Effects of Flow Depth on Water Flow and Solute Transport in Furrow Irrigation: Field Data Analysis

Fariborz Abbasi[1]; Floyd J. Adamsen[2]; Douglas J. Hunsaker[3]; Jan Feyen[4]; Peter Shouse[5]; and M. Th. van Genuchten[6]

Abstract: Because of field-scale heterogeneity in soil hydraulic and solute transport properties, relatively large-scale experiments are now increasingly believed to be critical to better understand and predict the movement of water and dissolved solutes under field conditions. In this study, five field experiments were conducted on short blocked-end furrows to assess the effects of irrigation water level on water flow and solute transport in furrows. Three experiments were carried out, each of the same duration but with different amounts of water and solutes resulting from 6, 10, and 14 cm furrow water depths, designated as low, moderate, and high water levels, respectively. Two more experiments were performed with the same amounts of applied water and solute and, consequently, different durations, on furrows with depths of 6 and 10 cm of water. Results show that both the water level and the duration play an important role in transporting and distributing water and solutes in the soil profile. A positive correlation was found between water level and infiltrated amount of water or solute. Irrigation/solute application amounts increased with decreasing water level. Water and solutes were both distributed almost vertically (one-dimensionally) for the low water level and short application treatments, while they moved much more two-dimensionally with low and moderate water depths but longer application times. Irrigation with the 14 cm water level and short application time improved the distribution of water and solutes within the soil profiles, while also causing relatively less deep percolation of water and solutes as compared to low and moderate water levels and relatively long duration times.

DOI: 10.1061/(ASCE)0733-9437(2003)129:4(237)

CE Database subject headings: Furrow irrigation; Water levels; Solutes; Water quality; Water depth; Data analysis; Transport phenomena.

Introduction

The transport of agrochemicals in soils is a significant aspect of both crop production and groundwater quality control. Solute transport in soils is affected by many factors including soil physical, chemical, and biological properties, the particular soil conditions at the top and bottom of the profile, and management practices (Wallach et al. 1991). Those factors, particularly in field studies, may vary over time and space. Irrigation is also one of the main factors affecting the fate and transport of agrochemicals in soils in arid and semiarid regions (Yaron et al. 1985). Predominant irrigation methods used in those regions include drip, sprinkler, and furrow irrigation. Water flow and solute transport under sprinkler irrigation most closely approximate one-dimensional flow. By contrast, flow and solute transport under furrow and drip irrigation are usually two- and three-dimensional, respectively. Our understanding of how different irrigation methods affect solute transport is still relatively poor.

The number of comprehensive solute transport studies at the field scale is still quite limited, in part because of often excessive demands in terms of time and available resources. Additional complications arise because of difficulties in controlling spatial and temporal variabilities in the soil hydraulic and transport parameters, and the presence of preferential flow, which has been reported in both well-structured and unstructured soils (Blake et al. 1973; Kanchanasut et al. 1978; Rice et al. 1991). Troiano et al. (1993) found that under furrow irrigation the herbicide atrazine and other chemicals leached more rapidly than under sprinkler and trickle irrigation. Izadi et al. (1993, 1996) conducted a field solute experiment on furrows and used several one-dimensional piston flow models to predict bromide movement in the soil profile. They found that while piston flow theory generally described the bromide position well during the first irrigation, the tracer was transported somewhat faster than predicted by piston flow. They attributed this discrepancy to the preferential flow.

Goderya et al. (1996) used the water quality models TDNIT (Bogardi and Bardossy 1984) and EPIC (USDA 1990a,b) for 13-year simulations of nitrogen transport in a furrow-irrigated field under continuous cultivation of corn. They found that the

---

[1] Institute for Land and Water Management, Katholieke Univ. Leuven, Belgium; Vital Decosterstraat 102, 3000-Leuven, Belgium. E-mail: Frabbasi@hotmail.com

[2] U.S. Water Conservation Laboratory, USDA-ARS, 4331 E. Broadway Rd., Phoenix, AZ 85040.

[3] U.S. Water Conservation Laboratory, USDA-ARS, 4331 E. Broadway Rd., Phoenix, AZ 85040.

[4] Institute for Land and Water Management, Katholieke Univ. Leuven, Belgium; Vital Decosterstraat 102, 3000-Leuven, Belgium. E-mail: jan.feyen@agr.kuleuven.ac.be

[5] George E. Brown Jr. Salinity Laboratory, USDA-ARS, 450 W. Big Springs Dr., Riverside, CA 92507.

[6] George E. Brown Jr. Salinity Laboratory, USDA-ARS, 450 W. Big Springs Dr., Riverside, CA 92507.

Note. Discussion open until January 1, 2004. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on December 17, 2001; approved on November 19, 2002. This paper is part of the ***Journal of Irrigation and Drainage Engineering***, Vol. 129, No. 4, August 1, 2003. ©ASCE, ISSN 0733-9437/2003/4-237–246/$18.00.

Table 1. Soil Texture, Textural Fractions, and Soil Bulk Density Measured at Different Depths of Experimental Field

Depth (cm)	Textural fractions (%)						Texture class	Soil bulk density ($g\,cm^{-3}$)	
	Sand		Silt		Clay				
		Standard deviation		Standard deviation		Standard deviation			Standard deviation
0–20	74.29	2.17	9.36	2.10	16.35	1.45	Sandy loam	1.49	0.08
20–40	75.04	1.74	9.31	1.66	15.65	2.49	Sandy loam	1.56	0.06
40–60	76.73	3.97	8.27	1.73	15.00	3.08	Sandy loam	1.50	0.09
60–80	72.34	5.53	11.94	2.85	15.72	3.85	Sandy loam	1.41	0.12
80–100	71.16	7.69	12.67	4.80	16.17	3.18	Sandy loam	1.46	0.07
100–140	69.57	7.37	14.51	5.29	15.92	3.69	Sandy loam	1.51	0.11
140–180	70.32	2.01	14.18	3.47	15.50	1.24	Sandy loam	1.38	0.02
180–220	75.30	7.21	10.75	4.74	13.95	2.47	Sandy loam	—	—
220–260	74.65	4.73	12.00	3.68	13.35	1.06	Sandy loam	—	—

two models predicted deep water percolation, plant transpiration, soil evaporation, and nitrate leaching satisfactorily, but that the TDNIT model underestimated mineralization and denitrification. Wang et al. (1997) used the CHAIN-2D model (Simunek and van Genuchten 1994) to investigate the effect of different irrigation methods and spatial variability in the saturated hydraulic conductivity (K_s) on solute transport in the soil. They found that sprinkler irrigation required the least amount of time to infiltrate a prescribed amount of water or chemical, followed by furrow and drip irrigation. Furrow irrigation appeared to leach the tracer more efficiently than either drip or sprinkler irrigation. They also showed that spatial variability in K_s had no significant effect on the solute distribution in the profile. Recent laboratory studies by Wildenschild et al. (2001) showed that the flow rate had a significant influence on both the soil water retention curve and K_s of a sandy soil, while the effect was not readily apparent for a finer-textured loam soil. Results by Vanderborght et al. (1997) using small soil columns also showed that soil type and flow rate can have an important impact on water flow and solute mixing in a soil. Significant effects of the flow regime on field-scale solute transport were also found by Bowman and Rice (1986) during intermittent flood irrigation and Jaynes et al. (1988) during continuous flood irrigation.

A closely related aspect of irrigation is the effect of water level on infiltration rate and ensuing soil water distributions in the soil profile. Previous studies have shown that the effect of water level on infiltration in borders is relatively minimal (Philip 1958; Parlange 1972) but that with furrows it has a first-order effect on the surface area over which infiltration occurs (Fangmeier and Ramsey 1978; Souza 1981; Wallender and Rayej 1990).

The main objective of this study was to monitor two-dimensional field-scale water flow and solute transport, and to more precisely evaluate the effect of water level on transport and distributions of water and bromide in a field with blocked-end furrows under variable conditions.

Materials and Methods

Field Experiments

Field experiments were conducted at the Maricopa Agricultural Center (MAC), 45 km southwest of Phoenix, in February 2001 on a Casa Grande sandy loam (fine-loamy, mixed, hyperthermic Typic Natrargids) with about 0.5% organic matter and 3–5% $CaCO_3$. Soil texture and textural fractions were determined using the hydrometry method and wet soil particle size distribution analysis (Table 1). We also took soil bulk densities using a Madera soil sampler up to 180 cm deep at different locations in and outside the experimental plots (Table 1). The experimental field was fallow for two years before the experiments started and bromide had never been applied to the field. The static ground water level in the area ranged from 45 to 90 m.

Five experiments were carried out on bare soil with short blocked-end level furrows using depths of 6, 10, and 14 cm of water, designated as low, moderate, and high water levels, respectively. Short blocked-end level furrows were used to enable the water levels to remain constant and uniform along the relatively short length of the furrow. The selected water levels, 6, 10, and 14 cm, are representative of water levels common in cutback, free draining, and blocked-end furrow irrigation regimes, respectively. More or less the same depths (4, 10, and 16 cm) were previously used by Vogel and Hopmans (1992) to simulate the effects of different water levels on infiltration using a two-dimensional numerical model. Furthermore, bromide was dissolved in irrigation water and just applied during the second phase of the first irrigation event. This was because of higher reported solute leaching during fertigation (application of fertilizers with irrigation water) compared with conventional fertilizer application methods. Earlier efforts revealed that fertigation could potentially increase deep leaching of agricultural chemicals (Bowman and Rice 1986; Jaynes et al. 1988, 1992; among others). Therefore, in this study we applied the solutes as late as possible to decrease leaching of the solutes beyond our measurement depths.

Two series of experiments were carried out (Fig. 1). We first performed the same duration (SD) experiments involving the three flow depths applied to two successive irrigation events, ten days apart. The first irrigation took place in two phases. In the first phase, water was applied for 60 min to wet the profile. Water was then removed from the furrow and measured using an electric scale. During the second phase, water amended with $CaBr_2$ was applied for 30 min. Water in the furrow was again removed and the amount determined. The second irrigation utilized the same depths of unamended water employed during the first irrigation and lasted 90 min. As for the first irrigation, water stored in the furrow was pumped out and measured at the end of the experiment.

The second series of experiments involved similar amounts of applied water and solutes (SWS). The amount of water applied was the same as that infiltrated for the 14-cm depth treatment of the SD experiments. Water levels of 6 and 10 cm were used. The first irrigation was carried out in two steps, similarly as for the SD scenarios, with unamended water being applied first followed by

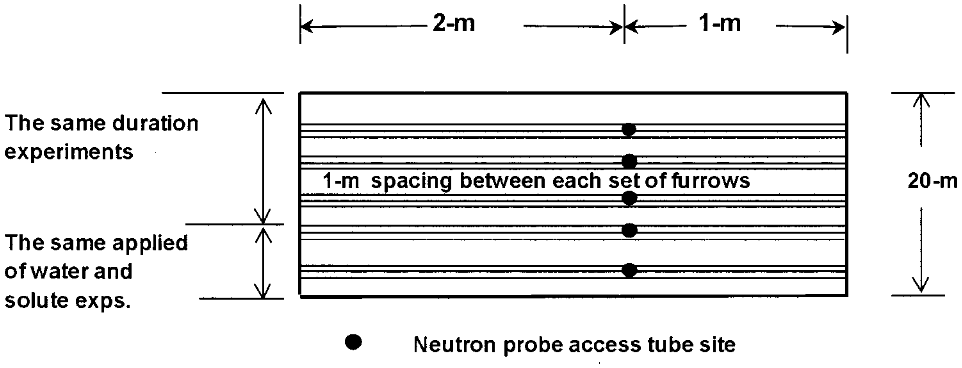


Fig. 1. Plane view of furrow irrigation experiments conducted at Maricopa Agricultural Center (MAC) in Phoenix (not to scale)

bromide amended water, except that the irrigation times were adjusted for each of the water levels such that the desired amount of water infiltrated. The second irrigation event again used unamended water applied with the same water levels as for the first irrigation, but with times adjusted so that again the same amount of water infiltrated during the second irrigation for the 14 cm depth as for the first set of experiments.

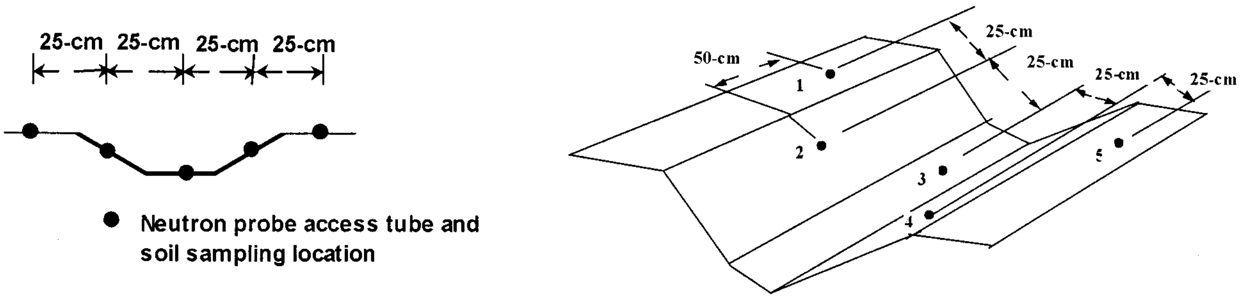
For all experiments, plots were made up of three furrows spaced at 100 cm intervals, common in the experimental area for row crops. The center furrow of each plot was a nonwheel furrow, which was monitored, with a wheel track furrow on each side of the monitored furrow. The blocked portion of the furrows was 300 cm in length. The remainder of this section lists measurements that we made for all of our experiments.

A set of neutron probe access tubes was established on each monitored furrow, which included five neutron probe access tubes each 330 cm in length installed at different locations perpendicular to the axis of the monitored furrows (Fig. 2). All five of the neutron tubes within a plot were a minimum of 50 cm apart, to avoid influence of adjacent tubes. Soil removed during the process of installing the neutron access tubes was saved for analysis. After installing the neutron access tubes, both the monitored and guard furrows were manually rebuilt.

A site-calibrated neutron probe (Campbell Pacific Nuclear 503, Martinez, California) was used to measure the soil water contents at each tube at soil depths of 20, 40, 60, 80, 100, 140, 180, 220, and 260 cm. Soil water content readings were taken before each irrigation (initial water contents) and immediately after pumping water out of the furrows. Those readings were followed by hourly measurements for 6 h after each irrigation and then every 3 h for the next 18 h. Readings were taken 3–4 times per day for 3 days and then 1–2 times per day until the next irrigation, or for 20 days following the second irrigation. Two to three neutron readings were taken for each soil increment depth and averaged in order to improve the precision of the neutron scatter methodology. Water contents of the surface layer (0–30 cm) were also measured using a site calibrated Time Domain Reflectometry (TDR), model 6050 XI (Soil Moisture Inc., Santa Barbara, California). The TDR probes with two-rod wave-guides were installed vertically 15 cm away from the neutron probe access tubes. The TDR and neutron probe readings were taken at the same times as indicated above for the neutron probe readings.

The geometry of the experimental furrows was determined using a profilometer before each irrigation event at two locations along the furrows in order to calculate the volume of water needed to fill the furrow section, and to infer geometry parameters required for the subsurface water flow and solute transport models.

Water and bromide solutions were supplied from 250 L barrels equipped with valves. Water depths were kept constant during the irrigation by adjusting the water level to the desired height determined from staff gauges placed at the bottom of the furrow and 70 cm away from the head of the furrow. The barrels that supplied water and the bromide for the monitored furrows were weighed



a) Front view

b) Perspective view. Numbers show the numbering of the neutron probe access tubes installed in two different rows, the first row includes tubes 2 and 4 on the sides and the second row includes tubes 1, 3, and 5. Note that all the tubes installed on the same furrow.

Fig. 2. Location of neutron probe access tubes and soil sampling points on experimental furrow cross section, (a) front view and (b) perspective view (not to scale)

Table 2. Infiltrated Amounts of Water and Bromide at Different Plots During Two Successive Irrigation Events

		Irrigation number 1			Irrigation number 2	
	Experiment	Water[a] (1 m^{-1})	Bromide[b] (g m^{-1})	Application time (min)	Water (1 m^{-1})	Application time (min)
SD[c]	Plot 1 (6-cm)	31.63	70.67	90(30)[e]	18.95	90
	Plot 2 (10-cm)	50.72	90.17	90(30)	32.57	90
	Plot 3 (14-cm)	98.83	218.17	90(30)	39.53	90
SWS[d]	Plot 4 (6-cm)	99.42	218.33	337(92)	39.58	208
	Plot 5 (10-cm)	98.42	218.33	123(48)	40.58	92

[a] Water applied in two phases.

[b] Grams bromide per 1 m furrow length.

[c] Same duration (SD) experiments.

[d] Same applied water and bromide (SWS) experiments.

[e] Total irrigation and bromide application times, respectively.

every 5 min during the irrigations. For each experiment, the volume of water or bromide solution needed to fill the furrows and bring the water level to a desired depth, was estimated using the measured furrow geometries and prepared in 50 L barrels for each furrow separately. The volume of water pumped from the furrow at the end of each experiment was compared to the estimated values based on the furrow geometries. In case of differences, the infiltrated amounts of water and bromide were later adjusted. The bromide concentration was 10 g L^{-1} for all experiments.

Soil samples were taken manually with a 2.5 cm auger up to 180 cm depth, corresponding in location and depth to the neutron probe access tubes prior to the experiments (soil saved from the neutron access tube installation), as initial values; 5 days after the first irrigation; 6 and 20 days after the second irrigation. The second, third, and fourth soil samples were taken at 225, 150, and 75 cm away from the head of furrows, respectively. The second and third soil samples from the first two SD experiments were taken up to 140 cm depth. In addition, holes from the soil samples were refilled after each soil sampling. The soil samples were also used for gravimetric soil water content measurements. Soil samples for Br analysis were air dried and crushed to pass a 2 mm sieve. Soil extractions (1:1 weight:volume) were made and kept at 7°C until analyzed. Bromide concentrations were determined using a QuikChem AE Automated Ion Analyzer.

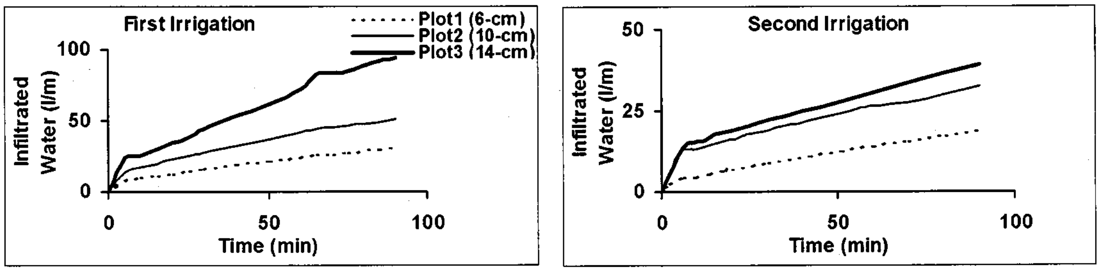
In the event of rain, the plots were covered with plastic sheets to avoid receiving rain water. The experimental plots were kept weed free manually. Furthermore, the SD and SWS experiments started on January 30 and February 26, 2001, respectively, and each lasted 30 days. Replications were not applied because of the experimental intensity used in this research and consequently the excessive demands in terms of time and adequate financial sources and labor.

Results and Discussion

Infiltrated Water and Bromide

In the SD experiments, a positive correlation was found between infiltrated water/bromide and applied water levels [Table 2 and

a) Same duration (SD) experiments



b) Same applied water and solute (SWS) experiments

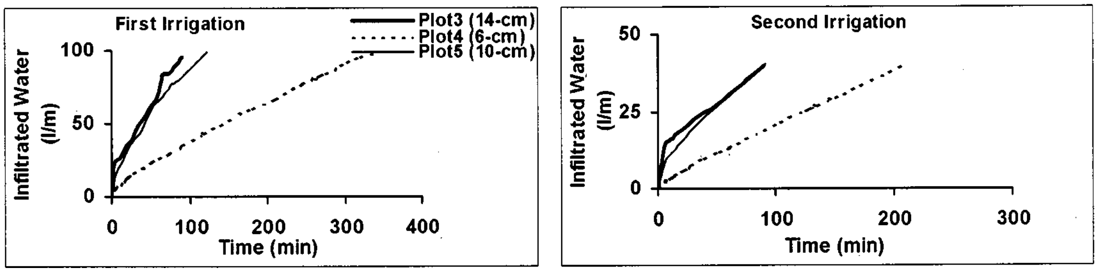


Fig. 3. Effect of water level on cumulative amount of infiltrated water and irrigation application time at various plots. (a) Same duration (SD) experiments and (b) same applied water and solute (SWS) experiments.

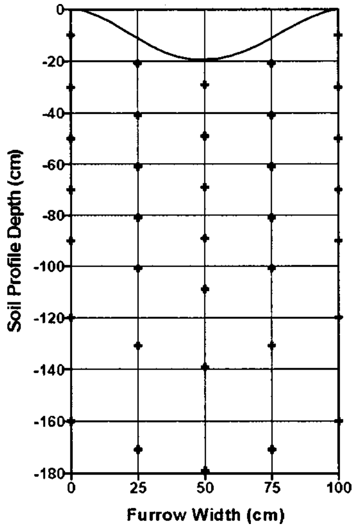


Fig. 4. Network of rectangular elements for estimating water and bromide recovery rates. Symbols represent locations of measured soil water contents and bromide concentrations.

Fig. 3(a)]. The infiltrated amounts of water (IW) and bromide increased with increasing irrigation depth during the two irrigation events. The infiltration rate during the first irrigation was considerably higher than during the second one because of lower initial soil water contents in the soil profile before the first irrigation as compared to the second one, and because of soil consolidation and surface sealing resulting from the first irrigation.

Similarly, in the SWS experiments there was a correlation between irrigation/bromide application time and water level. Irrigation and bromide application times increased, particularly during the first irrigation, with decreasing water level in the furrows [Table 2 and Fig. 3(b)]. Application times for the second SWS irrigation with 6 and 10 cm water levels were nearly the same (Table 2). This likely was due mostly to spatial and temporal (from one irrigation to another) variability in the soil hydraulic properties. We conclude from both series of the experiments (Table 2 and Fig. 3) that different water levels affected the amounts of infiltrated water/bromide and the irrigation/bromide application time. Regression coefficients (R^2) of linear relationships between the different variables (water levels and infiltrated water/bromide; water levels and water/bromide application times) ranged from 0.76–0.98. However, high obtained regression coefficients might be due to limited data points in making the linear regressions. Linear relationships between the infiltration rate and the wetted perimeter for furrows were previously also reported by Fangmeier and Ramsey (1978) and Samani et al. (1985).

Water and Bromide Recovery

For purposes of estimating water and bromide recovery rates, the soil profiles at each plot were subdivided into a network of rectangular elements (22–30 rectangles depending upon the soil sampling depth, each having 20 cm by 25 cm) and volume of water and mass of bromide were determined for each rectangle (Fig. 4). The mass of water/bromide in each profile was estimated by summation of water/bromide masses in the small rectangles. Neutron probe and TDR readings taken immediately before and after each irrigation event were used for estimating water recovery rates whereas measured bromide concentrations and gravimetric soil water contents collected during three different soil sampling events and soil bulk densities (Table 1) were used for calculating bromide recovery rates for each plot.

Water and bromide recovery rates for different plots during the different irrigation and soil sampling events are given in Table 3. Relatively higher water recovery rates were obtained during the second irrigation. This may have been caused by the fact that the neutron probe and TDR slightly underestimated water contents during relatively dry conditions (including initial water content values taken before the first irrigation).

Relatively high bromide recovery rates (Table 3) were obtained at the first and second soil sampling times, but much lower rates for the third soil sampling, except for Plot 4, mostly due to leaching below the soil sampling depths. Another reason for the low recovery of the third soil sampling could be lateral solute transport. However, the same depths of water or bromide solution were applied to the adjacent furrows during the irrigation. The low solute recovery for Plot 1 and Plot 5 during the third soil sampling (Table 3) could be caused by leaching beyond the maximum sampling depth of 180 cm.

Soil Water Contents

Soil water contour maps (Figs. 5 and 6) were made using the *SURFER* code (Golden Software, Golden, Colo., 1999). Kriging with linear variogram was selected as the gridding method since this approach is one of the most flexible and useful methods available for almost any type of data sets (Golden Software 1999). Water contents of the 0–30 cm layer beneath the furrow bottom, taken immediately after each irrigation event, were similar for all the plots [Figs. 5(a) and 6(a)]. The maximum measured water content of the surface layer beneath the furrow bottom was about 0.35 $cm^3\,cm^{-3}$, or

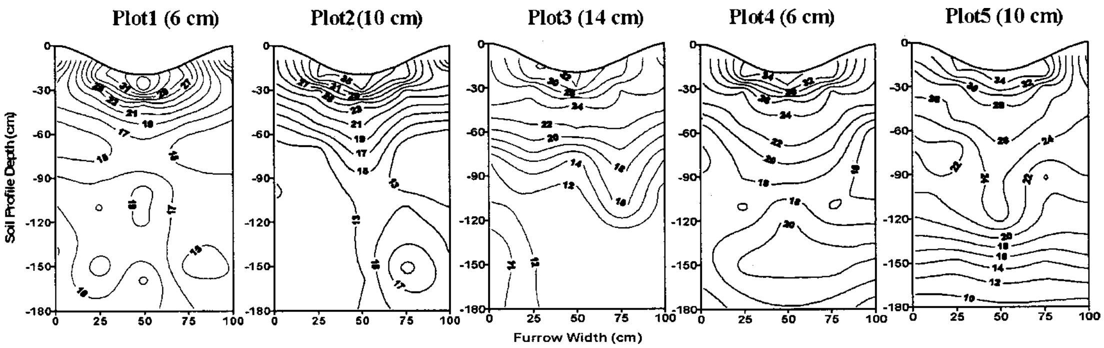
Table 3. Water and Bromide Recovery Rates for Different Experimental Plots During Various Irrigation and Soil Sampling Events (in %)

		Water recovery irrigation event		Bromide recovery soil sampling event		
	Experiment	Number 1	Number 2	Number 1[a]	Number 2[b]	Number 3[c]
SD	Plot 1 (6 cm)	88.4	97.3	96.8	96.1	63.2
	Plot 2 (10 cm)	88.4	90.4	93.2	80.02	70.8
	Plot 3 (14 cm)	92.6	91.0	85.2	79.9	71.1
SWS	Plot 4 (6 cm)	90.0	101.6	78.2	70.4	96.2
	Plot 5 (10 cm)	99.3	102.6	81.4	73.4	66.1

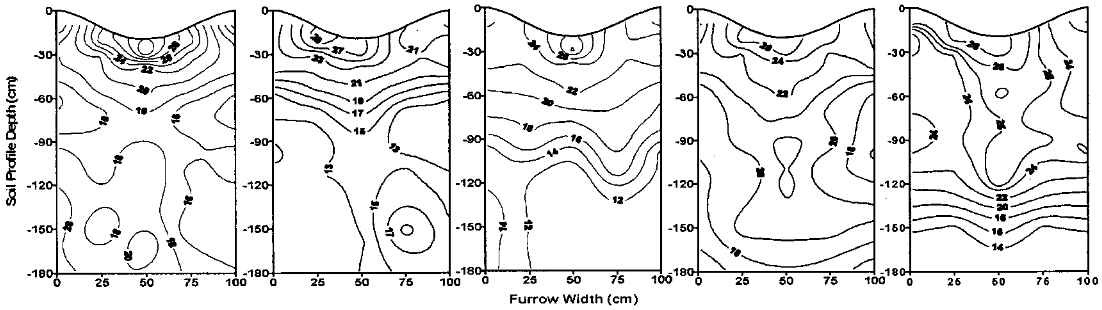
[a] Five days after the first irrigation.

[b] Six days after the second irrigation.

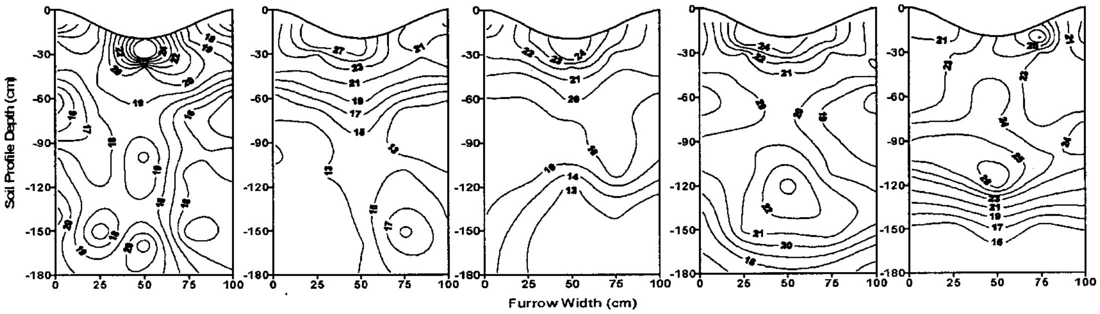
[c] Twenty days after the second irrigation (30 days from start).



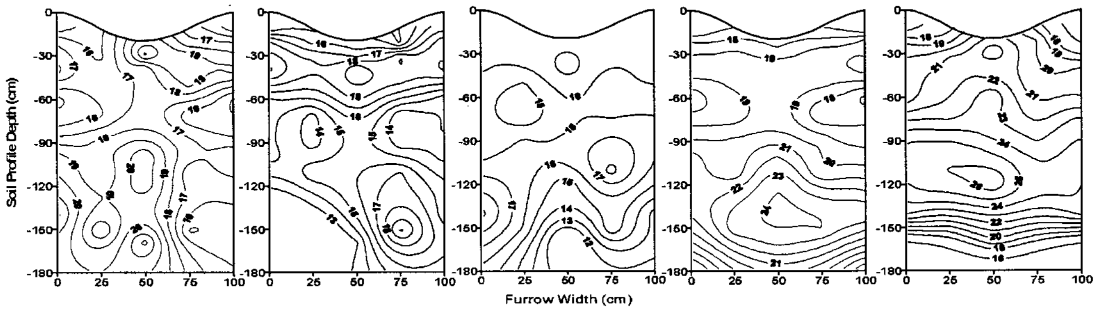
a. Immediately after irrigation



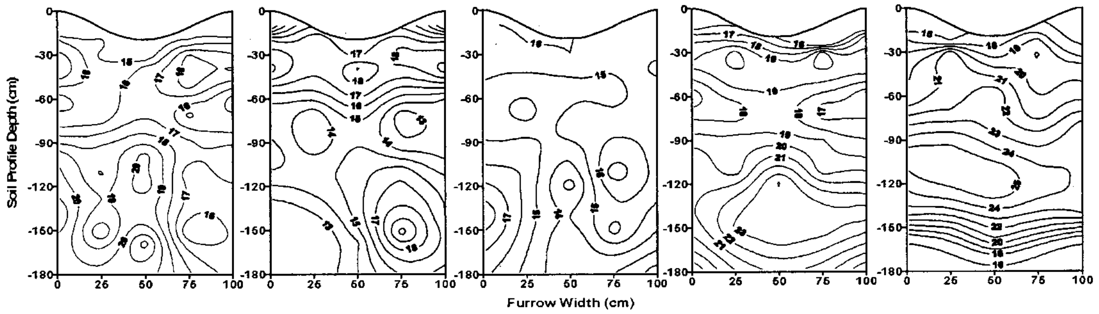
b. 6 hours after irrigation



c. 1 day after the irrigation

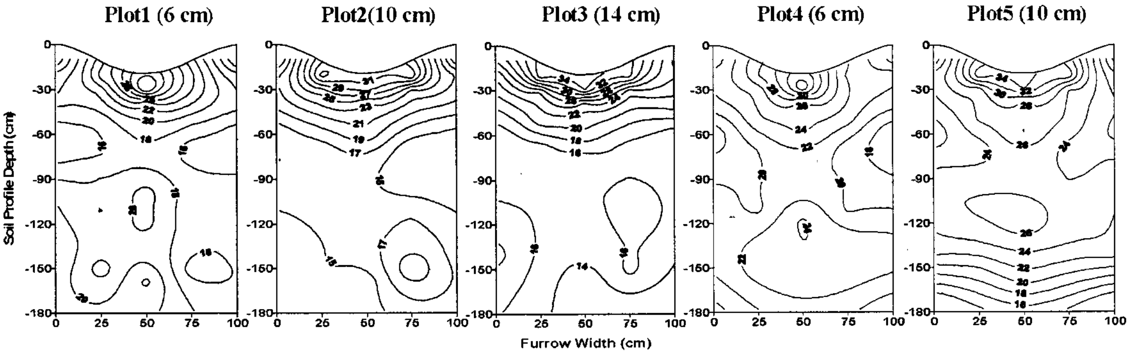


d. 5 days after irrigation

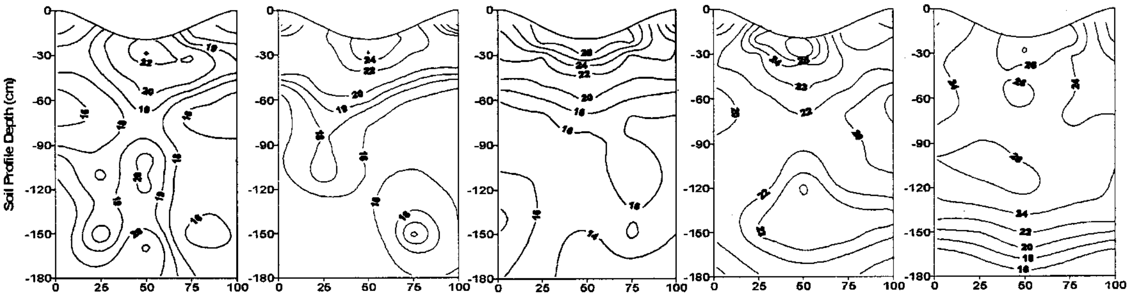


e. 10 days after irrigation

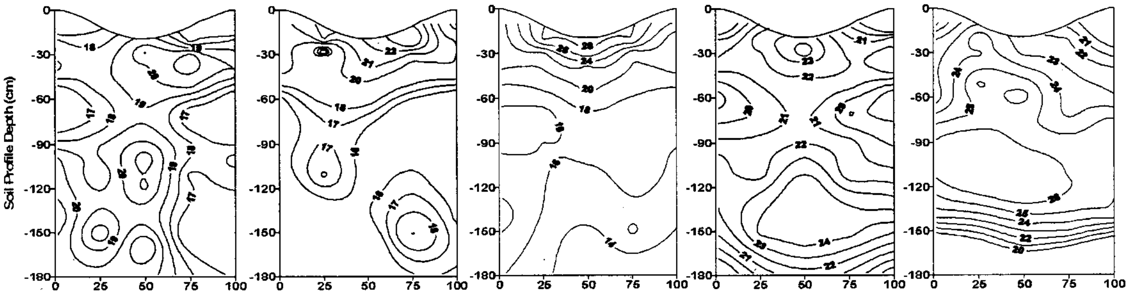
Fig. 5. Measured soil water contents (volumetric %) in different plots: (a) immediately; (b) 6 h; (c) 1 day; (d) 5 days; and (e) 10 days after first irrigation.



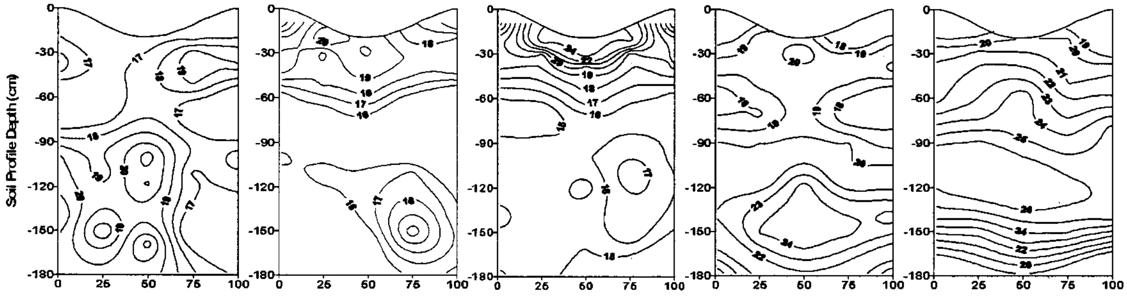
a. Immediately after irrigation



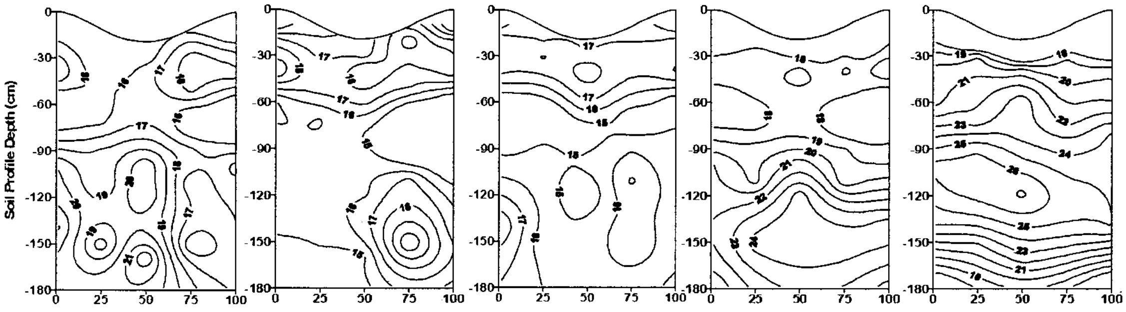
b. 6 hours after irrigation



c. 1 day after the irrigation



d. 5 days after irrigation



e. 10 days after irrigation

Fig. 6. Measured soil water contents (volumetric %) in different plots: (a) immediately; (b) 6 h; (c) 1 day; (d) 5 days; and (e) 10 days after the second irrigation

85% of the saturated water content, $\theta_s = 0.407\,\mathrm{cm}^3\,\mathrm{cm}^{-3}$, as measured in the laboratory. This is consistent with the fact that field-measured θ_s values are generally lower than porosity because of entrapped or dissolved air (e.g., Klute 1986).

Water in the SD experiments (6 and 10 cm WL) moved predominantly downward and not laterally to areas under the furrow ridge. Water contents there remained almost unchanged. Lateral flow in the present study was limited because of the relatively coarse-textured makeup of the soil (being sandy loam with over 70% sand). For the SWS experiments, however, water moved both vertically and horizontally, thus creating more favorable two-dimensional wetting patterns in the root zone shortly after each irrigation event. Wetting fronts from neighboring furrows in the SD plots (6 cm WL in particular) never reached the top of the furrows while they met each other in the SWS plots during or shortly after each irrigation. This may reflect the smaller amounts of water applied to the 6 and 10 cm SD plots as compared to the SWS experiments.

As expected, most of the changes in water contents of the SD plots occurred during the infiltration phase. Water contents, especially below depths of 100 cm, remained relatively unchanged, also during redistribution (Figs. 5 and 6), likely because of relatively small amounts of water applied and low pressure gradient in the soil profile. This is also true for the second irrigation. By contrast, more pronounced changes were observed in the SWS plots during both infiltration and redistribution. In those plots changes below depths of 140 cm were relatively large. For instance, water contents at the bottom of Plot 5 increased from about 10% [as the initial value; see Fig. 5(a)] to about 19% [10 days after the second irrigation, Fig. 6(e)]. This means that deep percolation in the SWS plots was substantially larger than that in the SD plots.

During the redistribution phase, water contents in the plots decreased with time in the surface layers [Figs. 5(c, d, and e) and 6(c, d, and e)], in part due to the evaporation from the soil surface and partly because of downward water redistribution within the soil profile. This caused the water contents of the different plots to be very similar in the surface layers almost ten days after each irrigation event [Figs. 5(e) and 6(e)]. Water distributions in all plots (SD and SWS) during the second irrigation were almost the same as during the first one. Even after the second irrigation, water contents of the SD plots below a depth of 140 cm remained similar to the initial values taken before the first irrigation. Differences in water contents in the lower portions of the different plots were mostly a consequence of having different initial conditions.

Bromide Concentration

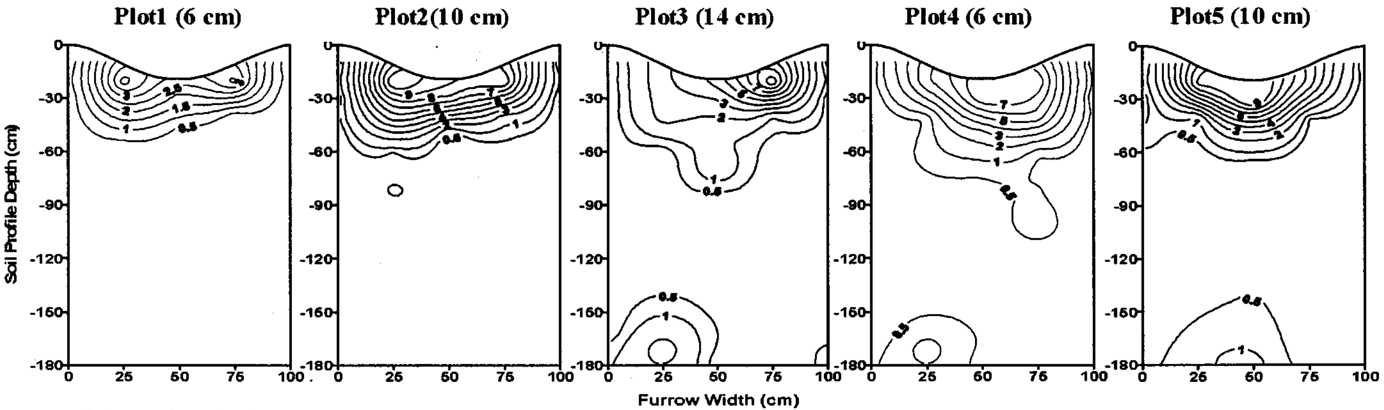
Bromide contour maps (Fig. 7) were made with the same method as indicated in the previous section. Peak bromide concentrations are clearly noticeable in the surface layers beneath the furrow bottom during the first soil sampling five days after the first irrigation. Subsequent upward fluxes caused by evaporation from the soil surface apparently moved bromide upward in the soil. Peak bromide concentrations during the second and third soil samplings were substantially lower as the second irrigation event leached and redistributed the solutes within the soil profile by means of advective transport and likely some dispersion. Higher solute concentrations were observed for the SWS experiments, particularly during the second and third samplings; this because of longer solute/water application times for the SWS plots as compared to the SD plots.

Overall, average solute fronts during the first soil sampling five days after the first irrigation reached depths of about 60 and 80 cm in the SD and SWS plots, respectively. However, solutes in the SWS plots were transported much deeper (to about 150 cm), presumably because of preferential flow [Fig. 7(a)]. The effects of preferential flow were observed during the second and third soil sampling times in all the experimental plots [Figs. 7(b and c)]. The second irrigation event caused the average solute fronts to move about 140 cm in all the plots except the 6 cm SD plot. However, soil samples with relatively high bromide concentrations were even obtained at 180 cm depth in some of the plots during both the second and third soil samplings. While preferential flow and spatial variability in the soil hydraulic and solute properties made it difficult to find a general relation between solute front and water level in the furrows, mean solute fronts in the SWS plots were clearly much deeper than those in the SD plots. Solute concentrations at relatively deep depths (140 cm and deeper) in the SD plots remained lower than those in the SWS plots throughout the sampling period. Bromide in the SD plots was transported primarily in the vertical direction (one-dimensional), leading to relatively high concentrations below the furrow. By contrast, it was distributed much more evenly throughout the root zone in plots subject to the SWS treatments.

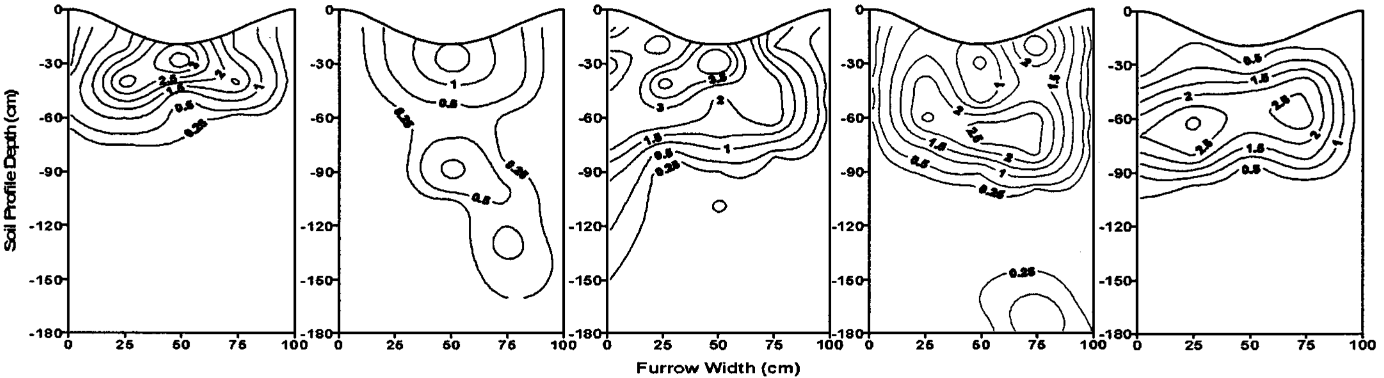
Applying fertilizers with irrigation water (fertigation) using relatively low water levels and short duration times such as those used for the SD experiments may hence be a concern from the point of view of fertilizer management. Under these conditions fertilizers may remain beneath the furrow bottom rather than being taken up by plant roots, and later leached beyond the root zone through subsequent irrigations during the growing season. This is particularly true at the beginning of the growing season before plant roots are fully developed. The concern is also valid when fertilizers are applied in solid form on the soil surface. In this case the fertilizers will remain insoluble since the soil surface will remain dry, particularly in the case of short-duration irrigations at relatively low water levels. Those fertilizers may later be lost through volatilization or other environmental processes.

Summary

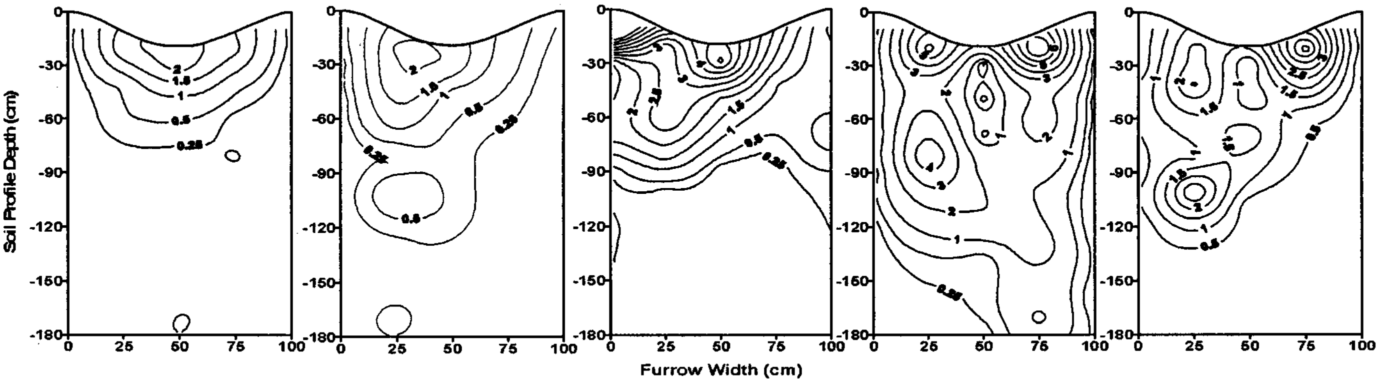
Several field experiments were carried out on short blocked-end furrows and run for two successive irrigation events in a sandy loam soil. The effects of different water levels were evaluated on water flow and solute transport in the soil profile. We found a positive correlation between the cumulative amount of infiltrated water/solute and water level in the furrows. Infiltrated water/solute increased with increasing water level. Higher water levels required less time for prescribed amounts of water/chemical to infiltrate. Results also indicate that irrigation with higher water levels and relatively short application times leads to more uniform water and solute distributions in the profile, and to less deep percolation of water and solutes as compared to irrigations with lower water levels and long durations. Irrigation with low and moderate water levels and relatively short application times could not provide water to all of the root zone and the surface layers. The ridges of the furrows in particular remained dry. Although irrigation with low and moderate water levels and long application times resulted in better water and solute distributions within the soil profile, they also caused water and solutes to move deeper into the profile. Irrigation with a 14 cm water level and relatively short duration (90 min) provided sufficient water for soil moisture to become more or less evenly distributed throughout the root zone, including near the top of the furrows.



a. 5 days after the first irrigation



b. 6 days after the second irrigation



c. 20 days after the second irrigation

Fig. 7. Measured bromide concentrations (g/L) in different plots: (a) 5 days after first irrigation; (b) 6 days after second irrigation; and (c) 20 days after second irrigation (30 days from the beginning)

From an irrigation management perspective in blocked-end furrow irrigated fields, it is recommended to use higher water levels and shorter durations to produce relatively uniform water distributions, while lower water levels with longer application times may be preferred for irrigations using low quality water. Furthermore, a good irrigation management practice may be to apply lower water levels and relatively short durations for fertilizers, during the second and third growing stage. Finally, we can conclude that water level and irrigation/solute application time played an important role in this study, however results lack statistical strength since no replications were used in order to reach a solid conclusion. Results of similar experiments on long realistic furrows will be given in the subsequent papers to investigate the effects of water level and application time under running water on subsurface water flow and solute distributions.

Acknowledgments

The first writer is very grateful to J. Jobes and J. Fargerlund at U.S. Salinity Laboratory, Riverside, Calif. and C. Arterberry, D. Powers, and C. Van Meeteren at U.S. Water Conservation Laboratory, Phoenix, for their help during the field experiments and subsequent laboratory analyses. Thanks to Robert Roth, Director of Maricopa Agriculture Center, and his colleagues for their collaboration during the field experiments and initial laboratory analysis.

References

Blake, G., Schlichting, E., and Zimmermann, U. (1973). "Water recharge in a soil with shrinkage cracks." *Soil Sci. Soc. Am. Proc.*, 37, 669–672.

Bogardi, I., and Bardossy, A. (1984). ''Stochastic forecasting of N budget in the unsaturated zone.'' *Proc., Int. Symp. of Recent Investigations in the Zone of Aeration*, RIZA, Munich, West Germany, 743–756.

Bowman, R. S., and Rice, R. C. (1986). ''Transport of conservative tracers in the field under intermittent flood irrigation.'' *Water Resour. Res.,* 22(11), 1531–1536.

Fangmeier, D. D., and Ramsey, K. K. (1978). ''Intake characteristics of irrigation furrows.'' *Trans. ASAE,* 21, 696–700.

Goderya, F. S., Woldt, W. E., Dahab, M. F., and Bogardi, I. (1996). ''Comparison of two transport models for predicting nitrates in percolating water.'' *Trans. ASAE,* 39(6), 2131–2137.

Izadi, B., King, B., Westermann, D., and McCann, I. (1993). ''Field scale transport of bromide under variable conditions observed in a furrow-irrigated field.'' *Trans. ASAE,* 36(6), 1679–1685.

Izadi, B., King, B., Westermann, D., and McCann, I. (1996). ''Modeling transport of bromide in furrow-irrigated field.'' *J. Irrig. Drain. Eng.,* 122(2), 90–96.

Jaynes, D. B., Bowman, R. S., and Rice, R. C. (1988). ''Transport of conservative tracers in the field under continuous flood irrigation.'' *Soil Sci. Soc. Am. J.,* 52, 618–624.

Jaynes, D. B., Rice, R. C., and Hunsaker, D. J. (1992). ''Solute transport during chemigation of a level basin.'' *Trans. ASAE,* 35(6), 1809–1815.

Kanchanasut, P., Scotter, D. R., and Tillman, R. W. (1978). ''Preferential solute movement through layer soil voids: II. Experiments with saturated soil.'' *Aust. J. Soil Res.,* 18, 363–368.

Klute, A. (1986). ''Water retention: Laboratory methods.'' *Methods of soil analysis. 1: Physical and mineralogical methods, agronomy*, A. Klute, ed., 2nd Ed., American Society of Agronomy, Madison, Wis., Vol. 9(1), 635–662.

Parlange, J. Y. (1972). ''Theory of water movement in soils. 6: Effect of water depth over soil.'' *Soil Sci.,* 113(5), 308–312.

Philip, J. R. (1958). ''The theory of infiltration: 6. Effect of water depth over soil.'' *Soil Sci.,* 85, 278–286.

Rice, R. C., Jaynes, D. B., and Bowman, R. S. (1991). ''Preferential flow of solutes and herbicide under irrigated fields.'' *Trans. ASAE,* 34(3), 914–918.

Samani, Z. A., Walker, W. R., Jepsson, R. W., and Willardson, L. S. (1985). ''Numerical solution for unsteady two-dimensional infiltration in irrigation furrows.'' *Trans. ASAE,* 28(4), 1186–1190.

Simunek, J., and van Genuchten, M. Th. (1994). ''The CHAIN-2D code for simulating the two-dimensional movement of water, heat, and multiple solutes in variably saturated porous media.'' *Res. Rep. 136*, U.S. Salinity Lab., Riverside, Calif.

Souza, F. (1981). ''Non linear hydrodynamic model of furrow irrigation.'' PhD thesis, Univ. of California, Davis, Calif.

Troiano, J., Garretson, C., Krauter, C., Brownell, J., and Huston, J. (1993). ''Influence of amount and method of irrigation water application on leaching atrazine.'' *J. Environ. Qual.,* 22(2), 290–298.

U.S. Department of Agriculture (USDA). (1990a). ''EPIC-Erosion productivity impact calculator. 1: Model documentation.'' *Tech. Bulletin No. 1768*, Washington, D.C.

U.S. Department of Agriculture. (1990b). ''EPIC-Erosion productivity impact calculator. 2: User manual.'' *Tech. Bulletin No. 1768,* Washington, D.C.

Vanderborght, J., Gonzalez, C., Vanclooster, M., Mallants, D., and Feyen, J. (1997). ''Effects of soil type and water flux on solute transport.'' *Soil Sci. Soc. Am. J.,* 61, 372–389.

Vogel, T., and Hopmans, J. W. (1992). ''Two-dimensional analysis of furrow infiltration.'' *J. Irrig. Drain. Eng.,* 118(5), 791–806.

Wallach, R., Israeli, M., and Zaslavsky, D. (1991). ''Small perturbation solution for steady non-uniform infiltration into soil surface of a general shape.'' *Water Resour. Res.,* 27(7), 1665–1670.

Wallender, W. W., and Rayej, M. (1990). ''Shooting method for Saint Venant equations of furrow irrigation.'' *J. Irrig. Drain. Eng.,* 116(1), 114–122.

Wang, D., Yates, S. R., Simunek, J., and van Genuchten, M. Th. (1997). ''Solute transport in simulated conductivity fields under different irrigations.'' *J. Irrig. Drain. Eng.,* 123(5), 336–343.

Wildenschild, D., Hopmans, J. W., and Simunek, J. (2001). ''Flow rate dependence of soil hydraulic characteristics.'' *Soil Sci. Soc. Am. J.,* 65, 35–48.

Yaron, B., Gerstl, Z., and Spencer, W. F. (1985). ''Behavior of herbicides in irrigation soils.'' *Adv. Soil Sci.,* 3, 121–211.