

Task 1

Drainage Reuse

Final Report

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Drainage Reuse Technical Committee

The San Joaquin Valley Drainage Implementation Program

and

The University of California Salinity/Drainage Program

DISCLAIMER

This report presents the results of a study conducted by an independent Technical Committee for the Federal-State Interagency San Joaquin Valley Drainage Implementation Program. The Technical Committee was formed by the University of California Salinity/Drainage Program. The purpose of the report is to provide the Drainage Program agencies with information for consideration in updating alternatives for agricultural drainage water management. Publication of any findings or recommendations in this report should not be construed as representing the concurrence of the Program agencies. Also, mention of trade names or commercial products does not constitute agency endorsement or recommendation.

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San Joaquin Valley Drainage Implementation Program

Report from the Technical Committee on Drainage Water Reuse

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I. INTRODUCTION

Reuse of saline drainage water is one management option on the west side of the San Joaquin Valley (SJV) for reducing the volume of drainage water (San Joaquin Valley Drainage Program, 1990). Management practices that result in less drainage water are attractive since they would reduce the area required for environmentally sensitive evaporation ponds, reduce the area for solar ponds and reduce the costs associated with disposal of the final effluent. In conjunction with other drainage management options such as source control and a means of removing salt and trace elements out of the valley, reuse could have additional benefits such as: (a) increase water use efficiency; (b) optimize production and environmental quality of irrigated farmland; (c) improve environmental quality of rivers and other water bodies; and (d) enhance economic viability of farming.

The salinity and sodicity of drainage water are the main parameters that determine the feasibility of its reuse. In addition, the presence of trace elements (e.g., B, Se, and Mo) in the drainage water pose a potential threat to crop yields, crop quality, aquatic life, the consumer and environmental quality. A successful adoption of reuse will require an integrated approach requiring new and flexible on-farm skills related to irrigation, crop and soil management within the context of being economically feasible and environmentally sound.

In this report, we define "drainage water reuse" as the use of drainage water for beneficial purposes. The committee has identified a number of potential uses such as irrigation, aquaculture (i.e., production of brine shrimp) and power-plant cooling among others. However, because the vast majority of research and technical information available on "reuse" in the SJV is related to reuse for irrigation, it will be the focus of this report.

Our definition of reuse for irrigation is broader than that described in the Rainbow Report (San Joaquin Valley Drainage Program, 1990). The concept of drainage water reuse as described in the Rainbow Report proposes sequential use of drainage water on progressively more salt-tolerant crops where application of concentrated effluents are applied to eucalyptus trees and then halophytes as the final steps in the sequence prior to disposal. Our report will elaborate on the technical aspects of this "sequential reuse" concept and expand upon it. This includes a review of a number of studies and reuse strategies where drainage water was either blended with good quality water or where two sources of water were used separately in a cyclic manner. There were a number of field, laboratory and computer-simulation studies that tested the feasibility of reuse on potentially new and existing crops and the impacts such practices could have on soil quality. Finally, we will discuss the development and implementation of the on-farm water management systems currently underway and the important role they will play in the future.

The feasibility of reuse however is ultimately determined by economics. Our report will review various economic analyses of reuse in the SJV and will describe the factors needed to make such assessments and how these factors interact with one another. The committee recognizes that the economic feasibility is dependent upon the

scale of reuse (e.g., on-farm vs. regional/district) and has to be weighed in relation to other options available.

II. USE OF SALINE DRAINAGE WATER FOR IRRIGATION: PRINCIPLES, METHODS AND GROWER EXPERIENCES

Drainage water may be used for irrigation for two purposes: to reduce the volume of drainage water and to achieve an economic return from a crop. The goal is to utilize drainage water to increase agricultural profitability while at the same time to reduce the volume of drainage water that must be disposed of by other means.

Use of saline drainage water requires several changes from standard management practices such as selection of appropriate crops, improvements in water and soil management, adjustments in crop rotations and in some cases, the adoption of advanced irrigation technology.

A. Methods of Drainage Water Reuse

Several approaches to drainage water reuse have been tested experimentally or demonstrated under field conditions. The methods differ regarding where, when or how the drainage water is applied to the grower's field.

Sequential Reuse

One strategy as described in the Rainbow Report is "sequential reuse". In this practice, part of the farm, usually the problematic areas or an area where the saline water table is close to the soil surface, is designated as the reuse area. It consists of a sequence of fields, within the boundaries of the farm, that are systematically irrigated with drainage water of increasingly higher concentrations for the main purpose of managing the salt on the farm and reducing the volume of drainage water. Although the Rainbow Report promotes eucalyptus and certain halophytes in this sequence, there is no need to restrict the type of crops in a sequential reuse scheme except for tolerance to salinity and trace elements. In the section entitled "Integrated on Farm Drainage Management" found later in this report, an expanded version of the "sequential reuse concept" is described.

Blending and Cyclic Reuse

Two other methods have been proposed and field-tested for recycling saline drainage water. Although these methods could be included into the "sequential reuse" method, they are described separately because they examine reuse on a particular area or field over a number of seasons. One strategy is referred to as the "Blending strategy" and the other the "Cyclic Strategy". Both strategies require an ample supply of good quality water and saline drainage water that are available for irrigation throughout the season. Blending involves mixing saline water and good quality water together to achieve irrigation water of suitable quality for the chosen crop's salt tolerance. This water is then used each irrigation. The other method, first

introduced and tested by Rhoades (1984), is called the cyclic strategy. Saline drainage water is used solely for certain crops and only during certain portions of their growing season. The objective of the cyclic strategy is to minimize soil salinity (i.e. salt stress) during salt-sensitive growth stages or when salt-sensitive crops are grown.

Blending saline drainage water with good quality water is often proposed as a means to expand the existing water supply. However, blending does not unconditionally increase the usable water supply (Grattan and Rhoades, 1990) nor is it always economically feasible (Dinar et al., 1986). Too often growers are faced with the need to blend water that is too saline for use by the intended crop.

There is an upper salinity limit of saline drainage water suitable for blending (Grattan and Rhoades, 1990). Since the purpose of blending is to increase the overall supply of water available to the crop, then the salinity of the saline water component of the blend can not exceed a value where, if used directly without blending, the crop could no longer extract water and grow. If the salinity of the saline component exceeds this value, rather than increasing the overall water supply, blending will decrease the usable water supply. Therefore the upper limit depends upon the crop and the maximum salinity at which that crop can still transpire and grow. Blending is not attractive if drainage water could not supply at least 20-25 percent of the total irrigation water requirement.

With a cyclic strategy, the soil salinity profile is not in steady state but is allowed to vary, permitting crops with lesser tolerances to be included in the rotation. Using equivalent amounts of drainage water, the cyclic strategy keeps the average soil salinity lower than that under the blending method, especially in the upper portion of the profile which is critical for emergence and plant establishment (Grattan and Rhoades, 1990).

The different reuse methods described above are not mutually exclusive. In fact a combination of one or more methods may be most practical in some cases. For example within a sequential reuse scheme, blending and/or cyclic methods are likely to be employed to control salinization and optimize production but at the same time, moving salt to an area of the field where it will eventually be disposed or harvested. It is important to note that while a considerable amount of knowledge has been acquired through field-testing and demonstrations, an integrated on-farm drainage management system of this nature needs more field testing.

B. Fundamental Principles in Relation to Irrigation with Saline and Saline/Sodic Water

Regardless of the purpose or the method of reuse, a number of basic principles apply to the use of drainage water for irrigation. Plants vary widely in their tolerance to salinity. Most traditional crops are glycophytes that have evolved under non-saline conditions. Therefore these plants are ill-equipped to cope with the stresses of saline and sodic conditions, while "salt-loving" plants, the halophytes, thrive under these conditions (Lauchli and Epstein, 1990). The most important factor is that plants transpire "pure" water thus concentrating salts within the root zone.

Regardless of being classified as a glycophyte or halophyte, all plants have an upper tolerance limit to the salt concentration in the root zone without damage. A net downward movement of salt through the root zone is the key to salinity control and to the sustained use of saline water for irrigation. Therefore, some downward displacement of salts below the rootzone, commonly referred to as leaching, is necessary regardless of plant type or conditions to maintain plant productivity. The amount of leaching needed is dependent on plant tolerance to salinity and the salinity of the irrigation water: the greater the salt-tolerance, the lower the required leaching, and the higher the irrigation water salinity, the greater the required leaching.

The maximum ET of a crop has been used for estimating the leaching fractions required for crop production when saline irrigation waters are used. The leaching fraction is the ratio of the amount of water percolating below the root zone to the amount of water that infiltrated the soil.

The leaching requirement is an attractive concept but has serious limitations. One major limitation is that the ET of the crop is assumed to be independent of the salinity of the irrigation water. Thus, calculated crop water requirements using average rootzone salinities corresponding to yield potentials reported by Ayers and Westcot (1985), will likely result in higher estimates of crop water use for yield potentials less than 100 percent. Furthermore, applying irrigation water to a field to achieve a given leaching fraction is very difficult, if not impossible. An additional limitation is that the leaching requirement is based on steady-state conditions and does not account for the initial salinity status in the soil profile. Despite these limitations, leaching fraction is still an important concept and must be satisfied whether it is achieved each irrigation, midway through the season or at the end of the season (Ayers and Westcot, 1985; Shalhevet, 1994).

The dynamic conditions of plant-soil-water interactions must be considered when developing the basic principles of salinity management. The simple water balance equation is:

$$I + P - D - ET + S = 0 \quad (1)$$

where I is the irrigation amount, P is the precipitation amount, D is deep percolation, ET is the cumulative evapotranspiration of the crop and S is the change in water storage in the root zone. In this equation, I and P represent the irrigation and precipitation that enters the soil and does not include runoff. For simplicity over the long term, S can be considered to be zero. For most crops, the soil-water content in the rootzone at the beginning of a crop cycle is high and at the end it is low. The change in S (i.e. ΔS) may be zero when comparing S from the beginning of a crop cycle to the beginning of next. This may be appropriate in terms of thinking about overall leaching. However, for a single crop season and transient salinities throughout a crop cycle, letting S equal 0 is inconsistent with what usually occurs in the field.

ET depends on climate, plant and soil factors. Numerous experiments have revealed that for a given climate and crop, ET increases linearly, at a rate m, with

increasing dry matter production (Hanks et al., 1977; Stewart et al., 1977) and can be described by the equation,

$$ET = b + m (RY) \quad (2)$$

where the value of b can equal or exceed zero and RY is relative yield in terms of total dry matter.

This relationship has significant implications to irrigation management with saline waters. When salt accumulation in the root zone is sufficient to reduce plant growth, ET is concurrently reduced. From the water balance equation, one concludes that a reduction in ET results in an increase in D (or a smaller decrease in ΔS) when irrigation and precipitation are constant. The increase in D causes an increase in salt leaching thus reducing the salinity in the root zone. Nature, therefore, provides a survival mechanism for plants against salinity: increased soil salinity leads to reduced plant growth which leads to reduced ET which leads to increased D which leads to decreased soil salinity.

Crop tolerance to salinity is a major factor affecting irrigation management when using saline waters. Maas and Hoffman (1977) proposed that crop salt-tolerance can best be described by plotting its relative yield as a continuous function of average rootzone salinity (EC_e) (Figure 1). They proposed that this response curve could be represented by two line segments, one, a tolerance plateau with a zero slope and the second, a concentration-dependent line whose slope indicates the yield reduction per unit increase in EC_e .

Relative yield can be estimated using the following expression:

$$RY (\text{percent}) = 100 - B(EC_e - A) \quad (3)$$

where RY is relative yield or yield potential expressed as a percentage, EC_e is the average electrical conductivity of the saturated soil extract within the crop rootzone, A is the threshold salinity and B is the slope of the yield-salinity curve when EC_e is greater than A .

Salt tolerant crops usually have a high value of A (threshold salinity) and a low value of B , although a low value of A and B is another characteristic of a salt-tolerant crop [e.g. *Eucalyptus camaldulensis* var. 4344, A and B both equal about 3.0 (Shannon et al., unpublished data)]. The value for these coefficients can be found for various crops from a table presented by Maas (1990).

Despite published guidelines on salinity threshold (A) and slopes yield decline (B), studies and experiences around the world developed management strategies that allow the profitable use of waters that are more saline than the threshold level of the crops grown. These experiences have been described in detail in review articles by Grattan and Rhoades (1990) and Oster (1994). For the benefit of the reader of this report, these experiences are described below.

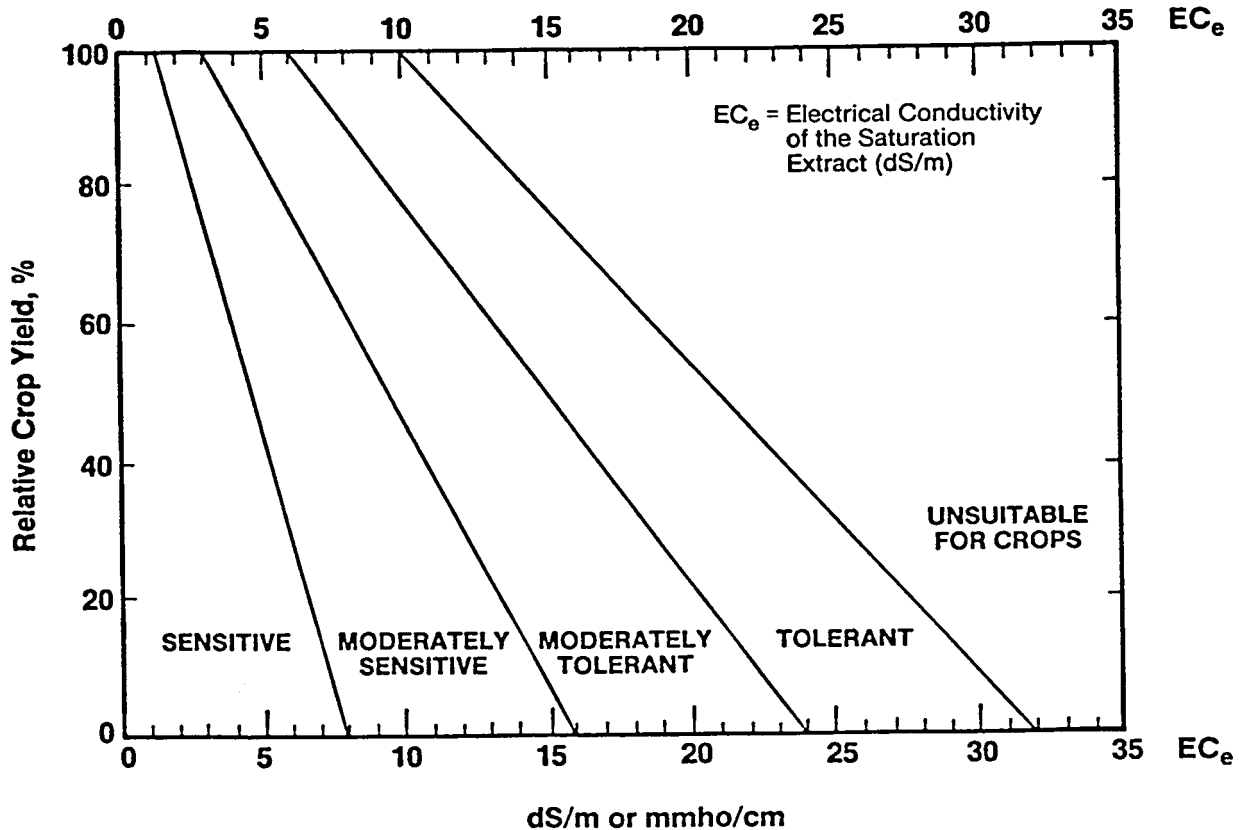


Figure 1. Response of relative crop yield (or yield potential) as a function of average rootzone salinity (EC_e) grouped according relative tolerance or sensitivity to salinity (after Maas, 1990).

C. Long Term Grower Experiences Using Saline Waters for Irrigation

Growers have successfully used saline waters to irrigate a broad spectrum of crops (Ayers and Westcot, 1985; Rhoades et al., 1992) in Bahrain, Egypt, Ethiopia, India, Iraq, Israel, Pakistan, Somalia, Tunisia, United Arab Emirates, and the United States. Food and Agricultural Organization (FAO) publications 29 (Ayers and Westcot, 1985) and 48 (Rhoades et al., 1992) and ASCE Manuals and Reports on Engineering Practice no. 71 (Tanji, 1990) provide comprehensive information on management practices for agricultural water and salinity problems. In this section, farmer experiences in the United States and Israel will be highlighted with the use of saline irrigation waters.

In the Pecos Valley of Texas, groundwaters with salinities averaging about 3.5 dS/m but ranging as high as 8.0 dS/m have been used successfully to irrigate chile pepper, cotton, small grains, sorghum and alfalfa (Miyamoto et al., 1984). The threshold salinities for these crops range from 2 to 8 dS/m. Examples of special irrigation practices used to mitigate the effects of salinity include alternate furrow irrigation to move salts to the dry side of the bed, planting seeds on the edges of flat beds where salt accumulation is minimal, replanting following rainfall if the resulting

crusting limits seedling establishment, and single-row plantings on narrow beds followed by removal of the peaks of the beds prior to seedling emergence to remove soil and/or salt crusts. In Arizona, farmers use well waters with salinities ranging from 3 to 4 dS/m together with alternate furrow irrigation to establish cotton (Oster, Personal Communication). Saline well waters as high as 11 dS/m are used after the crop is established. In southwestern Colorado, rainfall before and during the crop season facilitates the use of river waters with salinities ranging from 2 to 5 dS /m for the irrigation of alfalfa, sorghum, winter wheat, barley, and sugarbeets (Miles, 1977).

A grower can often maintain productivity by selecting an appropriate crop rotation. Alfalfa irrigation in the Imperial Valley of California is often just sufficient to meet the crop's ET needs, because no more water will infiltrate the soil. The result is inadequate leaching and increased soil salinity. Rotation of alfalfa (EC = 2.0) with winter crops that have a low ET requirement such as lettuce (EC = 1.3 dS/m) provides an opportunity to apply the additional irrigation water need for leaching. The salinity of the irrigation water from the Colorado River water used in the Imperial Valley ranges from 1.2 to 1.5 dS/m. This is relatively saline when compared to the threshold salinity of lettuce. However, because lettuce is shallow rooted, soil salinities in the root zone can be reduced to levels that are not hazardous by sprinkler irrigation during the seedling and germination phases of crop growth. Continued application of more water than needed by lettuce, can satisfy leaching needs left unmet during the time alfalfa was grown. This is an example of how farmers can take advantage of climate and the range in salt tolerance and rooting depths among crops to achieve the LR through the overall crop rotation system.

In the Arava Valley of Israel, where annual rainfall is generally less than 25 mm, peppers, melons, tomatoes, potatoes, onions, sweet corn, and alfalfa are grown commercially with surface drip and sprinkler irrigation techniques, using moderately saline groundwaters ranging in salinity from 2 to 4 dS/m (Oster, 1994). The threshold salinities for these crops range from 1.2 dS/m for onion to 2.5 dS/m for tomato. Where two waters with different salinities are available, the lower salinity water is used for irrigation during germination and seedling establishment. Sprinkler irrigation is commonly used for 2 to 3 weeks during the seedling and early stages of crop growth to leach the seed bed and obtain uniform plant stands. Thereafter, surface drip irrigation is used. Drip irrigation simplifies the use of saline waters for irrigation: low soil salinities are maintainable in the major portion of the root zone provided the crop and the drip line are located along the same line, and soil-water contents can be constantly maintained at high levels. "The drip irrigation method provides the best possible conditions of total soil-water potential for a given quality of irrigation water" (Shalhevet, 1994). However, farmers must be aware that salts accumulate at the perimeters of the wetted area and that tillage practices to incorporate crop residues and form new seed-beds can also incorporate these salts into the seed zone. Consequently, extra irrigation for leaching during seedling germination and plant establishment may be necessary to re-establish satisfactory soil salinity levels in the root zone.

Broadview Irrigation District

Broadview Water District is located in the northwest corner of Fresno County, California and includes 4050 ha (10,000 acres). Deep groundwater wells provided irrigation water in this region during the early 1900s. Water quality in the wells deteriorated over time as water levels declined and salt concentrations increased. The district was formed in the 1950s to obtain deliveries of freshwater from the Sacramento River Delta system. Deep wells were capped as soon as high-quality surface water became available from the federal Delta-Mendota Canal in 1955. The average salt concentration in the Delta-Mendota Canal ranges from 200 to 400 mg/L total dissolved solids (EC_w 0.3 – 0.6dS/m).

Surface runoff and subsurface drainage water from Broadview fields are combined in a single main district drain. The district did not have an outlet for disposal of subsurface drainage water until 1983. Consequently, prior to 1983, all of the drainage water was “uncontrollably recycled” within the district. This recirculation resulted in the application of high-salt irrigation water and the accumulation of salts in district soils. The ratio of drainage water to freshwater in quantities delivered to farmers increased, over time, from near zero in the 1960s to about 50 percent in the early 1980s. Since 1983, the ratio has decreased to an estimated 20 percent (Wichelns et al., 1988).

District personnel began collecting soil and water salinity information in 1980. The average salt concentration in the main district drain ranged from 2,700 to 2,960 mg/L, total dissolved solids, from 1980 through 1982 (Wichelns et al. 1988). Fresh canal water, on the other hand, contained between 300 to 350 mg/L. The blended drainage water and fresh water delivered to farmers averaged between 1,800 to 2,150 mg/L. These observations suggest that salts had accumulated in district soils and contributed to significant increases in the salt concentration of water applied to crops.

Several Broadview farmers have suggested that cropping patterns shifted significantly during the 1970s. They report that high-value crops such as tomatoes and melons were replaced with lower value, salt-tolerant cotton and grains as soil salinity problems increased. These changes were occurring even as subsurface drainage systems were being installed throughout the district.

Farm-level yield and acreage data for Broadview were collected from annual reports submitted to the district. Annual crop production and yield data for Fresno County were obtained from agricultural commissioner's reports (California, 1986). These data describe the amount of acreage planted and average yields of crops grown in the county. Unlike Broadview, most other areas of Fresno County are not adversely affected by salinity or high water tables. Yield and acreage data for the county are used for comparison with Broadview.

Information provided by farmers on changing soil and water quality conditions in Broadview suggests that yields and acreage of tomatoes declined over time, relative to production of this crop in nonsaline areas (Wichelns et al., 1988). Acreage in grain crops should be observed to increase through the years as salinity problems developed. A positive time trend for the proportion of total land planted to cotton is evident. Alfalfa

seed acreage and yields in Broadview were driven upward by the initial success of an intensive alkali bee management program in the mid-1960's, according to farmers. Alkali bees are better adapted to pollinating this crop than are honey bees, and yield increases of 100 and 200 percent were common during these years. The bee program was essentially unique to the district and its effects will not be detected in county-wide data. The sudden demise of alkali bee populations in the early 1970s led to rapid declines in alfalfa seed acreage and yields in Broadview. These observed changes should not be attributed to salinity or drainage effects.

Cotton acreage has increased, over time, in both Broadview and the whole of Fresno County. Differing trends are apparent for tomatoes and alfalfa seed. County-wide acreage of tomatoes and alfalfa seed either remained constant or increased since the early 1970s while acreage of these crops declined in Broadview. Acreage of tomatoes in Broadview was greatest in 1973, declining to near zero in 1982. Alfalfa seed acreage fell from nearly 4,000 acres (1620 ha) in 1970 to 560 in 1982.

The different time trends for tomatoes and alfalfa seed suggest that declining yields of these crops may have been occurring only in the water district. Tomato yields in Broadview are consistently higher than the county average, through 1973. District tomato yields are highest in the middle to late 1960s and decline in the 1970s. County yields are at or above the Broadview level from 1974 through 1982. Alfalfa seed yield data for Fresno County are not available for the 1960s, but from 1970 through 1982 yields in Broadview district are consistently higher than those in other parts of the county. Broadview cotton yields are generally higher than those in Fresno County. Acreage in sugarbeets has remained constant in Fresno County, but has increased in the water district.

Summary

There are several methods of applying drainage water to a grower's field. However to be sustainable, certain basic principle of irrigation and drainage need to be followed. Grower experiences indicate that saline water, above that classified as suitable for irrigation to maintain maximal yields (Ayers and Westcot, 1985), can be used to successfully irrigate crops provided crops are managed properly. Proper management requires that salts do not continue to build up in the rootzone over time. Transient soil salinity profiles allow flexibility in cropping patterns and are responsible for the success of the growers mentioned above. Adequate drainage is required to avoid continued salinization of the land. In areas that do not have adequate drainage, such as the Broadview Irrigation District in pre-1983, salinity will continue to rise forcing the more salt-sensitive crops out of production.

III. FEASIBILITY AND LIMITATIONS RELATED TO IRRIGATION WITH SALINE/SODIC DRAINAGE WATER OVER THE LONG-TERM

Irrigation with saline-sodic drainage water containing high levels of trace elements (e.g. B, Se and Mo) raises a number of concerns regarding the long-term feasibility of reuse. Irrigation management needs to be optimized to avoid salinization

and sustain production over the long term. This requires a higher level of management. Soil physical properties can be altered by irrigation with saline-sodic water particularly when good quality water or rains follow (Oster and Jayawardane, 1998; Oster et al., 1996; Shainberg and Letey, 1984). Alterations in soil physical properties can reduce infiltration of irrigation water as well as the rate it redistributes within the soil. Aeration can be reduced resulting in anoxic conditions for roots. These negative impacts on soil physical properties may be reduced with appropriate soil and water amendments. In addition there are concerns, real or perceived, that the presence of boron in the drainage water could accumulate in the soil and affect crop production. There may be an interaction between salinity and boron that negates, to some extent, boron's toxic affect on the crop. Selenium in the drainage water raises the concern that Se can be introduced into the food chain for animals and humans and pose a potential health risk. The need to leach salts and boron from the root zone will also leach nitrate which can be mitigated by additional fertilizer application. On the other hand if saline drainage water that contains nitrate is used for irrigation, N sensitive crops may be adversely affected although other crops will benefit. These negative aspects of reusing saline-sodic waters for irrigation must be considered along with potential beneficial factors will be discussed in following sections.

A. Water Quality Impacts on Soil Physical Properties

In order to grow crops, farmers must be able to maintain adequate physical properties by using various combinations of crop, soil and water amendments, and tillage practices. The primary properties of concern are water and air movement into and through soils and the ability to prepare seedbeds with a tilth that fosters seed germination, a crucial step in crop growth. Furthermore, hydraulic conductivities must be adequate so that salts and boron can be removed from the rootzone via leaching. Soil physical conditions within the soil, such as slow redistribution, poor aeration and trafficability, and compaction are often the consequences of low hydraulic conductivities. These conditions can occur quickly in a sodic soil when the salinity is too low to compensate for the effects of exchangeable sodium on soil physical properties.

Infiltration rates, hydraulic conductivities, and soil tilth decrease with decreasing soil salinity and with increasing exchangeable sodium (Oster and Jayawardane, 1998; Oster et al., 1996 ; Shainberg and Letey, 1984). At the soil surface, infiltration rates and soil tilth are particularly sensitive to salt and exchangeable sodium levels. The mechanical impact and stirring action of the irrigation water, or rain, combined with the freedom for soil particle movement at the soil surface, can result in low infiltration rates when the soil is wet, and hard, dense soil crusts when the soil is dry. Crusts can block the emergence of seedlings. Tillage of crusted soils can result in hard soil clods that are particularly difficult to reduce in size when the clod is dry. Extensive tillage can be required to prepare a seed bed with sufficient tilth to assure adequate soil/seed contact for seed germination.

Maintaining acceptable soil physical properties on soils with high salt and exchangeable sodium levels, i.e. saline/sodic soils, requires an understanding not only of the adverse impacts of salinity/sodicity on soil properties, but also of the consequent effects on root zone conditions for crop growth. Both water and air entry and its

subsequent redistribution within the soil are essential for root and crop growth. Vigorous root growth can play a key role in maintaining good soil physical properties below the soil surface (Robbins, 1986). Consequently, the focus of this section is on the closely-linked interactions between soil physical properties, and salinity and sodicity for (cropped) soils irrigated with good and poor quality waters. In the long run, the quality of the irrigation water in respect to its salinity and sodicity governs soil salinity and sodicity.

Hereafter, the word salinity will be used to refer to salt levels in the soil solution, and the word sodicity will be used to refer to either exchangeable sodium percentage (ESP), or the sodium adsorption ratio (SAR) of the soil solution. The ESP of the soil approximately equals SAR in the range from 0 - 40 (U.S.D.A Handbook 60, 1954).

Physical properties

Starting with the pioneering work of Fireman and Bodman (1939) research has documented many instances in which the tendency for swelling, aggregate failure, and dispersion increases as the salinity of the soil solution decreases even if the ESP is less than 3. That is, a soil with very low salinity can behave as a sodic soil (Rengasamy et al., 1984; Shainberg and Letey, 1984; Sumner, 1993). These tendencies increase as ESP increases, requiring increasingly higher salinities to stabilize the soil. However, the salinity/ESP boundary between stable and unstable conditions varies from one soil to the next (Pratt and Suarez, 1990). In addition, the stability boundary for water entry into the soil (infiltration) is different from that for water movement through the soil (unsaturated and saturate hydraulic conductivity). The soil surface is less stable than the underlying soil (Oster et al, 1996). The mechanical impact and the stirring action of applied water, or rainfall, on the soil surface destroy soil aggregates and rearrange soil particles into a densely packed, thin soil layer forming a seal on the surface. Furthermore, at low ESP levels and salinity levels, exchangeable magnesium can also have negative effects on soil physical properties (Sumner 1993; Keren, 1991).

Whether soil structure is affected by salinity, ESP, or magnesium depends on hydration and on the balance between repulsive and attractive forces between soil particles, particularly clay sized particles (Sumner, 1993; Quirk, 1986). Repulsive forces between clay surfaces and neighboring soil particles increase with decreasing salinity and increasing ESP. When repulsive forces exceed attractive forces, soil clays imbibe water, or swell, which can result in total separation of clay from neighboring soil particles, or dispersion. Swelling reduces the radii of soil pores while dispersion (Abu-Sharar et al., 1987) leads to the blockage of soil pores. Consequently the soils ability to conduct water, known as the hydraulic conductivity, depends on salinity, sodicity, and when the latter are low, on magnesium also.

Hydraulic Conductivity (K)

Historically, the hydraulic conductivity of salt-affected soils has been described in terms of the combined effects of salinity and ESP on flocculation and soil dispersion (Sumner, 1993). The U.S. Salinity Laboratory Staff (1954) described a saline soil

($EC_e > 4$ dS/m; $ESP < 15$) as follows: "Owing to the presence of excess salts and the absence of significant amounts of exchangeable sodium, saline soils generally are flocculated; and, as a consequence, the permeability 'hydraulic conductivity and infiltration rate' is equal to or higher than that of similar nonsaline soils. "A saline-sodic soil ($EC_e > 4$ dS/m; $ESP > 15$) was described as similar to a saline soil "as long as excess salts were present. However, upon leaching, the soil may become strongly alkaline (pH readings above 8.5), the particles disperse, and the soil becomes unfavorable for tillage and for entry and re-distribution of water in the rootzone. These numerical criteria used in 1954 to differentiate between saline, saline-sodic, and nonsaline sodic give only one point on what is a salinity-sodicity continuum. Quirk and Schofield (1955) introduced the concept of threshold salinity, the salinity at which a 10 - 15 percent decrease in K occurred for a silty loam soil. A plot of this threshold salinity against ESP resulted in an approximately linear line for ESP (SAR) values between 0 and 60.

Salinities above this line, for any given SAR, resulted in decreases in K that were less than 10 - 15 percent due to swelling and dispersion. Since 1955, various researchers have confirmed the validity of Quirk and Schofield's concept. Pratt and Suarez (1990) and Sumner (1993) have summarized data for different soils showing that each soil responds to EC and SAR in a unique manner. However, based on published data, significant reductions (10 - 25 percent) in K can occur for soils with ESP values of 15 if the salinities of saturated paste extracts (EC_e) are less than 0.5 – 5.0 dS/m. Furthermore, similar reductions can be expected for soils with ESP values as low as 3 if EC_e is less than 0.2 to 1 dS/m.

Changes in K brought about by changes in salinity or ESP, for a given soil, should be reversible, but they are usually not (McNeal and Coleman, 1966; Mitchell and Donovan, 1991). This suggests that irreversible clay particle movement and lodgment in conducting pores occurs together with clay swelling.

Infiltration Rate (IR)

When water is applied to the soil surface at a rate exceeding IR, whether by rainfall or by irrigation, some enters the soil, while the remainder either accumulates on the surface or runs off. Generally, IR is high during the initial stages of soil wetting but decreases exponentially with time to approach a constant rate. Two main factors are responsible for this decrease: (1) a decrease in the matric potential gradient, which occurs as infiltration proceeds, and (2) the formation of a seal or crust at the soil surface. In soils from semi-arid and arid regions, where the organic matter content is usually low, soil structure is unstable, and sealing is a major factor determining the steady-state IR (Morin and Benyamini, 1977). Seal formation is, in turn, due to two processes: (1) physical disintegration of soil aggregates and soil compaction caused by the impact of water, especially water drops from rain or sprinklers, and (2) dispersion and movement of clay particles and the resulting plugging of conducting pores. Both of these processes act simultaneously, with the first enhancing the second (Aggasi et al., 1981).

Dispersion becomes severe when soil salinity decreases below a critical level at which clay minerals separate from other clay minerals and the larger soil particles, silt and sand (Shainberg and Letey, 1984; Goldberg and Forester, 1990). This critical level increases as ESP increases. In studies in which waters of different qualities were applied to cropped columns filled with a loam soil, Oster and Schroer (1979) obtained a considerably better correlation between the final IR and the SAR and EC of the applied water than those of the soil solution averaged either over the total length of the soil column (0.53m) or for the surface soil (0.08m). Of equal significance, for a given SAR, the salinity associated with less than a 25 percent reduction in IR was as about equal to that to stabilize the K of a clay soil (McNeal and Coleman, 1966).

Hardsetting and crusting

Hardsetting, another type of surface condition with consequences similar to crusting, occurs after wetting soils that do not contain stable aggregates. Hardsetting soils exhibit a massive, compact and hard surface condition that forms on drying (Mullins et al., 1990). Soil conditions that facilitate hardsetting include low organic matter content and a texture conducive to high bulk density development. This is particularly true for loamy sands, sandy loams, sandy clay loams and sandy clays that possess clay mineralogy dominated by micas, kaolinite, or both. These soils do not crack upon drying. The major difference between hardsetting and crusting soils is the lack of any structural stability which permits complete aggregate breakdown and clay movement within the entire tilled zone, whereas in crusting soil, clay mobility is manifest only in the top few millimeters of the soil. The effects of salinity, sodicity and Mg on hardsetting are consistent with those for crusting (Sumner, 1993).

Water Quality Criteria for K and IR

Due to the limited ability to predict the effects of salinity and sodicity on K and no known ability to predict their effects on IR, water quality guidelines for soil and water management (Table 1) are largely based on data obtained from the laboratory, lysimeter, and field and by farmer's experience. The research data have been and continue to be related to farmer experience primarily by farm advisors with the assistance of researchers and extension specialists. They are guidelines, not firm criteria, because each soil behaves differently (Pratt and Suarez, 1990).

Table 1. Water quality guidelines: Combined effects of sodium adsorption ratio (SAR) and salinity of either a saturation extract (ECe) or an irrigation water (ECiw) on the likelihood of problems with low infiltration rates (IR) or hydraulic conductivities (K) (Ayers and Westcot, 1985, Oster and Jayawardane, 1998).

When sodium adsorption ratio of the irrigation water or soil water is	Potential water infiltration problem	
	Unlikely if ECe or ECw is	Likely if ECe or ECw is
0 – 3	> 0.7	< 0.3
3.1 – 6	> 1.0	< 0.4
6.1 – 12	> 2.0	< 0.5
12.1 – 20	> 3.0	< 1.0
20.1 – 40	> 5.0	< 2.0

ECe is the electrical conductivity of extract obtain from a saturated soil paste.
ECw is the electrical conductivity of the water in the soil.
ECiw is the electrical conductivity of the irrigation water

Magnesium is not as effective as Ca in improving IR as confirmed by Keren (1991) using the same soils that were used by Kazman et al. (1983). For K, Mg enhances the effects of Na on dispersion at ESP's less than about 12 (Oster and Jayawardane, 1998). The Mg ion present in water (hydrated Mg) is larger than hydrated Ca which decreases the linkages between external surfaces within soil aggregates, increasing the tendency for aggregate breakdown and clay dispersion. These effects of Mg on soil physical properties are not expected to be a significant problem in the use of saline/sodic drainage waters of the SJV, because of their high SAR levels.

Farming Practices to Promote Satisfactory Soil Physical Properties

On the farm, tillage plays a large role in modification of the soil matrix. Tillage to depths of 10-20 cm occurs frequently within a single year. Tillage to depths of 30-40 cm can occur as frequently as one time per year. Tillage of dry soils to depths of 1 - 2 m is done less frequently, but the practice is increasing (H. Colen, B. Fisher, D. Fisher and M. Grawall, private communications). This deep tillage, done by either long ripper shanks or slip plows, brakes-up compacted zones caused by traffic, and existing and developing soil layers of various descriptions throughout the root zone.

Application of gypsum to the soil surface after tillage, or incorporation of gypsum into the surface 10 cm, is an effective method to improve infiltration rates. Surface application of gypsum before the beginning of the rainy season of 1 to 3 tons per acre to a soil where the SAR exceeds 5 percent could significantly increase infiltration and reduce crusting. Kazman et al. (1983) found that as the ESP increased from 1.0 to 2.2 in a sandy loam soil, the final infiltration rate (the steady state infiltration rate) fell sharply from 7.5 to 2.3 mm/h and reached a value of 0.6 mm/h at ESP = 4.6. Similar results were obtained with a loessial silt loam. For both soils, spreading phosphogypsum on the soil surface, which increases the salinity and Ca concentration of the soil solution at the soil surface, was effective in reducing seal formation and the associated reduction in IR. Mined gypsum (87 percent finer than 2.4 mm, 52 percent finer than 0.3 mm, and 25 percent finer than 0.07 mm) will be somewhat less effective than phosphogypsum because the latter, a byproduct produced during the production of phosphorus fertilizer, has a more porous crystalline structure and a faster rate of dissolution than mined gypsum. Application of sulfuric acid to the surface of a calcareous soil will generate gypsum with a crystallinity and dissolution rate that should be similar to phosphogypsum. Application of gypsum and sulfuric acid to the soil surface are commonly used practices of long standing in California (Oster et al., 1996) for reclamation of sodic soils and to improve infiltration rates. Applying gypsum directly to irrigation water to foster improved IR is another common practice in California in use since at least the 1950s (R.S. Ayers, personal communication).

The injection of gypsum directly into the irrigation water at rates ranging from 470 to 940 lbs/acre-ft (0.17 to 0.34 kg/m³) is also possible (Oster et al., 1992) and is a commonly used practice for low salinity irrigation waters. These rates correspond to the addition of 2 to 4 meq/L of calcium and an increase of 0.15 to 0.30 dS/m in EC of the irrigation water. Both changes represent a considerable improvement in the quality of irrigation water with salinity less than 1.0 dS/m. Injection of gypsum into the low salinity water used in a cyclic strategy with saline/sodic drainage could be an appropriate practice.

Appropriate management practices following gypsum application can prolong its benefits, leading to a reduced need for repeated application. For example, Greene and Wilson (1989) demonstrated that, over a period of 3.5 years, the beneficial effects of gypsum on clay dispersion were lost as a result of leaching, but because the establishment of pasture protected the surface from impacting raindrops, no loss in K was recorded. Taylor and Olsson (1987) and Quirk (1978) demonstrated that increased levels of organic matter arising from pasture root systems stabilize soil structure after gypsum is no longer present at the soil surface. The adoption of farming practices such as minimum tillage and direct drilling without tillage lead to increased retention of crop residues in the form of surface mulches. This encourages soil faunal activity which helps increase and maintain the continuity of biopores, which in turn conduct water and air to subsoils (Jayawardane and Chan, 1994). Cropping also enhances the EC levels in the soil solution of calcareous soils because of the increased levels of the partial pressure of carbon dioxide. Robbins (1986) demonstrated cropping maintained adequate levels of EC to maintain K in a nonsaline sodic soil undergoing reclamation whereas this was not the case for uncropped soil amended with gypsum.

In the western Negev region of Israel there is a saline aquifer with EC values ranging from 2.5 to 8.5 dS/m and SAR values of 15 to 26. The dominant soils are silty loams and the climate is Mediterranean, with winter rainfall ranging between 250 and 400 mm. Cotton is the dominant crop.

Sixteen years of irrigation with water from a well at Kibbutz Nahal-Oz (EC of 4.6 dS/m; SAR of 26) demonstrates that irrigation with such a poor quality water can be sustained (Keren et al., 1990) provided that gypsum is applied in the fall. Irrigation during the summer (450 mm) results in ESP values in the upper 600-mm of soil of 20 - 26. There is no deterioration in soil hydraulic properties during the summer due to the high EC of the irrigation water. However, deterioration does occur during the rainy season due to the low salt concentrations of the rainwater. To offset this, phosphogypsum is spread annually on the soil surface, following tillage in the fall, at a rate of 5 Mg/ha (2.2 tons/acre). This prevents seal formation and maintains high infiltration rates, which, in turn provide sufficient infiltration of rainfall to leach salts from the root zone. Fall application of phosphogypsum and leaching during the rainy season, coupled with adequate irrigation with the saline-sodic water to meet crop needs during the summer months, has resulted in seed-cotton yields averaging 5 Mg/ha (2.2 tons/acre) between 1979 and 1988. These yields were similar to those obtained when only nonsaline water was used for irrigation.

Other Sodic Effects on Plants

In addition to potential adverse effects on soil physical properties, sodic conditions may also induce a calcium deficiency in the crop. Ca deficiency in the crop maybe obvious such as whip-like appearances in young emerging corn leaves but are more likely to be subtle where visual symptoms are absent (Grattan and Grieve, 1999).

Summary

There are a number of potential negative consequences from irrigation with saline/sodic drainage water on soil physical properties. Irrigation with saline/sodic water followed by rain or irrigation with nonsaline/sodic water can enhance soil crusting, reduce seedling emergence, adversely affect the tilth of the seedbed, reduce the infiltration rate, aggravate waterlogged conditions which reduces soil aeration affecting the crop. In addition, prolonged wetness reduces the trafficability and wet soils are more easily compacted aggravating the condition even more.

There are a number of management options to prepare the soil for the application of nonsaline/sodic water or to ameliorate poor soil physical properties after the application of nonsaline/sodic water if soil tilth is unsatisfactory for planting or severe crusting has occurred following planting. These options were developed with the help of M. Grewal of Boswell Land Co.

Prevention

1. Bed Planting: Top dress the soil with gypsum or sulfuric acid before listing to prepare furrows. It may be possible to apply the gypsum after listing but before the bed is retilled with a Lilliston.
2. Flat Planting: Light tillage after application of gypsum or sulfuric acid to incorporate the amendments in the top 1 - 3 inches of soil.

Remediation

1. Bed Planting: Retill the furrows/planting beds using a Lilliston and a bed mulcher if necessary.
2. Flat Planting: Switch to bed planting. This will require tilling the flat ground with a disk following by harrowing, then forming the beds/furrows by listing. If soil tilth is still not satisfactory, the beds could be retilled using a Lilliston and, if necessary, a bed mulcher.

B. Boron Accumulation and Potential Toxicity to Plants

Boron toxicity in reuse systems is an obvious concern because boron levels in the shallow groundwater on the westside of the SJV typically ranges from 10 to 60 mg/L (Westcot et al., 1988; Tanji and Grismer, 1989).

Despite such high levels of B in the drainage water, B-toxicity has not yet been reported on annual crops or crops grown as annuals (e.g. cotton). Field-grown crops in the SJV that have been irrigated with saline-sodic drainage water containing over 8 mg/L B include cotton, melon, salicornia, sugarbeet, tomato, and wheat (Ayars et al., 1990; Ayars et al., 1993; Grattan et al., 1987; Kaffka et al., 1999; Mitchell et al., unpublished data; Rhoades et al., 1988; and Shennan et al., 1995). At least part of the success may be attributed to the fact that many of these annual crops are tolerant of B such as cotton, sugarbeet and tomato (Maas and Grattan, 1998). An additional factor is that rainfall reduces the boron hazard, a factor that normally is not taken into account when assessing likely boron hazards. Another medicating factor is that most of the boron toxicity data is not based on yield, but on visible leaf injury. Leaf injury and yield are not invariably related.

Typically trees are more sensitive to boron than annual crops (Maas, 1990). As such, two studies have been conducted that addressed boron accumulation and injury in eucalyptus. One was a field survey conducted by Tanji et al. (unpublished data) and the other was a sand tank study conducted at the U.S. Salinity Laboratory (Poss et al., 1998). Based on a field survey conducted in 1995, a total of twelve eucalyptus trees from four sites in Fresno and Kings Counties were selected for use in this study. The trees represented nine selected varieties of eucalyptus ranging from 2 to 7 years old and varying in growth performance. Both younger (growing tip) and older (bottom branch) leaves were sampled. Since eucalyptus are perennial (evergreen), boron concentrations in leaf tissue should reflect the age of the tree and

the historical status of soil boron in the root zone. In controlled sand culture studies at the U.S. Salinity Laboratory, leaf boron concentration was related to that in the solution and concentrations varied spatially within the tree (Poss et al., 1998). Concentrations were highest in oldest leaves (lower branches in the proximal position) and least in the younger leaves (highest branches in the distal position).

At the Mendota eucalyptus site, B injury was observed on trees but a poor correlation was found between leaf boron concentration and soil boron (Tanji, unpublished data). This poor correlation may be attributed to large spatial variabilities in soil chemistry within the rootzone due to changes in water management during the life of the trees, differences in boron uptake by cultivars, and/or possible stresses suffered by the trees in regards to salinity and nutrients. Nevertheless the threshold level of boron in eucalyptus leaves, above which toxicity symptoms can be expected, was found to be between 500 and 800 mg/kg of boron on a dry weight basis. This concentration range for incipient injury is in agreement to that found in controlled studies at the U.S. Salinity Laboratory (Poss et al., 1998).

More importantly than interactive effects of salinity and boron on leaf injury is the impact on tree growth. The sand culture experiment conducted at the U.S. Salinity Lab was designed in a way to determine the interactive effects of salinity and boron on tree biomass. Data from the harvest of the first of two eucalyptus trees indicated that biomass was reduced by boron under nonsaline conditions but as salinity increased, effects of boron were not as dramatic (Grattan et al., 1996a). These data support the hypothesis that salinity mitigates boron's detrimental effects.

Despite the common occurrence of high boron and high salinity in many parts of the world, very little research has been done to study the interaction of the two. From sand-culture experiments conducted in a greenhouse, researchers found that wheat responded to boron in the soil solution independently of salinity (NaCl + CaCl₂) (Bingham et al., 1987). The salinity - B interaction was insignificant with respect to leaf B concentration. Similarly, Shani and Hanks (1993) and Mikkelsen et al (1988) reported data indicating boron and salinity effects were independent of each other for corn, barley and alfalfa. On the other hand Yadav et al.(1989) found that a mixed salt solution (i.e. Na⁺, Ca²⁺, Cl⁻ and SO₄²⁻) reduced leaf B concentration of chickpea grown in pots filled with loamy sand. In other studies using a mixture of chloride and sulfate salts, El-Motaium et al.(1994) found that salinity reduced B uptake and accumulation in the stem of several *Prunus* rootstocks thereby decreasing B-toxicity symptoms. They also found a negative relationship between B and SO₄²⁻ concentrations in tissue suggesting that SO₄²⁻ could be responsible for the salinity-induced reduction in tissue B. Others have also found that a mixture of chloride and sulfate salinity reduces leaf B accumulation in *Eucalyptus camaldulensis* (Grattan et al., 1996a,b). In these studies however the investigators were unable to determine the actual mechanism that supports this phenomenon such as direct ion interactions, reduced transpiration in salt-stressed conditions or both.

Leaf B concentrations in eucalyptus from the TLDD study however were not affected by gypsum treatment and the investigators conclude that the differences in leaf boron among clones were likely a result of different transpiration rates (Oster et al., 1999).

In addition to the potential sulfate-boron interaction, the interaction between B and Ca^{2+} in plant nutrition has long been recognized from field studies (Marsh and Shive, 1941). High concentrations of substrate Ca^{2+} , particularly under calcareous conditions, decreases B absorption and can induce a B deficiency (Gupta et al., 1985). Therefore in reference to experiments with mixtures of salts where salinity reduced B uptake and transport to the shoot (Grattan et al., 1996a, El-Motaium et al., 1994; Yadav et al., 1989), it is difficult to distinguish influences of either sulfate or calcium on B uptake since in each case these ions increased in the substrate with increasing salinity.

Ferreyra et al. (1997) reported data for 11 vegetable crop species and prickly pear cactus irrigated with 8.2 dS/m water containing 17 mg/L of boron that indicated foliar levels of boron were reduced because high soil salinity levels reduce plant water uptake. The coastal region of northern Chile is a desert and the salinity and boron levels in the soils are often high. Despite these conditions, the irrigation of alfalfa, winter grains, and vegetables has been practiced on the alluvial soils near the rivers for centuries. In the study reported by Ferreyra et al. (1997) the crops were planted in December of 1989, grown using drip irrigation and harvested the following May. The plant growth and crop yields of artichoke, asparagus, broad bean, red and sugar beets, swiss chard, carrot, celery, a local variety of sweet corn, potato, prickly pear cactus, onion, shallot, spinach, were greater than expected based on published salt and boron tolerance coefficients. If separate effects of salinity and boron were additive, little or no growth would be expected for all 12 of these crops. Interactions likely occur which increase the individual tolerance coefficients for boron and salinity when a crop is exposed to both sources of stress at the same time. Reduced plant water uptake due to high salinity levels is one interaction that would reduce the rate boron accumulates in the plant tissue thereby extending the time during which boron levels are not affecting plant growth.

Summary

Boron is known to be toxic to a number of crops but most experiments or observations have been done in the absence of salinity. Despite being toxic, there are no reliable growth response functions for most crops (Maas, 1990). Except for visual B injury on eucalyptus trees, no symptoms have been reported on crops that were irrigated with saline drainage water containing high levels of boron. Recent evidence suggests that salinity, comprised of a mixture of salts may, to some extent, mitigate boron's toxic effect. Nevertheless, reuse studies indicate that boron accumulates in soil and requires more water to remove than does common salts and selenate (Ayars et al., 1993; Shennan et al., 1995).

C. Selenium and Molybdenum Accumulation in Crops Irrigated with

Saline Drainage Water

Naturally occurring trace elements in soils and in the underlying shallow-groundwater on the west side of the SJV pose a threat to the sustainability of irrigated agriculture in this area. Selenium (Se) and molybdenum (Mo) are trace elements of particular interest since they are found in relatively high concentrations at many locations in the geochemically mobile and biologically available forms selenate and molybdate, which can readily be accumulated by crops.

The uptake of Se and Mo by plants is the primary process by which these essential trace elements for humans and animals are introduced naturally into their diet from the terrestrial environment. Se and Mo concentrations in plants varies widely among plant types and location. A number of greenhouse and field studies have conducted that have measured the accumulation of Se in edible tissue of crops (Tanji et al., 1988). Field studies included experiments where crops were grown in high Se soils and/or where crops were irrigated with saline drainage water containing high levels of Se.

Valoppi and Tanji (1988) reviewed the greenhouse studies funded by the U.C. Salinity/Drainage Task Force which included a number of vegetable crops i.e. Swiss chard, beet, tomato, alfalfa and barley as well as forage crops i.e. soft chess, subclover, ryegrass and astragalus. Below are the major findings:

1. Selenate uptake was more readily taken up by plants than selenite.
2. Plant uptake of Se as proportional to solution and/or soil-available selenate
3. The presence of sulfate dramatically reduces selenate uptake, resulting in lower concentrations of Se in its tissue.

A review of the various field studies (Biggar et al., 1988; Bureau et al., 1988; and Grattan et al., 1988) and surveys (Tracy et al., 1990) was also conducted by Valoppi and Tanji (1988). These studies showed that Se is not uniformly distributed within the plants. The general trend was that in the shoot, concentrations were higher in the leaves and stems than in the fruit. In the study by Grattan et al. (1988), tomato and melon plants grown in Mendota, an area with naturally high levels of Se in the soil, accumulated more "background" Se in its tissue than these plants grown at Five Points. When crops were irrigated with saline drainage water, tissue Se levels increased but more so in Mendota because of higher selenate concentrations in the drainage water. The Se concentration range in edible portions of plants in all these field experiments and surveys reviewed by Valoppi and Tanji (1988) was 0.002 to < 5.0 mg/kg, dry weight. However the health assessment indicates that crops consumed at these levels contribute minor amounts to the daily Se intake of humans.

An extensive field study was conducted at the Westside Research and Extension Center in Five Points where 13 vegetable crops were irrigated with either California aqueduct water or saline drainage water spiked with various concentrations of boron and selenate (Bureau et al., 1991). (Table 2).

Table 2. Total Se concentration in vegetable crops ($\mu\text{g}/\text{kg}$, dry wt of edible portion) grown at Five Points during the summer of 1989 as affected by irrigation water source and selenate concentration (Burau et al., 1991). Values averaged over 6 replicate plots.

Crop	Aqueduct			Saline Drainage		
	Selenium Concentration (mg/L)					
	0	0.030	0.150	0.045	0.165	0.600
Bean, Pink	17	951	2313	100	437	585
Bean, Snap	18	1364	2508	81	466	696
Cantaloupe	10	610	2483	62	435	532
Corn	27	647	1691	69	465	520
Cucumber, small	12	1192	2525	110	614	1017
Cucumber, large	7	1543	2878	168	703	931
Eggplant	18	353	2366	52	342	701
Pepper, green	10	1024	5136	79	603	1037
Potato	10	477	1746	168	492	499
Tomato, fresh	35	626	2132	211	628	865
Tomato, processing	40	604	1813	107	626	915
Zucchini, small	63	1190	2130	146	864	1187
Zucchini, large	26	1072	2564	90	836	1070

Vegetables grown with aqueduct water and no selenium have low Se levels in their tissue (Burau et al, 1991). However spiking the irrigation water with 0.15 mg/L Se (as selenate) increased Se in all vegetables approximately 100-fold. However Se uptake was substantially less in crops irrigated with saline drainage water due to the higher sulfate level in the water. Se accumulation in vegetable crops irrigated with saline drainage water spiked to 0.165 mg/L Se was about the same as those crops irrigated with aqueduct water spiked with 0.030 mg/L Se. It was concluded that vegetables from saline-drainage-water treatments will increase human dietary intake but not to the extent that it would be of concern for health risk.

More importantly than potential dietary concerns for humans is potential toxicological problems in livestock whose diet may rely almost entirely on forage grown in high Se and Mo areas within the SJV. Selenium and molybdenum are essential elements to animals and the concentration range in forage between deficiency and toxicity to livestock is rather narrow (James et al., 1968; Ohlendorf, 1989; Osweiler et al., 1985). Selenium toxicity can occur in livestock that graze on forage containing high levels of Se (Rosenfeld and Beath, 1964). Alkali disease is one form of selenosis that can result from ingestion of forage containing as low as 35 mg/kg Se (Klasing and Schenker, 1988). Molybdenosis is a nutritional disorder that ruminant animals, particularly sheep and cattle, may develop if the animals feed on forage that contains high levels of molybdenum (Barshad, 1948; Kubota and Allaway, 1972; Ward, 1978). Molybdenosis results from a molybdenum-induced Cu deficiency and is often called a molybdenum-induced hypocuprosis (Mason, 1990). However, high tissue concentrations of Mo is not the only factor that constitutes this syndrome. Susceptibility to molybdenosis is also related to the absolute concentrations of Mo and Cu in the forage, the ratio between them, and the protein content of the forage (Ishizaki et al., 1991). In addition, Mo levels as low as 5 mg/kg in forage delayed first oestrus in cattle

by at least 6 weeks and the pregnancy rate for Mo-treated animals was 30 percent, significantly lower than the control (Phillipo et al., 1985).

Some greenhouse studies using pot and solution cultures have examined Se uptake and accumulation in alfalfa, tall fescue and white clover (e.g. Wan et al., 1988; Mikkelsen et al., 1988; Wu et al., 1991). These studies showed that sulfate salinity substantially reduced Se accumulation by as much as two orders of magnitude in alfalfa (Mikkelsen et al., 1988). Similarly, solution culture studies showed that sulfate-salinity substantially reduced molybdate uptake in alfalfa (Lauchli and Grattan, 1993). A field study is currently underway that will examine Se and Mo accumulation in tissue when irrigated with saline drainage water and will hopefully shed more light on this issue (Kaffka, Oster et al., personal communication).

Summary

Data from field studies indicate that the crops accumulate selenium, primarily as selenate, when irrigated with saline drainage water. Sulfate in the drainage water has a remarkable influence on reducing the Se accumulated by the crop. Concentrations that accumulate in crops do not appear to pose a health risk to humans. More information related to Se and Mo accumulation in forages when irrigated with drainage waters containing high levels of these elements is needed to fully assess the potential risk ruminants that feed on this forage. This is particularly important for livestock that would use this forage as the primary source.

D. Saline Drainage Water's Effect on Crop Quality

Saline drainage water can affect crop quality and in many cases positively. Examples where saline drainage water improved crop quality are increased protein content and total digestible nutrients in alfalfa (Rhoades et al., 1988); improved netting, flesh color and taste in cantaloupe (Rhoades et al. 1988); increased soluble solids, fruit acidity and improved firmness and color in tomato (Grattan et al., 1987, Mitchell et al., 1991; Pasternak et al., 1986); and increased flour protein and loaf volume in wheat (Rhoades et al., 1988). It should be emphasized that these improved quality characteristics are not guaranteed when these crops are irrigated with saline water and that these beneficial effects do not justify the application of saline drainage water to crops. Nevertheless improved quality characteristics are attractive secondary benefits.

Irrigation with saline water would not necessarily be beneficial for all crops. The studies in California did not include for example leafy vegetables which are known to be sensitive to salinity and reduced size can largely affect marketability. Furthermore certain crops, for example sugar beet, requires low nitrates in the crop root zone late in the season to increase the sugar content in the beet. Since saline drainage water in most parts of the valley contains relatively high amounts of nitrate, irrigation with saline drainage after the crop is established can reduce the sugar content in the beet.

E. Nitrate in Saline Drainage Water

Saline drainage water can contain a substantial amount of nitrogen, primarily in the form of nitrate (NO_3^-). From the perspective of “reuse” of this water for irrigation of crops, one must consider the contribution of N in this source of water since it could supply the crop with the majority of its N requirements over the season.

Letey et al. (1977), carried out a survey of agricultural tile drain effluent in several of California's farming regions. They found that nitrate was present in all tile drain samples but in variable amounts. In the SJV area, nitrate concentrations ranged from approximately 1 to greater than 300 mg/L and discharge amounts were estimated to range from less than 10 to greater than 200 kg/ha/yr.

There is no equivalent survey of shallow wells reporting on nitrate concentrations, but the water in shallow wells is derived largely from water leaching from irrigation applications and surface conveyance systems, and from lateral flows from up-slope locations (Frio, 1997). Letey et al. (1977) also observed that some soils in the western SJV appear to be high in native N and are likely to lose N even in the absence of fertilizer use.

Over the last 11 years at the U.C. Westside Research and Extension Center, water from such a shallow well (18 m deep) was used for the irrigation of tomatoes, cotton, sugarbeets and safflower in a series of trials investigating the cyclic reuse of saline well water (Kaffka et al., 1998; Shennan et al., 1995). This water was also high in nitrates, with approximately 26 mg/L nitrate in the most recent trials (Kaffka et al., 1998) which is less than half its concentration a decade ago (Shennan et al., 1995). Over the twelve-year period of reuse, large amounts of nitrogen were accumulated in the soil profile, particularly in the second meter of soil, just below the depth where cotton and tomatoes effectively rooted. Deeper-rooted sugarbeet was able to recover some of this N resulting in a lower sucrose concentration in beet grown in salinized plots than in roots from adjacent plots without a history of saline irrigation.

There have been other studies in which a series of crops, including sugarbeet and sometimes wheat and cotton or alfalfa were produced with saline water containing nitrogen. In the Imperial Valley, Rhoades et al., (1988, 1989) irrigated wheat, alfalfa and sugarbeet with drainage water from the Alamo River, which is used to convey tile and surface runoff waters from fields to the Salton Sea in the Imperial Valley. In addition salts (EC_w 4.0 dS/m), nitrates also were present (43 mg/L). In the Mendota area, Ayars et al. (1990, 1993), grew cotton and sugarbeet and other crops with shallow well water. EC_e varied from 7 to 8 dS/m and nitrate N also was present in the drainage

waters at a concentration of 40 to 50 mg/L. Sugarbeet root quality was variably affected in these studies.

Nitrogen is the most important agronomic nutrient. It has multiple effects on crops, the chief among them the improvement of plant biomass yields. But it also affects crop quality (both positively and negatively) and can influence the occurrence of insect pests and plant diseases. Excess N in surface or groundwater can have undesirable ecological or health effects beyond the farm's boundaries. Because of these potential benefits and potential harms, N must be carefully managed. If tile drainage water and shallow well water are used, farmers must take into account the amount of nitrogen they are applying, as well as the amount of salt. If N in water used for irrigation is properly accounted, it can replace fertilizer sources, and save farmers money. But accounting for N as well as salts and trace elements like boron adds an additional variable to the use of saline water in a blending or cyclic re-use program.

Pang and Letey (1998) simulated the effects of applying variable amounts of nitrogen (0 to 310 kg N/ha) and water (21 to 115 cm) with an EC_{iw} of either 0.2 or 2.0 dS/m to a corn crop grown under the climatic conditions at Davis, California. They showed that high irrigation caused leaching of salts, reducing soil salinity and thereby reducing salinity's effect on yield. However high leaching of salts also caused high leaching of nitrates to the point where simulated yields were reduced under high irrigation, due to insufficient N in the soil solution. The main conclusion is that irrigation with saline waters has interactive effects with nitrogen management. Irrigation with saline water increase nitrate leaching with an added potential for groundwater degradation. Also larger amounts of nitrogen must be applied when irrigating with saline waters to achieve higher yields if the saline drainage water has low concentrations of nitrate.

It is also important to emphasize that the source of N being applied with the saline drainage water to the crop originated from below the root system before the season. Therefore excessive irrigation and N leaching would in fact be returning a lesser amount of N (assuming that the grower has reduced fertilizer application rates to account for the N in the drainage water) to the shallow water table than was there before the season began. Therefore on a regional basis there would be a net reduction in N from the shallow, saline drainage water.

IV. SALINITY MANAGEMENT: RESEARCH RESULTS AND DEMONSTRATION PROJECTS

A. Computer models

Computer models have been developed to characterize the relationships among irrigation amount, salinity effects on yield, and deep percolation and provide a way to combine the basic principals described earlier in this report to predict what occurs during irrigation with saline water for a given set of conditions. Models can be partially verified using data collected during field experiments that are conducted using a similar set of conditions. Thus model development and field research are closely linked.

Since about 1980, the need to determine the usability of saline drainage water has resulted in significant advances in computer model development and in field research related to irrigation with saline water. The findings from both types of studies are significant in terms of how saline drainage water should and should not be used. The remainder of this section will focus on reuse and salinity management by summarizing work done using computer simulations as well as field research and demonstration studies.

Letey et al. (1985) developed a model describing plant response to irrigation amount when the salinity in the rootzone was in steady-state (i.e. no change over time). The model accounts for both the salinity of the applied water and the effects of plant water uptake on the distribution of salinity with depth throughout the root zone. Letey and Dinar (1986) published simulated crop-water production functions for several crops based on the steady-state model as well as comparisons of simulated results with experimental data obtained by Hanks et al. 1978 to establish the reliability of the model. Figures 2, 3, and 4 illustrate output from the model for the relative yields of alfalfa. For comparison purposes, Figure 5 shows the relative yield of cotton lint plotted as a function of applied water. Cotton ($B = 5.2$; $A = 7.7$) is more tolerant to salinity than alfalfa ($B = 7.3$; $A = 2.0$) and the consequences are depicted in Figures 2 and 5. Cotton can be irrigated with relatively high saline waters with little effect on yield (Figure 5). This is not the case for alfalfa (Fig. 2).

Figures 2 through 5 illustrate basic relationships important in managing saline waters for irrigation. (1) Crops have different tolerances to salinity, (2) larger applications of more saline water are required than for less saline waters to achieve the same yield, (3) maximum yield may not be possible for more salt-sensitive plants when irrigating with saline water even with high water application, (4) reduced yield due to salinity is accompanied by reduced ET, and (5) reduced yield due to salinity is accompanied by higher amounts of deep percolation.

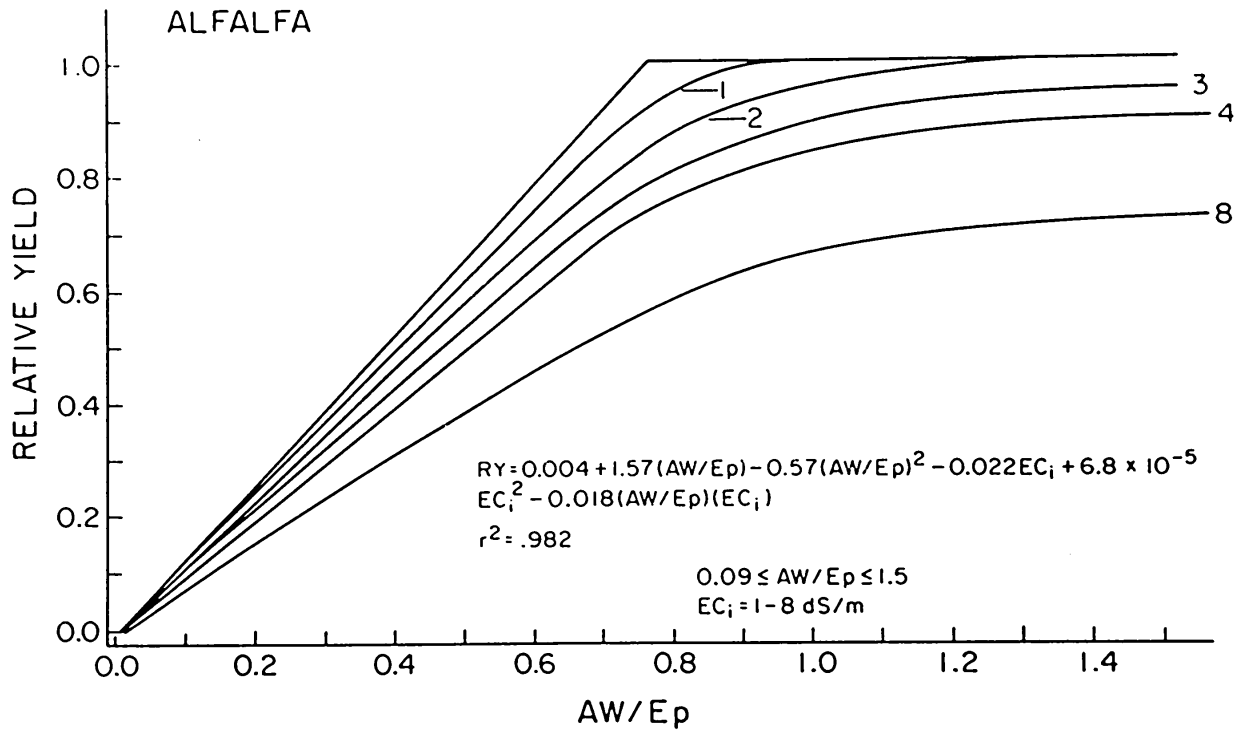


Figure 2. Computed relative yields of alfalfa for various quantities of applied water which are scaled to pan evaporation. Each curve is for a given EC (dS/m) of the irrigation water (Letey and Dinar, 1986).

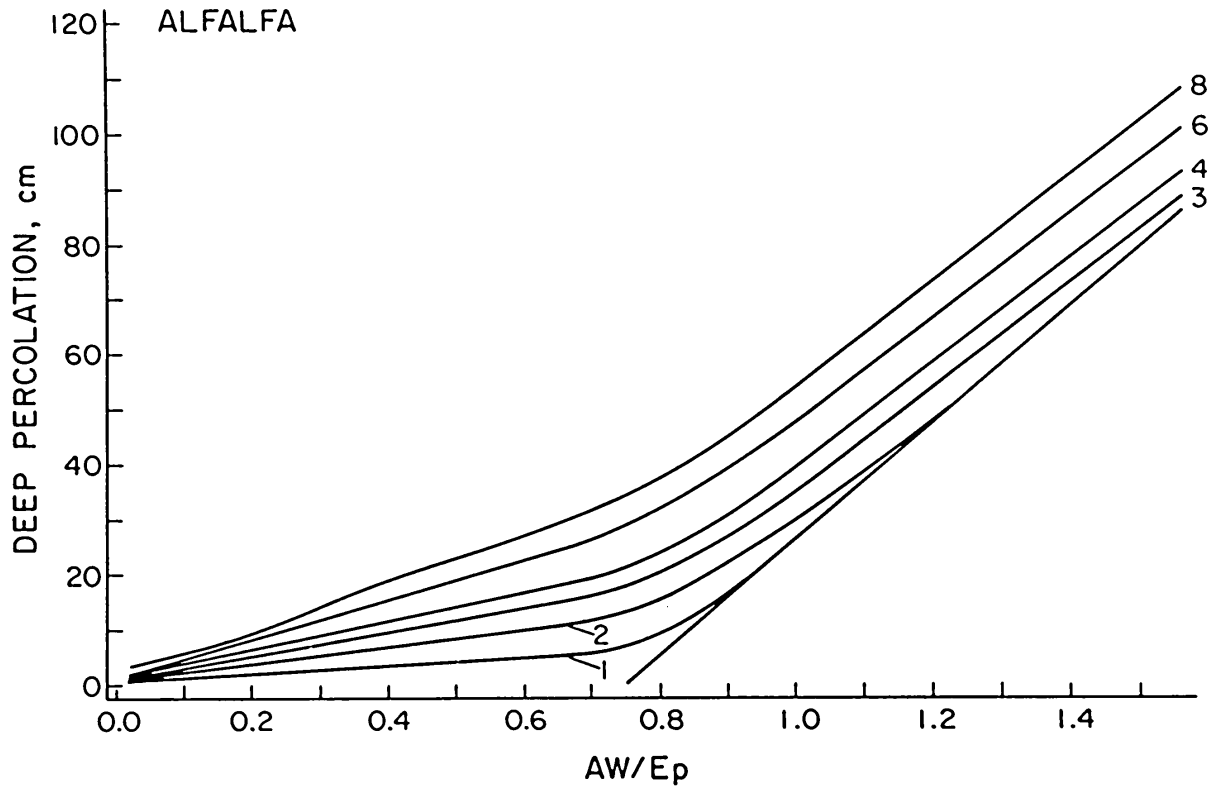


Figure 3. Computed values of deep percolation when alfalfa is irrigated with various quantities of applied water which is scaled to pan evaporation. Each curve is for a given EC (dS/m) of irrigation water (Letey and Dinar, 1986).

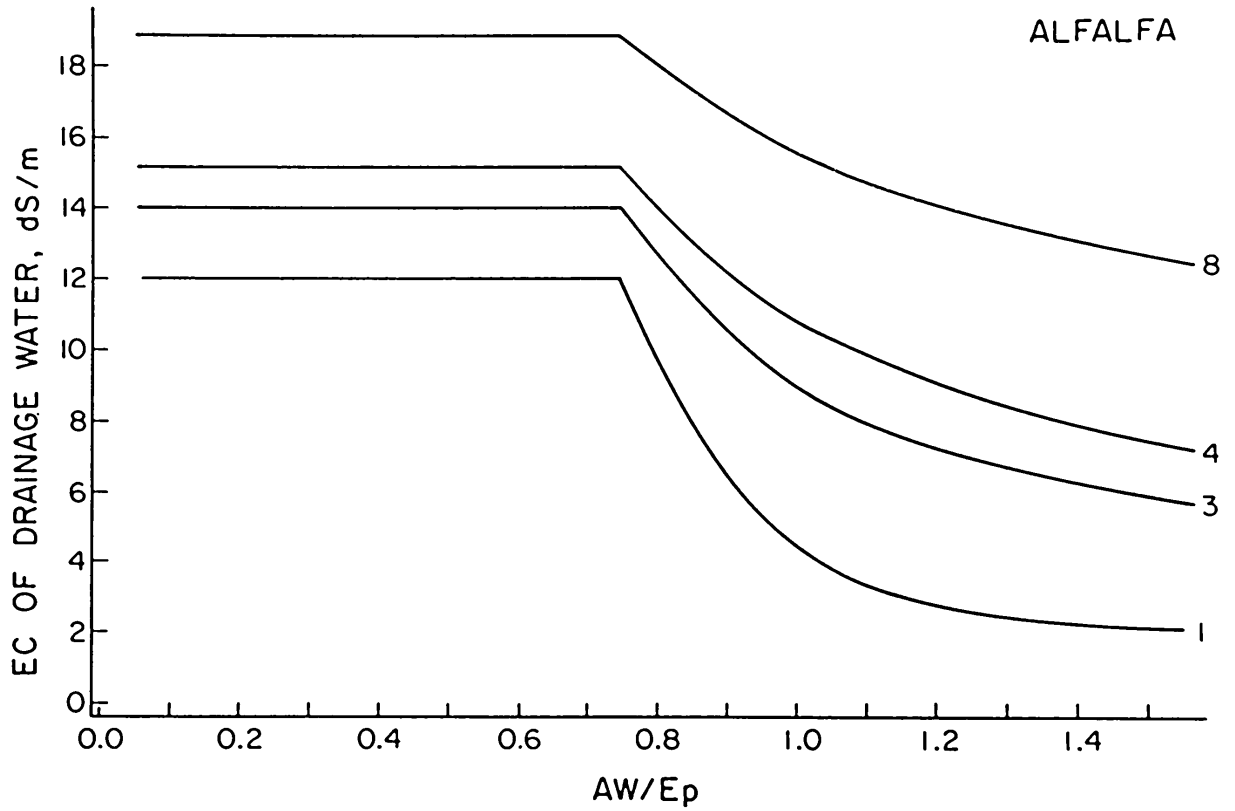


Figure 4. Computed values of EC of the drainage water when alfalfa is irrigated with various quantities of applied water which are scaled to pan evaporation. Each curve is for given EC (dS/m) of irrigation water (Letey and Dinar, 1986).

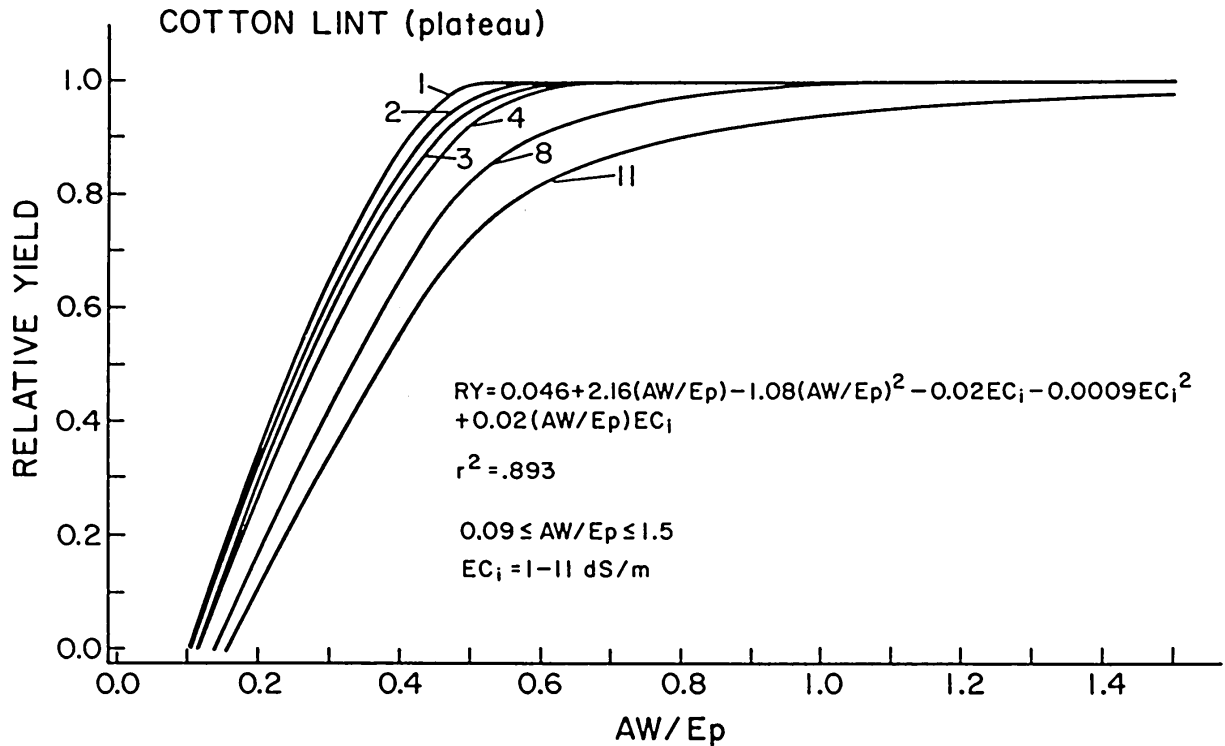


Figure 5. Computed relative yields of cotton lint (plateau) for various quantities of applied water which are scaled to pan evaporation. Each curve is for given EC (dS/m) of irrigation (Letey and Dinar, 1986).

Estimating Blending Ratios to Irrigate Specific Crops with Saline Drainage Water

The model developed by Letey and Dinar (1986) can be used to estimate the amount of saline water that can be blended with non-saline water to achieve relative yields of 80, 90, and 100 percent (Dinar et al., 1986).

The percentage of non-saline water that needs to be mixed with drainage water of different salinities to achieve maximal, 90 percent or 80 percent yields for various crops is contained in Table 3. The purpose of this exercise is to illustrate the consequence of crop salt-tolerance, salinity of the drainage water, and crop yield potential on the amount of saline water that can be used.

Table 3. The percent of nonsaline irrigation water with a EC_{iw} of 0.8 dS/m, when used in conjunction with saline irrigation waters and water management that achieves a leaching fraction of 25 percent, required to achieve 100, 90, and 80 percent yields of moderately sensitive (MS), moderately tolerant (MT), and tolerant crops (T).

100 percent yield					
Crop	Salt tolerance ¹	EC of the Saline Drainage Water (dS/m)			
		4	6	8	10
Lettuce	MS (1.3, 13)	98	98	99	99
Alfalfa	MS (2.0, 7.3)	86	91	94	95
Tomato	MS (2.5, 9.9)	75	85	89	91
Zucchini	MT (4.7, 9.4)	38	62	72	78
Cotton	T (7.7, 5.2)	0	38	56	65
90 percent yield					
Lettuce	MS (1.3, 13)	75	85	89	91
Alfalfa	MS (2.0, 7.3)	44	65	75	80
Tomato	MS (2.5, 9.9)	55	72	80	84
Zucchini	MT (4.7, 9.4)	3	40	57	66
Cotton	T (7.7, 5.2)	0	0	0	11
80 percent yield					
Lettuce	MS (1.3, 13)	63	77	83	87
Alfalfa	MS (2.0, 7.3)	20	48	61	69
Tomato	MS (2.5, 9.9)	22	52	65	73
Zucchini	MT (4.7, 9.4)	0	16	32	42
Cotton	T (7.7, 5.2)	0	0	0	0

¹ The first number in parenthesis is the threshold salinity for average rootzone salinity in dS/m, and the second is the percentage yield decline per unit increase in average rootzone salinity.

Percentages of nonsaline water requirements greater than 75 percent represent situations where use of saline water likely would not be considered practical, particularly for surface or sprinkle irrigation. It is unattractive because the drainage water fraction of the blend is less than a quarter of the volume. To emphasize this point, percentages of 75 or smaller in Table 3 are given in bold.

Leaching fraction significantly affects these percentages. That is for a given salinity, a lower leaching fraction under steady-state conditions translates into a higher root zone salinity which translates into a larger impact on crop yields. For example with alfalfa and a yield target of 80 percent, a leaching fraction of 30 percent results in a nonsaline requirement of 6, 42, 58, and 67 percent for saline waters of 4, 6, 8, and 10 dS/m, respectively. These numbers are lower than the corresponding numbers in the table, which are for a leaching fraction of 25 percent.

The total water requirement, nonsaline plus saline, to provide that needed for crop yields and leaching, decreases with decreasing yield targets. Table 4 provides the

corresponding percentages of the water requirement relative to that for 100 percent yields for the crops and conditions given in Table 3.

Table 4. Effect of targeted crop yield on the total water requirement relative to that needed for 100 percent crop yields when the leaching fraction is 0.25.

Crop	90 percent yield	80 percent yield
Lettuce	94	90
Alfalfa	88	78
Tomato	94	92
Zucchini	94	90
Cotton	94	83

The steady-state model used to develop these numerical relations ties together ET, crop salt-tolerance and yield potential but does not address transient conditions which occur in the field. For example, if a non-saline soil profile is irrigated with saline water, one or more years of irrigation may be required to build the soil salinity to a steady level consistent with the salinity of the irrigation water and crop-water uptake. If crops, rainfall and the amounts of drainage water applied vary, steady state conditions will not be achieved. Another limitation is that the model does not allow for upward water movement in the profile.

Transient state models are more useful to characterize these more complex relationships found in the field than are steady-state models. The transient-state model of Cardon and Letey (1992a,b,c) employs a one-dimensional finite-element solution to the Darcy-Richards equation for water flow and the convection-dispersion equation for solute movement. Plant water uptake is included as a sink term in the Darcy-Richards equation. Plant water uptake is related to the soil matric and osmotic (salinity) potentials, which links plant growth and soil water status. This transient model has the advantage of including the effects of temporal variation in potential transpiration, allowing any irrigation schedule, switching irrigation water qualities, allowing upward or downward soil water movement in the profile, and allowing differences in crop rotation. Water uptake is based in part on crop-salt tolerance data.

Bradford and Letey (1992) used the transient-state model to simulate the consequences of blending or cyclic strategies for irrigation with saline drainage waters. Drainage waters can be blended with good quality water to an acceptable salinity and then used to irrigate crops, a common practice in the Broadview Irrigation District during times when restrictions on drainage water discharge are in place (Wichelns et al., 1988). The degree of mixing is based primarily on availability of the water supplies adjusted, where possible, for the salt tolerance of specific crops.

In the cyclic irrigation strategy, the different waters are not blended, but used separately to take advantage of the different salt tolerance characteristics of crops, or changing salt tolerance of crops during their growth cycle, or existing soil salinities (Rhoades, 1984; Grattan and Rhoades, 1990). Bradford and Letey (1992) conducted simulations of the cyclic strategy for multi-year alfalfa production and for a corn and

cotton crop rotation. The corn-cotton rotation is not a common agronomic practice in the SJV, however it was selected to illustrate the rotation of a salt sensitive and a salt tolerant crop, respectively. The simulated alfalfa yields averaged over multiple years were similar for the cyclic and blending strategies that applied the same amount of salt and water. An interesting finding from the simulations using alfalfa was that the yields fluctuated annually but were out of phase with the imposed irrigation water salinity. High yields were achieved in years when irrigation was with the higher salinity and lower yields on years when irrigation was with lower salinity. This yield pattern was the result of high salinity at the beginning of the season that had been irrigated with high saline water during the previous year and vice versa. These findings are consistent with those of Meiri et al. (1986) that potato and peanut crops responded to the weighted mean water salinity regardless of whether different salinity waters were blended before application to the soil or were applied intermittently and allowed to blend within the soil. However, lower alfalfa yields were obtained with an early-season irrigation using saline water.

This "out-of-phase" soil-salinity profile with saline irrigation applications also explains the success of the tomato-cotton-cotton rotation described by Shennan et al. (1995). In that long-term cyclic reuse study, saline water was applied to the more sensitive tomato crop, grown initially in a non-saline profile, after the plant passed the salt-sensitive vegetative growth stage. Non-saline water was used to irrigate cotton grown initially in a salinized profile as means of "reclaiming" the profile to accommodate the subsequent tomato crop. Soil salinity profiles in this field study support this "out-of-phase" phenomenon.

Bradford and Letey (1992) found that the cyclic strategy was superior to blending in the corn-cotton crop rotation. The cyclic strategy produced higher simulated yields of salt sensitive corn than the blending strategy whereas the simulated salt tolerant cotton yield was not effected by the two strategies. Keeping drainage waters separate from fresh waters therefore provides greater flexibility in crop selection.

Bradford et al (1991) used the transient-state model to simulate crop production under a shallow saline-water-table condition. The initial condition consisted of non-saline soil above a shallow water table (1.5m depth) that had a salinity of 9dS/m. A further restriction was that an impermeable boundary existed at a 2.5m depth, which prevented any downward water flow beyond that depth. The irrigation water salinity was selected as 0.4 dS/m and the salt-tolerant cotton crop was used in the simulation. The results were that cotton could be grown successfully for several years without any drainage when irrigated with this water as long as the irrigation amount was neither greater than nor less than the annual ET. If the irrigation exceeded ET, the water table rose and created aeration problems. If irrigation was less than ET, the water table would drop and the crop would suffer from water deficiency.

When irrigating with non-saline water, maintenance of a high water table without drainage had benefits over a profile without a water table (Bradford and Letey, 1993). The benefits were achieved because any "excess" water applied during irrigation caused a rise in the water table that was later available for crop use. However, under free drainage conditions, "excess" water drained and was no longer available for the

crop. Another finding of that simulation was that in the presence of a water table, high yields were achieved by applying less irrigation during the crop season and more during the pre-irrigation for salt leaching purposes. However, the annual applied water must equal evapotranspiration to avoid long term water table rise or depletion.

Based on results from the models described above, the following appears to be an advantageous strategy for certain crops that can tolerate a certain amount of salinity and can take advantage of the water from the shallow water table. Under high water table conditions, a drainage system should have a controlled outlet. The drains should not be allowed to flow freely and irrigation should be with high quality water. Under these conditions, irrigation can continue for a considerable period of time without any drainage. A control outlet would allow removal of water under emergency conditions of a very high water table or after the salinity built to a level that it had to be discharged. If such a management strategy can be achieved, it could have advantages over reducing drainage volumes by directly applying the saline-sodic drainage water to the soil surface. Of course not all crops fall in this category but may be attractive to deep-rooted crops such as cotton, safflower, and sugarbeet.

B. Field Research Studies

Since the salt tolerance of some crops increase as the plant matures (Pasternak et al., 1986; Maas and Poss, 1989), the availability of some good quality irrigation water or a soil with low salinity, particularly before and during the early stages of plant development, facilitates the use of moderately saline irrigation waters. Rhoades (1987) tested the cyclic strategy of using waters of different salinities and found it to be sustainable in maintaining crop rotations that include both moderately salt-sensitive and salt-tolerant crops. In this cyclic strategy, the non-saline water is used for pre-plant and early crop irrigations of the moderately salt-tolerant crop and for all irrigations of the moderately salt-sensitive crop. Salt-tolerant crops were irrigated with saline water after they reached a salt-tolerant stage of growth. After the salt-tolerant crop is grown, a pre-irrigation with low salinity water reclaims the upper portion of the soil profile in order to establish the salt-sensitive crop. In a successful test of the cyclic strategy conducted in the SJV of California, a 0.5 dS/m water was used to irrigate cotton ($A = 7.7$ dS/m) during germination and seedling establishment, and 7.9 dS/m; SAR 11 water was used thereafter (Rhoades, 1987). Wheat ($A = 6.1$ dS/m) was subsequently irrigated with the 0.5 dS/m water, followed by 2 years of sugar beets ($A = 7.0$ dS/m) with the cyclic strategy used again for irrigation. Rhoades et al. (1988; 1989) reported the results from a second study conducted in the Imperial Valley of California. In a rotation of wheat, sugar beets, and melons, Colorado River water (1.5 dS/m; SAR 4.9) was used to irrigate the cantaloupe, a moderately salt-sensitive crop, and for the pre-plant and early irrigations of wheat and sugar beets. Alamo River drainage water (4.6 dS/m; SAR 9.9) was used for all other irrigations. Sugar beet and wheat yields were not reduced, and crop qualities were often improved from the use of saline drainage water.

Ayars et al (1990, 1993) used drip irrigation for three consecutive years to apply a 7 to 8 dS/m; SAR 9 water to cotton after it was established with 0.4 to 0.5 dS/m water. The saline water supplied 50 to 59 percent of irrigation water requirement. A wheat crop irrigated with the 0.5 dS/m water followed cotton; sugar beets followed wheat and

were irrigated with the 8.0 dS/m water after stand establishment. Yields under these conditions were the same as from continuous irrigation with the good quality water. The investigators did note however an increase in soil boron levels over time from drainage water application (B = 5 – 7 mg/L) despite annual rainfall and preseason applications of non-saline water in excess of 150 mm.

Others have expanded on the cyclic reuse approach to irrigate crops in the rotation with saline drainage water that are more sensitive to salinity than that tested by Rhoades (1987). Shennan et al. (1995) tested two, cyclic, drainage-water reuse practices on processing tomato (A = 2.5 dS/m) in a three-year rotation with cotton over a six-year period. In both practices, drainage water was applied to processing tomato after first flower to take advantage of salinities enhancement of fruit quality and continued to the end of the season. In one practice, non-saline water was used at all other times (i.e. saline water applied one out-of-three years). In the other practice drainage water (EC= 7.4 dS/m; SAR 12) was also applied to the following cotton crop after thinning while non-saline water was applied at all other times (i.e. saline water applied two out-of-three years). Non-saline aqueduct water (EC = 0.4 dS/m; SAR 1.6) was used as the source of irrigation water at other times and both reuse practices were compared to rotations where only fresh water was used. In the practice where drainage water was applied one-out-of-three years, yields of tomatoes were sustained even though drainage water supplied up to nearly 60 percent of the irrigation water requirements. In the cyclic reuse treatment where drainage water was applied two-out-of-three years, tomato yields were reduced in two of the six years. Soluble solids in tomato fruit, on the other hand, were increased five of the six years in drainage water treatments. Similar results were found in field studies conducted in different locations in the SJV but for only one-year where drainage water supplied over 65 percent of the irrigation water requirement (Grattan et al., 1987). Pasternak et al. (1986) also reported soluble solids in tomatoes increased when irrigated with a 7.5 dS/m water after the fourth or eleventh leaf stage, but yields were reduced by 30 percent. Differences between these studies may be due, in part, the differences in the anion composition of the saline water. In Israel, where Pasternak and colleagues conducted their work, the saline water is normally chloride dominated whereas in the SJV of California, the saline drainage water is sulfate dominated. Chloride salts are likely to be more damaging than sulfate salts.

The long term feasibility of cyclic reuse practices depends, in part, upon changes in soil chemical and physical properties over the long term. This is particularly important since a high SAR combined with low EC water can degrade soil physical properties -- tilth, infiltration rates, water redistribution rates in the soil and aeration -- through the swelling and dispersion of clays and slaking of aggregates (Sumner, 1993; Oster and Jayawardane, 1998). In the long-term cyclic study conducted on a clay loam soil by Shennan et al. (1995), they found no difference in water infiltration rates, measured with a steady-state infiltrometer, between plots that received saline water and those that did not. Nevertheless they did find a significant reduction in cotton stands in 1988 in plots that were salinized the previous year. Use of saline drainage water (9,000 mg/L TDS and 16-30 SAR) on a clay soil also caused a reduction in stands of both cotton and safflower (Rains et al., 1987; Rolston et al. 1988). The inability to prepare a seedbed with the tilth necessary for water transfer between the soil and cotton seed contributed

to poor stand establishment (Oster, 1994). This became increasingly evident beginning with the fourth year of the project.

The study by Shennan et al. (1995) also examined the behavior of salts, B and Se over time at different depth increments (Figures 6a,b,c). On a relative basis, Se was more readily leached than salts and salts were more readily leached than B. At the 60-140 cm depth interval, both Se and ECe in plots irrigated with saline water increased the first year (1986). Concentrations of B at this depth, on the other hand, were not found to increase until 1988 in plots that received drainage water two-out-of-three years and 1989 in plots that received drainage water one-out-of-three years. In the upper 15cm of the soil profile, the ECe increased after saline water irrigation but then after two years irrigation with non-saline water, the ECe returned to the level found in the control. Se was particularly responsive and concentrations at this depth interval and returned close to that of the control even after one season of irrigation with non-saline water regardless of whether plots were previously irrigated with saline water for one or two years. This was not surprising since most of the Se in the drainage water is in the selenate and hence more mobile form. Presumably the mobility of selenate is similar to sulfate but the ECe is affected by calcite and gypsum equilibrium and therefore can increase after leaching of salts due to dissolution processes. Boron, on the other hand, was not as responsive and concentrations in drainage-treated plots remained high after two years application with aqueduct water.

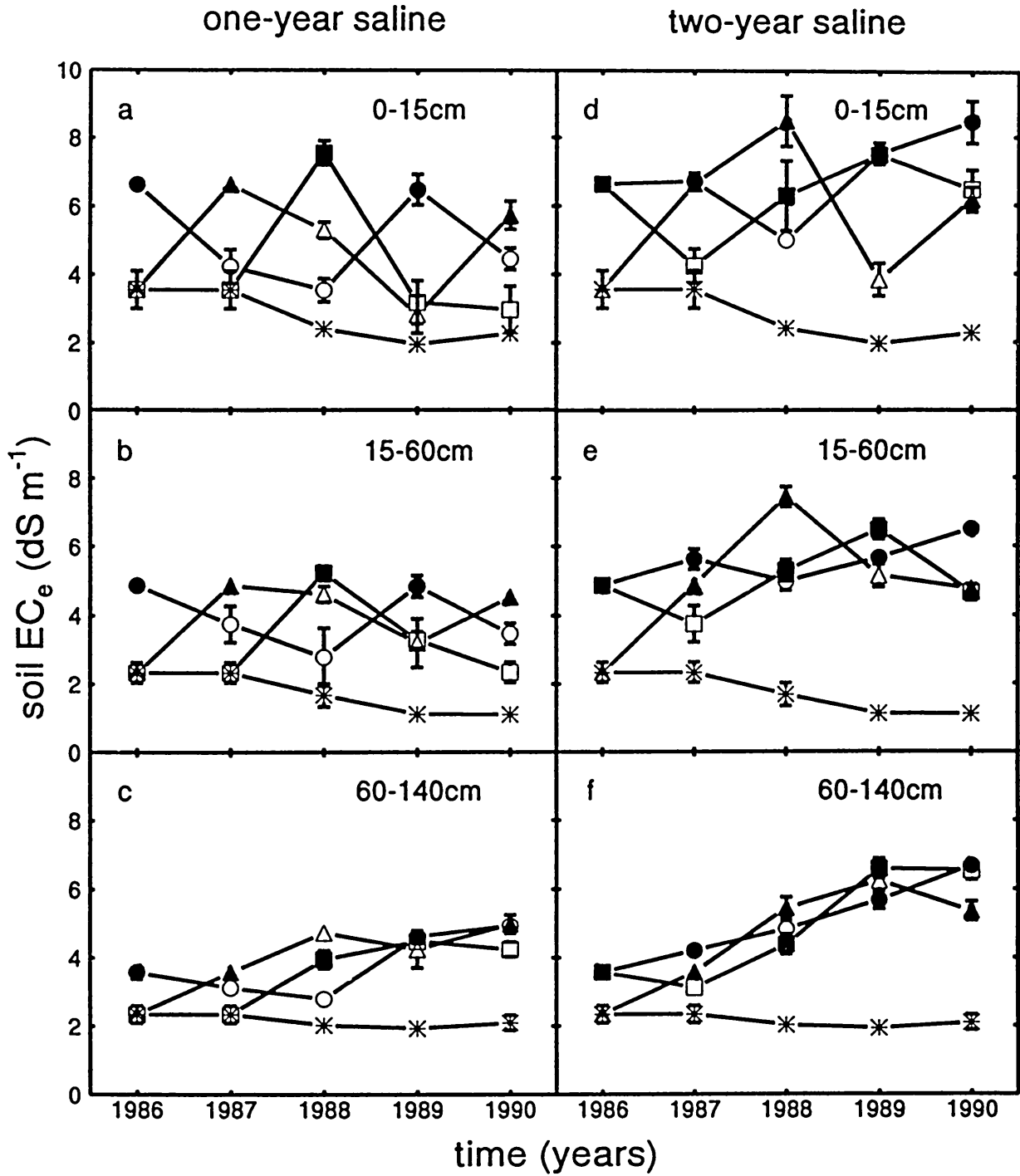


Figure 6a. Changes in soil EC_e over the years at the 0-15, 15-60, and 60-140cm depth intervals with different irrigation treatments (one-out-three years saline or two-out-of-three years saline). The non-saline control treatment is indicated by the star symbol. Solid symbols indicate years when saline drainage was applied to plots (Shennan et al., 1995).

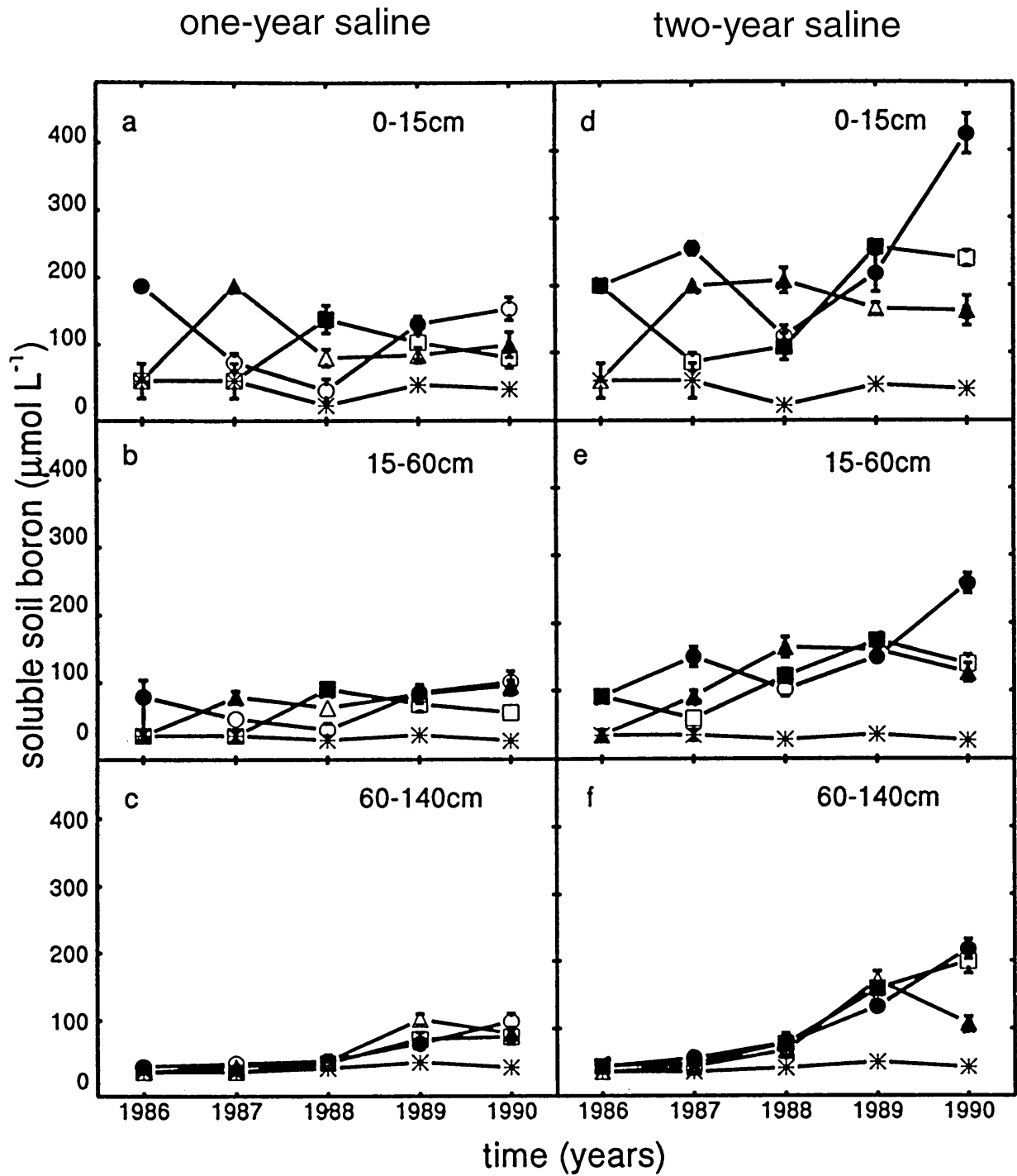


Figure 6b. Changes in soil B (saturated soil extract) over the years at the 0-15, 15-60, and 60-140cm depth intervals with different irrigation treatments (one-out-three years saline or two-out-of-three years saline). The non-saline control treatment is indicated by the star symbol. Solid symbols indicate years when saline drainage was applied to plots (Shennan et al., 1995).

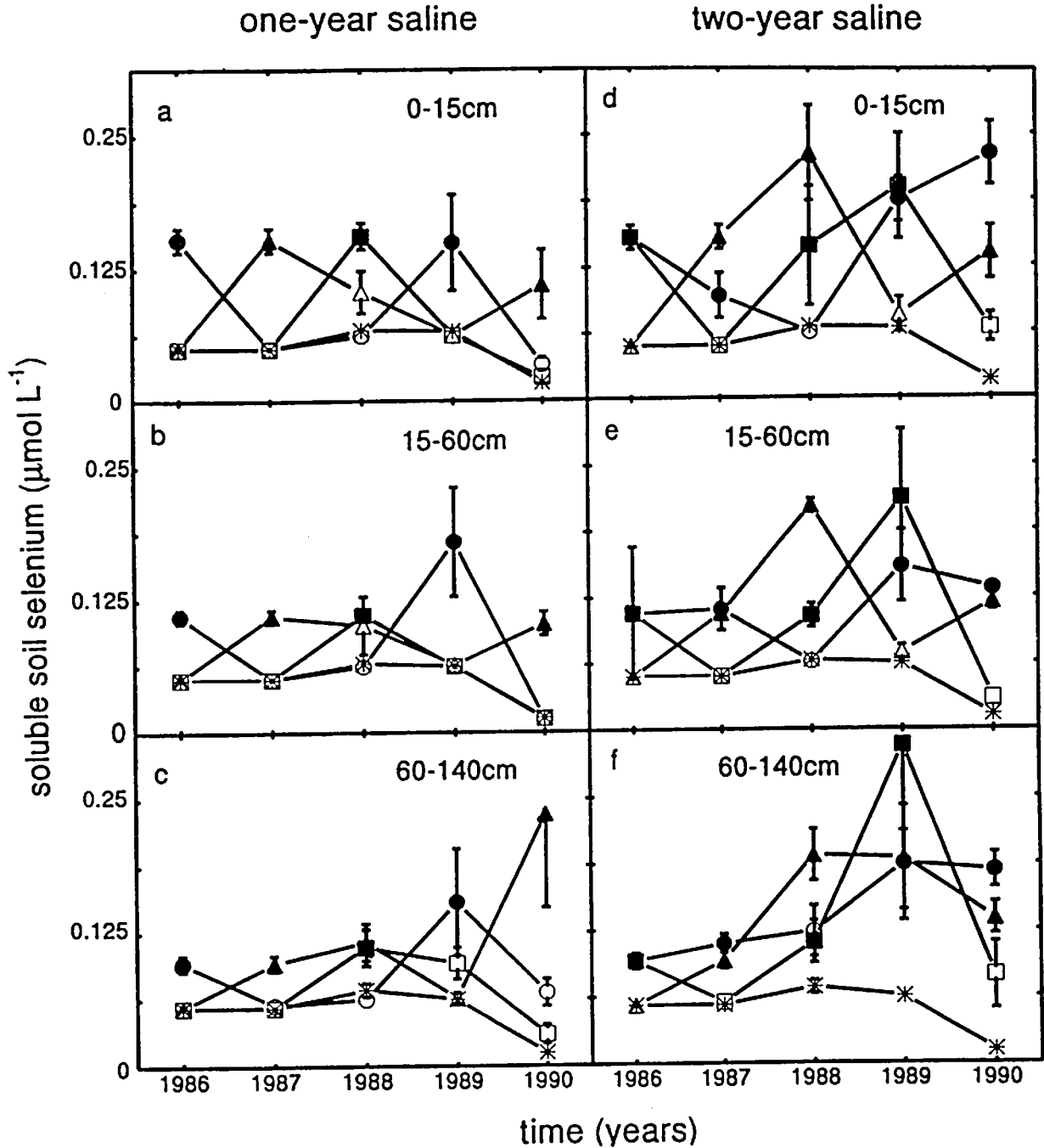


Figure 6c. Changes in soil Se over the years at the 0-15, 15-60, and 60-140cm depth intervals with different irrigation treatments (one-out-of-three years saline or two-out-of-three years saline). The non-saline control treatment is indicated by the star symbol. Solid symbols indicate years when saline drainage was applied to plots (Shennan et al., 1995).

C. Integrated On-Farm Drainage Management (IFDM)

Integrated on Farm Drainage Management (IFDM) is a practice for the management of drainage water, salt and trace elements on individual farms or in a farming area. The objective is to sustain the productivity and quality of the land by management of drainage water as a resource with economic value, while protecting wildlife safety and ground water quality (Cervinka, personal communication).

The IFDM system includes a number of components including, but not limited to (1) water conservation through efficient use (2) sequential reuse of drainage water to irrigate salt-tolerant crops, trees, and halophytes (3) management of trace elements (4) managing salt in solar evaporators and (5) salt utilization. It is beyond the scope of the Technical Reuse committee to examine all components of this integrated management system since it cuts across other committee's charges. Therefore our report will cover IFDM systems in terms of the first three components listed.

The IFDM system utilizes a variety of crops, plants, and trees to manage salt and drainage water on the farm site. This system provides an opportunity to maximize the area devoted to high-value salt sensitive crops on the farm or within the district as well as manage salts and to reduce the Se load in the system. The goal is to manage salt, trace elements and drainage water in a manner that is technically feasible, environmentally safe, and economically sound.

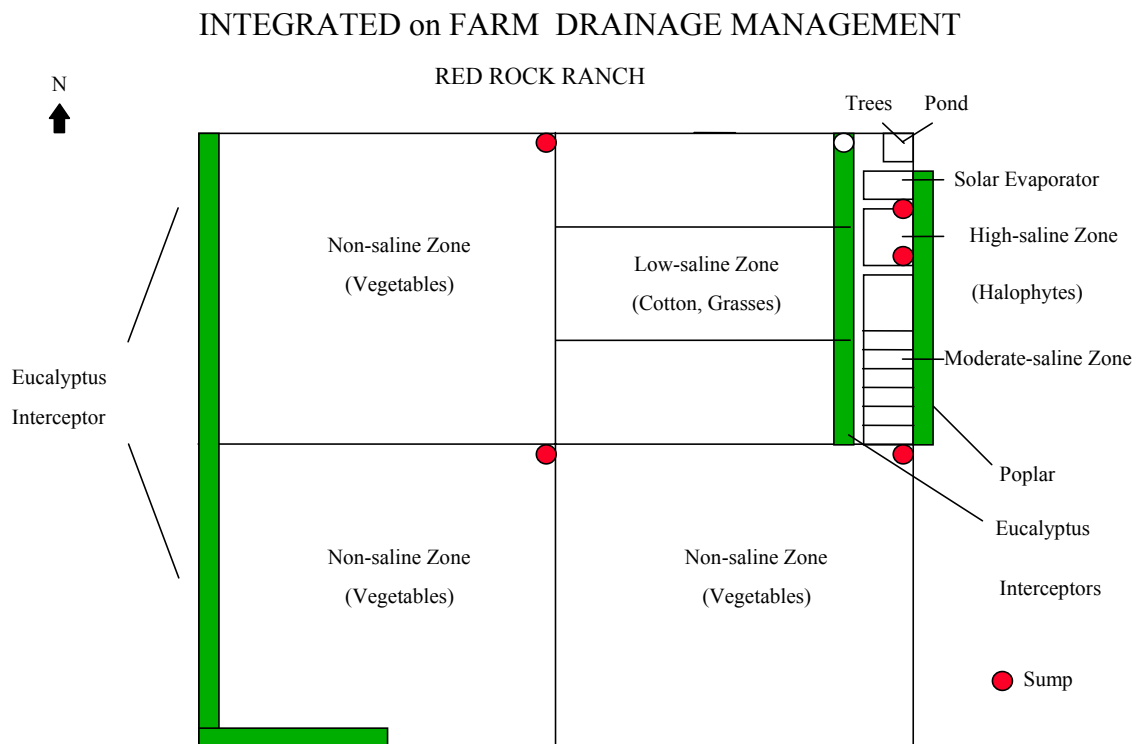


Figure 7. Schematic diagram of Integrated on Farm Drainage Management (IFDM) at Red Rock Ranch

IFDM system

An IFDM system is currently being tested at Red Rock Ranch. Salt is progressively moved with the drainage water from the zone of salt sensitive crops through a system of sequential reuse to a zone of highly salt tolerant crops (Figure 7). Salts are finally discharged into solar evaporation basins where it is crystallized prior to disposal or market.

The IFDM method has evolved substantially from the concept described in the Rainbow Report. For example the function of trees within the IFDM method is different from that described in the Rainbow Report (see discussion on Eucalyptus trees below). Trees in this scheme serve primarily as lateral-flow interceptors as a means to reduce drainage flow on-site.

The IFDM system outlined in Figure 7 can either be within the farm or within a district and is divided into various zones, ranging from non-saline to highly saline. Irrigation water is applied to conventional crops in the non-saline zone. Drainage water from the non-saline is sequentially reused on moderately salt-tolerant to tolerant crops (traditional crops, forages, or possibly salt-tolerant trees) in the saline zone. Within this zone, irrigation water can be applied undiluted or by using the blending or cyclic method to control soil salinity. Drainage water from the saline zone is sequentially reused on very salt-tolerant or halophytic species in the high-saline zone. The goal is to reduce the overall drainage volume by about 80 percent, if possible. The remaining fraction of hyper-saline drainage water is either discharged into a solar evaporator where it may later be disposed of or marketed (see Salt Utilization Committee Report). It is also possible to produce distilled water from concentrated saline brine (D. Peters, personal communication). However an economic analysis for the production of distilled water is needed to determine its feasibility.

The Mendota IFDM "Agroforestry" Site

Perhaps the most intensively studied site is the one located at Mendota. Between 1985 to 1986, 9.43 ha of *Eucalyptus camaldulensis* (Red Gum) were planted in 89 rows with 1.8m spacing. Trees were irrigated with non-saline water the first year to allow establishment in the already saline soil. Subsequently, trees were furrow-irrigated with saline drainage water dominated by sodium sulfate (EC 8-10 dS/m, SAR 11, 8-12 mg/L B, and 0.30-0.40 mg/L Se) from April to October each year.

In 1990, the experimental area received 0.96 m of drainage water; lesser amounts of water were applied in 1987, 1988 and 1989 (Tanji and Karajeh, 1993). In 1996, 6.56 ha of eucalyptus received 1.20 m of saline drainage water, the 2.43 ha of halophytes received 1.32 m of eucalyptus-tiled drainage water and 1.23 m of halophyte-tiled drainage water was applied to the 1.32 ha solar evaporator. Overall there was an 80 percent reduction in water volume from the amount of irrigation applied to the eucalyptus to the amount of drainage discharged into the solar evaporator (Karajeh et al., unpublished data). The marginal water applied to the eucalyptus in 1996 contained 498 tons of salt and 359 tons of evaporite minerals such as thenardite (Na_2SO_4) precipitated in the solar evaporator, a 72 percent salt recovery.

Salt and Water Management

In order for this type of sequential reuse to succeed, the crop root zone must be maintained within a certain salt concentration window to sustain sufficient growth and crop yields. This concentration window differs for the different crops within the system. Good management is required such that salts are moved sequentially until they are discharged into the solar evaporators and not allowed to concentrate within a particular section of land.

At the Mendota site, soil samples were routinely sampled at four locations to monitor changes in chemical quality over time. As indicated above the drainage water with an EC ranging from 8 to 10 dS/m was applied to the eucalyptus trees during 1989 to 1995. The targeted leaching fraction after 1990 was increased to 25-30 percent to reduce the salinity of the soil profile that had accumulated from the previous years. At the sampling station in the northwest quadrant, soil salinity increased to a maximal value averaging about 30 dS/m in 1990 but then decreased in later years as the applied water (i.e. leaching fraction) was increased (WRCD, unpublished data) (Figure 8). Ultimately (i.e. 1995/96), E_ce levels returned to where they were in 1989. The boron concentration in the top 100cm, however, doubled over this time period and the sodium concentration increased nearly 6 times (Karajeh, unpublished data). This indicates that sodicity and perhaps boron are “sustainability” issues of greater importance than salinity.

Selection of Crops in the Sequential Reuse System

The potential success of the IFDM system depends upon selecting the proper crops for each of the zones. High-value commercial crops are grown in the non-saline and low-saline zones. In the saline and highly saline zones, it would be valuable to select economically attractive crops that can not only grow well in saline-sodic conditions including high levels of boron but can sustain high rates of ET as well.

In the saline zones, crops that are sensitive to salinity (e.g. almond, plum, rice, bean, carrot, onion, strawberry) and or boron (grape vines and most tree crops) may be eliminated from the list of potentially suitable crops. However a rotation or sequence of crops that differ in salt-tolerance may be feasible if saline drainage water and a good quality water source are used at different times to create a transient soil-salinity profile to take advantage of crops that vary in salt-sensitivity (i.e. crops classified as moderately sensitive to tolerant).

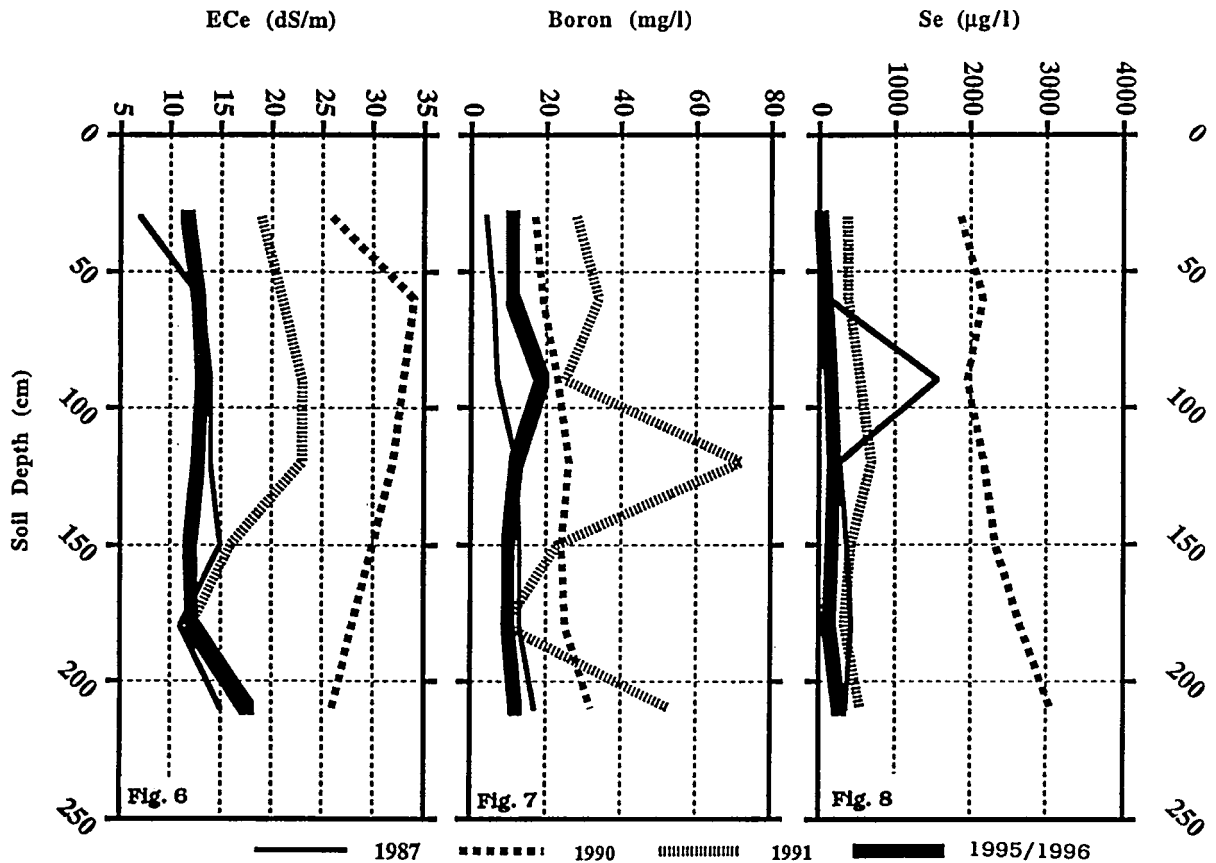


Figure 8. ECe, B, and Se concentrations at various depths over a number of years at the northwest sampling location in the Mendota Agroforestry site (WRCD, unpublished data).

There are a number of conventional crops currently grown in the SJV (e.g. cotton, melon, safflower, sugarbeet, tomato, and wheat) that have been tested to found to be effective in both short and long-term drainage water reuse studies (Ayars et al., 1990; Ayars et al., 1993; Grattan et al., 1987; Kaffka et al., 1999; Mitchell et al., unpublished data; Rhoades et al., 1988, 1989; and Shennan et al., 1995). However the success requires a number of additional management practices. For example irrigation with non-saline water is required at certain times particularly if tomato and other moderately sensitive crops are included in the rotation. Sugarbeet is a deep rooted salt-tolerant crop but field research indicates that the nitrates in the drainage water interfere with the percent sugar recovered from the beets (Kaffka et al., 1999). Therefore accounting for N and making sure soil levels are sufficiently low near the end of the season is necessary to assure adequate crop quality (Kaffka et al., 1999). Cotton is another salt-tolerant crop but some reuse studies have show that stand establishment in plots previous salinized with drainage water has been reduced (Mitchell et al., unpublished data; Rains et al., 1987; and Shennan et al., 1995). This type of information is useful to the design of a sequential reuse system.

There were a number of leafy (oriental) vegetables that were tested to determine if they could fill a niche within the drainage water reuse sequence (Shannon et al.,

1998). Vegetables tested included chard, spinach, red giant, kale, radicchio, pacchoi, tatsoi, greens and endive. Fresh weights of all vegetables tested were substantially reduced by drainage water. These vegetables, like most commercial vegetables currently grown, are moderately sensitive to salinity suggesting that they will perform best in the non-saline portion of the reuse sequence. Purslane, on the other hand, grew well in sand tank irrigated with simulated drainage effluent suggesting that this crop may be suitable in drainage reuse systems (Grieve and Suarez, 1997).

Currently, a field study is underway to test the feasibility of a number of salt-tolerant forages and forage cropping strategies (Oster et al., 1999b) as well as other crops such as wheat, forage brassicas, and safflower as forages as suitable crops in a IFDM system (Kaffka and Oster, personal communication). An important component of this study is to examine bioaccumulation of Se and Mo in forages under irrigation with saline drainage water. Results from this study will be particularly useful in the design of such a system.

Halophytes

Various salt-tolerant plants, including halophytes, have been tested and evaluated for the saline and high-saline zones. Some promising species include bermudagrass, saltgrass, Jose wheatgrass, cordgrass, perla, salicornia, purslane and atriplex (Cervinka, personal communication; Grieve and Suarez, 1997, Shannon et al. 1998). Amongst the halophytes, salt grass (*Distichlis* spp.), bermudagrass and *Atriplex* spp. have potential as forages, while others have potential for shade and for water table control (salt cedar) (Oster et al., 1999b).

Another halophyte, *Salicornia bigelovii* which is native to the North American coast, is able to grow well in the desiccating conditions of the SJV and maintain ET rates in excess of ETo (Figure 9) when irrigated with hypersaline drainage water (Grattan et al., 1999). In 1997 fresh biomass production in the field was 6.2 kg/ m² which was less than half that achieved the previous year. *Salicornia* is sold as a salad supplement in Europe and it produces oil in its seed that is equal in quality to soybean oil. It has considerable promise as a halophyte for seawater irrigation (Glen et al. 1998). This leafless plant may also remove a significant amount of selenium from irrigated farmland. For example, *Salicornia* at the Mendota site was found to contain up to 2 mg Se per kg. dry wt. (Grattan et al., 1998). Based on an average dry biomass of 1 kg/m², about 2 mg of Se would be removed per m² each season. A much larger amount is removed by volatilization (N. Terry, unpublished data). However, initial calculations indicate that Se removal based on both Se volatilization and plant uptake is a small fraction to that being applied on an annual basis (D. Peters, personal communication).

The evapotranspiration of saltgrass (*Distichlis spicata*) was evaluated under irrigation with hypersaline drainage water in 1998 using drainage from the same site (Mendota) and similar EC (28-30 dS/m) as that used to irrigate *Salicornia* in 1996 and 1997. Similar to *Salicornia*, the saltgrass ET rates, measured in August and September, were close to and sometimes exceeded reference ET rates (ETo) (S. Benes, personal communication). Thus, the cultivation of either of these halophytes shows promise as a means of reducing drainage volumes before discharge into a solar

evaporator. More work needs to be done on the selection, production, harvesting, processing, and marketing of the halophytes.

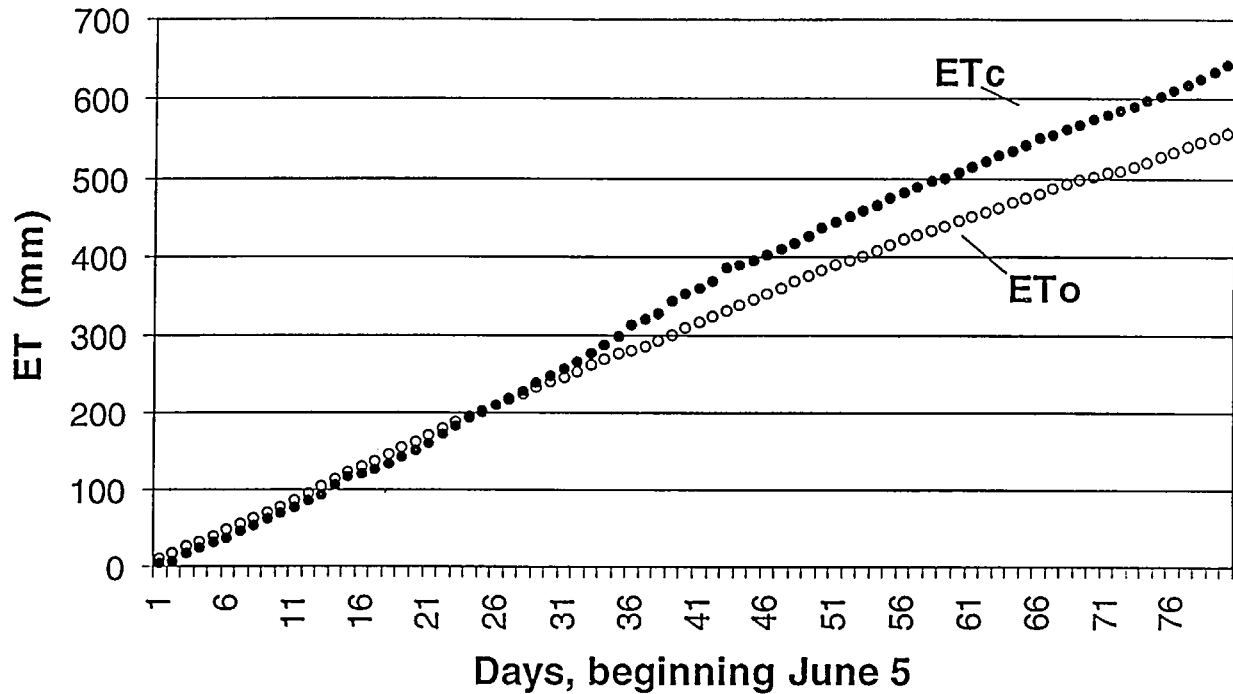


Figure 9. Cumulative ET of *Salicornia bigelovii* grown in Mendota from 5 June, 1997 in relation to cumulative ETo from the local CIMIS weather station (Grattan et al., 1999).

Can halophytes actually be used to “reclaim” salt from the soil?

The question is often posed whether or not plants can be used to harvest and remove salt from salt affected land. The answer to this question is “no” for reasons explained below.

The salt content of the plant tissue is generally only a small fraction of the salt contained in the soil and irrigation water. This is particularly true for glycophytes. However this is also true for halophytes that take up salts where concentrations in the plant tissue can reach 15 to 40 percent on a dry weight basis. These plants actually require high levels of salinity to grow well but the salt that they accumulate again is small fraction to that left behind in the soil. For example *Salicornia* in Mendota accumulated up to 40 percent salt on a dry weight basis but this was less than 10 percent of the total salt applied to the crop in the irrigation water over the season (D. Peters, personal communication).

Eucalyptus Trees

Eucalyptus plantations have been established throughout California's SJV for the purpose of reducing the volume of drainage water that needs ultimate disposal (Cervinka, 1994). Often the poorest or most problematic fields such as those with high saline water tables or those that are poorly drained are selected for the eucalyptus trees. Eucalyptus trees have been found to reduce dryland salinization in areas cleared of native vegetation in western Australia (Bari and Schofield, 1992). Re-vegetation with eucalyptus trees reduces ground water recharge and lowers raised saline-water tables thereby reducing salinization of the upper portion of the soil profile (Morris and Thomson, 1983).

Trees serve as biological “pumps” whose main purpose is to transpire water. This can lower saline water tables, intercept lateral flows from upslope areas and reduce the overall volume of drainage water. The goal is to select trees with the following characteristics; (a) act as efficient biological pumps that can maintain high rates of transpiration over long periods of time, (b) are low maintenance and low cost, (c) are tolerant to salinity, boron, drought and temporary flooding conditions, (d) act as biological filters for key trace elements and (e) provide a desirable environment for both humans and wildlife (Cervinka, 1994). To be effective as biological “pumps”, these trees must endure the various stresses they encounter in the SJV and at the same time, maintain a high rate of ET over the long term.

Observations from eight demonstration projects indicate that eucalyptus trees have been somewhat effective at reducing the volume of drainage water, lowering water tables and intercepting water flows. Most of the success has been attributed to trees planted to “intercept” lateral drainage water flows. However it is not clear to what extent high rates of ET were achieved and in a number of locations, trees suffered injury or died.

Eucalyptus trees have not performed particularly well where they have been grown as a crop within the “reuse sequence”. Poor tree performance has been attributed to a number of factors including frost, excessive salinization, boron toxicity, sodicity and poor aeration.

A recent study was conducted at the U.S. Salinity lab using large sand tanks to determine potential ET rates of *Eucalyptus camaldulensis* clone 4544 when irrigated with simulated drainage water that varied in salinity (EC 2-28 dS/m) and boron concentration (1-30 mg/L). Sand tanks were used because they drain well and the concentrations of salts and boron in the soil water are close to that in the irrigation-treatment water. This point is extremely important. In a field condition, irrigation with 10 dS/m water will result in an average rootzone salinity of 15 dS/m, assuming a steady-state leaching fraction of 15-20 percent is achieved (Ayers and Westcot, 1985) and the effects of calcite and gypsum precipitation during evapoconcentration within the rootzone are insignificant. Irrigation with 28 dS/m water in large sand tanks using leaching fractions approaching 100 percent would result in more or less the same average rootzone salinity (EC_e) as irrigating with 10 dS./m water in the field.

When the average rootzone salinity was 15 dS/m, tree ET was reduced to

53 percent of those in the non-saline treatment when evaluated over the entire period where trees were subjected to saline water.

Table 5. Percentage of cumulative ET relative to the low salinity treatment (EC_w 2 dS/m) averaged over the boron treatments. Cumulative ET was from Sept. 1995 – April 1996 (Shannon et al., unpublished data).

EC _w (dS/m)	Cumulative ET (percent)
2	100
6	89
10	75
15	53
22	38
28	11

The data above should be viewed as transpiration potentials. No other stresses other than those related to the concentration and composition of the irrigation water were imposed. As indicated above, the numerical values above can not be used directly to irrigation waters of similar concentration in the valley. In the sand tank study, water was applied daily and the majority of the applied water drained back into reservoirs below the sand tanks. This extremely large leaching fraction allowed the EC of the soil water (EC_w) to become very close to that of the applied water. Under field conditions, the EC of the applied water would translate into a much higher soil salinity.

The reduced ET is attributed largely to salinity's affect on tree biomass. Eucalyptus tree biomass decreased as the salinity of the soil water (more or less in equilibrium with that in the irrigation water) above 6 dS/m (Shannon et al., 1998). Note that there was a significant interaction between boron and salinity (Figure 10). Tree biomass was affected by boron at low salinity but not at higher salinity (i.e. equal to or greater than 22 dS/m). Based on these data, *Eucalyptus camaldulensis* is more appropriately classified as moderately salt-tolerant than salt-tolerant.

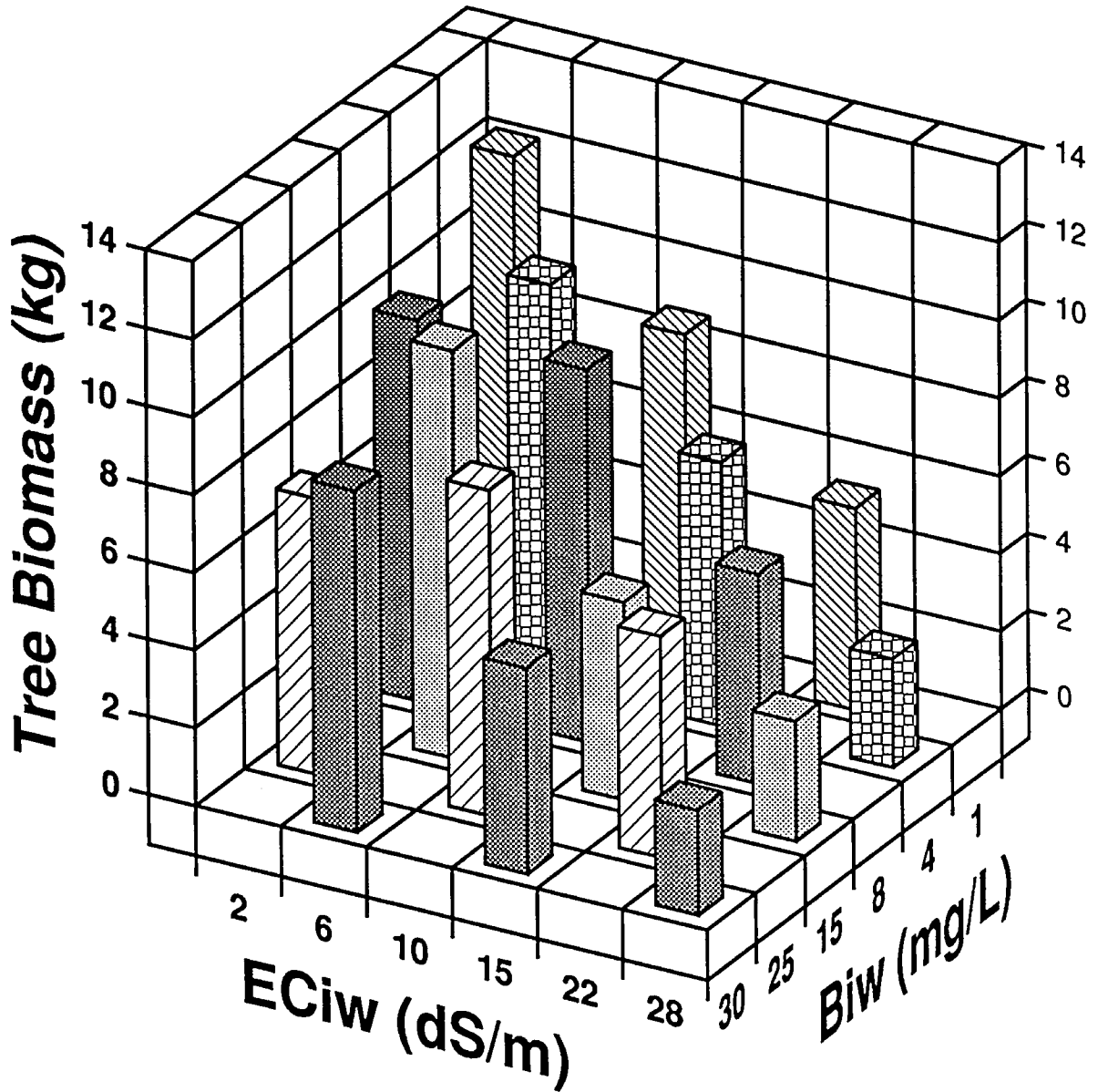


Figure 10. Effects of salinity and boron on the biomass of *E. camaldulensis*, clone 4544. Solid symbols indicate boron concentrations in the applied water < 25 mg/L whereas open triangles indicate that the boron concentration was 25-30 mg/L. Bars above and below low B treatments indicate standard deviation of the mean. (Shannon et al., 1998).

TLDD Eucalyptus Project

Three varieties of clonal Eucalyptus trees were planted, in October 1994, in three, 5.6-acre Checks (Checks 15 – 17) at the TLDD drainage water reuse facility (Oster et al., 1999a). The planting configuration was a row spacing of 14 feet and an in-row spacing of 6 feet (520 trees/ac). Each Check had tree rows of clonal varieties 4543

and 4544, and one row of 4573. Continuous irrigation with a saline-sodic drainage water (EC: 8.5 dS/m; SAR: 33.4) began in 1996. Although this combination of EC and SAR was not expected to degrade soil physical properties such as structural stability, tilth, infiltration rates, water redistribution rates in the soil, and aeration, rapid degradation was expected as a result of leaching during the winter rain season, particularly near the soil surface.

The hypotheses tested was that fall applied gypsum (Check 15) at a rate of 5 tons/ac, or a combination of fall applied gypsum and ripping (Check 17) would maintain, or restore the adequate soil physical properties for tree growth. All the Checks were disked periodically during the year to control weed growth. The major objectives were to determine the effects of fall applied gypsum and ripping on tree growth and yield, soil salinity and sodicity, and chemical composition of eucalyptus leaves.

Soil chemistry and leaf composition were monitored at nine locations in each Check from soil and leaf samples obtained in the spring and fall of each year from beginning in 1995. Applied irrigation water was measured with meters installed on the water turnout valve located at the head end of each Check. Rainfall was measured at the El Rico office of the Boswell Land Company located about 10 miles north of the experimental site. In 1998, groundwater chemistry was determined at 12 locations beneath Checks 15 - 17.

Wood yields

Five trees in each row were randomly selected for harvest in September 1998, and the height, trunk diameter and mass of each tree were determined. Check 15 had the highest yields (Table 6) whereas Check 16 had the lowest. Variety also affected harvest yield; variety 4544 yielded the least.

Table 6. 1998 wood yields in cords per acre. G, R, and GR represent gypsum, rip, and gypsum plus rip. (Oster et al., 1999a).

Ck #	Trt.	4544			4573	4543			Ave
		Row 1	Row 2	Row 3	Row 4	Row 5	Row 6	Row 7	
15	G	1.43	1.09	1.21	1.51	1.35	1.49	1.27	1.33
16	R	0.69	0.53	0.40	0.62	0.67	0.76	0.58	0.61
17	GR	0.70	0.50	0.32	0.90	0.90	0.96	0.99	0.75
Average		0.94	0.71	0.64	1.01	0.97	1.07	0.95	0.90

Growth rates, monitored at nine locations in each Check beginning in 1995, were negligible until the fall of 1996, and increased linearly with time thereafter. Consequently, division of the values in Table 6 provides estimates of annual growth rates.

Soil aeration

The lack of aeration in Check 16 was one cause of its lower yields. Oxygen diffusion rates (ODR) were monitored, between days 60 and 190 in 1998, at depths of 1, 2, 3, and 4 feet at two locations in both Checks 15 and 16. ODR was the same in both Checks, about $0.0 \mu\text{g}(\text{O}_2)/\text{cm}^2 \text{ min}$, until day 130. Whereas in Check 16, ODR remained between 0.002 and $0.02 \mu\text{g}(\text{O}_2)/\text{cm}^2 \text{ min}$ until day 190. After day 130, it improved rapidly in Check 17 reaching levels of 0.17 to $0.3 \mu\text{g}(\text{O}_2)/\text{cm}^2 \text{ min}$ by day 140. This improvement in Check 17 reflected a combination of little rainfall, soil drying and drainage which enhanced air permeability. The lack of fall application of gypsum in Check 16 resulted in high SAR levels relative to the ECe in the upper 6 inches of soil. This caused a degradation of soil physical properties to the point where poor drainage and low air permeability resulted.

Rooting depth/ripping

With only a few exceptions, ECe did not increase with depth between the falls of 1996 and 1998. This strongly suggests that the effective rootzone, in terms of water uptake, was very shallow. Although rooting occurred to a depth of 1.5 to 2.5 feet, most of the water uptake occurred in the upper half foot of soil. Ripping apparently caused significant damage to the root system. Checks which were ripped had the lowest yields (Table 6).

Crop water use

The applied irrigation water for Check 15 in 1998 was greater than the other two Checks (i.e. 33.6 inches vs 28.9 and 29.6 inches for Checks 16 and 17, respectively). This is consistent with the greater wood yields obtained in September 1998 (Table 6). Based on the average water applied of 32.4 inches/yr, and assuming 50 percent of the rainfall was effective (11.5 inches of rainfall in 1996/97 and 17.0 inches in 1997/98), the average total applied water was 39.5 inches/yr. The leaching fraction was about 0.23, based on the chloride concentrations in the groundwater (105 meq/L) and the average chloride in the applied water corrected for rainfall (24.1 meq/l). Consequently the average annual amount of water used by the crop was about 30 inches. Crop water use is low because salinity reduced tree growth and evapotranspiration.

Projected sustainable yields

Wood yields were projected through the year 2003 assuming linear growth continues and that one tree out of six is harvested each year. At the observed annual growth in Check 15 rate of 0.66 cords/(ac yr), the highest rate obtained, projected wood yields in 1998 would be 0.20 cords/ac and in 2003 they would be 0.77 cords/ac. Based on a wholesale value of Eucalyptus firewood at the TLDD site of \$30.00 to \$50.00 per cord, the annual sustainable yields of 0.2 to 0.8 cords per acre will not generate a level of annual income that exceeds the annual operating costs of \$137.50/ac and the fair share of the development cost of \$1200.00/ac.

Impact of trees on land required for management of drainage water

Operator experience in the Tulare Lake Basin indicates that 10 acres of drained land are served per acre of evaporation pond. This performance was combined with the estimated water use and leaching fraction observed in the TLDD trees project, coupled with an assumed effective rainfall of 4 inches/yr. The result was that 10 acres of drained land would require 1.6 acres of trees and 0.30 acres of evaporation pond. Resource economists will need to assess whether 1.90 acres of trees and evaporation ponds would be more profitable than 1.0 acre of evaporation ponds and no trees.

Another study was conducted using both the transient state and quasi steady-state model to simulate irrigation of eucalyptus trees with drainage waters of EC=10 dS/m (Letey and Knapp, 1995). The simulations were run with different levels of drainage water applications. The salinity coefficients¹ for eucalyptus were estimated to be A = 9 dS/m and B = 7. For the transient state simulation the initial soil profile was considered to be non-saline. During the first year of simulation, the transient state model predicted a higher yield than the steady-state model, which was a result of the assumed initial non-saline soil profile. During the second and subsequent years of simulation, the transient state and steady-state model simulated yields were within approximately three percent of each other. A significant conclusion is that the transient state model converges to the steady-state solution and that the steady-state model can be used if the same management practices are imposed for two or more successive years. Furthermore, the results of the model simulations were compared to field results reported by Tanji and Karajeh (1991). They reported the EC of the drainage water from the eucalyptus trees was 32 dS/m compared to 35 dS/m calculated by the steady-state model. Relative yields are assumed to be proportional to the relative evapotranspiration of the stressed to the non-stressed crop in the models. Dong et al (1992) estimated the crop coefficient for the trees irrigated with drainage waters to be 0.83 as compared to an expected crop coefficient of 1.2 for unstressed trees. This ratio equals 0.69, which was close to the simulated relative yield from the models. The reasonably good agreement between measured and simulated results provides some assurance that the model simulations can be used with some degree of confidence.

Some practical conclusions can be drawn from this analysis. A relatively high leaching percentage, ranging from 25 to 60 percent depending on the salinity and composition of the drainage water must be imposed when irrigating eucalyptus with saline drainage waters if maximum yield and evapotranspiration are expected.

Experimental data from Australia indicate that yields of *E. calymdulensis* can be maintained near maximal values when irrigated with 10 dS/m drainage water with a leaching fraction of 0.35-0.46 (Sweeney and Stevens, 1997). In the SJV however, achieving a high leaching fraction could create a logistic problem. Application of large quantities of drainage water to the soil could cause water logging and deficient aeration would impact eucalyptus production if the soil water transmission properties were not sufficiently good.

¹ Although the salinity coefficients assumed in this model (A=9 dS/m and B=7) differs from that from Shannon et al., unpublished data (A=3 and B=3), the Ece at 50 percent yield potential are not far off from one another.

Based on these studies, it appears that *Eucalyptus camaldulensis* should not be considered as a “crop” within the saline-irrigated sections of the reuse sequence as suggested in the Rainbow Report. Based on tolerance data, cotton would be a better candidate than *E. camaldulensis* in these saline sections provided a suitable stand can be established. However if the sole objective is to reduce drainage volume, one has to remember that Eucalyptus is a perennial and thus “transpires” throughout the year whereas cotton or other “salt-tolerant” annuals, transpire during the growing season. Rather trees of this type should be considered in smaller areas or strips as “drainage water interceptors”.

It is important to emphasize that there are more salt tolerant Eucalyptus species than *Eucalyptus camaldulensis* but it is unknown at this time whether these species would perform better under multiple stresses such as salt, saturated conditions, frost and high levels of boron.

Se Balance at the Mendota Agroforestry Site

The selenium concentration in drainage water varies quite dramatically from one location to the other. Where concentrations are high such as the Mendota area, reuse must be managed in a way such that Se does not become an environmental hazard. The sequential reuse of drainage water provides the opportunity for selenium to be volatilized, taken up by plants and trees, and removed from the system with harvested salt.

The behavior of Se in the soil profile at Mendota (see Figure 8) was similar to that in other long-term reuse studies in the valley where Se concentrations in the drainage water was more than an order of magnitude lower (Shennan et al., 1995) (see Figure 6c). Se concentrations were found to increase following irrigation with saline drainage water containing Se but dropped readily upon leaching. Se was more readily leached than salts. Se concentrations in 1996 in the top 2m of the soil profile were no different from samples collected in 1987 (WRCD, unpublished data).

It is important to point out that Se concentrations reported by WRCD (unpublished data) and Shennan et al. (1995) are water soluble Se in the saturated soil extract. To verify that Se is in fact not accumulating within the soil, a total Se analysis is recommended to rule out rootzone accumulation in either a reduced or bound form.

Selenium and Wildlife Safety

Although common agroforestry practices outside of the SJV have been shown to create valuable wildlife habitats, there are concerns regarding the ecological sensitivity of analogous in-Valley habitats which are irrigated with agricultural drainage water high in salts and selenium. Studies suggest that certain biota collected from in-Valley agroforestry sites are accumulating greater than background levels of selenium in their tissues (Dunn, personal communication). Elevated Se levels are currently being found in one specific terrestrial invertebrate-sowbugs (Isopoda). The only evidence of Se induced toxicosis was observed in deformed shorebird embryos collected from nests adjacent to agroforestry site solar evaporators; subsequent changes in site

management and the implementation of site specific hazing programs have proven successful in discouraging additional shorebird nesting. Ongoing monitoring of Se and associated toxicological effects in wildlife collected from in-Valley agroforestry sites is part of the continuing research to ensure that the planned large-scale use of agroforestry for agricultural wastewater management can proceed without developing into a contamination risk to wildlife.

Although the potential adverse affects from drainage water reuse have not fully been assessed, there are a number of management techniques that can be employed to reduce the risk to wildlife. For example, leveling fields planted to halophytes should reduce ponding thereby making the field less attractive to waterfowl. This practice in combination with hazing may reduce risks to wildlife (Cervinka, personal communication). It is also possible that certain crop management practices such as mowing or grazing could enhance wildlife safety and testing such practices are warranted.

Salt and Boron Leaching at Red Rock Ranch

At this time, Red Rock Ranch serves as the best model of a IFDM system, yet it is still under development. The IFDM systems at Red Rock Ranch has shown some immediate benefits. For example after only two years of salt management, vegetables are now planted on 320 acres of land that did not produce any economic yield of cotton or alfalfa before. This success is attributed to leaching of salt and boron, particularly in the upper portion of the soil profile (Table 7).

Table 7. Distribution of salinity and boron at various locations at Red Rock Ranch from 1995 to 1997 (WRCD, unpublished data).

Field ID	Depth feet	1995		1996		1997	
		ECe dS/m	B ppm	ECe dS/m	B ppm	ECe dS/m	B ppm
10NW	0-1	10.0	15.3	1.8	2.3	1.0	1.2
	1-2	11.3	15.6	6.8	7.0	4.1	4.1
	2-3	10.3	9.0	9.5	13.9	6.6	8.9
10SW	0-1	13.8	13.3	3.1	3.9	1.5	3.8
	1-2	10.7	10.9	7.5	6.6	8.4	12.4
	2-3	9.6	8.0	8.3	7.1	10.7	12.2
10NE	0-1	10.0	3.5	2.0	1.7	2.0	1.0
	1-2	4.4	4.8	6.9	6.3	4.5	2.9
	2-3	5.8	6.5	9.0	9.8	5.5	3.7
10SE	0-1	2.9	2.5	1.1	0.7	0.8	1.1
	1-2	6.1	4.4	3.7	3.4	1.8	2.5
	2-3	7.7	5.1	7.2	6.1	3.1	6.6

A number of studies are currently being conducted at the Red Rock IFDM site and it will be valuable to assess the results obtained in the coming years.

Summary

A major objective of the IFDM method, from an economic perspective, is to maximize the area devoted to high value commercial crops not subjected to crop growth restrictions from salinity or trace elements (e.g. at least 75 percent of the farm area). Source control is the best way to achieve this goal (see Source Control Technical Report). Economic benefits would have to be weighed against not having a sequential reuse system with a smaller percentage of area devoted to high value crops. The saline and highly saline areas should be planted to crops that can grow well and sustain high levels of ET and if possible be profitable. It is not clear at this point in time which crops are best at each stage along the sequence. A number of crops have shown promise and some forage crops, yet to be identified, may be appropriate. More research needs to be done on testing, selection and diversification of different species.

In order to reduce the salinity in the profile, leaching was required. Without sufficient leaching and a drainage outlet, salts, boron and trace elements will accumulate within the rootzone. At the Mendota site, a yearly leaching percentage of 25-30 percent was necessary for reclamation during cropping. Now that acceptable levels of salinity have been achieved, leaching fractions can be reduced. Because the soil at the site was a deep, saline clay loam, standing water was often found at the site long after an irrigation. Poor water infiltration can also be attributed to the saline/sodic

nature of the drainage water and soils will become more sodic over the years. Particularly problematic are the saline/sodic drainage waters in the Tulare Lake Drainage District and high clay content in the soils where this water is being applied. Gypsum applications have proven to be successful at reducing sodicity and improving the soil physical characteristics of the soil; thereby improving aeration and improve tree performance. Provided that the soil physical conditions can be improved, leaching may be most effective during the winter months when the evaporative demand is low. This was found to be beneficial in the Mendota area where the drainage water is less sodic than further South. If a targeted leaching fraction can be achieved, then sodicity and boron remain the greatest concerns over the long-term.

V. ECONOMIC EVALUATION OF DRAINAGE WATER REUSE

A host of economic questions arise in evaluating drainwater reuse as a solution strategy for drainage problems. These include the usual agronomic decisions such as choice of crop and irrigation system. They also include water management decisions: how much water to apply, the mix of waters from fresh and drainwater sources, timing of irrigation and so on. Use of drainwater will likely also imply changes in other cultural practices, including use of amendments, and may also require installation of plumbing systems to accomplish reuse. These kinds of questions go into determining ideal or best management strategies at the field-level under varying circumstances.

Given answers to these questions, one can then begin to estimate the costs of reuse as a drainwater management strategy in terms of reduced net value of agricultural production. These costs would then be compared to the costs of other drainwater reduction/disposal methods such as source control, treatment, evaporation ponds, etc., in order to arrive at an overall solution to the drainage problem for a farm or region.

A. Water Management with Reuse

Water management economics with reuse are generally analyzed using computer simulations. Results from a computer model used in several studies are summarized here for the field-level, taking as given both the crop and the irrigation system. Both the value of reusing water and the environmental damages/disposal costs from deep percolation flows are assumed known, and the analysis is conducted with respect to aggregate water quantities over the course of a single season.

The general model follows Knapp and Dinar (1984), but see also Dinar et al. (1986) for a related development. Let y = crop yield and d = deep percolation flows. There are two possible sources for irrigation water, where the first source represents the original freshwater source, and the second is drainwater available for reuse. Let w_i = seasonal applied water depth, c_i = salt concentration, and p_i = price, for source i . Generally the fresh water source has a low salt concentration and high price, while the drainwater has a higher salt concentration and low (possibly negative) price.

With these definitions, annual profits (social net benefits) are given by

$$p^y y - \sum_i p^i w_i - p^d d - \gamma \quad (4)$$

where p^y is the crop price net of harvest costs of producing the crop, p^d = the environmental damages/disposal costs associated with drainage flows, and γ = all other production costs. The reuse price is the per-unit net value of reusing drainwater in terms of avoided damages/disposal costs. This price can be negative, reflecting the fact that reusing drainage water for irrigation saves on disposal/environmental costs which would otherwise be incurred by that drainage water. The price on deep percolation flows reflects the per-unit damages resulting from residual deep percolation flows are also known.

Crop-water production functions give crop yield and deep percolation flows for the field as a function of quantity and quality (salt concentration) of applied water.

Mathematically this is denoted by:

$$\left. \begin{matrix} y \\ d \end{matrix} \right\} = f(w, c) \quad (5)$$

where

$$w = w_1 + w_2 \quad (6)$$

is total seasonal applied water depth and

$$c = \frac{c^1 w_1 + c^2 w_2}{w_1 + w_2} \quad (7)$$

is the seasonal average salt concentration of applied water.

In (5), f is a vector function with the respective components for yield and deep percolation flows. Included in the field-level production function (5) are the plant-level response to infiltrated water as well as the non-uniformity of water infiltration over the field corresponding to the particular irrigation system being considered. Other inputs to the production process are assumed constant and suppressed in the crop-water production function but included as costs in γ . This production function is specific to the crop and irrigation system being considered, and varies according to climatic conditions and other cultural inputs.

Table 8. Optimal water management with reuse for cotton with a furrow, 1/2 mile irrigation system (computed by K. Knapp).

P_1 (\$/(ha-cm))	P_2 (\$/(ha-cm))	P^d (\$/(ha-cm))	W_1^* (cm/yr)	W_2^* (cm/yr)	(\$/(ha-yr))	
0.75	-0.02	2	105	0	907.98	
		4	95	0	851.67	
		0	0	310	1050.61	
	.08	2	105	0	907.98	
		4	95	0	851.67	
		0	0	275	1021.50	
	.18	2	105	0	907.98	
		4	95	0	851.67	
		0	0	275	1021.50	
	1.75	-0.02	2	45	85	821.41
			4	90	0	761.03
			0	0	310	1050.61
.08		2	60	60	814.57	
		4	90	0	761.03	
		0	0	275	1021.50	
.18		2	75	35	809.76	
		4	90	0	761.03	
		0	0	275	1021.50	
2.75		-0.02	2	0	160	808.00
			4	70	25	674.96
			0	0	310	1050.61
	.08	2	0	0	160	792.00
		4	85	0	674.23	
		0	0	275	1021.50	
	.18	2	0	0	155	776.38
		4	85	0	674.23	
		0	0	275	1021.50	

Salt concentrations = .67 dS/m and 10 dS/m for the first and second sources respectively.

Table 8 reports optimal water management for cotton using a furrow irrigation system using a run length of 1/2 mile. The empirical specification of the production function in (2) follows Dinar et al. (1985); other data are from Knapp (1992). The salt concentrations are .67 dS/m and 10 dS/m for the fresh and drainwater sources respectively, while various prices are considered for the two water sources and for the cost of drainage disposal. The freshwater prices range from a low of \$9/a-f to a high of \$34/a-f. The middle price for the second source (e.g. reuse) represents the cost of

pumping water from a shallow (8 foot) water table. The low price of a negative \$.02/(ha-cm) represents a subsidy to encourage growers to use drainage water, while the high price represents a situation where drainage water is considered a scarce resource with some value. Drainage disposal costs range from a low of zero to a high of approximately \$50/a-f. Higher prices were evaluated for the freshwater source, but these resulted in 100 percent drainwater reuse for the range of prices considered, and are therefore not reported in the table.

The results illustrate that some drainage water reuse - at least in terms of seasonal averages - can be optimal. This occurs at both the moderate and high freshwater prices for several values of drainage costs and cost of the second source. The results also illustrate that optimal water management including reuse varies significantly with the various prices. In general optimal (profit-maximizing) reuse increases as either the price of freshwater increases or the price of the second source decreases. Optimal reuse decreases as the cost of deep percolation flows increase. While the direction of these effects is what would be expected, what is most striking is the magnitude and significance of the effects, especially considering that the range of prices considered is probably well within the range of variation within the SJV.

Interestingly enough, these results also show that reuse can be privately optimal even when the disposal value of reuse is ignored. In this instance drainwater reuse is serving as a mechanism for reducing usage of expensive surface supplies. This is likely to be increasingly true as surface supplies to agriculture become scarcer and more expensive due to reallocation to urban and environmental uses.

The analysis in this section has several limitations, even within the confines of the particular problem being considered. Only seasonal water use is being considered. In actuality the decisions facing growers are when to irrigate, and how much and what blend (if any) to irrigate with, when irrigation occurs. Knapp and Dinar (1988) develop a daily model to investigate this intra-seasonal, irrigation scheduling problem; however, the analysis is limited by the fact that only uniform irrigation is being considered. To date, no models appear to be available to investigate optimal water management and reuse for the irrigation scheduling problem with nonuniform water infiltration over the field. The analysis here also considers only general salinity effects. It does not account for specific ion effects such as boron, nor does it consider effects on soil structure. The model also does not consider quality effects on yield, or the salt concentration of the deep percolation flows being generated, and how that might influence damages and disposal costs incurred elsewhere.

B. Crop and Irrigation Systems

Besides water management decisions, growers also choose what crops to grow and what irrigation systems to use. As with water management, these decisions are affected by the opportunity, need for, and cost of reuse, as well as other prices and costs.

There are several possible crops that can be grown, and several possible

irrigation systems which can be used. Profits for crop i and irrigation system j are denoted π_{ij} and computed according to the formula in (1). Likewise there is a production function (2) for each crop-irrigation system combination. Optimal water management is then chosen for each crop-irrigation system combination as in the previous section. This will depend on the particular prices being evaluated as illustrated in table 8. Finally, the crop-irrigation system with the highest profits evaluated at optimal water management is then selected as the best choice.

This is illustrated empirically for two crops (cotton and tomatoes) and five irrigation systems (furrow with 1/4 and 1/2 mile runs, linear move, LEPA, and subsurface drip), with data sources as before. For the range of prices considered (e.g., as in table 9), tomatoes are invariably the most profitable crop, and there is no reuse. While a larger selection of crops would find more response of crop choice - and reuse - to water and deep percolation charges, these results do suggest that crop choice may well be driven by other considerations.

Irrigation system decisions are explored further in table 9. The results are only for cotton, but with the choice of the five irrigation systems noted above. Two situations are considered: the first is where there is no reuse opportunity, i.e., all irrigation water must come from the first source, and the second is where irrigation can occur out of either or both sources. Considering first the reuse case, the choice of irrigation system can be influenced by any of the three water prices being considered. Nevertheless, for the range of prices considered, furrow, 1/2 mile is generally the system of choice.

Table 9. Optimal irrigation systems and net returns for cotton under alternate water prices. (computed by K. Knapp).

P ₁ (\$/(ha- cm))	P ₂ (\$/(ha- cm))	P ^d (\$/(ha- cm))	No Reuse		Reuse	
			I. S.	II (\$/(ha- yr))	I. S.	II (\$/(ha- yr))
2	-.02	3	furrow, 1/2	760.76	furrow, 1/2	760.95
		6	linear	711.24	linear	711.24
		0	furrow, 1/2	845.59	furrow, 1/2	1025.34
	.08	3	furrow, 1/2	760.76	furrow, 1/2	760.76
		6	linear	711.24	linear	711.24
		0	furrow, 1/2	845.59	furrow, 1/2	1005.34
	.18	3	furrow, 1/2	760.76	furrow, 1/2	760.76
		6	linear	711.24	linear	711.24
		0	furrow, 1/2	845.59	furrow, 1/2	1005.34
5	-.02	3	linear	506.27	furrow, 1/2	720.41
		6	linear	498.24	furrow, 1/2	514.48
		0	furrow, 1/2	557.46	furrow, 1/2	1025.34
	.08	3	linear	506.27	furrow, 1/2	706.02
		6	linear	498.24	furrow, 1/2	502.62
		0	furrow, 1/2	557.46	furrow, 1/2	1005.34
	.18	3	linear	506.27	furrow, 1/2	692.02
		6	linear	498.24	linear	498.69
		0	furrow, 1/2	557.46	furrow, 1/2	1005.34
8	-.02	3	linear	296.27	furrow, 1/2	720.41
		6	linear	289.25	furrow, 1/2	514.48
		0	furrow, 1/2	310.85	furrow, 1/2	1025.34
	.08	3	linear	296.27	furrow, 1/2	706.02
		6	linear	289.25	furrow, 1/2	502.62
		0	furrow, 1/2	310.85	furrow, 1/2	1005.34
	.18	3	linear	296.27	furrow, 1/2	692.02
		6	linear	289.25	furrow, 1/2	491.12
		0	furrow, 1/2	310.85	furrow, 1/2	1005.34

Salt concentrations = .67 dS/m and 10 dS/m for the first and second source respectively.

More interesting is to compare choice of irrigation systems between the reuse and no reuse cases. With no reuse, choice of irrigation systems is fairly sensitive to freshwater prices and the cost of deep percolation flows. As both of these increase, growers have a strong incentive to switch over to more uniform systems. However, when the possibility of reuse is allowed, then in fact it becomes optimal to meet the higher freshwater price by substituting in low-quality water and using a traditional irrigation system instead of switching over to a high-cost system. Thus reuse may be a reasonable response to both reduced supplies of high-quality surface water as well as

the drainage problem, and one that substitutes for the oft-recommended capital-intensive and expensive irrigation systems.

While the results in tables 8 and 9 support the idea that reuse can be economically optimal, it also needs to be recognized that reuse imposes additional costs on growers beyond the costs explicitly considered so far. These costs might be in the form of additional plumbing and hardware, additional crop risk, more agronomic knowledge, long-term soil quality degradation, and so on. Thus it is also important to consider the potential increase in profitability from reuse. If the increase is small, then reuse may not be optimal when all factors are taken into account. To that end, Table 9 also compares profitability with and without reuse. As can be seen, the potential differences in profitability with and without reuse can be quite large. This is especially true for the higher freshwater prices and the lower deep percolation charges.

This analysis was conducted assuming steady-state conditions. That is, soil salinities are assumed to come to steady-state within the course of a single irrigation season, and they are independent of previous soil salinity levels. This analysis also ignores the fact that in most instances growers need to rotate crops; they cannot necessarily grow the same crop (e.g. tomatoes) on the same piece of land continuously, or ignore previous plantings, and that once an irrigation system is installed and in place growers will be reluctant to change it before the end of its useful life. Ideally the reuse problem should be analyzed in an intertemporal, multi-year setting accounting for crop rotations, dynamic soil salinity, and irrigation investment. For example, reuse on cotton might need to be tempered if a salt-sensitive crop such as tomatoes is to be planted subsequently. Some progress along these lines is reported in Knapp (1992) and Dinar et al. (1993). These models tend to be computationally intensive and hence much more difficult to use for regional policy analysis in comparison to the static model used above.

Also as noted above, there are a number of other possible costs associated with reuse beyond just the water costs and yield effects in the model. These are likely very site and grower specific, and no organized attempt has been made to quantify these to our knowledge. However, these costs would need to be assessed before carrying out reuse in an actual setting.

C. Reuse Economics at the Farm and Regional Level

At the farm and regional level, there are several general strategies available for solving drainage problems. For the sake of illustration we will consider three here. These are source control, reuse, and disposal. In general there are a number of different options for achieving a given level of drainage reduction for each strategy. For example, source control could be achieved by moisture-stressing, new irrigation systems, crop switching and so on. For each strategy one finds the cost-minimizing set of options for achieving alternate levels of drainage reduction. This then determines functions for each strategy showing the cost of achieving alternate levels of drainage reduction with that strategy.

Figure 11 illustrates hypothetical marginal cost curves for each of the three strategies, where marginal costs are the derivative of the cost functions; they can be

interpreted as the additional cost of achieving one additional unit of drainage reduction. As illustrated, the curves both slope up and are convex. This is both intuitive and realistic; it says that the cost of reducing additional units of drainage water becomes increasingly difficult and expensive the more one tries to reduce with a given strategy.

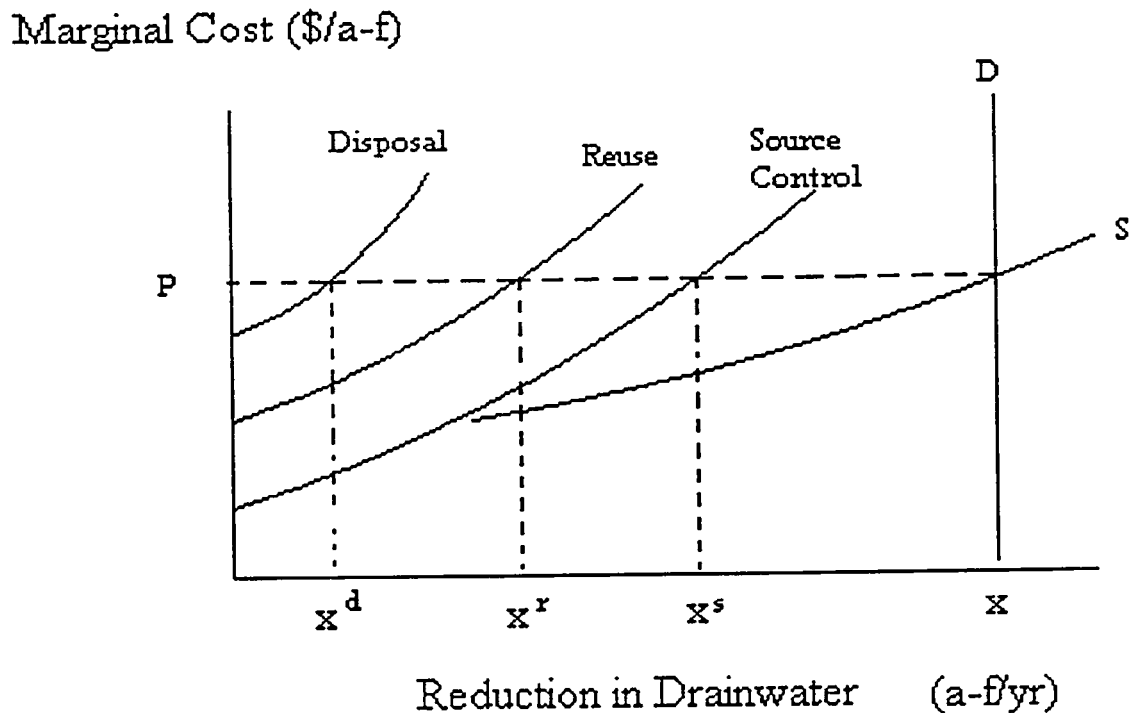


Figure 11. Least-cost allocation of drainage reduction burden (Courtesy of K. Knapp).

In Figure 11, D represents the desired level of total reduction in drainage emissions. This might be set to meet water quality standards in a river or maintain a high water table level below some level causing damages. Note that this is a reduction of emissions below current levels, not the final ending level. The goal is to achieve this target level of reductions at the least-cost to society.

For least-cost pollution control, the burden of pollution control (drainage reductions in this case) should be allocated so as to equalize the marginal costs of control across all strategies. The reason for this is quite simple: if marginal costs are not equalized, then it is always possible to re-allocate the burden from the high-cost source to the low-cost source, thereby still meeting the target while lowering overall costs. To get an aggregate marginal control cost curve, we then horizontally sum the individual marginal cost curves. This means that for each price (marginal cost), we add up the individual quantities to get a total quantity. This results in a curve such as S in the figure. This curve shows the aggregate marginal cost of achieving alternate total levels of drainage reduction, given that the burden is allocated across strategies (source

control, reuse, etc.) in a least-cost fashion.

To achieve the desired drainage reduction D in a least-cost fashion, we read off the "price" P where aggregate marginal cost S cuts the desired reduction level D . With this price, we can then read off the desired levels of each strategy to achieve the goal at least cost to society. For example, in the figure we would carry out source control to the level of x^S , reuse to the level of x^r and so on. This would achieve the desired total reduction level while minimizing costs to society of achieving that level.

Several conclusions flow from this analysis. First is that reducing drainage flows is likely to involve a combination of strategies; it's highly unlikely that any one strategy alone will solve the problem. Second, it can be seen that the optimal level of reuse to be achieved depends on the cost and availability of other alternatives. For example, if a new irrigation technology were to be developed, that could shift the source control marginal cost function to the right (increased control for the same marginal cost). This would then shift the aggregate marginal cost curve S to the right, thereby lowering the "price" of drainage water and hence the desired level of reuse. Thus, at least in theory, the desired level of reuse should be determined simultaneously with source control and disposal.

Third, figure 11 also illustrates the regional nature of the problem. Whether or not reuse should be practiced on a given farm depends on the "price" of drainage flows, and that "price" is determined by the costs, opportunities, and actions of all farming operations in the region. Micro-level data and analysis is needed to formulate the regional problem, but solving the regional problem is necessary to generate relevant "prices" for then determining what micro-level actions are desirable.

Realistic empirical analyses for reuse and drainage management involve a number of complexities, and hence most economic analyses at the regional level rely heavily on computer simulations. An early model in Knapp et al. (1986) uses a targeted approach in which drainage water from individual crops are sent (possibly) to specific other crops. They found that long-run sustainability can be achieved on farms without explicit drainage outlets using a combination of source control, reuse, and evaporation ponds. The needed evaporation pond size was found to be significantly less than current recommendations at the time the study was completed. While reuse is optimal when only variable costs were considered, they did find that it might not be optimal when reuse involves setting up an extensive plumbing system.

Posnikoff and Knapp (1996) develop a three-stage sequential reuse model with freshwater crop production as the first stage, reuse of crop production drainwater for agroforestry production as the second stage, and disposal of residual deep percolation flows in an evaporation pond as the third stage. Under the base set of results they find that using agroforestry for reuse is economically efficient for maintaining water table levels in a district with no explicit drainage outflow mechanisms. However, they also noted that there is considerable uncertainty about several key parameters, and that, depending on the value of those parameters, agroforestry reuse may not be optimal. In particular, agroforestry production with reuse only made sense if a significant market could be developed for the wood being produced. A related approach to drainage and

reuse is being developed in Weinberg et al. (1997) for the northern SJV.

These analyses are aimed at identifying least-cost solutions to regional drainage problems. Once a desired solution is obtained, it still remains to specify policy instruments for achieving the desired outcome. These could take the form of standards where growers are required to follow certain practices or restrict emissions below some level. Other possibilities include pricing instruments and the use of transferable discharge permits. The significance of choice of policy instruments is that they typically differ in terms of their impacts on grower income, incentives for adoption of new technology, uncertainty with respect to outcome, and other variables, even for the same average level of drainage reductions being achieved. Discussion of policy instruments relevant to the drainage problem can be found in Knapp et al. (1990), Caswell et al. (1990), Dinar et al. (1991), Wichelns (1991), Weinberg et al. (1993), and Weinberg and Kling (1996), among others.

VI. INSTITUTIONAL CONSTRAINTS

Irrigation of salt tolerant crops with saline water is not in itself of concern to regulatory agencies (Shannon, Personal communication). Concerns may arise, however, if the drainage water contains constituents that are potentially harmful to wildlife or the environment particularly if significant deep percolation occurs past the collector drains or if solar ponds or similar facilities are used as a final disposal method.

The State Water Resources Control Board and the nine Regional Water Quality Control Boards (Regional Boards) have primary responsibility for water quality protection in California. Regulatory authority comes from the Porter-Cologne Water Quality Control Act (Water Code) and related code sections. Titles 22 and 27 of the California Code of Regulations provide further requirements affecting drainage reuse may be contained in the Water Quality Control Plans (Basin Plans) which are adopted by each regional board.

Drainage water reused for irrigation contains varying amounts of salts, trace elements and other constituents. Such components may become concentrated through the evapotranspiration process and pose a threat to wildlife that are using the reuse sites for their habitat. The principle component of concern is selenium. Further exposure may occur through bio-magnification in the food chain. The California Department of Fish and Game is conducting studies of selenium exposure at reuse sites in the SJV (Shannon, Personal communication). Preliminary data indicate elevated levels of selenium in some birds and mammals. However impacts have not as yet been identified, except as noted below. If such effects are observed, it could affect the feasibility of reuse as a drainage management option.

The primary purpose of reuse is to reduce drainage volume and manage salts. As such, there is little incentive for conservation of applied drainage water. Also, due to the need to maintain an acceptable salinity level in the rootzone, higher leaching fractions are needed to move the salts out of the rootzone. This could increase the potential for percolation of concentrated drainage water below the drains or lateral

movement off-site. Both could cause pollution of surface or ground waters and would be a cause for regulatory concern.

Currently the most significant institutional and regulatory concerns are with the use of solar ponds for the final disposal and crystallization of salt. Because of the high concentrations reached in these facilities as they are evaporated to dryness, some components may reach levels subject to regulation as hazardous waste under Article 9.5 of the Health and Safety Code (Toxic Pits Cleanup Act of 1984) and Titles 22 and 27 of the California Code of Regulations). Monitoring data at the solar pond at Red Rock Ranch showed selenium concentrations in excess of the hazardous waste criterion (1000 ppb). Also, ponded water at this facility attracted nesting showbirds and resulted in a high incidence of deformed embryos.

Title 27 contains regulations governing the land disposal of wastes. It exempts drainage water and sediments if 1) the applicable Regional Water Quality Control Board issued Waste Discharge Requirements (WDRs) or waived such issuance 2) the discharge complies with the applicable Basin Plan or 3) the wastewater does not need to be managed according to Title 22 CCR, Division 4.5, Chapter 11, as a hazardous waste.

Title 27 is written to generally preclude the discharge of wastewater to groundwater by requiring compliance with specified standards. An exception is made where the nature of the waste and the underlying groundwater (and any surface water that may be affected) is such that a discharge of waste would not cause degradation in violation of adopted State Board or regional Board policies, or violate any water quality objective or other provisions of the Basin Plan. The determination of compliance with the Basin Plan is based on a comparison of the quality of the wastewater with that of the underlying groundwater. A facility would not be exempt if poor quality wastewater could impair the beneficial uses of good quality groundwater.

There are two operating solar ponds connected with reuse operations in the SJV. The Central Valley Regional Board has issued WDRs to both. WDRs prescribe the design and operational criteria for the facilities as well as the monitoring and reporting requirements. It is unlikely, given the problems that have been experienced to date, that regulatory requirements and oversight will become less rigorous.

VII. SUMMARY AND RECOMMENDATION

Reuse of saline/sodic drainage water is an important management option in areas of the SJV affected by shallow ground water. The long-term success of reuse will depend on the evolution of practical management strategies. Particularly important are careful management of irrigation water, controlled drainage flows to foster crop use of saline/sodic groundwaters within or close to the lower portion of the rootzone, and close attention to the environmental impacts of surface-stored groundwater waters and evaporation ponds. Without attention to irrigation and drainage water management, the proportion of lands subjected to irrigation with saline/sodic drainage, and consequent negative impacts on soil quality, will be greater than necessary. Potential environmental impacts of surface impoundments of saline/sodic groundwater for reuse, timely discharge into the San Joaquin River, or evaporation also provide valid reasons to minimize drainage flows in the first place through careful irrigation and drainage water management.

This committee report summarizes a significant number of scientific investigations, computer simulations and demonstrations involving drainage water reuse conducted during the past twenty years. Although much has been learned from this work, adoption has been limited. Further, we recognize that more remains to be learned, some of which will be learned during forthcoming field tests of potential cropping strategies, before full-scale adoption should be encouraged.

The major factors affecting the sustained reuse of drainage water is salinity, sodicity and crop salt tolerance. Studies have shown that soil quality can be maintained provided sound irrigation and soil management is used coupled with sufficient leaching for the crop grown. Slow water infiltration and subsequent slow redistribution within soils is a characteristic of many soils along the trough of the SJV. This condition can be aggravated with the use of saline/sodic drainage water. Adverse effects occur not as much by the direct use of saline/sodic water for irrigation, but by subsequent rainfall or irrigation with low-salinity water. For example irrigation with saline/sodic water followed by rain or irrigation with nonsaline/sodic water can enhance soil crusting, reduce seedling emergence, adversely affect the tilth of the seedbed, reduce infiltration rates, and aggravate waterlogged conditions which can reduce soil aeration thereby affecting crop growth. Researchers and farmers have established that adverse affects can be mitigated by incorporation of gypsum or other amendments that liberate calcium in the upper portion of the soil profile. Also it is likely that California farmers could adopt mitigation strategies developed elsewhere that include crop rotations which temporarily increase the organic matter in the surface soil and conservation tillage techniques.

The sodic nature of drainage water varies from location to location in the western part of the SJV. For example the drainage water within and near the Tulare Lake Basin is higher (e.g. 33) than that near Five Points (e.g. 12) or Mendota (e.g. 9-11). Sodicity is likely a more important problem to manage in the Tulare Lake Basin not only because of the higher SAR's in the drainage water but because many of the soils in that region contain high clay contents.

Trace elements such as B, Se and Mo also affect the feasibility or extent to which drainage water can be used to irrigate certain crops. Particularly important is crop tolerance of B, or the accumulation of Se and/or Mo to levels hazardous for human or livestock nutrition. Boron toxicity has not been observed on many commercial (tomato, cotton, sugarbeet, melon) or non-conventional crops (Salicornia) in drainage water reuse studies. Boron toxicity has been observed on fruit trees and on Eucalyptus trees. On Eucalyptus, some of this injury has been transient and it is not clear to what extent the observed injury reduces tree growth. Some studies indicate that there is an interaction between salinity (containing mixed salts) and boron whereby salinity reduces the toxic effects of boron. Despite these encouraging observations, long-term effects from boron accumulation in soils still remain somewhat uncertain, particularly if management practices are operated to control only soil salinity. Boron tends to be more resistant to leaching than salts. Consequently, it is possible that B concentrations may continue to levels that reduce yields of sensitive crops.

Selenium concentration was found to increase in crops that are grown with saline drainage water. Crop uptake varies by species. In no instance reported did crop concentrations pose a potential health risk, even when irrigated with drainage water containing over 300 ppb Se. It remains unclear whether or not Se and/or Mo will pose a potential threat to ruminants if they are fed with forages irrigated with saline/sodic water containing these constituents. This warrants further studies and some work to address this concern is currently underway.

Ultimately, the feasibility of drainage water reuse is determined by economics. Ideally a grower or manager should strive to minimize the area for portion of the land devoted to reuse. Good irrigation management is essential to optimize this situation (see Source Control Report). The committee recognizes that the economic feasibility is dependent upon the type of management practices and decisions selected by the grower, the scale of reuse (e.g., on-farm vs. regional/district), and all have to be weighed in relation to other options available.

A sequential reuse strategy such as the Integrated on Farm Drainage Management (IFDM) system shows considerable promise provided it remains flexible. The system currently installed at Red Rock Ranch warrants future investigations involving crop selection, characterization of the soil physical conditions, trace element accumulation, crop quality among others, and drainage control. The economics of various aspects of the IFDM need closer examination such as marketing of distilled water and salts from hyper-saline drainage water.

In addition, much more research is needed to identify appropriate crops in such a system. For example, research is needed to identify appropriate salt-tolerant forages. There is a shortage of forage in the valley that will likely continue in the near future as dairies continue to increase, and pressure to remove beef cattle from foothill and mountain ecosystems increases.

Much has been learned about reuse over the past two decades, however this committee believes that more research and demonstrations are needed to continue this learning curve. Although the same set of scientific principles apply in all cases, there is

no one reuse management practice that will be appropriate in all areas within the valley, or within a sub-region, appropriate to every farmer, or farming operation. Rather reuse will have to be customized. In order for reuse to be sustainable, the system must remain flexible.

Also, more training and education is needed not only to assist growers and managers in optimizing irrigation management but also to transfer the latest findings regarding drainage water reuse and appropriate practices to growers and districts in need of ideas. It is recommended that a working group be established among agencies, districts, the University and the USDA to maintain cohesion and to provide a means of communication and collaboration.

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