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REVIEW

Modeling Approaches to Salt Management Problems in Irrigated Agriculture: A Review

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Abstract: Irrigation projects have been developed throughout human history to increase food production, but they frequently contribute to salinization and drainage problems as well. Examples where salinization and drainage water disposal due to agricultural activity are a critical problem can be found in irrigated areas in different parts of the world. To find possible solutions to irrigation and drainage related problems, government agencies, scientists, and soil and water resources managers recommend a broad array of management alternatives for conducting investigations. The concept of management alternatives of salinization and drainage problems can be evaluated by field experiments and/or by simulating conditions with reliable numerical or conceptual models. This paper provides a review of the implementation of modeling approaches for evaluating commonly proposed salt management alternatives on two different spatial scales: (1) Local (farm) scale, and (2) Regional scale. The conceptual and numerical-hydrologic modeling efforts presented here were generally limited to assessment of the effects on surface or groundwater quality. However, the development of a spatially and temporally distributed agroeconomic model using economic and hydrologic submodels might be a promising approach for better evaluation of management strategies. After accomplishing integration of hydrologic processes with economic submodels, the economic, environmental and social impact of management alternatives can be quantified to address the ubiquitous salt and pollution issues of irrigated agriculture, with potential application to arid and semiarid regions such as Turkey in the future.

Key Words: Salinization, salt management alternatives, drainage water reuse

Sulanabilir Tarım'da Tuz Amenajmanı Sorunlarına Modelleme Yaklaşımları: Bir Derleme

Özet: İnsanlık tarihi boyunca gıda üretimini arttırmak için sulama projeleri geliştirilmiştir. Fakat bu projeler sık sık tuzlulaşma ve drenaj problemlerine de yol açmışlardır. Dünya'nın değişik bölgelerinde sulanan alanlarda tarımsal faaliyetler sonucu oluşan tuzlulaşma ve drenaj suyu atığının kritik bir sorun olduguna dair örnekler bulunabilir. Sulama ve drenaj ile ilgili sorunlara olası çözümler bulmak için hükümet makamları, bilim adamları, ve toprak ve su kaynakları yöneticileri, gerekli araştırmaların yürütülmesi için geniş kapsamlı amenajman seçenekleri önermişlerdir. Kavram olarak tuzlulaşma ve drenaj sorunlarının amenajman seçenekleri, arazi denemeleri veya güvenilir sayısal veya kavramsal matematik modellerin kullanılmasıyla da değerlendirilebilir. Bu makale yaygın olarak önerilen tuz amenajman seçeneklerinin değerlendirilmesi için (1) Yerel (tarla) ölçek ve (2) Bölgesel ölçek olarak iki farklı uzaysal ölçekte uygulanan matematiksel model yaklaşımlarının bir derlemesini verecektir. Bu makalede sunulan kavramsal ve sayısal hidrolojik modelleme çabaları genellikle yüzey ve yeraltı suyu kalitesi üzerinde olan etkileri değerlendirmekle sınırlı kalmıştır. Ancak ekonomik ve hidrolojik alt modellerin beraber kullanılması ile geliştirilecek uzaysal ve zamansal dağılımlı agroekonomik bir model, amenajman stratejilerinin daha iyi değerlendirilmesi için umut veren bir yaklaşım olabilecektir. Ekonomik alt programların hidrolojik süreçler ile bütünleştirilmesi başarıldıktan sonra, amenajman seçeneklerinin ekonomik, çevre, ve sosyal etkileri, sulu tarım sonucu yaygın olarak oluşan tuz ve kirlilik sorunlarının gelecekte Türkiye gibi kurak ve yarı kurak bölgelere uygulabilirliği değerlendirilebilinir.

Anahtar Sözcükler: Tuzlulaşma, tuz amenajmanı seçenekleri, drenaj suyu kullanımı

Introduction

Irrigation projects have been developed throughout human history to increase food production. However, the benefits of irrigation can be short and ultimately fail due to the development of soil salinity and inability to remove salts from soils and shallow groundwater. The earliest historic example of soil salinity and its effects on society has have been traced back to 2400-1700 B.C. in ancient Mesopotamia, now southern Iraq (Jacobsen and Adams, 1958). The main purpose of the developed irrigation

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projects was to deliver water for stimulating agricultural production and the prospering civilization. However, the abundant supplies of water contributed to an increase in seepage, flooding, over-irrigation, and consequently a rise in the water table. Ultimately, due to the disastrous decline in yield, much of the agricultural area was transformed into barren, nonproductive land that persists to this date (Letey and Knapp, 1995). Although the story of Mesopotamia is ancient, other areas can potentially share the same fate as Mesopotamia and this could be repeated in anywhere in the world where irrigation systems have been established (Gupta et al., 1983; Ghassemi et al., 1995).

The climatic conditions of arid and semiarid regions in the world require the importation of irrigation water for economic agricultural production. Importing irrigation water simultaneously carries dissolved salts and delivers them to agricultural fields. Irrigation to achieve high yields is virtually impossible without some water percolating below the root zone, and the deep percolation helps to leach salts that accumulate in the root zone to the water table. However, after reaching the water table, percolation can result in a rise of the water table to the shallower depths of the soil profile. Subsurface drainage systems are commonly installed when the water table rises to the land surface and more importantly reaches to the crop rooting zone. Such drainage systems provide relief from high water tables and salinity in the root zone. Despite its benefits, a drainage system also carries saline water which that might be contaminated with toxic elements introduced by other agricultural practices to the surface where they must be disposed of. For example, in California, USA, the Imperial Valley and western San Joaquin Valley are two major areas of concern where agricultural drainage water disposal is a critical problem (Letey, 2000). Without a solution for dealing with salts, long-term agricultural productivity is jeopardized unless salt management strategies are developed.

The development of alternatives for managing soils subject to salinization in arid and semiarid regions can be evaluated by field experiments or by simulating conditions with reliable models. Due to the time and labor constraints of extensive field testing to establish long-term relationships, numerical and conceptual models have been used extensively to simulate field conditions for understanding basic processes and the long-term effects of various management and application alternatives on the fate of salts at the regional or local (farm) scale (Sarwar and Bastiaanssen, 2001; Gates et al., 2002). Models have some advantages over rigorous field experiments with respect to synthesizing information inexpensively and quickly. However, the reliability of model results is contingent upon the degree to which the models accurately represent the natural processes. Thus, model results must be compared to results from field experiments to ascertain the degree of model reliance. The task of estimating the impact of salt management strategies has become increasingly important to agencies concerned with salinization problems in the world.

This paper presents a review of past and current modeling approaches for evaluating salt management alternatives in irrigated areas with salinity problems. Our aim in this review is to show how modeling efforts have been used to evaluate the impact on soil and water salinity of several management procedures that are considered to be potentially viable for controlling and/or improving salinity at on two different spatial scales: (1) Local (farm) scale, and (2) Regional scale. Moreover, we will briefly discuss existing studies and possible implications of modeling approaches for irrigated areas in Turkey.

Local (Farm) Scale Approach to Salt Management Problems

Local scale modeling of salt management strategies is usually conducted to improve the understanding of the cause of drainage or salt-related problems at a particular field site. To find solutions to the drainage and salt-related problems in on the farm scale, researchers have used the modeling approaches extensively for investigating and estimating the response of the system to proposed management strategies. These efforts also give a preliminary view of the practical outcome of applications for management of the system. In this section, we will give a concise review of the current and past conceptual and numerical modeling efforts to describe the effects of several management alternatives on the control of drainage and salt-related problems in on the farm scales.

Conceptual modeling efforts

Reuse of drainage water

Sequential reuse is a water-management program involving the reuse of drainage water on successively more salt-tolerant crops (Drainage Reuse Technical Committee, 1999). This strategy was developed to reduce water use due to problems with the disposal of agricultural drainage water. In this system, high-quality water is used to grow a salt-sensitive crop, and the drainage from this operation is collected by tile lines and subsequently used on a more salt-tolerant crop. This process is continued on progressively more salt-tolerant species until the final residual is collected and sent to evaporation ponds. Since substantial water is evaporated at each stage, the drainage water volume available for irrigation is progressively reduced, while the salt concentration is correspondingly magnified.

The sequential reuse concept has been tested in Australia, and in the western San Joaquin Valley, California, USA (Ghassemi et al., 1995; Cervinka et al., 1999). The California project was conducted and designed based on the steady-state assumption that the concentration of water collected in the drainage system of each stage was the same as the concentration of water leaving the root zone. However, the drain water concentrations during the years of operation of this project have differed significantly from their anticipated steady-state values due to considerable transition times of adjustments to the new management (Cervinka et al., 1999; Letey et al., 2001). Based on the work of Jury (1975), Jury et al. (2003a) developed a conceptual-mathematical model of water and chemical movement through the soil and to the tile drain that is used to represent the sequential reuse system and calculate the buildup of salinity in the soil and drainage water over time in the presence of an impermeable clay barrier in the subsurface. The purpose of this analysis was to construct a simple model of the tile-drain concentrations in a system where agricultural drainage water is sequentially pumped to fields containing increasingly more salt-tolerant crops. Applying the model to the sequence of drains, the tile drain concentration from each stage of the sequential reuse system was calculated as a function of cumulative drainage. Results of the calculations showed that response times of fields managed in this way are extremely long, so that the drain lines primarily capture resident ground water for decades or more after the operation is started, especially if the clay barrier is assumed to be at a substantial depth below the surface (Figure 1). During the sequential reuse of drainage water, each successive field required longer time to reach steady-state than the previous one and steady-state concentrations can be exceeded during the transient stage because the high concentration of the resident groundwater can magnify as it passes through the system (Figure 2a). The behavior of the field with a deep barrier was qualitatively the same as that of the field with a

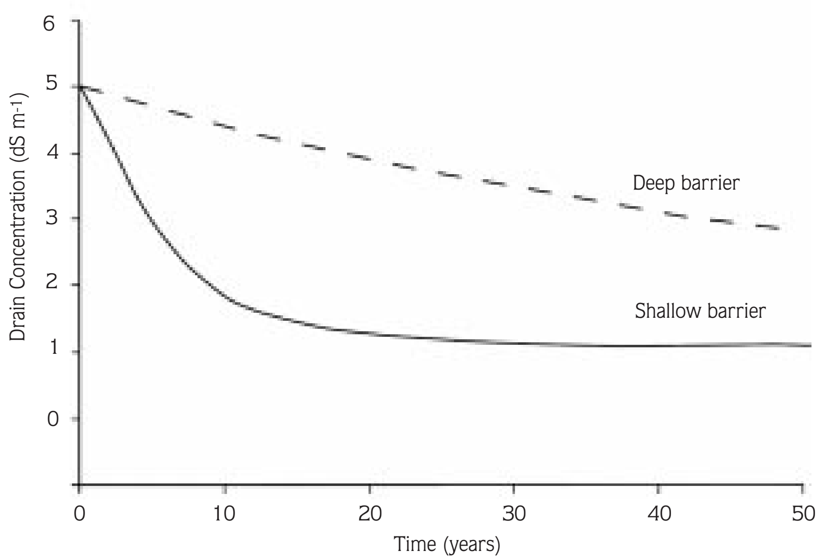

Figure 1. Response time and equilibration time of first stage of a reuse operation system overlying a shallow (3-m) and deep (60-m) barrier, using parameters from the Red Rock Ranch of Cervinka et al. (1999). At the first stage, high quality irrigation water was applied.

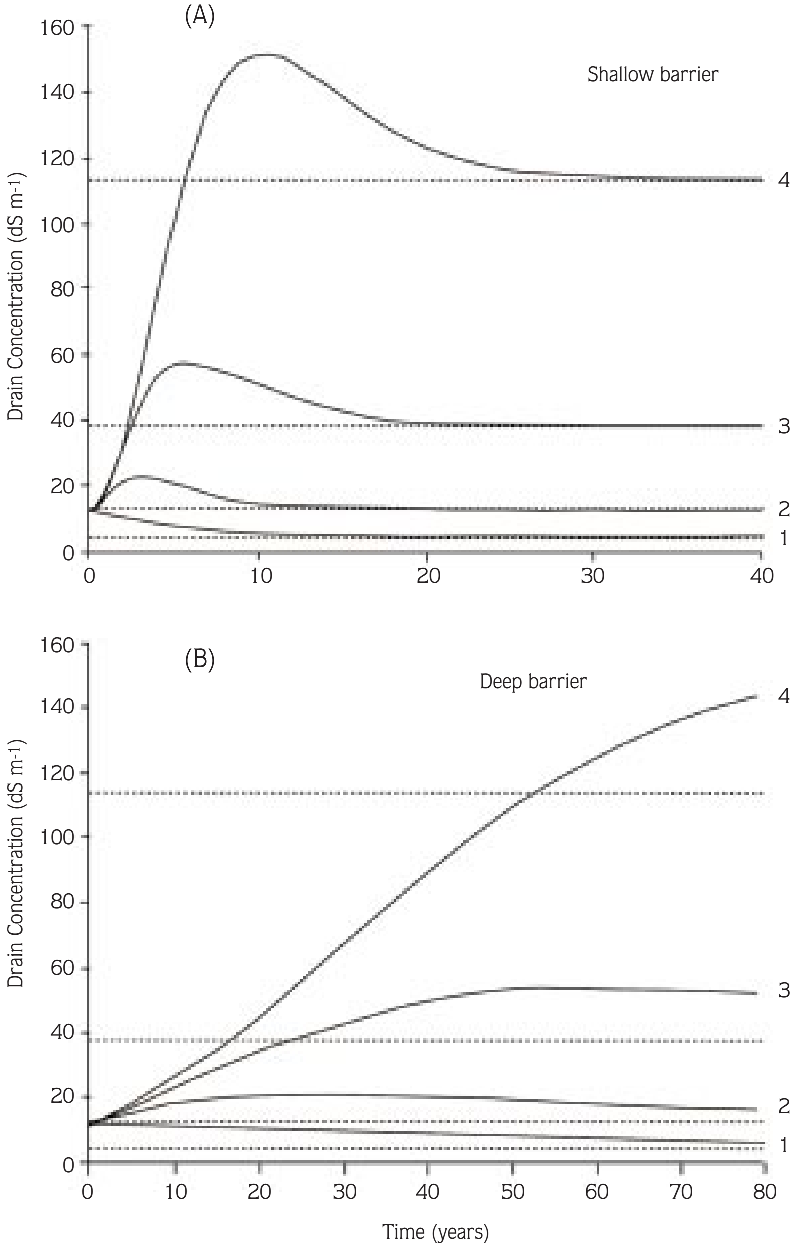

Figure 2. Drain concentration from all four 4 stages of reuse operation overlying (a) a shallow (3-m) barrier, (b) a deep (60-m) barrier, using parameters from the Red Rock Ranch of Cervinka et al. (1999). Dashed lines represent steady-state concentrations and numbers beside the solid lines shows each subsequent stage. After the first stage, drainage water collected by tiles lines was used for irrigation of the subsequent field.

shallow barrier except that the time scale for transition to the steady-state was expanded considerably because of the significantly greater volume of resident water that must be leached (Figure 2b).

Numerical modeling efforts

Source Control

Irrigated agricultural practices employed in arid and semiarid areas have contributed to an ongoing process of soil and groundwater quality changes that include elevated water tables, increased soil and groundwater salinity levels, and the concentration of trace elements in the environment. Source control, which is the most common salt management practice, requires the farmer to apply irrigation water uniformly across the field, to accurately control the amount irrigation water applied and to schedule irrigation properly.

Numerical models are useful tools for analyzing water and solute dynamics in agroecosystems. Several hydrological models developed specifically to address irrigation-related drainage problems have tended to concentrate on simulating surface water and groundwater systems without linking evaporative, surface, and unsaturated vadose zone processes. For example, Skaggs (1982) developed a model for the design and evaluation of water management strategies for soils with natural or induced high water tables. Nour el-Din et al. (1987) simulated 2-dimensional flow and salt transport to agricultural drains under irrigated conditions including evaporative processes. Although to a certain extent, the developed model made considerable improvements in estimation of the effect of applied management practices, the assumptions made about evapotranspiration caused limitations to the application of the model. In a study of 37 farms in the Batinah region of Oman, Al-Ajmi et al. (2002) used a physically -based 1-dimensional irrigation management model for salinity control. Combining the model results with the limited available data, they concluded that soil water salinity in irrigated farm areas was strongly sensitive to the size of the irrigation area and the amount and scheduling of irrigation.

Scientists should work on providing technical information to guide farmers and policymakers in making decisions that optimize the dual goal of high crop yield and low environmental degradation. Experimentally quantifying the combined effects of irrigation amount, water salinity, and N management on yield and chemical leaching is expensive. Based on the modified model of Cardon and Letey (1992a) for simulating crop production under various irrigation management regimes, Pang and Letey (1998) developed and evaluated a model that describes water, salt, and nitrogen (N) movement through soil under a cropped system for the plausible utilization of fertilizer and irrigation management in problematic areas. With the aid of Pang and Letey's (1998) modeling approach, Feng et al. (2003a, 2003b) evaluated the consequences of differing management strategies under saline conditions on crop yield and salt distribution. While the model generally performed well, resulting in good agreement between simulated and measured yield, salt and root distribution under saline conditions, it needs to be used cautiously to be useful in developing optimal management strategies of source control strategies. Root zone salinity management received a lot of attention from researchers wanting to examine closely the processes that constrain agricultural production.To look more closely the processes that constraints the agricultural production, root zone salinity management took a lot of attention from researchers. Ali et al. (2000), Kara (2002), and Jorenush and Sepaskhah (2003) used a 1-dimensional soil salinity model to simulate the effects of various management alternatives and initial conditions on root zone salinity, given a consistently high water table. Moreover, modifying the 2-dimensional model of Simunek et al. (1994), Tarboton et al. (2002) suggested that the model can be used as a tool for evaluating performance of irrigation and drainage management practices on root zone salinity. Smets et al. (1997) and Sarwar and Perry (2002) used an agro-hydrological model to study the impact of irrigation practices, i.e. irrigation quantity, quality and frequency on soil salinity and crop transpiration in Punjab, Pakistan, by analyzing the water flow and salt transport for the existing conditions.

To develop an integrated 3-dimensional model that couples surface management practices and processes with vadose zone and groundwater flow and transport processes, Buyuktas and Wallender (2002) improved the model of Simunek et al. (1995) by adding new features incorporating evapotranspiration partitioning, dynamic root water uptake, and heterogeneous fluxes of water and salts through the soil surface. Their verification against analytical and experimental data in the literature showed that the improved model can simulate the existing processes within the system of complex agricultural management strategies with satisfactory results.

Reuse of drainage water

To study the effect of sequential reuse drainage water as a management strategy in the long-term, more sophisticated numerical modeling exercises were performed to simulate the water and solute flow through soil and to the tile drains. For example, Letey and Knapp (1995) evaluated transient and steady-state models for simulating the consequences of applying saline drainage water to eucalyptus trees under conditions typical to of the San Joaquin Valley of in California, USA. Using the model findings and anticipating the degradation of soil physical properties by adding saline drainage water to soils over the long term, they hypothesized that the application of drainage water causes degradation of soil physical conditions such that crop productivity and water disposal per unit land area becomes progressively lower.

In addition to their conceptual modeling approach, Jury et al. (2003b) also focused on numerical modeling of the reuse of drainage water system, using the HYDRUS-2D model (Simunek et al., 1999) to simulate drain concentration as a function of time for the first stage of a reuse operation system overlying a shallow (3-m) and deep (60-m) clay barrier within the saturated zone. Figure 3 shows the numerical analysis of the response time and equilibration time of the first stage of the reuse operation where high-quality irrigation water was applied for the shallow and deep barrier cases. It is obvious that the system showed a trend similar to that in the conceptual analysis (Jury et al., 2003a) in which the system was inherently transient for both barrier cases, and did not reach steady-state in any practical time as well. Jury et al. (2003a) cautioned that soil layering might distort the streamlines before reaching deep into the saturated zone. To illustrate this effect, the horizontal/vertical conductivity ratio was changed by doubling and quadrupling the horizontal conductivity component in the simulated system (Figure 4). Figure 4 shows the effect of increasing conductivity ratio on response time and equilibration time of the system. This effect was insignificant in the shallow barrier case, but significantly decreased the travel time in the deep barrier

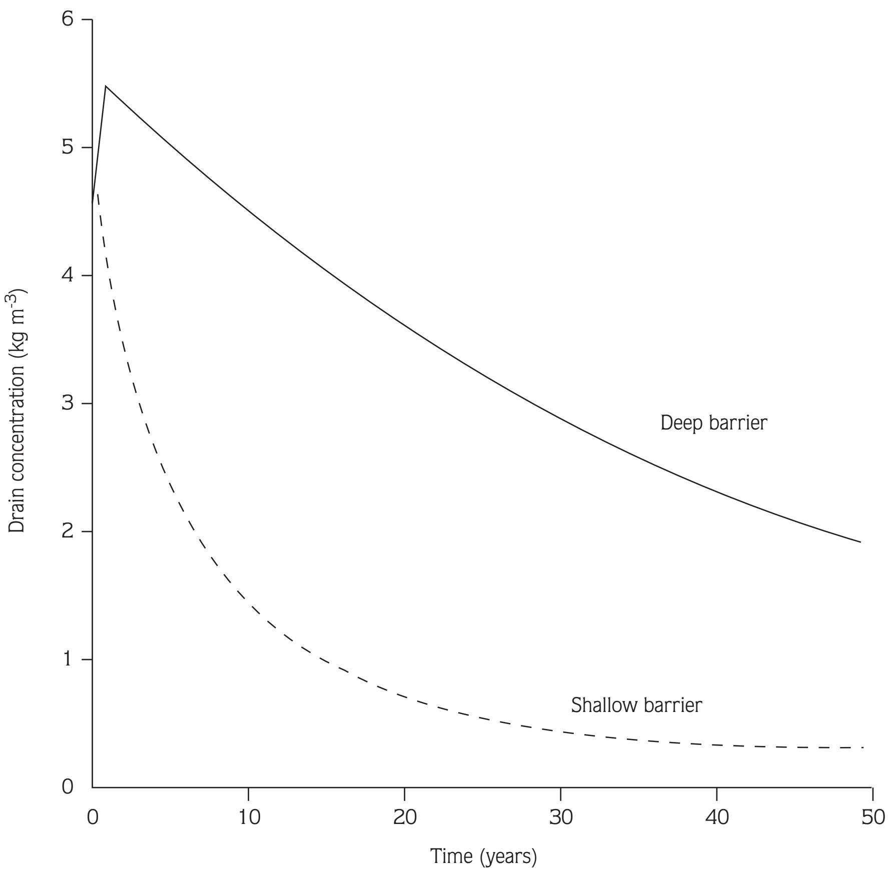

Figure 3. Numerical analyses of response time and equilibration time of the first stage of a reuse operation system overlying a shallow (3-m) and deep (60-m) barrier, using parameters from the Red Rock Ranch of Cervinka et al. (1999).

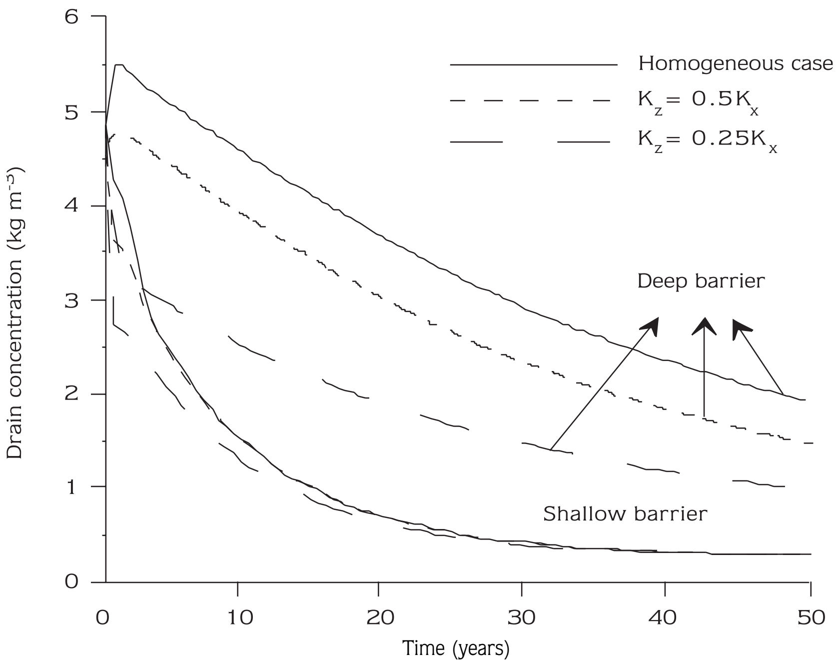

Figure 4. Numerical analyses of response and equilibration time of the first stage of a reuse operation system overlying a shallow (3-m) and deep (60-m) barrier with different horizontal (K_X)/vertical (K_Z) conductivity ratio.

simulation. However, travel times still were still very long in the latter case.

Cyclic and blending strategies for reuse of saline water

As Letey (1993) pointed out, when supplies of waters of different quality are available for irrigation, including drainage water and groundwater for irrigation, various strategies can be applied to use these saline waters. Although the optimal mixing of saline and non-saline waters for growing different crops could be determined from the equal yield curves (isoquant) like those presented by Letey (1993), detailed management strategies were not possible due tobecause of the limited information utility in guiding management decisions in a typical agricultural operation.

The use of saline waters can be achieved effectively with properly adapted management practices. This approached has little appeal to most farmers, because it restricts them to salt-tolerant crops, and it requires special management practices and equipment to obtain a good stand on saline land. Rhoades (1984) proposed a cyclic strategy for substituting saline water for normal (low-salinity) water to irrigate certain crops in rotation. The irrigation plan for the entire crop rotation is based on the crop tolerance to salinity, salt sensitivity at specific growth stages, and salinity of irrigation waters (Letey, 1993). Non-saline water is used for pre-plant and early irrigation of salt-tolerant crops and all irrigation of the moderately salt-sensitive crops. Saline water is used for salt-tolerant crops after they have reached a salt- tolerant stage of growth. A pre-irrigation is applied with low-salinity water to leach excess of salt from the upper portion of the soil profile. This is proposed to re-establish the salt-sensitive crop. Meanwhile, the blending strategy involves mixing two waters of different qualities quality to obtain water that is appropriate for irrigation purposes. Shalhevet (1984) discussed in details the principles of two different blending processes.

Bradford and Letey (1992) used a multi-seasonal transient- state modified van Genuchten-Hanks model (Cardon and Letey, 1992b) to investigate the effects of cyclic or blending strategies for using non-saline and saline waters for irrigation with two salinity levels on alfalfa (*Medicago sativa* L.), and on a corn (*Zea mays* L.) and cotton (*Gossypium hirsutum* L.) crop rotation. Simulated alfalfa yields were similar for both strategies, in which applied the same amount of salt and water was applied. The cyclic strategy produced higher simulated yields of salt-sensitive corn than the blending strategy, whereas the simulated salt-tolerant cotton yield was not affected by either strategy. The main finding was that no significant differences in yield occurred whether the waters were mixed prior to application, or intermittently applied for different lengths of time. Furthermore, they strongly emphasized that the value of the cyclic strategy was in a crop rotation system which that includes salt-sensitive and salt-tolerant crops. There was little benefit when only one crop is was used, as their alfalfa results illustrated. The consistency of the simulated results with the concept of cyclic strategy proposed by Rhoades (1984) and field experiments (Rhoades et al., 1988) showed that low salinity in the initial stages is more important than at latter stages of plant growth. The recent work of Ragap (2002) provides another example of an integrated modeling approach for irrigation water management using blending and cyclic water management strategies.

Regional Scale Approach to Salt Management Problems

Specific geological settings and long-term irrigation practices have caused a variety of salinization and drainage problems in agricultural soils in arid and semiarid regions. For example, long-term irrigation with reclaimed water on soils of the northern Adelaide Plains, South Australia, causes significant increases in soil salinity, sodicity, and boron (B) concentrations (Stevens et al., 2003). Several approaches have been studied to evaluate management alternatives for reducing subsurface drainage and consequently retaining the salts and toxic elements below the soil surface (Letey, 2000; San Joaquin Valley Drainage Implementation Program, 2000). In particular, high salinity in drainage water requires appropriate management and disposal not only to sustain agricultural productivity but also to protect the environment and wildlife habitats (Letey et al., 2003).

In recent years, water table height control has been receiving substantial discussion attention as a drainage management option. The plausible management schemes proposed for water table height control are the land retirement in regions with poor drainage, controlling the discharge from a subsurface drainage system and groundwater pumping. In the following section, we will discuss some management studies conducted on a regional scale rather than a farm scale.

Conceptual modeling efforts for the management alternatives

Conceptual modeling can be a valuable tool for understanding the hydrologic response and salinization tendency of large areas such as catchments prior to developing analytical or numerical modeling efforts for predicting system behavior (Peck and Hatton, 2003). Peck and Hatton (2003) summarized the extensive literature, emphasizing the importance of a hydrogeological conceptualization of the saline catchments in southwestern Australia. They concluded that surface water control, groundwater pumping, tile drains and disposal pools were the best management practices for the control of salinity in this region. To explore the possibility of reducing the need for drainage and salt accumulation, Letey and Oster (1993) used a conceptual steady-state approach to estimate quantities of controlling practices under the conditions having a clay barrier at the subsurface in the Westland water district in California and developed several strategies to reduce subsurface drainage outflow entailing adjustments in irrigation, water pumping, and drainage practices. Their results suggested that several approaches can be applied to reduce subsurface drainage outflow: (1) To manage the water table level within the root zone to increase its use to meet crop evapotranspiration (ET); (2) To shut drainage lines for increasing leakage through the existing clay barrier at the subsurface; (3) To apply irrigation water in quantities less than crop ET; and (4) To increase groundwater pumping.

Numerical modeling efforts for the management alternatives

Recharge and groundwater pumping

A quantitative understanding of the hydrologic and geochemical factors related to the distribution of chemical constituents in groundwater and groundwater flow to drain laterals is necessary to develop effective water management practices. For example, Kim and Sultan (2002) constructed a 2-dimensional groundwater model to investigate the long-term hydrological impact of Lake Nasser and related irrigation projects in southwestern Egypt for potential flooding and salinization problems. Using basic information about geochemistry, groundwater flow, and advective solute movement in groundwater underlying an artificially drained field, Fio and Deverel (1991) qualitatively assessed the hydrologic processes affecting groundwater and solute movement to drain laterals with the aid of groundwater flow modeling. The simulation of irrigated conditions indicated that as recharge (deep percolation) increases, the proportional contribution of deep groundwater to drain lateral flow decreases and the groundwater containing high concentrations of selenium will continue to enter drain laterals for decades. Belitz and Phillips (1995) and Wu (1998) conducted a regional hydrogeologic-numerical study of management alternatives to agricultural drains in the central part of the San Joaquin Valley in order to avoid long-term salinization of the soil and shallow groundwater. The transient, 3-dimensional model was used to evaluate the response of the water table to three management alternatives that alter recharge to or discharge from the groundwater flow system. These management alternatives were retiring land, reducing recharge through improvements in irrigation efficiency, and increasing groundwater pumping. Modeling efforts indicated that reducing recharge through irrigation efficiency and/or increasing groundwater pumping were much more effective in reducing bare-soil evaporation and drain flow. A similar study has also been conducted in an irrigation area of Argentina to evaluate salinity control measures using a regional hydrological model (Kupper et al., 2002). Their simulation scenarios revealed that increasing groundwater pumping for irrigation and improving drainage would be a very effective alternative for controlling salinity.

Land retirement strategy

Land retirement is a management strategy proposed to reduce the volume of drainage water requiring surface disposal in countries such as Australia (Ghassemi et al., 1995) and the USA (San Joaquin Valley Drainage Implementation Program, 2000). In addition to regional modeling efforts of land retirement strategy, the need for more refined work at on the subarea scale was essential for better assessment of the long-term consequences of the proposed strategy. One good example of numerical modeling efforts for a land retirement scenario was by Purkey and Wallender (2001), who focused on a land retirement strategy for determining the drainage reduction potential in a region where discharge to the San Joaquin River is possible. Their numerical analysis for different land retirement scenarios over 50 years suggested that the retirement of large contiguous tracts of land produced the greatest drainage reduction benefit. The practical application of the contiguous scenario seems particularly unrealistic to large land owners whose land is entitled to the retirement program. Since the land retirement program is based on the willing-seller approach, the owners will likely preclude the acquisition of any such vast holding. A much more realistic approach would be to proceed with land retirement through multiple, disjointed acquisitions of smaller parcels. In this case, simulations revealed that the maximum benefit in drainage reduction would be gained with the retirement of downgradient parcels that are already plagued by shallow groundwater and equipped with subsurface tile drains (Purkey and Wallender, 2001).

Implications of Modeling Approaches for Turkey

As discussed above, modeling is an important tool for achieving efficient salt management programs in areas with salinization problems. However, only a limited number of studies exist on the use of simulation models for analyzing performance and problems of agricultural practices in Turkey. Although Turkey has 25.85 million ha of land which that can be potentially irrigated, only 8.5 million ha is economically suitable for irrigated agriculture and these areas can face the danger of potential salinization due to improper use of agricultural practices (Çetin and Özcan, 1999).

Traditionally, many researchers in Turkey have focused on field experiments to determine irrigation-yield relationships, irrigation scheduling, and potential irrigation-related problems. These studies were generally performed over a limited period of time and on small scales (farm scales), ignoring any temporal and spatial variability. There are several published works describing experimental assessments of salinization by soil sampling (Çullu et al., 1998; İnce and Özkutlu, 1999; Çullu, 2000; Cetin and Kirda, 2003). Conclusions and discussions in these traditional studies are principally based on point samples collected from random locations within the study area without any geostatistical considerations except for the study of Cetin and Kirda (2003), which includes an elaborate conventional and geostatistical analysis to assess the temporal and spatial effects of low quality irrigation water on soil salinity at the small farm scale.

Since our focus is on the use of modeling approaches to study salinity management alternatives, we found very few studies describing modeling approaches to evaluate the potential risk of soil salinity for sustainable crop productivity in irrigated agricultural areas in Turkey. Recently, Droogers et al. (2000a, 2000b) and Droogers and Bastiaanssen (2002) used an agro-hydrological model for evaluating irrigation performance, including water productivity, risk and system analyses in the Gediz Basin, western Turkey. In addition to using the agro-hydrological model, Droogers and Bastiaanssen (2002) also combined remote sensing modeling to produce high spatial coverage of important parameters in the model for the basin. Their study can potentially be extended to the other irrigated areas such as the Seyhan and Harran plains for studying soil salinity risk assessments and some foundational problems of salinity. For example, the problems related to irrigated and non-irrigated areas in the Lower Seyhan Plain given by Çetin and Özcan (1999) can be investigated for long-term effects and alternative agricultural practices using conceptual or numerical simulation models as applied to the Gediz Basin in western Turkey. The most intriguing and sophisticated study of salinity we found in the literature was by Saysel and Barlas (2001), who introduced a dynamic simulation model of salt accumulation as an integral part of a large scale regional model (Saysel et al., 2002). They developed a large scale regional model for long-term comprehensive environmental analysis of the Southeastern Anatolian Project (GAP) in semiarid southeastern Turkey. While this model provides a comprehensive and general description of the long-term process of salt accumulation under continuous irrigation practices for the whole project area (GAP), it needs to be integrated and modified with information technology tools such as those Çullu (2003) applied, to obtain much more detailed farm and basin scale based solutions and estimations for potential salinization problems on irrigated lands in the future.

In summary, our literature search showed that the agricultural and environmental scientific community in Turkey needs to fill the gap between traditional field research and the use and/or development of conceptual and numerical modeling within quality assurance guidelines (Oreskes et al., 1994; Refsgaard and Henriksen, 2004) in irrigated areas for a better understanding of current and future problems created due to agricultural practices. This may be accomplished by interdisciplinary research by specialists with different responsibilities such as code developers, model users and soil and water resources managers.

Conclusion

In the studies summarized above, conceptual or numerical hydrologic modeling efforts were limited to either surface water or groundwater related processes, but we discussed the most common modeling applications for salt management alternatives on in irrigated agriculture. To a certain extent, the conclusions drawn were a function of the constraints of the modeling exercise. However, there was general agreement about the merits of systematic land retirement and other practices for salt management. More recent studies have shown that some of the consequences (high cost, habitat effects) of the different schemes may be significant factors in decision-making. For this reason, studies combining hydrologic modeling with cost-benefit analysis and environmental analysis should be the most valuable to policy makers. With respect to Turkey, interdepartmental collaborations with different backgrounds must be encouraged and initiated to use and/or development of such simulation models.

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