



Salinity Problems in Arid Lands Irrigation: A Literature Review and Selected Bibliography

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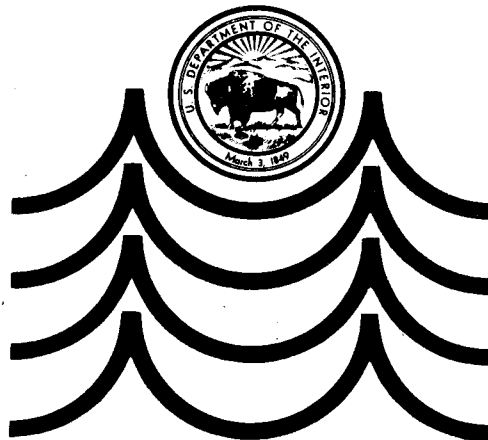
Salinity Problems in Arid Lands Irrigation

A Literature Review and Selected Bibliography

**by Hugh E. Casey
Research Assistant
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University of Arizona**

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Arid Lands Resource Information Paper No. 1

SALINITY PROBLEMS IN ARID LANDS IRRIGATION:

A Literature Review and Selected Bibliography

by

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FOREWORD

The Arid Lands Resource Information Paper presented here is the first of a series to be prepared for the Water Resources Scientific Information Center of the U. S. Department of the Interior, Office of Water Resources Research, on Grants 14-01-0001-1616 and 14-31-0001-3391, to the University of Arizona, Office of Arid Lands Studies (OALS), Patricia Paylore, Principal Investigator.

The historic role of the OALS has been the identification, evaluation, and computerized control of documentation relating to the world's arid lands. As our information services have expanded and become better known, certain contemporary topics emerge repeatedly as being of deepest concern to those who have sought our help. This particular paper was selected as the first to be developed because of the urgent need to find answers to the pressing problem of increasing salinity in the irrigation water furnished Mexico under Government Treaty from the Colorado River and its main tributary in Arizona, the Gila. International concern is equally as great as Arizona's or the Federal Government's, and ways of dealing effectively with this issue are the recurring subject of diplomatic and political discussions.

While this particular immediate case in point is the most highly visible at the moment, its extension to comparable problem areas throughout the arid world is imminent. Because of its timeliness, then, it is our hope that this paper will be a useful adjunct to permanent, realistic, and proper solutions to this worldwide problem. In providing this review of world technical literature, we believe it can be instrumental in the decisions that must be taken nationally and internationally to insure equitable answers to a matter demanding scientific, environmental, and social considerations of the highest order.

We have tried to tie this array of information together in such a way as to express a continuity of development by concept, following through on an idea on this basis rather than a simple chronological or author arrangement. The evaluative narrative, then, is the vehicle for presenting our findings.

The views expressed are those of Mr. Casey and myself, and in no way should be construed as the official views of either the U. S. Government or the University of Arizona.

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PREFACE

In presenting a bibliography on irrigation-related salinity problems, there is wide latitude for judgment in selection. We have chosen to accept the basic view that these problems do not relate exclusively to crop growing or farm irrigation practices, but extend into all other activities in a drainage basin that affect the quality of irrigation waters. Since so many problems exist on this wide spectrum, and since only recently have the interconnections between them begun to be investigated, the philosophy behind our bibliographical choices has been that the error of inclusion of possibly irrelevant material is considerably less serious than that of excluding potentially relevant items. Even so, the bibliography is not intended to be exhaustive, but rather to document amply the evaluative part of the paper and thus serve as a springboard into the entire literature relating to each part of the subjects discussed.

This paper has two goals: evaluation and education. It is not, in the usual sense, a critical review paper, since no effort is made to assess the quality of the various research contributions cited. Rather, an attempt is made to stand back, gauge the broad accomplishments, trends, and gaps in the literature, pinpoint areas most pressingly in need of attention, and finally make relevant recommendations in the light of these analyses. Every aspect of the subject is at least briefly taken up, which, together with the bibliographical entries for that section, should serve as an introduction to the subject.

Within this framework, by which the information gathered together is presented, we have attempted to define the problems in terms of water-soil-plant components and the resulting limitations on agricultural potential, plus a section on reclamation and prevention. Then we have considered the legal, political, and economic problems deriving from the wider and more amorphous problem of the entire salt-polluted drainage basin. In such a treatment, one inevitably asks some basic questions, hoping for some proper answers which, while not totally definitive, at least should present reliable guidelines for policy decisions. The answers that become manifest throughout the literature reviewed emerge with unmistakable urgency and clarity: Is arid lands irrigation agriculture destined to founder on its self-generated and ever-mounting salinity problems to the point where the very desirability of irrigation agriculture itself is called into question? We hope our recommendations will provide some viable alternatives.

A final word about the arrangement: The numbering of the 986 citations is continuous, but the bibliography itself has been broken into narrow subject headings that correspond to the arrangement of the accompanying text. However, since many references cut across these individual sections of the text, we have chosen

to leave the bibliography intact rather than break it up within the text. We believe the detailed contents will be helpful to users in locating wanted information. The permuted title index should provide a further mechanism for locating specific citations beyond this detailed subject arrangement. The name index includes secondary as well as primary authors.

I should be remiss if I failed to acknowledge the help of Kathryn J. Gloyd, Information Specialist, Office of Arid Lands Studies, University of Arizona, whose insistence on meticulous bibliographical verification and attention to sources will make the references recognizable wherever there is occasion to retrieve; of Rosemary Quiroz, Research Assistant, OALS, who masterminded the computer-produced indexes; and Cecilia Gonzalez, for assistance in the preparation of the manuscript.

I. IRRIGATION-RELATED SALINITY PROBLEMS
IN ANCIENT HISTORY:
A Perspective

World population has increased from about 1.4 billion in the last century to about 3.7 billion today. In most regions with high birth rates, there has accrued little evidence to indicate any amelioration of these trends. Agricultural productivity has not everywhere kept pace with human fecundity and the difference between them has equalled starvation. While always asserting the necessity for improved birth control programs, agriculturists, not suprisingly, have maintained that starvation need not occur if appropriate agricultural expansion programs and improvements are undertaken (6). Such measures involve both intensification and extensification of crop production. Intensification would increase the productivity per unit area of cultivated soil by improved crop quality, irrigation, increased inputs of herbicides, pesticides, and fertilizers, multiple cropping, the use of tractors and other modern labor-saving machinery, and various additional agronomic improvements. Extensification is simply the recruitment of more lands into agriculture.

Some combination of the two approaches promises the greatest yield increments. In this vein, W. H. Pawley, director of the Policy Advisory Bureau of the FAO, has recently argued (33) that world agriculture could feed ten times the present global population without recourse to synthetic foods if two major technical breakthroughs could be achieved: 1) techniques for continuous soil cultivation in the humid tropics after deforestation, 2) a means for furnishing cheap, fresh water for irrigation of the world's warm deserts, and a cheap source of power for moving the water inland. To be sure, Pawley has phrased his requirements in such a way that they can never be achieved. For instance, a cheap source of fresh water for the warm deserts is unlikely because not only must it come from seawater desalination but it will also have to be transported long distances, to many regions, with great evaporative losses.

Nevertheless, it is probably fair to say that this broad outlook on food-supply solution is shared not only by many other scientists, but also by the general public. The lush natural vegetation of the humid tropics certainly hints at an enormous crop-growing potential, while limitless solar radiation, vast land areas, and success of existing irrigation schemes imply much the same for many arid regions. The realization of such projects would place the Sahara Desert and the Amazon Basin in positions of enormously important food-producing regions, which

today they most assuredly are not.

It is unlikely that water will be found to irrigate desert areas as extensive as many envision, but a number of large water-harnessing schemes are being planned or built with the goal of irrigating sizable desert regions. Some examples are the Aswan High Dam of Egypt, recently completed, a North America water plan which would divert northern waters to the southwestern deserts, and the Soviet plan to divert Siberian rivers from their Arctic Ocean courses to the deserts of the Caspian Sea region. Clearly, these projects will absorb astronomical amounts of capital, and failure would be disastrous for the governments involved and for large numbers of people. Even for those national projects on a smaller scale, such as the California Water Plan, the Central Arizona Project, or the Texas Water Plan, the proportions allocated for irrigation will be much too great to contemplate failure. Such large amounts of water are involved because no other human activity consumes more than a fraction of the amount of water consumed by crop irrigation (9).

It is at this juncture that irrigation-related salinity problems must be considered. Briefly described, the problems center on the accumulation of soil salts on croplands as a result of irrigation activities, with the consequence of diminished or completely inhibited crop growth. This problem may be accompanied by waterlogging, which is saturation of crop soil by water to the extent that crops cannot grow in it because of root aeration difficulties. It usually results in soil salinization. Vast areas of irrigated croplands around the world suffer from one or both of these problems to the point of total agricultural inutility. A legion of soil, water, and plant scientists maintain that these problems could have been prevented or can be solved by practices based on known scientific principles. Difficulties arise, they argue, because these principles are ignored or misapplied. By contrast, there are others who maintain that soil salinity problems are system properties, that is, they are physically inherent in the system of irrigation itself, cannot be avoided, and eventually limit if not eliminate the economic feasibility of the irrigation system. As a first approximation their arguments may be divided into two categories: 1) human history is replete with whole civilizations whose demise was parallel with the demise of their irrigation systems; 2) tremendous acreages of croplands in the modern world suffer from irrigation-generated salinity problems whose creation is an ongoing process that will increase with the increase of irrigated lands. In this section, we will briefly examine the first of these arguments.

Anyone with an interest in irrigated agriculture and its salinity problems soon encounters a plethora of references to the declines of prehistoric, ancient, and relatively recent civilizations dependent on irrigated agriculture ("hydraulic civilizations"). That these declines were attributable in large part to soil salinization seems to have become part of the conventional wisdom of that vast, floating mass

of people who at least peripherally concern themselves with the arcana of decline and fall of civilizations.

A review of the existing record, however, permits no such sweeping clear-cut conclusions. The civilizations of the Tigris-Euphrates and the Nile Valley were probably the most river-dependent cultures in history. Unfortunately, the irrigation records of these civilizations are scanty, the historical geographical research is limited, and what is available seems open to broad interpretation. Wittfogel (49, 50), in assuming the decline of these hydraulic civilizations from a variety of causes, developed a well-known thesis to the effect that such cultures inevitably evolved toward highly organized, tyrannical regimes because of the organizational disciplines imposed by the maintenance and upkeep of the complex irrigation works. He maintained that the failure of organization after the system had reached some critical threshold led to a breakdown, illustrating this thesis by reference to the decline of some civilizations that occurred for just those reasons. In general, his assertions that irrigation civilizations require high levels of organization have been accepted.

Eaton (13), in studying the salinity-laden fields of present-day Iraq, seemingly accepts the thesis that such salinity levels were a long time accumulating. Although he does not say how long, he believes that the condition had progressed so far by the 11th century that the Mongolian invaders have been blamed unjustly for the demise of the region at that time. Lewis (26), who differentiates between the various great past civilizations of the region, seems to feel that the major reasons for their decline lie in the great endogenous cyclic mass movements and disruptions of human affairs. Of salinity, he says, "It is ... doubtful that over many years, this problem has been as serious as some writers have claimed."

Jacobsen and Adams (23), who participated in the Diyala Basin Archaeological Project, reached different conclusions. Using data from ancient records, paleobotanical studies, aerial photographs of irrigation canal systems, and salinity deposits, they reasoned that the region experienced three major salinity intervals: from 2400-1700 B. C. in southern Iraq, a milder phase in Central Iraq between 1300-900 B. C., and sometime after 1200 A. D. in the Nahrwan area east of Baghdad. The first phase, occurring during the time of the Sumerian civilization, was signalled by a gradual shift to salt-tolerant barley production. Other phases occurred during the Babylonian and Arab eras and are of great significance in world history.

Boumans (*in* Dieleman, 11), however, after a long period of reclamation work on Iraqi soils, conceded that the first phase of salinity probably occurred, but that otherwise "salinity was not a problem in ancient times," this, despite the fact that before 1950, Iraq has no record of the construction of any canal intended to drain or carry away salt residues from its irrigated lands (13). Almost everywhere in

Iraq there is a film of salt (11), but when it was deposited seems a matter of some debate.

The Nile Valley, like the Tigris-Euphrates region, has been irrigated for about 6000 years. Each year the amazingly gentle Nile flood brought sediments and nutrients which meant perpetual fertility. When the river was low, the gravel beds underlying the Nile mud provided drainage from the land to the river. This obviated the need for construction of elaborate drainage canals to handle salinity buildups. In general, salinity was not a problem except in the delta and other regions where return flow to a low river was incomplete, resulting in highly saline groundwater. This unique Nile flood and its effects do not seem to be well understood by all writers who compare ancient irrigation systems.

The Indus River, too, has a long history of settlement and civilization, but intensive irrigation schemes do not seem to have been extant for most of its settled history (41). The twin problems of waterlogging and salinity now plaguing West Pakistan are of relatively recent genesis. It is unfortunate that few historical studies or hard facts are available for other great river systems, particularly those of Mesoamerica and Peru (21). An extensive archaeological study is being conducted in southern Arizona on the Hohokam Indian irrigation systems. The Hohokam began irrigating about 300 B.C. and achieved a complex, highly organized culture which reached its maximum size about 900 A.D. By 1450 A.D., they had disappeared after a population crash signalled by some sudden, drastic change. Because their irrigation engineering seems to have lacked an appropriate salinity-preventing technology, it is surmised they could not maintain crop productivity adequate for the large population that their irrigation culture had created (4). Not enough as yet is known, but Ayres' comments signal an awakening of many to the importance of studying these phenomena: "There is more archaeological information available on use than on abuse of rivers. Archaeologists until recently have not been particularly concerned with abuse."

It seems fair to say, in evaluating the literature dealing with the salinity problems of the past, that it hints at much, but offers little hard data and a great deal of contradiction and counter assertion. Certainly the universality of irrigation salinity problems is not borne out. But this literature does not dwell on salinity problems alone. It includes descriptions and appraisals of problems of siltation and debris accumulation, canal construction, water-plant choking, warfare, and legal, political and general social organization. All of these factors affected operation and maintenance of irrigation systems. Marr (28) is undoubtedly right in asserting that separating causes and effects in the relationship of irrigation to ancient civilizations is quite impossible, but that tentative statements can be made.

This serves to introduce a fact which will be discussed in various facets in

subsequent sections, namely, that irrigation salinity problems are not as simple as the definition given in a previous paragraph would imply. They embrace not only a spectrum of agronomic problems, but by their existence tend to generate interactions with other irrigation-connected problems such that a whole series of new problems comes into existence, including questions of canals and siltation, dams, public health, and social organization. It is here that a critical point must be made: those who question the value and effectiveness of massive irrigation engineering schemes do so not only on the basis of salinity problems alone, but out of many considerations. It is the purpose of this paper to consider the larger issue of irrigation only from the point of view of the salinity problems it creates. Nevertheless, it will not always be possible, or even desirable, to separate salinity from other irrigation problem subsets.

If salinity cannot be proven as a problem stretching over millenia, it is most certainly a contemporary problem of great magnitude. Tens of millions of acres in the Middle East and Pakistan alone are currently biologically crippled by this scourge (34). Almost everywhere there is irrigation, salinity has arisen (29). This comprises the second category of the arguments, mentioned earlier, of those who question the wisdom of massive arid zone irrigation projects. It is, in fact, the main subject of this paper.

One final way of subdividing salinity problems must be discussed. A problem that was probably not often critical with historic hydraulic civilizations was the fate of the downstream neighbors. Today however there are two types of salinity problem: 1) that obtaining on any given piece of soil or stretch of water, 2) that which may result at some point downstream as a consequence of salt and water conveyance from the original point. Nor need the actual problems necessarily be the same as the original ones. For instance, the salts that lower soil fertility at point A may be carried downstream to point B where they cause the destruction of wildlife cover or even the pollution of a municipal drinking supply.

There is no denying an ever-increasing complexity.

II. BASIC WATER BALANCE PROBLEMS IN RELATION TO IRRIGATION

The subject of irrigation-related soil salinity problems is at once simple and complex. This seemingly paradoxical situation is reflected in the fact that no really adequate, comprehensive treatise exists on the subject. This lack is all the more surprising in view of the ubiquity and seriousness of the problems. Reeve and Fireman (34) assert that salt problems presently exist on about one-third of the world's irrigated agricultural lands as well as on "untold millions of acres of potentially irrigable lands," and this applies to every one of the 25 or more nations having more than a million acres currently under irrigation.

The subject is simple if one wishes to describe the nature of existing salinity problems. However, the factors involved in the creation of a salinity problem and the necessary steps in its prevention or improvement may become rather complex, both conceptually and operationally. A student of the subject must master facets of chemical thermodynamics, soil physics and chemistry, meteorology, plant physiology, hydrology, and agronomy. The practical man in the field must at least be acquainted with cropping practices, soil tillage operations, drainage engineering, and irrigation technology.

In many quarters there is a growing recognition that the practices of agriculture, municipalities, and industry tend to potentiate each other's contribution to salinity pollution, and that the salinity problem is a problem for society as a whole. In many areas, such as the Colorado River Basin, it may be the most serious problem of all (868). It follows that legal, socioeconomic, and political ramifications are valid concerns in this arena.

This report will be concerned with irrigation-related salinity problems on two levels: the cropped field and the drainage basin. The salinity problem is really part of the more general problem of arid zone agriculture. Most desert irrigation systems suffer from a low ratio of available irrigation water to potentially irrigable land, so that the more general consideration is one of water use efficiency. When water is very scarce, it is a human tendency to use as little water as possible per unit area of crop land so that the total crop area may be as large as possible. If this is overdone, crop drought symptoms and diminished productivity follow. Even in situations where just enough water is allocated to insure maximal crop growth, in some years it will sink below this level for the simple reason that there is less

available water to apply because of natural fluctuations in supplies. Another human tendency in dry regions is to overwater when sufficient supplies are available, on the theory that it can have only beneficial effects on the crop. As we shall see, both overwatering and underwatering may lead to salinity problems.

It has been asserted by many agricultural scientists that irrigation salinity problems are, in the main, preventable, if appropriate irrigation technology practices are assiduously observed. For a number of reasons, relating to eventual assessment of usefulness and feasibility under various conditions, these practices will be reviewed. The technical framework underlying their development will also be outlined and reviewed. Such a review must necessarily be broad and lacking in much important detail. However, the accompanying bibliographical sections should, in compensation, encompass at least the major review and research papers in most subject areas. In later discussions concerning the effectiveness, both present and future, of arid land salinity control and reclamation programs, many of these technical concepts will be drawn upon.

It is possible in this section, if desired, to skip over the technical discussion and maintain enough continuity to move on to the next chapter by reading the chapter summary.

Since we are here mainly concerned with problems relating to arid lands irrigation schemes, it would seem important to identify and delimit the concepts of aridity and semiaridity. In a general sense, they are areas where little or no natural precipitation may be anticipated to supplement irrigation waters, sunshine is a non-limiting factor since cloudy conditions are rare, relative humidity is quite low, and soils are generally sandy. Many precise classification schemes have been devised since the impetus furnished by Köppen (74) with his temperature and precipitation criteria. Meigs' scheme utilizing agronomic criteria has been especially popular (78). There seems little doubt that classifications based on precipitation and evaporation have become generally useful as more people have begun to appreciate that precipitation alone is not an adequate criterion for a desert. Hoare's definition is reasonably typical, "A land area can be considered semiarid if it has an annual rainfall of less than 15 inches and if the evaporation from a water surface exceeds 45 inches (72)". There is here no need for a lengthy discussion or appraisal of the various schemata for classification. For the agriculturalist, Simons' comment is probably quite appropriate, "...There is no argument about the general position and extent of the desert lands; it is only the margins which are sometimes in doubt (83)."

Plants suffering from insufficient water usually maintain leaf stomata at least partially closed and are characterized by low or non-existent transpiration rates. This in turn limits inward diffusion of carbon dioxide and growth is retarded. If

deprived of water long enough, the plant may permanently wilt. It is the sole function of crop irrigation not only to prevent wilting but to expedite growth at some level near its potential maximum. Any irrigation-connected problem therefore has no meaning except insofar as it affects plant growth, and this is just the effect of soil salinity when it rises above some threshold level of salt concentration in the plant root zone.

When irrigation water is applied to the soil surface, it may either run off or infiltrate. If it infiltrates, it may still evaporate from the surface layers. If it moves deeper into the soil, it may reach the root zone, be taken up by the plant roots, move up the xylem, and evaporate (transpire) at the mesophyll cell surfaces, where, as vapor, it moves through anastomosing leaf channels and eventually out the stomatal openings. If the irrigation water had entered a saturated soil, it might have moved, under gravity, down past the root zone to the water table. If the root zone is taken as our "reference point", then it may be said that water can move into it not only from above, but also from below. As the upper soil layers dry out, a negative pressure (or decrease in soil water potential) results in capillary movement of water from the water table to overlying soil layers. This water may reach the root zone if the water table is high enough, and undergo utilization by plants. Alternatively, it may reach superficial soil layers and evaporate to the atmosphere. If the water table is very close to the root zone, as it often is as a result of irrigation, very small decreases in water potential around the roots will suck water upward and the root will be constantly bathed by this liquid from below.

In reviewing these phenomena, it is extremely important to remember that: 1) at any point, while in the liquid state, water may be carrying dissolved salts, and 2) if water evaporates from the salt water mixture, the remaining salts will be more concentrated. It is this concentration increase that results in a soil salinity problem, since in effect, more salts will have been brought into the soil than removed. Basically, the process of soil salt concentration will have been achieved by a combination of root membrane permeability to water relative to salts and evapotranspiration, which is evaporation either directly from the soil or from the plant leaves after root water uptake. In both cases the salts are left behind. This applies also to groundwater reaching the root zone by capillary action. If it has any significant amount of salts it may be an extremely serious source of soil salinization.

However, the process may work in the other direction. Water entering the soil may dissolve soil salts and carry them along through the soil down past the root zone. For any given salt concentration of applied water, there is some volume of that water that is great enough to carry all the salts down through the root zone even after losses through evapotranspiration. It will leave no salts

behind that it brought in. The process is known as leaching, and is fundamental to both soil salinity prevention and reclamation. More of this later.

To recapitulate: Soil salts may build up through concentration of the salts in applied water by the evapotranspiration process. If enough water is applied, then the evapotranspirative losses are not great enough to significantly concentrate the remaining solution and all salts are leached out of the root zone.

Given an irrigation water of some initial salinity, the resulting soil salinity may therefore be understood by reference to soils and their water-conducting properties, climate, soil drainage and the water table. In effect, the salt budget is a consequence of the irrigation water budget, and shifts in water are usually accompanied by shifts in salts.

The goals of the irrigator are twofold. He must supply enough water for plant consumption (evapotranspiration) and enough additional water for the leaching of salts past the root zone. Balanced against these supply requirements is the need to achieve a reasonably high irrigation efficiency in order to conserve usually scarce and expensive irrigation water, as well as the necessity of avoiding the creation of a high water table. This is a balancing act which is often, but by no means always, accompanied by a fairly wide error margin. In fact, it is fair to say that irrigation agriculture is usually a balancing of offsetting water control measures.

In reviewing the general aspects of irrigation technology and hydrology, an effort will be made to concentrate on the area of intersection between the general irrigation goal of soil water retention for availability to crop root systems and the specific goal of moving enough water containing dissolved salts down past the root zone.

Over the past 10-15 years, soil scientists, plant physiologists, and hydrologists have incorporated many physicochemical concepts and terms into their disciplines. Some of these will be discussed briefly because knowledge of them should confer not only greater understanding of current research literature in the various disciplines but also some insight into the causes of salinity problems and the reasoning behind certain reclamation methods.

The free energy of a substance is a measure of its ability to do work. This is a concept derived from thermodynamics and the fact that energy is a scalar quantity or a potential. Because two elements within a system may possess different potentials, there is a potential gradient between them. Movement along this gradient results in work being done. Water in different regions lies at different potential levels, and tends to move down the potential gradient. Hence the term "water potential". Intuitively water potential may be thought of as a reflection of

water concentration. The hydrostatic pressure exerted by a column of water on its component molecules tends to force them closer together, increasing their concentration. Water will flow from a region of greater hydrostatic pressure to one of lesser hydrostatic pressure. Solutes increase distances between water molecules and lower their concentration. In the classic osmotic pressure experiment in which a salt solution is separated from pure water by a semipermeable membrane, the pure water moves across the membrane into the solution of lower water potential, doing work in the process. It follows that the greater the osmotic potential of a solution, the lower its water potential. In plant cells, hydrostatic pressure potential and osmotic potential work against each other and the resulting water potential reflects the hydration level of the cell (57). Other factors affecting water potential are gravity and "tension", or negative pressure.

Tension is a particularly important factor in drying soils. In general, soils are porous and may be thought of as a collection of crude tubes. As the tubes lose water, more surface area is exposed. Since the pore walls are hydrophilic, loss of some of the water results in greater forces holding the remaining water. The total effect is a soil "suction" or negative pressure, and is a measure of the dryness of the soil. Water placed on the surface of a drying soil naturally tends to move into the soil, demonstrating that matric potential, like osmotic potential, lowers the energy state of water.

The usefulness of the water potential concept is that it combines a number of factors influencing water status into a single term. Potential differences may be thought of as "driving forces".

There are essentially two kinds of soil pore, large and small (capillary). Large pores are created by a variety of causes such as root activity or cracking. When all pores are filled with water after a rainfall or irrigation application, the soil is saturated. In this situation water in the large pores drains fairly quickly in response to gravity. It was thought that this water moved directly down to the water table, but recent evidence indicates that it may move through capillary pores (207). In any case, the rate of drainage is directly related to soil pore sizes. Coarser-grained sands drain rather quickly and water for plant roots is not available long. In finer-grained clays, the soil acts as a storage reservoir, retaining water for gradual uptake by plant roots. When water has drained out of all the larger pores, the soil is said to be at field capacity (FC). This is a quasi-equilibrium state since some water is always moving out through the soil, albeit much more slowly when only the small pores contain water.

It can be seen that soil structure, porosity and texture are critical factors in soil water movement and retention. Because clays furnish most of the internal surface of a soil and because of their colloidal properties, the clay fraction controls

the most important soil properties (57).

In soils or plants, water and dissolved substances may move as mass flow or diffusion. Diffusion, whose driving force is concentration gradient, is relatively unimportant in soil water movement except perhaps in fairly dry soils. Mass flow is so named because it is the motion of a column of liquid including all dissolved contents. The velocity of mass flow is proportional to the net pressure and gravitational gradients, which is known as Darcy's Law. The proportionality factor (K) is the hydraulic conductivity, and is a function of the soil pore structure, viscosity and water content. It is at a maximum in saturated soils and decreases with drying. The flow of water in unsaturated soils is much more difficult to analyze than saturated flow. Darcy's Law may still be used to describe such flow, and K is termed the capillary conductivity (145). Water moves more slowly in drying soils, and such movement undergoes an interesting reversal with texture. In the saturated range, transmissibility is much greater with sands than clays, but as the soils dry out at water contents not much below saturation, clay transmissibility is the greater (58). The greater matric forces of clay are holding water at greater soil moisture tensions than is the case with coarser sands. This has great importance to soil-water-plant relationships, since water is available to plants over much greater ranges of soil water contents in the clayey soils.

Vapor transfer is also probably important in drying soils, and is largely a temperature-dependent function (124).

An irrigation program may result in water losses in one or all of three directions: runoff, evapotranspiration, and deep percolation. Runoff is usually the result of physiographic factors, water application to an already saturated soil, or low soil permeability. Since physiography and application are controlled in irrigation systems, soil permeability and its effects on infiltration usually constitute the limiting factor on runoff rates. Occasionally one encounters soils with too high infiltration rates, but more usually the problem is one of too low infiltration rates. In order to apply water most efficiently, a knowledge of the optimal rate of application would be useful, and to this end much research has been done on the subject of infiltration. The importance of soil infiltration rates, as limiting factors in the irrigation process, is underlined by Henderson and Haise (96): "...The rate of water infiltration into soils is a universal factor in design and operation of all irrigation systems."

The most obvious factors influencing infiltration rates have been soil texture and surface aggregate structure, depth of applied water, presence and depth of impermeable layers, and soil water content at the time of irrigation. Infiltration tends to be higher in warm months than in cool months and is greatly affected by the type of soil vegetation cover. Aggregate structure, and hence porosity, is

often broken down by such factors as tillage practices, raindrop surface impact when protective plants are absent (93), lack of organic material and high levels of exchangeable sodium in the soil solution (105). Such problems are dealt with by improved water and tillage management practices (110), various types of mulching and green manuring (111), soil amendments, and perhaps most importantly, cultivation of desirable crop plants.

Infiltration rates may be described by Darcy's Law (103); by using the diffusivity equation, derived from Darcy's Law and the law of conservation of mass, computer solutions of infiltration rates may be found, provided there is available data on the critical parameters of volumetric water content, K and soil tension. Whether this and much other important analytical research on infiltration (97, 98, 105, 107, 109) will be translated into major techniques of field irrigation efficiencies, is not yet clear.

Water movement into and through soil and plant to the atmosphere involves a series of interdependent flow phenomena. Starting in the soil, it flows down a series of water potential gradients. From the soil, it is taken up by the plant roots, moves into the root xylem and up to the leaves. The leaf cell osmotic potential is the critical component of plant water potential. In well-watered plants, it is offset by the hydrostatic pressure or cell turgidity. Root water potentials must be less than soil water potentials or there would be no driving force into the plant. Leaf water potentials in turn must be less than root water potentials so that water reaches the evaporating surfaces. This series of driving forces is effectively regulated by a physiological process—stomatal closure.

Transpiration decreases leaf water content and therefore leaf water potential. This decrease is transmitted to the roots where the equilibrium with the soil is upset and the resulting driving force moves more soil water into the root. When no soil water is available, the leaf stomata close and no further decreases in leaf water potential ensue. Because the plant transpires far more water than it uses in growth, it follows that fluxes in different parts of the soil-plant-atmosphere system are generally about equal. Since the driving forces are quite different, flow resistances must vary considerably. The highest resistances are located in the roots and at the evaporating surfaces. In fact, the resistance drop from soil and evaporating surface may be an order of magnitude, while from evaporating surface to atmosphere, it may fall several orders of magnitude (149).

Russell (149) points out that the capacity of a soil to supply water to living plants is not determined solely by its moisture content, but its rate-dependent as well as water-potential dependent and will be strongly affected by the dynamic characteristics of the soil-water-plant system. For instance, knowledge of a given soil-water content does not necessarily indicate whether or not there is

enough water available for plant consumption since what might be adequate at a given transpiration rate could be inadequate at a higher transpiration rate.

Transpiration and evaporation are the same physical process, differing only in the nature of the surface at which the process takes place. For the physical process of evaporation to occur, the following conditions must be present: 1) a vapor pressure gradient (driving force) between the evaporation surface and the surrounding air; 2) an energy supply (usually from solar radiation) known as the latent heat of vaporization; 3) a source of water for vaporization. The first two conditions insure high evaporation rates in deserts where a water source for evaporation is present.

For irrigation purposes there is no point in differentiating between evaporation and transpiration, so the two phenomena are lumped together under the term "evapotranspiration (ET)!" Linacre (180) and others believe that it is better to use the term "evaporation" for both processes since they are identical physically and because it is a less cumbersome term. When water is lost through ET it is known as "consumptive use". This term is probably used because, unlike runoff, the water is completely unrecoverable for human use.

The two crucial problems of irrigation are to determine when to irrigate and how much water to use. Measurement of soil and plant water contents is the solution to the timing problem while evapotranspiration determinations should indicate how much to use.

At high levels of soil moisture, tensiometers, which are manometer devices, yield reliable values of soil moisture tension. In dry soils, computations must be made from the moisture release curve previously constructed for a given soil (129). Unfortunately the laborious gravimetric determination method on soil samples is still the only usable method in many situations (131).

Plant water potential determinations should be much more practical irrigation timing methods than soil moisture measurements. This will be discussed more fully in a later chapter, but it can be said here that no practical field method has yet been developed for agriculture.

Consumptive use or ET determinations are necessary in answering the question of how much irrigation water to apply. There are three basic ways of obtaining ET values: 1) water balance studies, 2) standard measuring instruments, 3) calculations using meteorological data.

In water balance studies, simplification is accomplished by creating situations in which the runoff, subsurface drainage and soil water storage change components

are insignificant, leaving only the ET component balanced off against a known application of irrigation water or rainfall. Some form of this approach is usually accomplished by lysimeter studies. Lysimeters are devices in which a volume of soil, which may be planted to vegetation, is located in a container to isolate it hydrologically from the surrounding soil. Changes of water content in this container may be monitored. This is the only method in which the experimenter is able to determine every term in the water balance equation (161). There are many types of field lysimeter, of which the most useful is probably the weighing lysimeter. These instruments serve a variety of studies including salt balance studies (855) and as checks on other methods of determining ET. They also present many problems, such as whether or not such a limited surface area is representative of a field as a whole, border effects, time-consuming maintenance and operation, and expense. They are a valuable research tool but it is unlikely that they will ever be more than a research tool. Evidently the lysimeter is flexible in concept; Bingham, et al, (854) in studying the water and salt balance of a small isolated watershed, refer to it as a "macrolysimeter".

Of the standard ET measuring devices, only the U.S. Class A pan and a few similar devices have been widely adopted around the world. The amount of evaporation from a standard water-filled pan is determined for a given period of time, which is a very easy operation. In considering evaporation generally, the maximum rates per unit surface area are over water surfaces. Evaporation rates over very wet soil are comparable. As the soil dries from the surface downward, evaporation quickly decreases, and the pan will overestimate ET. How much evaporation from drying soils does occur is an interesting question. Alizai and Hulbert (158) showed that finer soils lose more water, by evaporation, than coarser soils in arid and semiarid regions. Depth of drying is also important, and Ramdas (185) established relationships between evaporation and soil water depth. In dry regions, the amount of evaporation from a surface will depend on the area of the evaporating surface, which limits the accuracy of pans. Empirical coefficients for a given area can be developed for pan data (168, 174), and measurements in many areas have been extremely accurate. Unfortunately, no universal pan coefficient is possible (191). Other ET-measuring devices have severe shortcomings, but cannot be reviewed here.

When we come to the methods for calculating ET from meteorological data, a further complication is introduced, the necessity of devising methods for estimating the contribution of plants. In direct sunlight, plants absorb radiation, usually reaching temperatures greater than the surrounding air temperature. Because higher leaf temperatures create greater vapor pressure gradients at the evaporating surfaces, more evaporation occurs, tending to cool the plant. Different microclimates create a variety of air-plant energy balances. One of the most interesting and important to desert agriculture is the advective process in the leaves as the air

passes over them. This results in transpiration levels greater than the maximum possible rates where direct solar radiation is the only energy source. Advection is an extremely critical effect mainly confined to arid and semiarid regions.

Generally, the ET of a stand of small, scattered plants is less than that of a taller, denser, older stand. The reflectivity of the crop will directly affect the amount of solar radiation absorbed and therefore the amount of energy available for transpiration. Although certain facets of evaporation from plants can be determined, the total surface area of evaporating surfaces as well as other physical properties which would affect plant ET as compared to evaporation from soil or water surfaces are unknown. An important difference is that evaporation goes on all the time while transpiration is strictly a diurnal event.

Thornthwaite (195) developed the concept of potential evapotranspiration (PE) as the amount of water transpired by a given crop when water is not a limiting factor. Since the goal of irrigation agriculture is to remove water as a limiting factor on crop growth, it follows that the PE of a crop is determined by climatological factors. It has been pointed out that PE can be defined more specifically as the evaporation equivalent of the available net radiation, i. e. PE is equal to the ratio $R(N)/L$ where $R(N)$ is the net solar radiation and L is the latent heat of vaporization (59 cal per sq cm). This is an accurate concept usually, but advective effects may invalidate it in desertic areas.

Assuming a close positive correlation of solar radiation with temperature, Thornthwaite expressed the PE as an exponential function of mean monthly air temperature with a day length factor correcting for season and latitude. The advantage of his method is that only temperature data are needed and laborious calculations are unnecessary because of the availability of tables and nomograms. While this is a highly useful method in some contexts, it has not worked everywhere since it is an empirical equation and the constants are simply not applicable in many regions. It has been especially inaccurate in arid regions.

Penman's method (184) is on much sounder theoretical grounds, having been developed from a combination of energy balance and aerodynamic methods. Unfortunately it requires data on air temperature, humidity, wind and cloudiness which must then be used in a laborious calculation. As originally developed, it was based on the assumption that the PE of a mature short crop surface was independent of crop type and similar to the PE of a pure water surface. Surprisingly, these assumptions have proven quite accurate in many regions. In arid and semiarid regions the method gives estimates 50-100% greater than those of Thornthwaite's method. It is often very close to class A pan figures for the desertic regions, and is probably a good method for such areas (165,171,178,199). Budyko, quoted in Lane (179), has developed a similar formula based on energy balance considerations alone,

and there have been a large number of other efforts, many of which are quite accurate in some regions (162, 167, 174, 190).

Following Thornthwaite's work, a number of important empirical methods involving simple calculations and a minimum of meteorological data were developed to help working irrigators in the field. The most widely used is the Blaney-Criddle method (159), developed for arid and semiarid regions of the western U.S. This method uses temperature data and coefficients determined for each different crop. It has been very successful in the region where it was developed but has suffered the geographical limitations of most empirically derived formulae. As the state of the art improves, general equations applicable and accurate everywhere will undoubtedly be developed and empirical formulae will be used less.

The problems of ET calculation and measurement have engendered an unusual amount of theoretical and applied research. Indeed, it has inspired the whole field of agroclimatology, which has in turn put irrigation agriculture on a more efficient scientific basis.

It has been pointed out that the two avenues of water loss in irrigation are through ET and deep percolation. If an amount of water equivalent to ET is applied, any volume of water beyond this amount will probably percolate to deeper soil layers and the water table. It is this water which is the basis of leaching, since it is mass flow and carries along with it any dissolved substances. If we wish to determine how much irrigation water to apply to salty soil, we calculate consumptive use by one of the methods just discussed, calculate leaching requirement by a method to be discussed in a later chapter, and add the two amounts.

The water table is defined as the locus of points at which the soil water is at zero pressure. Below it in what is known as the saturated zone, water is at a positive pressure. Above, where water climbs into the unsaturated zone by capillary forces, there are only water tensions or negative pressures. The amount of water in the "capillary fringe" zone decreases with distance above the water table. Above this there is usually a dry intermediate or unsaturated zone, and above that the "soil water" zone (208). Depending upon the prevailing conditions, the relative depths of the various zones may change or even disappear.

In a uniform saturated soil with a constant water input, the vertical influx may be described by a Darcy-type equation. When water pulses are applied, as in irrigation, water content bulges result, pressures exist in both vertical directions and flow must be described by the equation of continuity. This equation may be solved for volumetric water content over distance at various time intervals and appropriate profiles constructed (204). This is essentially the method used in drainage engineering in order to plot the depth and spacing of drains that must inevitably be

built if any considerable amount of leaching is necessary and waterlogging avoided (203).

Irrigation efficiency is defined as the percentage of total irrigation water supplied to a given area made available within the root zone for beneficial consumptive use by crops. It is to the benefit of the individual to maximize this quantity in arid lands where water is so often extremely scarce and where as in Arizona, 90% or more of the water consumed in the state is for crop irrigation. This prompts much study of the methods of conveyance to the crop field and to the form of application. All too often the conveyance is via dug canals from which much water is lost both by evaporation and by seepage. This results not only in supply problems, but in field waterlogging, which in turn leads to salinity problems. The problem is most acute in regions of slight relief and high soil permeability where canal waters move slowly (44).

Summary

The first part of this chapter was devoted to showing that soil salinity problems develop through the concentration of soil salts in the root zone by evapotranspiration. The salts are extremely deleterious to plants and the problem can be solved only by the application of excess water to wash the salts downward out of the root zone. The problem of leaching, and hence salt control, is therefore part of the overall problem of water control and application in irrigated agriculture.

Water moves through the soil in response to driving forces or potential gradients. The extent of flow is also a function of the soil texture and structure and water content and is termed the hydraulic conductivity. The concepts of water potential and hydraulic conductivity are used to analyze the forces operating on water movement through saturated and unsaturated soils, across plant roots, and through the plants to the evaporating surface. The consumptive use or evapotranspiration is the volume of water used by a crop during growth and without which optimal growth could not take place. This leads to the concept of potential evapotranspiration, or the amount of water a crop would use if water were not a limiting factor. The physical factors that influence potential evapotranspiration are discussed and methods of measuring and calculating are described. The other major "sink" for irrigation water, deep percolation of leaching water to the water table, is also described. The water losses and soil problems attendant in certain methods of irrigation conveyance are briefly considered.

The actual nature and amounts of the salts brought to the root zone are not considered. In the next chapter the origin and species of the salts conveyed to agricul-

tural fields in irrigation waters will be detailed. It will be shown that too much salt in irrigation waters leads to several different types of salinity problems, depending on the types of salt. Analyses of irrigation waters before their application can result in accurate predictions of potential soil problems, as well as the requisite leaching required to control those problems.

III. SOIL AND WATER SALTS: THEIR CLASSIFICATION, LEACHING, AND DRAINAGE

The salinity problem in agriculture is really a composite of several different problems all created by irrigation water solutes. The problems, defined in terms of their effects on soils and plants, include: 1) total dissolved solids (TDS) which presumably act to limit plant growth through the deleterious effect of soil solution osmotic potential; 2) alkalinity, which is chemically a reflection of the amount of exchangeable Na present, and physically a condition of poor soil structure resulting in low soil hydraulic conductivity and aeration; 3) boron and other toxic ions, which are usually present in minute quantities but act directly and poisonously on plant metabolism.

In developing an irrigation scheme, one of the first considerations in planning is the quality of the water supply and the quality of the soils. If the soils were "perfect", then one would wish to be able to predict the effect of the irrigation water on them. If the irrigation water were "perfect", one would wish to gauge its probable effectiveness on a given soil, which in the case of a highly alkaline soil might be nonexistent. In practice, neither are "perfect", and so one is left with the problem of predicting their interactive effects and planning the best possible soil and water irrigation practices.

The first approach to the problem is a set of well-established salinity standards or indices which have the advantage of practical experience and applicability.

Because of the importance and extent of agricultural salinity problems, the U.S. Department of Agriculture established the U.S. Salinity Laboratory at Riverside, California, with a mandate to undertake a wide spectrum of salinity-related research activities. In 1954, "Diagnosis and Improvement of Saline and Alkali Soils" (222) was published, and since has come into worldwide use as a reference work because of its distillation of experience and theory into a thoroughly practical guidebook for the working irrigator. Standards are set for the measurement, classification and reclamation of irrigation waters and saline and alkaline soils. Following its publication, much of the literature in the irrigation-related disciplines has dealt with testing, verification, rejection, and revision of the classification schemes and methods of this influential guidebook (229, 245, 271, 277).

Because the literature is so thorough on the subject of salinity classification,

there is little need here to do other than cite it and mention a few major points.

Waters are classified on the basis of electrical conductivity (EC) and the sodium adsorption ratio (SAR). The SAR can be related to the exchangeable sodium percentage (ESP) of the soil solution by a regression equation and conversion tables or nomograms are available for ease of use. There are four classifications of water on the basis of salinity, ranging from low to very saline, and four classifications on the basis of Na hazard ranging from low to very high. There are thus sixteen water quality classes. Eaton's (241) residual sodium carbonate (RSC) or bicarbonate hazard is simply the difference between the sum of bicarbonate ions and the sum of the Ca and Mg ions. This is essentially another approach to Na hazard, since an excess of bicarbonate-carbonate over Mg-Ca means that with evaporation, all of the Ca and Mg will precipitate out as carbonates and Na will remain as the only important base. It has been variously criticized by Bower (263) and others as has the SAR. Both have advantages and disadvantages.

There are four soil classifications ranging from nonsaline-nonsodic to saline-sodic. The criteria used are the EC of the soil saturation extract, soil pH and ESP.

Of the four, the most difficult soil is the nonsaline-alkaline. Because of the high sodium levels present in these soils they are also called sodic soils. The soil is nonflocculated or dispersed so that it has very little structure. This feature of disaggregation usually manifests itself in a hard, nonporous surface layer, which guarantees extremely poor infiltration, while the generally low permeability levels do not facilitate much leaching.

The soils may be classified morphologically as solonetz soils. The corresponding saline soils are solonchaks. Exchangeable sodium is not the only distinguishing characteristic of solonetz soils. They are also usually identified by a prismatic or columnar B horizon (223). Such a soil results from long-term irrigation with waters of a high SAR. The SAR is the ratio of the Na concentration to the square root of the sum of the Ca and Mg concentrations, and when it is high, Na replaces Ca and Mg on the exchange complexes of the clay soil particles. This illustrates a rather basic fact of life of soils, that the relative concentration of different ion species can be as important as their absolute concentrations. Generally, any water with an SAR greater than 10 will ultimately be deleterious to the soil. In effect, the exchangeable Na levels of the soil will be high and this may be expressed by exchangeable sodium percentage (ESP). By regression analysis, ESP may be calculated from SAR values. Evidently, the exact relationships between SAR and ESP may differ from differing soils. A large number of studies have been undertaken (221, 227) for the purpose of establishing and refining these relationships.

Because there is much evidence that ESP and pH may be correlated, a number of workers have sought to develop this (234, 243, 245, 277). Unfortunately, in tropical regions, the correlations between these parameters decrease with humidity. It is difficult to reclaim these soils because of the problem of moving enough leaching water through the relatively impermeable layers. The introduction of Ca in solution, usually by gypsum, is successful in displacing Na from the exchange complexes when it can be leached through, but this may be a slow process. However, it has been shown (221) that if saline irrigation water is used for leaching, the soil tends to flocculate, making it easier subsequently to leach with high-Ca waters. It can be seen, therefore, why the more common saline-sodic soils do not present as great a reclamation problem as do the sodic soils.

There are few major studies of alkali soils (223). One of the most notorious alkaline regions of Europe is the Great Plains region of Hungary, which suffers from extremely unfavorable topography combined with a high-Na shallow groundwater table. It is no surprise, then, that the Hungarians have pioneered many important studies of sodic soils (223, 313, 316).

Boron is a problem in only a few areas. It is extremely difficult to remove. Unfortunately, the range separating its concentration as a trace nutrient and its toxic concentration is very narrow (213, 214).

The quality classification of the U.S. Salinity Laboratory and others, on both soil and irrigation waters, have generated over the past decade a large number of studies in nations around the world (231, 233, 234, 239, 242, 253, 256). Many workers have pointed out that although classifications are important and helpful, they are by no means definitive. Soil structure, plant tolerance, and other factors affect the ultimate soil reaction to an irrigation water. In general, however, the effects on soils of low quality irrigation waters have been a focus of field research all over the world (226, 227, 230, 238, 261, 279). The results have generally supported the classification criteria.

Given a certain quality irrigation water, salinity prevention through soil management depends on the application of an adequate volume of leaching water. The leaching requirement (LR), which is the percentage of total water applied that is used for leaching, is dependent upon the salinity of the applied water and the maximum allowable salt concentration in the root zone of the crop under irrigation. Since the salinities can be expressed as EC's, LR equals the ratio of irrigation water EC to drainage water EC, which in turn is equal to the ratio of equivalent drainage water depth to irrigation water depth. The irrigation water depth may be expressed in terms of ET and the resulting equation for LR is only slightly more complicated, expressing LR in terms of irrigation water salinity, crop salt tolerance, and consumptive use (222).

This equation is based on several assumptions: 1) that no salt is introduced except through irrigation water or lost through precipitation, which is usually accurate; 2) that there is no other water source, which is usually accurate in arid regions; 3) that the maintenance of salt balance is under steady-state conditions which makes the equation useful only as a long-term average; 4) that there is a close relationship between crop salt tolerance expressed as allowable maximum root zone saturation extract EC and the EC of the drainage water, which is probably usually true within 5-10%. The advantage of the equation is that when the assumptions hold, soil moisture and salt storage, cation exchange reactions, root zone depth, and general soil drainage conditions may all be disregarded as long as drainage permits the specified LR.

Eaton (241, 242, 581) devised a complex quantitative approach to water quality evaluation which includes formulae for leaching and calcium requirements. The salinity component is Cl plus 1/2 sulfate, which recognizes a purported greater physiological potency of Cl. Doneen (239) developed a permeability index which takes into consideration the effects of both Na and bicarbonate on permeability. Others have developed models of leaching without some of the more unrealistic assumptions of the U.S. Salinity Laboratory model (249, 253).

It was shown in the last chapter that a large amount of investigation has been undertaken on moisture flow in saturated and unsaturated soils. Much of this has been on the flow of salt solutions in soil. This uncovers many of the problems of leaching and profile salt distributions. The hydraulic conductivity tends to decrease for mixed salt solutions as the clay fraction increases (333, 334, 352). It is possible that clay swelling will prove useful as an index for relating hydraulic conductivity to solution strength (333).

Miscible displacement is the dynamic mixing of two soil solutions of different composition. Flow in such solutions is complex, and both diffusion and hydrodynamic dispersion (327) are known to occur. The flow properties of many mixtures, one displacing the other, have been elucidated by Biggar and Nielsen's breakthrough curves (321, 336-338). They have developed new concepts of leaching requirements, demonstrating that, depending on soil-water movement rates and method of application, the amount of water needed to replace the accumulated salts depends much less on the salt concentration than the effects of texture and structure on pore geometry (337). Also, after studying the effects of leaching by rainwater under unsaturated conditions, they suggest (321) that leaching of unsaturated soils could produce more efficient leaching by reducing the LR which would then also reduce the subsequent danger of high water tables. Such an approach to leaching seems promising.

Time relations of profile distributions of soil salts have been relatively little-studied. Jackson (301) sampling soluble salt movements in the soils of an

Australian region of shallow saline ground waters, found that the zones of accumulation moved upward during the dry summer and downward during the wet season. In arid lands, the salt movements are probably determined by irrigation schedules interacting with whatever seasonality exists.

Qayyam and Kemper (307) found that the water-holding capacity of saline soils is considerably less than that of nonsaline soils, and that the evaporation from slightly saline soils is considerably greater than from nonsaline soils. The movement of salt solutions through saturated and unsaturated porous media has been the subject of considerable theoretical and laboratory investigation (328, 331, 342, 349, 351).

Kemper has pointed out (332) that the physical model visualized by soil scientists, arrangements in soils below field capacity, is changing. The present view is that the geometry of the water is mainly thin films connecting wedge-shaped volumes. A consequence of this is a partial separation of solutes and solvent ("salt sieving") which has been explained for considerable local subsoil salt buildups (324). Schufle argues (209) that the commonly accepted view, that soil water retention in arid and semiarid lands is temporary because evaporation rates are high may be wrong. Evidence is presented that the water may travel downward in dry soils toward the water table in thin films which are, however, thick enough to carry dissolved salts.

Starting from the miscible displacement work, many have shown experimentally and in the field that various water management practices achieve various degrees of solute movement control (321). Relatively simple predictive theories have been developed building on soil and salt water movement and using much of the recent leaching data (329, 349, 350, 351). The development of computer techniques for analyzing various leaching methods (344-348) appears promising.

These several paragraphs on the movement of salt solutions in soils are presented in an attempt to show that potentially such work can enlarge our understanding of the leaching process and lead to improved irrigation techniques. Unfortunately, no important reviews yet exist which tie this body of work together and relate it to field problems.

It has long been known that fallowing of crop lands tends to increase soil salt content (221). The salts usually concentrate in a thin surface layer (213) from which evaporation took place. This serves to introduce one of the most critical aspects of irrigation salinity. While it is the universal method of reclaiming salty soils, leaching suffers from a potentially lethal weakness. In many areas high leaching volumes lead to a high water table, relatively close to the soil surface. This capillary fringe zone then reaches the soil surface and evaporates, leaving at the surface salts which

had previously been leached downward. This quickly leads to salinity problems. In modern times, whole river basins have simply drowned under salt because of lack of adequate drainage (230).

The only solution is to keep the water table below some arbitrarily workable depth. There are three ways this may be done: 1) maintain an irrigation regime geared to some maximal leaching efficiency so that not enough water percolates downward to significantly raise the water table; 2) pump from tubewells, thereby lowering the water table; 3) engineer an adequate drainage system to carry away the excess leachate. In most cases leaching efficiency is already as high as possible for the prior reason of conserving irrigation water. In other situations, however, this approach has proved effective. Pumping from tubewells (vertical wells) is practiced increasingly in many regions of permeable overlays. It is essentially a mixing process and cannot be practiced in closed basins.

Drainage is the most widely used and effective solution to the problem of high water tables, and there is now a familiar world-wide litany among irrigation experts that we cannot have irrigation without drainage.

The whole subject of drainage, both theory and field engineering, is quite complex. Few readable papers exist for the novice on the theory of the subject (622) but there are many excellent advanced treatments (632-635).

Essentially a drain establishes a surface of zero hydrostatic pressure, at some point below the ground above which water table rise is undesirable. When the water table rises to the drain level, the groundwater merely flows down a potential gradient and is carried out of the area. The drains are a series of open ditches or tiles which discharge into collecting ditches from which the effluent is carried out of the area. Depth and spacing of drains are critical problems. Depth alone depends on evaporation rates, groundwater salinity, irrigation regime and soil water conducting properties. Soil anisotropy and heterogeneity also complicate matters.

Summary

Starting with the premise that salt movement exists only as part of water movement, the components of the hydrologic cycle were covered much as they were in the last chapter, but with difference in emphasis.

The salinity problem is composed of three separate interconnected problems: 1) saline soils, 2) sodic or alkaline soils, 3) soils containing trace amounts of plant-toxic substances, primarily boron. Such soils are mainly created by the

use of irrigation waters of detrimental mineral compositions, so a system of classifying irrigation waters as to their suitability for irrigation has been devised. Electrical conductivity, pH and exchangeable Na contents of both soils and waters are the critical parameters. Saline soils exert their effects mainly on the basis of their salt concentrations. Alkaline soils, which are not well understood, exert their effects on the basis of a dispersed soil structure and possibly by exchangeable Na and Ca levels.

Leaching and drainage are a "you can't have one without the other" duo. Leaching is absolutely necessary in moving excess salts out of the root zone. However, it leads to high water tables and sometimes soil waterlogging. These problems in turn lead to soil salinity problems from the opposite direction, that is, instead of from above, through salty irrigation water, the salts are borne to root zones from below, through salty groundwater. When such problems occur, changes in the irrigation regime or groundwater pumping may be useful ameliorative activities, but the most universally practiced solution is drainage. Some of the conditions and problems of drainage systems are discussed.

In a sense, consideration of leaching and drainage belongs in the chapter on salinity prevention and reclamation, and will be presented there in more detail. First, however, there will be an intervening chapter on plant growth in saline soils. It has already been pointed out that the purpose of irrigation is to provide optimal soil moisture in the root zone, and that salinity is a problem only because it somehow interferes with plant utilization of that water. Consideration of the mechanisms of salt interference with crop growth should lend important perspective to an overall discussion of salinity problems.

IV. SALINITY AND DROUGHT EFFECTS ON PLANTS

It has been suggested by a number of workers (373, 377, 413, 426, 428) that salts effect reduction in plant growth by creating a "physiological drought." However accurate the idea may be, the term suggests affinities between drought symptoms and salt injury symptoms.

The soil-plant-atmosphere continuum is a physical framework of environmental water potential gradients which has been invoked to account for the movement of water in the phytosphere. This concept has been accepted generally, although Philip has demurred on a number of points (395). The two ends of the continuum are the soil and the atmosphere, or more properly, absorption and transpiration. Since they are partially decoupled (385, 390), plant water status is dependent on a balance between them.

Plant growth depends on dry matter production, cell elongation, and cell division. Productivity is a direct function of leaf area, since the greater the leaf area, the greater the amount of actively photosynthesizing tissue. When leaf area is maximal, transpiration is also maximal for a given set of environmental conditions. Plant growth, however, is not directly dependent on total transpiration. It was pointed out in an earlier section that transpiration is a function of the vapor pressure difference between the evaporating surface and the surrounding atmosphere. With high relative humidity the difference would be small and transpiration would be minimal. However, plant water levels would be high and the stomata would not close and thereby limit carbon dioxide diffusion into the plant for photosynthesis.

As soil dries out, hydraulic conductivity decreases with a resulting decrease in soil water flow rates. Root growth is an important plant adaptation which counters the effects of soil dehydration by increasing the volume of soil available for root exploitation. Obviously, crops bred for maximal root growth require less irrigation-water application.

Irrigation scheduling should be keyed to plant water needs, and it should now be obvious that soil water measurements, however precise, are simply not reliable indicators of plant water status. The most effective approach to irrigation scheduling would be direct plant water potential measurement. This would signal, when

it reached some empirically determined value for a given crop, the need for an irrigation. The total amount of water subsequently applied would necessarily be dictated by some kind of consumptive use determination for local conditions.

A number of techniques for plant water potential have been developed (380, 383, 392, 396) but none is readily appropriate for quick, accurate field use. Hellmuth and Grieve (388) modified a dye technique for in situ plant measurements during an ecophysiological study. Hopefully such approaches will soon lead to greatly improved practical methods for agriculture.

Compared to other parts of agronomy and plant physiology, the area of salinity effects on plants is not intensively studied. The modern era may be roughly divided into pre- and post-1962. In the "pre" period, much work had been done on salt tolerance of various crop plants, several hypotheses of salt effects on plant metabolism had been formulated and partially tested, and a great deal of work had been done on the physiology of ion uptake. A number of important reviews cover this work (373, 428, 440, 442, 445, 462, 463, 473-475, 487, 517, 518, 520, 521), a great deal of which is especially pertinent to arid lands. Since that time, much valuable work has been done on salt tolerances of various crop plants (493-507), but the real advances have come in molecular level studies. Unfortunately, no major, broad review has been published since about 1964 (432). Nor have any specialized books on the subject been published in recent times except Stroganov's monograph (377) which was published in the USSR in 1962 and translated into English in 1964. It is a thorough collation of much research and thinking which had previously been unavailable in English. It suffers from a limited consideration of the extant western literature.

In a later chapter it will be shown that, for various reasons, such as exclusively low-quality available irrigation water, a vast amount of irrigated land around the world is more or less permanently salt-laden, but still capable of producing crops. For this reason, it is amazing that probably no nations except possibly Israel and the USSR have major national commitments to the study of salt-tolerant crops. Epstein and Jefferies (442) seem thoroughly justified in noting that, "In contrast to the vast efforts invested in reclamation of saline soils, attempts at breeding for salt tolerance have so far been on an exceedingly modest scale."

The effects of salinity on plants are not always prominent. Salt-affected plants are usually stunted and bear small dark green leaves. Close examination reveals many of the standard symptoms of plant senescence, including succulence and thick, waxy cuticles which result in decreased leaf extensibility. It should be noted that these symptoms are also characteristic of moisture-stressed plants. With increasing salinity, the top/root ratio decreases, leaf scorch may appear and the plant becomes more sensitive to moisture stress. Such plants may differ from drought-

stricken plants by the absence of wilting symptoms (373) and leaf-burn patterns associated with specific ion toxicity.

Presumably the major drawback to plant growth on nonsaline-sodic soils is the deficiency of soil structure which simply makes plant culture extremely difficult. Most plants are tolerant to exchangeable Na on partially reclaimed land (460).

On saline or saline-sodic soils, salts may slow plant growth by three possible mechanisms of action: 1) osmotic effects, 2) specific ion effects, 3) toxic ion effects. These mechanisms are not independent and may often be indistinguishable. This problem has plagued numerous studies of the effects of salinity on plant metabolism.

An almost universal finding is the proportionality of plant growth reduction to osmotic pressure of the growth medium. This has led to the general theory that salts mainly exert their effects on plants through osmotic pressure. Certainly a soil with a high osmotic pressure has a low water potential and there is thus a low water potential gradient between plant and soil. The consequences of this are expressed in the "physiological drought" idea in which it is thought that the driving force is too small for root water uptake. It has been shown that the roots of many plants will take up ions to adjust internal osmotic pressure to the soil environment, thereby restoring the driving forces (403, 419, 424). Although this should eliminate salinity or drought symptoms, the uncomfortable fact is that it does not. Strogonov (377) has argued that there is much evidence contradicting the osmotic theory. There is also much evidence supporting it. Most workers accept the view that osmotic effects, while not necessarily acting alone, are the major components of salinity effects on plants. Certainly the U.S. Salinity Laboratory salinity tolerance ratings are based on this assumption, since they use the EC of the saturation extract which is directly proportional to the osmotic pressure.

Toxic substances are specifically injurious. This group includes boron, lithium, selenium bicarbonate and in various plants, Na, Ca, Cl and virtually any ion present in excess. Single salt solutions are always toxic. When the effects of different salts on plant growth are studied, they are usually added to a base nutrient solution or soil.

Specific ion effects are manifested as nutrient or toxic ion problems. If Ca acts to exclude K, for instance, the problem may be one of a deficiency of K or a toxic level of Ca. In bean plants on saline soils, Ca acts to exclude the uptake of Na, making the growth of these plants possible on saline soils as long as Ca levels are adequate. When they are not, Na is taken up and is toxic to the plant. Much study has been undertaken on the mechanisms of antagonism and active transport lending much insight into the nutrition and physiology of plant cells.

The clear theme of Strogonov's book is the importance of differentiating between chloride and sulfate salinities because of their generally different expressions in plants. Chloride salinity is usually, but not always, the more deleterious. Such concern with anions has not characterized salinity investigations in the U.S. and investigators often seem unconcerned about anionic species. In several recent investigations, differences between these salts have emerged (527, 546).

A number of studies on naturally-occurring halophytes were undertaken in hope of shedding some light on salt tolerance mechanisms. Interestingly, *Atriplex* (saltbush) is one of the few plants which takes up Na from the soil and utilizes it (511). It has even been used to reclaim saline soils by taking up the salts (220).

Temperature increases seem to decrease salt tolerance. This probably results from increased transpiration rates which quickly produce plant moisture deficits. Generally, transpiration rates are lower in salt-affected plants. Pea root resistance to flow increases in saline media even though salts are taken up by the plant and the osmotic driving force maintained (424). The resulting plant water deficit can be relieved by increasing humidity which results in decreased transpiration, allowing absorption and transpiration to equilibrate. It has been suggested that crop growth with saline irrigation waters would be successful in situations where maintenance of a high relative humidity is possible.

The salt tolerance of many plants varies with life cycle stage. Germination has seemed, for many plants, to be a particularly susceptible stage. Bernstein has argued (462) that this may be more apparent than real because of surface layer salt buildups, but there is little doubt that in many species it is real enough. Manohar et al (520) feel that salinity may affect germination by either osmotic or toxic ion effects. The ability of some plant varieties to germinate in saline media parallels their ability to germinate under drought conditions. Varietal differences seem to exist with respect to germination in soils of low osmotic pressure (373, 463), offering some potential for plant breeding.

Of considerable interest is the report of Henckel (quoted in 373) that soaking cotton seeds for 24 hours in 3-4% NaCl induced salt tolerance and increased germination by as much as 30%. Subsequent efforts to repeat this experiment were unsuccessful (373). Recently however, Chaudhuri and Wiebe (516), using Ca chloride pre-treatments, successfully induced significant increases in germination on high NaCl media. After three days, germination of water pre-treated seeds was 8% while the calcium chloride pre-treatment resulted in 90% germination because of a large decrease in seed Na uptake. This would seem to offer a promising area of research in salt tolerance.

In the past decade, much investigation has been conducted on salinity effects

on cellular mechanisms. Protein synthesis and carbohydrate metabolism have been demonstrated to be significantly affected by salinity (528, 530-533, 537, 547, 550). Nieman and Poulsen (422) investigated the interactive effects of salinity and light on plant growth by subjecting bean seedlings cultured on saline media to varying light intensities. Results indicated that the salts suppressed chloroplast development, and that nucleic acid and protein synthesis were abnormally low. Low water potentials had much the same effect on chloroplasts of several other species (381) with accompanying decreased photosynthesis.

Poljakoff-Mayber and others have detected decreases in malic hydrogenase, protein synthesis, amino acid uptake and ATP levels in both salt- and moisture-stressed plant cells (529-533, 541, 543, 545, 549, 550, 552, 553). These stresses seem to interfere with the Krebs cycle and hence the carbohydrate metabolism of the cell. Mitochondria of stressed cells suffer lipid breakdown and increased cytochrome oxidase levels (530, 542, 554). The pentose sugar pathway seems to become more important in stressed cells.

Itai and Vaadia (536) in a very important discovery demonstrated that osmotic or moisture stress decreased the root-shoot translocation of cytokinins, which are hormones produced in the root. Cytokinins seem to play a powerful role in protein synthesis, which would explain the senescence-inducing effects of salt and moisture stress. O'Leary and Prisco (544) treated control and salt-affected bean plants with growth hormones. This treatment did not affect salt-induced root flow resistance increases, but did increase leaf resistance to water loss and fresh and dry plant weights.

The problem of salt-tolerance may become a problem in determining what types of hormone deficiencies have been created, followed by direct application of the missing hormones.

It is still too early to assess the probable agricultural application of much of the work concerning biochemical effects of salt-affected plants.

Summary

Drought stress and salinity stress seem to have much the same effect on plants. It was argued that absorption and transpiration are the critical physiological parameters in drought stress and that critical factors in plant growth are leaf area and root system enlargement in drying soil. Consequently any breeding program for drought tolerance should utilize these parameters.

Salt-affected plants do not have optimal leaf areas but do have low shoot/root

ratios. They demonstrate, along with moisture-stressed plants, a premature senescence syndrome. Three interacting mechanisms of salt action on plants are discussed. One, the osmotic effect, is simply an assertion that physiologically drought and salinity stress are the same.

Possible salt-tolerance mechanisms are discussed wherein it is pointed out that ionic uptake mechanisms and germination in saline soils demonstrate varietal differences which may be potentially improved through breeding. Seed pre-treatment with saline media and irrigation with saline water under conditions of high relative humidity also demonstrate salt-tolerance mechanisms worthy of further intensive study.

Current work on the cellular biochemistry of salt-affected and moisture-stressed plants is outlined. Generally the effects of both treatments are identical, confirming the importance of the osmotic effect in salt-affected plants. The role and suppression of root-produced cytokinins is discussed. In all probability, salinity effects may be traced to interference with the root-shoot hormone translocating mechanism. This may point the way to further breakthroughs in "salinity agriculture".

V. SALINITY PREVENTION AND SOIL RECLAMATION IN AGRICULTURE

Reclamation of saline soils should have the goal of: 1) reduction of TDS in the root zone to a level compatible with crop tolerance, 2) reduction of ESP below ten percent with a concomitant increase in exchangeable Ca, 3) prevention of upward movement of groundwater, and 4) exclusion of waters high in bicarbonate from any part of the system. This should lead to an irrigation program which not only maximizes crop production, but also perpetuates the advantages gained by reclamation.

The literature of land reclamation and salinity prevention is vast. Fortunately, it can be encompassed because in substance there are actually only two main themes: leaching and drainage. The use of either technique is not a completely exact science, so that a great deal of sophistication and expense may be required to apply it successfully. This creates problems in all parts of the world, and in some regions the necessary resources for handling this technology simply may not exist.

Aside from the complexities of application, the leaching process suffers from a number of inherent problems that always complicate its use, and which may in certain situations render it impractical. These include: 1) the necessity for determining leaching curves, which may be time-consuming and difficult (34); 2) the loss of soil nutrients, sometimes at an unacceptably high rate; 3) the differential leaching rates of various ionic species such as Cl and sulfates (11); 4) occasional unfavorable effects on soil structure; 5) the difficulties of integrating the crop watering function with the salt removal function; and 6) leaching water is usually overapplied during irrigation by ponding, which can lead to microorganism development and pore clogging. Probably the most critical factor in the success of leaching is evenness of application so that the irrigated area will not become a mosaic of salty and leached patches.

Drainage installation is almost always expensive. In the case of open drains, the greatest difficulties are clogging with silt or vegetation, less crop land, and decreased field access. Tile drains require heavy capital investment (885, 943), suffer from clogging (615, 629, 651), and require expertise in planning and installation. Errors could be financially disastrous.

Perhaps a more general drawback to drainage is that it leaves the soil far less equipped to deal with drought which in some cases may result in greater consumption of irrigation water.

This approach of discussing the drawbacks of leaching and drainage is taken in order to stress that this technology is far from "cookbook" in application, that it suffers from weaknesses, and that much need exists, therefore, for supportive technological advances.

The fundamental LR formula, the ratio of the EC of irrigation water to the EC of the maximum crop tolerance, implies that if more tolerant crops are planted or less saline irrigation water is used, then more irrigation water will be available for consumptive use since for any given combination of crop tolerance and irrigation water quality, LR is a constant. Salt management, therefore, depends on accurate LR determinations for salt removal, accurate consumptive use determinations for plant growth, and the delivery of enough water to satisfy both demands while providing for adequate drainage or conducting a water application program that minimizes drainage needs.

Depending on the given situation, efforts may be made to decrease salinity levels, prevent salinity buildups, or live with relatively high salinity levels while preventing further increases. Maintenance of any of these alternatives requires some combination of water application, soil management, and agronomic techniques. Having started with the assumption that they must be tied to leaching and drainage, this chapter attempts to outline what seem the most important techniques in use and the most promising for further research and development. Most of the methods are consequences of the considerations of previous chapters, so that this chapter is mainly a synthesis. It is not meant to be an exhaustive listing of all possible salinity prevention or reclamation measures.

It was pointed out in a previous chapter that, for a variety of reasons, arid lands suffer high ET rates, so that with limited available irrigation water, high water-use efficiencies are necessary. In such regions, high water-use efficiencies leave less water available for evaporation and consequent salt buildups. For a given volume of available irrigation water, a larger fraction will be available for LR. This will be especially important where the irrigation waters are of relatively low quality or where the volume of water available for irrigation is limited, which is nearly everywhere.

If the source of irrigation water is surface diversion, lining the canals results in more water delivery to the irrigation site and minimizes field waterlogging with its consequent soil salinization (225, 230). At the irrigation site, high efficiencies of scheduling and application are absolute necessities if high water-use efficiencies are to be attained. Application amounts are determined by consumptive use calculations or measurements. The use of accurate, usable methods for predicting consumptive use are necessary and much research is still needed on this subject.

Application then becomes a matter of timing and skillful water spreading. Timing is probably still more of an art than a science. Soil moisture measurements may help, but as previous discussions have already stressed, soil moisture levels are not truly diagnostic of plant water status because of climatic factors. Probably the general appearance of the plant is useful, in a relatively crude way, to the experienced irrigator. Because the direct measurement of plant water potential has not been practically achieved, it should be one of the primary goals of research in irrigation agriculture.

The timing and amounts of water application also depend on surface permeability and water table height. Up to a point, irrigation efficiencies will be enhanced by high infiltration rates. This is an especially critical factor in sodic soils. The most important methods of increasing this parameter will be covered at several points in this chapter.

It is becoming appreciated that intermittent irrigation water applications to unsaturated soils often lead to much higher irrigation efficiencies than application to saturated soils by such methods as ponding (321, 339). Although such research is tentative, it is felt that it should be intensively pursued because it could conceivably lead to considerably improved water economies.

Runoff or tailwaters from surface irrigation usually differs little in quality from the originally applied waters and should be recycled if significant amounts are involved (800). While the LR must be considered "lost" for crop-growing purposes, it may often be postponed until the crop-growing season is over. When possible, such a deferral lends itself to high water-use efficiencies.

A general rule is that one foot of irrigation water per foot of soil depth will leach about 80 percent of the soluble soil salts (34). If it is necessary to leach four-five feet of soil, the LR may exceed the available amount of irrigation water or the water table may rise to generous levels. The practice of mulching with thick surface mulches limits the rates of upward salt and water movement and often greatly improves infiltration rates and leaching efficiencies (701). Fanning and Carter (692, 694) used a 3-ton/acre cotton burr mulch which facilitated reclamation of a saline soil by rainfall and found that cotton burr and chopped shrubbery mulches were equally effective in improving salt removal and leaching efficiencies of a periodically sprinkled surface-mulched saline soil as compared to a flooded or periodically sprinkled bare soil. Benz et al (688, 708) induced significant reductions in the salinity of fallowed soil under straw mulches and subsequently increased wheat production by 15-20 bushels/acre. A wide variety of mulches have been used, including gravels and plastics (701, 704, 712) that have greatly facilitated reclamation and increased the leaching efficiencies of many soils.

Sanding (693, 698) is a form of mulching in which a 10cm layer of washed sand is spread over a flattened saline soil layer. The soil subsequently produced good irrigated crops, even of the salt-sensitive variety. The results may be explained by an almost complete suppression of soil water evaporation by the sand layer (697).

Because of sand transportation costs, the practice can probably prove practical only in regions not more than 10km distant from a sand source. But this is still a potentially important technique for vast areas of coastal deserts around the world.

A general assumption of LR formulae is evenness of irrigation water application. The continuing development of application methods has resulted not only in more even water application, but possibly also in more effective use of lower quality waters.

Border, furrow, and flood irrigation are all common and need not be discussed here except for the observation that they can be extremely wasteful of water and that with decreasing water quality these methods require a great deal of skill to prevent soil salinization. Sprinkler irrigation introduces the advantages of very even application at controllable rates with the desirable microclimatic alterations of soil surface cooling and local vapor pressure increases (655, 659). The major disadvantage is high cost, although some claim that it is not really excessive (668, 671). Irrigation efficiencies of 85 percent are attained in comparison with the 45-65 percent range in furrow irrigation. It has been claimed that yields are 15 percent higher (664). When water of low quality is used, foliar damage is a danger, particularly with fruit crops (658).

The use of low quality irrigation waters has become a major problem in arid land irrigation. The critical challenges concern the upper limits of salt concentration and the problem of application leading to further concentration increases after evaporation. Boyko (718, 719) claimed that water as saline as ocean water could be used for high quality vegetable crop irrigation if they were grown in extremely permeable sandy soils with no clay fraction. He argued that, given the right soil, the water quality limitation concerned ionic ratios, not absolute concentrations. His theory of root water uptake from subterranean dew formation has confused plant physiologists (57). This would be irrelevant if his methods had resulted in economic irrigated crop production, which unfortunately they have not.

While the upper limits of crop tolerance to total salinity vary greatly with respect to local conditions, crop deterioration with progressively increasing salinity levels is well-known and universal. Recently, Goldberg et al (662, 663), have obtained surprisingly high yields of intensively-grown, high-income vegetable crops with waters of over 3500 ppm salinity levels. This was accomplished using "drip" or "trickle" irrigation, where the water is laterally spread on the irrigated surface from a relatively close-spaced grid of outlets from which it is discharged at virtually zero pressure. The method demands very frequent irrigations so that the soil is constantly at or above field capacity, and frequent applications of nitrogen fertilizer along with the irrigation water. A high soil matrix potential is thus maintained and salt accumulation is prevented.

This method has been used in two arid regions of Israel where the soils are coarse-textured. Yields compared well with those obtained from sprinkler irri-

gation. A rather definite treatment effect was seen. The low salt (400 micromhos/cm) and the saline (3000 micromhos/cm) treatments gave almost identical yield with trickle irrigation, while the classical yield decrease with increasing salinity was noted with the sprinkler irrigation. Should this method prove generally workable, an immediate consequence would be a shift in the direction of plant salt tolerance boundaries to much higher salinity values. The only obvious drawback of the method is the generally limited range of soils and climates in which it has been used. Nevertheless, it is felt that this is an unusually promising approach and may lead to production breakthroughs in some irrigated areas.

Both mulches and improved water application systems facilitate efficient infiltration and decrease surface salt accumulations.

Soil salinity measurement has not been listed generally as a mode of reclamation or salinity prevention, but it may assume that role increasingly as the state of the technology improves. Richards (745) developed a soil salinity sensor of parallel plate configuration using platinum electrodes, a considerable improvement over earlier ceramic unit electrode probes. Reicovsky et al (743) seem to have overcome the external field problem in developing an electrical conductivity sensor for both saturated and unsaturated soils. More accurate methods are continually being introduced. Obviously more immediate and accurate soil salinity measurements will expedite the use of more finely-tuned reclamation and salinity prevention practices.

Myers et al (741), using infrared radiometer measurements of cotton plants growing on saline fields, have extended salinity detection into photogrammetry and remote sensing. Calibrating leaf temperature with different salinity ranges, they concluded that salinity causes measurable plant physiological changes and that various environmental factors such as soil salinity and soil moisture, which influence growing cotton plants, can change from year to year. Remote sensing methods may determine the existence of critical salt buildups long before they become evident in reduced crop yields. Ameliorative methods can then be initiated more quickly.

So far there has been no consideration of the problems of low permeability sodic soils. Excess Na salts must be leached out while at the same time exchangeable Na is being replaced with exchangeable Ca. Since permeability is so low, leaching is extremely slow, at times almost impossible.

The use of soil amendments is the most widespread method of introducing exchangeable Ca (674-686). The most common amendments are gypsum (hydrated Ca sulfate), lime (CaO), elemental sulfur, and sulfuric acid. Bohn and Westerman (676) make the interesting suggestion of using the sulfur dioxide effluents of the mining industry in the southwestern U.S. to create a sulfuric acid industry. The sulfuric acid would be added to irrigation waters to remove bicarbonate ions and help alleviate a serious sodic soil problem in that region. Whether such an industry could prove economically viable is not known, but there is ample precedent for its creation. A possible drawback to the plan could be possible critical buildups of soil

sulfate. The suggestion, however, contains much merit because sulfuric acid is a superior amendment in many ways, and because this would link irrigation agriculture with an industrial process.

Another such link is also possible. Soil polysaccharides and polyuronides, through their decomposition and binding action, promote the formation and stabilization of soil aggregates. This property would seem to qualify them for a role in the aggregation of dispersed sodic soils. Much work has been done on the subject in Puerto Rico, using bagasse and molasses, waste products of the sugarcane milling industry. Weber and Van Rooyen (711), working in an arid part of South Africa, compared the ameliorative effects of molasses meal to more commonly used sodic soil amendments. Results proved its long-term effectiveness and superiority. After a relatively short period, soil physical properties were drastically improved, while TDS, pH, and SAR were unchanged. It was felt that polysaccharide aggregating powers were much stronger than Na dispersing powers. The economic efficiency of both the molasses industry and irrigation agriculture would probably both be enhanced if this method fulfills its promise.

Deep plowing or subsoiling increases permeability and breaks up the prismatic B horizon, mixing it with the Ca-bearing lower layers (695, 700, 707). This method has been extensively used, in some areas of both the U.S. and the U.S.S.R., quite successfully. In the saline-alkali soils of the Casa Grande Valley of Arizona, deep tillage opened up the soil enough to permit easy water penetration and subsequent reclamation without the use of amendments (703). Cairns (691) accomplished much the same thing with deep plowing to 18-24 inch depths in solonchic soils of Alberta. Because of the heavy equipment needed, the method can be quite expensive.

Reeve and Doering (727, 728) demonstrated that soil-flocculating properties of saline waters can be used to increase the permeability of sodic soils so that leaching with amendments can proceed. The "valence dilution" method involves leaching with waters high in Ca, Mg, and TDS so that the salinity flocculation effect moves forward and exchangeable Ca is increased.

A rather esoteric, but possibly very effective, method has recently been resurrected and improved. Puri and Anand (706) in 1936, experimented with the passage of DC current through alkaline soil solutions with good results in both the laboratory and the field. As soon as the current was turned on, percolation rates increased, which seems more like electroosmosis than electrodialysis. However, they recovered NaOH and claimed this could be an economic by-product of the method. Apparently it excited very little interest until recently when Gibbs (696), using box-like blocks of saline-alkaline soils, passed currents through them, promoting dissociation of Ca carbonate which increased the exchangeable Ca and moved Na toward the cathode. In the U.S.S.R. where this method has generated wider interest, Berezin (689, 690) passed currents through almost "worthless" or impermeable solonchic soils in Azerbaijan, with the resulting soil and water movements improving permeability and expediting leaching considerably. He claimed that lower density currents were most effective and the power costs during amelioration low. It would seem that more field testing of this method is justified, particularly from the point of view of economic feasibility.

It was pointed out that the LR can be influenced by either changes in the irrigation water quality or changes in plant tolerance to a given root zone salinity. Sometimes the two methods can be combined by choosing crops appropriate to a given leaching method. Rice is often planted early in reclamation projects (735-737) because the ponded leaching water would drown out other crops. However, the method is not always as desirable as some have claimed because land surrounding the rice field often becomes more saline. Judicious crop rotation, keyed to cyclic soil profile salinity movements, has long been a method of living with salinity problems while they are gradually ameliorated. Asghar and Khan (731) described such a rotation scheme for rice, wheat, sugar cane, and cotton-senji whereby soil salts moved from eight feet in depth to five, in a region of the Indus Valley.

In describing agronomic approaches to dealing with the soil salinity problems, it was shown that this promising avenue has been much neglected. Working from the plant salt tolerance end of the salinity problem will probably generate the future major breakthroughs in productivity under saline conditions. A note of caution must be sounded, however. Experimental information on crop salt tolerance has usually been obtained under optimal growth conditions with respect to a wide range of critical environmental parameters (34). Further, there is evidence that individual plant salt tolerance may vary with growth stage, climate, or soil moisture. Seed germination may be a particularly sensitive stage.

On the basis of arguments from the last chapter, research in the following methods of increasing plant salt tolerance is urgently needed because it is felt that they contain great promise:

- 1) saline water pre-treatment of seeds (373, 516)
- 2) massive plant breeding programs for increased salinity tolerance under various environmental conditions and growth stages
- 3) hormonal foliar application (544)

Both physiological effects and the possibilities of economic hormone production must be assessed.

If relative humidity is close to 100 percent, plant transpiration will be close to zero, since it is a function of the vapor pressure difference between the mesophyll evaporating surfaces and the surrounding atmosphere. Assuming that adequate light reaches the plant for photosynthesis, carbon dioxide is present in normal atmospheric concentrations, and adequate nutrients are available, plant growth should proceed with very little water consumption. This leads the way to techniques which differ significantly from current arid land irrigated agriculture. The development of controlled climate structures such as plastic greenhouses would enable plants to take advantage of the one non-limiting desert resource, sunshine, while eliminating the high water requirements usually so characteristic of arid land agriculture because of the high evaporative demand.

This has been done by the Environmental Research Laboratory of the University of Arizona, at desert seacoast locations in Sonora, Mexico, and Abu Dhabi on the Persian Gulf (746, 748), and the results are most encouraging. The water for these facilities comes from desalination projects. However, there is no reason why such a facility cannot be adapted to any arid region with some water sources, even low quality water sources. Goldberg et al (662) point out that their drip irrigation method is well suited to such conditions. Additionally, the use of plastic mulches increases productivity enormously in the greenhouses (747). Possibly the integration of direct plant hormone foliar spraying into this type of crop raising could further potentiate productivity.

This example should point out that improvements and innovations in dealing with salinity problems should not only be dealt with singly or in isolation, but should be used in various combinations and integrated into broad-based research and development programs. It is certainly difficult to understand why the U.S. and other countries are not channeling into this type of research even a fraction of the research budgets that now support conventional agriculture.

Finally, as Jewitt (220) points out, soils often, inexplicably, defy all rational attempts to reclaim them. Thus it should be remembered that it is probably inevitable that some reclamation attempts, no matter how well conceived, will fail.

Summary

Leaching and drainage are the backbone of salinity reclamation and prevention techniques. It was stressed that they permit the existence of irrigated agriculture in many regions, particularly where saline irrigation waters prevail, but that they contain their own inherent difficulties that contribute to system instability.

No effort was made to review in depth or to describe exhaustively all the methods used in agriculture to deal with salinity problems. Rather, those touched upon were those which it is felt are the most effective or contain some prospect of progress in achieving high effectiveness. These include irrigation timing and consumptive use determination, canal lining, methods of increasing infiltration rates, including the use of mulches and new water application systems, use of low quality waters for irrigation, soil salinity measurements, sodic soil treatments, agronomic methods of utilizing plant salt tolerances, and controlled environment high humidity agriculture.

Drainage methods were not considered. Childs (623) has written: "During the last thirty years drainage theory has developed more rapidly than its application." A number of excellent references are furnished and it is felt that in the amelioration of salinity problems there is little more that can be expected from drainage than the state of the art is already permitting.

There seem to be three directions in which solutions to salinity problems are trending:

- 1) those that improve on existing methods. This group includes mulching, intermittent leaching of unsaturated soils, sprinkler irrigation, and improved salinity measuring methods.
- 2) those that improve so much on existing methods that they may constitute major breakthroughs in production. These include trickle irrigation with saline water, and crop spraying with plant hormones.
- 3) those that improve existing production and involve such basic changes that they may alter the fundamental nature of arid land irrigated agriculture. The candidate here is the controlled environment plastic greenhouse.

In the final chapters, major chronic shortcomings of arid land irrigation agriculture as it is practiced today will be pointed out. This will serve to emphasize the importance of point #3, above.

VI. WATER QUALITY AND THE TOTAL DRAINAGE BASIN

The tendency of modern science to fractionate rather than synthesize seems nowhere more manifest than in the choice of the root zone or crop field as the basic unit of interest. While this choice has much to recommend it, the neglect of the total drainage basin as an object of study has been puzzling. The same principles of salt and water balance apply to the drainage basin, and most of the data necessary for balance studies are available. The work of Pillsbury and Blaney (753) did much to stimulate thinking about basin-wide salt balance studies, and more recently the U.S. Environmental Protection Agency published a study (754-758) which is probably the most thorough treatment yet undertaken of salt problems in a single river basin.

It is rapidly becoming an article of faith in modern environmental science that nothing operates in a vacuum, which is a way of saying that some consequences of a unit operation are always externalized. An overall view of the drainage basin must consider both surface and groundwater, salt sources, salinity variations in time and space, the various components of the drainage basin as both sources and targets of salinity, and, when necessary, approaches toward integrated, basin-wide ameliorative measures.

Russell (65) describes a river which is flowing through an arid region and holding in solution Ca, Na, Cl, sulfate and bicarbonate ions. Because of the high ET, the salts will become progressively more concentrated and Ca carbonate will first precipitate from solution. Further downstream, after more evaporation, Ca sulfate precipitates next, leaving a solution of Na salts. Under some conditions, when evaporative levels are high, the Na salts will be left as a white efflorescence on the soil surface. This example brings out three critical properties of arid zone rivers: 1) progressive salt concentration with distance downstream, 2) the importance of relative salt solubilities, 3) the tendency for Na salt concentrations to increase in a downstream direction while Ca salts decrease (771). Studies of salinity-contributing factors in river systems indicate the importance of climatic phenomena (779, 780). Downstream, the combined effect of ET and irrigation return inputs is usually the critical salt-concentrating factor, although various other salt sources may also exist.

Salt accrual in a river basin may be by salt-loading or salt concentrating. Salt loading is an increase in the absolute amount of salts by input from various sources.

Salt concentrating is an increase in relative salt levels, mainly through water loss by evaporation. Salt sources may be either point sources which are easily identifiable and controllable, or diffuse sources spread over wide areas and not readily controllable.

In assessing the salts of natural waters which are used for irrigation, a natural starting point is identification of the many and diverse sources of these salts. The ultimate source of all salts is the process of rock-weathering (769, 771, 783). The redistribution of the products of the weathering process over time now furnishes a number of secondary sources as well as the still-operative primary source.

A major secondary source is the ocean. A form of salt pickup in arid lands often neglected is the accretion of airborne or "cyclic" salts. While this is obvious in coastal regions, it is also an important salt source in some regions at distances inland (762, 764, 773). Eriksson in a classic review (769) points out that some major evidence for this process is the presence of large amounts of chlorides in arid regions that cannot be accounted for by weathering processes. The salts, mainly NaCl, are taken up from ocean spray and form aerosol clouds. These invisible clouds are continuously present at various heights above the Earth (765). Salts are removed from the atmosphere by rain and by collision with ground structures such as plants and buildings. According to Cassidy (764), there is evidence that these aerosols, in certain regions, are 1000 times more important in Cl deposition than rainfall. In certain places they have altered vegetation and led to the paradox of salt problems in high rainfall areas. In parts of the deserts of Iraq and Iran, there is an accumulation of 1 kg/ha from this source, which is small, but over 10,000 years would result in accumulations of 1 kg/sq m (237).

Surface streams in arid regions pick up salts by natural leaching and weathering of rocky outcrops containing soluble salts (771, 780, 816). This is salt-loading from numerous small diffuse sources, but the integrated uptake from the entire drainage basin may be enormous. In some regions, the sources may not be small or diffuse. The southern High Plains are underlain by thick salt layers, derived from an oceanic past. In the basin of the Red River alone, several tributaries pick up 2500 tons/day (759).

Thermal and mineral springs are extremely significant salt contributors to many surface waters (755, 842, 868). Such point sources constitute 23% of the salt load from natural sources of the Colorado River drainage reaching Hoover Dam (754).

Gibbs (771), on analyzing the chemical data for many surface water bodies around the world, including oceans, concluded that it was possible to distinguish between waters on the basis of salt-accretion mechanisms, which are, at least in part, reflections of climate. The waters of arid region rivers are characterized by the evaporation-crystallization process, in contrast to the atmospheric precipitation

or the rock dominance mechanisms of other regions. The resulting high salt concentrations are dominated by Na and Cl and the precipitation of Ca carbonate. Examples of such rivers are the Jordan River of Israel, the Pecos, and the Colorado Rivers.

The properties of rapid water turnover and salt-concentration downstream, typical of surface waters, are balanced by the groundwater properties of long retention times and salinity increases with depth, though neither is an invariant property. Just as with surface water, climate influences salinity, and the salt levels of arid region groundwaters may be extremely variable over both short horizontal and vertical distances (845). The salinity ranges of groundwaters are much higher than those of fresh waters. A number of factors contribute to this high variability.

In the case of shallow aquifers alone, retention times average about 200 years as compared with about nine days for stream channels (842). Such retention times are sufficiently long for the establishment of most chemical equilibria. It then follows that the critical factors in the creation of groundwater salinity are: 1) the nature of the aquifer rock, 2) retention time, 3) mode of aquifer recharge, since infiltration from rainfall or surface waters can lower salinity levels while underground evaporation may have opposite effects. In the recharge process, natural leaching as well as irrigation-connected leaching may bring high levels of salt-loading into the aquifer, usually at the shallower levels.

Fresh water layers may overlies denser salty layers. Because of their tremendous inherent structural variability, desert aquifer groundwater patterns are extremely complex. Hydrogeologic patterns in arid lands normally include a recharge area in mountains and a discharge system in lowland areas with an often intermediate area of lateral discharge (835). Many local geologic, physiographic and climatic factors are superimposed on this basic system, and local study of such factors leads to much insight into man-made contamination problems which are usually concentrated in the lowlands. This includes most irrigated agriculture which is mainly in valleys or basins.

A relatively new and potentially widespread source of groundwater mineral pollution, which is mainly a consequence of human activities, is salt intrusion into coastal aquifers (760, 767, 778). The marine inflow is usually the result of groundwater overdraft by agriculture or municipalities. It has become a serious problem in southern California, Florida, and India. In all probability, the problem will spread and intensify in many regions.

We have seen that natural weathering, leaching, and evaporation, sometimes in somewhat different forms, are the important salinization factors in both surface and subsurface waters. Further, such events as movement of salty underground water

through springs to surface waters and leaching of salty surface waters downwards illustrate the enormous extent of crossover existing between the two hydrologic compartments.

It follows that the large amounts of salts generated by human activities will find their way into both surface and groundwaters. The effects are usually obvious immediately in surface waters, which can lead to a heightened public awareness of the problem. The effects on groundwater salt levels can be enormous and of potentially great social consequences (842), but not so immediate because of long retention times.

Essentially, water uses lead to salt buildup, thereby limiting potential reuses. The reuse chain is in many respects similar to a biological food chain, with salt concentration analagous to energy losses. Just as with the food chain and its energy losses, the water reuse chain is limited in length, because salt levels soon build up well past the point of potential value to any user (714).

Irrigation is the biggest water-using process in modern society (751, 940, 947) and the largest man-caused contributor to salt buildup (225, 794). Irrigation leaching results in drainage water two-eight times more concentrated than the applied water. It is difficult to overstate the massive contributions of irrigation to both surface water and groundwater salinities (278, 794, 842-844). Meron and Ludwig (837) estimate an irrigation contribution of about 60 percent to the groundwater salt buildup in southern California as compared to about 40 percent derived from general urban activities. Of the Colorado River, Holburt and Valentine (868) say that "... the primary activity in the River's salinity is the application of water to lands for irrigation and the return of the salts contained in the diverted water to the River, together with those salts picked up by the return irrigation waters." Of the one million tons of salt passing Hoover Dam each year, over one-third is donated by irrigation return flow. Wilcox (278) maintains that the doubling of the annual salt load of the Rio Grande passing through Ft. Quitman is mainly the result of irrigation.

Public health standards dictate a desirable upper TDS limit of 500 ppm for municipal drinking water, so it is obvious that the effects of irrigation drainage water on municipal supplies are not beneficial. Correspondingly, because the TDS of treated sewage waters may run as high as 500 ppm, this source could in theory make a significant total contribution to river salinity, particularly if several large cities are donating sewage effluent. However, in the Yakima region, the contribution of salts from treated sewage waters was insignificant compared to the contributions of irrigation return flows (805).

Other man-caused salinity sources include oil-field brines, manufacturing processes, mining, and abandoned wells. They all essentially constitute identifiable point sources.

It is possible to apply salt-reducing techniques to the drainage basin. The most important methods are:

1) reduction of natural salts, by:

- a) elimination of point sources: natural springs or seeps, diversion, evaporation from collecting basins (868)
- b) reduction of pickup from soluble salt formations: paving of stream-beds (873), diversion of stream from the formation (868, 754)

Neither of these methods is always possible or economically feasible, but where they can be used, as in the Colorado River drainage basin, their contribution to salt reduction can be substantial (754, 757). Similar programs are necessary in Israel because of the salination of Lake Tiberias by mineral springs (752).

2) river bank treatment, by:

- a) channel straightening and deepening: channeling-stream sediment load and turbulence would both decrease, which in turn would decrease salinity levels (753) in some way not well understood or quantified; would reinforce the above effects and lower the amount of water accessible to phreatophytes
- b) general phreatophyte control: these plants are thought to be immense water consumers in the southwest, and thereby help to raise river salt levels (859). Important river improvements such as those undertaken for the Central Arizona Project include phreatophyte control programs. There is little quantitative information on their water consumption levels.

3) drainage, by:

- a) horizontal drainage: Pillsbury and Blaney (753), in considering a flood plain, argue that it is axiomatic that alluvium is heterogeneous and anisotropic, and that as one proceeds downstream, the ratio of horizontal to vertical hydraulic conductivities, always greater than one, steadily increases. Horizontal subsurface drainage is thus important in maintaining basin salt balance.
- b) bypasses: upstream, drainage effluents can be diverted back into the main channel, but as the salinity of the river increases, this becomes less desirable because downstream agriculture quickly becomes marginal. An ideal solution is the construction of a separate drainage

channel that would prevent any mixing and empty directly into the ocean or an evaporation basin. The San Joaquin Master Drain, which would carry irrigation waste waters out of the San Joaquin Valley and empty them into San Francisco Bay is an example of this. So far the channel has not been built because of the environmental controversy it has generated concerning San Francisco Bay (924, 926). Ebert has proposed (793) a similar tile drain for the increasingly salty Murray River Valley of Australia. Increasingly in the future, such bypass drains will probably be built when feasible. Even a small bypass around Mexico's Morelos Dam has proved moderately successful (911).

- 4) groundwater salinity abatement: In the long run, this may be one of the most critical irrigation-related salinity problems. As surface waters deteriorate downstream, the groundwater basins they recharge also deteriorate. This, together with irrigation leaching, is introducing vast amounts of salt into groundwaters. Partial solutions to the problems include:
 - a) pumping out of the groundwater basin: The water table is lowered by the pumping of relatively saline groundwater. In the San Joaquin Valley (869) the water is discharged into the irrigation canals, mixed with the higher quality gravity supply and reused. As Christiansen et al observe (857), this is a fine solution for the drainage problem, but does very little for Valley salt balance. In the Wellton-Mohawk District of southwestern Arizona, pumping is a form of reclamation as well as water table control (801). The drainage water is so salty that it has created problems with Mexico (see next chapter). Pumping is also being used more extensively as a control measure in the waterlogged Indus Valley of West Pakistan (976, 978).
 - b) maintenance of an intensive network of observation wells so that the pressure and direction flows in a basin can be determined
 - c) development of water table and soil salinity maps to identify the gravity points of salinization (849)
- 5) managing river basins with the sequential use established according to relative purity requirements and pollution potential (753, 799). Probably not usually practical because water is only one component of the total resource mix that determines where users locate
- 6) elimination of man-caused point sources by:

- a) irrigation: there are two avenues of approach in reducing or eliminating salinity contributions from this source. One is higher water-use efficiency: this probably becomes increasingly difficult downstream as the saltier water available for irrigation creates progressively greater LRs, even with more salt-tolerant crops. The other is usually considered somewhat radical: curtail new irrigation developments and possibly even eliminate some of those already in existence

- b) other: elimination of other point sources as feasible, as examples elimination or cleanup of industrial effluents and injection of oil well brines into deep strata. A point source not so amenable to solution is reservoir evaporation, which accounted for 12 percent of the salinity in the Colorado River at Hoover Dam under 1960 conditions (754).

Nitrates have not been mentioned as salt problems until now, because they are not a problem to agriculture, except possibly for certain vegetable crops. However, they are a public health problem when concentrations rise above 45 ppm in municipal waters (903). Although there are many possible nitrate sources, irrigated agriculture has been considered one of the possible major contributors because of the leaching process and resultant movement of fertilizer nitrates into groundwater. Groundwater concentrations have risen above safe levels in some parts of the San Joaquin Valley (891, 903, 904, 906). Municipal sewage, septic tanks, industrial waste waters, and fertilizers have all been implicated (903). In the Fresno (California) area, hydrographs indicate sewage treatment plants are the main source. In the arid Delano area (898), nitrate increases were closely correlated with rises in the water table following the onset of importation of water from northern California. It appears that the rising water table solubilized fertilizer nitrate in the soil. A study on the upper Rio Grande shows that great increases in the use of nitrate fertilizers have taken place over the last 30 years but have not been accompanied by higher river nitrate level (896). The problem is complex and likely to get worse because of intensifying fertilizer use.

There are a number of water-conserving or water-producing techniques that have been much discussed, particularly in the popular media, but which so far have gone unmentioned in this paper. These include antitranspirants, evaporation-suppressing surface films for reservoirs, interbasin water transfer, seawater desalination, and rainfall production by weather modification. Because it has been considered virtually a panacea for water shortages by a wide range of both well- and ill-informed observers, the omission of seawater desalination may in particular seem strange to many.

A consideration of the drawbacks and potentialities of these various proposals could easily fill volumes. For the purpose of this paper, it will have to suffice to consider a small number of critical failings which would seem to rule out any of these alternatives for at least the near future.

It is doubtful that anyone familiar with the research to date on antitranspirants or reservoir evaporation suppressants would consider them likely to have an appreciable impact on national water resources. A revolution in the state of the art of either is probable but does not presently seem possible. As the lack of cure for the common cold and frequent incorrect weather forecasts show, modern technology has certain practical, if not theoretical, limitations. Probably the correct weather forecasts as a percentage of all weather forecasts is much greater than the percentage of probably successful attempts at weather modification. The simple fact is that despite great promise, artificial rainfall production, like antitranspirants and evaporation suppressants, simply has not worked. In the case of weather modification, the achievement of the technological goals may not necessarily be crowned with social acceptance. It has not yet been shown that any particular region can be given rain without taking it away from some other region. The social bitterness and even warfare that might result when certain regions suffer droughts while others are benefitting from induced rainfall will surely not await conclusive demonstrations of cause-and-effect.

In the case of interbasin water transfer, existing technology indeed seems adequate to the task, but sociopolitical considerations on both national and international levels may constitute immovable barriers to many proposed projects. A major case in point is a proposed transfer of water from the water-rich Columbia Basin to the Colorado Basin. Political opposition and resentment have been steadily building in the Pacific northwestern states. Their congressional representatives succeeded in passing a bill limiting any action for a decade solely to feasibility studies. It is a fair bet that the region will soon have acquired enough political power to permanently thwart the southwestern states. A gigantic proposed transfer of water from Alaska and Canada (NAWAPA) will involve such enormous capital and planning considerations that it will probably take a generation to build. Even this may be stalled, however, by blossoming intransigence on the part of Canada.

The U.S.S.R. has encountered a large amount of internal opposition to its plan to divert the Arctic-flowing Ob', Yenesei, and Pechora Rivers to the semiarid central Asian region around the Caspian Sea. Most of the opposition stemmed from the possibility of world-wide climatic changes. South Africa and Australia have both achieved some interbasin transfers, but on a very small scale compared to the proposed NAWAPA. While such transfers may be created on some small-scale national levels, it is difficult to envision them underwriting extensive new irrigation developments around the world in the near future.

The volume of literature on seawater desalination has probably grown exponentially in the past several years because there is scarcely a single country with the technological capabilities that has not extensively investigated its possibilities. Certainly those countries with large cultivable tracts of arid lands have found it especially interesting.

A number of difficult problems such a technology poses have not been adequately considered. Starting with the fact that irrigation agriculture far outdistances any other human activity in water consumption, one may compare water needs for the production of various diets. High protein western diets require about 4.5 af/year while low protein eastern need about 1.5 af/year. Hoare (71, 72) calculates that at current rates of power consumption, and using atomic energy for seawater distillation, equivalent amounts of energy needed for production of this much water would be about 16,000 kwh and 50,000 kwh for eastern and western diets. Currently, average per capita consumption of electric energy in the west is 2000-4000 kwh/year.

It would certainly appear that only a very few wealthy regions could ever afford to produce food at such costs. Another problem that few have considered (927) is the problem of disposal of the enormous amounts of brine produced by the desalination of so much water.

It seems fairly certain that such water can be produced economically for municipal and certain types of industrial consumption and probably for specialized types of agricultural production such as greenhouses. It seems unlikely that it can be consumed economically by plant growth, much less for leaching salts in soils. Since the availability of large amounts of cheap, desalted water is a necessary condition for Pawley's theory (33) described in Chapter I, that the Earth can feed enormous human populations in part by irrigation of deserts, it would appear that the theory may never be put to a test.

In summation, it would be folly to ignore the record of modern technology in the solution of such difficult problems by asserting that they will never be solved. However, it is also folly to plan huge irrigation projects dependent on presently nonexistent or uneconomic or socially untenable technologies. That is why this paper takes the position that the most likely "source" of more water for irrigation is elimination of low quality water sources in river and groundwater basins as far as is possible, together with protean concentration on high water use efficiencies.

Summary

Salts and salty waters, like almost everything, must originate somewhere. The sources of salts that eventually enter rivers may be roughly subdivided into diffuse and localized (point) sources. Salts from atmospheric precipitation and natural weathering with subsequent concentration are examples of diffuse sources difficult or impossible to control. The point sources, mainly mineral springs and human activities, are identifiable and usually more controllable. An exception is irrigation return flow, about which it is basically impossible to do much except dilution with fresher waters if they are available, or the construction of a bypass drain. The bypass drain method may, in the future, become an important method of "desalting" downstream regions of heavily irrigated drainage basins.

Groundwater pollution, either directly or indirectly by leaching water, is probably a much more serious problem than most people presently realize. This could become one of the greatest issues of irrigation agriculture.

The nitrate problem is briefly considered. Generally agriculture is probably not a serious contributor, but fertilizer usage is increasing and the problem will probably get much worse.

Some methods of water conservation or augmentation which have been widely considered as solutions to fresh water problems were discussed and considered improbable as major irrigation influences in the foreseeable future. These include antitranspirants, reservoir evaporation suppressants, interbasin water transfer, weather modification, and seawater desalination.

On the drainage basin level, any given irrigation operator comes into contact with other operators, municipalities, governments and regulatory bodies. The next chapter thus treats the scantily-studied socioeconomic part of the salinity problem.

VII. SOCIOECONOMIC ASPECTS OF SALINITY PROBLEMS

An economic analysis of salinity problems should, in all probability, be based on the "yield decrement" method. This would determine how much lower crop yield is, in the presence of a given amount of salinity, than it would be in a nonsaline soil. The value of this lost production could be estimated and an appropriate economic analysis be undertaken, utilizing such data as capital costs and water values. Models could be generated, and budgeted costs and returns projected for various sets of conditions. Such analyses have not been done because physical data relating crop yields to irrigation water quality under field conditions have simply not been collected. It is thus impossible at this time to establish salinity damages or costs as functions of water quality.

Pillsbury and Blaney (753), in an effort to find an economic index for evaluating low-quality irrigation water, devised the degradation ratio, which is the fractional equivalent of degraded water to good water for irrigation use. The efforts of Yaron and his group (948), in such matters as finding the least cost combination of water quantity and salinity that provides for a given soil salinity index at the end of the irrigation period, will undoubtedly be of great value.

Degraded water quality is a detriment to other beneficial uses besides agriculture and these too must be identified and given cost evaluation. Water hardness affects domestic users, increasing soap and water costs and causing metal water pipes and water heaters to corrode. Industrial users suffer from high mineral contents when water is needed for boiler feed and cooling (946).

The U.S. Environmental Protection Agency and its predecessor Federal agencies undertook a massive and detailed study on the Colorado River Basin (754-758), with the goals of identifying the magnitudes and causes of salinity levels in the river, identifying physical and economic impacts of salinity on water uses, and assessing the economic costs and benefits associated with various levels of salinity control. The study did not fall into the common error of treating water as a homogeneous commodity or the quality needs of various users as identical. The data was used to make economic and physical predictions for various future conditions.

Not surprisingly, it was shown that as salinity levels rise above 500 mg/l, net economic returns from irrigated agriculture decline, and this is paralleled by increased municipal water system costs because of the 500 mg/l public health limit-

ation. For every 100 ppm rise in river salinity, agriculture loses 3-4.5 million dollars. Economic effects on users were defined in terms of total penalty costs which are the sum of direct penalty costs incurred by water users and indirect penalty costs suffered by the regional economy, and which represent the total marginal costs of increases in the salinity concentrations above base conditions. Agriculture in the Colorado River incurs over 80 percent of the penalty costs, and this is mostly in the lower basin and the southern California water service area.

The present salinity levels are calculated to exact a total penalty toll of \$16,000,000 per year in the basin. If no salinity controls are implemented and if planned water resources development is completed, these costs will rise to \$28,000,000 in 1980 and \$51,000,000 in 2010. Limiting future development to those projects now underway would reduce the salinity costs to \$21,000,000 and \$29,000,000 in 1980 and 2010.

Three possible basin management approaches were considered: 1) allow unlimited resources development with no salinity controls, 2) limit developments that are expected to increase salt loads or decrease streamflow, 3) construction of salinity control works that would allow benefits to proceed. The last alternative was recommended as the most desirable salinity policy aimed at maintaining river salinity concentrations at or below present levels. The salinity control costs with this approach were estimated at \$7,000,000 for 1980 and \$13,000,000 in 2010 as against salinity control benefits of \$11,000,000 and \$22,000,000.

Although this may be the most thorough and thoughtful economic analysis of salinity problems yet attempted for an entire river basin, its conclusion can be accepted only guardedly.

Pincock (938), using admittedly sparse data, but similar to that of the EPA, estimated crop yield from salt tolerance and water quality with a method introduced by Bernstein. He used river water quality deterioration estimates through 2010 similar to those of the EPA, but came to the differing conclusion that although salt damage was inevitable, it would be offset by net yield increases in a number of crops as a result of improved agrotechnical methods so that rising salinity levels would exact no net cost to the basin economy.

A growing criticism of many water resource developments concerns the failure of the planners to assign costs to factors about which there is little hard economic data or to qualitative factors. The EPA study admits to having failed in assigning costs to certain recreational features and to Mexican agriculture to which the last part of the Colorado River flows. Additionally, no costs were assigned to groundwater contamination. Such questions will eventually have to be faced. In tropical countries no effort is made to evaluate the increase in water-borne diseases after dam projects are completed (876). Certain assumptions also need to be questioned.

In evaluating the economic effects of basin salinity management, the alternative of limiting developments that might increase river salt loads or decrease flow was rejected because it was felt that a possible consequence of this action would be regional economic stagnation. In such a situation it is not always easy to separate economic considerations from political considerations.

In the United States water resource developments have a "pork-barrel" tradition. This has always been thought to be a marriage of economic necessity and political gain. Our evolving awareness of the complexities of many kinds of water development leads to doubts concerning the inevitability of economic necessity. This is illustrated by the Central Arizona Project (CAP), in which water will be moved from the Colorado River above Parker Dam to the Phoenix and Tucson areas. Some of it will be used for municipal water supplies, most for irrigation agriculture. Young (1986), applying cost-benefit analysis to the project, could find no economic advantages and many economic disadvantages. O'Leary (543) has questioned the advisability of bringing water with 700 ppm salinity levels into central Arizona in an agricultural region where many of the soils are already saline. The cost of the CAP will be about \$8,000,000,000. A situation is thus evolving in which enormous sums of money will be spent to divert saline waters from the Colorado River, thereby helping to worsen a Mexican salinity problem (see below). They will be brought to a region for reasons having no economic justification and for which they may be too salty even though no economic impact study of the possible salinity effects has been made. Essentially, as a result of much pertinent research, the necessity of certain irrigation projects has been questioned on economic and agronomic grounds. This is an interesting development in a world where the economic desirability of arid lands irrigation projects is rarely questioned.

The Colorado River Basin furnishes a number of precedents on matters not available from other basins. This is because it flows through the hot, arid southwestern U.S. and is one of the world's most intensively exploited rivers. Its drainage basin includes two countries and seven states of the United States, which often act among each other like sovereign, warring nations. Conflict between the states of the upper basin and those of the lower basin has never been too intense because the former have been slow to develop their share of the river. Arizona and California have a somewhat unhappier history of conflict, which has presumably been settled by the U.S. Supreme Court decision of 1968 fixing their respective allotments of lower basin water (922, 933, 944). The allotment dispute is only one of a number of problems in the lower basin that continue to plague the area. Increased recent irrigation developments in the upper basin combined with more intense general usage of the river promise an ever-increasing salt problem. A recent proposal by the EPA and Bureau of Reclamation that salinity standards be imposed to keep the river from getting any worse, was rejected by most of the basin states (914). Probably the interstate jealousies and mistrust of the federal agencies will combine to make im-

provement projects difficult.

The adequacy of prediction of salinity problems is a major difficulty. It is hard to believe that when water of 700 ppm salt content was first brought into the Wellton-Mohawk District in 1952, planners predicted the resulting high water table problems and the creation of over 5000 ppm drainage waters out to the Colorado River near the Mexican border.

The resulting crop reductions in the rich Mexicali Valley on the Mexican side has become a hot political issue in Mexico. Every time Mexican President Echeverria journeys north, he is reminded by Baja California officials of the political feeling among the farmers of Mexicali on the subject of the high salinity waters coming from Arizona and particularly from the Wellton-Mohawk District (912). A short bypass channel around Morelos Dam, combined with timely releases from upstream, have helped (934). It remains a difficult international problem, however, even though the U.S. Congress has committed itself to finding a solution within the Colorado Basin, which as yet has not emerged.

When President Echeverria was in Washington in June 1972, on an official state visit, he made several public statements concerning the disruptive effect of this problem on Mexican-American relations, and he called for a solution (912). The last user in the U.S. gets water of 900 ppm TDS while the first Mexican user gets 1240 ppm. President Nixon subsequently announced an agreement in which the U.S. agreed to deliver water of no higher salt content than that obtaining on the Arizona side (913).

It would appear that for the short term the problem will be solved by timed releases from storage, but as the CAP, Southern Nevada Project, and other committed developments appear, this storage water will no longer be available. The issue is extremely sensitive politically, and this is reflected in statements of concern about the Mexican agreement by several lower basin state senators. Many have speculated that the U.S. may have to resort to river desalination in order to meet its obligations. Should this come to pass, it will be of more than passing interest to compare the costs of meeting the treaty obligations compared to the economic benefits of the irrigation agriculture that is creating the salinity problem.

Steiner (941) lends some historical perspective with the interesting comment that the international problem with Mexico is a problem because of a "trade" with Mexico for Rio Grande water. When the Colorado River Compact with Mexico was ratified in 1944, the chairman of the strategic Senate Committee on Foreign Relations was Senator Connally of Texas. Texas gained Rio Grande water while Mexico gained Colorado River water.

The U.S. is certainly not the only country in which water-resources problems and politics have become entwined. Greenwood concludes (1970) from a study of Soviet water policy in Armenia that "considerable political overtones are involved." This is probably the case in every nation with serious water resources problems.

Generally, international political problems specifically involving salinity-related difficulties are fairly rare because of the general failure to appreciate the possible future importance of these problems. It is not difficult, however, to glance at a world map and pinpoint national borders with high probabilities of developing conflicts.

The Soviets also seem to have had an "anti-drainage lobby" (1968) who were able, in Lysenko-like fashion, to suppress the construction of required drainage structures in the south Golodnaya Steppe. There are indications that the results were catastrophic.

The very important point which this chapter seeks to illustrate and stress is that salinity problems are not solely matters of water supply, drainage, and other purely technical considerations, but in true multidisciplinary fashion, include socioeconomic factors.

Hagan (1971) correctly notes that a successful irrigated agriculture requires a combination of research information, wise legislation, and enlightened farming. The necessary legal machinery and regulatory agencies are absolutely necessary in controlling and minimizing the adverse effects of irrigation waste waters. Because of the mounting complexities in river basin water quality problems, we can no longer afford to ignore critical economic factors or outmoded political traditions.

VIII. OVERVIEW AND RECOMMENDATIONS

C. A. Bower, director of the U.S. Salinity Laboratory, assures us (285) that "...Enough has been learned about the cause, prevention, and cure of salinity to say with certainty that irrigation agriculture can be permanent."

Kelley argues (977) that the main cause of soil salinity buildup is the development of a high water table and that if this is prevented, "...There is no inherent reason why irrigated agriculture should be short-lived," and "...the future development of water supplies for arid regions will continue to be largely an engineering problem."

Hagan, in considering the technical problems of irrigated agriculture, concludes (971), "By making good use of modern science and technology, I am confident that Man by wise management can truly achieve a productive and permanently successful agriculture."

Allison asserts (213) that, "Based on our present scientific knowledge of soil and water problems and management practices, there appears to be no valid reason why irrigation agriculture, once established, should not remain permanently successful."

In arguing that irrigation water quality is not in itself the decisive parameter in arid land agriculture, Fireman maintains (170), "...There is no serious threat to the permanence of irrigation agriculture, except the failure of man to use the practices and knowledge now available to him.

If this is the case, then all too many men are failing to avail themselves of these practices and the knowledge. Despite a substantial number of statements throughout the agricultural literature like those above, salinity problems seem generally to worsen everywhere.

In West Pakistan, 100,000 acres per year are going out of production because of salinization (720, 962, 978). For those whose tastes in statistics are more macabre, in 1964 the country lost 1 ha of prime irrigated agricultural land to waterlogging and salinity every 17 minutes, while a child was born every 12 seconds (949).

In neighboring India, about 6.07 million ha (15 million acres) have gone completely

out of agriculture because of TDS and exchangeable Na accumulations (975, 985).

Iran has about 25 million salt-affected hectares which includes the majority of irrigated lands where crop yields are depressed (958, 978). Large-scale irrigation developments are presenting new dangers by bringing in vast new quantities of moderately saline waters for irrigation of large land areas.

More than 50 percent of the soils of Syria are salt-affected (220,000 ha). In 50,000 ha, yields have been reduced by 50 percent more. Over 65 percent of the population depends on agriculture (964, 978). Similar data can be found for Afghanistan (978), Cyprus (957), the U.A.R. (966), Iraq (11, 953, 959, 978), the Republic of South Yemen (967, 978), Somalia (978), Jordan (953, 960), Kenya (978), and Turkey (965).

These examples certainly do not seem to conflict with the many assertions concerning the permanence of irrigated agriculture, since they are mainly dependent upon the correct application of salinity amelioration and prevention techniques. Some might argue that the list of nations presented are mainly underdeveloped, with small reservoirs of scientific expertise and technological experience. While these assertions might be somewhat debatable in the cases of India and West Pakistan, the thrust of the argument would still appear valid.

Review of the evidence, however, casts doubt on that argument for even the most advanced nations. The Murray River system supports about nine-tenths of all irrigated land in Australia. Ebert's study (793) indicates that salty irrigation runoff from fields is held in evaporating ponds near the river and seeps back into the river creating 3500 ppm salinity levels in the river bed compared to surface salinity levels of 300 ppm. Every indication is that the problem is steadily worsening and calls for massive reclamation projects. This would seem to support Ebert's claim that, "Nowhere else has there been more misuse and resource deterioration than in the irrigation districts of arid lands," particularly in view of the relatively short Australian growing season and the shortage of irrigated land.

The Golodnaya Steppe of Uzbekistan in the arid region of Soviet Central Asia is the major cotton producing area of the U.S.S.R. Developed in czarist times, its productivity has waxed and waned. In the past decade or so, the Soviets have invested about one-half million rubles in reclamation of salinized areas and expansion of the canal system (981). Yet, so extensive is the soil salinization problem that they cannot successfully overcome it and it is suggested that it may be cheaper to import part of their cotton requirements than to continue attempting to farm that vast irrigated section. Nor does this seem to be an isolated instance. Gerasimov (968) says that the salinization process has not yet been stopped in Soviet Central Asia as a whole and that, despite advances in water management, secondary salinization continues to develop, largely cancelling out the development of newly irrigated land and higher yields.

Saline soils and brak (sodic soils) are a continuing problem in South Africa, particularly in the semiarid and arid regions (974), being partly responsible for recent suggestions to eliminate irrigation in those parts of the country. Arar (949) quotes the U.S. Salinity Laboratory to the effect that 25-30 percent of the irrigated land in the United States suffers from salt-caused yield impairment.

Predictions of salinity in the already too-saline Colorado River seem to fall at about 30 percent increases over present levels (754, 867, 868). The Rio Grande begins to suffer salinity problems at Elephant Butte Dam and downstream because of irrigation water losses and progressive salt concentration (952, 973). Hagan claims (971) that even the relatively new Columbia Basin project with an abundant supply of good quality water has developed a high water table and a salinity problem. The soil salinity problems of the California crop-growing regions in the Central Valley (984) and the Coachella Valley (855) have already been mentioned. They are of varying degrees of seriousness. It is interesting that the Imperial Irrigation District does not feel that anything less than immediate channeling of the lower Colorado can solve their pressing salinity problems (873).

One is left with the conclusion that at least the existence of serious salinity problems does not seem to depend on the wealth or technological level of a society. Although it probably pays to be suspicious of the accuracy of figures in the salinity area, it appears that the statement of Reeve and Fireman (34), that about one-third of the irrigated land of the world, or 100,000,000 acres, is affected by salt problems, is likely to be fairly close to the truth.

Those who have argued that salinity is a problem of enormous magnitude and consequently that it is too much neglected (225, 799, 971), are very much correct.

A fair part of this report and most of the bibliography is concerned with the array of field and drainage basin technologies and supportive research designed to control or ameliorate the salt problem. By any reasonable standard of success, salinity technology seems to have been a failure. The problem is to determine why.

A first guess is that the technology is flawed, perhaps fatally so. Yet no one has demonstrated serious error in the broad theory or even in most applications of that technology. Among other goals, it was the intention of the first five chapters to show that irrigation agriculture is not a simple undertaking. It is fundamentally intensive, highly productive, unstable. The technology, in practice, is not simple. High investments, whether in capital goods or labor, can make failure a costly enterprise.

The exigencies of water control and storage usually bring political and legal controls which may superimpose social instability on technical instability. The development of

an irrigation scheme or a major water storage project such as a dam, may be a massive undertaking which consumes both economic and political capital. This in turn leads to an inability to admit mistakes in the planning and execution of the project, and may explain why it is so difficult to obtain hard data on so many problems in the salinity domain. It is very likely that many nations have tended to be most circumspect about advertising mistakes of this order of magnitude especially when so vital a matter as crop production falls far short of much publicized predictions. In turn, this phenomenon may have much to do with the generally dim perspective of salinity problems around the world.

It is amazing that a recent, extensive work on the agriculture of the Middle East should have practically nothing to say of salinity problems (953). We thus have a picture of irrigation agriculture as a technologically complex undertaking which demands socially complex institutions and commitments for its maintenance. If both technical and social requirements are met and salinity still remains or becomes a problem, then the fact must be faced that arid land agricultural projects, at least some of them, should not exist as they are presently constituted.

The large gaps in awareness, research and development in both the agronomic and socioeconomic areas that have been alluded to need to be corrected. By and large in the U. S. and most other countries, the field of salinity control has been dominated by agricultural scientists, a group intimately involved with irrigation and drainage. This has led to the formation of one kind of problem-solving approach to the exclusion of other kinds of approaches, both technical and social. The salinity problems of irrigation agriculture are broad in both origin and ramification and call for multidisciplinary efforts, something which American science, at least, has not always excelled in.

It has been shown that salinity problems do not respect neat, arbitrary boundaries and that their study deserves the attention of a wide spectrum of disciplines. Thus the consequences of salinity problems are not limited to agriculture alone. In most nations, dams, canal systems, and other construction and expenses dealing with irrigation systems are usually government-subsidized, so that the entire society has a stake, often an immensely expensive one, in irrigation systems.

The Aswan High Dam of Egypt, which is complicated by a number of problems (979), will have cost over a billion dollars when completed, and the Columbia Basin Project will cost only about \$150,000,000 less (720). Irrigated farms in the San Joaquin Valley represent land investments alone of about one-half to one million dollars each. One well, sufficient to irrigate one square mile, may cost from fifty to sixty thousand dollars (720). Obviously, costs vary around the world, but everywhere they are considerable. It follows that such crucial undertakings should be truly needed and productive.

Not only has it been shown that agricultural productivity in arid regions worldwide is severely limited by salinity problems, but also that leaching-related salinity contamination of groundwater can be a serious problem. McGauhey (1980) has argued: "The hazard of man-made contamination ... is that although we have learned how to prevent the poisoning of land from our irrigation practice, we may go the way of Mesopotamia by poisoning the water instead."

Certainly this, and other salinity-related phenomena, will exact a great price from the whole society.

In view of this lessened productivity combined with the deleterious side effects, the following recommendations are made:

- 1) That the generally accepted field and drainage basin methods outlined in previous chapters for ameliorating salinity problems in standard irrigation projects be adopted where possible and where helpful,
- 2) that every effort be made to experiment with or incorporate those methods outlined in previous chapters involving major departures from standard irrigation projects, particularly trickle irrigation with saline water, plant breeding for salt-tolerance, and high humidity greenhouses,
- 3) that in all appropriate nations scientific priority be given on the highest governmental level to a variety of research projects and information gathering activities that recognize the critical need for expansion of knowledge and methodology in dealing with salinity problems,
- 4) that such priorities result in the establishment of information-gathering and research-directed irrigation and salinity study institutes, long-term funded and divorced from university departments or other specialty organizations, managed and staffed in ways appropriate to the conduct of multidisciplinary studies. It is stressed that many institutes are needed, not a single monolith, and, finally,
- 5) that planning, construction and reclamation of arid lands irrigation projects be largely suspended or slowed until it is reasonably possible to assess their value and contributions vis-a-vis their seldom-recognized weaknesses.

The last recommendation will, for obvious reasons, be the most difficult to implement, and yet it is critically important that such a step be taken. It is only

through such a hiatus that it will be possible to step back and realistically evaluate such projects, divorced of tunnel vision, vested interest, prejudice, and unrealistic expectations.

Many will again repeat the argument that in a growing, overpopulated world it is absolutely necessary to continue such projects lest food production fail to keep pace with hungry mouths. While this argument has some substance, no responsible scientist can fail to see that the world's population can not continue to grow indefinitely and that practices that may be wreaking long-term destruction to the world's food-producing capabilities in order to achieve short-term gains, may possibly be worse than we have been willing to admit. Certainly it would seem that the nations of the world, both developed and underdeveloped, would be better off with realistic assessments of our food-producing abilities, rather than with complacent dependence on a form of agriculture that in a long-term sense may not be adequate to the needs of the future.

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