2001-2002
Technical Progress Reports

University of California

Salinity/Drainage Research Program and Prosser Trust

Division of Agriculture and Natural Resources, University of California

October 2002

Conceptual Modeling of Salt Management Problems in the Western San Joaquin Valley of California

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ABSTRACT

Sequential reuse of agricultural drainage water recovered in tile lines has been proposed as a strategy for reducing drainage volume in the Western San Joaquin Valley of California. 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. In this paper we develop a transfer function model for simulating the drainage concentrations of each stage of a sequential reuse project. Transient salt concentrations are calculated for typical drain spacing and water management strategies, under the assumption that a subsurface barrier eventually restricts downward movement of water. Results of the calculations show 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 barrier is assumed to be at a substantial depth below the surface. As a result, the system will never reach steady state in any practical period of time, and system design strategies based on steady state behavior will be flawed.

KEYWORDS

Tile drainage, chemical transport, sequential reuse, travel times

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INTRODUCTION

California's Western San Joaquin Valley is experiencing a variety of irrigation-induced problems such as water scarcity, deteriorating water quality, and salinization of agricultural soils (Letey et al., 1986; San Joaquin Valley Drainage Program, 1990; Letey, 2000). A largely impermeable subsurface layer has caused drainage water to accumulate over many years, resulting in rising water tables and saline seepage into low-lying flood plains (San Joaquin Valley Drainage Program, 1990). As a consequence, agricultural fields in this region are commonly tile drained to keep the root zone aerated and free of salts. Earlier plans for surface detention and export of excess drainage water to the ocean through the San Francisco bay area were canceled because of high selenium levels in evaporation ponds, and concerns that export through the bay would have adverse environmental consequences for the local habitat (Letey, 2000). Since that plan was disrupted, efforts to control salinization have focused more on water reuse or various forms of land management (Letey and Oster, 1993; Belitz and Philips, 1995).

One strategy for salinity control consists of periodic leaching of the crop root zone to reduce the dissolved salt content to the tolerance limits of the crop to be grown (Biggar et al., 1984). Rhoades (1984) has proposed alternating saline and nonsaline irrigation waters together with crop rotation, including both salt-sensitive and salt tolerant crop species. Rhoades et al. (1988) tested this cyclic strategy in a field experiment with crops having different salt tolerance levels, and showed that high crop yield and quality could be achieved. Moreover, they concluded that the soil salinity level could be maintained within acceptable limits over time. Bradford and Letey (1992) used computer modeling to confirm the results of the Rhoades et al. (1988) experiments. They also showed that the soil salinity at the beginning of the cropping season was a significant factor influencing crop yield.

Another idea for drainage and salt control that is attracting considerable attention is a water-management program involving reuse of drainage water on successively more salt-tolerant crops, sometimes referred to as sequential reuse (Drainage Reuse Technical committee, 1999). 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.

Cervinka et al. (1999) presented results from a sequential reuse demonstration project conducted on irrigated farmland in the Western San Joaquin Valley. The crop areas, drainage volumes, anticipated dilution, and expected yields were all 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, drain water concentrations during the years of operation of this project have differed significantly from their anticipated steady-state values, suggesting that the transition times to adjust to the new management may be considerable, and that correct design of a sequential reuse system will require knowledge of the response time of the soil to a change in surface management (Letey et al., 2001). Jury (1975a) calculated the response time of tile-drained fields as a function of their drainage rates, drain spacing, and depth to barriers reducing or preventing downward flow, and found that it may take years to leach existing salt out of fields of the type found in the San Joaquin Valley. This delay time might substantially affect the performance of a system designed for water reuse or remediation of saline soil (Jury, 1975b).

This report develops 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.

METHODOLOGY

The purpose of this analysis is 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. Tile drain concentrations are easily modeled as transfer functions, where the input concentration to the field C_{in} is converted to an output concentration C_{out} at the drain using the drainage probability density function (pdf) *f(Q)*, where *Q* is the amount of drainage required to move a mobile chemical from the surface to the drain (Jury and Roth, 1991). This pdf is assumed to be a unique function of the geometry and soil properties, so that a single pdf is all that is required to model the system. If portions of the system are draining at different rates, the cumulative drainage-time function *Q(t)* may be used to convert the modeled concentration outflow to a time record. The following assumptions are used to construct the model:

- Each stage of the system has the same drain depth *H*, and drain spacing *2S*.
- The soil is homogeneous and bounded by a vertical flow barrier at a depth *D* below the drain
- The initial salinity level C_s in the soil and throughout the ground water is uniform.
- The first stage of the system using high quality irrigation water of concentration C_{irr} is leached at a low drainage rate R_1 and leaching fraction x_1.
- Subsequent stages are leached at a higher drainage rate R_2 and leaching fraction x_2.
- The water table is flat and the lateral ground water velocity is zero.

The travel time to the drain from any point of entry on the surface is the sum of two terms: i) the travel time t_u through the unsaturated zone (assumed to be constant); and ii) the variable travel time t_s from the point of entry at the water table to the tile drain. The saturated zone travel time t_s (and hence the pdf) is calculated by a model.

The two-dimensional calculation of the travel time t_s from the water table to the tile drain is described in detail in Jury (1975a). It begins with the Kirkham and Powers (1972) solution for the stream function *Y(x,z)* through the saturated zone of a tile-drained system with drain spacing *2S* and depth to barrier *D*. Lines of constant stream function represent water flow paths. First, the geometry of a given field is scaled by defining new variables *X=x/S, Z=z/S*. Then the streamlines of the scaled system are calculated as a Fourier series. This solution is given by (Jury, 1975a)

$$\Psi(x,z) = 1 - \frac{2}{p}\sum_{N=1}^{\infty}\frac{\sin[NpX]\sinh[Np(h-Z)]}{\sinh[Nph]};$$

$$h = \frac{S}{D};\ X = \frac{x}{S};\ Z = \frac{z}{S} \qquad (1)$$

Streamlines are constructed for equally spaced points of entry into the saturated zone along *X* separated by *DX*. An illustrative set of streamlines for the particular geometry *h = S/D* = 1 is given in Figure 1.

The travel time from a point of entry at the water table to the drain is calculated from this information as follows. Since any water entering between two adjacent streamlines must remain between the lines all the way to the drain, the travel time of any mobile solute in the water is approximately equal to the amount of time required to replace the amount of water in storage (the area *a(x)* times the saturated water content q_s) between the lines. Similarly, the cumulative drainage flux *Q(x)* arriving at the water table that is required to move solute from a point of entry a distance *x* laterally from the drain (multiplied by the area per width Dx between the lines) is equal to the water stored between the lines. If the system is draining at a steady flux rate *R* then $t_s(x)=Q(x)/R$. Thus, the travel time is equal to

$$t_s(x)=\frac{q_s a(x)}{R\Delta x}=(\frac{q_s S}{R})\frac{A(X)}{\Delta X} \quad (2)$$

where $A(X)=a(x)/S^2$ is the dimensionless area between the two streamlines originating at the water table at X-DX and X. $A(X)$ is estimated by numerical integration.

Since after a given amount of drainage Q_1, a fraction $X_1=x_1/S$ of the chemical added to the field at $t=0$ has arrived at the drain, we may interpret $X(Q)=x(Rt)/S$ as the cumulative probability density function (cdf) $P_s(Q)=P_s(Rt)$ of the saturated zone travel time. Thus the pdf of the cumulative drainage through the saturated zone is given by $f_s(Q)=dP_s(Q)/dQ$.

Under these assumptions, the sequential outflow may be solved by the mathematics of transfer functions as follows. In general, a given tile drain outflow concentration $C_{out}(Q)$ is expressed as a function of its input concentration $C_{in}(Q)$ at the water table by (Jury and Roth,1991)

$$C_{out}(Q)= \quad (3)$$

$$\int_0^Q C_{\text{int}}(Q-Q')f_s(Q')dQ'+C_s[1-P_s(Q)]$$

Note that Eq. [3] contains two terms, one representing the arrival of the drainage water that has reached the tile and a second describing the resident water in the saturated zone (assumed to be spatially uniform at $t=0$) being pushed out ahead of the incoming water. We may easily combine the saturated zone and unsaturated zone travel times (expressed as cumulative drainage), since the latter is assumed to be constant. The cdf of the total cumulative drainage is thus

$$P(Q)=0 \qquad 0<Q<Q_u \quad (4)$$

$$P(Q)=P_s(Q-Q_u) \qquad Q>Q_u$$

where Q_u is the amount of drainage required to move solute from the soil surface to the water table at depth *H*.

We may now apply the model to the sequence of drains, noting that as the irrigation water passes through the unsaturated zone of a field with a leaching fraction x_i, it is concentrated by a factor $N_i=1/x_i$. Thus, if the irrigation water added to the first stage has a constant concentration C_{irr}, a drainage rate R_1, and a leaching fraction x_1, then the outflow concentration in the first drain is equal to

$$C_1(Q)=C_1(R_1t)=N_1C_{irr}P(R_1t)+C_s[1-P(R_1t)] \quad (5)$$

Similarly, since all other stages have drainage rates R_2 and leaching fractions x_2, the outflow in the Jth drain is equal to

$$C_J(Q)=C_J(R_2t)= \quad (6)$$

$$N_2\int_0^{R_2t} C_{J-1}[R_2(t-t')]f_1(R_2t')R_2dt'+Cs[1-P(R_2t)]$$

These expressions become very simple after Laplace transformation (Jury and Roth, 1991)

$$\hat{C}_1(s)=N_1C_{in}\frac{\hat{f}}{s}+\frac{C_s}{s}(1-\frac{\hat{f}}{s}) \quad (7)$$

$$\hat{C}_J(s)=N_2\hat{C}_{J-1}(s)\hat{f}+\frac{C_s}{s}(1-\frac{\hat{f}}{s}) \quad (8)$$

where

$$\hat{f}(s)=\int_0^\infty \exp[-sQ']f(Q')dQ' \quad (9)$$

is the Laplace transform of *f(Q)*. The recursive Eqs. (7)-(8) may be combined into a general expression for the solute concentration entering the Mth drain as follows.

$$(10)$$

$$\hat{C}_M=N_1(N_2)^{M-1}(\hat{f})^M\frac{C_{irr}}{s}+\frac{C_s}{s}(1-\frac{\hat{f}}{s})\sum_{J=0}^{M-1}(N_2\hat{f})^J$$

Thus, if the Laplace transform of *f(Q)* is known and Eq. (10) can be inverted, the tile drain concentration from each stage of the sequential reuse system may be calculated as a function of cumulative drainage and converted to time.

RESULTS AND DISCUSSION

Figure 2 shows the dimensionless cdf *P(T)* as a function of the scaled travel time $T=Rt/q_sS=Q/q_sS$ for drain spacing to barrier depth ratios $h=S/D$ of 1, 5, and 20. In all calculations the dimensionless unsaturated zone travel time was set equal to 0.005. Each of these curves were parameterized approximately by fitting to the exponential model

$$P(T)=1-\exp[-w(T-0.005)];\ T>0.005 \quad (11)$$

The representation in Eq. (11) becomes exact for shallow barriers (large *h*), but underestimates long times and overestimates short times when the barrier is deep (small *h*). With this parameterization, the solution to Eq. (10) may be obtained analytically or by numerical inversion of the Laplace transform. The solution may also be converted to actual time when the parameters of a particular system are known. We will illustrate the calculation using the data shown in Table 1 from the Red Rock Ranch sequential reuse demonstration facility (Cervinka et al. 1999). This facility overlies the Corcoran clay barrier at a substantial depth below the surface. However, it is possible that soil layering could distort the streamlines before they reach deep into the saturated zone. For this reason, we will conduct analyses for both a shallow barrier and a deep one. We will use the small drainage rate and leaching fraction in Table 1 for stage 1 and the larger leaching fraction and drainage rate for all subsequent stage calculations.

Figure 3 shows the response time and equilibration time of the first stage alone for the shallow and deep barrier cases. Even when only the first stage is considered, it is obvious that the system is inherently transient and does not reach steady state in any practical period of time. Moreover, the response time is lengthened considerably as the depth to barrier is increased. During the early stages, the drainage water concentration consists primarily of resident ground water that was removed by the tile lines.

Figure 4 shows the drain concentrations from all four stages of a system overlying a shallow barrier, using parameters from the Red Rock ranch in Table 1. Several features are noteworthy. First, each successive field requires longer to reach steady state than the previous one. Second, steady state concentrations (shown as dashed lines in the figure) can be exceeded during the transient stage, because the high concentration of the resident ground water can magnify as it passes through the system. Figure 5 is identical to Figure 4, except that the barrier now resides at great depth (*h=S/D=1*). The behavior of the field is qualitatively the same as the field with a shallow barrier, except the time scale for transition to the steady state is now expanded considerably because of the significantly greater volume of resident water that must be leached.

An approximate index of the response time of a field with a given geometry and flow rate may be estimated from Figure 2. Table 2 gives the time in years for 25%, 50%, and 75% of the solute added at t=0 to reach the drain for all of the cases studied. Median response times vary from a low of 2.1 years for the shallow system leached at 0.50 m/y to a high of 31.2 years for the deep barrier system leached at 0.225 m/y. The systems are also very asymmetric, requiring much longer to leach the remaining percentages of the field than early ones. What this implies is that during the first few years after initiation of the sequential reuse strategy, drain concentrations for systems with a large spacing between drains will consist mainly of water extracted from the ground water at or near the ground water concentration (Figure 5). Thus, the predominant early function of a sequential reuse operation would be ground water reclamation. This prediction is in qualitative agreement with the findings of Deverel and Fio (1991), who determined from oxygen 18 measurements that up to 60% of the water extracted by a drain tile in the San Joaquin Valley was from deep resident ground water. These authors also simulated water flow for the system they measured and calculated travel times of up to 34 years for arrival at the drain (Fio and Deveral, 1991).

The extremely long transition times to steady state for the tile geometries studied indicates that any management design for sequential reuse based on steady-state criteria will be flawed. For example, if crops are selected for the fields in succession based on their ability to tolerate the steady-state salinity coming from the previous drain, the irrigation water may have to be diluted for a substantial period of time to avoid damaging the crop. This transient effect persists for many years and must be part of any management design. The problems associated with a steady-state analysis are illustrated in Figure 6, which shows the percent dilution of the drainage water from stage 1 required to maintain the irrigation water to stage 2 at 5 dS/m or less (suitable for growing cotton at zero yield depression), using the Red Rock ranch parameters in Table 1. Since the steady state concentration coming from stage 1 is 4.2 dS/m, the steady-state design calls for zero dilution, whereas there is substantial dilution required for 20 years in the shallow barrier case, and indefinitely in the deep barrier case.

CONSLUDING REMARKS

Our analysis demonstrates the dominant effect of transient solute movement on the performance of a sequential reuse operation. For drain tile geometries of the type found in the San Joaquin Valley, steady state will never be reached, and initially saline ground water will significantly affect the concentration of irrigation water for stages beyond the first for the entire practical lifetime of the project. Because this resident ground water becomes concentrated after passage through a root zone, substantial dilution may be required to reduce the drainage water to levels suitable for irrigation of all but the most salt-tolerant of species.

The conceptual model used in this analysis was intended primarily to demonstrate the dominant effects of travel time on performance of a sequential reuse operation. A number of potentially important factors such as soil layering, ground water movement, or deep seepage unimpeded by a barrier were neglected in this study and will be examined by numerical methods in the coming year.

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William A. Jury*, Atac Tuli, and John Letey, Effect of Travel Time on Management of a Sequential Reuse Drainage Operation. Soil Sci. Soc. Amer. J. (in review).

Table 1. Tile drain and management parameters estimated for the Red Rock Ranch sequential reuse demonstration facility. (Cervinka et al. 1999)

Parameter	Symbol	Value	Units
Irrigation water concentration	*Cirr*	0.6	dS/m
Ground water concentration	C_s	12	dS/m
Tile drain half spacing	*S*	60	m
Depth to tile	*H*	2.4	m
Drainage rate (stage 1)	R_1	22	cm/y
Leaching fraction (stage 1)	x_1	0.14	-
Drainage rate (beyond stage 1)	R_2	50	cm/y
Leaching fraction (beyond stage 1)	x_2	0.33	-

Table 2. Time in years for *P(t)*=0.25,0.50, and 0.75 of the water added at the surface to arrive at the drain for a system with *S*=100m, q_s= 0.45, and *R*=0.22 or 0.5 m/yr.

P(t)	R (m/y)	*h* = 1.0	*h* =2.0	*h* =5.0	*h* =10.0	*h* =20.0
0.25	0.22	7.1	6.9	5.4	3.6	2.2
0.50	0.22	31.2	28.1	15.9	8.7	4.7
0.75	0.22	110.6	83.1	35.1	17.7	9.1
0.25	0.50	3.1	3.0	2.4	1.6	1.0
0.50	0.50	13.7	12.4	7.0	3.8	2.1
0.75	0.50	48.7	36.6	15.4	7.8	4.0

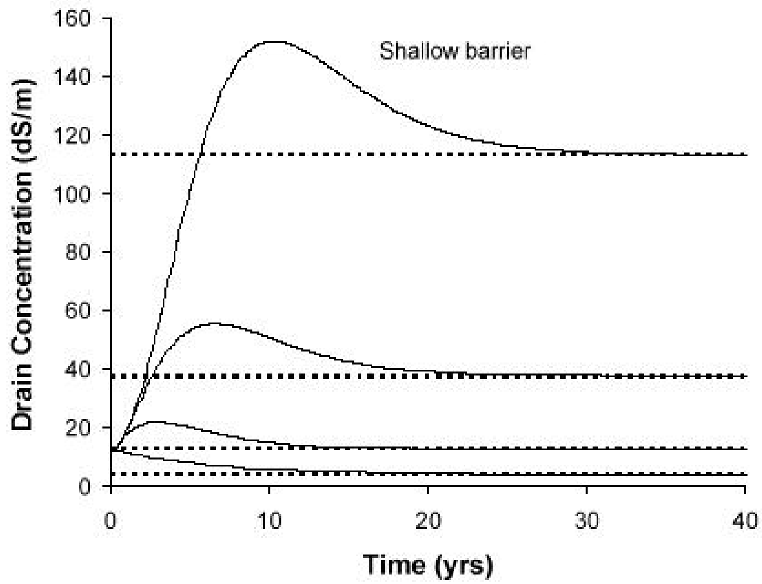

Figure 1. Water flow streamlines through the saturated zone of a tile line with η=S/D=1.

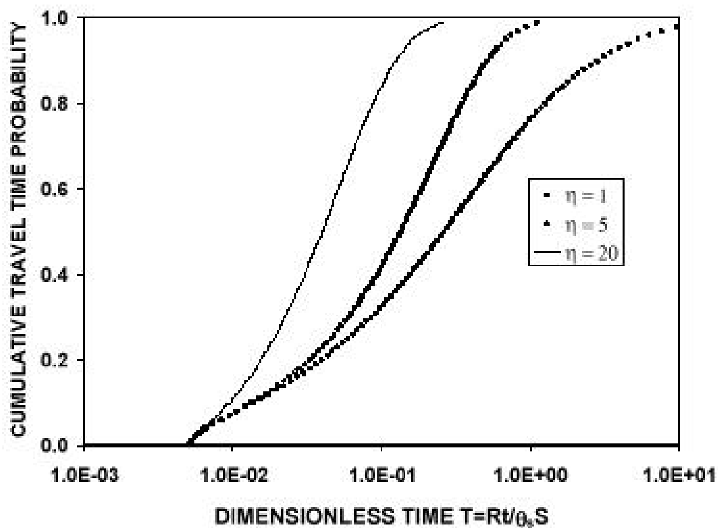

Figure 2. Dimensionless cumulative travel time probability density functions calculated for various ratios η = S/D.

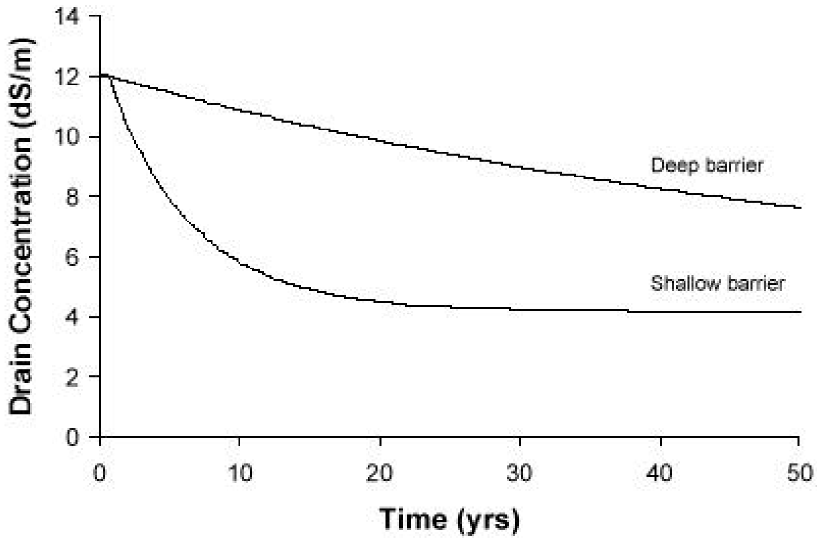

Figure 3. Response time and equilibration time of the first stage for the shallow and deep barrier cases.

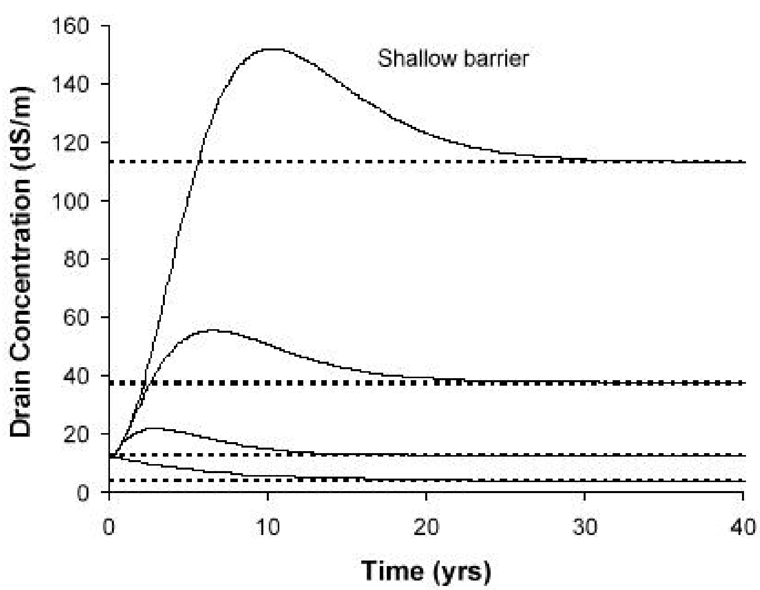

Figure 4. Drain concentrations from all four stages of a system overlying a shallow barrier, using parameters from the Red Rock ranch in Table 1. Dashed lines represent steady-state concentrations.

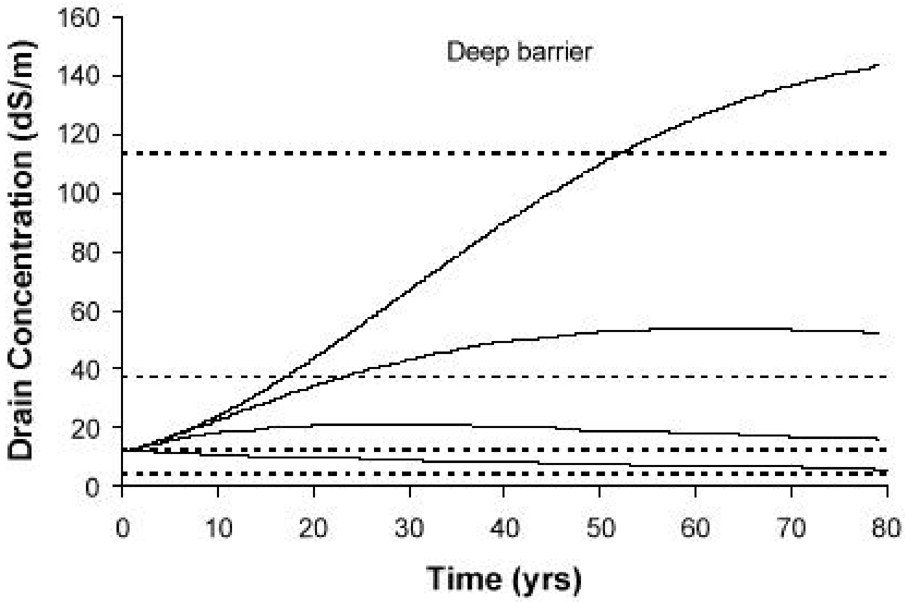

Figure 5. Drain concentrations from all four stages of a system overlying a deep barrier, using parameters from the Red Rock ranch in Table 1. Dashed lines represent steady-state concentrations.

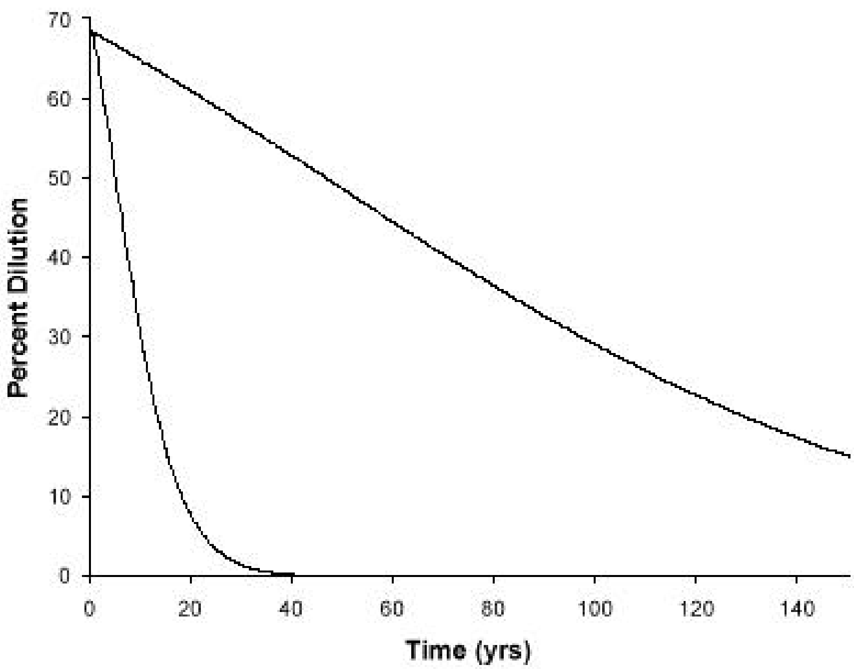

Figure 6. Percent dilution required to maintain the irrigation water of stage 2 at 5 dS/m or less, using parameters from the Red Rock ranch in Table 1. The predicted dilution using the steady-state model is zero.