The Problem of Salt in Agriculture

by James D. Rhoades

For centuries irrigation has increased the salinity of soil, reducing the fertility of such land. The problem has become worse in recent years, and effective control measures must be developed.

Irrigation is an ancient practice that predates recorded history. While only about 15% of the world's farmland is irrigated, it contributes about 35–40% of the total supply of food and fiber, and it stabilizes production against the vagaries of weather. Inevitably, however, irrigation leads to the salination of soils and waters. The salt contained in the irrigation water tends to be left behind in the soil as the pure water passes back to the atmosphere through the processes of evaporation and plant transpiration (the passage of watery vapor through membranes or pores). Typically, excess water is applied to the land or enters it by seepage from delivery canals. These waters percolate through the soil and underlying strata and flow to and cause waterlogging in land of low elevation. In turn, saline soils are formed in such land through the process of evaporation.

The salt problem in irrigated agriculture is not new. The rise and fall of the Mesopotamian civilization nearly six thousand to seven thousand years ago has been attributed to the development of irrigated agriculture and to its subsequent failure as a result of rising water tables and soil salination. In the American Southwest the decline of ancient Indian civilizations centuries ago is also attributed to salination of land and water. Today salinity seriously affects productivity on about 20 million hectares (one hectare equals 2.47 acres) of the world's irrigated land. It threatens the economy of many arid countries, such as Egypt, Iraq, and Pakistan, where irrigation is the backbone of agriculture. In the United States an estimated 30% of all irrigated land suffers from reductions in yield caused by salt. Salinity also constitutes the most serious water-quality problem in many rivers and groundwater systems that are located in arid and semiarid regions. The problems of soil salination, waterlogging, and water pollution are increasing as irrigation is being expanded and as less suitable waters and soils are being used to meet the ever increasing need for food in the world.

Surviving the salinity threat requires that the seriousness of the problem be widely recognized, that the processes contributing to salination be understood, and that effective control measures be developed and

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J. D. RHOADES *is a Research Leader at the U.S. Salinity Laboratory, Riverside, California, and Adjunct Professor of Soil Science at the University of California at Riverside.*

(Overleaf) Salt builds up on the banks of an irrigation canal in Colorado. Irrigation inevitably leads to the salination of soil and water. Photograph, Soil Conservation Service; photography by Tim McCabe

implemented that will sustain the viability of irrigated agriculture. Considerable advancement has been made in the development of control methods in recent years, but information gaps continue to exist, and new and improved technologies are still needed. This necessitates the continuation and expansion of research and development. The causes of salination, the extent of the problem, practices used to control salinity, and research opportunities and needs are discussed in this article.

Effects of salt on plants and soils

Salt-affected soils are those that are of reduced value for agriculture because of their content (or the past effects) of salts, consisting mainly of sodium, magnesium, calcium, chlorides, and sulfates and secondarily of potassium, bicarbonates, carbonates, nitrates, and boron. Saline soils contain excessive amounts of soluble salts for the practical and normal production of most agricultural crops. Soluble salts exert both general and specific effects on plants, both of which influence crop yield. Excess salinity in the crop root zone causes a general reduction in growth rate. In addition, certain salt constituents are specifically toxic to some plants. For example, boron is highly toxic to many crops when present in the soil solution at concentrations of only a few parts per million. In some woody crops sodium and chloride may accumulate in the tissue over time to toxic levels. These toxicity problems are, however, much less prevalent than is the general salinity problem.

Salts also may reduce the suitability of the soil as a medium for plant growth. The suitability of soils for cropping depends appreciably on the readiness with which they conduct water and air (permeability) and on their aggregate properties (structure), which control the friability (ease with which crumbled) of the seedbed (tilth). In contrast to saline soils, which are well aggregated and whose tillage properties and permeability to water and air are equal to or higher than those of similar nonsaline soils, sodic soils have reduced permeabilities and poor tilth. Sodic soils are those that contain excessive adsorbed sodium, given the electrolyte concentration (salinity) of the infiltrating water; this combination causes the breakdown of soil structure and loss of permeability. Sodic soils are less extensive than saline soils.

Sources of salt and causes of salt-affected soils

The original sources of salts are the dissolved products of mineral weathering, emanations from volcanic eruptions, discharges from deep thermal sources, and the primary ocean. These salts have been redistributed over time. Winds blowing over the oceans pick up salt particles, which originate at the sea surface as spray, and carry many of them onto the land, where they are mixed with other salts derived from weathering products and sedimentary sources.

As a result of specific local conditions of climate, topography, geologic history, land use, or the nature of the sediment or soil, salts have accumulated in certain locations in amounts many times higher than the average concentration. In landscapes with good rainfall and effective

Soil Conservation Service; photos, Tim McCabe

drainage systems, soluble salts are transported by flowing surface waters and groundwaters eventually to the sea. During this migration their concentration and composition undergo many changes as a result of their different mobilities and their varying affinities to form or interact with compounds they meet in their path. The migration and redistribution takes place essentially exclusively through the agency of water, which acts both as solvent and as transporting vehicle. But in many parts of the world with internal or ineffective drainage, the salts accumulate in relatively low-lying regions such as valley basins or upland depressions. Such obvious areas of accumulation account for only a fraction of the salts in the landscape. Much salt is stored in subsoils and deeper substrata of the hydrogeologic system as well as in groundwaters. In some

Salt in the soil kills alfalfa in California (top) and stunts corn in Colorado (left and above). The salt consists primarily of sodium, magnesium, calcium, chlorides, and sulfates.

regions marine incursions in the past have left buried saline sediments in the landscape; often these underlie irrigation projects or rain-fed agricultural lands. Such salt reservoirs may be returned to circulation after a change in the local topographical or climatic conditions or through the actions of humans.

Salt-affected soils occur mostly in regions having an arid or semiarid climate; that is, where evapotranspiration (the combined effects of evaporation and plant transpiration) exceeds rainfall and, therefore, where leaching (dissolving out by the action of a percolating liquid) and transportation of salts to the oceans are not so nearly complete as in humid regions. Such soils also usually occur in relatively low-lying places that receive water by gravitational flow from higher locations. Sodic soils usually occur in slightly elevated areas that receive salt inputs from the upward, capillary (caused by surface tension) flow of soil water and are often found adjacent to saline and periodically waterlogged areas; sodium accumulates there because of its comparatively high solubility and mobility. These slightly elevated areas are periodically leached by rain or snowfall, which, at least temporarily, reduces the concentration of soluble salts in them.

Restricted drainage usually contributes to the salination of soils and may involve low permeability of the soil or the presence of a high groundwater table. High groundwater tables often are related to topographic position. The drainage of waters from the higher lands of valleys and basins may raise the groundwater level so that it is near the soil surface in the lower lands. Low permeability of the soil causes poor drainage by impeding the downward movement of water.

While salt-affected soils occur extensively under natural conditions, the salt problems of greatest importance in agriculture arise when previously productive soil becomes salinized as a result of irrigation or removal of natural vegetation and certain dryland agricultural practices (so-called secondary salination). The activities of humans have increased salt-affected areas considerably, either by adding more water by irrigation or by using less, as when dryland agriculture replaces native vegetation. In either case water infiltrated into the soil in excess of that used by the agricultural crops passes beyond the root zone, picking up salts from the soils and substrata and often creating waterlogged sections in low areas. When this occurs, soluble salts stored in the ground are mobilized to accumulate at the surface in the seepage areas, salinizing the soils where the rising water tables approach ground level and increasing solute concentrations in associated groundwaters and streams.

The role of irrigated agriculture in salinizing soils and water systems has been well recognized for hundreds of years. However, it has only relatively recently been recognized that the clearing of lands for dryland agriculture has created analogous problems. The latter problem occurs even in areas such as Australia, where the level of soil salinity under natural conditions is typically very low. Also it is of relatively recent recognition that salination of water resources from agricultural activities is a major and widespread phenomenon of likely even greater concern than that of the salination of soils. Only in the past few years has it become apparent that trace toxic constituents, such as selenium, in agricultural drainage waters can cause serious pollution problems.

Occurrence and extent of salinity problems

The major naturally saline regions of the world are found in poorly drained low-lying lands under semiarid and arid conditions where large quantities of salts leached from higher regions have accumulated in the slowly flowing groundwater and basin sinks, where the water table is at or close to the soil surface, and where the salts have ascended into the soil because of the high evapotranspiration rate. A close relationship between the depth and salinity of the water table and the extent of salt accumulation in soils is established in naturally semiarid regions for the reasons given above.

The impact of humans on the circulation of salts has been profound. As a consequence of irrigation more water and salt have been applied to soils, more salt has been stored in the soil, deeper soil strata have been affected as more leaching and deep percolation have occurred, and the groundwater table has risen in many places. Large areas of irrigated lands have, therefore, become waterlogged and salinized, and associated surface waters have become increasingly salinized because of a reduction in their volume and because of their reception of salt-laden drainage waters.

It is estimated that nearly 10% of the total land area of the world has been sufficiently affected by salt that its utilization for crop production is limited. These areas of salt-affected soils are widely distributed throughout the world. No continent is free from salt-affected soils. Serious salt-related problems occur within the boundaries of the following countries:

Europe—Austria, Bulgaria, Cyprus, Czechoslovakia, France, Greece, Hungary, Italy, Portugal, Romania, the Soviet Union, Spain, Yugoslavia

North and Central America—Canada, Cuba, Mexico, the United States

South America—Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Peru, Uruguay, Venezuela

Middle East and South Asia—Afghanistan, Bangladesh, Burma, India, Iran, Iraq, Israel, Jordan, Lebanon, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia, Sri Lanka, Syria, Turkey, the United Arab Emirates, Yemen (Aden), Yemen (San'a')

North and East Asia—China, Mongolia, the Soviet Union

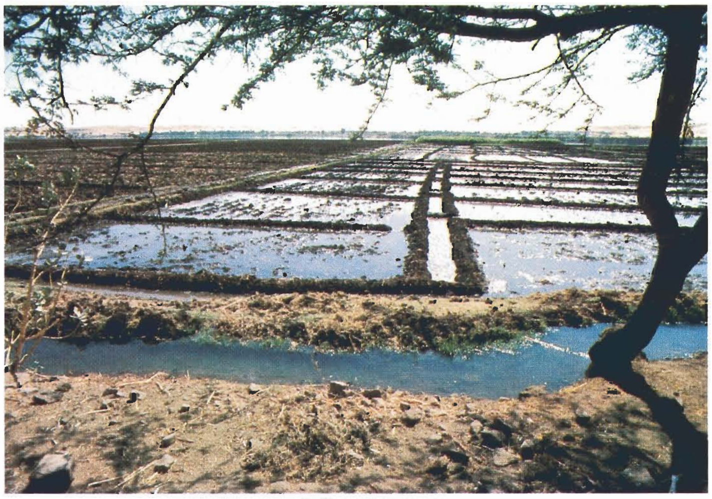
Southeast Asia—Indonesia, Kampuchea, Malaysia, Thailand, and Vietnam

Africa—Algeria, Angola, Botswana, Cameroon, Chad, Djibouti, Egypt, Ethiopia, The Gambia, Guinea, Guinea-Bissau, Kenya, Liberia, Libya, Mali, Mauritania, Morocco, Niger, Senegal, Sierra Leone, Somalia, South West Africa/Namibia, The Sudan, Tanzania, Tunisia, Zaire, Zambia

Australasia—Australia and the Solomon Islands

Thus, salt-affected soils occur under widely varying conditions of climate, geology, agriculture, and, of course, social and cultural systems. The economic and social repercussions of soil salination are felt most acutely by the populations of arid zones and mainly by less developed

(Left) Robert Frerck—Odyssey Productions; (right) Donald Smetzer—CLICK/Chicago



An irrigation canal is under construction near Manzanillo, Mexico (above), and irrigated fields extend toward the horizon near the Aswan High Dam in Egypt (above right). Irrigation is used to help grow crops in arid and semiarid regions throughout the world.

nations that depend primarily upon irrigated agriculture for their food production.

The increasing population of the world requires that the viability of the Earth's soil and water resources be maintained in order for the increasing demand for food to be met. The projected increase in croplands for the final quarter of the century is only 10%, yet the world demand for food is expected approximately to double, according to the UN World Food Conference Report of 1974. In addition, it has been predicted that agricultural lands will increasingly be diverted from agricultural production to other uses and increasingly be degraded through various means, a major one being salination. Associated with the latter is the increasing pollution of water resources with various chemicals and salts. Irrigated agriculture is heavily involved in these matters.

While irrigated agriculture makes up only about 15% of the world's agricultural land base, it supplies about 35–40% of the food and fiber because of its higher yields per unit of cropland. The amount of irrigated land increased from about 8 million hectares in the year 1800 to 48 million hectares by 1900. It then approximately doubled in the following 50 years and again doubled during the last 30 years. In some arid countries, such as Egypt, nearly 100% of the agricultural land is irrigated, while in others, such as Pakistan, it is about 50%. In less arid nations irrigated land occupies a much lower proportion of the total cropland, but even there it is continuing to increase and is reaching significant levels; for example, in Thailand the percentage is 26, in France 13, in Spain 10, and in Greece 15. In the U.S. the area under irrigation doubled between 1949 and 1973 to 21 million hectares and by 1987 had more than doubled again. In the Soviet Union about one million hectares of new irrigated land are developed each year. In Hungary the irrigated area has increased tenfold since World War II.

It is estimated that the world's total irrigated area will be about 400 million hectares by the year 2000. This increase has resulted not only in an increased world production in agriculture but also in increased water consumption, in increased waterlogging of irrigated lands, and in increased salt buildup in water supplies and irrigated lands. Unfortunately, no one has predicted how much of this irrigated area will succumb to salt problems, but past experience indicates that the problem of salt in irrigated lands will likely increase at an even faster rate than that of the expansion of irrigation itself.

It is well known that large areas of the world (for example, old Mesopotamia, large parts of the Indus River Valley, and vast territories in South America and China) that previously supplied abundant crops by means of irrigation have since succumbed to salination and waterlogging problems. For example, it is estimated that at one time Mesopotamia fed a population of between 17 million and 25 million people and was a food exporter. At present this area has a population only about one-half of the previous total, and it imports a large quantity of food. People were forced to abandon the affected lands and to develop new areas. As long as new territories were available, the shifting of irrigated agriculture temporarily solved the problem. Today, however, with the growing density of population, increased degradation of land and water resources, and shrinkage of a suitable land base for agriculture, this practice of land abandonment is no longer generally acceptable.

In spite of the general awareness of these problems and past sad experiences, salination and waterlogging of irrigated lands continues to increase. According to the estimates of the UN Food and Agriculture Organization and Unesco, as much as half of the area of all existing irrigation systems of the world is seriously affected by salinity, waterlogging, or both; the area potentially subject to secondary salination is estimated to be equal to or greater than the area presently affected; and ten million hectares of irrigated land are abandoned yearly as a consequence of the adverse effects of salination and waterlogging. This phenomenon is common not only in old irrigation projects but also in areas where irrigation has only recently been introduced.

In some countries the salt problem threatens the national economy. Those countries most seriously affected include Argentina, Egypt, India, Iran, Iraq, Pakistan, and Syria. Roughly half the irrigated land in Syria's Euphrates River Valley has become so saline that crop losses there now total an estimated $300 million annually. Between one-quarter and one-half of all irrigated land in South America is affected by salination, and the problem there appears to be increasing. In India 35% of all irrigated land is seriously saline. In Pakistan, where 80% of all cropland is irrigated, one-third of it (approximately six million hectares) is experiencing severe salt problems, and another 16% is threatened with salination by high water tables.

The future development of planned large irrigation projects, which involve diversions of rivers, construction of large reservoirs, and the irrigation of large land areas, has the potential to cause large changes in the water and salt balances and to affect the salinities of entire groundwater and river systems. The impact will certainly extend beyond that of the immediate irrigated area and can even affect neighboring nations.

Control of soil and water salinity

There are three principal aspects of the salt problem and its control in irrigated agriculture. One is the improvement (reclamation) of soils that are salt-affected under natural conditions or have become so because of mismanagement. A second aspect is the management of productive or only slightly salt-affected soils so as to prevent an increase in their salinity and reduction in crop yields. A third aspect is management to minimize the pollution of groundwater and surface-water supplies with salts and chemicals as a consequence of irrigated agriculture.

Saline soils are reclaimed by improving drainage and by leaching with irrigation water to remove excess salts. The improvement of sodic soils involves (besides drainage and leaching) the replacement of excessive adsorbed sodium by calcium or magnesium and practices that develop better soil structure and permeability. Adequate drainage is essential for the permanent improvement of salt-affected soils. In order to prevent waterlogging, drainage must remove the precipitation and irrigation water infiltrated into the soil that is in excess of crop demand and also any other water that seeps into the area. In order to avoid soil salination, drainage also must provide an outlet for the removal of salts that accumulate in the root zone, and it must keep the water table sufficiently deep to prevent the flow of salt-laden groundwater up into the root zone by capillary forces.

Drainage systems are essentially engineering structures that remove water according to the principles of soil physics and hydraulics. New materials, new methods of installation, and the use of larger and more powerful machinery have revolutionized this industry in recent years, so that drainage facilities can now be constructed much more easily, quickly, and precisely than ever before. Typically, plastic drain tubes enveloped by synthetic "filter-socks" are "plowed-in" at the desired depth and grade. This "plow" is precisely and automatically controlled by a laser-guidance system that is an integral part of a relatively fast-moving,

Soil Conservation Service; photo, Tim McCabe

An irrigation canal in the Imperial Valley of California is lined with concrete to prevent seepage of the water into the adjacent soil. Such seepage increases the salt content of the soil.

self-propelled drain-installation tractor unit. Computer models that can simulate water-table levels and salt removal under alternative conditions of cropping and water management are available to better assess and design the drainage needs of the area. Various tillage equipment can even invert whole soil profiles or break up substrata as deep as 2.5 meters (8.2 feet) that impede deep percolation, so that many adverse physical soil conditions causing or associated with salt-affected soils can be modified.

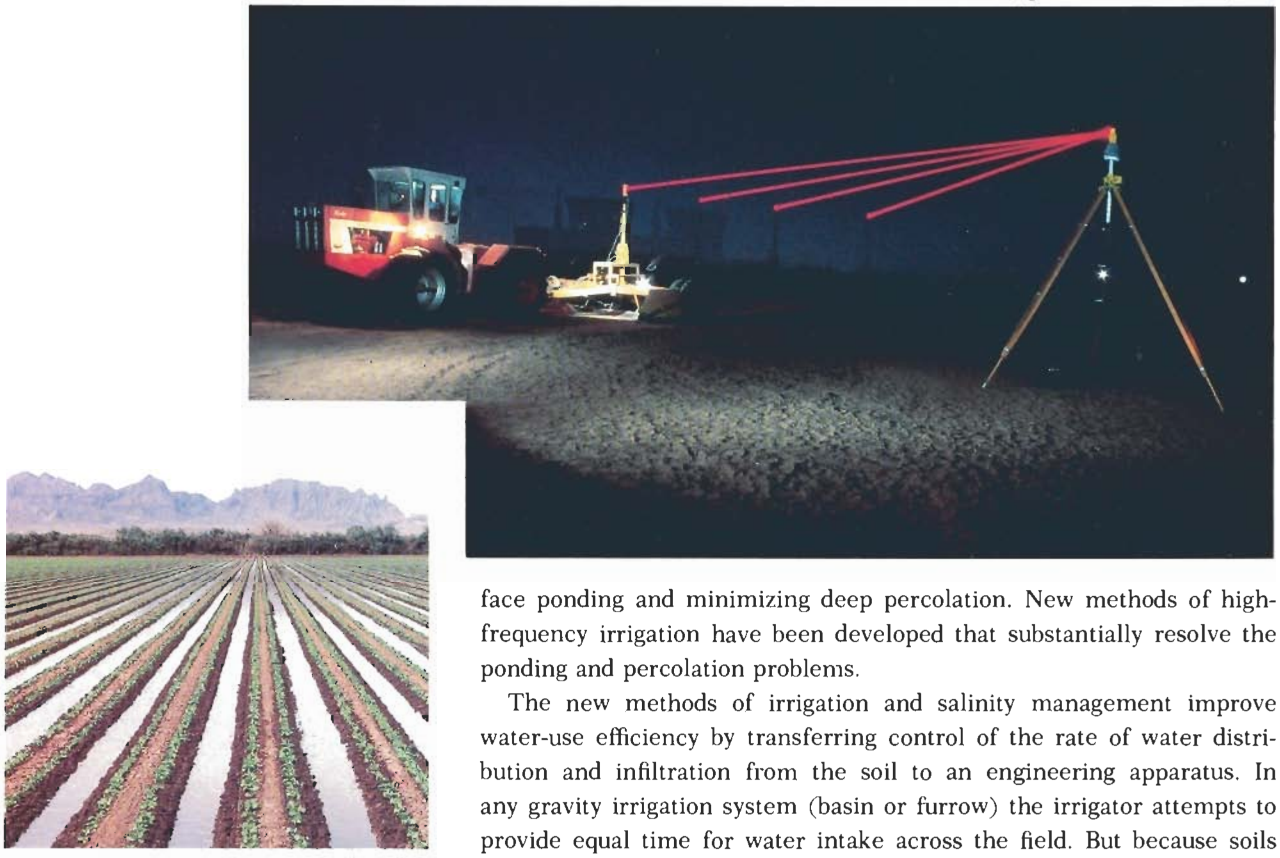
Once drainage has been provided, saline soils are reclaimed by applying water to the soil surface and allowing it to pass downward through the root zone. Leaching efficiency has been greatly increased through improvements in the accuracy and precision of land-leveling techniques and by the ability to apply water uniformly across an area. New theories and guidelines have been developed to predict the amounts of water needed to reduce the soluble salts for various conditions of soil properties and methods of water application. A better understanding of the chemistry of soil permeability has been achieved, and quicker and more cost-effective procedures have been developed for reclaiming sodic soils.

Much more is now known from experience and research about how to manage agricultural lands so as to prevent the excessive accumulation of soluble salts and adsorbed sodium. Management practices include selection of crops and varieties that are appropriately tolerant of salts; use of land-preparation and tillage methods and irrigation techniques that maximize the availability of water (both soil and irrigation water) to the plant and that also minimize deep percolation losses and excess waterlogging while preventing excessive salination within the root zone; the use of special planting procedures and seedbed configurations that minimize salt accumulation in the vicinity of the seed; and construction, maintenance, and operation of water conveyance, delivery, and drainage systems that avoid or control seepage losses and provide water to the fields as needed and in the amount required.

The relative tolerances to salinity of most agricultural crops have been established in controlled studies, and better varieties have been developed through selection processes. Certain practices can also reduce the effects of salinity on crops. Planting on sloping beds or in furrows, transplanting established seedlings, and employing special irrigation techniques can be used to establish a good stand. Closer plant spacings and optimization of irrigation to maintain a high content of soil water can also be used to offset many of the harmful effects of salinity on small and slow-growing plants.

Substantial progress has been made in recent years in controlling soil salinity through improvements in irrigation management. The key to salinity control is close water control that maintains a net downward movement of soil water in the root zone over time while minimizing excess deep percolation. A new theory has been developed, and field experiments have been carried out that show that the optimum salinity control scheme is to provide water to the plants in a way that continuously maintains the soil-water content in the root zone within a narrow range at a relatively high level while at the same time avoiding sur-

Photos, Agricultural Research Service, UDSA



Guided by laser light, an earthmover levels a field (top). When cropland is level, farmers are able to apply the exact amount of water needed—evenly and quickly. This improves crop yields and reduces the salt-producing runoff that results from the need to apply extra water to sloping fields. Above is a lettuce field in Arizona that has been leveled by a laser-controlled earthmover.

face ponding and minimizing deep percolation. New methods of high-frequency irrigation have been developed that substantially resolve the ponding and percolation problems.

The new methods of irrigation and salinity management improve water-use efficiency by transferring control of the rate of water distribution and infiltration from the soil to an engineering apparatus. In any gravity irrigation system (basin or furrow) the irrigator attempts to provide equal time for water intake across the field. But because soils are typically not homogeneous, even a uniform intake opportunity time does not guarantee uniform intake. If the water ponds on the soil, its rate of infiltration is controlled by the soil's intake rate, which is usually quite variable from place to place within the field and which changes markedly with time. Therefore, typically, excess water is applied to the field to meet the needs of the area of lowest intake rate. This results in excessive deep percolation and salt discharge and also in waterlogging and salt pollution in the areas receiving the drainage. In a closed-conduit system of irrigation (such as sprinkler, bubbler, or trickler) the uniformity of application is more subject to equipment control, and the actual intake may be made as uniform as the application if the rate is less than the soil's intake rate. Thus, closed-conduit systems are being increasingly adopted for irrigation and salinity control.

New developments in gravity irrigation systems improve irrigation efficiency and salinity control, even though surface ponding still does occur. Automated gravity irrigation systems, called cablegation, have been developed for fields irrigated by furrows; these systems progressively "cut back" flow to the furrows in order to reduce losses of tailwater (surface water that drains from a field) and to increase intake uniformity along the row. So-called surge irrigation systems have been developed to reduce runoff losses and increase intake uniformity by pulsing water onto the fields in successive increments. Multiset systems use shallow, buried ditches laid across the furrows at intervals down the field in order to reduce the length of row that is irrigated and thereby increase uniformity and reduce runoff. Systems have also been developed to reduce water losses and increase the efficiency of water use by recirculating and reusing surface runoff from irrigated fields.

Improvements in efficiencies and salinity control are also being obtained in flood irrigation systems by the use of level basins (no grade in any direction) combined with large-flow systems of water delivery. The commercial development of effective, practical, and inexpensive laser-controlled grading equipment provided the impetus for implementation of this method. These relatively small (2–15 hectares) basins, when used with either multiple outlets or single large-flow turnouts, permit a field to be irrigated with less water than used by conventional methods, with higher application efficiencies, with increases in water infiltration uniformity, and with less deep percolation. Consequently, they minimize soil salinity, waterlogging, and salt-loading problems.

Improved irrigation efficiency and salinity control have been enhanced through the implementation of irrigation scheduling techniques. These determine the need for irrigation and the amount required based on calculated evapotranspiration amounts, measured depletion of soil water, or both.

In addition to effective methods of irrigation scheduling and application, effective irrigation and salinity management also require an effective delivery system. As irrigation methods become more efficient, the demands on the distribution system are increased. The operations of delivery systems (usually designed and operated by civil engineers) and of on-farm irrigation systems (usually designed by agricultural engineers and operated by farmers) have typically been in conflict. Delivery systems have generally been designed to provide water on a regular schedule. Efficient irrigation systems require more flexible deliveries that can provide water on demand as each crop and particular field need it. Salinity problems created from poorly designed and operated delivery systems are prevalent throughout the world. Substantial losses

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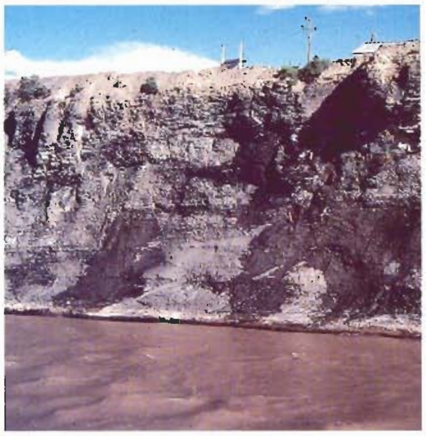
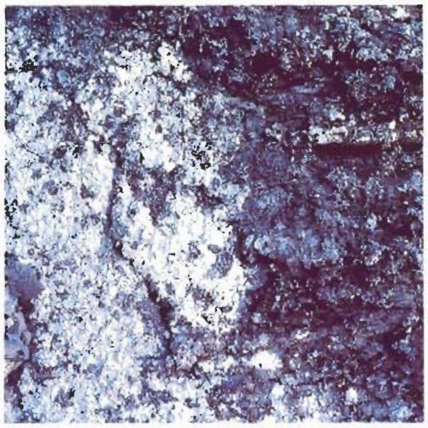
Wastewater laden with salt drains from irrigated land in California's Imperial Valley into the Salton Sea. J. D. Rhoades estimates that as much as 70% of such water can be intercepted and reused to irrigate such salt-tolerant crops as sugar beets and cotton. As well as providing irrigation this would prevent the water from draining into such lakes as the Salton Sea and increasing their salinity.

Soil Conservation Service; photos, Tim McCabe





Salt seeps into the Colorado River (top) as a result of irrigation drainage. Bottom, a close-up of a small area in the top photograph reveals a heavy accumulation of salt on the shale that lines the banks of the river.

from seepage from unlined canals, from spills, and from excessive or unneeded water deliveries have contributed substantially, often primarily, to the excessive waterlogging and salination of irrigation projects. These systems can be improved by lining the canals, by containing the water within closed conduits, and by implementing techniques that increase the flexibility of delivery.

Irrigated agriculture is a major contributor to the salinity of many rivers and groundwaters. The agricultural community has a responsibility to protect the quality of these waters while at the same time maintaining a viable irrigated agriculture. Irrigated agriculture can not be sustained without adequate leaching and drainage to prevent excessive salination of the soil, as discussed above. Yet these processes are the very ones that contribute to the salt loading of rivers and groundwaters. In recent years pollution of water resources has become the major problem involving irrigated agriculture and salinity control in the United States, South Africa, and Australia. Significant increases in understanding not only how salts affect plants and soils but also how cropping and irrigation affect soil and water salinity have been made in recent years; correspondingly new strategies to minimize the pollution generated by irrigated agriculture have been developed and implemented. A brief synopsis of these developments is given below.

The concentration of soluble salts is known to increase in soils as the applied water, but not the salts, is removed by evaporation and transpiration. Evapotranspiration can cause an appreciable upward flow of water and salt from lower soil depths into the plant root zone. By means of this process many soils with shallow, saline water tables become salinized. Soluble salts eventually accumulate in irrigated soils to such an extent that crop yields suffer unless preventive steps are taken. To prevent the excessive accumulation of salts in the root zone, irrigation water (or rainfall) must be infiltrated in excess of that needed for evapotranspiration and must pass through the root zone to leach out the accumulating salts. This is referred to as the leaching requirement. Once the soil solution has reached a salinity level compatible with the cropping system, then subsequent irrigations must remove at least as much salt from the root zone as they bring in, a process called maintaining salt balance. In fields irrigated to steady-state conditions with conventional irrigation management, the salt concentration of the soil water is essentially uniform near the soil surface regardless of the leaching fraction (the fraction of infiltrated water that passes through the root zone), but it increases with depth as the leaching fraction decreases. If the leaching fraction is decreased too much, average root zone salinity increases, and the crop yield will decline. Improved methods to calculate the leaching requirement and salt balance have recently been developed and tested; they show that much less leaching is required for salinity control than was previously advocated.

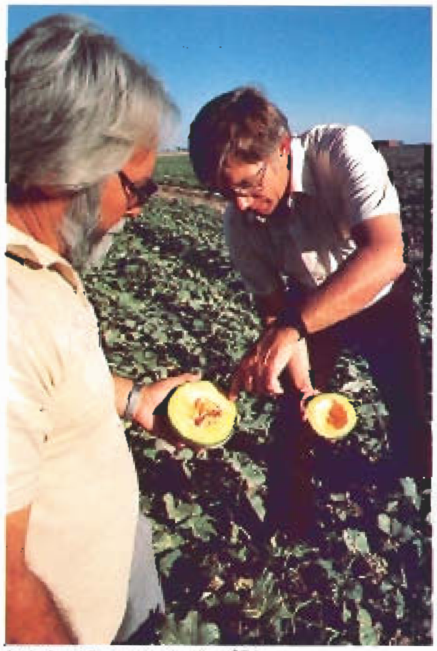
Irrigation water may contain from 0.05 to 3.5 tons of salt per 1,000 cubic meters (one cubic meter equals 35.3 cubic feet). Therefore, with crops requiring annual irrigations of 6,000 to 9,500 cubic meters of water per hectare, from 0.3 to 33 tons of salt per hectare are added to irrigated soils annually. Reducing the volume of water applied reduces the amount of salt added and the amount needed to be removed by leaching. Additionally, minimizing the leaching fraction by the use of frequent, light, and uniform applications of water minimizes the "pick-up" of weathered and dissolved salts from the soil. The salt load discharged from the root zone can be reduced about 2–12 tons per hectare per year by reducing the leaching fraction from 0.3 to 0.1. The volume of deeply percolating water is reduced in proportion to the reduction in the leaching fraction. Reducing deep percolation generally lessens the salt load that is returned to rivers or groundwater.

The interception of saline drainage water before it is mixed with water of better quality is advocated. Intercepted saline drainage water can be desalted and reused, disposed of by pond evaporation or by injection into some suitably isolated deep aquifer, or used as a water supply in a situation where brackish water is appropriate.

A strategy for salinity control of water systems has been recently developed and successfully tested. In this system salt-sensitive crops (lettuce, alfalfa) are irrigated with "low salinity" water, and salt-tolerant crops (cotton, sugar beets, wheat) are irrigated with drainage water. For the tolerant crops the switch to drainage water is usually made after seedlings are established. The feasibility of this strategy is supported by the following conditions: (1) the maximum possible soil salinity in the root zone resulting from continuous use of drainage water does not occur when the water is used for only a fraction of the time; (2) substantial alleviation of salt buildup resulting from irrigation of salt-tolerant crops with drainage water occurs during the time salt-sensitive crops are irrigated with normal, low-salinity water; (3) proper preplant irrigation and careful irrigation management during germination and seedling establishment leaches excessive salts out of the seed area and from shallow soil depths, permitting good stand establishment; and (4) data obtained in modeling studies and in field experiments support the credibility of this reuse strategy. This strategy conserves water, sustains crop production, and minimizes the salt discharge from irrigated lands and the salt loading of receiving waters. It also reduces the need for diversion of water and for the development of new water supplies for irrigation.

Desalination of agricultural drainage waters is not now economically feasible, but improved techniques for doing this exist and some are being implemented. However, more needs to be done in this regard.

Scientists check melons grown on land that had previously been irrigated with salty wastewater for the production of wheat and sugar beets. The yield of melon seeds per acre equaled that from fields that had been irrigated only with water of good quality.



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Research needs and opportunities

A number of ways in which salinity control is being improved were identified in the preceding sections. Yet other control possibilities exist, some of which await advancements in knowledge and technology. For example, additional research is needed to improve the salt tolerance of crop varieties. Research on the genetics of salt tolerance has not been adequately supported, and differences in salt tolerance within species should be exploited. A plant-breeding program for the development of salt-tolerant species should be undertaken that would include identifying varieties with superior salt tolerance and crossing them with high-yielding adapted varieties, screening segregated generations for increased tolerance under controlled stress conditions, and testing advanced generations in the field.

An alternative approach to improving the salt tolerance of current crops would be to introduce new crops that grow well under saline conditions. These include atriplex, salicornia, and spartina, among others. If economic uses for them could be found, such as for fuel production, such plants could be developed as crops and grown in salt-affected soils. Unfortunately, though they thrive in adverse environments, such plants tend to grow much more slowly than conventional crops. It may be that those genetic mechanisms that protect them against stress are, at the same time, the ones that restrict their growth rate.

As in the case of breeding, the development of new crops is an area deserving increased attention, but it also is subject to false claims and hopes. The fact that a plant is native to, and survives in, saline environments does not mean that it can be cultivated successfully as a crop because biomass production tends to be proportional to transpiration; plants in saline environments have a low rate of transpiration.

The ability to improve salinity control in crop production should also improve if a better understanding is gained as to how to relate current crop-tolerance information to field conditions. Though an extensive literature exists on the salt tolerances of crops, it mostly deals with information collected in growth chambers or small-plot environments. Knowledge about crop water use as affected by salinity and stage of plant growth is also insufficient, though recently new research has been undertaken in this regard. The salt tolerances of various crops under a variety of water-management practices need more investigation. The

In a search for salt-tolerant crops a scientist examines a stunted batch of Egyptian wheat that has been grown in a tub of saline water. Behind him is Egyptian wheat that is flourishing in fresh water.

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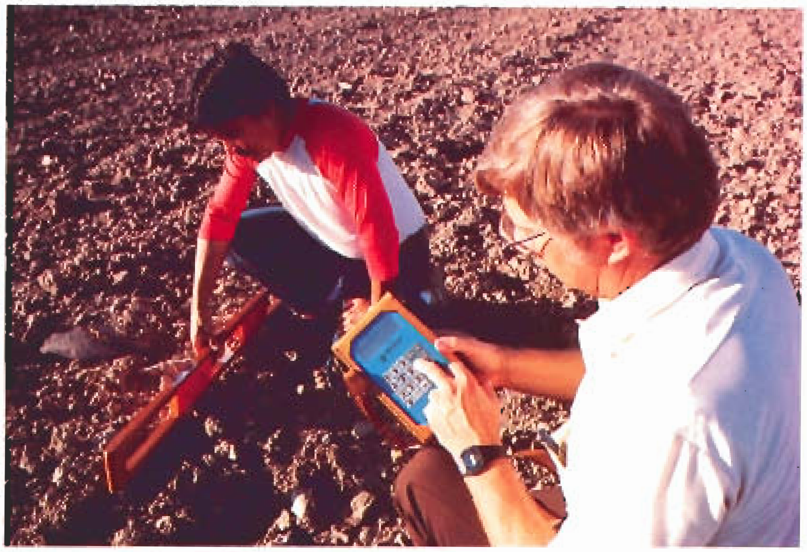
Agricultural Research Service, USDA



Researchers use an electromagnetic monitor to measure soil salinity in the Imperial Valley of California. The device produces a flow of electric current in the soil that increases proportionally to the salinity.

studies should include evaluations of short-term effects of high salinity at various stages of growth, especially the seedling establishment and flowering stages.

Although increased efforts in genetics and breeding for greater salt tolerance are needed, it must be recognized as a false premise that management research is outdated and no longer needed. The increasing need for conserving soil and water resources dictates that breakthroughs are needed in this regard if a permanent viable irrigated agriculture is to be sustained and, especially, if irrigated agriculture is to be practiced under even higher levels of salinity. The protection of water resources against excessive salination, while sustaining agricultural production through irrigation, will require the implementation of comprehensive land- and water-use policies that incorporate an understanding of the natural processes involved in the soil-plant-water and associated geohydrological systems. For this purpose the long-term effects of alternative irrigation and agronomic practices for salinity control need to be more thoroughly evaluated. Rather than using only crop yield as a measure of the success of salinity-management practices, scientists and engineers should also consider the effectiveness of such practices in the protection of the quantity and quality of water resources. Since crop salt tolerance, soil salt balance, and salt discharge from irrigated fields are interrelated, better techniques for determining optimum leaching requirements are needed, especially for dynamic situations.

Prediction techniques that will describe the quantity and quality of subsurface return flow from different irrigation and management are also needed. To evaluate fully the changes in chemical quality of the flow, the research models should be capable of handling salt precipitation, mineral weathering, adsorption, and the ion-exchange reactions that take place as water moves through the soil and deeper substrata. Present limitations to the use of such models include insufficient knowledge about the pathway(s) of subsurface return flows and about the chemical and physical properties of the substrata in the pathway(s) for the large hydrogeologic systems (such as irrigated valleys or large basins) that are involved. Because of the lack of such models and techniques for acquiring the required information, the problems resulting from the development of new irrigation projects, particularly those involving lands not previously irrigated, will usually be confronted only after the fact.

A need exists to identify and quantify the damages that occur as a result of salination of soils and waters and the benefits of alternative control practices. Such economic studies should also consider effects on water resources, including the local, regional, and national benefits that would accrue from the implementation, in either an irrigated valley or a river basin, of a salinity-control program. For example, a control measure implemented in a particular valley has direct benefits not only to the local area, including the nonagricultural sectors, but to downstream water users as well. Benefits resulting from increased crop yields, saved fertilizer, reduced drainage, reduced pollution, and reduced water costs accrue to both upstream and downstream users.

Improved methods are needed for making areawide investigations to define the need for and potential benefit of salinity-control measures. These studies should pinpoint the sources and causes of salinity and provide the information required for selecting the most appropriate control measures. Once the sources of salts have been defined, more detailed studies should be undertaken to specify how those sources may best be controlled. Demonstration projects and extensive educational programs will be needed to evaluate and demonstrate feasibility and accomplish the implementation of selected programs.

The proper operation of a permanent irrigated agriculture that uses water efficiently requires periodic information on the status of soil salinity. Only with this information can the need for management change and effectiveness of irrigation project operations be assessed with respect to salt balance and water-use efficiency. Suitable inventories of soil salinity either do not now exist or are inadequate; nor are there effective programs to monitor the salinity status of soils and to assess the adequacy of irrigation and drainage systems on a projectwide basis. Presently used methods are primarily based on "salt balance" concepts and models that are inadequate.

The need for monitoring will increase because less water will be available for leaching as the competition increases for water now used in irrigation. In addition, in order to protect water resources, more restrictions will likely be placed on the discharge of salt from irrigation projects. With less leaching there will be a corresponding increase in soil salinity. New instruments for remotely measuring soil electrical conductivity, coupled with computer mapping and satellite-based positioning techniques, have the potential for meeting salinity-monitoring and mapping needs. These methods will have to be integrated into a geographic information system for inventorying salinity. A network of representative soil-salinity-monitoring stations should be established in irrigation projects, especially those projects undergoing changes in operation.

Symbolizing the destruction that could take place unless effective control measures are carried out, an iodine bush killed by salt in the soil stands at the edge of the Kesterson Reservoir in California (opposite page).

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The present approach to salinity research, where studies are carried out in artificial, small, controlled, and relatively simple systems that exclude much of the "real world" of irrigated agriculture and the larger hydrogeologic system, leaves much to be desired. This should be corrected with research being undertaken that encompasses the variability and complexity of the real world. In spite of this limitation, much more is known about salinity and its control than is currently being used. Known principles should be adapted, and innovative management systems appropriate to existing field circumstances and crop-production and conservation needs must be developed.

Finally, a proper balance between basic and applied research must be maintained. Accomplishments in basic biotechnology and genetic engineering research should not be expected to supplant the need for research and improvements in management and engineering. Nor should the real goal for research be forgotten: to feed mankind while conserving dwindling soil and water resources.

FOR ADDITIONAL READING

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