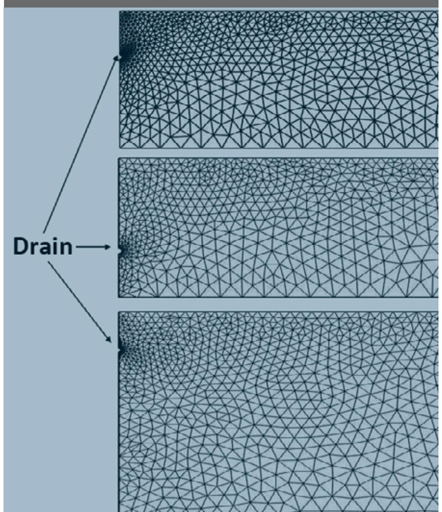
Original Research

A.A. Siyal*
T.H. Skaggs
M.Th. van Genuchten

Reclamation of Saline Soils by Partial Ponding: Simulations for Different Soils

A traditional method of reclaiming salt-affected soils involves ponding water on a field and leaching salts from the soil through a subsurface tile drainage system. Because water and salts move more slowly in areas midway between drain lines than in areas near the drains, achieving a desired level of desalinization across the entire field requires that ponding continue long after areas close to the drains are already free of salts, thus causing an inefficient leaching process that wastes water. A partial ponding method of leaching was recently suggested to improve the leaching efficiency by up to 85%. In this study, we tested the partial ponding method for its potential to save water and time by simulating the leaching of salts from salt-affected profiles with various soil textures, tile-drain depths, and soil depths. Simulations for laboratory sand tanks and field conditions both showed that transport velocities midway between drains are greater under partial ponding than under total ponding because the local hydraulic head gradient is larger under partial ponding conditions. As the ponded area increases toward the drain, water originating from areas near the drain moves faster than water from midway between the drains. By adopting partial ponding, water and time savings of 95 and 91%, respectively, were found possible for a sandy soil. The method also showed water savings of 84% when applied to a loam soil and 99% for a layered sand over loam soil but only 13% when applied to a layered loam over sand soil.



Complete surface ponding of tile-drained fields is an inefficient method of leaching salts because of large differences in infiltration that exist across the field. Simulations with HYDRUS-2D/3D were used to investigate an alternative, water-conserving, partial ponding, leaching strategy for various soil textures and profiles.

A.A. Siyal, Dep. of Land and Water Management, Sindh Agriculture Univ., Tandojam, Pakistan; T.H. Skaggs, U.S Salinity Lab., 450 W. Big Springs Rd., Riverside, CA 92507; and M.Th. van Genuchten, Dep. of Mechanical Engineering, COPPE/LTTC, Federal Univ. of Rio de Janeiro, Rio de Janeiro, RJ 21945-970, Brazil. *Corresponding author (siyal@yahoo.com).

Vadose Zone J. 9:486–495
doi:10.2136/vzj2009.0129
Received 19 Sept. 2009.
Published online 3 May 2010.

Problems of soil salinization and sodification are increasing in many irrigated arid and semiarid regions where rainfall is insufficient to leach out salts from the vadose zone. An estimated 45 million ha out of a total 230 million ha (19.5%) of irrigated land worldwide, and 32 million out of 1500 million ha (2.1%) of dry land, are salt affected to varying degrees (Ghassemi et al., 1995). Some 0.25 to 0.5 million ha of land around the world are lost from production every year as a result of soil salinization (FAO, 2002).

Salinity problems in Pakistan mirror these global trends. Irrigated agriculture in Pakistan is mainly confined to the Indus plains. About 33 million Mg of salt per year is moved into these plains by the Indus River and its tributaries. Of this total, about 24 million Mg is retained in the Indus basin each year, with 13 million Mg staying in the Punjab province and 10 million Mg in the Sindh province (Mughal, 2002). These provinces are experiencing severe irrigation-induced salinity problems. Approximately 6.3 million ha of land are affected by salinity (Alam et al., 2000), 3.45 million ha due to irrigation (Pakistan Ministry of Food, Agriculture and Livestock, 2005). Productive land in Pakistan is being damaged by salinity at a rate of about 40,000 ha yr^{-1} (Alam et al., 2000). This suggests that fertile land is being converted into unproductive, salt-affected soils at a rate of about 110 ha d^{-1}. Soil salinity may be depriving Pakistan of about 25% of its potential production of major crops (World Bank, 1992)

A common practice in Pakistan and elsewhere is to leach salts from affected soils. Small ridges (called bunds) are constructed around an entire field, good-quality water is ponded on the soil surface, and the salts are leached from the root zone to deep groundwater or to nearby surface waters, either directly or via tile drains. Because of more rapid infiltration and shorter travel distances, areas above the drains in tile-drained systems are leached far more quickly using this method than areas midway between the drains (Youngs and Leeds-Harrison, 2000). Thus, to achieve a desired level of desalinization across an entire field, ponding needs to continue long after areas close to the drains are already free of salts. This process wastes large amounts of good-quality water that could be used for irrigation or other purposes.

Calculations by Youngs and Leeds-Harrison (2000), using an analytical solution for seepage to a tile drain, revealed that more uniform and efficient leaching can be achieved by dividing the salt-affected field into strips separated by bunds, and then flooding the field incrementally, starting from strips located midway between the drains and progressing toward strips located over the drains. Termed *partial ponding*, this method progressively increases the area of the field under ponding. For the conditions studied, Youngs and Leeds-Harrison (2000) found that the partial ponding method required as much as 84% less water to leach a soil than uniform ponding and 76% less time. While their theoretical analysis was for coarse-textured soils, they suggested that the methodology should also be suitable for fine-textured soils. The partial ponding concept was recently tested by Mirjat et al. (2008) and Mirjat and Rose (2009) using laboratory sand tanks. Their results were relatively close to the theoretical predictions by Youngs and Leeds-Harrison (2000). The experiments by Mirjat and Rose (2009) and Mirjat et al. (2008), however, were limited to uniform sand. A need exists to test the partial ponding concept for fine-textured and layered soil profiles. Computer models such as HYDRUS-2D/3D (Šimůnek et al., 2006) that simulate water and solute transport in two-dimensional, variably saturated media would be appropriate tools for such an analysis.

The objective of this study was to use variably saturated flow modeling to evaluate the partial ponding leaching technique (Youngs and Leeds-Harrison, 2000; Mirjat and Rose, 2009). We used HYDRUS-2D/3D to evaluate the leaching of salts from sand tanks as studied by Mirjat et al. (2008), as well as to perform several leaching simulations for field conditions. The simulations considered full and partial ponding, initially saturated and unsaturated conditions, and various drain and soil depths, soil textures, and soil layering.

Numerical Simulations

Governing Flow and Transport Equations

Simulations of the partial leaching problem using HYDRUS-2D/3D were based on the standard Richards equation for flow and the equilibrium advection–dispersion equation for solute transport in a two-dimensional, variably saturated medium. For a two-dimensional isotropic medium, the Richards equation is given by

$$\frac{\partial\theta(h)}{\partial t}=\frac{\partial}{\partial x_i}\left[\mathbf{K}_{ij}(h)\frac{\partial h}{\partial x_j}-\mathbf{K}_{i2}(h)\right] \quad [1]$$

where θ is the volumetric water content [L^3 L^{-3}], h is the soil water pressure head [L], t is time [T], x_i (i = 1,2) are spatial coordinates [L] with $x = x_1$ and $z = x_2$ in this study representing the horizontal and vertical (positive downward) coordinates, respectively, and $\mathbf{K}_{ij}(h)$ is the soil hydraulic conductivity tensor [L T^{-1}]. For an isotropic medium, the off-diagonal entries of $\mathbf{K}_{ij}$ are zero, while the main diagonal entries ($\mathbf{K}_{11}$ and $\mathbf{K}_{22}$) are equal to the unsaturated hydraulic conductivity, $K(h)$. For the soil hydraulic properties $\theta(h)$ and $K(h)$, we used the equations of van Genuchten (1980):

$$\theta(h)=\theta_r+\frac{\theta_s-\theta_r}{\left[1+|\alpha_{vg}h|^{n_{vg}}\right]^m} \qquad \left(m=1-1/n_{vg}\right) \quad [2]$$

$$K(h)=K_s\sqrt{S_e}\left[1-\left(1-S_e^{1/m}\right)^m\right]^2 \quad [3]$$

where θ_r and θ_s are the residual and saturated water contents, respectively [L^3 L^{-3}], α_{vg} [L^{-1}] and n_{vg} (dimensionless) are empirical shape parameters, K_s is the saturated hydraulic conductivity [L T^{-1}], and S_e is the effective saturation:

$$S_e(h)=\frac{\theta(h)-\theta_r}{\theta_s-\theta_r} \quad [4]$$

Assuming no sorption or decay reactions, the standard advection–dispersion equation for solute transport is given by

$$\frac{\partial(\theta C)}{\partial t}=\frac{\partial}{\partial x_i}\left(\theta\mathbf{D}_{ij}\frac{\partial C}{\partial x_j}-\mathbf{q}_i C\right) \quad [5]$$

where C is the solution concentration [M L^{-3}]; $\mathbf{D}_{ij}$ is the dispersion coefficient tensor [L^2 T^{-1}], described here using standard expressions (e.g., Bear, 1972) involving the longitudinal (ε_L) and transverse (ε_T) dispersivities [L] but without the contribution of diffusion in the liquid phase; and $\mathbf{q}_i$ is the volumetric fluid flux density vector [L T^{-1}] given by the Darcy–Buckingham law.

Flow Domain

To enable comparisons with the partial ponding experiments of Mirjat and Rose (2009), the first set of simulations used the flow-domain geometry used in their laboratory sand tank studies, i.e., a rectangular cross-sectional (x,z) domain 100 cm wide and 15 cm high. This geometry is 1/40th of the size of the tile drainage system considered by Youngs and Leeds-Harrison (2000) in their theoretical analysis. Because of symmetry, only one side of the drain was simulated. Figure 1 shows example flow domains and finite-element meshes with 0.5-cm-diameter drains located at depths of 5 and 10 cm, thus mimicking the experimental setups of Mirjat and Rose (2009). Similar flow domains and discretizations were used for the different leaching scenarios considered in this study. Additional simulations were done using field-scale dimensions: a drain spacing of 40 m, drain depth at 2 m, and an impermeable layer at 6 m. The various scenarios are summarized in Table 1. Most of the cases considered involved uniform soil profiles. We also studied two layered profiles (sand over loam and loam over sand), with the boundary between the layers located at the depth of the drain.

The flow domain for all simulations was initially (at $t = 0$) assumed to be uniformly saturated ($h = 0$), with a relative salinity of 1.0.

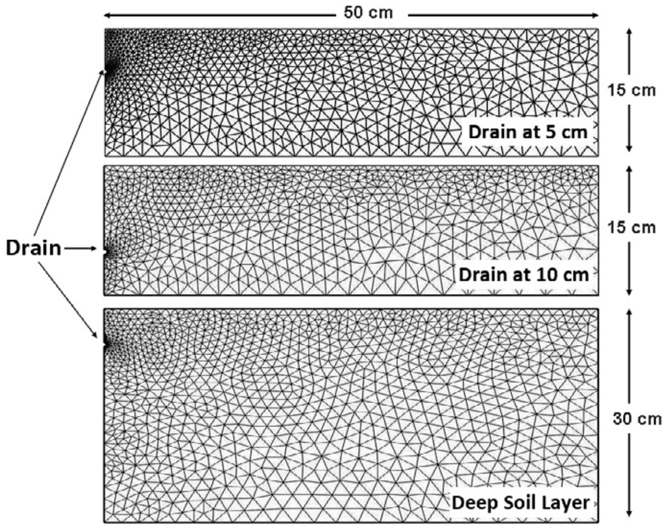


Fig. 1. Typical geometries and finite element meshes for the flow domains used in the HYDRUS-2D/3D salt leaching simulations.

Table 1. Simulated salt leaching scenarios.

Case	Soil depth	Drain depth	Soil type	Ponding method
	——— cm ———			
C_0	15	5	sand	complete
P_0	15	5	sand	partial
C_1	15	10	sand	complete
P_1	15	10	sand	partial
C_2	30	5	sand	complete
P_2	30	5	sand	partial
C_3	15	5	loam	complete
P_3	15	5	loam	partial
C_4	15	5	sand over loam	complete
P_4	15	5	sand over loam	partial
C_5	15	5	loam over sand	complete
P_5	15	5	loam over sand	partial
C_6	600	200	sand	complete
P_6	600	200	sand	partial

For the sand tank simulations, a constant pressure head of 0.5 cm (i.e., 0.5 cm of water ponding) was imposed on all or part of the soil surface boundary, depending on the invoked leaching scenario, and zero flux on the remainder. For the field-scale simulations, the ponding depth was 20 cm. A third type (Cauchy type) boundary condition was used to prescribe the concentration flux along the ponded surface, with the incoming water being salt free ($C = 0$). The bottom, right, and left boundaries were assumed to be zero-flux boundaries for both water and salt. The drain boundary was specified as a seepage face for water flow and as a zero concentration gradient for solute transport.

Soil Hydraulic and Solute Transport Parameters

For the sand tank simulations, we assumed hydraulic properties similar to those of the Mirjat et al. (2008) experiments. The hydraulic parameters in Eq. [2] and [3] were estimated with the Rosetta pedotransfer functions (Schaap et al., 2001) using as input soil texture (sand) and bulk density (1.63 g cm^{-3}) as reported by Mirjat et al. (2008) to obtain the following estimates: $\theta_r = 0.05$, $\theta_s = 0.34$, $K_s = 0.89$ cm min^{-1}, $\alpha_{vg} = 0.031$ cm^{-1}, and $n_{vg} = 4.43$. The values for θ_s and K_s estimated in this way compared favorably with the porosity (0.37) and saturated conductivity (0.84 cm min^{-1}) values estimated by Mirjat et al. (2008) (they did not estimate unsaturated hydraulic parameter values). For simulations on the loam soil, we used soil textural class averages as estimated by Carsel and Parrish (1988): $\theta_r = 0.078$, $\theta_s = 0.43$, $K_s = 0.017$ cm min^{-1}, $\alpha_{vg} = 0.036$ cm^{-1}, and $n_{vg} = 1.56$.

For the solute transport simulations, we assumed that for the simulated flow velocities and transport times, molecular diffusion was negligible relative to hydrodynamic dispersion (Skaggs and Leij, 2002). The longitudinal dispersivity was set equal to one-tenth of the depth of the flow domain (i.e., $\varepsilon_L = 1.5$ or 3.0 cm), which is consistent with various studies indicating that ε_L is about one-tenth the scale of a transport experiment (Beven et al., 1993; Cote et al., 2003). The transversal dispersivity (ε_T) was assumed to be one-tenth of the longitudinal dispersivity (e.g., Hanson et al., 2006). Solute sorption or decay were not considered.

Leaching Time Required with Complete Ponding

With complete ponding, hydraulic head gradients along the surface are much greater in the vicinity of the drain than elsewhere, such that most of the drain flow originates from the area above the drain (Kirkham, 1949). Consequently, the area above the drain leaches much more quickly than the area midway between drains. Let n be the fraction of the total drain flow that originates from a narrow section of the field that is midway between drain lines, has a width of Δs, and is parallel to the drain line. Then, assuming piston flow, the depth of leaching below the section during time t will be $z = nQt/f\Delta s$, where f is the saturated water content of the soil and Q is the drainage flux [L^2 T^{-1}]. If Z is the targeted depth of leaching, then the time T required for desalinization is

$$T = \frac{f \Delta s Z}{nQ} \qquad [6]$$

The parameters n and Q can be computed with HYDRUS for a given Δs and ponding depth. Note that in the case of complete ponding, the target depth of leaching refers to the area midway between drains.

Leaching Times Required with Partial Ponding

The partial leaching approach by Youngs and Leeds-Harrison (2000) is based on the premise that more efficient and uniform leaching can be achieved by dividing the soil surface into strips separated by bunds, and progressively increasing the flooded area from strips midway between the drains toward the drains until the whole area is flooded. Implementing this approach requires estimates of the leaching times for each stage such that at the end of the final stage the cumulative leaching in each strip will equal the desired target depth, Z. Youngs and Leeds-Harrison (2000) and Mirjat and Rose (2009) provided a procedure for calculating the required flooding times, which we summarize here. For more detail, see Youngs and Leeds-Harrison (2000) and Mirjat and Rose (2009).

Assume that the drains are separated by a distance $2D$ and that the area between the drains is divided into $2N$ strips, such that the strips have a width D/N. According to the strategy of Youngs and Leeds-Harrison (2000), the first strip midway between the drains is flooded for a time period t_1, after which the bund between the first and second strip is broken to allow flooding of the second strip. Strips 1 and 2 are kept ponded for a time period t_2, after which the third strip is included and the three strips are flooded together for a time period t_3. The fourth strip is incorporated next, with the process continuing until all N strips are included and the whole area is flooded.

The times t_i needed to obtain uniform removal of salt to a target depth Z across the whole area can be estimated from the system of equations (Youngs and Leeds-Harrison, 2000)

$$Z = \frac{\sum_{i=j}^{N} n_{i,j} Q_i t_i}{(D/N) f} \quad (j = 1, \ldots, N) \qquad [7]$$

where Q_i is the drain flow when Strips 1 through i are flooded, and $n_{i,j}$ is the fraction of Q_i originating from Strip j. For $N = 2$ (two strips of width D/N), partial ponding involves two strips in which the center strip is leached first for time t_1, with $n_{1,1} = 1$ at rate Q_1. The bund between Strips 1 and 2 is then broken and the two strips are leached together for time period t_2, with the flux in the center Strip 1 being $n_{2,1}Q_2$ and the flux in Strip 2 closer to the drain being $n_{2,2}Q_2$. Figure 2 shows schematically the partitioning of the flow for the case of $N = 4$, which is the number of strips used in our study. Using HYDRUS-2D/3D, values of Q_i and $n_{i,j}$ were calculated numerically. Results are shown in Tables 2 and 3, respectively.

The ponding times are found by solving Eq. [7] for the values of t_i. For four strips, these times are

$$t_4 = T \frac{n_{4,1}}{n_{4,4}} \qquad [8]$$

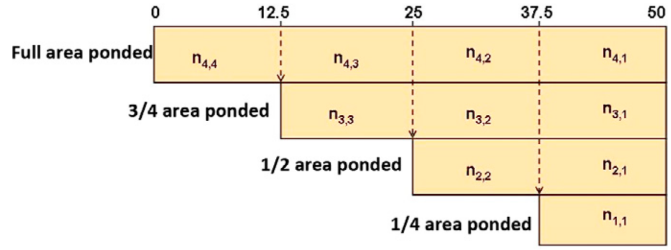


Fig. 2. Illustration of the partitioning of the total drain flow under partial ponding with four strips. Strip 1 is midway between the drains ($x = 50$), while Strip 4 starts at the drain ($x = 0$); Q_i is the drain flow when Strips 1 through i are ponded and $n_{i,j}$ is the fraction of Q_i originating from the jth strip.

$$t_3 = \frac{T Q_4 n_{4,1} (n_{4,4} - n_{4,3})}{Q_3 n_{3,3} n_{4,4}} \qquad [9]$$

$$t_2 = \frac{T Q_4 n_{4,1} \left[n_{3,3} (n_{4,4} - n_{4,2}) + n_{3,2} (n_{4,3} - n_{4,4}) \right]}{Q_2 n_{2,2} n_{3,3} n_{4,4}} \qquad [10]$$

$$t_1 = \frac{T Q_4 n_{4,1} \left[n_{3,3} (n_{2,1} n_{4,2} - n_{2,2} n_{4,1} + n_{2,2} n_{4,4}) - n_{4,4} (n_{2,2} n_{3,1} - n_{2,1} n_{3,2} + n_{2,1} n_{3,3}) + n_{4,3} (n_{2,2} n_{3,1} - n_{2,1} n_{3,2}) \right]}{Q_1 n_{1,1} n_{2,2} n_{3,3} n_{4,4}} \qquad [11]$$

where $T \equiv DfZ/n_{4,1}Q_4$.

Table 2. Drain flux densities for partial and complete ponding scenarios.

Soil texture	Cases	Flux density				Increase in flux†
		1/4 area ponded	1/2 area ponded	3/4 area ponded	Complete ponding	
		cm^2 min^{-1}				
Sand	C_0 and P_0	1.340	1.720	2.420	4.100	3.06
Sand	C_1 and P_1	2.534	3.266	4.605	6.180	2.44
Sand	C_2 and P_2	1.640	2.031	2.711	4.251	2.59
Loam	C_3 and P_3	0.025	0.033	0.048	0.080	3.20
Sand over loam	C_4 and P_4	0.581	0.883	1.451	3.100	5.33
Loam over sand	C_5 and P_5	0.165	0.245	0.295	0.331	2.00

† Comparison between 1/4 and complete ponding (times).

Table 3. Fractions of the total drain flow originating from different strips under partial and complete ponding, where $n_{i,j}$ is the fraction of the drain flow when Strips 1 through i are ponded that originated from the jth strip.

Soil texture	Case	1/4 area ponded, $n_{1,1}$	1/2 area ponded		3/4 area ponded			Complete ponding			
			$n_{2,1}$	$n_{2,2}$	$n_{3,1}$	$n_{3,2}$	$n_{3,3}$	$n_{4,1}$	$n_{4,2}$	$n_{4,3}$	$n_{4,4}$
Sand	P_0	1.0	0.19	0.81	0.06	0.12	0.84	0.01	0.03	0.14	0.82
Sand	P_1	1.0	0.15	0.85	0.05	0.13	0.82	0.02	0.06	0.22	0.70
Sand	P_2	1.0	0.24	0.76	0.11	0.18	0.71	0.04	0.05	0.13	0.78
Loam	P_3	1.0	0.19	0.81	0.04	0.12	0.84	0.03	0.05	0.13	0.79
Sand over loam	P_4	1.0	0.03	0.97	0.001	0.03	0.969	0.00	0.002	0.047	0.95
Loam over sand	P_5	1.0	0.46	0.54	0.28	0.31	0.41	0.19	0.20	0.25	0.36

Leaching Simulations

To simulate partial ponding in the sand tanks, the soil surface was divided into four equal strips of 12.5 cm each. At the beginning of the simulation, the central strip midway between the drain lines (37.5–50 cm) was ponded for a period of time t_1, after which the ponded area was increased to 25 to 50 cm for a time period t_2. The flooded area was next increased to 12.5 to 50 cm and then to 0 to 50 cm, with leaching proceeding for times t_3 and t_4, respectively. The calculated pressure head and salinity distributions obtained with HYDRUS-2D/3D at t_1 for the 1/4 area ponding scenario were used as initial conditions for the 1/2 area ponded calculations. Similar distributions obtained at t_2 for the 1/2 area ponding case were used as the initial conditions for the 3/4 area ponding, and so on. The procedure for the field-scale simulations was the same except that the dimensions were 40 times larger, including the ponding depth (20 cm).

For the complete ponding simulations, the entire surface of the flow domain was ponded at a constant pressure head (0.5 cm in the sand tank simulations and 20 cm in the field-scale simulations). The HYDRUS code was executed for the leaching times given by Eq. [6] to reach the targeted leaching depth Z, with $Z = 2$ cm and $\Delta s = 12.5$ cm for the sand tank simulations and $Z = 80$ cm and $\Delta s = 500$ cm for the field-scale simulations.

Results and Discussion

Flow Paths

Figure 3 shows flow paths computed for partial and complete ponding in sand tanks with drains installed at depths of 5 or 10 cm. The flow paths in these figures were created with the HYDRUS 2D/3D particle tracking option. Shown are flow paths traced by individual particles released simultaneously at equally spaced points along the surface. The figures show the particle paths after a fixed time period ($t = 400$ min) such that particles along faster or shorter paths had already reached the drain at that time, while others had not. The results indicate that particles originating from the strip between 37.5 and 50 cm moved faster and covered more distance with only one-fourth of the area ponded (Cases P_0 and P_1) compared with the other partial and complete ponding scenarios. Similarly, flow along paths from the 1/2 area ponded scenario moved faster than flow from the same area during 3/4 and complete ponding. This shows that increasing the ponded area substantially reduces flow velocities along streamlines from the strip already ponded midway between drains. The reason is that expanding the ponded area toward the drains reduces the local hydraulic head gradient in the previously ponded areas. Thus as the area increases, water originating from the strip near the drain moves faster than water coming from midway between the drains. As flooding progresses, the greatest leaching occurs under the newly opened bunds, while leaching under the earlier bunds decreases significantly. The results are similar for both drain depths considered and are consistent with the theoretical studies of Youngs and Leeds-Harrison (2000) and the sand tank experiments by Mirjat et al. (2008) and Mirjat and Rose (2009).

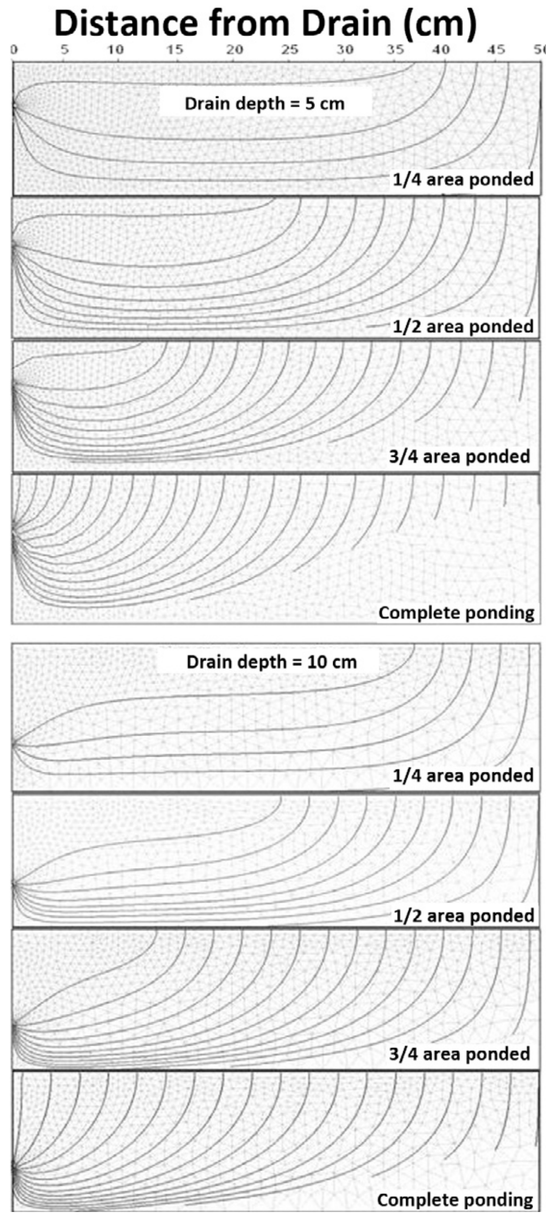


Fig. 3. Flow paths for drains installed at 5- (Cases C_0 and P_0) and 10-cm depths (Cases C_1 and P_1) in a sand soil subject to partial surface ponding scenarios.

Figure 4 shows flow paths under complete ponding after the same period of time ($t = 2000$ min) for a uniform sand, a uniform loam, and the layered systems (sand over loam and loam over sand) with the drain installed at the 5-cm depth (Cases C_0, C_3, C_4, and C_5, respectively). The figure shows that in sand (Case C_0), particles from the 0- to 37.5-cm area had already arrived at the drain, whereas those originating from 37.5 to 50 cm were still only halfway or less. For the loam (C_3) and the sand over loam (C_4), flow paths from only the 0- to 12.5-cm area had reached the drain. By contrast, particles from the 12.5- to 37.5-cm area had traveled only very short distances,

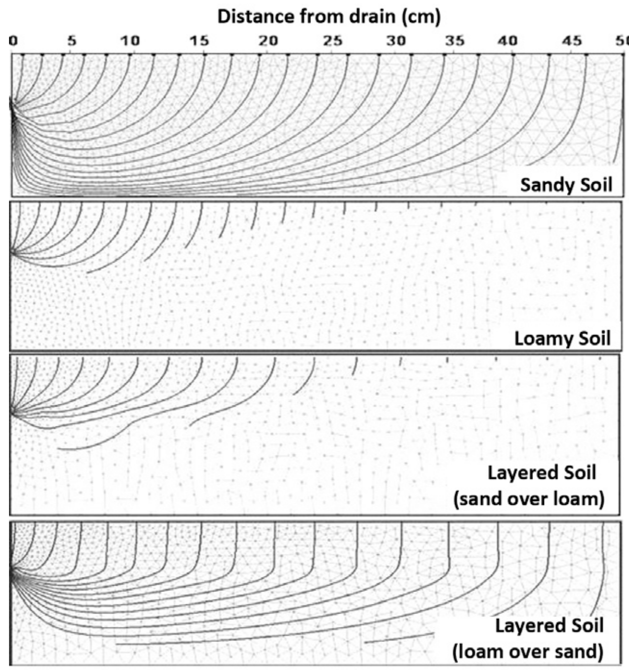


Fig. 4. Flow paths for drain installed at the 5-cm depth for different soil textures (Cases C_0, C_3, C_4, and C_5) subject to complete surface ponding.

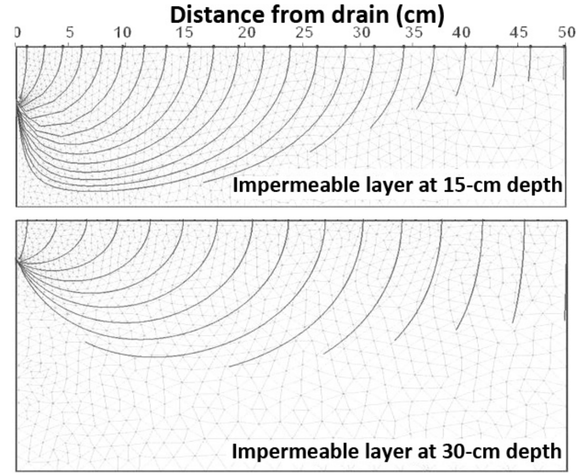


Fig. 5. Flow paths for tanks with an impermeable soil layer at 15- or 30-cm depth and a drain installed at the 5-cm depth (Cases C_0 and C_2).

whereas those from 37.5 to 50 cm had barely entered the soil. The situation for the loam over sand (C_5) layered soil is not that different from the sand in that flow paths from the 0- to 37.5-cm area reached the drain while those from 37.5 to 50 cm were still only halfway. Notice that the particles in the loam over sand system initially moved mostly vertically downward through the loam until they reached the sandy soil, where they then started to move more horizontally toward the drain. In comparison, for the sand over loam profile (C_4), flow paths for particles closest to the drain developed a horizontal component more quickly and converged at the drain without penetrating the underlying loam soil.

Figure 5 shows flow paths for drains installed at 5 cm in sand with impermeable layers at 15 (Case C_0) and 30 cm (Case C_2). Having a deeper soil profile (C_2) resulted in particles traveling faster and penetrating deeper into the soil before converging at the drain. This suggests that salts in tile-drained systems will leach quicker in deeper soil profiles. These results again are consistent with theoretical calculations by Youngs and Leeds-Harrison (2000) for an infinitely deep soil profile (no impermeable layer).

Flow Velocity Vectors

Figure 6 shows relative flow velocity vectors under partial and complete ponding with drains at 5 and 10 cm. The same velocity scale factor was used for all plots, meaning that velocity vectors of similar size in different plots represent the same flow velocity. The plots indicate that under 1/4 area ponding, the flow velocities under the outer strip were greater for the drain at 10 cm (Case P_1) than 5 cm (Case P_0). Table 2 shows that the drain discharge was 1.34 cm^2 min^{-1} for P_0, compared with 2.53 cm^2 min^{-1} (1.89 times larger) for P_1. Moreover, most of the streamlines in P_0 converged from below the drain, whereas they reached the drain more from the top in P_1. Similar trends were obtained for the 1/2 and 3/4 area ponding scenarios. The velocity vectors for P_1 for complete ponding were relatively large up to about 25 cm laterally from the drain, but only up to about 12.5 cm for P_0. The drain discharge for P_0 and P_1 increased 3.1 and 2.4 times, respectively, when the ponded area was increased from 1/4 to complete ponding. These results are again consistent with the experimental results of Mirjat et al. (2008).

For complete ponding with the drain at 5 cm, 82% of the water entering the drain originated from the first quarter of the area next to the drain line ($n_{4,4}$), 14% from the next quarter of the area ($n_{4,3}$), 3% from the next area ($n_{4,2}$), and only 1% from the area midway between the drains ($n_{4,1}$). These values, shown in Table 3 for P_0, are essentially identical to those predicted by Youngs and Leeds-Harrison (2000) using their analytical solution (82, 13, 4, and 1%, respectively). The HYDRUS-simulated values were also close to the experimental results (75, 14, 7, and 5%, respectively) of Mirjat et al. (2008), except for the quarter midway between the drains. With the drain at 10 cm, the fractions of flow from the four strips were 70, 22, 6, and 2%, again very close to the experimental results of Mirjat et al. (2008). These numbers indicate that salts will be leached more uniformly from a coarse-textured profile under complete ponding when the drain is positioned deeper, all other conditions being the same.

As the depth below the drain increases, flow from the quarter closest to the drain decreases, while it increases for the central strip midway between the drains. The simulated results for the impermeable layer at 30-cm depth (C_2 in Table 3) show that 78% of the water reaching the drain originated from the first

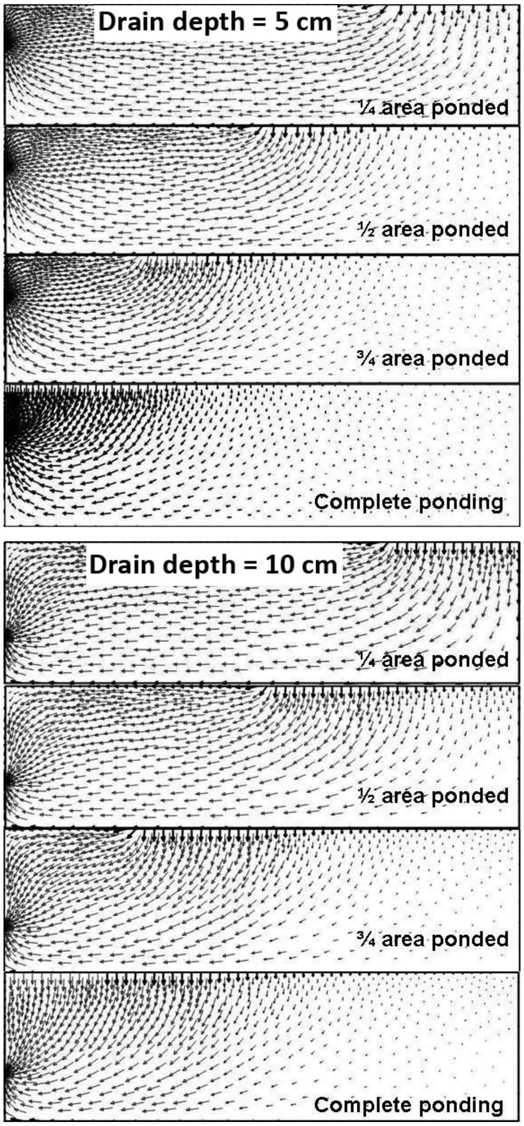


Fig. 6. Relative flow velocity in a sand soil with drains installed at 5 or 10 cm under various partial and complete ponding scenarios.

quarter of the area next to the drain line, while 13, 5, and 4% originated from the next three quarter sections. These results agree with those obtained by Youngs and Leeds-Harrison (2000) for an infinitely deep soil.

Figure 7 shows the effects of soil texture (sand vs. loam) and layering (sand over loam vs. loam over sand) on the flow velocity for complete ponding when the drain is again at 5 cm. For sand, the velocity vectors from the 0- to 25-cm area were much larger than those coming from the 25- to 50-cm area. The drain flow rate from the sand (4.10 $cm^2\ min^{-1}$) was much higher than that from the loam soil (0.080 $cm^2\ min^{-1}$). The loam had low flow velocities throughout the profile except very close to the drain. For complete ponding of the loam soil, 79% of the drain discharge came from the first quarter section near the drain, followed by 13, 5, and only 3% from the next three quarters (Table 3, Case P_3).

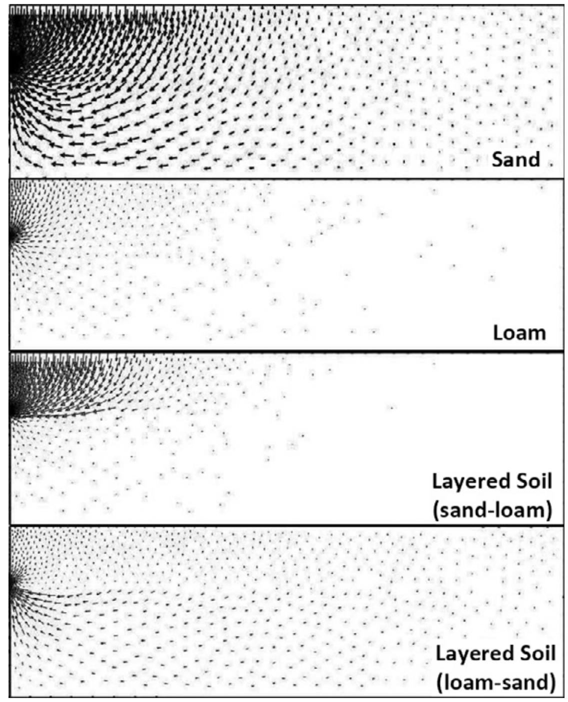


Fig. 7. Relative flow velocities in tanks having different soil textures, with drains at 5 cm and the soils subject to complete surface ponding.

Velocity vectors in the sand-over-loam layered soil were large only in the first quarter section (Fig. 7) and were very small in the remaining part of the soil profile. The drain discharge in this case was still relatively large (3.10 $cm^2\ min^{-1}$), but with nearly all of the water (95%) coming from the first quarter section near the drain (Table 3, Case P_4) and very little (only 0.001%) from the area midway between the drains. By comparison, the velocity vectors in the loam-over-sand layered soil were much more uniform, except in the sand just below the drain (Fig. 7). This case (P_5 in Table 3) exhibited the most uniform leaching pattern throughout the entire cross-section, with 36, 25, 20, and 19% originating from the four quarters, starting with the area near the drain.

Salt Leaching

Figures 8 and 9 show the relative salt concentrations remaining in the profile after leaching for the time period needed to leach salt to a target depth of 2 cm (recall that the target depth applies to the entire field with partial ponding and to the region midway between the drains with compete ponding). To uniformly leach the soil to 2 cm, 13.3% of the salt initially present needed to be leached from the sand and loam profiles (i.e., the salts initially present in the top 2 cm of the 15-cm-deep profile). The figure of 13.3% is a useful benchmark for assessing leaching for the different scenarios. As expected, leaching was not uniform for the complete ponding scenarios, with salts in areas next to the drains leached to much greater depths than those midway between the drains. At the time the targeted depth midway between drains was reached, salts in areas next to the drain were leached to depths that were

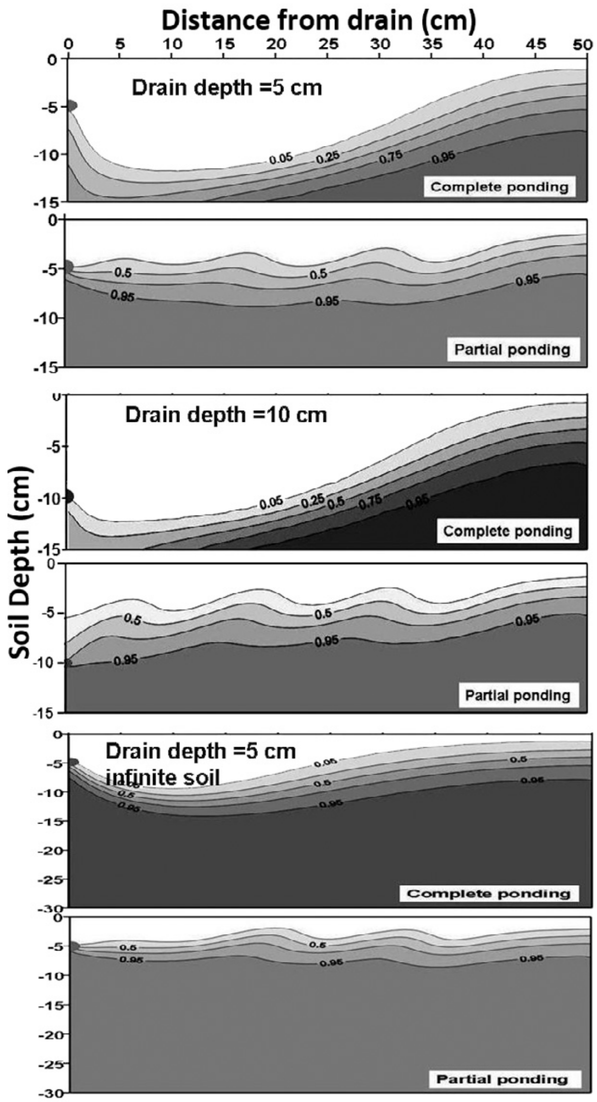


Fig. 8. Relative salt concentration profiles in sand tanks after leaching for pre-determined times for differing drain and soil profile depths. White areas correspond to completely leached soil.

5.7, 6.8, 4.0, 8, 10, and 3.1 times deeper than the targeted depth for cases C_0, C_1, C_2, C_3, C_4, and C_5, respectively. As a result, 44 to 67% of the initial salts had leached out of the tank during the optimum leaching time period. This extra leaching wasted much good-quality water. By comparison, far more uniform leaching was achieved with the partial ponding method, where only 27 to 33% of the initial salts had leached below the targeted depth of 2 cm.

Time and Water Savings with Partial Ponding

Figure 10 summarizes the potential for water and time savings with partial ponding. Desalinization of a 15-cm-deep, uniform sand with the drain at 5 cm using the partial ponding method required 95% less water and 91% less time than the complete ponding method. Desalinization of a 30-cm-deep sand resulted in water and time savings of 87 and 78%, respectively. These results are very close to those obtained by Youngs and Leeds-Harrison (2000) for their field

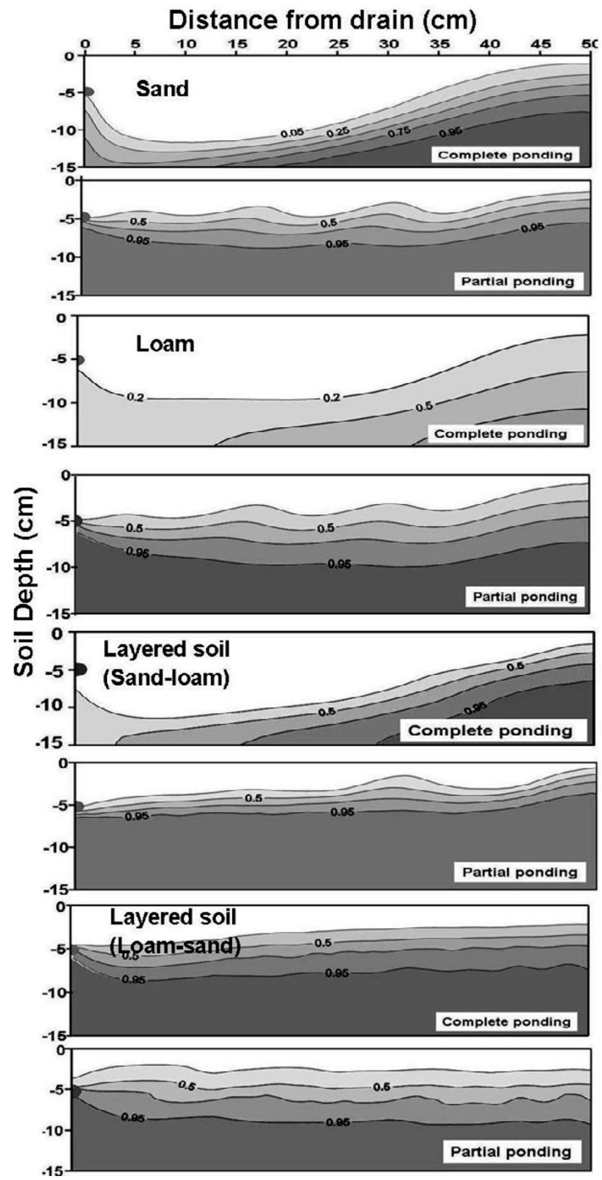


Fig. 9. Relative salt concentration profiles in tanks with different soil textures after leaching for a predetermined time with drains installed at 5 cm. White areas correspond to completely leached soil.

scenario, which had a spatial scale about 40 times larger (drain spacing of 40 m and drain depth at 2 m). They calculated 98 and 92% water and time savings, respectively, for uniform sand with an impermeable layer at 6 m, and 84 and 75% water and time savings for an infinitely deep soil profile. Even more water and time savings (up to 99%) were possible with partial ponding for the loam-over-sand case, but only 13% for the sand-over-loam layered profile.

Field and Laboratory Scales

Our calculations thus far used a scaled-down version of the field case considered by Youngs and Leeds-Harrison (2000) so that we could compare our results directly with the laboratory sand tank experimental data of Mirjat and Rose (2009). We did additional simulations for the larger scale, however, and found results that

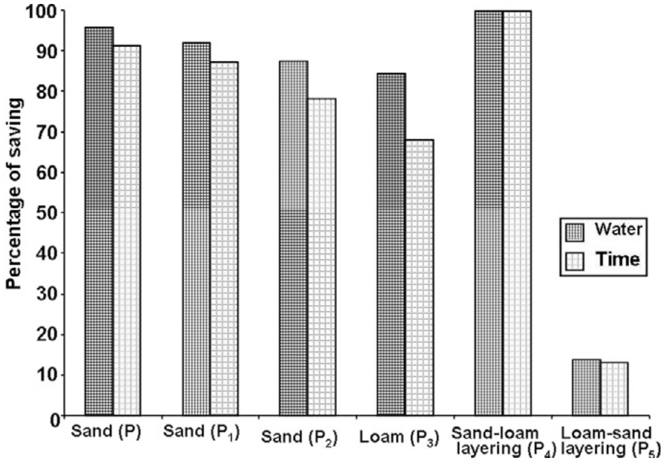


Fig. 10. Predicted water and time savings with partial ponding for different soil textures.

were essentially identical or very similar at the two scales. As an example, Fig. 11 shows the results for complete and partial ponding (C_6 and P_6) for both the field scale (sand soil texture, drain spacing of 40 m, drain depth at 2 m, impermeable layer at 6 m) and the laboratory scale (C_0 and P_0) of Mirjat and Rose (2009). The laboratory results are for 500 min of leaching and the field simulations for 20,000 min. The solute concentration profiles for the two scales in the figure are basically scaled versions of one another.

Several other simulations using partial ponding produced very similar results. These simulations included a case where, contrary to the experiments by Mirjat and Rose (2009), the soil was initially unsaturated. For that example, we assumed a hydrostatic pressure head profile in equilibrium with a water table at the depth of the drain (2 m). The initial water contents in the case of the sand ranged from 0.34 at and below the water table to a value of 0.07 at the soil surface. The results of the simulation showed initially a much more uniform leaching pattern, mostly because the initial infiltration rates were the same across the field. As the leaching process proceeded and drainage started, however, the partial ponding method again became more efficient, producing essentially the same results in terms of salts being leached to the targeted depth of leaching midway between the drains. When initially unsaturated, 67% of the initial salts were leached to the targeted depth with full ponding vs. 29% with partial ponding. This compares with values of 66 and 29% for full and partial ponding, respectively, when the soil was initially saturated. Simulated salinity profiles for this example were approximately the same as those shown in Fig. 11.

The work of Miller et al. (1965) suggested an interesting possibility for further increasing the efficiency of partial ponding under field conditions. In field experiments, Miller et al. (1965) found that the leaching efficiency was higher when intermittent ponding was used instead of continuous ponding. A probable reason for this finding is that with continuous ponding, part of the water will flow continuously through preferential flow paths, with limited contribution to salt leaching. With intermittent ponding, however, more time would be available for solutes to diffuse from relatively immobile water to the preferential flow paths, thus increasing concentrations in the main flow paths when ponding would restart. A leaching strategy that should be investigated in the future would be to implement the partial ponding using intermittent ponding at each stage of the leaching process rather than continuous ponding.

Conclusions

We used HYDRUS-2D/3D to analyze a partial ponding method of leaching (Youngs and Leeds-Harrison, 2000) that saves considerable amounts of water and time to leach salts from the surface horizons of tile-drained, salt-affected soils. The method was tested for its potential to save water by simulating the leaching of salts from a flow domain with various soil textures, tile-drain depths, and soil depths. The simulation results showed that streamlines originating from midway between the drains traveled faster under 1/4-area ponding than those from the same area under 1/2, 3/4, and complete ponding. The reason is that the hydraulic head gradient midway between drains is larger during partial ponding. When ponding was expanded to include the entire field, water from areas near the drain moved faster than water from midway between the drains. Compared with complete ponding, partial ponding of coarse-textured soils resulted in water and time savings of 95 and 91%, respectively. The method also led to water savings of 84% for a loam soil, and 99%

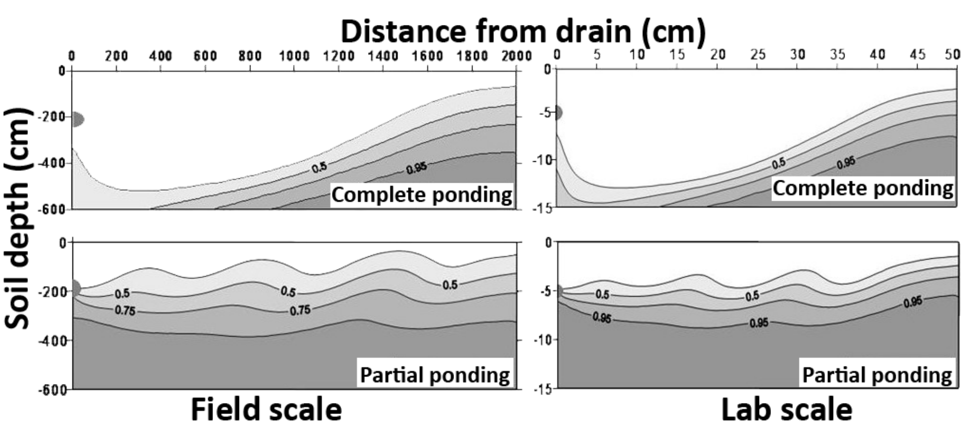


Fig. 11. Comparison of salt concentration profiles for the full field case (drain spacing of 40 m, drain depth at 2 m, impermeable layer at 6 m) and the scaled-down laboratory setup. Results are for complete (Cases C_0 and C_6) and partial (Cases P_0 and P_6) ponding. White areas correspond to completely leached soil.

for a sand-over-loam layered soil but only 13% for a loam-over-sand soil. Our numerical computations for flow in coarse-textured soils under partial ponding were in very good agreement with previous analytical results given by Youngs and Leeds-Harrison (2000). Our results indicate that partial ponding can be used to efficiently leach salts not only from coarse-textured soils but also from fine-textured and layered soils.

Acknowledgment

We acknowledge with gratitude Dr. Jirka Šimůnek, Univ. of California, Riverside, for valuable suggestions regarding the HYDRUS-2D/3D simulations.

References

Alam, S.M., R. Ansari, and K. Athar. 2000. Saline agriculture and Pakistan. Available at www.pakistaneconomist.com/issue2000/issue19&20/i&e3.htm (verified 1 Feb. 2010). Pakistan Economist, 8–21 May.

Bear, J. 1972. Dynamics of fluids in porous media. Elsevier, New York.

Beven, K.J., D.E. Henderson, and A.D. Reeves. 1993. Dispersion parameters for undisturbed partially saturated soil. J. Hydrol. 143:19–43.

Carsel, R.F., and R.S. Parrish. 1988. Developing joint probability distributions of soil water retention characteristics. Water Resour. Res. 24:755–769.

Cote, C., K. Bristow, P. Charlesworth, F. Cook, and J. Thorburn. 2003. Analysis of soil wetting and solute transport in subsurface trickle irrigation. Irrig. Sci. 22:143–156.

FAO. 2002. Crops and drops: Making the best use of water for agriculture. FAO, Rome.

Ghassemi, F., A.J. Jakeman, and H.A. Nix. 1995. Salinisation of land and water resources: Human causes, extent, management and case studies. CAB Int., Wallingford, UK.

Hanson, B.R., J. Šimůnek, and J.W. Hopmans. 2006. Evaluation of urea–ammonium-nitrate fertigation with drip irrigation using numerical modeling. Agric. Water Manage. 86:102–113.

Kirkham, D. 1949. Flow of ponded water into drain tubes in soil overlying an impervious layer. Trans. Am. Geophys. Union 30:369–385.

Miller, R.J., J.W. Biggar, and D.R. Nielsen. 1965. Chloride displacement in Panoche clay loam in relation to water movement and distribution. Water Resour. Res. 1:63–73.

Mirjat, M.S., and D.A. Rose. 2009. Streamline pattern and salt leaching through progressive flooding between subsurface drains. Irrig. Drain. 58:199–208.

Mirjat, M.S., D.A. Rose, and M.A. Adey. 2008. Desalinisation by zone leaching: Laboratory investigations in a model sand-tank. Aust. J. Soil Res. 46:91–100.

Mughal, F.H. 2002. Irrigation-induced salinity: Environmental impacts. Available at dawn.com/2002/05/06/ebr11.htm (verified 1 Feb. 2010). Daily Dawn: Business (Karachi, Pakistan), 6 May 2002.

Pakistan Ministry of Food, Agriculture and Livestock. 2005. Agricultural statistics of Pakistan 2004–2005. Government of Pakistan, Ministry of Food, Agriculture and Livestock, Islamabad.

Schaap, M.G., F.J. Leij, and M.Th. van Genuchten. 2001. ROSETTA: A computer program for estimating soil hydraulic properties with hierarchical pedotransfer functions. J. Hydrol. 251:163–176.

Šimůnek, J., M. Šejna, and M.Th. van Genuchten. 2006. The HYDRUS software package for simulating two- and three-dimensional movement of water, heat, and multiple solutes in variably-saturated media. Technical manual, Version 1.0. PC Progress, Prague, Czech Republic.

Skaggs, T.H., and F.J. Leij. 2002. Solute transport: Theoretical background. p. 1353–1380. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA Book Ser. 5. SSSA, Madison, WI.

van Genuchten, M.Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44:892–898.

World Bank. 1992. Irrigation planning with environmental consideration. Tech. Pap. 166. World Bank, Washington, DC.

Youngs, E.G., and P.B. Leeds-Harrison. 2000. Improving efficiency of desalinization with subsurface drainage. J. Irrig. Drain. Eng. 126:375–380.