salinity to vary spatially within the field. The quantity of water applied during an irrigation season was assumed to be constant; however, they also assumed multiple sources of irrigation water differing in cost and salinity with the choice of which one to use in each time period being a decision variable.

Matanga and Marino (1979), and Dinar and Knapp (1986) formulated dynamic optimization models with soil salinity being a single state variable. They assumed that soil salinity is uniform throughout the field.

A more recent example is the work of Knapp (1992). He incorporated three factors into his dynamic programming model that bear on the soil conditions affecting plant roots: crop rotation during the planning horizon, spatial variability in both water infiltration and soil salinity, and investment in new irrigation systems. The decision variables were the depth of irrigation, the irrigation system to be adopted, and the crop rotation to be chosen. The model was applied to a three-year crop rotation (i.e., corn-corn-tomatoes) in California.

Dynamic programming models are convenient vehicles for problem formulation. They are discrete in time and lend themselves to application. But this may come at the price of

analytical insight. If one desires a better under-
standing of the economics of optimal planning
over time, then the analytical method known
as *optimal control* may be a better tool. It offers
the advantage of calculating shadow prices,
thus providing additional information about
the system under consideration.

The optimal control approach was taken by
Plessner and Feinerman (1995). They assumed
a field of a given size, on which a chosen crop
is grown. The only variable factor of produc-
tion is water. The irrigation water contains
soluble salts at a given concentration (q milli-
grams per liter). The soil solution contains
soluble salts at a concentration ss, which is a
function of the irrigation policy. The effective-
ness of irrigation depends on the amount of
water used, ws, (cubic meters per hectare per
unit of time) and the salinity of the soil solu-
tion. The irrigator's long-run dynamic optimi-
zation problem is to maximize the discounted
stream of future profits

$$(13) \quad \Pi = \underset{ws(t)}{MAX} \int_0^\infty [P_Y \cdot f(ws(t)), ss(t)) - P_w \cdot ws(t)]e^{-rt}dt$$

subject to the equation of motion or the evolu-
tion of soil solution salinity

$$(14) \quad \dot{ss} = f2((q) \cdot ws(t); ss(t))$$

where f is the crop production function, r is the
discount rate, P_Y and P_w are prices of the out-
put and water, respectively, assumed to be con-
stant over time. This is an optimal-control
problem that is solved via the current-value
Hamiltonian procedure.

This analysis has important policy and man-
agement implications. For example, if q > ss,
then the buildup of salinity will be slower the
smaller is the amount of irrigation. Once ss >
q, increased irrigation will first slow down the
rate of buildup of soil salinity, and then, at large
enough amounts, will actually cause a decline
in soil salinity, and the pace of decline will in-
crease with the volume of irrigation.

Another finding is that when an additional
unit of water causes an acceleration of
salination, then its marginal-product value
must exceed its price, because there is an addi-
tional item of cost in terms of the future loss of

revenue due to increased salination. The pen-
alty is measured by the magnitude of accelera-
tion multiplied by the shadow price of the state
variable, which is actually the reduction in the
discounted stream of future profits caused by
the last marginal unit of soil salinity. Con-
versely, when an additional unit of water brings
about a deceleration of salination, then its mar-
ginal-value product is less than its price. This
occurs because there is an additional benefit in
terms of the avoided damage, or increased ad-
dition, to future revenues.

At the farm level, Yaron and Polovin (1974)
applied computer simulation and linear pro-
gramming models to analyze the long-run im-
pact of irrigation with saline water on a farm
in the northern coastal plain of Israel. Alterna-
tive irrigation and leaching policies were de-
fined and the processes of irrigation, stochastic
rainfall, and salt leaching and accumulation
over periods of 5, 10 and 15 years were simu-
lated. The results dictate the optimal policy with
respect to irrigation and leaching, modifications
in the crop mix, and the farm's expected loss
due to the increased salinity of its water supply.

Estimated income losses for kibbutz (collec-
tive) and moshav (small-holder cooperative)
farms in the Negev region of Israel are pre-
sented in Table A3 (Yaron et al., 1979). These
calculations represent existing crop mixes and
irrigation practices, which were not adapted for
salinity. The salinity-induced losses in moshav
farms are about double those of kibbutz farms,
due to the larger share of salt-sensitive fruit and
vegetable crops grown on moshav farms. The
magnitude of the salinity damage is highly de-
pendent on the composition of the crops. Ad-
justments of the crop mix and irrigation
treatments to salinity have the potential of sig-
nificantly reducing these damages.

**Table A3   Estimated income losses for
various salinity levels of irrigation water**

Salinity Level	Income Loss (percent)	
Ppm Cl	Kibbutz farms	Moshav farms
200	5	10
300	14	30
400	23	45

Note: Estimates are for the Negev region of Israel.
Source: Yaron et al. (1979).

A study by Yaron and Voet (1983) focused on stochastic long-run optimization or irrigation (with random rainfall) on a farm in the south of Israel with dual quality (salinity) water supplies, two fruit groves (avocado and tangerine) and field crops, mainly cotton. The farm receives an annual quota of low-quality water, which is allocated to the two groves and field crops. The fruit groves are salt-sensitive, whereas the field crops are less so. The analysis was performed with the aid of integrated dynamic and linear programming models. Results showed that the returns to allocating water for salt leaching in the fruit groves are much lower than the returns to allocating water to the field crops. The optimal policy is therefore to irrigate the groves with conventional water quantities, and to use the remaining water for the field crops, rather than for leaching the groves. The derivation and calculation of the expected value of perfect information on one of the model's parameters (a salt-leaching parameter) were also included in this study.

The stochastic long-run model of Feinerman and Yaron (1983b) assumed random rainfall and considered the effects of short-run decisions and rainfall uncertainty. Results from a short-run model were used to formulate the relevant irrigation-water mixing alternatives for the long-run model, which was applied to the water-soil-crop-farm system over several irrigation seasons. In practice, the values of the model parameters were updated for each short-run and new solutions were obtained by first solving the SR model, and then the long-run model.

Most field and farm-level long-run analyses have not explicitly considered the costs of investment in drainage facilities and the negative effects associated with contamination of surface and groundwater reservoirs. These considerations, as well as the evaluation of various policy instruments aimed at internalizing the negative social costs resulting from contamination of water sources, are often included in regional-level analyses.

2. Regional Level Analyses. As productive soils and good or fresh quality water resources

diminish, and as pressure for greater agricultural productivity increases, farmers are driven to utilize marginal soils and marginal water supplies, including treated wastewater, as well as higher chemical inputs. In the absence of public regulation or external market signals, farmers have few incentives to take into account the negative environmental costs (negative externalities) arising from undesired byproducts generated in the production process. Their input decisions are often solely based on private interests (namely, maximizing their profits), while potential social costs are mostly ignored. Government, on the other hand, often wish to maximize social profits or welfare, taking into account the well-being of the entire society, not only that of farmers. Thus, governmental intervention is often required to internalize the negative social costs resulting from excessive or socially inefficient water use.

Governmental actions are necessary both to combat damage already done to the environment and to encourage more widespread adoption of environmentally beneficial practices. Conflicts often arise between farmers, who may believe that they should be compensated for respecting environmental rules, and environmental activists, who may believe farmers should bear responsibility for on-farm pollution. The latter group adheres to the principle that the "Polluter Pays." It is not always easy to agree on the line that should be drawn between actively benefiting the environment and avoiding doing it damage. The distinction is often based on social perceptions, and may vary with time.

The Polluter Pays principle should apply to agriculture as to any other sector. It requires farmers to comply with environmental rules at their own expense, as long as the activities that have a negative impact are not covered by defined property rights. This is the case for a broad range of pollution policy measures, including those aimed at protecting water supplies. In other instances, however, the pursuit of environmental objectives may interfere with private property rights, in that the provision of environmental improvement entails the use of privately owned resources. In this case, the privately-delivered service must be paid for by

the government, as it entails the provision of public goods by private parties.

Since the two options in principle exist — to reward farmers for environmental services or to make them comply with environmental standards at their own expense — conflict is bound to arise over who should pay. The difficult task in practical policy-making is to strike a balance between the two solutions and to be consistent in their application.

Agri-environmental policies can be roughly subdivided into two types: (a) policy instruments aimed at encouraging farmers to utilize environmentally friendly water-management strategies, and (b) regulatory policies that are aimed at forcing the farmers to comply with environmental rules and standards at their own expense.

A key assumption often made by economists is that people pursue their own self-interest. Therefore, policies recommended by economists usually aim to provide incentives that align self-interest with societal or public goals, rather than condemn self-interest and create burdensome regulations. Such economic principles may be used to develop policies that will attain environmental quality objectives at the least cost, or the least impact on income distribution. Policies may be devised to tax activities that damage the environment, subsidize activities that improve environmental quality, and support research and extension activities leading to the development and adoption of environmentally sound practices. However, policies may not be supported enthusiastically in the political arena if they are thought to be inequitable.

a. A socially optimal solution.

We now create a model that assumes that a region is managed by a social planner whose objective is to maximize the sum of discounted net benefits associated with agricultural production in the region, net of possible damages of water quality on human health and wildlife habitats, and subject to the equations describing the evolution of the state variables over time and other agricultural and hydrological constraints. Formally, assuming a discrete and final time horizon T, the planner's problem is to:

$$\text{Maximize}_{wg_t, ws_t, M_t, X_t} \Pi = L \cdot \left\{ \sum_{t=1}^{T} [P_Y f(sm_t, ss_t, X_t) - P_S \cdot ws_t - P_g(G_t) \cdot wg_t \right.$$

$$(15) \qquad \left. - C(X_t) - e(M_t) - m \cdot d_t - D_t(Q_t, X_t)]/(1+r)^t \right\}$$

subject to (1), (2), (4), (5); and sm_0, ss_0, G_0, Q_0 are given, and possibly constraints aimed at protecting the groundwater aquifer from being destroyed (like $G_t \geq \bar{G}$ and/or $Q_t \geq \bar{Q}$, where $\bar{G}$ and $\bar{Q}$ represent the minimum "red-levels" of groundwater stock and quality, respectively). The parameter m is the unit cost of drainage activity and $P_g(G_t)$ is the cost of pumping one unit of water from the aquifer.

Other agricultural and hydrological constraints are not detailed here for the sake of simplicity. With the exception of D_t, all of the symbols were described above. $D_t(Q_t, X_t)$ is a damage function, accounting for the effect of groundwater quality and agricultural non-water inputs (like fertilizers and pesticides) on human health and wildlife habitats.

The solution for the optimization problem provides values for the decision variables wg_t, ws_t, M_t and X_t as well as for the state variables Q_t, G_t, sm_t, ss_t for every t between period 1 and period T (the end of the planning horizon). Derivation of the first (and second) order conditions for the above optimization problem is a complicated mathematical task and is outside of the scope of the current chapter. We present only a few general conclusions based on the available literature. Good examples are the studies of Tsur (1991), Shuh and Zilberman (1991) and Chakravorty et al. (1991).

A few generalizations can be made, based on the results of the above-mentioned three studies.

i. Let us denote the changes in Π associated with a marginal (small) changes in G_t or Q_t (the derivatives of Π with respect to G_t or Q_t) by Π_G and Π_Q respectively. These quantities represent the unit value of G or Q at time t and are thus referred to as the shadow prices of G or Q. Π_Q is expected to be positive (one would be willing to pay a positive amount to have Q increased and the groundwater quality improved), while Π_G may be positive or negative. At low levels of G, where the groundwater

table is well below the root zone, Π_G will be positive since the finite stock of the aquifer entails a positive royalty value (the forgone benefit of not being able to use in the future the unit of groundwater pumped today). On the other hand, at high G levels where groundwater has invaded the root zone, the damage to yield may outweigh the benefit of additional water, causing Π_G to become negative (Tsur, 1991).

ii. As long as the total economic costs of groundwater irrigation (consisting of immediate pumping costs $P_g(G_t)$ plus the shadow price of groundwater $\Pi_G(G_t)$), exceeds that of surface water (P_s), irrigation will be applied only from surface sources. If the total costs fall below the costs of surface water, irrigation will be applied from groundwater. The total economic costs reflect the money value of the impact of increasing G_t by 1 unit at time t on the discounted stream of future profits. The water will be applied at a rate that will equate the marginal productivity of water—$P_Y\left(\dfrac{\partial f}{\partial wg_t}\right)$—to its economic costs—$P_g(G_t)+ \Pi_G(G_t)+ \Pi_Q(Q_t)\cdot\dfrac{\partial Q_t}{\partial wg_t}$ —where the last term can be interpreted as the marginal pollution cost of groundwater, which reflects the net additional pollution caused by a unit of applied groundwater (Tsur, 1991). In cases where $P_g(G_t) + \Pi_G(G_t)=P_s$, irrigation water will be derived from both ground and surface water sources. The mix of ground and surface water of each time period is determined as needed to preserve this equality.

iii.   Since it is relatively expensive to build drains and dispose of the drainwater (i.e., the value of m is high), investment in these operations may be expected to be delayed until the saline water stock has risen to a certain critical level. The determination of this critical level is based on economic considerations. Assume, for example, a case where the groundwater table lies well below the root zone. In such a case, the economic cost of groundwater exceeds that of surface water and the drainage problem is not yet present; hence, it is plausible that irrigation utilizes only surface water sources.

As water percolates into the aquifer, the groundwater table rises toward the root zone and its quality deteriorates. This causes both the extraction cost, $P_G(G_t)$ and the groundwater shadow price $\Pi_G(G_t)$ to fall. Eventually, the equality $P_G+\Pi_G=P_S$ holds, extraction begins and irrigation water is derived both from the aquifer and from surface sources at just the right mix so as to preserve this equality.

What happens if surface-water irrigation is implemented above its optimal level (say, because growers behave myopically)? Then the groundwater table and salinity continue to rise (as the stock increases and its quality deteriorates) and $\Pi_G(G_t)$ diminished (both because groundwater is less scarce and of lesser quality). As long as $\Pi_G>$-m drainage activities are not required, but if the situation is severe enough it will warrant irrigation with groundwater only and the cessation of surface water irrigation. The situation becomes drastic when the groundwater stock achieves a level in which its shadow price Π_G falls below -m; in such a case, drainage activities are in order from this point of time on.

iv. The introduction of a drainage system (such as a canal) reduces drastically the shadow price of pollution. Determination of the optimal timing for the construction of the canal involves trading off savings in pollution costs associated with the earlier construction date, with savings in the canal operation, disposal costs, and construction costs (as the construction date is delayed). Since it is relatively expensive to build drains and dispose of the drainwater, investment in these operations may be expected to be delayed until the saline water stock has risen to a critical level.

Generally speaking, drainage has two kinds of costs associated with it: one is the cost of building the drains and the other is the cost of transporting and disposing the drainwater. Disposal of drainwater in wetlands and evaporation ponds is often considered the least expensive alternative in the second category of costs. However, the continued exercise of this option may cause the level of toxins in the environment to increase over the years, thereby creating a social need to resort to more expensive disposal alternatives involving treatment

of drainwater and to special irrigation practices designed to reduce the generation of drainage. In such cases, one may view the problem as an exhaustible resource created by the limited capacity of the environment to safely absorb agricultural waste. Under such circumstances, the productive lifetime of the agricultural region is in question (Shah and Zilberman, 1991).

In principle, some of the groundwater pollution generated by the production process can be abated through chemical or biological treatment processes. The abatement technologies can be used in early stages and may be improved in time through research and experience.

The relative marginal costs of the abatement and drainage pollution-control technologies are important in determining their choice. If canal disposal costs were low, which could be the case, say, in sparsely inhabited areas or coastal regions (and when preservation of these environments is not valued much), the preferred policy option might be to forgo pollution abatement and build a canal at a relatively early stage. On the other hand, canal disposal and operation might be relatively costly in built-up areas, or in regions from which dumping sites are difficult to access, in which case abatement will dominate and canals will be introduced at a late stage in the program or will not be built at all. Similar tradeoffs could be discussed in terms of applying conservation technologies at the source (Chakravorty et al., 1991).

b. Socially optimal versus competitive outcomes.

As a common property resource, groundwater use is likely to be inefficient in the absence of regulation (Gisser and Sanches, 1980; Shah and Zilberman, 1991). Under competition (assuming a large number of farmers in the region relative to the size of the aquifer), each farmer perceives that his water use and technological choices in the current period will have only a negligible effect on the water stock (G_t) and water quality (Q_t) of the underlying aquifer as well as on the environment. Hence, the decision-making of each farmer is based solely on consideration of his or her immediate profits. In other words, a competitive water user tends to maximize instantaneous profit at each time period without incentive to take into account the external diseconomies imposed thereby on other users and on the environment.

While the actions of an individual farmer in each time period on the aquifer and environment may be negligible, they may be substantial with respect to his or her own prospects for immediate profits. A socially optimal behavior requires that each farmer give up some present income in return to future income. But future gains will be materialized only if all (or most) farmers follow the intertemporal rules.

It is in the interest of the individual farmer to try to gain advantage by assuming that his effect on the aquifer is negligible; thus he can enjoy larger profits both in the present and in the future. If all other growers behave myopically then a specific grower should do the same, since otherwise there will be no future gains to compensate for the present losses. Realizing that this line of reasoning is not exclusive to any particular individual, the grower has good reasons to suspect that others will not follow the intertemporal rules, in which case he should not obey them either. Clearly, some regulatory policies (quota, taxes) or market mechanisms (water rights) to restore socially optimal behavior are in order (Tsur, 1991).

Under competition, farmers' withdrawals from the aquifer in each time period are commonly larger than socially optimal. Moreover, since an individual farmer cannot ensure a reduction in deep percolation through his actions alone, there is no incentive for him to adopt a technology that is more efficient than the one that maximizes his individual profits, and there is also no incentive for him to use any given irrigation and/or technology more conservatively than is profitable from his individual point of view. Therefore, the competitive rates of adoption of conservation technologies and investments in drainage systems are likely to be lower than socially optimal.

Consequently, the rate of deep percolation under competition is always greater than the rate of deep percolation under the socially optimal program in a given time interval. The saline water stock attains its upper bound more quickly under competition than under the socially optimal program. It follows that if productivity of the region is exhaustible (i.e., not

sustainable in the long run), production under competition must end earlier than under a socially optimal management scheme (Shah and Zilberman, 1991).

Sustainable development may be defined as development that meets today's needs without compromising the ability of future generations to meet their own. For agriculture this means preservation of the resource base (especially soil and water) while assuring resilience against fluctuations in external environmental conditions. Thus, sustainability is not simply a maintenance function but should progressively reduce and eliminate unsustainable activities. Agriculture in arid and semi-arid regions has been shown to be profitable in the short term but long-term sustainability is questionable. Prevention of soil and water resources degradation is the prime issue for achieving sustainable agro-ecosystems in these regions.

The increasing scarcity and deteriorating quality of the water supply is a problem affecting many regions around the world. As the major user of water, agriculture jusstifies the investment of research and resources aimed at developing and applying technologies and practices that would enable the maintenance of both food production and environmental quality.

Attention in arid and semi-arid regions is being increasingly focused on the development of so-called "marginal" resources—saline and sodic water and sewage effluents. A large-scale transition in agricultural water use from good quality to marginal water is predicted to occur in many countries, and the continued development of the agricultural sector depends heavily on the development and efficient utilization of marginal water supplies. Indeed, over the last four decades, a tremendous effort to understand salination processes, and to find solutions to the salinity problems at field, farm and regional levels has been undertaken. The effort has been continuous, involving researchers from several disciplines.

Future research and policy efforts aimed at improving our ability to cope with salinity and to achieve sustainable agro-ecosystems are summarized below.

1. In order to be effective in addressing environmental problems and conducting policy-

relevant research, economists have to integrate their economic analysis with biological and physical models. This can be done fruitfully only by communication with experts from other disciplines. If economists establish good communication with biologists, soil scientists, environmentalists and others, they will be able to develop better policies that will allow society to achieve both environmental quality and economic efficiency.

2. Improved water-use efficiency is needed in all sectors, in particular in agriculture, which is the largest user of water, but also in industry and the urban sector. The use of low-quality water, such as brackish groundwater, for agriculture and industry requires a parallel development. This includes use of reclaimed wastewater for irrigation and for flow augmentation in streams and waterways. Wastewater should be treated to levels compatible with these uses, and an equitable and efficient allocation of treatment costs between the producers (the cities) and the users should be fixed. The option of groundwater or seawater desalination should be evaluated based on economic environmental considerations.

3. Soil and water resources research should include:

   a. Policy and institutional aspects of water quantity and quality. Most of the current studies are management rather than policy-oriented. Increasing the effectiveness of water policy will probably require more attention to strategies of policy-advising (e.g., it is advisable not to stress the "superiority" of the economists' viewpoint). Important criteria for the choice of policy tools are simplicity, equity, and political feasibility. An encouraging development is the increasing tendency to direct agricultural policies so as to meet environmental as well as economic objectives.

   b. Non-market valuation of water quality and environmental amenities in cases where water has alternative values in uses other than agriculture (e.g., utilization of treated wastewater for rivers and recreation sites, and utilization of water for ecosystems and bio-diversity production).

c. Simultanous utilization of technological, economic, legal and educational means to influence urban, agricultural, and industrial demands for water.

If such research is carried out and a dialogue among biophysical scientists, economists, and political scientists established, we should be better able to develop more effective policies for water management. The objective is to increase efficiency in allocating water to the most socially desirable uses, while preventing local and regional conflicts. Special emphasis should be given to environmental quality and the quality of the water resources remaining for future generations.

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