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ORIGINAL PAPER

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# Water flow and solute transport in furrow-irrigated fields

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**Abstract** Field-scale solute transport experiments are not easily implemented because of the overwhelming problems of soil heterogeneity and variability in subsurface hydraulic and solute transport properties. In this paper, the results of four field-scale furrow irrigation experiments designed to investigate the effect of flow depth and solute application time on bromide distribution along and below the furrows are presented. One experiment was conducted under free-draining (FD) conditions in which bromide was applied during the entire irrigation event. Three experiments were carried out in blocked-end furrows in which bromide was injected either during the entire irrigation event (100%), the first half of the irrigation (FH), or the second half of the irrigation (SH). The FD experiment was equipped with neutron probe tubes for measuring soil water contents at different times and locations in furrow cross-section whereas soil samples for bromide analysis and gravimetric soil water contents from all the experiments were collected at different depths up to 1.80 m, 5 days after the irrigation at three locations near the inlet, in the middle, and close to the outlet of the furrows. Overland flow depths along the furrows were also recorded using staff gauges at the inlet, middle, and outlet sites every few minutes during the entire irrigation. Results showed substantial non-uniformity in solute movement along the monitored furrows, with the degree of non-uniformity depending upon flow depth and solute application time. Non-uniform distributions were observed especially at the outlet sites, compared with those at the inlet and middle sites. Solute application efficiencies for the FD, 100%, FH, and SH experiments were 50, 100, 64, and 93%, respectively. The effects of flow depth and irrigation/solute application time on soil water contents were more pronounced in the soil surface layers and were found to be relatively minor at deeper depths. Water and solute deep percolation rates also showed dependency to flow depth and solute application/opportunity time and gradually decreased along the furrows.

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## Introduction

Water flow and solute transport processes into and through natural soils can be very complex, even in relatively uniform soils. This has been demonstrated in a number of large-scale tracer experiments reported during the past several decades. Difficulties in carrying out and modeling such experiments stem from the presence of considerable soil surface heterogeneity, variability in subsurface soil hydraulic and solute transport parameters, lack of expedient methods for accurately measuring soil properties (e.g., soil water retention, hydraulic conductivity, and solute transport parameters) at the desired scale, and the high cost and labor required for field experiments. While measurement techniques have improved considerably recently (e.g., Eching et al. 1994; van Dam et al. 1994; van Genuchten et al. 1999, among others), these are generally still far too expensive for routine characterization of large fields at sufficient resolution.

The importance and implications of spatial variability in the soil hydraulic and other properties on field-scale water and/or solute transport have been described in many studies (Nielsen et al 1973; Biggar and Nielsen 1976; Jury 1985; Mohanty et al. 1994; Mallants et al. 1995; among others). Nielsen et al. (1973) and Biggar and Nielsen (1976) were among the first to demonstrate considerable spatial variability in the hydraulic conductivity of a field soil. An extensive review of spatial variability in soil physical and chemical properties was carried out by Jury (1985). He defined three groups of soil properties depending upon their degree of spatial variability. Static soil properties such as bulk density, particle size fractions, and porosity were found to be only moderately variable with coefficients of variation (CVs) less than 20%. Water flow parameters (e.g., infiltration rate and hydraulic conductivity) generally displayed a much higher variability, with CVs larger than 100%, while CVs for solute transport properties such as solute velocity and concentration varied between 60% and 194%. Mallants et al. (1995) also reported large spatial variability for the saturated hydraulic conductivity ($K_s$), moderate variability for the residual water content ($\theta_r$) and the shape factor $\alpha$ in van Genuchten's (1980) water retention model (VGM), and low variability for the saturated water content $\theta_s$ and the shape factor $n$ in the VGM equation.

An additional difficulty in large-scale water flow and solute transport experiments involving relatively long furrows/borders is the change in solute concentration and application (opportunity) time as water flows along the field, and ways to specify overland solute concentrations with distance and time. For instance, fertigation (applying fertilizers with irrigation water) in long borders or furrows can result in considerable fertilizer non-uniformity along the field (Playan and Faci 1997; Garcia-Navarro et al. 2000; Abbasi et al. 2003b). Under such conditions, water and the fertilizer will reach different locations at different times depending upon the fertilizer application time and the rate of advance. Consequently, subsurface transport and resultant distributions of water and solutes in the soil profile are likely different at different locations along the field. Abbasi et al. (2003b) developed a combined overland water flow and solute transport model for analysis and management of surface fertigation practices. The model was successfully applied to study/predict overland solute concentrations along free-draining and blocked-end furrows. The model also provided the information required to define the upper boundary conditions (e.g., flow depths and overland solute concentrations at different locations and times along the furrow) needed to run subsurface water flow and transport models (e.g., HYDRUS-2D; Simunek et al. 1999) as a complement to, or in lieu of, direct measurements.

In a related study, Abbasi et al. (2003a) found that both flow depth (water level) and water/solute application time significantly affected water and solute distributions below short 3-m-long blocked-end furrows during steady flow. The main objective of this paper is to present the results of four field-scale solute transport experiments conducted on more realistic 115-m-long free-draining and blocked-end furrows, in order to investigate the effects of flow depth and solute application time on subsurface uniformity of water and solute distributions along and below the furrows.

## Materials and methods

### Field experiments

The field experiments were conducted during 2001 at the Maricopa Agricultural Center (MAC) in Maricopa, Arizona, on a bare Casa Grande sandy loam soil (fine-loamy, mixed, hyperthermic Typic Natrargids). Depthwise soil texture, textural fractions, and soil bulk densities measured in the experimental field are presented in Table 1. Details about the experiments can be found in Abbasi et al. (2003b) and are only briefly summarized here.

Four experiments, one under free-draining and three under blocked-end conditions, were conducted. The experiments were carried out on 115 m furrows spaced 1 m apart. Each experiment included three furrows; one monitored non-wheel furrow in the middle, and two guard-wheel furrows, one on each side.

One experiment was conducted under free-draining end conditions. The experiment was run for two irrigation events spaced 10 days apart. The first irrigation lasted 275 min and the second 140 min. The average inflow rates were 1.07 and 1.03 l $s^{-1}$ for the first and second irrigations, respectively. Bromide in the form of $CaBr_2$ was injected at a constant rate (6.3 g Br $l^{-1}$) during the entire period of first irrigation. The second irrigation was carried out with unamended water (without bromide) to investigate distributions of moisture and Br in the soil profile below and adjacent to the furrow. Two sets of neutron probe access tubes were established at $x=5$ m and $x=110$ m along the monitored furrow. Hereafter, we refer to these locations as the inlet and outlet stations, respectively. Each set consisted of five 2.2 m tubes, installed across the furrow axis in two rows 50 cm apart to avoid mutual interference of the readings. A site-calibrated neutron probe was used for regular measurements of the soil water content at depths of 0.20, 0.40, 0.60, 0.80, 1.0, 1.4, and 1.8 m. In addition to the initial observations before each irrigation, water contents were recorded 6 h and 12 h after each irrigation followed by daily measurements up to 15 days after the second irrigation event. Water contents of the surface layer (0–30 cm) were also measured using site-calibrated time domain reflectometry (TDR). The TDR probes with two-rod waveguides were installed vertically 15 cm away from the neutron probe access tubes, and readings were taken at the same times as indicated above for the neutron probe readings.

Three experiments were carried out on blocked-end furrows using the following solute application options (referred to as the 100%, FH, and SH experiments, respectively):

- bromide applied during the entire irrigation event (100%),
- bromide applied during only the first half of the irrigation event (FH), and
- bromide applied during the second half of the irrigation event (SH).

All three experiments in blocked-end furrows involved one 140-min-long irrigation. The average inflow rates for the three runs were 1.29, 1.32, and 1.28 l $s^{-1}$, respectively. Water reached the end

**Table 1** Depthwise soil texture, textural fractions, and soil bulk density measured in the experimental field

| Depth (m) | Textural fractions (%) | | | Texture class | Soil bulk density (g $cm^{-3}$) |
|---|---|---|---|---|---|
| | Sand | Silt | Clay | | |
| 0.00–0.20 | 74.33 | 9.61 | 16.06 | Sandy loam | 1.49 |
| 0.20–0.40 | 72.83 | 9.13 | 18.04 | | 1.56 |
| 0.40–0.60 | 70.30 | 10.15 | 19.55 | | 1.50 |
| 0.60–0.80 | 71.33 | 12.20 | 16.47 | | 1.41 |
| 0.80–1.00 | 71.36 | 11.79 | 16.85 | | 1.46 |
| 1.00–1.40 | 72.76 | 11.46 | 15.78 | | 1.51 |
| 1.40–1.80 | 68.85 | 14.30 | 16.85 | | 1.38 |

of the field after 107 and 114 min for the 100% and FH experiments, respectively, but never reached the end for the SH experiment because of higher infiltration and roughness properties of that furrow. Average applied bromide concentrations for the 100%, FH, and SH experiments were 2.36, 2.79, and 5.35 g $l^{-1}$, respectively. As discussed earlier, the solute application time was 140 min for the 100% experiment and 70 min for the FH and SH experiments. Below we summarize the remaining measurements obtained for both the free-draining and blocked-end experiments.

In all experiments, the inflow rate was measured using pre-calibrated 2.5 cm size double water meters (two water meters on the same line). Water meter observations were recorded every 5–10 min during the experiments. Applied bromide amounts and concentrations were determined separately for each experimental furrow using small site-calibrated solute boxes of 4 l capacity each and equipped with valves and floaters and connected to 220 l barrels having a particular bromide concentration (see Abbasi et al. (2003b) for more details). Overland water samples for analysis of bromide concentrations were taken at 10, 60, and 100 m from inlet for the blocked-end experiments, and at 5, 60, and 110 m for the free-draining experiment (i.e., the inlet, middle, and outlet sites, respectively). Water samples were collected as soon as water reached a particular station. Samples were collected initially every minute, decreasing gradually to once every 10 min and then increasing to once every 2–3 min after termination of the solute application (such as for the FH experiment). The samples were stored in an air-conditioned environment pending analysis for bromide concentrations. Moreover, water flow depth readings were recorded each 20 m using staff gauges placed at the bottom of the monitored furrows at the same time as overland water samples were collected.

Soil samples for analyzing bromide concentrations and gravimetric soil water contents were collected 5 days after each irrigation at the same locations where water samples were taken (inlet, middle, and outlet sites). At each site, the samples were taken on one side of the monitored furrows at three locations in a cross-section perpendicular to the furrow axis (Fig. 1a) at similar depths as used for the neutron probe measurements. Soil samples from the free-draining experiment were taken 5 days after both irrigations. The water and soil samples were analyzed for bromide with a Lachat QuikChem flow injection analyzer using standard colorimetric procedures.

Runoff water in the FD experiment was collected at the end of the furrows and removed using a small pump, since the furrows were almost level. The pumped water was weighed every 5 min during the irrigation period using an electronic scale. Measured reference pan evapotranspiration (RE) rates from the nearest weather station (about 150 m from the experimental field) and

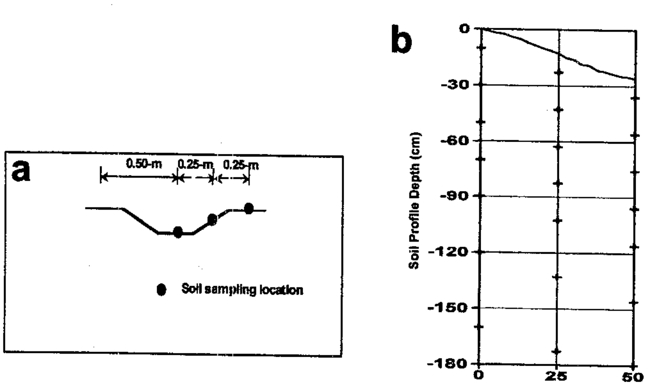



**Fig. 1** **a** Soil sampling locations on furrow cross-section and **b** network of rectangular elements used for estimating bromide recovery rates, solute application efficiency, and water and solute deep percolation rates (*symbols* represent locations of the collected soil samples for gravimetric soil water content and bromide concentration measurements)

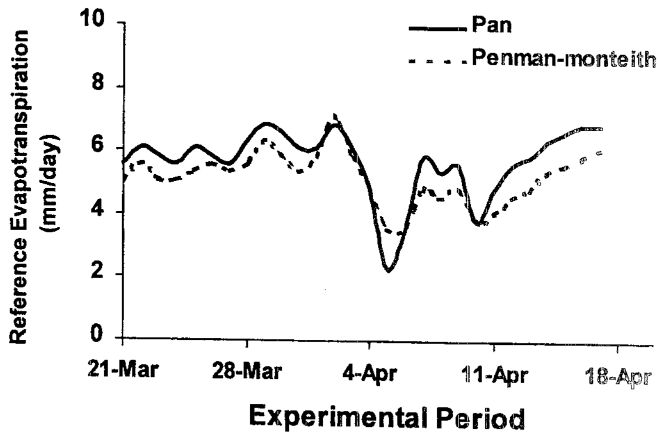



**Fig. 2** Pan reference evapotranspiration rates (*solid line*) and rates estimated using the Penman-Monteith method (*dashed line*)

estimated RE rates obtained using the Penman-Monteith (PM) method (http://www.ag.arizona.edu/azmet) are presented in Fig. 2. The first FD irrigation was run on 23 March 2001, and the second irrigation 10 days later, while the 100% and FH experiments were carried out on the same day (3 April 2001) and the SH experiment 1 day later. An 18 mm 3-h-long rainfall event occurred on 7 April. Furthermore, static ground water depth in the area was too deep, ranging from 45 to 90 m, to affect the results of this study.

Solute recovery rates and application efficiencies

For estimating bromide recovery rates, the soil profiles at each monitoring (inlet, middle, and outlet sites) site were subdivided into a network of 12 rectangular elements ($0.30 \times 0.25$ m each) as shown in Fig. 1b. The measured bromide concentrations and gravimetrical soil water contents of 12 elements were averaged for each rectangle and used to calculate the mass of bromide in each profile by summation over all rectangles. Bromide masses obtained in this way for the different sites of a particular experiment were subsequently averaged and used to estimate bromide recovery rates for each experiment.

As mentioned earlier, fertigation is often used to move solutes with the irrigation water into the soil root zone. To judge the solute application efficiencies of the invoked fertigation scenarios in our study, we also calculated for each experiment the stored bromide masses in the root zone, assuming a rooting depth of 1.0 m. Solute application efficiency (SAE) is defined here as the mass of solute stored in the soil root zone divided by the total amount of solute applied. Solute application efficiencies close to 1.0 indicate that all or most of the applied solute remained in the soil root zone, while efficiencies less than 1.0 indicate the transport of solutes to depths below the rooting depth such that these are no longer available for root uptake.

We also prepared contour maps of the measured soil water content and bromide concentrations using the SURFER code (Golden Software 1999) selecting kriging with a linear variogram for gridding operations.

## Results and discussion

Bromide recovery rates were 67.4 and 50.6% after the first and second irrigation of the FD experiment and 110.3, 81.8, and 108.9% for the 100%, FH, and SH experiments, respectively. Relatively high bromide recoveries were obtained except in the FD furrows in which bromide was mostly leached below the lowest sampling depth. Having high observed bromide concentrations in the bottom parts of the profile generally resulted in lower recovery rates. This is mostly an immediate consequence of the longer irrigation and solute application times, being 275 min as compared to 70 and 140 min for the blocked-end experiments (Table 2). Other possible reasons that may have contributed to the low recovery rates for the FD experiment are spatial variability in the soil bulk density and probable minor errors in field data collection and subsequent laboratory analysis.

Average of water flow depths, opportunity times, and solute applications at various sites of different conducted experiments are listed in Table 2. Flow depth changes within the monitored sites in the FD experiments were more pronounced likely because of the outlet conditions, being free-draining, while they were more uniform in the blocked-end furrows (Table 2, Fig. 3). Similarly, opportunity times changed considerably from one site to another in the different experiments.

**Table 2** Average of water flow depths, opportunity times, and solute application times for the various experiments. Values for the FD experiment during the second irrigation are given in parenthesis

| Experiment | | Flow depth (cm) | Opportunity time (min) | Solute application time (min) |
|---|---|---|---|---|
| FD | Inlet | 8.7(7.7) | 305(185) | 275 (0) |
| | Middle | 6.0(5.8) | 243(162) | |
| | Outlet | 2.7(2.5) | 70(92) | |
| 100% | Inlet | 9.0 | 184 | 140 |
| | Middle | 6.7 | 155 | |
| | Outlet | 6.2 | 75 | |
| FH | Inlet | 8.0 | 168 | 70 |
| | Middle | 7.8 | 142 | |
| | Outlet | 6.7 | 90 | |
| SH | Inlet | 8.1 | 156 | 70 |
| | Middle | 5.3 | 118 | |

Measured subsurface bromide concentration contours at different sites of the FD experiment are compared in Fig. 4. Notice the substantial non-uniformity in the bromide distributions within sites and between the different sites. Bromide concentrations at the inlet and middle sites distributed uniformly throughout the entire soil profile, while distributions at the outlet site were very non-uniform and limited to a small part of the furrow cross-section. This was mainly due to the low water flow depths and short solute application times at the outlet site. Average water flow depths during the first irrigation were about 8.7, 6, and 2.7 cm, and bromide application times (opportunity times) 305, 243, and 70 min, for the inlet, middle, and outlet sites, respectively (Fig. 3a). Flow depths were almost identical during the second irrigation (Fig. 3b), as almost the same inflow rates were used during the two irrigations. Opportunity times during the second irrigation for the sites were 185, 162, and 92 min, respectively.

The second irrigation (75 mm average depth) and the 18 mm rainfall event about 1.5 days prior to sampling (i.e., 3.5 days after the irrigation) caused the solute to leach down and distribute more evenly within the profile, especially at the inlet and middle sites, whereas the solute distribution at the outlet site remained more or less the same as after the first irrigation (Fig. 4b). Peak bromide concentrations decreased from about 9 g $l^{-1}$ after the first irrigation to about 3.5 g $l^{-1}$ after the second because of advective transport and probably some dispersion. Results show much deeper solute movement towards and across the bottom of the inlet and middle sites, whereas solute at the outlet site transported to a

**Fig. 3** Measured water flow depths in the furrows at different sites and experiments

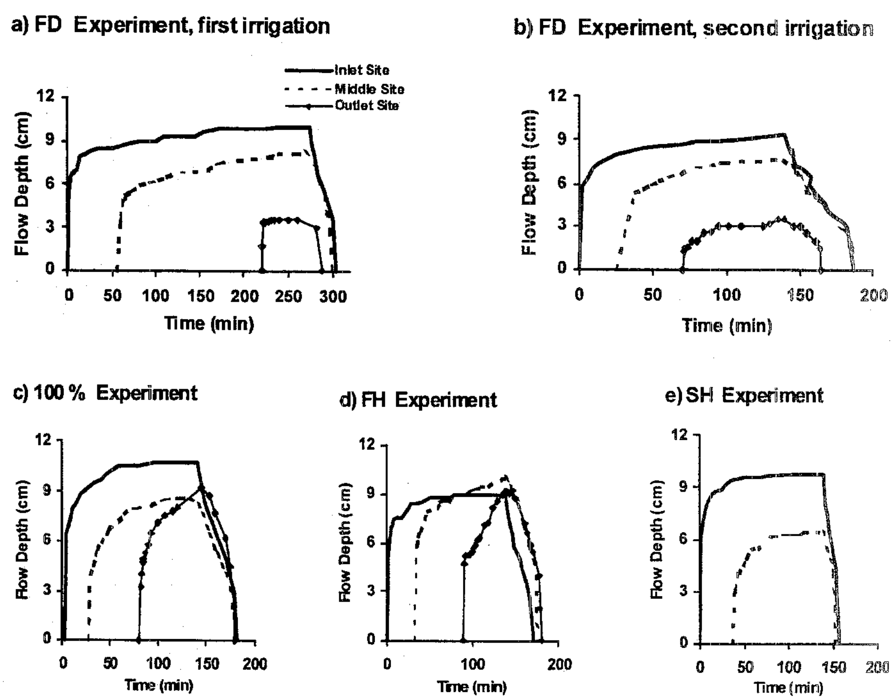
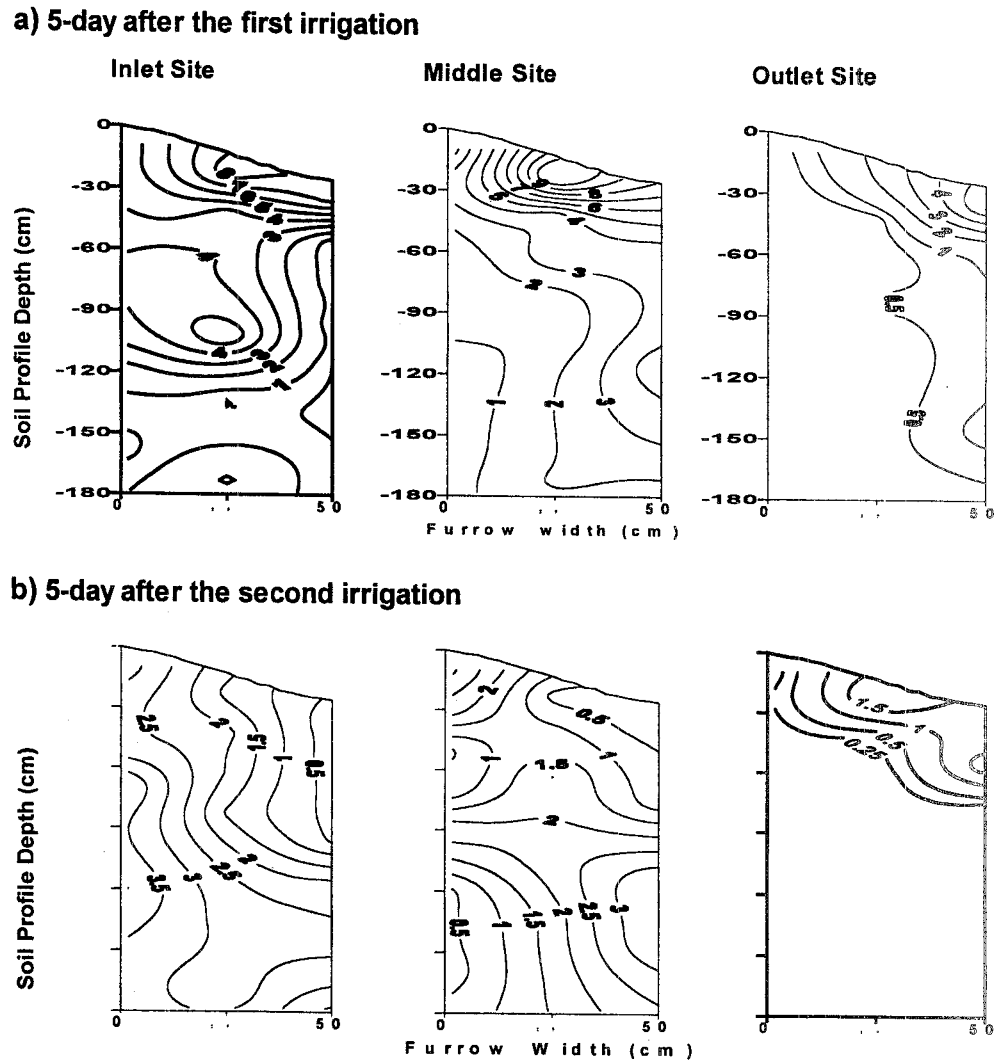


Fig. 4 Measured bromide concentrations (g $l^{-1}$) at the different sites of the free-draining experiment: a 5 days after the first irrigation and b 5 days after the second irrigation




maximum depth of only about 60 cm. Abbasi et al. (2003a) found more or less similar results for short blocked-end furrows during steady flow at the same experimental field. They showed that relatively low flow depths (e.g., 6 cm) and short solute application times (about 30 min) did not lead to uniform solute distributions, while higher flow depths (e.g., 10 or 14 cm) with the same application times resulted in more uniform distributions within the soil profile. However, solute leached much more deeply at relatively low and moderate flow depths (6 and 10 cm) with relatively longer solute applications.

Overall, results from the blocked-end experiments (Fig. 5) showed qualitatively more or less the same trends as for the FD experiment, i.e., non-uniform solute distributions at the outlet sites, and uniform and similar distributions at the inlet and middle sites, except for the 100% experiment. Notice that water failed to reach the outlet during the SH experiment (Fig. 5c) because of higher infiltration and roughness properties (see Abbasi et al. 2003b).

Quantitatively, the results should be explained separately for each experiment, since the amounts of applied bromide for the different experiments were not identical because of several unexpected technical and practical problems during execution of the field experiments.

The similar observed distributions at the middle and outlet sites for the 100% experiment were somewhat unexpected, since the flow depth and the solute application time for the middle site were closer to the inlet site than to the outlet. This suggests that spatial variability in the soil hydraulic and transport properties may have played an important role. Measured flow depths were about 9, 6.7, and 6.2 cm and application times 184, 155, and 75 min for the inlet, middle, and outlet sites, respectively.

Solute application efficiencies (SAEs), defined earlier, were used to quantitatively compare the effectiveness of the fertigation schemes considered in this study. SAEs for the FD, 100%, FH, and SH experiments were 49.8, 100, 64.0, and 92.7%, respectively. The low efficiency of the FD experiment was partly due to deep percolation beyond the root zone, and partly because of solute runoff losses at the end of the field. The blocked-end experiments (100% and SH in particular) generally provided higher efficiencies than the

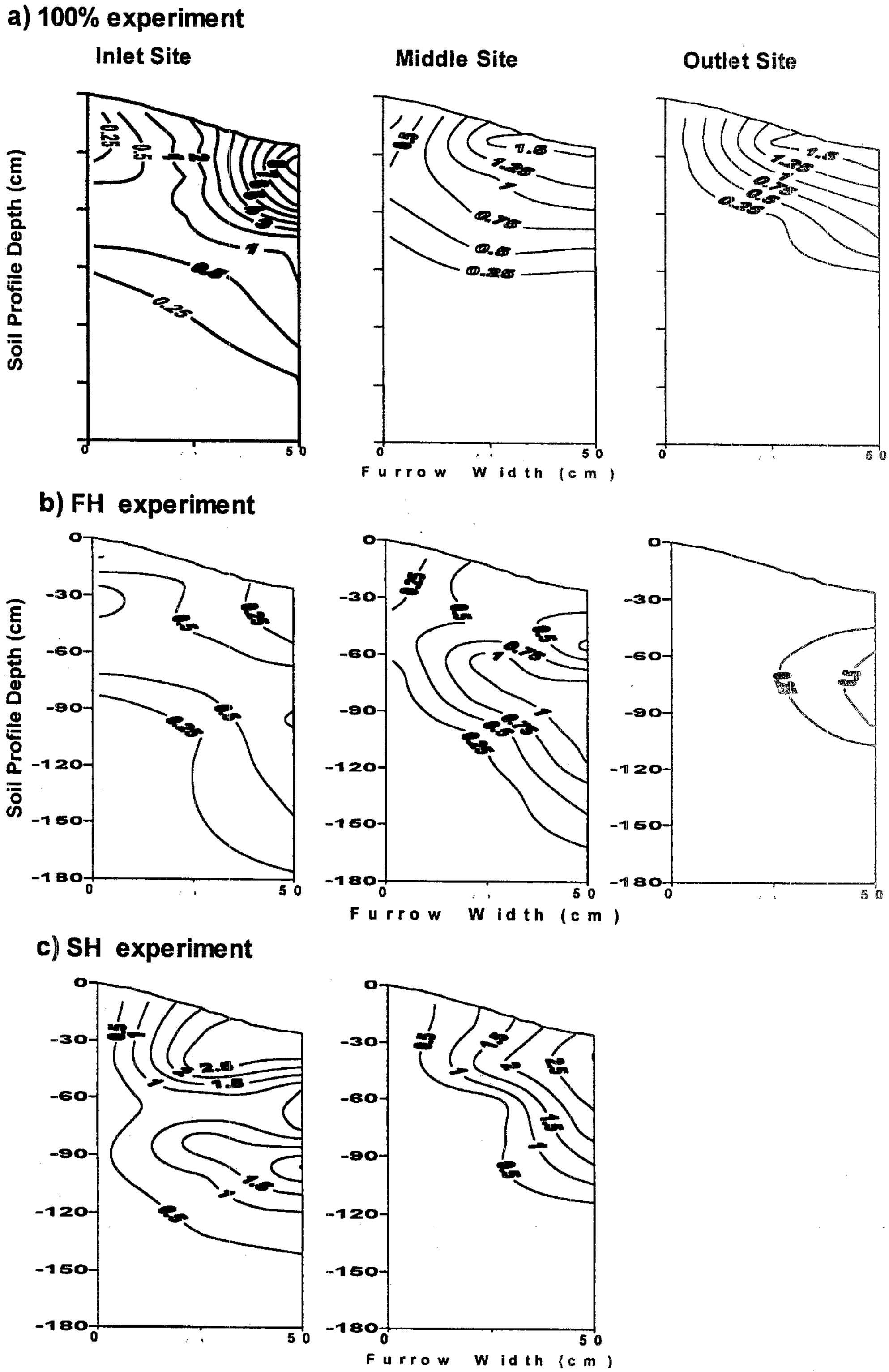



**Fig. 5** Measured bromide concentrations (g $l^{-1}$) at the different sites of the blocked-end experiments: **a** 100% experiment, **b** FH experiment, and **c** SH experiment

free-drainage experiment, due to higher inflow rates, and shorter irrigation and solute application times. Applying solute during the first half of the irrigation (e.g., the FH experiment) also caused transport to deeper layers because of leaching during the second half of the irrigation. The higher efficiencies for the 100% and SH experiments were likely caused in part by having too high estimates of the bromide masses in the profiles. Abbasi et al. (2003a) reported low-half solute distribution uniformities ($DU_{LH}$) of 72, 88, 62, and 74% for the FD, 100%, FH, and SH experiments, respectively. Having relatively high distribution uniformities (such as for the FD experiment) does not necessarily mean high SAE values, since some of the applied water and dissolved solutes may be leached below the soil root zone.

Volumetric soil water contents, taken with neutron probe and TDR, 6 h after each irrigation event at the inlet and outlet sites of the FD experiment, are compared in Fig. 6. Generally there was little difference between the two sites. Water at the inlet site distributed reasonably well within the soil profile, whereas at the outlet water moved predominantly downward but not laterally to areas under the ridge of the furrow. Water contents in those areas remained almost unchanged. Water flow toward the furrow ridge depends mostly on capillary forces, which should be relatively low in the present experiments because of the coarse-textured nature of the field site (a sandy loam). As expected, water percolated to deeper depths at the inlet site. For instance, water contents at the bottom of the inlet site increased from an initial value of about 20% to 25% 10 days after the first irrigation (results not shown), while water contents at the outlet site remained unchanged (about 14%). These results agree with the findings of Abbasi et al. (2003a) on 3 m short blocked furrows. They reported much deeper transport of water and solutes for experiments in which the same amounts of water and solutes were applied, as compared with the same-duration experiments.

For a better judgment, a one-dimensional comparison of depthwise soil water contents at the bottom and ridge of furrows is presented in Fig. 7 for the inlet and outlet sites. A noticeable difference in soil moisture was observed between the two locations in the soil surface layers in particular. Difference at the outlet site was more pronounced due to lower flow depth being about 2.7 cm (Table 2). Discrepancies below a depth of 80 cm (e.g., Fig. 7a) were mostly because of the initial conditions.

Soil water contents, measured gravimetrically and converted to volumetric values using soil bulk densities, at the various sites and for the different experiments 5 days after irrigation are presented in Figs. 8 and 9. Water content contours were more or less uniform and the same for the different sites and experiments, mostly because of evaporation from the soil surface and an 18-mm rainfall several days after the irrigation but before the soil sampling. Earlier measurements soon after the irrigation would probably have provided a better comparison between the different sites and experiments.

Deep percolation rates of water and solutes below a depth of 1.0 m were estimated 5 days after the irrigation at different monitored sites (Table 3). For this purpose, the mass of water and bromide was counted using the network of rectangular elements shown in Fig. 1b and measured water contents, solute concentrations, and soil bulk densities. Results showed a substantial difference in percolated rates within the sites and also experiments

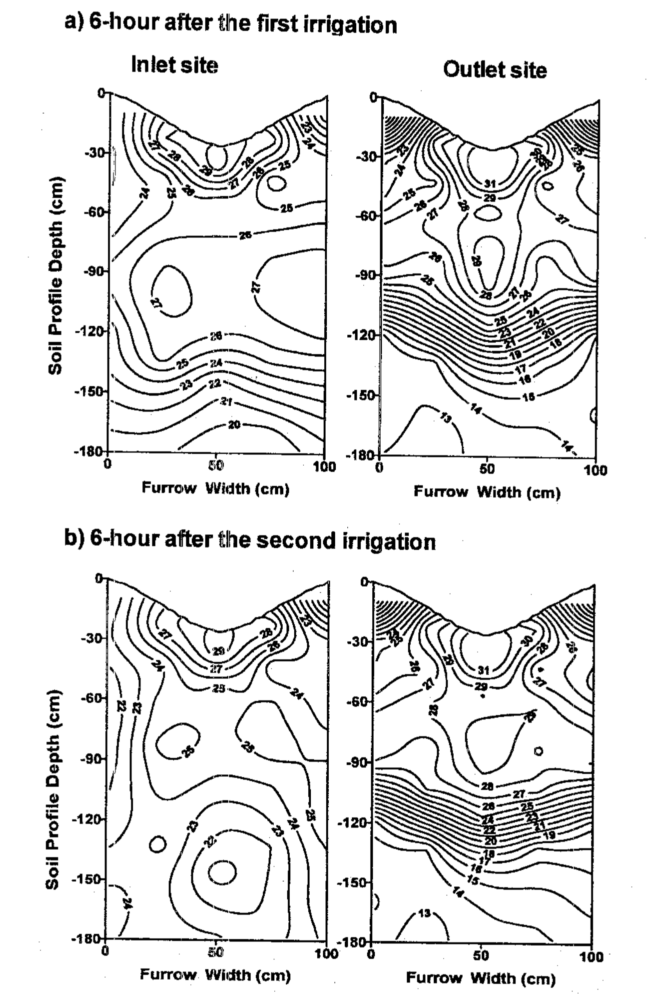



**Fig. 6** Soil water contents (cm$^3$ cm$^{-3}$) at the inlet and outlet sites of the free draining experiment **a** 6 h after the first irrigation, and **b** 6 h after the second irrigation (taken with neutron probe and TDR)

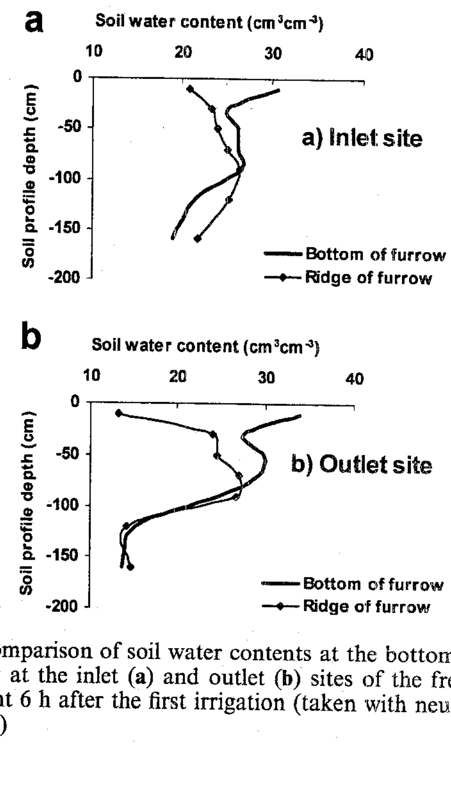



**Fig. 7** Comparison of soil water contents at the bottom and ridge of furrow at the inlet (**a**) and outlet (**b**) sites of the free-draining experiment 6 h after the first irrigation (taken with neutron probe and TDR)

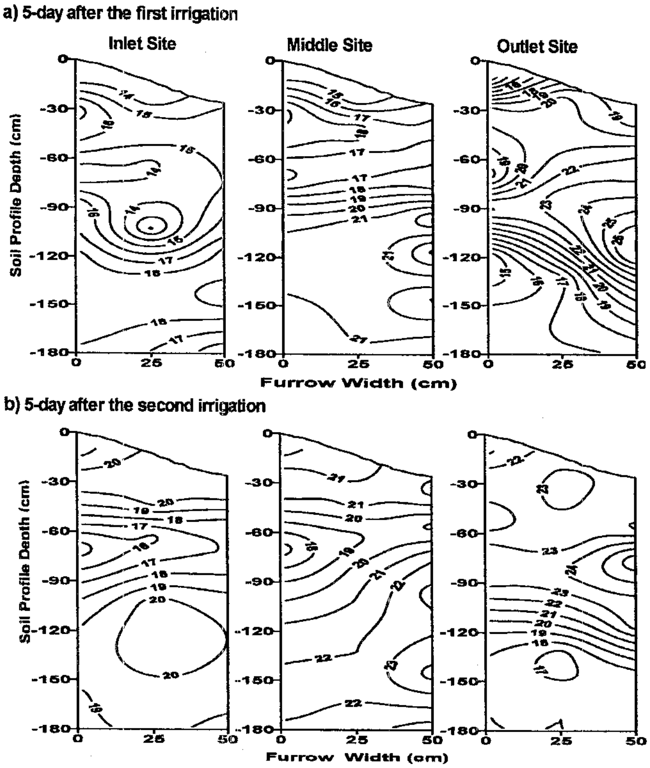



**Fig. 8** Measured soil water contents ($cm^3$ $cm^{-3}$) at the different sites of the free-draining experiment: **a** 5 days after the first irrigation, and **b** 5 days after the second irrigation

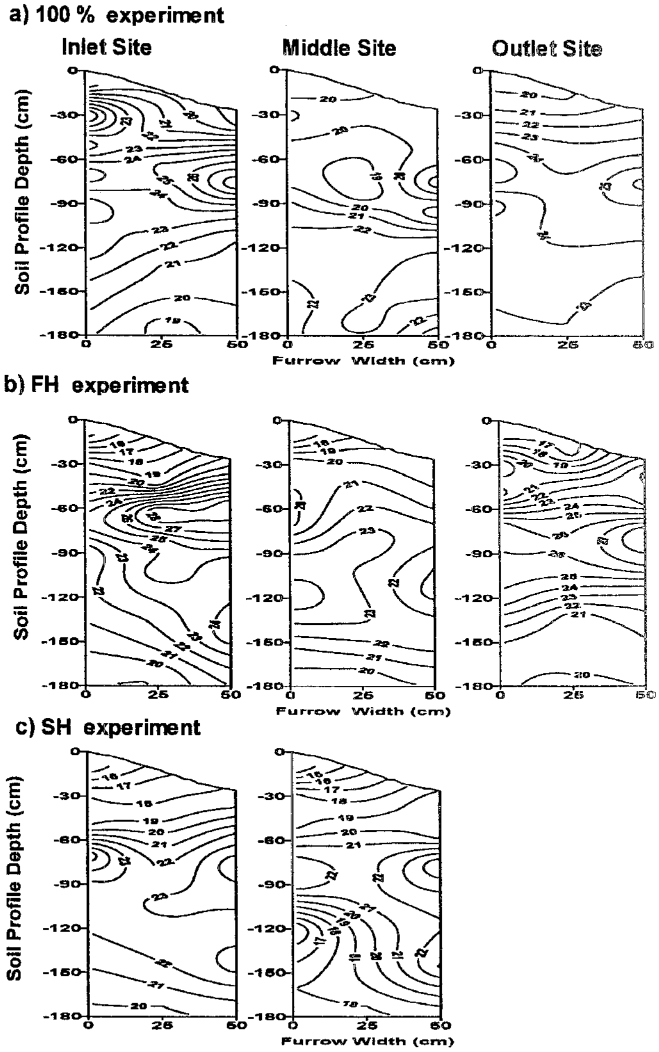



**Fig. 9** Soil water contents ($cm^3$ $cm^{-3}$) measured at the different sites of the blocked-end experiments, 5 days after the irrigation: **a** 100% experiment, **b** FH experiment, and **c** SH experiment

with a dependency to flow depths and solute application/opportunity times. For instance, the FD experiment with longer irrigation and solute application resulted in more deep percolation of both water and solutes and 100% and in particular SH experiments provided less percolated rates. Deep percolated rates decreased along the furrows in all the experiments because of differences in flow depths and solute application/opportunity times.

**Table 3** Deep percolation rates of water and solute at the different sites of the various experiments

| Experiment | | Water (l/m) | Solute (g/m) |
|---|---|---|---|
| FD | Inlet | 82.7 | 139.7 |
| | Middle | 50.2 | 95.9 |
| | Outlet | 24.1 | 8.4 |
| 100% | Inlet | 57.0 | 13.0 |
| | Middle | 71.6 | 3.2 |
| | Outlet | 46.6 | 1.1 |
| FH | Inlet | 68.6 | 16.1 |
| | Middle | 66.9 | 11.2 |
| | Outlet | 45.9 | 0.7 |
| SH | Inlet | 40.3 | 23.0 |
| | Middle | 23.6 | 5.8 |

## Summary and conclusion

Results of four alternative fertigation practices during two irrigation regimes in long furrows were presented to illustrate the effects of flow depth and solute application time on water and solute distributions below the furrows under realistic field conditions. The results show a dependency of downward solute transport on flow depth and application time, and considerable non-uniformity in the solute distributions as observed at various sites along the furrows. However, it was difficult to associate the observed solute non-uniformity with only flow depth and/or application time since heterogeneous soil surface conditions and variability in the soil hydraulic and transport properties, commonly found at large field sites, can substantially influence solute transport and leaching. Subsurface solute distributions below the first half-length of the furrows were much more uniform than in the second half, regardless of the irrigation regime and the solute application time. Solute distribution uniformity and application efficiency together can provide useful information about invoked fertigation practices. The effects of flow depth and irrigation application time on the distribution of water below the furrows were more pronounced in the soil surface layers, and found to be relatively minor at deeper depths. However, it was not fully investigated because of common practical problems of large field-scale studies (e.g., rain and different initial conditions observed at various sites and experiments). Water and solute deep percolation rates also showed dependency on flow depth and solute application/opportunity time and gradually decreased along the furrows. As conclusion, both flow depth and solute application/opportunity time can play a major role in water flow and solute distribution and small changes in flow depth can result in considerable non-uniformity in water and solute distributions below the furrows.

Fertigation is a complicated process affected by such factors as the initial water contents and soil surface conditions, the adopted irrigation regime, and flow properties (e.g., inflow rate, infiltration characteristics, and soil hydraulic properties). Applying fertilizers during a second irrigation, or even with subsequent irrigations, rather than only the first irrigation, may improve the solute distribution uniformity and application efficiency since the effects of several of those factors (e.g., initial condition, infiltration, and roughness properties) can substantially decrease during the second and particularly subsequent irrigations.

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