Drainage Water Reuse: Biological, Physical, and Technological Considerations for System Management

Lynn M. Dudley* Florida State University
Alon Ben-Gal Gilat Research Center
Naftali Lazarovitch Ben-Gurion University of the Negev

Previous reviews of drainage water reuse have discussed principles of water reuse and disposal; provided examples of reuse practices; offered reuse criteria for salinity, for trace elements, and for bacteria; discussed mitigation of dissolved trace elements in reuse strategies; and summarized the California experience with a focus on discussion of salinity, sodicity, B, Mo, and Se issues. This review emphasizes recent literature contributing to understanding physical and biological constraints to drainage water reuse. The potential for drip irrigation and, particularly, low-flow/high-frequency systems to enhance the use of drainage water while minimizing the deleterious effects on yield and on water and soil resources is examined using the numeric HYRDUS-2d model. Additionally, an analytical model is used to illustrate physical and biological limitations to drainage water management that result from the self-regulating nature of the soil–plant–water system. The models suggest that crop, soil, irrigation frequency, and delivery systems might be manipulated to reduce the quantity of drainage water, but they also suggest that the nature of the system may seriously constrain the amount of reduction that might be achieved.

Drainage water is a product of irrigation that may be viewed as a valuable resource or as a waste product. Possible scenarios for the fate of agricultural drainage water include return through the normal hydrologic cycle to natural water sources, capture and reuse via cycling or blending as irrigation water, or collection as a waste product for disposal. For example, the Middle East, India, and Pakistan exhausted their renewable water resources more than a decade ago, and reuse of collected agricultural drainage water has become significant in their overall water budgets (Willardson et al., 1997). Approximately 60% of the rest of world faces similar water shortages (Qadir et al., 2007), suggesting that reuse of drainage water and the use of nonconventional sources is required to meet the demand of a growing population. Although agricultural drainage water can be a valuable resource, agricultural drainage water in the San Joaquin Valley, California, has become a serious problem as a waste product (Letey et al., 1986; Presser and Ohlendorf, 1987). Australia has a similar problem to California, where there is a need to minimize drainage to reduce salt loading in the River Murray system (National Water Commission, 2006). The San Joaquin and Australian experiences remind us that the luxury of excess irrigation and high levels of leaching is nonsustainable and that minimization of drainage quantity and salinity is desirable in any context. Drainage water management will become increasingly important not only for providing alternative agricultural water resources as competition increases for high-quality water but also to prevent contamination of those environmental resources as agriculture is forced to rely on lower-quality water, such as waste water from urban sources that may contain a variety of contaminants (Dillon, 2000; Bouwer, 2002; Anderson, 2003).

Because of the importance of the topic, a number of review articles explaining principles of drainage water management, crop production, potential soil problems, issues associated with trace contaminants, and crop and water systems have been published within the past two decades. Westcot (1988) gave an excellent review of the principles of drainage water reuse and disposal with

Published in J. Environ. Qual. 37:S-25–S-35 (2008).
doi:10.2134/jeq2007.0314
Received 15 June 2007.
*Corresponding author (dudley@gly.fsu.edu).

677 S. Segoe Rd., Madison, WI 53711 USA

L.M. Dudley, Dep. of Geological Science, Florida State Univ., Tallahassee, FL 32306-4100. A. Ben-Gal, Environmental Physics and Irrigation, Agricultural Research Organization, Gilat Research Center, mobile post Negev 85280, Israel. N. Lazarovitch, The Wyler Dep. of Dryland Agriculture, Jacob Blaustein Inst. for Desert Research, Ben-Gurion Univ. of the Negev, Sede Boqer 84990, Israel.

Abbreviations: EC, electrical conductivity; I, irrigation; LR, leaching requirement; LF, leaching fraction; SAR, sodium adsorption ratio; T, transpiration; Y, yield.

worldwide examples of practices that might serve as models for development of strategies in other regions and strongly emphasizes the site-specific nature of drainage water management. Willardson et al. (1997) presented examples of drainage water reuse from Egypt, India, and the Intermountain region of the USA where water not consumed by crops is a critical component of water resources for subsequent irrigation. Their review also presented criteria for salinity, trace elements, and bacteriological limits for drainage water reuse. Grattan et al. (1999) provided a detailed summary of the California experience and a thorough discussion of crop production, trace element issues, and soil resource protection in their review of reuse strategies, such as blending and cycling. Most recently, Oster and Grattan (2002) provided an additional informative review of the California experience with drainage water management as they focused on salinity, sodicity, B, Mo, and Se issues.

In this article, we review the principles and practices of drainage water management with consideration to the dual nature of drainage water as potentially valuable resource and as waste product. This review emphasizes the physical and biological limitations to drainage water management that result from the self-regulating nature of the soil-plant-water system and the potential for drip irrigation systems including low-flow/high-frequency application to minimize the production of saline drainage water and maximize yield. We supplement the review with computer simulations to illustrate the potential for management and technology to limit the amount of drainage water.

Principles of Drainage Water and Salinity Management

Salinity

The interplay of a number of factors such as salinity, salt composition, B, Se, Mo, nitrate, and bacterial levels should be considered in drainage water management. However, use criteria and most strategies for reuse consider components individually. The leaching requirement (LR) provides a simple model for a water management strategy for saline water that is based on crop tolerance, climate demand for water, and the salinity of the irrigation water, expressed by Rhoades (1974) as

$$LR = EC_{iw}/[5 \times (EC_e^* - EC_{iw})] \quad [1]$$

where EC_e^* is the average soil electrical conductivity (EC in dS m^{-1}) of a saturated paste extract, denoted by the subscript e, that is related to crop tolerance to salinity, and the subscript iw is used to denote the EC of the irrigation water. The EC_e^* values used to determine LR are usually either EC_e of threshold value (Maas, 1990) (EC_e-0%) meaning 0% yield decrease due to salinity or EC_e-10% levels reflecting 10% yield loss. Although the leaching requirement in various forms has been used as a basis for water and salt management (Beltrán, 1999), it is not a complete model of system behavior for reasons discussed in detail by Corwin et al. (2007). First among those reasons is that crops in the field have been shown to tolerate much greater salinity levels than published values used to obtain EC_e^* (Meiri and Plaut, 1985; Shannon, 1997; Flowers, 2003). In the field, crop root zones are not restricted as in the lysimeters typically used to conduct salt tolerance experiments; salt is distributed unequally in contrast to the uniform distribution in lysimeters, and crop tolerance varies considerably with growth stage. The LR also fails to consider the dynamic character of the soil–plant–atmosphere continuum, neglecting factors such as irrigation frequency, climate demand, exposure time, and chemical reactions (Corwin et al., 2007). Thus, the leaching requirement has been reported to inaccurately estimate the actual amount of water transpired and that produced as drainage (Meiri et al., 1977; Letey et al., 1985).

Computer simulation models of transient water flow and solute transport are better options for developing drainage water management practices (Corwin et al., 2007), and a number of models have been developed. The HYDRUS model (Šimůnek et al., 2006) (or the version of the model with salt chemistry, UNSATCHEM-2D; Šimůnek and Suarez, 1993) represents the most used and most accessible simulation tool for water and solutes in soil today. The model is useful in designing and analyzing reuse operations because the approach captures many essential features of root water uptake under stressed conditions (Skaggs et al., 2006). Other transient models are the one-dimensional, numerical model with equilibrium salt chemistry SOWATCHM (Dudley and Hanks, 1991), ENVIRO-GRO (Pang and Letey, 1998), and the one-dimensional, numerical model presented by Cardon and Letey (1992). These models contain sophisticated finite-element or finite-difference solutions to equations of continuity for water flow and salt transport and UNSATCHEM and SOWATCH consider ion-pairing, ion exchange, and precipitation reactions for the major ions. Because they consider chemical reactions, the models UNSATCHEM and SOWATCH were able to simulate evolution of water chemistry in systems where Na was the dominant cation (Suarez and Dudley, 1998). Although the algorithms that model physical components of the system are well developed, the largest component of the water budget in arid and semiarid environments is transpiration. Thus, the ability of the models to provide meaningful simulations of drainage water management options is predicated on their ability to simulate water uptake in response under conditions of water and salt stress.

Recent reviews modeling water uptake and plant response functions to water and salt stress by Hopmans and Bristow (2002) and Feddes and Raats (2004) point out that the biological components of the soil–plant–atmosphere continuum have received less attention than the physical components. Typically, the models calculate water uptake or transpiration under potential constraints of insufficient soil moisture and excess soil water salinity. The specific choice of root distribution and uptake functions can be critical in changing results of simulations (Mmoloawa and Or, 2000). A possible approach to modeling crop response to simultaneous water and salt stress is to combine potential flow (Gardner, 1960; Feddes et al., 1974) and transpiration partitioning (Zhang and Elliot, 1996; Homaee et al., 2002) by using the matric potential gradient (Nimah and Hanks, 1973) to compute uptake from a transpiration rate computed from a salinity response function (van Genuchten, 1987). This approach has been applied to numerical (Dudley and Shani, 2003) and analytical (Shani et al., 2007) solutions to water flow. Basic limitations of using models need to be recognized and include lack of representation of variability found in soils, nonhandling of preferential flow, and dependence of input regarding root distribution and activity, particularly as models are applied to problems in which the goal is to minimize drainage and maximize salt storage.

Drainage Water Composition

The composition of the salinity is an important consideration for drainage water reuse because plants may exhibit a differential response to osmotic stress caused by ratios of Ca, Na, Cl, or SO_4 as well as toxic responses to B, Na, or Cl (Westcot, 1988). Although increasing the salinity of the soil solution decreases its osmotic potential, drying of the soil decreases the matric potential and decreases the solution's osmotic potential as ions are concentrated. The interactions between the soil environment and plant response regarding increased potential gradients and specific ion concentrations, uptake, and toxicity are, therefore, complicated and extremely difficult to quantify.

The relationship between general osmotic and specific ion effects differs from crop to crop and is a function of the specific ions involved. Separation of the effects is not simple and may be impossible. Shani and Ben-Gal (2005) showed short-term, osmotic consequences of salinity on transpiration and long-term toxicity leading to reduced yields and mortality in a study on the effects of irrigation water salinity on grapevines (*Vitis vinifera*). Differences measured between irrigation with waters of EC 1.0 and 3.0 dS m^{-1} in producing vegetative biomass were explained by osmotic potential gradients and reduced water uptake, witnessed immediately on the outset of vine exposure to saline conditions. Electrical conductivity values >3 dS m^{-1} produced toxic effects accompanied by Na and Cl ion accumulation in leaves and disruption of physiological processes. Plant response time for osmotic effects is rapid (seconds to minutes). Toxic responses can be rapid as well, especially in cases where the mechanism for toxicity occurs in the roots, but responses due to toxic effects often materialize only after accumulation in shoots (a process that takes days to months) (Munns, 2002). Sensitivity to Cl and Na ions is also crop specific, with individual crops showing sensitivity to either or both Na and Cl (Bernstein, 1975). The system is further complicated by the fact that high ratios of SO_4 to Cl have been demonstrated to ameliorate Na toxicity (Awada et al., 1995).

Boron–salinity interactions are particularly important regarding to drainage water reuse. Soils in semiarid and arid regions where little or no natural leaching occurs tend to have high levels of B but also are high in overall salinity (Keren and Bingham, 1985; Nable et al., 1997; Oster and Grattan, 2002). Reuse of drainage water, therefore, often demands an understanding of plant response to simultaneous exposure to stress-causing factors from salinity and excess B. Plant stresses caused by salinity or B alone have been thoroughly investigated, and, although their independent effects on growth and yield have been well described in the literature (Bernstein, 1975; Gupta et al., 1985; Munns and Termaat, 1986; Nable et al., 1997), insufficient knowledge exists concerning cases where they occur concurrently.

A large percentage of the studies that do concern combined high B with salinity have indicated amelioration of B toxicity by salinity (Grattan et al., 1997; Bingham et al., 1987; Ferreyra et al., 1997; Holloway and Alston, 1992; Mikkelsen et al., 1988; Grieve and Poss, 2000; Alpaslan and Gunes, 2001; Yermiyahu et al., 2007; Tripler et al., 2007). Ben-Gal and Shani (2002), Shani et al. (2005), and Tripler et al. (2007) suggested that among the factors B and salinity, plants respond to whichever is dominant at any particular combination of the two. Recently, data for bell pepper (*Capsicum annum*) (Yermiyahu et al., 2008) and re-analysis of data from the literature for wheat [*Triticum aestivum* (L.)] (Bingham et al., 1987; Holloway and Alston, 1992) and tomato [*Lycopersicon esculentum* (L.)] (Ben Gal and Shani, 2002) implied amelioration of toxicity (an antagonistic relationship) regarding growth and yield for combined B toxicity and salinity (Yermiyahu et al., 2008). Antagonism between salinity and B may be a result of decreased toxicity of B in the presence of NaCl, reduced toxicity of NaCl in the presence of B, or both. Yermiyahu et al. (2008) have suggested a possible explanation for bell peppers whereby uptake of B is reduced in the presence of Cl and uptake of Cl is reduced in the presence of B. However, the mechanism of B–salinity interactions is not clear, and there are no satisfactory physiological or physical explanations for B–Cl uptake relationships.

In addition to the direct effects of salinity on plants, indirect effects are caused through changes in soil physical-chemical properties. Examples of possible indirect consequences of salinity are loss of soil structure and reduced infiltration (Shainberg and Letey, 1984; Ben-Hur et al., 1998) and aeration (Bethune and Batey, 2001), changes in redox potential (Qadir and Schubert, 2002), and changes in adsorption properties regarding specific ions, including B (Yermiyahu et al., 1988).

The sodium adsorption ratio (SAR) is used as an index of potential of the irrigation water to cause deterioration of soil hydraulic properties that result from the adsorption of Na on soil clays. Deterioration of the soil physical properties results from dispersion and swelling of clay quasicrystals that is driven by the osmotic potential differences between the bulk soil solution and the solution between quasicrystals or interlayer positions within the quasicrystal. The potential for deterioration of soil physical properties is greatest when the osmotic potential difference is greatest (i.e., when Na dominates the cation exchange and the bulk solution EC is low). Willardson et al. (1997) presented suitability criteria for SAR and EC combinations for drainage water reuse that are graphically presented in Fig. 1. Figure 1 generally illustrates the relationships between SAR and deterioration of soil physical properties because the actual relationship is soil specific. According to Willardson et al. (1997), Zone 1 waters are suitable for use on any soil texture; Zone 2 waters are not suitable for use on silt loam textures; Zone 3 waters may be used on loamy sand, coarse sandy loam, and sandy loam textures; and Zone 4 waters are not suitable for use on any soil texture. However, a number of studies reported that annual application of gypsum

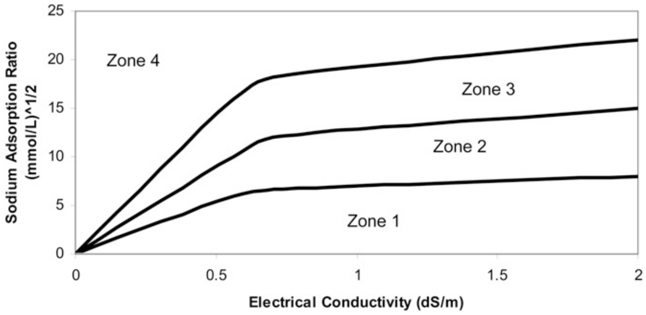

Fig. 1. Zones of irrigation water suitability for combinations of sodium adsorption ratio and electrical conductivity.

permitted continual use of waters with a high SAR without damage to soil physical properties (Oster and Grattan, 2002).

Blending and Cycling Strategies for Reuse of Drainage Water

Water management strategies have been developed to reduce the previously discussed deleterious effects on soil properties and crop yield associated with salts and other drainage water constituents. One strategy for maintaining an economic yield of higher value and less salt-tolerant crops is to blend saline drainage water with higher-quality water to reduce salinity, minimize the LR, and extend water supplies (Westcot, 1988). Blending has been extensively practiced in Egypt where drainage canals collect water for return to the Nile River, resulting in an increase in salinity of approximately 0.5 dS m^{-1} (Willardson et al., 1997). Plans are to increase the amount of drainage water blended with Nile River water from 5.2×10^9 m^3 yr^{-1} to 8.2×10^9 m^3 yr^{-1} by the year 2010 (El-Hawary, 2005). There are limitations to the effectiveness of blending as a means of reusing drainage water as demonstrated by Rhoades (1989) in a review of case studies. The drainage water used in the blending must possess a salinity level that is suitable for irrigation (less than an acceptable yield loss value) in order for blending to extend water supplies (Grattan and Rhoades, 1990).

Cycling irrigation with drainage water and high-quality water, developed and tested by Rhoades (1989), has been successfully used to extend water supplies and assist in drainage water disposal. One method of cycling is accomplished by crop rotation whereby salt-sensitive crops are irrigated with good-quality water and more salt-tolerant crops are irrigated with drainage water in the same field. Salts that accumulate during irrigation with drainage water on the salt-tolerant crops are leached from the soil during the irrigation of the more salt-sensitive crops, and thus the soil is reclaimed. Another method of cycling is to use high-quality water to irrigate during germination and seedling establishment or other salt-sensitive growth stages and to irrigate with more saline water during less salt-sensitive growth stages. Experiments and successful field experience with drainage water use by cycling are reviewed by Westcot (1988), Grattan et al. (1999), and Oster and Grattan (2002). More recently, Sharma and Tyagi (2004) reported results of field studies of cycling in India. In a combined blending and cycling study, wheat, pearl millet (*Pennisetum americanum*), and sorghum (*Sorghum bicolor*) were pre-irrigated with canal water with EC 0.5 dS m^{-1} and monsoon rainwater to reduce salinity during germination. Such a cycling strategy should be undertaken with caution where Na is a major constituent because the reduction in salinity associated with rainwater could result in deterioration of soil physical conditions (Letey, 1993). The crops were irrigated with blended waters of EC 6.0, 9.0, 12.0, and 18.8 dS m^{-1}, and yields ranged from about 96 to 78% of the maximum. In a second study (Sharma and Tyagi, 2004), mustard (*Descurainia pinnata*) and barley (*Hordeum vulgare*) were irrigated with the canal water during germination followed by two or three irrigations with drainage water of EC 12 to 15 dS m^{-1} without measurable yield loss. Bradford and Letey (1992) conducted a modeling study comparing cycling and blending and found that yields for a salt-sensitive crop were higher in a cycling scheme than in a blending scheme. Yields of a salt-tolerant crop were the same for the cycling and blending.

Irrigation Technology and Drainage Water Management

The irrigation system is an important consideration in drainage water reuse strategies. For example, surface irrigation may be advantageous to sprinkler systems because foliar adsorption of sprinkler applied water increases salt uptake and plant sensitivity to B toxicity (Grieve et al., 2003; Ben-Gal, 2007). The nature of drip irrigation whereby water application is by definition nonuniform in micro-spatial but very uniform in macro-spatial and temporal terms raises some interesting possibilities regarding its appropriateness for using saline drainage water. Most work investigating drip irrigation and saline water has concentrated on water requirements, crop response, and leaching capability (Hillel, 1997; Kan 2003; Choi and Suarez-Rey, 2004; Burt and Isbell, 2005; Daleshwar Rajak et al., 2006). The basic indication is that the wetting and solute movement patterns under drip irrigation are conducive to crop production under saline conditions because of the local relatively moist, relatively leached areas around the drippers where roots can efficiently grow and function.

Irrigation Frequency and Salinity

The question of whether increasing irrigation frequency is advantageous under conditions of salinity is unanswered. Benefits and disadvantages of high-frequency application of saline water have been suggested, and experimental and modeled results regarding leaching efficiency and frequency provide contradictory conclusions. Several advantages of high-frequency irrigation should be true, regardless of salinity. These advantages include increased water availability for root uptake and improved nutrient management options. Mineral nutrition has been shown to reduce the specific toxicity of salts (Kafkafi, 1984), and thus proper high-frequency fertigation could be particularly beneficial for saline conditions (Silber, 2005). In general, potential benefits of increased frequency are considered to be greatest for horticultural crops on shallow or coarse-textured soils (Lamm and Trooien, 2003). One of the problems in reviewing this issue is an imprecise definition of "high-frequency" irrigation because the definition of "high-frequency" depends on the specific crop, soil, and climate considered. For example, irrigation once every several weeks may be the norm, and daily irrigation may be considered extremely frequent for cool climate crops in heavy soils (Lamm and Trooien, 2003; Kang et al., 2004; El-Hawary, 2005). Irrigation of vegetable crops in light soils or soil-less media, on the other hand, might be by many short pulses per day or continuous, low-flow water application throughout the hours of evapotranspiration (Assouline, 2002; Segal et al., 2006; Assouline et al., 2006).

Leaching and salinity management may or may not benefit from highly frequent application of relatively small quantities of water. One school of thought presents the theory that the small root volumes and small root-to-shoot ratios found under high-frequency irrigation are problematic in salinity management where a larger, deeper root zone would allow more efficient leaching because more time would pass before root zone salinity rises to problematic levels. Intermittent leaching and less frequent irrigation have been promoted by Meiri and Plaut (1985), Shalhevet (1994), Caballero et al. (2001), and Feng et al. (2003), with the reasoning that a large enough root zone allows maintenance of upper soil layers that are relatively leached. Intermittent, non–steady-state leaching strategy would then use rainfall and potentially leach more efficiently than constant, steady-state regimes. Several field studies supported this theory (Hoffman et al., 1990; Shalhevet, 1994) but may be compromised by the fact that their frequency regimes were reflected in different water application quantities and that they did not use the irrigation for fertigation (Silber, 2005).

Alternatively, it has been suggested that increased irrigation frequency maintains a relatively leached zone for root activity where there are little or no compounding stress effects due to drying and wetting cycles. Small, frequent irrigations would, therefore, allow reduced deep percolation regardless of application method (Hanson and Ayars, 2002). Infrequent regimes subject plants to stress due to osmotic and matric potential decreases between irrigations; frequent regimes would eliminate the matric potential decrease and minimize the osmotic potential (Hillel, 2000). For drip irrigation, the low-salinity zone around and below drippers allows for high yields while controlling (minimizing) the leaching fraction (LF) (Phene 1986; Hillel, 2000). A number of recent studies support this theory. Assouline et al. (2006) found identical yield and less salt removal when comparing pulsed with daily irrigation of bell pepper with saline water. Daily irrigation with salty water lowered the average profile salinity compared with twice-weekly frequency (Ayars et al., 1985). Five pulses a day of saline (EC, 6.2 dS m^{-1}) water was found to overcome the detrimental effects of salinity observed in daily irrigation by Pasternak and De Malach (1995), who measured reduced midday salt concentration in the rhizosphere as a function of the increased frequency. Dehghanisanij et al. (2006) also showed the advantage of timing drip irrigation with saline water to maximum evapotranspiration demand in maintaining maximum moisture and minimum salinity in the immediate area of roots.

Modeling approaches also produced conflicting conclusions regarding the effects on the LF of application frequency of saline water. Feng et al. (2003), using an adaptation of the ENVIRO-GRO model (Pang and Letey, 1998) integrating water, salinity, and nitrogen, concluded that deeper root systems, possible only with less frequent irrigation regimes, are preferable in reducing leaching. Cote et al. (2003), using the HYDRUS-2D model, concluded that increased frequency was desirable and that pulsing the irrigation (application during first half hour of each of 10 h) led to 25% less drainage than continuous (5 h straight) water application.

HYDRUS Simulations of High-Frequency Irrigation

Two research teams have recently addressed questions of solute distribution from drip irrigation to determine fertigation scheduling (Cote et al., 2003; Gärdenäs et al., 2005). Both use HYDRUS-2D to evaluate management strategies. Although Cote et al. (2003) conclude that fertigation at the beginning of the irrigation cycle reduces leaching, Gärdenäs et al. (2005) found the opposite—that fertigation at the beginning of irrigation cycles causes more leaching than at the end. Although the major difference between the studies involved root placement and uptake, other variables in the conditions defined for the simulations are may have influenced the results. The use of models such as HYDRUS-2D for evaluation of water reuse strategies must, therefore, be critically evaluated on a case-by-case basis.

With the above stated, we present an evaluation of three strategies for drainage water reuse using HYDRUS-2D to simulate sprinkler application with 5-d frequency, subsurface drip with 5-d and daily application, and continuous subsurface drip application of water. In the evaluation, we used numerical solutions of Richards' equation as implemented in the HYDRUS-2D code (Šimůnek et al., 1999). The HYDRUS-2D model has been previously used to successfully simulate water flow for drip irrigation systems (Skaggs et al., 2006; Lazarovitch et al., 2005). Model parameters, boundaries, and initial conditions for the simulations are given in Appendix A.

The simulations indicate that, without negatively affecting transpiration, salt load to drainage can be reduced by using drip irrigation and by increasing the frequency of irrigation events as long as the crop is sufficiently salt tolerant (Table 1 and Fig. 2). Drip irrigation, with three-dimensional wetting, solute transport, and salt accumulation, has the potential to reduce the salt load to drainage because salts are stored in the upper root zone but beyond the plant's zone of active uptake. Figure 2 compares sprinkle irrigation to two drip-frequency regimes and shows the relatively high concentrations of salts above and around an emitter. Table 1 shows seasonal water and salt-balance constituents for the four irrigation methods and regime combinations for the tolerant crop where transpiration (T) was not decreased relative to potential transpiration (T_p) and for a more salt-sensitive crop. Increasing crop sensitivity to salinity may lead to decreased transpiration and therefore to greater drainage and an increased LF (Letey et al., 1985; Dudley et al., 2008). For the salt-tolerant crop, the LF was slightly greater and total salt leached out of the root zone was substantially greater for sprin-

Table 1. Comparison of total seasonal irrigation (I), transpiration (T), and drainage (D) quantities; total seasonal relative transpiration ($T T_p^{-1}$); relative irrigation ($I T_p^{-1}$); leaching fraction (LF); and total seasonal salt load in irrigation and drainage water for two crops with different relative salinity tolerance levels. Results from simulations with HYDRUS-2D.

	Water amount				Salt load				
	T_p	T	I	D	I	D	$T T_p^{-1}$	$I T_p^{-1}$	LF
	m²				$mol_c\ m^{-1}$				
Tolerant									
Drip 5 d	4.8	4.799	5.950	1.078	2400	96	1	1.24	0.18
Drip day	4.8	4.799	5.951	1.014	2400	97	1	1.24	0.17
Drip cont	4.8	4.798	5.952	1.024	2400	108	1	1.24	0.17
Sprinkler	4.8	4.800	6.000	1.152	2400	133	1	1.25	0.19
Moderately sensitive									
Drip 5 d	4.8	3.182	5.950	2.629	2400	177	0.663	1.87	0.44
Drip day	4.8	3.334	5.952	2.420	2400	171	0.695	1.79	0.41
Drip cont	4.8	3.359	5.950	2.412	2400	179	0.700	1.77	0.41
Sprinkler	4.8	3.666	6.000	2.208	2400	173	0.764	1.64	0.37

kler irrigation compared with drip in spite of the fact that yield (transpiration) was not effected. For the more salt-sensitive crop, the LF was higher in drip compared with sprinkle irrigation, and there was no difference in salt load. Comparing frequencies of drip irrigation in these simulations shows only small differences regarding salt balance and potential for salt storage. The continuous irrigation regime resulted in a slightly greater salt load compared with the less frequent regimes. The relatively high LF and reduced T for the moderately sensitive crop were greater than differences due to method or frequency and further highlight the importance for choice of appropriate crops in saline drainage water recycling schemes. Better understanding of root growth, development, and function under the conditions relevant to high and continuous irrigation regimes is needed to more accurately simulate the potential for these options for short- or longer-term salt storage.

Plant, Soil, and Salinity Limitations on Drainage Water Disposal

The premise of the previous discussion was that drainage water is a potential resource for reuse and that cycling, blending, and irrigation delivery systems can be considered for using the water and minimizing deleterious effects to crop yield and environmental resources. California's experience in the San Joaquin Valley with agricultural drainage water created additional considerations for drainage water management. Strategies to dispose of the water via evaporation in wetlands failed miserably in the late 1970s and early 1980s due to high concentrations of Se that caused fish mortality and bird deformities (Letey et al., 1986; Presser and Ohlendorf, 1987). Demands of zero environmental release of agricultural water waste have been established to prevent environmental contamination from salts and nutrients. These demands, which are necessary for sustainability, create major challenges to irrigation management in California and elsewhere. Sequential reuse (Oster and Grattan, 2002) reduces the quantity of drainage water produced by collecting drainage water from fields where high-value, salt-sensitive crops are irrigated to irrigate more salt-tolerant crops in other areas. Drainage water from irrigation of the salt-tolerant crop may be collected for irrigation on non-economic species. Eucalyptus trees (*Eucalyptus*

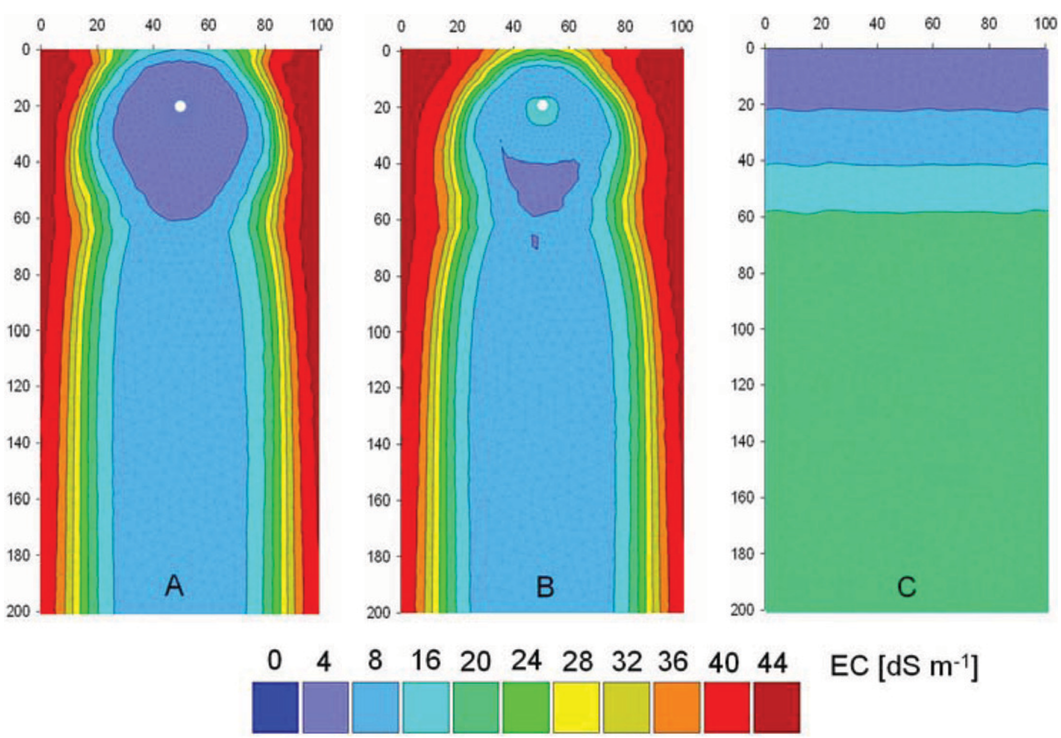

Fig. 2. Illustration of the salt concentrations in the soil profile at the end simulations of seasonal irrigation for (A) 1-d drip, (B) 5-d drip, and (C) sprinkler regimes for a salt-tolerant crop. Details of seasonal water and salt balance for these examples are shown in Table 2. Axis units are centimeters. EC, electrical conductivity.

globules) have been included in the sequence because they have the potential to transpire water from shallow ground water, reducing the overall volume of drainage (Tanji and Karajeh, 1993; Cervinka, 1994). The trees have not performed particularly well, possibly due to frost, excessive salinization, boron toxicity, sodicity, and poor aeration (Grattan et al., 1999). The goal of sequential reuse is to reduce the amount of drainage water for ultimate disposal to evaporation ponds to a minimum. Grieve and Suarez (1997) proposed the use of halophytes for the final plant in the sequence to reach this goal.

Dudley et al. (2008) used a 1-D, numerical model to investigate the extent to which the LF might be minimized. Model-computed LFs as functions of irrigation, irrigation water salinity, soil hydraulic properties, and crop response parameters to salinity and water stress demonstrated that the soil–plant system has a self-regulating nature that determines the maximum salt storage within the root zone and the minimum values of the LF. Irrigation in amounts that resulted in salt accumulation within the root zone reduced T and water not extracted by the plant due to salinity became drainage. Eventually, the system reached a steady state wherein salt left by previous irrigation was removed by the drainage water. Interaction of the irrigation water salinity, crop salt sensitivity, and, to a degree, soil hydraulic properties determined the minimum LF (Dudley et al., 2008). For any given combination of irrigation water salinity and plant salt tolerance, there was an irrigation level that produced the minimum amount of drainage water.

To illustrate the self-regulating behavior of the system herein, the steady-state analytical model of Shani et al. (2007) was used to compute the LF as a function of irrigation water salinity, irrigation amount, crop sensitivity to salinity and water stress, and soil hydraulic properties. Shani et al.'s (2007) analytical solution predicts plant yield and transpiration under user-specified environmental, biological, and management parameters and was used to generate irrigation, salinity, and yield relationships. Specific

Table 2. Brooks-Corey soil hydraulic parameters used in the simulations. Ks is the saturated hydraulic conductivity, δ and β are empirical soil characteristic parameters, θ_s is the saturated water content, θ_r is the residual water content, and ψ_e is the air-entry matric potential.

Parameter	Sandy loam†	Silt loam†	Clay
K_s, m d^{-1}	3.60	0.60	0.53
δ	4.91	10	15
β	0.55	0.25	0.55
θ_s, m^3 m^{-3}	0.41	0.46	0.50
θ_r, m^3 m^{-3}	0.06	0.05	0.04
ψ_e m	−0.20	−0.30	−0.30

† Shani et al. (2007).

input variables for the model include quantity and salinity of irrigation water, a parameter for plant sensitivity to salinity, the minimum root water potential, T_p, and soil hydraulic parameters. The model assumes steady-state conditions and that plant response may be computed from representative values of the water content and salt concentration in the root zone. Essentially, the model predicts T as a function of water and salt stress where irrigation is frequent, regular, and delivered at a constant ratio potential evapotranspiration. The analytical model does not consider dynamic processes that influence the LF (Meiri and Plaut, 1985; Corwin et al., 2007; Letey and Feng, 2007) but should be appropriate for developing a conceptual understanding of system limitations on drainage reduction. For model computations, EC_{50} (EC of a soil saturation paste associated with a 50% decrease in potential yield) was 7.7 dS m^{-1} (tomato), and EC_i (EC of the irrigation water) was 1.0 to 8.0 dS m^{-1} in unit steps. Brooks-Corey hydraulic parameters (Brooks and Corey, 1964) are given in Table 2, and the minimum value of the root potential was assumed to be −6 m (Shani et al., 2007).

There is strong curvature in the LF surface plotted as a function of normalized irrigation (I T_p^{-1}, where I is used to denote irrigation) and normalized salinity (EC_i EC^{-1}_{50}) (Fig. 3a). The use of normalized variables eliminated the effect of the crop salt

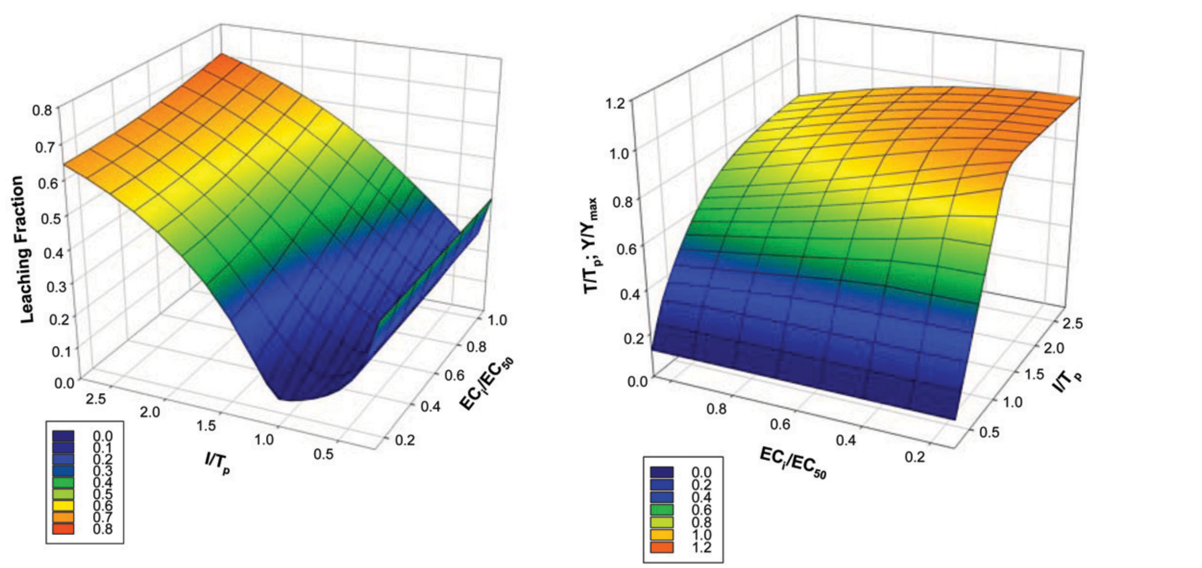

Fig. 3. The leaching fraction or relative transpiration and yield as functions of the ratio of irrigation (I) to potential transpiration (T_p) and of the electrical conductivity of the irrigation water (EC_i) to the electrical conductivity of a soil saturation paste associated with a 50% of potential yield for the sandy loam soil texture (EC_{50}).

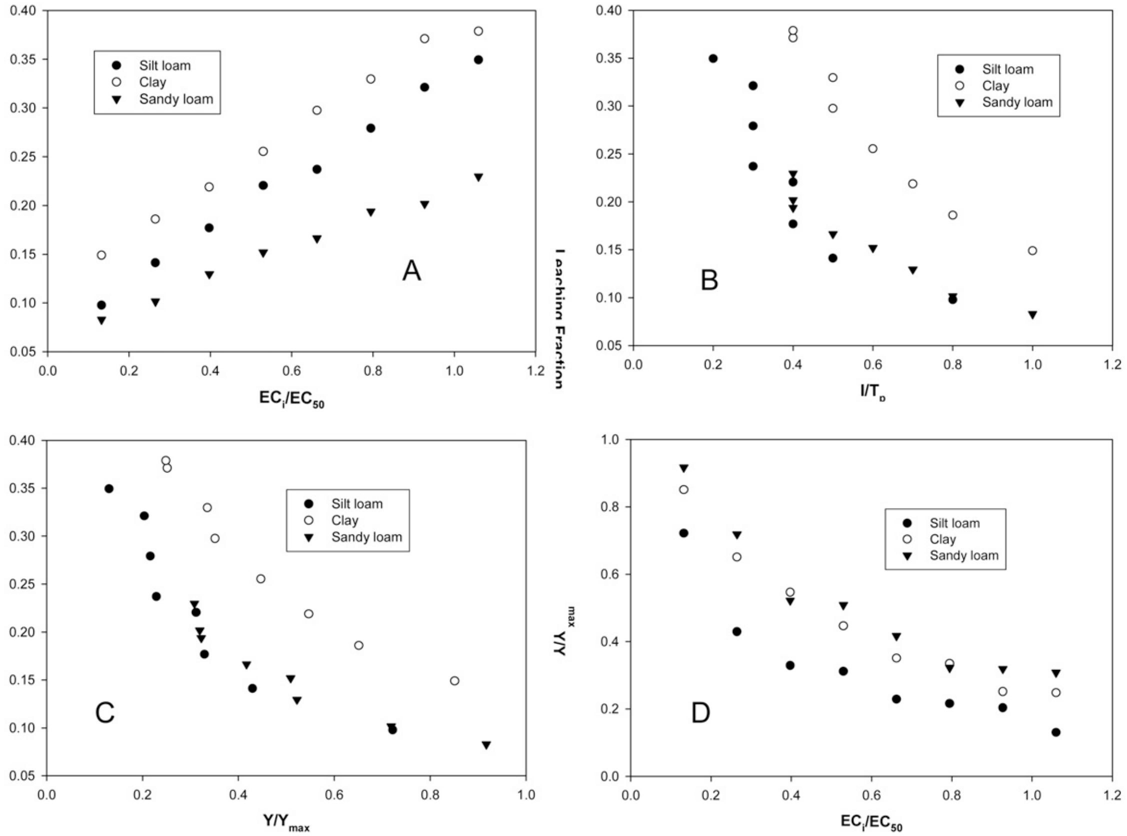

Fig. 4. The minimum values of the leaching fraction as a function of normalized irrigation water salinity (A), normalized irrigation water quantity (B), and normalized yield (C) and corresponding relative yield (Y/Y_{max}) as a function of (D) normalized irrigation water salinity computed by a steady-state, analytical model where soil saturation paste associated with a 50% of potential yield (EC_{50}) was 7.7 dS m^{-1} (tomato) and irrigation water salinity (EC_i) values were 1 to 8 dS m^{-1} in unit steps for three soil textures.

sensitivity from the figure. The model assumes that the relative transpiration (T/T_p) is equal to relative biomass yield (Y/Y_{max}, where Y_{max} is the maximum yield obtained without water or salt limitation), so the two ratios are interchangeable. Reducing the amount of irrigation from that associated with the LF minimum results in an accumulation of salt that significantly reduces transpiration and creates additional drainage water (Fig. 3b). Even when the amount of irrigation was small, the LF was large when salinity was high because only a small fraction of the water could be used by plants. This supports earlier reports that evaluated LF using water-salinity production functions (Letey et al., 1985; Solomon, 1985; Letey and Dinar, 1986) and data recently presented for bell peppers (Ben-Gal et al., 2008). Consistent with the results of Dudley et al. (2008), the LF minimum occurs at an $I\ T_p^{-1}$ value of 1.0 when the irrigation water salinity is much less than EC_{50} and the value of $I\ T_p^{-1}$ corresponding to the minimum decreases with increasing salinity. The implications of Fig. 3 for sequential cycling are significant because increasing salinity of the irrigation water results in a decrease in the amount of water that can be applied to produce the minimum amount of drainage.

The minimum values of the LF obtained from the stepwise model computations increased with increasing salinity (Fig. 4a). The effectiveness of a sequential cycling system in minimizing the amount of drainage water is reduced as the salinity of the irrigation water approaches EC_{50}. Figure 4b is a plot of the relationship between the LF and amount of irrigation, corresponding to the minimum value of the LF computed by the model for the range of salinity values. The amount of water that can be disposed of decreases as the salinity of the irrigation water approaches EC_{50}. The sequence of crops should be selected to maintain a maximum difference between the salinity of the applied water and the crop salt tolerance. Figure 4 also demonstrates the cost to biomass production resulting from minimizing the LF when irrigating with saline water (Fig. 4c and 4d).

The model suggests that heavy-textured soils are more difficult to use for sequential cycling systems (Fig. 4). A greater range of deficit irrigation produced low values of the LF for the clay texture compared with the sandy loam or silt loam. The model results also illustrate observed and intuitive evidence suggesting that salinity management is simpler and crops are essentially less sensitive to salt stress on light-texture soils (Hillel, 2000).

Conclusions

Crop, soil, irrigation frequency, and delivery systems might be manipulated to reduce the quantity of drainage water, but the experimental data and model simulations in the literature also forward the notion that the nature of the system may seriously constrain the amount of reduction that might be achieved. Moreover, these results indicate that more experimental work is warranted on high-frequency drip irrigation as a strategy for reduction in drainage. Highly frequent drip irrigation may allow optimization of water and nutrient uptake by plants and maximum accumulation of salts at the surface and along the edges of wetted zones. This soil storage of salts could reduce salt load in drainage water.

Any irrigation delivery system might be used to achieve a temporary reduction in drainage water and salt loading to ground water. Deficit irrigation by any method may result in salt accumulation within the root zone, but the salt storage capacity is finite (Dudley et al., 2008). Maintaining soil productivity requires eventual removal of salt from the lower portions of the profile under surface irrigation and from the margins of the wetting zone for dripper irrigation. The savings in discharge of saline water to ground water during storage must be weighed against the salt loading during reclamation. Particularly with drip irrigation, experimental investigations into management of salt accumulated at the wetting margins are desirable.

The nature of the LF and its relationship to irrigation and salinity must be determined experimentally under field conditions. However, the minimum concept does have an important implication for sequential recycling schemes. The lowest LFs were computed for cases where the difference between EC_i and EC_{50} was large. The EC_{50} values for crops that might be used in sequential cycling operations are, therefore, constrained. The quality of water initially used in a sequential cycling operation dictates to a significant degree the amount of drainage water produced. A critical consideration for the agricultural use of nonconventional waste water sources (Qadir et al., 2007) is the quality of that water. Delivery of low-quality water to irrigators results in the production of significant quantities of poorer quality drainage water that could contaminate high-quality water resources.

Appendix A

Applicaton of Hydrus-2D for Evaluating Frequency and Method of Irrigation with Saline Drainage Water

The two-dimensional vertical flow domains (1-m width × 2-m depth) were discretized into 1546 nodes with significantly greater detail around the subsurface line source. The flow domain of the sprinkler irrigation scenario was discretized into 1026 nodes. Additionally, the lower boundary condition was set to free drainage, and the side boundaries were set to no flow in all the domains. The van Genuchten-Mualem soil hydraulic properties model (Mualem, 1976; van Genuchten, 1980) was selected for the numerical simulations. A homogeneous soil with $\theta_r = 0.078$, $\theta_s = 0.43$, $K_s = 0.25$ m d^{-1}, $\alpha = 0.00036$ m^{-1}, $n = 1.56$ [-], and $m = 0.359$ [-] was selected for the simulations. Homogeneous initial water content was set to 0.24 for all the simulations, and the soil was salt free. The discharge rate (per unit length) of the subsurface line source was 0.24 m^2 d^{-1} for the daily and the 5-d and 0.015 m^2 d^{-1} for the continuous regime. Irrigation durations ware 7.5 and 1.5 h for the 5-d and daily irrigation, respectively. The surface flux for the sprinkler irrigation was 0.01 m h^{-1} for irrigation duration of 5.287 h. Simulated duration was 9600 h for all simulations, with data saved at 20 evenly spaced times. The radius and depth of the subsurface line source were set to 0.02 m and 0.2 m, respectively. Constant potential transpiration was 0.012 m d^{-1}, and no evaporation was used in the simulation. These numbers yielded $I\,T_p^{-1} = 1.25$. The irrigation salinity was set to 4.0 dS m^{-1} for all simulations. Conservative chemistry with no adsorption was assumed with longitudinal and transverse dispersivity of 0.005 and 0.001 m. Root distribution was assumed to be linear for the sprinkler irrigation with maximum depth of 0.70 m. Roots in the drip irrigation scenarios were concentrated in the areas determined, according to preliminary runs, to be the zone of wetting and leaching immediately surrounding emitters. The root adaptability factor, which represents a threshold value above which root water uptake reduced in stressed parts of the root zone is fully compensated by increased uptake from other parts (Šimůnek et al., 2006) was set to 0.5 in all simulations. The water stress-response function suggested by Feddes et al. (1974) was used with maximal uptake between matric heads of 0 and −12 m and wilting point at −150 m. The effect of salinity stress on root water uptake was accounted for by using the threshold model (Maas, 1990). Crops with two salt sensitivity levels (tolerant and moderately sensitive according to Maas, 1990) were chosen for the simulations. Threshold values (EC_e) for response to salinity were 8.0 and 2.0 dS m^{-1}, and the declines per unit increase in EC_e beyond the threshold were 5 and 10% for the tolerant and moderately sensitive crops, respectively. The multiplicative approach was used allowing for combined water and solute stresses.

Acknowledgments

This research was supported by Research Grant Award No. IS-3826-06 from BARD, the United States– Israel Binational Agricultural Research and Development Fund.

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