Sustainability of Irrigation: An Overview of Salinity Problems and Control Strategies

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A. Introduction: Irrigated Agriculture Needs to Be Sustained and Rejuvenated

The primary objective of agriculture is to provide the food and fiber needs of human beings. These needs increase as the population increases; additionally, the demand increases as average income increases. The world population is projected to be 6.3 billion in the year 2000 and 8.5 billion in 2025 (UN, 1990). The average income of much of this population is also increasing. The population increases alone will require an estimated increase in agricultural production of about 40 to 50 percent over the next thirty to forty years (a 20 and 60 percent increase for developed and developing countries, respectively), in order to maintain the present level of food intake. This conclusion is based on recent estimates of the Food and Agriculture Organization of the United Nations (FAO) that the global demand for food, fiber and bio-energy products is growing at an annual overall rate of 2.5 percent and at a rate of 3.7 percent in developing countries (FAO, 1987). According to the UN (UNEP, 1992), the annual rate of increase in agricultural production during the period 1970 to 1990 was about 3% in the developed countries and about 2% in the developing countries. Given these data, it is concluded that many countries of the world must increase their ability to produce food and/or to control population, if they are to meet their future food needs.

According to FAO (FAO, 1989), the potential area of arable land in the world is 3190 Mha, about 46 percent of which is already under cultivation. Worldwide, the area of cultivated land increased by only 4.8 percent over the period 1970-1990 (0.3% in developed and 9% in developing countries). The per capita arable land decreased from a worldwide average of 0.38 ha in 1970 to 0.28 in 1990, mainly due to the relatively larger increase in population than in new land for agriculture. It has been estimated that, if the arable land is maintained constant at the present worldwide level of 1474 Mha, the per capita arable land will progressively decline to 0.23 ha in 2000 and to 0.15 ha in 2050. It also has been estimated that nearly two-thirds of the increase in crop production needed in the developing countries in the next decades must come from increases in average yields, since only a fifth is expected from increases in arable lands and the balance from increases in cropping intensity (FAO, 1988). About two-thirds of the increase in arable lands is expected to come from the expansion of irrigation. It may be concluded, given the above and additional data given later, that the needed increases in food production in developing countries must come primarily from irrigated land, if the world is to stand a chance of avoiding mass starvation in the future.

Food famines were predicted to occur in many parts of the world beginning in the 1960s. These famines did not occur. Their avoidance was credited to the so-called "Green Revolution". I believe that this avoidance more deservedly should have been credited to the "Blue Revolution", by which I mean the rapid increase in the development of water supplies and irrigation projects that occurred around the world during the period 1950-1980. During this period the rate of growth in irrigation exceeded the rate of population increase (see Table 1 and Figure 1-calculated from data of Ghassemi et al., 1995 and FAO, as assembled by the Worldwatch Institute, 1997, respectively). The expected increase in production from the increase in irrigation and the increased yield that results from irrigation can largely account for the preponderance of the increase in food production that occurred and which met the needs of the expanding population during this period. Of course, the higher yielding varieties of wheat, rice and corn developed during the early part of this period also helped in this regard. But, it seems important to correctly separate the relative contributions of these two factors, not so much in order to correctly credit the exact sources of the past increases in food production but so as to be able to better plan for the future.

Irrigated land presently accounts for about 15 percent of the cultivated land but produces 36 percent of the world's food (FAO, 1988). In the developing countries, almost 60 percent of the production of major cereal grains, rice and wheat, derives from irrigation (Field, 1990). The world's irrigated land is variously estimated to be 220 million hectares (Jensen et al., 1990), 227 million hectares (Ghassemi, et al., 1995) or 244 million hectares (FAO records compiled by Worldwatch Institute, 1997). About three-quarters of the irrigated land is found in the developing countries; by the year 2000 this proportion is projected to be about 90 percent.

It has been estimated that expansion in irrigation overall needs to be 2.25 percent per year in order to meet world food needs by the year 2000 (FAO, 1988). However, the present rate of expansion in irrigation has recently slowed to less than 1 percent per year (CAST, 1988). This rate has been rapidly declining since the 1960s; the percent compounded rates of increase in irrigation were estimated to be 4.1 in 1960, 3.5 in 1970 and 2.3 in 1980 (see Table 2, after Jensen, et al., 1990, and Table 3, after Smedema, 1995). The rate of increase in irrigation fell below the rate of increase in population beginning about 1979 (see Figure 1). The reasons for this slowing in expansion rate of irrigation, or even of a net loss, are many. Among them are the high cost of irrigation development and the fact that much of the suitable land and water supplies readily available for irrigation have been already developed. Lack of available water is the limiting constraint for almost 600 million hectares of potentially suitable arable land (FAO, 1988). Another reason for the current slowed expansion in world irrigation is the fact that the overall performance of many irrigation projects has been less than expected due to inadequate operation and maintenance and to inefficient management (FAO, 1990). It is not unusual to find that less than 60 percent of the water diverted or pumped for irrigation is actually used in crop transpiration. Furthermore, as will be shown in Section B, improper irrigation has resulted in substantial degradation of the presently developed soil resources (which most likely

Table 1. Population and area of irrigated land in world since the year 1800 (data obtained from Ghassemi, et al., 1995 and Worldwatch Institute, 1997).

World Irrigated Area and Population Over Time			
Year	**Population (billions)**	**Irrigated area (Mha)**	**Ha per 1000 people**
1800	1	8	8
1900	1.5	40	26.7
1950	2.5	94	37.6
1961	3.07	139	45.3
1965	3.35	151	45.1
1970	3.71	169	45.5
1975	4.08	190	46.6
1979	4.37	209	47.8
1980	4.45	211	47.4
1985	4.86	226	46.5
1990	5.30	239	45.1
1994	5.63	249	44.2

Table 2. Rate of increase in area of worldwide irrigation agriculture during the period 1960-1984 (data obtained from Jensen, et al., 1990).

Rate of Increase in Irrigation Area Over Time	
Year	**Percent**
1960	4.1
1970	3.5
1980	2.3
1984	1.0

Table 3. Rate of expansion in the world's irrigated area (after Smedema, 1995).

Expansion of World's Irrigated Area Since 1800	
Period	**Mha per year**
1800-1900	**0.3**
1900-1940/45	**1.0**
1940/45-1970	**5.0**
1970-1980	**4.0**
1980-1990	**2.0**

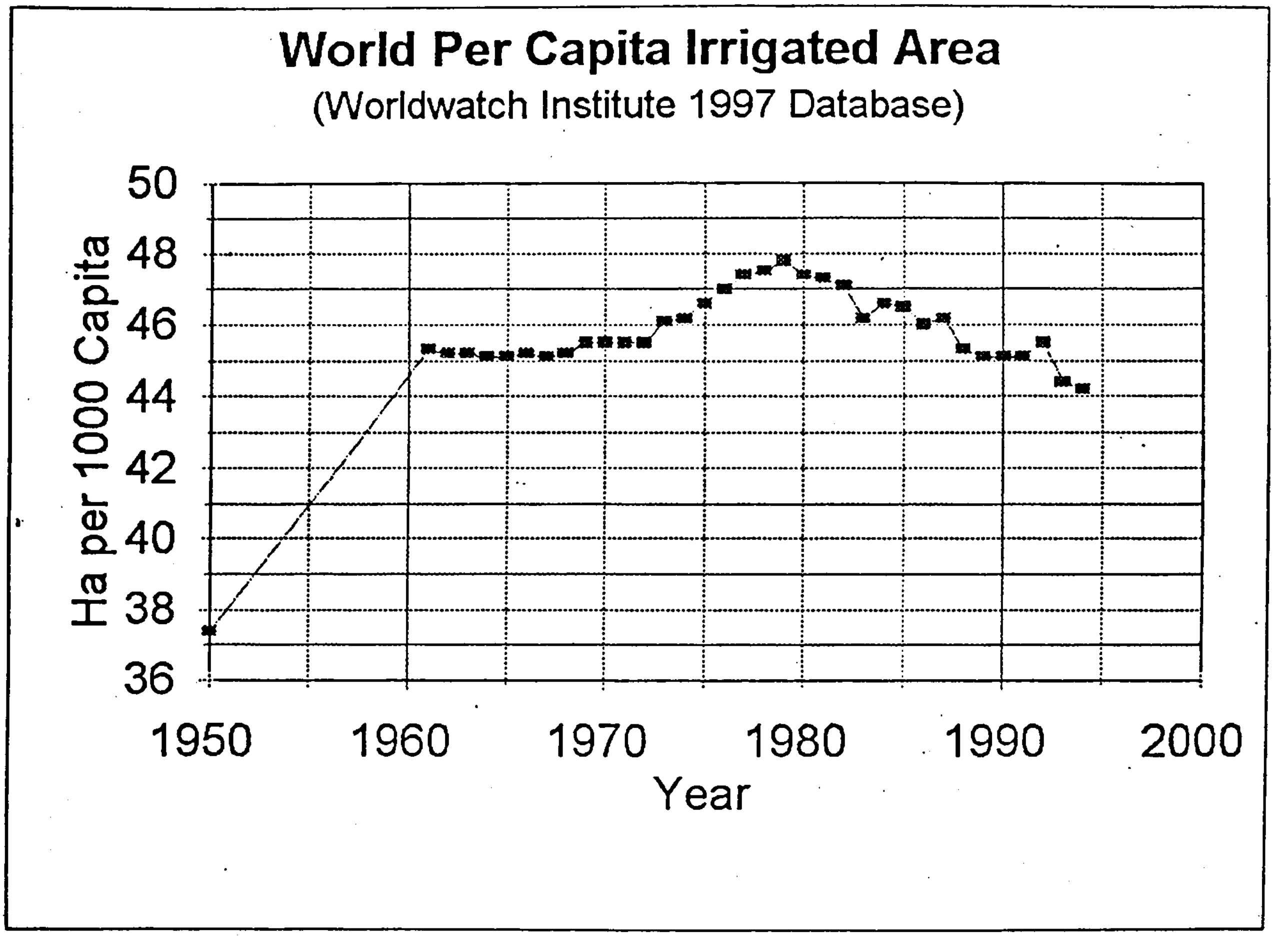

Figure 1. World Irrigated Area per Capita, 1950-1994; data from FAO as summarized in Worldwatch Institute-1997 Database.

have not been adjusted for in the statistics presented above for the area of irrigated land; hence the effective soil resources available for crop production is likely less than the statistics would indicate) and is increasingly causing environmental and ecological concerns about the viability of present projects, as well as discouraging further development. According to David Seckler, Director General of the International Irrigation Management Institute, the losses now are likely exceeding the gains (Seckler, 1996). According to Umali (1993), the salinity affected area is growing at a rate of about 1-2 Mha per year which is of the same order of magnitude as the annual expansion of the world's total irrigated area. The facts given above support the conclusion that there is a great need, on a world-wide basis, to sustain irrigated agriculture. The data presented in Section B will show the additional great need and opportunity that exists to rejuvenate the presently developed but degraded irrigated lands

Given the greatly slowed rate of irrigation development referred to above, the apparent reduced ability to alter this slowing trend and the extensive degradation in presently developed irrigated lands (and in associated water supplies, as will be shown in Section B), the mass famine being predicted to occur in another few decades in many parts of the world should be taken very seriously and should be considered much more likely to occur than the one predicted for the 1960s. Since the crop breeding programs have not been producing much in the way of higher yielding crop varieties in the past couple of decades, the expectations of a truly "green" revolution happening to counter this predicted famine are not very optimistic (Brown, 1997; York, 1994). To illustrate, the worlds rise in land productivity has dramatically slowed in the 1990s to a rate of only 0.5% per year; it increased at a rate of 2.5% per year during the period 1950-1986 (York, 1994). In fact, it has been concluded that most cereal crops may have already attained their physiological limits to further yield increases, especially regarding water use efficiency (Sinclair, 1994). If this is true, the demands on our limited soil and water resources will become even more important to the challenge of meeting our expanding food production requirements.

According to the Panel on Food, Agriculture, Forestry and the Environment of the World Commission (1987), " The next few decades present a greater challenge to the world's food systems than they may ever face again. The efforts needed to increase production in pace with an unprecedented increase in demand, while retaining the essential ecological integrity of food systems, is colossal, both in its magnitude and complexity. Given the obstacles to be overcome, most of them man-made, it can fail more easily than it can succeed."

From the facts and projections cited above it is concluded that: (i) global food needs are increasing markedly while soil and water resources are becoming more limited, (ii) there is a major need to conserve water, to utilize it more efficiently and to protect its quality, and simultaneously to protect soil resources, and (iii) world agriculture must both expand its base of production and produce more with presently developed resources. Because higher yields are obtained with irrigated agriculture and because it is less dependent on the vagaries of weather, it assumes special importance in this regard; it must not only be sustained, it must be rejuvenated. Expansion of irrigated agriculture could also contribute significantly towards achieving and stabilizing our food and fiber needs. However, new water supplies for such expansion are limited. Irrigated agriculture is already the largest consumer of developed water resources. Due to the limited water resources of the world, emphasis should be placed on making more efficient use of the presently developed irrigation-water resources and on the use of waste waters for irrigation. Emphasis should also be placed on sustaining the irrigated land that already is in existence and on increasing crop production on it, especially that which is now degraded..

B. Soil and Water Degradation Resulting from Irrigation/Drainage

In many locations around the world, strains upon the environment are occurring increasingly and concern is mounting about the sustainability of irrigated agriculture due to waterlogging, salinization, erosion, desertification, loss of biological diversity, waterborne diseases, and the adverse effects of potentially toxic agricultural chemicals upon human health and the biota of associated ecosystems (World Commission on Environment and Development, 1987). Presently, 5 to 7 million hectares of arable land (0.3 - 0.5 percent) are being lost every year through soil degradation. The projected loss by the year 2000 is 10 million hectares annually (0.7 percent of the area presently cultivate d). Soil salinization is identified as one of the major causes of chemical soil degradation; waterlogging is identified as one of the major causes of physical soil degradation. Thus, a critical need facing many countries is to halt and to reverse the present extent of environmental degradation resulting from excessive irrigation and drainage, especially those manifested in waterlogging and soil and water salinization, in order to ensure the food needs of the future generations. FAO has concluded that the future expansion of food production will be increasingly dependent upon sound irrigation and soil & water management and upon the concurrent maintenance of the present agricultural resource base and the environment and that these are among the most challenging tasks facing mankind today (FAO, 1988), especially in the Near East Region (FAO, 1995).

The scope and nature of the soil and water degradational problems associated with irrigation will be discussed in some detail in this Section, in order to better define the nature, extent and causes of these problems.

1. Extent and Causes of Soil Degradation

While there is no doubt that large and increasing proportions of the world's irrigated land are deleteriously affected by salinity and water–logging, no one knows for sure the exact extent of their affected areas. It has been variably estimated that the salinized area is as low as 20 and as high as 50 percent of the world's irrigated land (Adams and Hughes, 1990). The results of the Global Assessment of Soil Degradation (GLASOD) reported by Oldeman et al. (1991) estimated that worldwide 76.6 Mha of land have been degraded by human-induced salinization in the last 45 years, but the separation between irrigated and non-irrigated land was not made. Buringh (1977) estimated that the world is losing at least three hectares of arable land every minute to soil salinization (about 1.6 Mha per year), second only to erosion as the leading worldwide cause of soil degradation. Dregne et al.

(1991) estimated that about 43 Mha of irrigated land in the world's dry area are affected by various processes of degradation, mainly waterlogging, salinization and alkalization. They also estimated that the world is losing about 1.5 Mha of irrigated land each year due mainly to salinization. Umali (1993) reported a similar rate of loss by salinization. Ghassemi, et al. (1995) reviewed many of the various sources and estimates on the extent of soil degradation by salinity. They estimated that about 20 percent, or 45.4 Mha out of the total of 227 Mha of irrigated land, are salt affected. They arrived at this number by extrapolating the average percentage reported by others for the five countries with the most irrigated land, ie. India, China, US, Pakistan and the former USSR No continent is free from salt–affected soils; serious salt–related problems occur within the boundaries of at least seventy–five countries (Szabolcs, 1989; Ghassemi et al., 1995). Countries with serious salinity problems include Australia, China, Egypt, India, Iraq, Mexico, Pakistan, Soviet Union, Syria, Turkey, and United States. The 1977 United Nations Conference on Desertification estimated that 22 Mha of the world's irrigated lands are waterlogged (Holdgate et al., 1982). According to the GLASOD report, 10.5 Mha of land became degraded by waterlogging by human activity over the last 45 years. White (1978) concluded that 50 percent of the irrigated soils in the Euphrates Valley in Syria, 30 percent in Egypt and more than 15 percent in Iran are affected by salinity or waterlogging. Based on information derived from the FAO/UNESCO Soil Map of the World, Mashali (1995) estimated that 83.4 Mha of land area (not necessarily arable land) in the Near East Region is salt-affected. He also concluded that countries in the Near East Region most affected by human-induced soil salinization include Egypt, Iran, Iraq, Pakistan, Syria, Turkey, Algeria, Tunisia, Sudan and the Gulf States. Mashali further characterizes and summarizes the salinity problem in the Near East as follows:

> "In Iraq, salinity and waterlogging are problems in more than 50% of the lower Rafadain Plain. In Syria, about 50% of the irrigated land in the Euphrates Valley is seriously affected by salinity and waterlogging. In Egypt, about 33% of irrigated land is affected by varying degrees of salinity and sodicity. In Iran, a combination of salinity, sodicity and waterlogging creates problems in over 15% of the area. In Pakistan, out of a total 15 million Ha of irrigated land, about 11 million ha are affected by salinity, waterlogging or both to varying degrees. Of the 3 million ha recently surveyed in Algeria, 600,000 ha were classified as salt-affected soils, mainly of irrigated land in Oued Chaliff Governorate. Salt-affected soils in Tunisia cover about 1.5 million ha, of which 200,000 ha are irrigated."

A summary of some of the above estimates of the percentages of irrigated land affected by salinization in selected countries and the world is given in Table 3.

The data cited above is extremely qualitative and observational in nature because a practical means to measure the extent and severity of salinized land has been lacking till now. The numbers can not be assumed to be accurate. But for our purposes it doesn't matter, since regardless of the exact numbers, it is obvious that the worldwide area of salinized soil is enormous. Furthermore, it has been concluded by experts of the ICID, World Bank and FAO, who should know, that "the greatest technical cause of declining agricultural productivity on irrigated land, or irrigation failure, is waterlogging and salination of the soil in arid and semiarid regions" (Jensen et al., 1990). Another international group of irrigation and population/food production specialists deliberated such problems at the United Nations Conference on Desertification (UNCOD) held in Nairobi in 1992. Their deliberations led them to make the following recommendation (UNEP, 1992):

> "It is recommended that urgent measures be undertaken to combat desertification by preventing and controlling waterlogging, salinization and sodication by modifying farming techniques to increase productivity in a regular and sustained way, by developing new irrigation and improvement of the soil, social and economic conditions of people dependent on agriculture."

It is evident in the above-mentioned data and reports that waterlogging and salinity are typically combined, or at least not clearly separated, in the assessments. This is because a close relationship exists between the depth of the water table, the salinity of the groundwater, the soil hydraulic properties and the extent of salt accumulation in soils, especially in natural, semi–arid regions. The major saline regions of the world are generally found in semi–arid and arid regions and in relatively low–lying, poorly drained lands. This generally is the result of the mobilization of large quantities of salt present initially in the soils and underlying substrata through the effects of excessive irrigation and leaching and the redistribution and subsequent accumulation of the mobilized salt in localized areas of restricted drainage. Areas of restricted drainage are typically found in lower–lying regions of the landscape where the water table is near the soil surface, and it is in such places that the salts typically accumulate in the topsoil due to evaporation–driven, water-flow processes. Likewise, the occurrence of shallow groundwaters themselves often are similarly related to topographic position. The drainage of waters from the higher–elevation regions of valleys and basins may raise the groundwater level in the lower–lying lands so that it becomes too close (within 2 m) to the soil surface. Permeability of the soils is typically lower in these basin positions because of the higher content of clays generally found in basin soils, which impedes the downward movement of water and results in poor drainage. Many irrigation projects are located in these lower lying alluvial-fan and basin–position areas because of their favorable slopes (more level conditions) for irrigation and closer proximity's to easily accessible water supplies.

While salt–affected soils occur extensively under natural conditions, the salt problems of greatest importance to agriculture arise when previously productive soil becomes salinized as a result of agricultural activities (so–called secondary salinization). As explained above, the extent of salt-affected areas have been modified considerably by the redistribution of water (hence salt) through irrigation and drainage. The development of large–scale irrigation and drainage projects, which involves diversions of rivers, construction of large reservoirs and the irrigation of large landscapes, causes large changes in the natural water and salt balances of entire geohydrologic systems. The impact of such developments can extend well beyond that of the immediate irrigated area; even neighboring nations can be affected. It is not unusual to find that less than 60 percent of the water diverted for irrigation is used in crop transpiration (Jensen et al., 1990). According to Bybordi (1989), the irrigation application efficiency in Iran is seldom above 20 percent. Irrigation water infiltrated into the soil in excess of that used by the agricultural crops passes beyond the root zone. As mentioned above, this drainage water often dissolves salts of geologic origin from the soils and underlying substrata and causes waterlogging in the lower areas where it accumulates. When this occurs, soluble salts present in the soil and substrata are mobilized and transported to the lower areas where they accumulate and over time salinize the soils and groundwaters. Seepage from unlined or inadequately lined delivery canals occurs in many irrigation projects and is often substantial. Law et al. (1972) estimated that 20 percent of the total water diverted for irrigation in the United States is lost by seepage from conveyance and irrigation canals. Biswas (1990) estimated that 57 percent of the total water diverted for irrigation in the world is lost from conveyance and distribution canals. These seepage waters typically percolate through the underlying strata (often dissolving additional salts in the process), flow to lower elevation lands or waters and add to the problems of waterlogging and salt–loading associated with on–farm irrigation inefficiencies there. A classic example of the rise in the water table following irrigation has been documented in Pakistan and is described in Jensen et al. (1990) and Ghassemi et al. (1995), after Greenman et al. (1967). The depth to the water table in the irrigated landscape located there between three major river-tributaries rose from 20 to 30 meters over a period of 80-100 years, ie. from pre-irrigated time (about 1860) to the early 1960s, until it was nearly at the soil surface. In one region, the water table rose nearly linearly from 1929 to 1950, demonstrating that deep percolation and seepage resulting from irrigation were the primary causes. Ahmad (1986) concluded that about 50 percent of the water diverted into irrigation canals eventually goes to the groundwater by seepage and deep percolation. In 1986, Aziz (1986) estimated that about 10 million hectares of cultivable land was waterlogged in Pakistan.

It should be understood that some soil (and water) salinization is inevitable with irrigation (Rhoades, et al., 1974). Typical irrigation waters contain from 0.1 to 4 kg of salts per m^3 and are generally applied at annual rates of 1.0 to 1.5 m. Thus, from 1 to 60 metric tonnes of salt per hectare may be added to irrigated soils annually. The salt contained in the irrigation water is left in the soil as the pure water passes back to the atmosphere through the processes of evaporation and plant transpiration. Therefore, some water in excess of evapotranspiration must be applied with irrigation to achieve leaching and to prevent excess salt accumulation in the rootzone. Thus, some water must drain from the rootzone if irrigation is to be sustained. But, as explained above the amount is excessive and, along with canal seepage, a major general cause of salinization and waterlogging on the large scale.

More exact inventories of soil salinization and waterlogging are needed, as are practical monitoring and assessment procedures to detect trends and identify the root-causes of these problems operating at field- and regional-scales, in order to better deal with these problems. Such a methodology is described later in Section C.

2. Extent and Causes of Water pollution

Irrigated agriculture's' role in salinizing soils has been well recognized for hundreds of years. However, it is of relatively recent recognition that salinization of water resources from agricultural activities is also a major and widespread phenomenon of great concern. Indeed, only in the past decade has it become apparent that trace toxic constituents, such as Se, Mo and As, in agricultural drainage waters may cause pollutional problems that threaten the continuation of irrigation in some projects (Letey et al., 1986; Letey, 1994).

As explained above, water infiltrated into the soil in excess of that used by the agricultural crops passes beyond the rootzone containing most of the applied salts in a reduced volume of higher concentration. This water, together with that percolating downward from canal seepage, often dissolves additional salts (over and above those present in the irrigation water) from the soil and underlying substrata. Such concentrated and additionally mobilized salts, when transported to receiving waters, are generally a source of pollution. Additional potential sources of pollutants from irrigation are the agrochemical (fertilizers and pesticides) applied to the soils which may also be, in part, mobilized (by leaching) and discharged in the drainage water. These salinized and otherwise polluted drainage waters reduce the potential usability of better–quality, receiving–waters when they are allowed to co–mingle with them.

Almost all countries which have soil salinity problems, also suffer from water salinization problems caused by the consumption of the water in crop production and from the discharge of salinized drainage water into them. This is particularly true in rivers whose flow is largely consumed through irrigation and whose drainage is returned either directly or indirectly back into it in successive downstream segments. Some examples of such rivers have been reviewed by Ghassemi et al. (1995). The River Murray in South Eastern Australia and the Colorado River in Southwestern United States are two well documented, prime examples in this regard. Another classic example is the Syr Darya River in the former USSR.. In America, 30 percent of the salt load carried in the Colorado River in its lower sections are estimated to be derived from irrigation-related processes. In Iran, six billion m^3 of brackish water flow annually through its major rivers. Much of the salt load of these rivers come from the saline sediments through which the rivers traverse, but substantial amounts result from irrigation-related drainage processes, especially in the cases of the following rivers: Karun, Dez, Zayandeh-Rud, Zarrineh-Rud and Kor. In Iraq, the Tigris River salinity levels measured in 1982 increased from 292 mg/l in Mosul, to 469 mg/l in Baghdad and to 822 mg/l in Qurna, located about 60 km north-west of Basra. Much of this increase is the result of irrigation, though the exact contribution is not known. Some rivers are not so deleteriously affected by irrigation as those discussed above. For example, the Nile River in Egypt is of excellent quality for irrigation (<350 mg/l) throughout much of its length, even though most of its drainage is returned to it (El-Din, 1989). Apparently, this is because the water is so relatively pure in its source (~25 mg/l) and because there is no large source of geologic-salt in the sediments underlying the irrigated lands south of the northern delta region. However, in the northern delta region, which is subject to sea water intrusion, the pickup of salt by the drainage water is huge (Abu-Zeid, 1989). As the river becomes more fully consumed in the future (Egypt's water resources are already beginning to come under severe stress and the intentional use of drainage water for irrigation is already underway), the salinity of the total water supply will increase and become more like drainage water in its composition (Abu-Zeid and Biswas, 1990; Abu-Zeid and Abdel-Dayem, 1991). In Pakistan, the Indus River and its tributaries are major sources of water for irrigation. Like the Nile River, the Indus River is of excellent quality throughout its length, ranging from about 150 to 420 mg/l. The salinity of the Indus River does not increase excessively with distance downstream in spite of the fact that about 70 percent of its average annual flow is diverted for irrigation. In this case this lack of downstream salinization is because there is little return of drainage waters to the river. Pakistan is also fortunate in that a large unconfined aquifer of high hydraulic conductivity underlies the whole of the Indus Plain in Pakistan. Its capacity is about 50-100 times that of the average annual flow of the Indus River system. This aquifer is recharged by rain, the rivers, and seepage from irrigation systems and irrigated fields (Ahmad and Chaudhry, 1990). The salinity of the groundwater in the aquifer increases from about 1000 mg/l in the upper basin (~6.4 Mha) to greater than 3000 mg/l in the lower basin (~6.5 Mha). About 3.65 Mha of the irrigated area is underlain with groundwater of 1000-3000 mg/l salinity (WAPDA, 1988). In addition to salinity, the groundwater quality is polluted with nitrate from fertilizer sources. It has increased from pre-irrigation time nitrate-levels of less than 3 mg/l to present levels that exceed hundreds of mg/l in some places (Sajjad, et al., 1993). Thus, Pakistan has not only an ample supply of surface water that is suitable for the irrigation of most any crop but also large groundwater supplies that are suitable for selected crops. According to Ahmad and Chaudhry (1988), irrigation deliveries to farms in the canal command areas in 1980-1981 was about 120.55 billion m^3, of which 80.4 billion m^3 was supplied by canal water and 40.1 billion m^3 was derived from groundwater. The high proportional use of groundwater for irrigation in Pakistan serves a number of useful purposes besides just water supply. In particular, it helps lower the watertable under the irrigated land which in turn facilitates leaching and thus the control of soil salinity. Most other countries do not have such good and ample surface and groundwater supplies for irrigation. Such countries must be extra careful in conserving water and in protecting its quality. The protection of their limited supplies from excessively drainage return-flows is especially necessary in this regard.

The above discussion points out that it is the excess diversion of water for irrigation, the concentration of this water through evapotranspiration, deep percolation of the concentrated drainage water, mobilization of the additional "geologic" salts encountered by the drainage water in the substrata and return of such salt-laden waters to surface waters that cause the increase in downstream salinity (pollution) that typify many of the river systems used both for irrigation and drainage in the world. Agricultural drainage is sometimes intentionally returned to common water supplies with the intent to conserve water, to increase water use efficiency or to gain additional water to enable the expansion of irrigation . Also, governmental water-quality agencies often deal with agricultural drainage pollution problems by setting allowable concentrations of total salts and specific solutes in the waters that are to be returned to the water supply system, or in the resultant mix of the waters, and by blending or diluting the drainage waters with a good–quality water so that the concentration of total salt (or of a specific solute) in the blend does not exceed a value (the so–called safe limit) that is deemed allowable in the water supply. This practice is presently being undertaken in a major way in Egypt as part of their program to develop new irrigation lands in the eastern and western deserts (Abu Zeid and Abdel-Dayem, 1991). Presently each year, about 13.5 billion m^3 of Egyptian drainage water flows unused into the Mediterranean Sea and coastal lakes. About 65 percent of this drainage water has a salinity of less than 2000 mg/l. Their plan is to blend much of this drainage water with low salinity canal water in order to obtain a mixture of 500-600 mg/l water that will be used for irrigation in the new lands. I think that such blending may be short sighted and counter productive. Those who advocate such blending programs should consider the potential deleterious effect that they can have upon the usability of the total water supply. The blending process generally reduces the maximum practical benefit that can be derived from the total water supply. The return of saline waters to the water supply, even when sufficient dilution occurs to keep the salinity of the mixture within apparently safe limits, reduces the quantity of the total water supply that can be used in consumptive processes which are limited by salt concentration, such as the growth of salt–sensitive crops (the reasons for this are explained below).

The above shows that the extent and areal sources of water pollution related to salinization from irrigation has not been well quantified; an inventory needs to be undertaken in this regard, especially one that considers the effect that salinity has on the potential usability of the water supplies for consumption. A logic is presented later regarding appropriate concepts for assessing such usability. Additionally, a methodology is introduced for determining the areal, diffuse sources of salt-loading from irrigation.

C. Principles, Strategies and Practices for Controlling Salinity

Others have written about the question: is irrigation sustainable? (Letey, 1994; van Schilfgaarde, 1990). I will not repeat nor critique their evaluations, because I agree with their primary conclusions that sustainability is technically possible. Most of the salinity-related degradational problems associated with irrigated agriculture can be prevented, or greatly minimized, with the proper design and operation of the irrigation and drainage systems, together with the implementation of proper crop and soil management practices provided proper political and social structures are in place which permit such undertakings. The implementation of appropriate irrigation/drainage management practices are key, essential requisites to the conservation of the worlds soil and water resources, to the protection of their quality and to the preservation of the irrigation-based agriculture that is needed to meet the food needs of the expanding world population. Implementing an appropriate means of minimizing leaching and disposing of the saline drainage effluent resulting from irrigation are very important in this regard. Furthermore, based on the data presented in Sections A and B, I believe that we have no alternative but to sustain irrigation and, where its productivity has been degraded, to rejuvenate it, if we are to meet our future food needs on a worldwide basis. Therefore, I believe that a more relevant question than is irrigation sustainable is: what must be done to sustain and rejuvenate irrigation from the ravages of salinization and waterlogging?

The attention given to the problem of soil and water degradation to date has not been sufficient to avoid its continuing onslaught upon our dwindling land and water resources, nor to remediate the degradation that has already happened. Seemingly, the governing bodies around the world have not yet taken the impending salinity-threat to our ability to produce enough food for our expanding population seriously enough to plan and implement the programs that are necessary to solve the present problems of soil and water salinization much less than to prepare for the dismal outlook that emerges from the kind of data reviewed above. I believe that the misconception that the "blue" revolution was "green" and primarily due to the accomplishments of plant breeders and geneticists is partly responsible for this. It also has unduly misdirected research and developmental efforts away from soil and water conservation management to bio-engineering and has caused key decision-makers to place undue reliance upon the latter group to meet the increasing worlds food needs. If the conclusions presented in Sections A and B are correct, our future food production capacity will, most likely, be more dependent upon protecting and enhancing the worlds soil and water resources.

This paper was developed with the hope that the information presented will: 1) enhance the awareness of the importance of irrigation to food production and the seriousness of the salinity and waterlogging problems in this regard, 2) encourage the initiation of studies and programs to deal with the present and emerging soil and water salinization problems and , as well, 3) provide some information that planners and managers may use to effectively develop and implement meaningful, effective programs to bring about real solutions to these problems. Towards this goal, the extent of and the major causes of soil and water salinization and some important effects of irrigation/drainage on soil and water quality and on their usability for crop production were discussed in the preceding section, as was the importance of irrigation agriculture to the worlds food productivity capacity. In the following sections, some important needs and principles & strategies for the control of soil salinity and the protection of water quality from irrigation will be highlighted and recommended. The justification for presenting this technical, management information is the belief I have that many well intentioned, but technically misdirected, salinity control programs have been undertaken in the past. I hope to provide a clear and rational focus that decision makers may use as a basis for the selection of alternative management strategies, approaches and practices, ones that will be more appropriate than many that have been used in the past and that even now are being adopted and implemented around the world, to deal with soil and water salinization problems in food production and environmental protection. I want to emphasize that rejuvenation of degraded irrigated lands needs to be distinguished and stressed in this matter, though much of the management that is needed to control the further decline in the productivity of developed irrigated lands will also assist in the rejuvenation of presently salinized lands.

1. Introduction

As explained above, irrigated agriculture is necessary but, like most all of technology, comes with a down side as well. While irrigation has greatly increased crop productivity, excessive irrigation has wasted water and the excessive drainage resulting from it has polluted surface waters and groundwaters, and has degraded the productivity and altered the ecology of vast areas of land in the world. As also reviewed above, contamination of water supplies by drainage is, in many places, posing health risks and surface and groundwaters in many areas are being contaminated by salts, fertilizers, herbicides and pesticides. Toxic chemicals are rendering some developed water supplies unfit for drinking and even for irrigation, in some cases. These pollutants also degrade the recreational use and esthetic value of surface waters. At the same time, costly restrictions are being placed upon irrigation in some places in the world, in order to reduce or mitigate its pollutional drainage-discharges. Finding a suitable, acceptable place for the discharge of drainage water is increasingly becoming a major problem, especially in the developed countries of the world. Blending saline and fresh waters is often undertaken to reduce the pollutional consequences of drainage disposal, but this action reduces the potential usability of the total water supply. Use of polluted waters for irrigation, as will be shown in this Section, limits crop production potential, as well as posing some potential health hazards to the consumers of the food produced with it.

As also explained in the preceding Section, the majority of the soil degradation (salinity and waterlogging) related to irrigated agriculture occurring throughout the world, and of the associated degradation of water-quality as well, are caused by inefficiencies in the distribution and application of irrigation water, the resulting mobilization and accumulation of excess water and salts in certain localized regions related to geohydrologic conditions and to the return of excessively saline drainage waters to fresh water supplies. It is important to note that these problems have occurred even where low-salinity waters have been used for irrigation. Thus it might be argued that the use of saline waters for irrigation can only increase these problems, since more salt will be added to the soils with such waters and relatively more leaching (hence drainage) is required in this case for salinity control of the rootzone. However, as seemingly paradoxically as this may seem to be, such need not be the case. The reuse of certain saline drainage waters should not, as will be discussed later, result in excessively saline soils nor cause waterlogging with proper management. In fact, the interception of drainage waters percolating below rootzones and their reuse for irrigation should reduce the overall (regional basis) amount of soil degradation associated with excessive deep percolation, salt mobilization, waterlogging and secondary salinization that would otherwise occur in irrigated lands (Rhoades, 1989). It should also reduce the water pollution problems associated with the discharge of drainage water to good–quality water supplies (Rhoades, 1989). For these reasons, an integrated irrigation and drainage management system for facilitating the use of saline drainage waters for irrigation is advocated for purposes of water conservation and for minimizing the soil degradational and water pollution problems associated with drainage. This system will be discussed a little more detail later.

To overcome the soil- and water-salinity problems discussed in Section B, new ways must be developed and implemented in the worlds irrigated lands to reduce excessive water uses in irrigation, to reduce soil salinization and water-logging and to protect the quality of associated water supplies and better ways must be found to implement existing technology appropriate to these needs. Efficiency of irrigation must be increased by the development and adoption of appropriate management strategies, systems and practices and through education and training. Reuse of saline drainage water and shallow groundwater for crop production, should be made an integral component of water conservation, soil conservation and environmental protection programs. Effective salinity control measures must be implemented to sustain irrigated agriculture and to prevent pollution of associated water resources. Such measures must be chosen with recognition of the natural processes operative in large irrigated, geohydrologic systems, as well as those on–farm, and with an understanding of how they affect the long-term quality of soil and water resources, as well as crop production. Some practices can be used to control salinity within the crop rootzone, while other practices can be used to control salinity within larger units of management, such as within irrigation projects, river basins, etc. Additional practices can be used to protect off–site environments and ecological systems – including the associated surface and groundwater resources. "On–farm" practices, which consist of agronomic and engineering operations, must be applied by the individual farmers on a field–by–field basis. "District–wide" or "larger organizational basis" practices, which generally consist primarily of engineering structures for water control (both delivery and discharge) and systems for the collection, reuse, treatment and/or disposal of drainage waters, are usually most appropriately applied by the responsible governmental entities.

There is usually no "single–way" to achieve salinity control in irrigated lands and associated waters. Many different/alternative approaches and practices potentially can be combined into satisfactory control systems; the appropriate combination depends upon the specific economic, climatic, social, as well as edaphic and geohydrologic situations. Thus, no specific recommendations are given here for "the" appropriate set of control practices for different situations or countries. They are too numerous. However, there are some important principles, goals and strategies of salinity management that can be given and that should be understood and considered by planners and decision makers in order to facilitate the sustainability and rejuvenation of irrigation. The proper management of salinity and drainage requires an understanding of how salts affect plants and soils, of how geohydrologic processes affect waterlogging and salt accumulation, and also of how cropping and irrigation activities affect soil and water salinity. These principles, goals, strategies and practices will be briefly presented and discussed in the remainder of this paper. References will be given where more detailed information may be obtained. The intent is to provide policy-makers and managers with enough of an understanding in these matters to help guide them to develop and implement the more appropriate irrigation-, drainage- and salinity control- strategies, activities and programs that are needed, in order to better deal with the emerging problems that they will be increasingly faced with in the future. This material is discussed more fully elsewhere (Rhoades, et al., 1992; Rhoades, 1993a). Additionally, some research needs will be identified where present knowledge and methodology is inadequate.

2. Management Goals for Enhanced Crop Production and Soil Protection

Grow Suitably Tolerant Crops

Because different crops and even different cultivars of the same crop vary considerably in their tolerance to salinity, crops should be selected that will produce satisfactorily for the particular existing conditions of salinity and those expected to occur in the rootzone during the growing season. For degraded lands, cropping rotations need to be selected to facilitate rejuvenation. The most comprehensive list of salinity tolerance values of common cultivated crops presently available for use in this regard are those summarized by Maas [1990]. Plant density should also be increased to compensate for smaller plant size that exists under saline conditions. This increases the interception of the incoming energy of the sun, and hence crop yield, relative to normal densities. It is especially important to consider the crop's salt tolerance during seedling development. This is often the most sensitive growth stage (Shannon, [1982]), and optimum yields are impossible without the satisfactory establishment of crop stand. Salt present in the seedbed reduces the rate of germination and thus increases the time to emergence. The stand may then suffer because the seedling is unable to emerge through the soil crusts which result from surface drying, as well as because of the increased opportunity-time for disease problems to develop due to the delay in emergence. When a crust is likely to develop, sowing rate should be increased to facilitate seedling emergence and stand establishment. Other techniques should be used to combat crusts, including the use of various forms of mulching and, in the case of sodic soils, the application of certain tilth-improving amendments, such as gypsum. Some of these techniques are discussed more in the next section. More knowledge of the differences in plant salt-tolerance during the various growth stages need to be established so that the "cyclic" strategy of irrigating with saline waters, which is described later, can be better optimized. Crop-plants of increased tolerance to salinity and associated stresses should be sought and developed through genetics and bio-engineering and halophytes need to be sought and adapted to cropping and the production of useful biomass utilizing saline waters and lands (Shannon, et al., 1993). More attention needs to be directed to developing crop rotations that promote the lowering of water tables, leaching and soil aggregation to help rejuvenate salinized and water-logged soils, while cropping continues. Computer programs need to be developed to adjust salinity analyses made on extracts of gypsiferous soil samples for the additional salts brought into solution during the extraction process, which cause the determined salinities to appear to be erroneously high-since such errors often cause misinterpretations and inappropriate management decisions.

Prevent Excessive Salinity Accumulation in the Seedbed

Excessive salt accumulation can be especially damaging to germination and seedling establishment when raised beds or ridges are used and "wet-up" by furrow irrigation, even when the average salt levels in the soil and in the irrigation water are moderately low. Since salts move with the water, the salt accumulates progressively towards the surface and center of the raised bed or ridge and is most damaging when a single row of seeds is planted in the central position. This is so because salts tend to accumulate under furrow irrigation in those regions of the seedbed where the water flows converge and evaporate; this problem is magnified when saline waters are used for irrigation (Bernstein and Fireman, 1957). Information from this early, classic study show that seedbed and furrow shape can be designed to minimize this problem. Seed placement and surface irrigation strategies (e.g., alternative furrow, depth of water in furrows, etc.) that can be used to optimize plant establishment under saline conditions are described by Kruse et al. (1990). Thus, seedbed shape, seed location and irrigation procedures should be managed to prevent the excessive, localized accumulation of salts in the region of the soil where the young plants roots are developing. Saline, "bed–peaks" can be de-topped to prevent exposure to emerging shoots. With double-row beds, under moderately saline conditions, most of the salt is carried into the center of the bed, leaving the shoulders relatively free of salt and more suitable for seedling establishment. Sloping beds are best suited for soils irrigated with saline waters because the seedling can be established "downslope" below the zone of salt accumulation. The salt is moved away from around the seedling instead of accumulating near it. Planting in furrows or basins is satisfactory from the stand-point of salinity control but can be unfavorable for the emergence of many row crops because of crusting or poor aeration. Pre-emergence irrigation by sprinklers or drip lines placed close to the seed may be used to keep the soluble salt concentration low in the seedbed during germination and seedling establishment. Special temporary furrows may also be used in place of drip lines during the seedling establishment period. After the seedlings are established, the special furrows may be abandoned and new furrows made between the rows; likewise sprinkling may be substituted for furrow irrigation during this critical period. Sprinkler irrigation can be effective in leaching excessive salinity from the top–soil and in producing a favorable low–salinity environment in the upper soil layer which is necessary for the establishment of salt–sensitive seedlings (Bernstein and Francois, 1973). However, other problems (such as foliar injury) are can result from the sprinkling with saline water. Under drip irrigation, the salt content is usually lowest in the soil immediately below and adjacent to the emitters and highest in the periphery of the wetted zone. Removal of salt that has accumulated in this wetting zone "front" must be addressed in the long–term. The management requirements of drip-irrigated crops for such long-term salinity control needs more research and development.

Sodic soils are prone, especially when irrigated with low-salinity waters or when subjected to rainfall, to undergo clay dispersion, disaggregation and slaking and, upon drying and consolidation, to surface crusting (Rhoades and Loveday, [1990]). Frequently the surface soil "sets-up" into a massive layer, or the aggregates fuse together to form a tilth that is too coarse and cloddy for a suitable seedbed. Application of various chemical amendments, such as gypsum and various soil conditioners, should be used to alleviate such conditions, thus enabling better seedling emergence, improved water entry and water storage, increased leaching of soluble salts, reduced tillage costs and greater flexibility of "bedding" operations. Practices which maintain high organic matter levels in the soil, e.g., green manuring and incorporation of crop residues, also help in the maintenance of good tilth. Where structural conditions are likely to hinder seedling emergence and crop establishment, more frequent light irrigations may be applied to soften crusts. More research is needed to quantify the amendment requirements for different conditions of soils, irrigation waters, rainfall and crop management.

Barren or poor areas, in otherwise productive fields, are often high or low spots that receive insufficient or excessive water for good plant growth. Where irrigation is by flood or furrow methods, careful land grading, such as that obtained using laser-controlled earth-moving equipment, is required to achieve uniform water application and consequently better salinity control. Where perennial crops are planned, planting should be delayed after land grading for 1 or 2 years during which time annual crops are grown and the fill-areas allowed to settle prior to re-grading for the permanent planting.

Deliver Water to Fields in Correct Amounts and Timing

Salinity control of irrigated lands generally requires good irrigation management. The prime requirements of irrigation management for salinity control are timely uniform irrigations, adequate leaching, adequate drainage and water table depth control. Various contributing and interacting factors are involved in fulfilling these requirements. These include the delivery system and the method and manner of irrigation. The key to effective, efficient irrigation (and hence salinity control) is to uniformly provide the plants with the proper amount of water at the proper time, without excess. Thus, careful control of timing, of application uniformity and of amount of water applied are prerequisites to high water use efficiency and to high crop yield, especially when irrigating with saline waters. This calls, optimally, for water delivery to the field on demand which, in turn, requires close coordination between the irrigator and the organization that distributes the water; it calls for measurement of water flow (rates and volumes), feedback devices that measure the water and salt content of the soil, ways to predict or measure the rate of water use by the crop and ways to detect or predict the onset of plant stress, and it also calls for the accurate control of volume delivered to each field and its uniform areal distribution within it.

For efficient control of a supply system, the water volume passing critical points, including the outlets to individual fields, needs to be controlled and metered. This demands the installation of effective flow controlling and measuring devices, without which seepage losses are difficult to identify and an over-application of water to fields is likely to occur. Additionally, many delivery systems encourage, if not cause, over-irrigation because the water is supplied for fixed periods, or in fixed amounts, irrespective of seasonal variations in on-farm needs. Such systems also preclude the use of some types of irrigation that are more capable of higher efficiency; such as sprinkler and drip. The optimum drip-irrigation scheme provides water nearly continuously, but very slowly, to keep the soil water content in the rootzone within narrow limits, although carefully programmed periods of stress may be desirable and provided in order to obtain maximum economic yield with some crops; cultural practices also may demand periods of "dry" soil. Thus, for such systems, water delivery needs to be on-demand, which requires appropriate delivery facilities.

Excessive loss of irrigation water from canals constructed in permeable soil contributes considerably to high water tables and the creation of saline soils in many irrigation projects. Such seepage losses should be reduced by lining the canals with impermeable materials or by compacting the soil in the wetted perimeter to achieve low permeability.

The maintenance of the drainage system is also important in this regard and the tile lines or open ditches of the fields and project should be kept clean and on-grade. Over-irrigation also contributes to shallow water table and salinity problems, as well as increasing the amount of water that the drainage system must accommodate. Therefore, a proper relation between irrigation management and drainage must be maintained in order to prevent irrigated lands from becoming salt affected and waterlogged. The amount of water applied should be sufficient to supply the crop and satisfy the leaching requirement but not enough to overload the drainage system. It is important to recognize that inefficient irrigation is the major cause of salinity and shallow water tables in most irrigation projects of the world and that the need for drainage can usually be reduced through improvements in irrigation management. Ways to improve irrigation efficiency should usually be sought first before the drainage capacity is increased.

The primary sources of return flow from an irrigation project are bypass water, canal seepage, deep percolation, and surface (tailwater) runoff. Bypass water is often required to maintain hydraulic head and adequate flow through a gravity–controlled canal system. It is usually returned directly to the river, and few pollutants, if any, are picked up in this route. Evaporation losses from canals commonly amount to only a small percentage of the diverted water. But seepage from unlined canals is often substantial. It may contribute to high water tables, increase groundwater salinity and phreatophyte growth, and generally increases the amount and salinity of the required drainage from irrigated areas. If the water passes through salt–laden substrata or displaces saline groundwater, the salt pickup from this source can be substantial. Canal lining can reduce such water-logging and salt loading. Closed conduit conveyance systems can minimize both seepage and evaporation losses and the use of water by phreatophytes. The closed conduit system also provides the potential to increase project irrigation efficiency and to thus lower salt loading (van Schilfgaarde and Rawlins, 1980). Thus, canals should be lined and closed conduit delivery and drainage systems should be provided, wherever possible, to facilitate salinity control and water conservation.

Irrigate Efficiently with Minimized Leaching and Provide Drainage

As mentioned earlier, the concentrations of soluble salts increase in soils in proportion to the amount and salinity of the irrigation water and as the soil water, but not salt, is removed by evaporation and transpiration. Additionally, evapotranspiration (ET) can cause the upward flow of water (and, hence, salt) from a shallow groundwater into the rootzone, thus also increasing soil salinity. It is by this latter process, that most soils with shallow, saline water tables become salinized. In either case, soluble salts will eventually accumulate in irrigated soils to the point that crop yields will suffer unless steps are taken to prevent it.

To prevent the excessive accumulation of salt in the rootzone from irrigation, extra water (or rainfall) must, over the long term, be applied in excess of that needed for ET and this excess must pass through the rootzone in a minimum net amount. This amount, in fractional terms, is referred to as the "leaching requirement" (L_r, the fraction of infiltrated water that must pass through the rootzone to keep salinity within acceptable levels; US Salinity Laboratory Staff, 1954). In fields irrigated to steady–state conditions with conventional irrigation management, the salt concentration of the soil water is essentially uniform near the soil surface regardless of the leaching fraction (L, the fraction of infiltrated water that actually passes through the rootzone) but increases with depth as L decreases. Likewise, average rootzone salinity increases as L decreases; crop yield is decreased when tolerable levels of average salinity are exceeded. Methods to calculate the leaching requirement and to predict crop yield losses due to salinity effects, under steady-state and uniform field conditions, are described elsewhere (Hoffman, et al., 1990; Rhoades, et al., 1992). Once the soil solution has reached the maximum salinity level compatible with the cropping system, at least as much salt as is brought in with additional irrigations must be removed from the rootzone; a process called "maintaining salt balance." The extent to which leaching and drainage can be minimized is limited by the salt tolerances of the crops being grown, the irrigation system distribution uniformities and the variability in soil infiltration rates. In most irrigation projects, the currently used leaching fractions (and resulting drainage volumes) can be reduced appreciably without harming crops or soils, especially with improvements in irrigation management (van Schilfgaarde et al., 1974). They <u>should be minimized</u> because the prevalent excesses in leaching are a major, fundamental cause of both soil and water salinization, for the reasons explained previously.

To prevent waterlogging and secondary salinization, drainage must remove the precipitation and irrigation water infiltrated into the soil that is in excess of crop demand and any other excessive water (surface or subsurface) that flows into the irrigated soils; it must provide an outlet for the removal of salts that accumulate in the rootzone in order to avoid excessive soil salinization, and it must keep the water table sufficiently deep to permit adequate root development, to prevent the net flow of salt–laden groundwater up into the rootzone by capillary forces and to permit the movement and operations of farm implements in the fields without excessive compaction. Artificial drainage systems should be provided in the absence of adequate natural drainage. The water table depth required to prevent a net upward flow of water and salt into the rootzone is dependent on irrigation management and is not single–valued as is commonly assumed (van Schilfgaarde, 1976). Methods to calculate drainage requirements are given elsewhere (Rhoades, 1974; Kruse et al., 1990; Hoffman et al., 1990).

The time–averaged level of rootzone salinity is affected by the degree to which the soil water is depleted between irrigations, as well as by the leaching fraction. As the time between irrigations is increased, soil water content decreases as the soil dries, and the matric and osmotic potentials of the soil water decrease as salts concentrate in the reduced volume of water. Water uptake and crop yield are closely related to the time- and depth-averaged total soil water potential, i.e., matric plus osmotic. Following irrigation, plant roots preferentially absorb water from rootzone depths with high water potential. As water is removed from a soil with nonuniform salinity distribution, the total water potential of the water being absorbed by the plant tends to approach uniformity in all depths of the rootzone. Normally this means that most of the water uptake is initially from the upper, less saline soil depths until sufficient water is removed to increase the total water stress to a level equal to that in the lower depths. After that, water is removed proportionately more from the deeper, more saline soil depths and the effect of salinity, per se, on crop growth is magnified. This implies that: (i) forms of irrigation that minimize matric stress, such as drip irrigation, should be used to minimize the harmful effects of irrigating with saline water, and (ii) leaching fractions should be increased, as needed, to minimize the buildup (hence harmful effects) of excessive levels of salinity in the deeper regions of the rootzone (Rhoades and Merrill, 1976).

The distribution within and the degree to which a soil profile becomes salinized also are functions of the manner of water application, as well as the leaching fraction. More salt is generally removed per unit of leachate with sprinkler irrigation than with flood irrigation. Thus, the salinity of water applied by sprinkler irrigation can be somewhat higher, all else being equal, than that applied by flood or furrow irrigation with a comparable degree of cropping success, provided foliar burn is avoided. The high salt–removal efficiency of sprinkler irrigation may be explained as follows. Solute transport is governed by the combined processes of convection (movement of solutes with the bulk solution) and diffusion (independent movement of solutes as driven by a concentration gradient); convection is usually the predominant process in flood–irrigated soils. Differential velocities of water flow can occur within the soil matrix because the pore size distribution is typically nonuniform. This phenomenon is called dispersion. It can be appreciable when flow velocity is high and pore size distribution is large; diffusion often limits salt removal under such conditions. Soils with large cracks and well–developed structure are especially variable in their water and solute transport properties because the large "pores" are preferred pathways for water flow, as are earthworm channels, old root holes, interpedal voids, etc.; most of the flow in flooded soils occurs via these "pores". Much of the water and salt in the small and intra–aggregate pores is "bypassed" in flood irrigated soils. Flow velocity and water content are typically lower in soils irrigated with sprinklers; hence, bypass is reduced and efficiency of salt leaching is increased with sprinkler irrigation. Other soil–related processes also affect salt concentration and transport during the irrigation and leaching of soils. In most arid land soils, the clay particles are dominated by negative charges, which can retard cation transport through adsorption and/or exchange processes. Simultaneously, anions are largely excluded from that part of the pore solution adjacent to the negatively charged clay surface; this accelerates their relative transport. The borate anion also undergoes adsorption reactions that retard its movement. For a more quantitative description of effects of convection and dispersion, as well as other soil factors, on solute transport in soils see the reviews of Wagenet (1984) and Jury (1984).

Susceptible crops should not be sprinkler-irrigated with saline water, since their foliage absorbs salts upon wetting. Salts can accumulate in leaves by foliar absorption of such crops until lethal concentrations have been reached. Crop sensitivity to saline sprinkling water is related more to the rate of foliar salt accumulation than to crop tolerance to soil salinity, per se (Maas, 1990). Hence, applications should be made during the night and in a manner to achieve frequent wetting ("washing") of the leaves in order to minimize foliar absorption of salts when irrigating with saline waters by sprinkler methods.

Monitor Soil Salinity to Evaluate Irrigation/Drainage Adequacy

Traditionally, the concepts of leaching requirement (LR) and salt-balance-index (SBI) have been used to judge the adequacy and appropriateness of irrigation and drainage systems, operations and practices with respect to salinity control, water use efficiency and irrigation sustainability (U. S. Salinity Laboratory Staff, 1954). However, these latter approaches are inadequate for these purposes. There are many reasons for this conclusion; some are given in the following paragraphs.

The leaching requirement, which refers to the amount of leaching required to prevent excessive loss in crop yield caused by salinity buildup within the rootzone from the irrigation water per se, is a "concept" based on assumptions of steady-state and absolutely uniform conditions of irrigation, infiltration and evapotranspiration, none of which is achieved in most field situations which, typically, are dynamic and variable, both spatially and temporally. Salt buildup in the rootzone caused by "subbing" of water from a shallow, water table is not accounted for in this concept nor is it in the traditional method for determining the SBI. Additionally, there is no practical way to directly measure the degree of leaching being achieved in a field, much less in the various parts of a field, in order to determine its uniformity, adequacy and appropriateness. On the other hand, it is possible to measure soil salinity and its distribution within a field and through the rootzone and, from this information, to assess whether it is within acceptable limits for crop production and to infer whether leaching is adequate and uniform, or not, anywhere in a field and likewise to assess whether drainage is adequate, since salinity is a tracer of the net processes of infiltration, leaching, evapotranspiration and drainage. In fact, the concentration and distribution of salinity through the rootzone is a direct reflection of the net interaction of these processes and gives you a meaningful measure of the adequacy/appropriateness of irrigation/drainage. The magnitude and distribution of salinity within the field and the soil profile provide direct information of the uniformity and direction of net water flux and hence of the adequacy of the irrigation/drainage system in the field (Rhoades, 1976, 1980, 1992a). Thus, I recommend that direct monitoring of rootzone salinity levels and distributions across fields be undertaken periodically to evaluate the effectiveness of salinity, irrigation and drainage management programs (Rhoades, 1978, 1979; Rhoades, et.al., 1997).

As explained earlier, the salt-balance index, which refers to the net difference between salt added to an irrigation project in the irrigation water and that removed in its drainage effluent, has been traditionally used to evaluate the adequacy/appropriateness of leaching, irrigation and drainage practices at the project scale. This approach is inadequate for these purposes because it provides no information about the absolute level of salinity within the rootzones of any crop or specific field within the project. Nor does it provide a realistic measure with which to judge whether, or not, the project is trending towards an increase, or decrease, in salinity within the rootzone, because salinity from below the soil profile and of geologic origin is typically contained in the drainage water collected from the subsurface drain system (Rhoades, 1974; Kaddah and Rhoades, 1976). Additionally, the transit times involved in the drainage flows resulting from a given irrigation event are so long (usually more than 25 years) that the index values are not reflective of current trends (Jury, 1975a, 1975b).

Thus, I conclude that the effectiveness of irrigation & drainage design and management and of water-table & salinity control can not be achieved using LR and SBI concepts. I also conclude that periodic information of soil salinity levels and distributions within the crop rootzones and fields of the project is practical to obtain and useful to inventory conditions of soil salinity, to assess the adequacy of leaching and drainage and to guide management practices. Such information can also be used to delineate the diffuse source-areas of salt-loading within irrigated lands and to map the distribution and extent of drainage problem areas.

In my opinion, the proper management of soil and water salinity requires the following: 1) an adequate knowledge of the level, extent, magnitude and distribution of rootzone soil salinity in the fields of the irrigation project (a suitable inventory of conditions); 2) the ability to be able to detect changes and trends in the status of soil salinity over time and the ability to determine the impact of management changes upon the conditions (a suitable monitoring program); 3) the ability to identify salinity problems and their underlying/inherent causes, both natural and management-induced (a suitable means of detecting & diagnosing problems and identifying their causes); 4) a means to evaluate the adequacy and effectiveness of on-going irrigation and drainage systems, operations and practices with respect to controlling soil salinity, conserving water supplies and protecting water quality from excessive salinization (a suitable means of evaluating management practices), and 5) the ability to determine the areas in fields and in irrigation projects where excessive deep percolation is occurring, i.e., where the water- and salt-loading contributions to the underlying groundwater are coming from (a suitable means of determining areal sources of pollution). I refer to the above set of measurement-related techniques and methods and the means of evaluation of adequacy & appropriateness, as "salinity assessment" (Rhoades, et al., 1997). I believe that the countries of the world with salinity problems should implement assessment programs which provide the above information in a timely and efficient way. Smedema (1995) has similarly concluded that " in many developing countries policy formulation and project preparation are severely handicapped by lack of reliable information on the nature and extent of the affected area. Salinity is a highly variable condition and difficult to monitor and to map with presently used observation methods. Development of suitable remote sensing methods, therefore, would be of considerable aid to countries in their combat of the problem of waterlogging and salination of irrigated land."

The achievement of an assessment technology such as the above begins with a practical methodology for measuring soil salinity in the field, which is complicated by its spatially variable and dynamic nature caused by the effects and interactions of varying edaphic factors (soil permeability, water table depth, salinity of perched groundwater, topography, soil parent material, geohyrology), management induced processes (irrigation, drainage, tillage, cropping practices), as well as by climate-related factors (rainfall, amount and distribution, temperature, relative humidity, wind). When the need for repeated measurements and extensive sampling requirements are met, the expenditure of time and effort to characterize and map a field's or project's salinity condition with conventional soil sampling and laboratory-analysis procedures becomes prohibitive. A more rapid, field-measurement technology is needed. This assessment technology should account for the spatial location of the measurement sites involved with the required large intensive and extensive data sets, it should provide a systematic methodology for evaluating management effects, and it should be able to detect changes or differences occurring in an areas salinity condition over both time and space.

Over the course of many years I, with the help of my colleagues, have been developing such a technology. It is now mostly completed. It is an integrated system comprised of rapid, mobile instrumental techniques for measuring bulk soil electrical conductivity (EC_a) directly in the field as a function of spatial position on the landscape, procedures and software for inferring salinity from EC_a, computer-assisted mapping techniques capable of associating and analyzing large spatial databases, and appropriate spatial statistics to infer salinity distributions in rootzones and changes in salinity over space and time. Descriptions of this assessment system, its theory, software and algorithms and examples of its utility are given in the following references: Rhoades, 1990c, 1992b, 1993b, 1994; Rhoades, et al. 1989a, 1989b, 1990d, 1993, 1996a, 1996, 1997; Lesch et al., 1992, 1995a, 1995b, 1997). The equipment is now commercially available, with improved modifications. The mechanical design of an earlier (second generation) version of this system is described in Carter, et. al. (1993).

3. Management for Water Quality and Environmental Protection

As explained in Section B, drainage from irrigated agriculture is a major contributor to the salinity of many surface and groundwaters. The agricultural community has a need and responsibility to protect the quality of these waters. It must also maintain a viable, permanent irrigated agriculture. Irrigated agriculture cannot be sustained without adequate leaching and drainage to prevent excessive salinization of the soil, yet these processes are the very ones that contribute to the salt loading of our surface and groundwaters. But surface and groundwater salinity could be reduced, if salt loading contributions from the irrigation processes were minimized or eliminated. The protection of our water resources against excessive salinization, while sustaining agricultural production through irrigation, requires the implementation of comprehensive land and water use policies that incorporate the natural processes involved in the soil–plant–water and associated geohydrologic systems. Appropriate policies in this regard need to be developed and effectively implemented in the worlds irrigated lands to protect associated water resources.

Alternative strategies to consider in decreasing salinity in receiving water supplies affected by irrigation and drainage include: (i) eliminating irrigation of certain polluting lands, (ii) intercepting point sources of drainage return flow and diverting them to appropriate disposal sites or treatment facilities, (iii) reducing drainage by reducing the amount of water lost in seepage and deep percolation and (iv) isolating saline drainage water from good quality water supplies and reusing them for irrigation. Only the last two strategies are discussed herein, primarily the last one. Since some effects of irrigation/drainage are operative at the scale of whole projects and entire geohydrologic systems, management practices for drainage disposal and salinity control should address this larger scale. Therefore, the following several paragraphs also provide a brief review of such information, as a basis for developing appropriate management requirements and establishing relevant policy for controlling water (and soil) salinity.

Minimize Deep Percolation and Intercept Drainage

As shown by Rhoades et al. (1974) and Oster and Rhoades (1975, 1990), the total salt–load discharged from the irrigated rootzone in percolation-water can be reduced by about 2 to 12 metric tons/ha/year as the leaching fraction is reduced from 0.3 to 0.1. Such a reduction in salt return is achieved in three ways. Less salt is discharged with reduced leaching because less irrigation water, and hence less salt, is applied. The percent reduction in salt discharge due to reduced application is 100 $(V_H - V_L)/V_L$, where V_H and V_L are volumes of irrigation water applied with high and low leaching, respectively. Reduced leaching reduces the discharged salt-load still more because the fraction of applied salt that precipitates as minerals (such as calcite and gypsum) in the rootzone region of the soil increases. A further benefit of reduced leaching is that less additional "geologic" salts are "picked-up" by the percolating water from the weathering and dissolution of soil and substrata minerals, because the through–put of drainage water is reduced and the "solvent" capacity of the more saline water resulting from low leaching is likewise reduced. Thus, as compared to high leaching, minimized leaching reduces the amount of salt added to soils and discharged from irrigated rootzones because it maximizes the precipitation of applied Ca, HCO_3 and SO_4 salts as carbonate and gypsum minerals in the soil, and it minimizes the "pick–up" of weathered and dissolved salts from the soil and substrata. While minimized leaching reduces the volume of drainage water and the absolute amount of salt discharged; it increases the concentration of the drainage water. Thus, where the drainage waters can be intercepted before being returned to surface or groundwaters, such reductions of salt load and volume of drainage and increases in salt concentration are of substantial benefit. This is especially true where the drainage waters are to be collected and desalted (Rhoades and Suarez, 1977), as has been undertaken for the drainage effluent from the Wellton-Mohawk irrigation project in Arizona (van Schilfgaarde, 1982) and as might more logically be considered for implementation in the Gulf States where the use of desalting technology is more economically feasible.

On the other hand, minimizing leaching may, or may not, reduce the salinity degradation of the receiving water where the drainage water is returned to a surface or groundwater (Rhoades and Suarez, 1977). A reduction of degradation will generally always occur where saline groundwaters with concentrations in excess of those of the recharging rootzone drainage waters are displaced into the receiving water or where additional salts, other than those derived from the irrigation water per se, are encountered and mobilized in the drainage flow–path and brought into solution by weathering and dissolution processes. Examples are the Colorado River in America and many rivers in Iran where much of the irrigated landscape is underlain with strata which contain high amounts of readily soluble salts. Here, minimizing leaching should substantially reduce the salt load in the rivers downstream of the irrigation projects by reducing the "pick–up" of geologic salts as the drainage water percolates past the rootzone and through these strata and/or displaces highly saline groundwater present in the underlying aquifers which connect with the rivers. For conditions like these, reduced leaching will always reduce the salinity of the river downstream from the project. Similar results will also occur under conditions where the irrigated soils, or underlying substrata, contain gypsum or other forms of mineral–salts, such as are typical of Iraq, Iran and Syria.

On the other hand, for geohydrologic situations, such as the Nile River south of the northern delta and much of the Indus River in Pakistan, where little salt of geologic origin exist in the soils or substrata associated with the irrigated lands, the composition of the deeply percolating drainage water is little changed from that leaving the rootzone. For such cases, the composition of the co–mingled drainage plus receiving water may be about the same regardless of leaching fraction, depending upon the saturation status of the receiving water with respect to calcium carbonate and gypsum and fate of water "saved" by reduced leaching. Thus, minimized leaching will be less beneficial, from the point of view of reducing the salinization of the water supplies receiving drainage water, for the geohydrologic conditions of the irrigated lands associated with the Nile and Indus Rivers due to the absence of major sources of salts in the underlying strata of these lands.

As with river systems, degradation of groundwaters receiving irrigation drainage may or may not be benefited by reduced leaching, depending on the geohydrologic situation. With no sources of recharge other than drainage return flow, the groundwater eventually tends toward the composition of the drainage water, which will be more saline with low leaching (Rhoades and Suarez, 1977). However, reduced leaching slows the arrival time of the leachate. Thus, the groundwater salinity will generally be lower for an interim period of time with reduced leaching (Suarez and van Genuchten, 1981). Low leaching management can continuously reduce degradation of the groundwater, only if other sources of high–quality recharge into the basin exist and if flow out of the basin is high relative to drainage inflow. This matter is one that should be considered in the case of the Nile and Indus River systems, especially the latter, given their extensive groundwater basins and, for the case of Pakistan, the major use made of the groundwaters for irrigation. For more discussion of the effect of drainage management on groundwater pollution see Rhoades and Suarez, 1977.

For the above reasons, the "minimized leaching" concept of irrigation which reduces deep percolation should be adopted and implemented to reduce salinization of water resources associated with irrigation projects, especially in projects underlain by salt–laden sediments (van Schilfgaarde et al., 1974; Rhoades and Suarez, 1977). In addition, saline drainage water should be intercepted. Intercepted saline drainage water can be desalted and reused, disposed of by pond evaporation or by injection into some isolated deep aquifer, or it can be used as a water supply where use of saline water is appropriate. Desalination of agricultural drainage waters for improving water quality is not generally economically feasible even though was implemented for the return flow of the Wellton–Mohawk irrigation project of Arizona, USA. The high costs of the pretreatment, maintenance, and power are deterrents. Only in extreme cases, or for political rather than technical reasons, is desalination advocated (van Schilfgaarde, 1979, 1982).

Intercept, Isolate and Reuse Drainage Water for Irrigation

The ultimate goal of irrigation management should be to minimize the amount of water extracted from the projects good–quality water supply and to maximize the utilization of the extracted portion during irrigation use, so that as much of it as possible is consumed in transpiration (hence producing biomass) and as little as possible is wasted and discharged as drainage. Towards this goal, to the extent that the drainage water from a field or project still has value for transpirational use by a crop (ie., the crop is sufficiently salt-tolerant to be able to extract the water from the saline solution at a rate fast enough to meet its transpirational requirement), it should be used again for irrigation before ultimate disposal (Rhoades, 1977, 1984b, 1984c, 1989). This will reduce drainage and the associated water salinization, as well as increase the available supply of water for irrigation. It will also reduce the waterlogging and overall amount of soil salinity degradation in the associated region.

Drainage waters are often returned by diffuse flow to the water course and automatically "reused". Drainage waters are also sometimes intentionally blended with low-salinity water supplies and then "reused" for irrigation as a means to increase water supplies. Additionally, saline drainage waters are sometimes blended with low-salinity waters before being discharged to good water supplies as part of water quality protection programs. All of these blending activities have serious drawbacks and limitations when one considers the overall effect that such blending has on the total volume of usable water in the combined supply relative to the separate supplies, and they should not be undertaken or advocated as a general method of salinity control (Rhoades, 1989, 1990b). There is considerable misconception about blending that needs to be corrected. A brief case will be made later to show the fallacy of the blending concept as it pertains to the objectives of increasing water supplies and protecting water quality.

A preferred and more fundamentally sound strategy to control the salinity of water resources associated with irrigated lands and to increase effective water supplies for crop growth (or other consumptive uses limited by salinity) is to intercept drainage waters before they are returned to the river (or other low-salinity water supply) and to use them directly for irrigation by substituting them for the low–salinity water normally used for irrigation at certain periods during the irrigation season of certain, suitably salt-tolerant crops grown in the rotation (Rhoades, 1984a, b, c, 1988). When the drainage water is too saline to be used directly for the crop in question, then its potential for reuse is exhausted and it should be discharged to some appropriate disposal outlet or treatment facility. Blending such an unusable water with pure water can not create usability in the saline component of the mix. At best during consumption of the blend, when a volume equal to the purer water is consumed, the original volume of the saline component will be regained (with the same salt concentration and condition of unusability), since salt is not removed in the consumption process. The alternative strategy that I have developed, however, will conserve water, will permit essentially full crop production, as well as minimize the salt loading of rivers that occurs by way of drainage return flows (Rhoades, 1984c, 1989). It will also reduce the amount of water that needs to be diverted for irrigation. Data obtained in modeling studies and in field experiments support the credibility and feasibility of this "cyclic" reuse strategy (Rhoades, 1977, 1984c, 1988, 1989a, b, and c; Minhas et al., 1989, 1990a and b). The strategy is now being tested in a pilot project in Australia (Heath and Heuperman, 1996). A modification of the concept to use the drainage water directly from the shallow water table by deficit irrigation and water table depth control has shown promising results (Ayars, 1996).

There are many different situations where the use of saline water for irrigation in the recommended strategy could be practical. One situation is where high quality water is available during the early growing season but is either too costly or too limited in supply to meet the entire seasons requirements. This situation is common in parts of Pakistan, for example. Where high quality water costs are prohibitive, crops of moderate to high salt tolerance could be irrigated with saline drainage or groundwater, especially at later growth stages with economical advantage, even if this practice results in some reduction in yield relative to that obtainable with a full supply of fresh water. Use of saline water for irrigation reduces the amount of high–quality water needed to grow crops and hence expands the total water–resource base for crop production.

Another situation conducive for such reuse is one where drainage water disposal, or a means of lowering an excessively shallow water table, is impractical due to physical, environmental, social and/or political factors. Reuse of the drainage water for irrigation in this situation decreases the volume of drainage water requiring disposal or treatment, and their associated costs (Rhoades, 1977). Furthermore, a reduction in the drainage volume also reduces the salt loading of the receiving water (Rhoades, 1984b). As an example, many growers in the San Joaquin Valley of California (USA) are presently undertaking reuse of drainage water, at least as a temporary solution, in order to reduce drainage volume and to meet recently imposed discharge restrictions related to protection of the quality and ecology of receiving water systems (Letey, 1994).

The long–term feasibility of using drainage water for irrigation in order to reduce drainage volume would likely be increased if implemented on a project or regional scale, rather than on a farm scale (Grattan and Rhoades, 1990, 1996). Regional management permits reuse in dedicated areas so as to avoid the successive increase in concentration of the drainage water that would occur if the reuse process were to operate on the same water supply and same land area (i.e., in a closed loop). With regional management, certain areas in the region can be dedicated to reuse while other areas, such as up-slope areas, are irrigated solely with high quality water as usual. The second–generation drainage water from the primary reuse area is discharged to other dedicated reuse areas where even more salt–tolerant crops are grown, or to regional evaporation ponds or to treatment plants. Ideally, regional coordination and cost sharing among growers should be undertaken in such a regional reuse system.

In order to plan and implement a successful practice involving the use of the cyclic, dual–rotation strategy for irrigating with saline drainage waters, various other technical, economic and soil considerations must also be addressed. These considerations are discussed elsewhere (Grattan and Rhoades, 1990, 1996).

Avoid Blending Waters for Irrigation or Disposal

As stated previously, the ultimate objective of drainage water reuse and of water quality protection should be to permit the maximum practical benefit (use) to be derived from the total water supply, ie. drainage water plus fresh water. Broadly speaking, water users may be classified into two groups: (1) those who consume the water in the process of use, and (2) those who use it without appreciable consumption. The type (1) users (which include crop producers) will suffer disbenefit in the "blending" philosophy of drainage water reuse and water quality protection. This conclusion will be briefly justified in this section.

Plant growth is directly proportional to water consumption through transpiration. Literature clearly demonstrating this fact and an explanation for its physical and physiological basis are given elsewhere (Sinclair, 1994). From the point of view of irrigated agriculture, the objective is to increase the amount of water available to support transpiration. In considering the use of a saline water for irrigation and in selecting appropriate policies and practices of drainage management to protect water quality, it is important to recognize that the total volume of a saline water supply cannot be beneficially consumed in crop production (ie., transpired by the plant); the greater its salinity, the less it can be consumed before the concentration becomes limiting to growth. Plants must have access to water of a quality that permits consumption without the concentration of salts (individually or totally) becoming excessive for adequate growth. In the process of transpiration, plants essentially separate nearly pure water from the salt solutions present in the rootzone; the pure water is transpired into the atmosphere and the salts are concentrated in the remaining unused soil water. This water ultimately becomes drainage water. A plant will not grow properly when the salt concentration in the soil water exceeds some limit specific to it under the given conditions of climate and management (Bernstein. 1975). This is even true for halophytes (Miyamoto, et al., 1996). Thus, it is obvious that not all of the water in a supply can be consumed by a plant, if the water contains salt. The practice of blending or diluting excessively saline waters with good quality water supplies should only be undertaken after consideration is given to how it affects the volumes of consumable (usable) water in the combined and separated supplies.

Various case-examples have been given in detail elsewhere to justify and illustrate some of the preceding conclusions (Rhoades, 1989; Rhoades and Dinar, 1991; Rhoades, et al., 1992). The principles illustrated in these case-examples apply equally to river systems in which waters are diverted upstream for irrigation and drainage waters are returned downstream. The case of such a hypothetical river system is also given elsewhere (Rhoades, 1989 and Rhoades and Dinar, 1991). This river-case study showed that the pollution of rivers that occur through the return of drainage waters to them can be avoided by intercepting the drainage return flows, reusing them for irrigation and isolating the ultimate unusable drainage from the river. Additionally, field experiments undertaken to test them have verified them. For the sake of space, I refer you to the following publications for this information (Rhoades, 1977, 1984c, 1988, 1989a, b, and c; Minhas et al., 1989, 1990a and b).

The results of the case-studies referred to above clearly show that blending waters that are themselves too saline for the intended consumptive use with good quality water supplies results in a volume of potentially consumable water in the combined supply that is less than that of the good–quality water fraction itself. The amount of such reduction in usable water will depend upon the relative volumes and concentrations of the low salinity (receiving) water and of the saline waste (drainage) water and upon the tolerances of the crops to be produced through irrigation. Therefore, the merits of blending should be evaluated on a case–by–case basis. In some cases, it may make economic sense to blend and to bear the consequences of the losses of water usability and of potential crop yield when the alternative costs of disposal are much more costly. The principle to be understood in this matter is the following: if a drainage (waste) water is too saline to be solely suitable for the crop in mind, then no additional consumptive-use benefit can be gained from it by blending it with a low-salinity water. But a loss can occur in the amount of such benefit that could have been achieved from the sole use of the low-salinity water for crop production.

Sometimes drainage waters are purposely diluted with a "good–quality" water to meet some specified discharge standard and then returned to a good–quality water supply. But as the above–described studies show, even when a relatively small volume of excessively saline water is incorporated into the larger good–quality water supply, the net result is that a fraction of this latter water is made unusable for transpiration by salt–sensitive crops. Thus it is concluded that blending or diluting drainage waters with good quality waters in order to increase water supplies or to meet discharge standards may be inappropriate under certain situations. Even though the concentration of the blend may appear to be low enough to be acceptable by conventional standards, the usability of the good–quality water supply for growing salt–sensitive crops (or for other salt–sensitive water uses) may be reduced through the process of blending. Each time the salt content of an agricultural water supply is increased, the degree to which it can be consumed before its concentration becomes excessive and limiting is decreased. More crop production can usually be achieved from the total water supply by keeping the saline and fresh water components separated. Serious consideration should be given to keeping saline drainage waters separate from the good–quality water supplies, especially when the latter waters are to be used for irrigation of salt–sensitive crops. The saline drainage waters can be used more effectively by substituting them for good–quality water to irrigate certain crops grown in the rotation after seedling establishment. Reuse of drainage water for irrigation of suitably salt–tolerant crops reduces the volume of drainage water needing ultimate disposal and, hence, the off–site pollution problems associated with the discharge of irrigation return flows.

D. Conclusions and Recommendations

A brief summary of some of the more salient aspects of the material that I have presented above on the matter of irrigation sustainability follows. For other views and opinions, see van Schilfgaarde, 1990; Letey, 1994; Smedema, 1995. For world-wide views on related research needs, see the summary of the NATO workshop on "Sustainability of Irrigated Agriculture (Sustainability of Water Resources Utilization in Agriculture) " prepared by Pereira, et al. (1996).

1. Crop Production Dependency on Irrigation

The demand for food in the world is on the increase and expected to become seriously limiting within the next decades. Irrigated agriculture is presently a major contributor to crop production. It contributes at least one-third of the worlds production and proportionately much more in arid countries like Egypt and Pakistan. The dependency on irrigation in this regard is expected to increase, especially in the Middle and Near East Regions of the world, over this period and beyond. But growth in the expansion of irrigation has dramatically slowed over the past decade or two to a present rate that is inadequate to keep up with the expanding food requirements, especially in these latter Regions. At the same time, presently developed irrigated lands and associated water resources are becoming substantially and increasingly degraded through salinization caused by irrigation and drainage activities. The seriousness of this matter needs to be fully grasped by the responsible leaders and agricultural and water resource managers of the various world organizations and appropriate policies and effective programs need to be developed and implemented to deal with this most serious matter.

2.. Degradational Aspects of Irrigation/Drainage

Irrigated agriculture has resulted in major environmental disturbances and its very sustainability is being questioned in many places in the world. In a number of countries, extensive areas of land have been degraded by waterlogging and salinization resulting from over–irrigation and other forms of poor agricultural management. Somewhere between 20-50% of the irrigated land produces substantially reduced yields because of salinity and waterlogging. Irrigated agriculture has also depleted water supplies, especially readily available surface waters and shallow groundwaters, and has polluted some of them as well. Contamination of water supplies by irrigation is, in many places, posing health risks and drastically increasing the costs of treating waters for domestic and industrial uses, as well as limiting crop production potential. The recreational, aesthetic and habitat values of many water systems and agricultural landscapes have also been degraded by irrigation development and practices. Costly regulations are being placed upon irrigation in some developed countries to reduce its pollutional discharges or to treat its wastes before discharge. Finding a suitable, acceptable place for such discharge is increasingly becoming a, if not "the", major problem concerning the sustainability and viability of irrigated agriculture, especially in some developed countries.

Most of the problems of waterlogging and secondary salinization prevalent in irrigated lands have resulted from the excessive use of water for irrigation due to inefficient irrigation distribution systems and poor on-farm management, and the discharge of "spent" drainage water into good–quality water supplies which are used elsewhere for crop production, or for domestic and industrial purposes. These problems have occurred even where low salinity waters have been used for irrigation. This might lead one to conclude that the use of saline drainage waters for irrigation can only increase these problems. However, this is not necessarily the case. The use of typical, saline drainage waters for irrigation will not result in excessively saline soils with proper management. In fact, the interception of drainage waters percolating below rootzones and the extraction of shallow underlying groundwaters and their reuse for irrigation is recommended to reduce the soil degradational processes associated with excessive deep percolation, salt mobilization, waterlogging and secondary salinization that typically occur in irrigated lands and the water pollution problems associated with their discharge to good–quality water supplies.

In considering the use of a saline drainage water for irrigation, especially with blending approaches, and in selecting appropriate management to protect water quality, it is important to recognize that: the total volume of a saline water supply cannot be beneficially consumed for irrigation and crop production; and the greater its salinity, the less it can be consumed before the salt concentration becomes limiting. It is advised that the practice of blending excessively saline waters with good quality water supplies should only be undertaken after consideration is given to how it affects the volumes of consumable water in the combined and separated supplies. Blending drainage waters with good quality waters in order to increase water supplies or to meet discharge standards is inappropriate under certain situations. More crop production can potentially be achieved from the total water supply by keeping the water components separated. Serious consideration should be given to keeping saline drainage waters separated from the good–quality water supplies, especially when the latter waters are to be used for irrigation of salt–sensitive crops. The saline drainage waters can be used more effectively by substituting them for good–quality water to irrigate certain, suitably salt-tolerant crops grown in the rotation after seedling establishment.

While efforts to prevent excessive environmental pollution and to restore and protect natural ecosystems may require the shifting of some water away from agriculture, it is concluded that the implementation of management practices to conserve water, to reduce deep percolation and to avoid the disposal of drainage wastes into good water supplies will go a long way towards minimizing these problems and needs. The goal of increasing food production and conserving water can, and realistically must, be achieved by improving water use efficiency in our presently developed irrigated lands. Getting the fraction of these lands that are presently degraded back into productive condition is essential, both from the view of increasing food production and conserving & protecting the quality of our limited water resources.

3. Management Principles, Strategies and Practices to Control Salinity

An integrated holistic approach is needed to conserve water, prevent soil salinization and waterlogging and to protect the environment and ecology. Firstly, source control through the implementation of more efficient irrigation systems and practices should be undertaken to minimize water application and to reduce deep percolation. Unavoidable drainage waters should be intercepted, isolated and reused to irrigate a succession of crops of increasing salt tolerance, possibly including halophytes, so as to further reduce drainage water volumes and to conserve water and minimize pollution, while producing useful biomass and habitat. Conjunctive use of saline groundwater and surface water should also be undertaken to aid in lowering water table elevations, hence to reduce the need for drainage and its disposal, and to conserve water. Various means should be used to reclaim or to dispose of the ultimate unusable final drainage effluent. Unusable drainage waters should never be discharged into good quality water supplies.

To achieve these goals, new technologies and management practices must be developed and implemented to reduce excessive water uses in irrigation, to conserve limited water supplies and to protect water quality. Efficiency of irrigation must be increased by the adoption of appropriate management strategies, systems and practices and through education and training. Such measures must be chosen with recognition of the natural processes operative in irrigated, geohydrologic systems, not just those on– farm, and with an understanding of how they affect the quality of soil and water resources, not just crop production. Some practices should be used to control salinity within the crop root zone, while other practices should be used to control salinity within larger units of management, such as irrigation projects and river basins. Additional practices should be used to protect offsite environments and ecological systems – including the associated surface waters and groundwater resources. The "on–farm" practices usually consist of agronomic and engineering techniques applied by the farmer on a field–by–field basis. The "district–wide" or "larger organizational basis" practices generally consist primarily of engineering structures for water control (both delivery and discharge) and of systems for the collection, reuse, treatment and/or disposal of drainage waters.

There is usually no "single–way" to achieve salinity control in lands irrigated with drainage waters and associated waters. Many different approaches and practices can be combined into satisfactory control systems; the appropriate combination depends upon economic, climatic, social, as well as edaphic and geohydrologic situations. Thus, no one-set of control practices can be specified as "the" appropriate set for all situations. The latter are too numerous and varied. But some important goals, principles and strategies of salinity management exist that should be used, at both on–farm and project–levels, to develop appropriate "packages" of management to deal with the need for the amelioration of presently degraded lands, to increase water use efficiency in irrigated regions where excessive water is used and to reduce the discharges of drainage water from the projects that pollute and reduce the usability of associated water supplies for irrigation and domestic use. Such goals, principles and strategies for the selection and implementation of control practices are reviewed and discussed in this paper. The new assessment-based technology described herein that utilizes satellite and geophysical sensor technologies should be included in the "packages" to provide a more meaningful basis for planning, monitoring and managing soil salinity than the traditional methods which are based on leaching requirement and salt balance concepts.

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