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### Abstract

Understanding the influence of irrigation methods on solute transport is essential to properly manage chemical use in agricultural soils. In this study, we compare the transport of a conservative solute (bromide) under sprinkler and flood irrigations on a sandy clay loam (mixed Ustollic Haplargid) under no-till condition. After spraying 148.8 kg/ha of KBr on the surface,  $\approx$  25 cm of irrigation water was applied in six increments over two months as flood irrigation on one plot and as sprinkler irrigation on another plot. The net applied water (NAW = irrigation + precipitation – evaporation) was similar for both plots, which allowed the comparison of the Br profiles for the two types of irrigation. Water content and Br concentration were sampled at 5, 19, 34, and 68 days after chemical application.

The recovered mass of Br and the location of center of mass were comparable for the two types of irrigation. The spread around the center of mass, however, was higher for the flood-irrigated plot. On the flood-irrigated plot, more mass leached below the depth of 90 cm, with the differences being statistically significant. The velocity of the Br center of mass was consistently 10%–20% larger than the piston displacement velocity. Dispersion and velocity coefficients varied substantially between sampling time. A recent quasi-steady solution of the convection–dispersion equation [M.H. Nachabe, L.R. Ahuja, Quasi-analytical solution for predicting the redistribution of surface-applied chemicals. *Trans. ASAE* 39(5) (1996) 1659–1664], which accounts for variable flow and dispersion, simulates the Br profiles fairly well. © 1999 Elsevier Science B.V. All rights reserved.

**Keywords:** Solute transport; Irrigation; Tillage; Bromide

### 1. Introduction

Agriculture systems in arid and semi-arid regions are becoming increasingly dependent on irrigation and fertilizers. For sustainable agricultural production in these systems, we need to understand the role irrigation on the transport of soluble chemicals in soils. In

particular, the no-till or reduced-till techniques, which are replacing conventional tillage in many parts of the United States, enhance the development of macropores near the surface (e.g. Fleming, 1992). If no-till is combined with a flood irrigation scheme, macropore flow may rapidly channel the available irrigation water and agro-chemicals from the surface, preventing their efficient uptake by plants' roots. On the other hand, if irrigation water is applied at a relatively slow rate with a sprinkler to avoid surface ponding, macropore flow may be reduced. Van Ommen et al. (1989)

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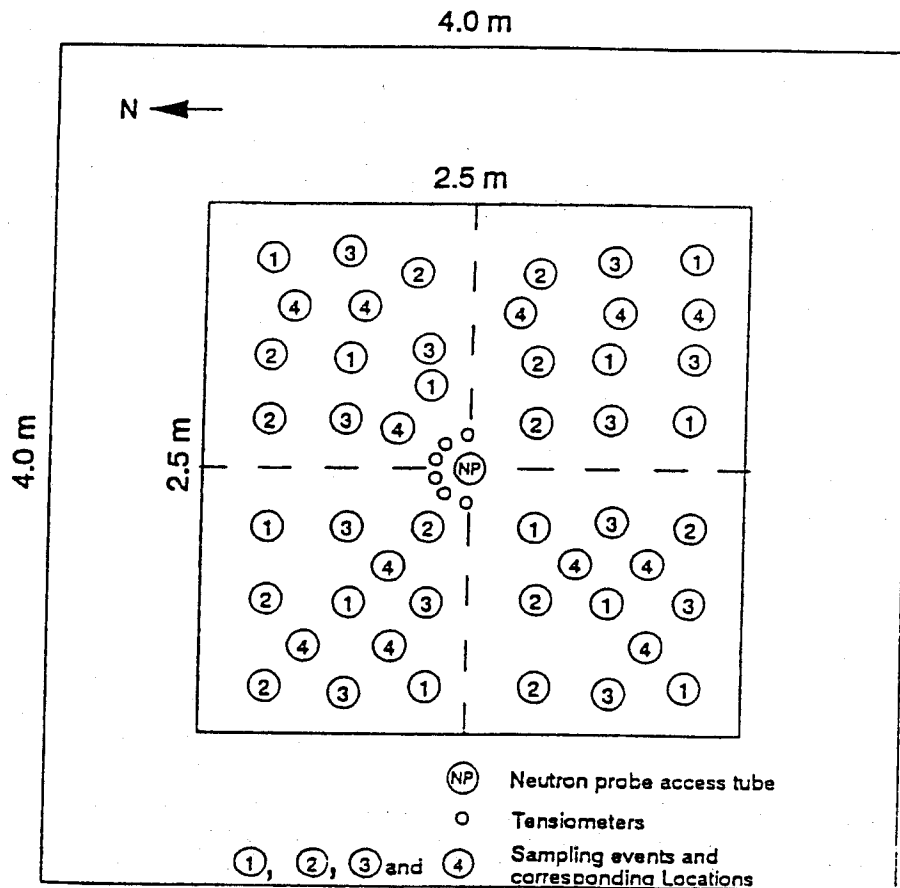


Fig. 1. Layout of soil core sampling locations for each sampling time: (1) 5 days; (2) 19 days; (3) 34 days; and (5) 68 days.

have shown that macropore flow is less likely to occur during light rainfall than during ponding. Under macropore flow condition, the velocity of solute transport may exceed the pore water velocity (ratio of Darcy's flux to average water content). For intermittent ponding, Rice et al. (1988) found the solute velocity to be nearly five times the average pore water velocity.

In addition to irrigation, evaporation plays a significant role in controlling the distribution of applied agro-chemicals in soils of semi-arid systems. The influence of evaporation on solute transport in the root zone has been overlooked by many researchers, perhaps because of the time required to observe transport due to evaporation. Whereas preferential transport of solute is typically detected by sampling a few hours after water and chemical application, evaporation is a slower process. In general, evaporation pulls

the soil solution upward, thus more chemicals are retained in the root zone close to the surface. The combined influence of preferential flow and evaporation on solute distribution has not been studied in detail in semi-arid agricultural systems (Great Plains Agricultural Council Water Quality Task Force, 1992).

In this study, we analyse the experimental data on transport of an inert, nonreactive solute (bromide) under sprinkler and flood irrigation in Waverly, Colorado. The experiments lasted 68 days and were conducted on soil plots that have not been tilled for at least 5 years to allow macropore development. We model the resulting Br profiles using a new quasi-steady state solution of the two parameters convection–dispersion equation (CDE). Introduced recently by Nachabe and Ahuja (1996), this new solution

allows for quasi-steady state flow conditions: average water content and flux are used within a time period, but the water content and flux are allowed to change for following time periods. In many field situations, including these experiments, measurements are conducted at discrete time intervals, and constant averages have to be assumed between these intervals. Thus quasi-steady assumption provides a description of flow conditions which is consistent with data collected in the field. The CDE can be quite successful in predicting the average behavior of solute transport in soils. In particular, for agricultural applications we are interested in quantifying the total mass of solute in the root zone, the movement of solute center of mass, and the spread around the center of mass. To assess potential contamination of ground water by agrochemicals, we are also interested in deep leaching below the root zone.

The objectives of this study are to: (i) conduct field experiments to compare solute transport under flood and sprinkler irrigation on a no-till soil; (ii) analyze the influence of preferential flow and evaporation on the transport of solutes; and (iii) test the prediction of the new CDE solution under field conditions. This study will contribute to our understanding of agricultural systems management in semi-arid regions.

## 2. Materials and methods

### 2.1. Field experiments

#### 2.1.1. Site description

The experiments were conducted on private land in Waverly, 19.2 km north of the Colorado State University in Fort Collins, CO. The soil at this site (fine loamy mixed Ustollic Haplargid) has not been tilled for over five years. The texture is sandy clay loam, with a moderate sub-angular blocky structure. Earthworm channels can be visually observed in the top layer of soil. The channels are approximately 2 mm in diameter, with a density of 160 pores/m<sup>2</sup>. No macropore channels were observed below 1 m.

Two 4 × 4 m plots were clipped of their native grass vegetation for the experiments. A sprinkler irrigation system was installed on the first plot, while the other plot was dyked for flood irrigation. Each plot contained a 2.5 × 2.5 m inner area for soil core

sampling. The layout of plots, instrumentation, and sampling locations are shown in Fig. 1. The general surface slope in the area is mild, but two flat plots were selected to prevent erosion during the experiments.

#### 2.1.2. Chemical and irrigation applications

A knapsack hand sprayer was used to pre-apply 148.8 kg/ha of KBr on each plot. The sprinkler-irrigated plot was irrigated with eight sprinkler heads, producing a discharge rate of 3 cm/hr<sup>1</sup> (but operated intermittently to prevent ponding) and a coefficient of uniformity of 90%. In the flood-irrigated plot, flooding was accomplished with four 2.54 cm diameter hose with a total discharge of 1.6 l/s. To minimize erosion with flood irrigation, the discharge end of each hose was inserted into a beaker which was laid horizontally on its side. The hoses were shifted a few times to improve the uniformity of water application. On the day of chemical application, four soil cores were taken from each plot to determine the initial soil moisture. These holes were backfilled directly after sampling.

#### 2.1.3. Soil-water and bromide sampling

Evaporation was measured daily during the experiments using draining micro-lysimeters. For soil-water and bromide analysis, we collected cores four times at the locations indicated in Fig. 1. The sampling times were 5, 19, 34 and 68 days from the time of application of the Br. Systematic sampling (Peterson and Calvin, 1986) was used to collect the soil cores with a 2.33 cm 'environmentalists soil probe' (Clements Associates Inc., Newton, IA). At each sampling time, 12 different points were sampled (see Fig. 1). The depth of sampling was 2.5 m for days 19, 34 and 68, and 0.96 m on day 5. After removal, soil samples were stored immediately at 4°C until sectioning and extraction. To minimize soil disturbance and compaction at all times, the plots were accessed via planks supported by bricks at the ends. All holes were backfilled immediately following sampling.

Polyethylene bags were then used to store the sectioned soil samples for bromide and water content analysis. Soil water content analysis was done gravimetrically by drying 15–40 g of soil for 24 h at 104°C (Gardner, 1986). The Br extraction method was similar to the procedure detailed in Rhoades

(1986). Extraction efficiency tests were performed on five replicates outside the plot to verify the accuracy. Bromide analysis was done using ion chromatography at the University of Illinois.

## 2.2. Data analysis and modeling

From the measured water content and bromide concentration profiles, we calculated the total mass of Br in the profile,  $m_i$ , with the formulae:

$$m_i = \int_{z=0}^D \theta(z, t_i) c(z, t_i) dz \quad (1)$$

where  $\theta(z, t_i)$  and  $c(z, t_i)$  are the measured water content and bromide concentration at depth  $z$  and sampling day  $t_i$ . The integral is from the soil surface to  $D$ , the depth of sampling in this study. Note that, in this case, the maximum depth of Br distribution was always shorter than  $D$ . The recovery is defined as  $r(\%) = 100 \times m_i/M$ , where  $M = 148.8$  kg/ha, the total mass of Br applied at the surface. The shapes of the Br profiles were described using the depth to center of mass and the spread around the center of mass calculated as:

$$X_i = \frac{1}{m_i} \int_{z=0}^D z \theta(z, t_i) c(z, t_i) dz \quad (2)$$

$$\sigma_i^2 = \frac{1}{m_i} \int_{z=0}^D (z - X_i)^2 \theta(z, t_i) c(z, t_i) dz \quad (3)$$

where  $X_i$  is the depth to center of mass (in cm) and  $\sigma_i$  is the spread around the center of mass (in cm) at sampling day  $t_i$ . The  $r$ ,  $X_i$ , and  $\sigma_i$  evaluated from the measured data provide an overall description of Br profile at sampling times.

To evaluate the nature of Br transport, we compared the average pore water velocity with the velocity of the solute center of mass. The average pore water velocity is calculated as:

$$v_w(\text{cm/day}) = \frac{\text{NAW}}{\Delta t} \frac{1}{\theta} \quad (4)$$

where NAW is the net applied water between two sampling times (NAW in cm = irrigation + precipitation – the measured evaporation),  $\Delta t$  is time between two sampling dates ( $\Delta t = t_i - t_{i-1}$  in days), and  $\theta$  is the average water content from the soil surface to the maximum depth of solute between

the two sampling dates (in  $\text{cm}^3/\text{cm}^3$ ). If the transport of Br in the soil solution is like a piston displacing fluid, then the pore water velocity,  $v_w$ , will be the velocity of movement of Br. This piston behavior is well explained by Nachabe and Morel-Seytoux (1995), among others. On the other hand, the actual velocity of solute center of mass between two sampling dates is:

$$v_s(\text{cm/day}) = \frac{X_{i+1} - X_i}{\Delta t} \quad (5)$$

where  $X_i$  and  $X_{i+1}$  are the depth to center of mass of Br at sampling times  $t_i$  and  $t_{i+1}$ . In general,  $v_s$  can be larger than  $v_w$  because of mixing and preferential movement of solute and water. The preferential movement of the infiltrating water and solute may bypass (not displace) the initial soil water, so the actual movement occurs in a fraction of the soil pore that is smaller than the measured  $\theta$  used in Eq. (4).

Because evaporation influences mass transport close to the surface, we computed the change with time of the chemical mass in the top 10 cm of soil. Also we determined the mass of chemical leached below 90 cm to assess deep leaching.

Finally, to statistically assert the significance of the differences between Br transport under the two irrigation treatments, we conducted factor analysis [analysis of variance (ANOVA)] to compare variation within and between plots. The hypothesis of equal means is rejected if  $F_c$ , the ratio of mean square variation between plots to the mean square variation within plots, is larger than  $F_{1-\alpha}$ , the  $1 - \alpha$  quantile of the  $F$  distribution. Details on the application of analysis of variance can be found in Draper and Smith (1981).

### 2.2.1. Simulation with CDE

We used the two-parameters CDE to predict the movement of Br. The CDE is:

$$-\frac{\partial(qc)}{\partial z} + \frac{\partial}{\partial z} \left( D_p \theta \frac{\partial c}{\partial z} \right) = \frac{\partial(\theta c)}{\partial t} \quad (6)$$

where  $z$  is depth (in cm),  $t$  is time (in days),  $q(z, t)$  is Darcy's flux (in cm/day),  $\theta(z, t)$  is water content, and  $D_p$  is dispersion coefficient (in  $\text{cm}^2/\text{day}$ ). The convection–dispersion equation is linked to the transient water flow field through  $q(z, t)$  and  $\theta(z, t)$ , which need to be specified in order to solve Eq. (6). Analytical solution of the CDE in a transient water flow field

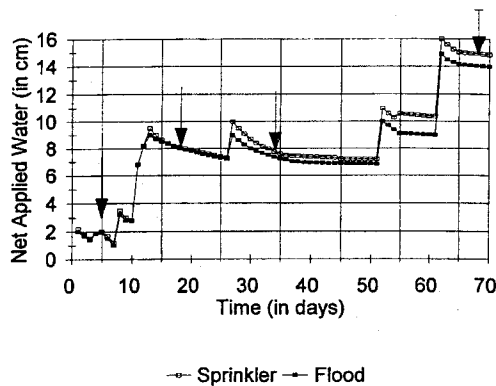


Fig. 2. Net applied water (NAW) on the plots. The arrows indicate the time of sampling.

can be achieved for particular infiltration models like Broadbridge and White and Green and Ampt (Nachabe and Morel-Seytoux, 1995). Van Genuchten and Alves (1982) derived analytical solutions of the CDE for constant  $q$  and  $\theta$ . These solutions are used in traditional modeling with the CDE. More recently, Nachabe and Ahuja (1996) introduced a quasi-analytical solution for Eq. (6), which approximates the transient flow field as quasi-steady state flow field: average  $q$  and  $\theta$  are assumed constant within a time period, but  $q$  and  $\theta$  are allowed to change for different time periods. For this experiment, the time period is the time between two sampling dates. For an arbitrary initial solute distribution, the quasi-analytical solution is given by (Nachabe and Ahuja, 1996):

$$c(t, z) = \sum_{m=1}^i \frac{(i+j-m-1)!}{(i-m)!(j-1)!} A^{i-m} B^j c_m \quad (7)$$

where  $i$  is an index for depth,  $z = i\Delta z$ , where  $\Delta z$  is a layer thickness,  $j$  is an index for time,  $t = j\Delta t$ , where  $\Delta t$  is a time step, and  $A$  and  $B$  are functions of the measured  $q$ ,  $\theta$ , and the dispersion coefficient  $D_p$ , all assumed constant in a period (Nachabe and Ahuja, 1996).

### 3. Results and discussion

#### 3.1. Water content distribution

The NAW (NAW = irrigation + precipitation – measured evaporation) is shown in Fig. 2 from the time of application of bromide. As demonstrated by the negative slope of the NAW curve, evaporation decreased rapidly from its maximum, attained immediately following irrigation. Following irrigation, soil water content near the surface is high, and evaporation is at its maximum. As soil water is depleted, evaporation decreased and reached a relatively steady value. Even though we tried to achieve similar NAW conditions on both plots, the NAW on the flood-irrigated plot was slightly less than the NAW on the sprinkler-irrigated plot. Those differences can be attributed to irrigation method and variation in evaporation, which cannot be controlled in the experiment.

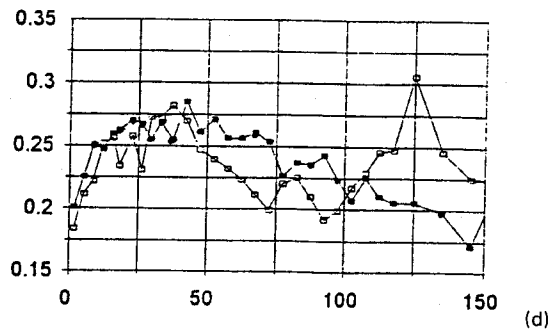
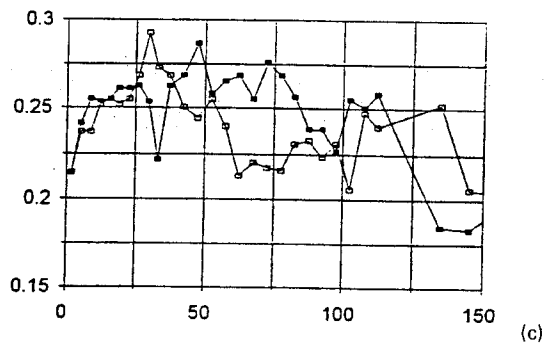
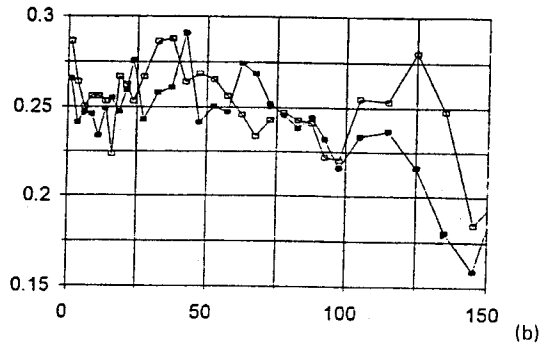
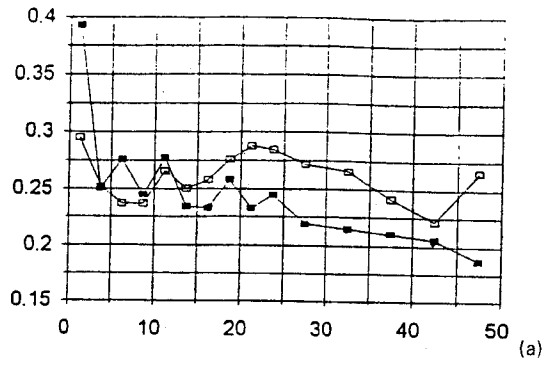
The water content profiles for the two plots are shown in Fig. 3. The flood-irrigated plot had a consistently higher water content deeper in the profiles. Under ponding flood irrigation, all pore sizes participate in water flow, whereas the largest pores are expected to be excluded under the non-saturating sprinkler irrigation. Because of this preferential flow, water flow in the largest pores is deeper. At a time of 5 days, the water content on the flood-irrigated plot was between 15 and 50 cm higher. As more NAW is provided, the flood-irrigated plot had a higher water content, of between 1 and 1.5 m [Fig. 3(b)–(d)]. The difference in water content distribution between plots is unlikely to be caused by local soil heterogeneity, because all profiles are averages of 12 soil cores in each plot (Fig. 1). In practice, these differences in water content distribution do impact the efficiency of irrigation method in meeting crop water demand, especially if plants' roots do not extend below 1 m. Apparently, because of the activation of large pores, water supplied in flood irrigation may bypass a shallow root zone.

#### 3.2. Solute transport

The percent Br recovery,  $r$ , the location of center of

Fig. 3. Comparison of water content profiles under sprinkler (filled squares) and flood (empty squares) irrigation at time: (a) 5 days; (b) 19 days; (c) 34 days; and (d) 68 days.

Water Content ( $\text{cm}^3 / \text{cm}^3$ )



Depth (cm)

Table 1  
Comparison of mean bromide transport under sprinkler and flood irrigation.

Sampling time (days)	Flood irrigation				Sprinkler irrigation			
	5	19	34	68	5	19	34	68
$r$ (%)	95.0	80.8	90.4	48.8	90.0	76.0	89.6	55.2
$X_i$ (cm)	5.0	36.8	33.8	66.9	6.7	36.7	40.0	64
$\sigma_i$ (cm)	8.0	23.2	45.1	53.4	6.8	20.2	33.7	36.6
% mass in top 10 cm	88.9	6.6	14.6	11.9	79.0	5.8	8.5	4.8
% mass below 90 cm	<sup>a</sup>	2.9	3.6	30.7	<sup>a</sup>	0.92	3.1	14.7

<sup>a</sup> not measured.

mass,  $X_i$ , and the spread around the center of mass,  $\sigma_i$ , are documented in Table 1. All values are means of 12 soil cores in each of the  $2.5 \times 2.5$  m. Table 2 documents the factor analysis results to test the hypothesis of equality of these means on the plots. For both plots, bromide recovery was over 75% for the first three sampling dates and around 50% for the last sampling date. The percentage of Br mass recovered was similar on the two plots, regardless of the irrigation implement. As indicated by factor analysis, the hypothesis of equality of mean recoveries cannot be rejected. Therefore, the type of irrigation did not affect the fraction of mass recovered. With the exception of the last sampling date, these recoveries are satisfactory and consistent with other investigations that used bromide under no-till (e.g. Fleming and Butters, 1995). In these experiments, the loss of mass cannot be attributed to deep leaching below the depth of sampling, because Br distribution was confined to the top 1.5 m, which is less than the sampling depth. Less than full recovery can be due to several factors, such as incomplete extraction of Br from soil cores in the analysis, uptake of Br by roots, and local heterogeneity within the plot. Another reason for incomplete recovery can be the lateral spread of Br to outside the sampled area (thus reducing Br mass in the plot) due to soil-water gradients between the irrigated plot and surrounding soils.

### 3.2.1. Evaporation and preferential flow

The movement of the center of mass of Br appeared to be controlled by the NAW. The average transport of the center of mass was downward before day 19, and then upward (by 3 cm) between sampling days 19 and 34 on the flood-irrigated plot. This upward movement

is due to the reduction in the amount of irrigation between these two dates, which resulted in a slight deficit in NAW on the flood-irrigated plot between these dates (Fig. 2). In this case, due to evaporation, soil solution was sucked upward, defying gravity. As expected, the upward movement of solute was mostly noticeable in the evaporation zone close to the surface. On the flood-irrigated plot, the fraction of bromide mass in the top 10 cm of soil increased from 6.6% to 14.6% between days 19 and 34. Similarly, the mass of Br in this zone increased from 5.8% to 8.5% on the sprinkler plot (Table 1). Perhaps it is the first time in the literature that upward transport of a soluble chemical is reported in an irrigated field. Due to evaporation and deficit in NAW, the chemical mass entrapped in the top 10 cm of soil was consistently higher in the flood-irrigated plot (Table 1). For example, at a time of 68 days, this zone contained 11.9% of the total mass of solute on the flood plot vs 4.8% on the sprinkler-irrigated plot. These differences are statistically significant (Table 2). In semi-arid systems, a delicate balance between evaporation

Table 2  
Summary of factor analysis, testing the hypothesis of equality of means between plots at 5% significance level. NR hypothesis of equal means cannot be rejected. R hypothesis of equal means is rejected.

Sampling time (days)	5	19	34	68
$r$ (%)	NR	NR	NR	NR
$X_i$ (cm)	R	NR	NR	NR
$\sigma_i$ (cm)	R	NR	R	R
% mass in top 10 cm	R	R	R	R
% mass below 90 cm	<sup>a</sup>	R	R	R

<sup>a</sup> not measured.



Table 3  
Comparison of piston velocity with velocity of solute center of mass

Sampling time (days)	Flood irrigation				Sprinkler irrigation			
	5	19	34	68	5	19	34	68
$v_w$ (cm/day)	<sup>a</sup>	1.90	-0.08	0.88	<sup>a</sup>	1.84	0.2	0.59
$v_s$ (cm/day)	<sup>a</sup>	2.27	-0.2	0.97	<sup>a</sup>	2.10	0.2	0.70
$v_s/v_w$	<sup>a</sup>	1.19	0.42	1.10	<sup>a</sup>	1.14	1.0	1.19

<sup>a</sup> not calculated.

and irrigation shall be maintained to achieve a proper distribution of solute in the profile.

With the exceptions of velocities calculated between days 19 and 34, the velocity of Br center of mass,  $v_s$ , was 10%–20% greater than the pore water velocity,  $v_w$  (Table 3). This suggests that piston displacement using average pore water velocity may slightly underestimate or overestimate (in the case

of negative velocities) the downward transport of the solute center of mass. This also indicates that faster than piston displacement of solute can occur without saturation of the soil surface like the case of the sprinkler-irrigated plot.

To evaluate deep solute transport and potential preferential flow between the two types of irrigation, we compare the mass of Br that leached below 90 cm.

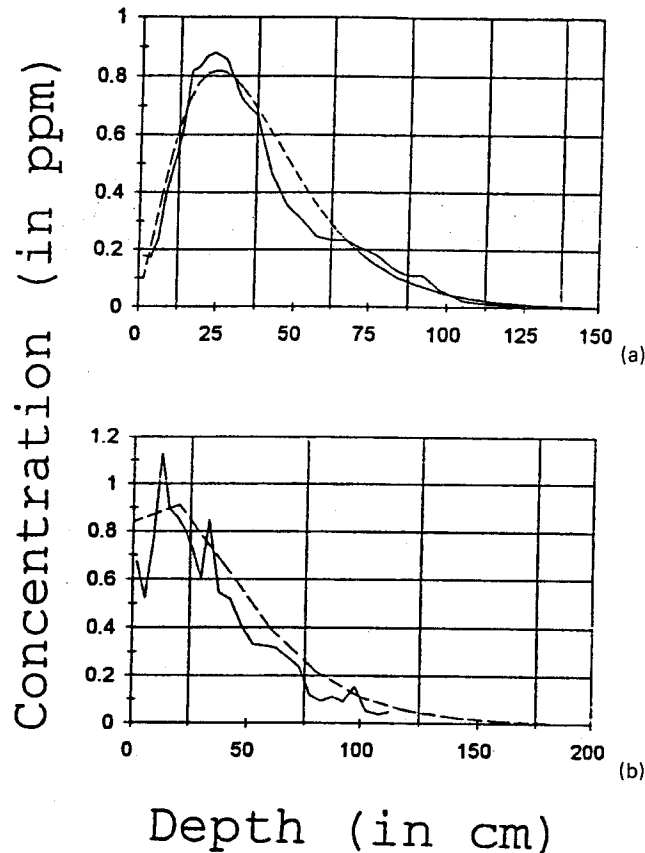


Fig. 4. Measured (solid line) and simulated (dash line) bromide profiles under flood irrigation at times: (a) 19 days; and (b) 34 days.

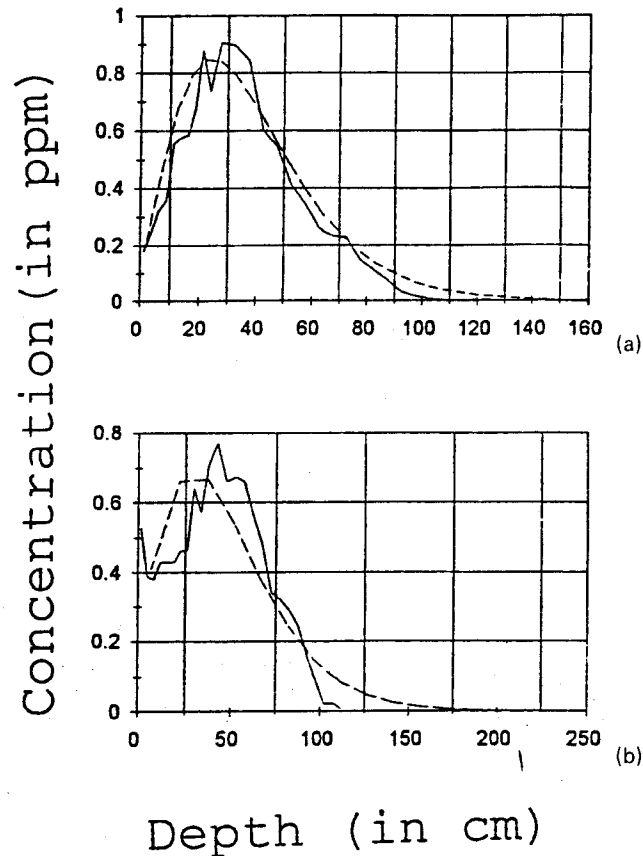


Fig. 5. Measured (solid line) and simulated (dash line) bromide profiles under sprinkler irrigation at times: (a) 19 days; and (b) 34 days.

The fraction of Br mass that leached below 90 cm was always greater for the flood-irrigated plot, although more NAW was available on the sprinkler-irrigated plot (Fig. 1). At a time of 68 days, the leachate under flood irrigation was over two times the mass of leachate in the sprinkler plot. This finding is consistent with the water content profile showing higher water content deeper in the profile on the flood-irrigated plot. Therefore, due to deep leaching, less nutrients will be available for crops in the case of flood irrigation. In reality, it will be difficult to determine the influence of macropore flow on the preferential and deep transport of Br when the chemical is sprayed at the surface. Before floodwater channels bromide through macropores, channels open at the surface and the irrigation water should mix and pick the chemical from the soil surface. Raindrop impact, which enhances chemical release with free water at

the surface (e.g. Ahuja, 1990), is not a factor in flood irrigation.

Evaporation and preferential flow spreads the solute in opposite directions resulting in the flattening of the Br profile. The spreads,  $\sigma_i$ , increased monotonically with time on both plots (Table 1). This indicated that the Br distribution is becoming flatter and more uniform with time. Because saturation of the soil surface allows all soil pores to transmit water and solute,  $\sigma_i$  were larger under flood irrigation than under sprinkler irrigation (Table 1 and Table 2).

### 3.2.2. Simulation with the solution by Nachabe and Ahuja (1996)

Fig. 4 and Fig. 5 show the measured and simulated Br profiles on the two plots. The Br profiles for all cases were well-simulated by the new solution. Again, the merit of the new solution lays in its ability to

mimic quasi-steady conditions, thus allowing non-uniform transport of center of mass and dispersion with time. Traditionally, simulations with the CDE had to assume constant flow conditions for the entire simulation period. In practice, we found two advantages for the new solution. First, the new CDE solution contains only two parameters, average velocity and dispersion coefficient, which can be easily calibrated from field data. In contrast, many of the now available models contain parameters that are difficult to estimate with the limited field data. Second, the new solution is efficient computationally, therefore, it can be used to simulate long-term transport of soluble agro-chemicals.

#### 4. Conclusion

This study documents the differences in water and solute transport between flood and sprinkler irrigation on a no-till soil. For the same soil and similar amount of irrigation water, these differences can be summarized as follows: (1) the flood-irrigated plot has higher water content deeper in the profile. Sprinkler-irrigation can be more efficient in providing crop water uptake, especially if the roots do not extend below 90 cm; (2) movement of the center of mass of bromide was similar for both types of irrigation; (3) the spread around the center of mass, however, was higher for flood irrigation; (4) the velocity of solute center of mass was greater by 10%–20% than the piston displacement velocity; (5) evaporation keeps the solute close to the surface which may assist plants' uptake of nutrients.

We emphasize that the analysis of profiles in this study is determined from average water and chemical profiles over long period of times. Thus, the Br profiles in this analysis are the results of the interplay of numerous factors including irrigation, preferential flow, evaporation, hydrodynamic dispersion, diffusion, and exclusion of anionic solute from negatively charged minerals. Unlike laboratory experiments, it will be difficult to isolate the influence of a particular factor on transport. Therefore, one should be

cautioned before extrapolating the results of laboratory experiments into the field.

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