Macropore Transport of a Surface-Applied Bromide Tracer: Model Evaluation and Refinement

L. R. Ahuja, K. E. Johnsen, and G. C. Heathman

ABSTRACT

Rapid transport of surface-applied agrichemicals to groundwater through macropores is a major problem that requires a better understanding and quantification. A simple model of macropore flow and transport of a surface-applied Br\textsuperscript{–} tracer under rainfall was evaluated and refined by testing against soil-column data reported earlier. The experiments consisted of eight treatment combinations, each in duplicate, of the following conditions: soil initially air dry vs. soil initially wetted by rainfall; a 10-mm layer of dry aggregates on the surface vs. no aggregates; and a 3-mm artificial macropore made along the column’s vertical axis vs. no macropore. A solution of SrBr\textsubscript{2} was atomized over the surface, followed by application of simulated rainfall. Evaluation of the model indicated that: (i) once the Green-Ampt infiltration parameters were calibrated on control columns, water flow into other columns was simulated correctly; however, in order to match the macropore bottom outflow, the lateral absorption of water from macropore to soil matrix had to be adjusted for compaction of the macropore wall and variable water pressure around the pore circumference under small macropore flow rates; (ii) for chemical mass in macropore outflow, better results were obtained if, in the wetted portion of the soil profile, the water flow down the macropore mixed with \(0.5\) mm of soil around the walls and its soil solution; (iii) microporosity of surface aggregates determined from control columns resulted in fairly good simulations of the increase of the chemical in macropore flow caused by aggregates.

The term macropore is used here to refer to relatively large noncapillary pores or channels, such as worm holes, channels left by decayed roots, interpedal voids, and drying cracks in soils (Ahuja et al., 1993). Preferential flow and transport, or short-circuiting, through macropores is an important mechanism in the movement of pollutants to groundwater (Thomas and Phillips, 1979; Beven and Germann, 1982; White, 1985; Everts and Kanwar, 1990; Singh and Kanwar, 1991; Czapar et al., 1992). A number of field and laboratory studies conducted during the past decade have enhanced our understanding of the mechanism and, to some extent, the processes involved. There is, however, still a need to gain further understanding of rapid macropore flow and transport by conducting careful experiments under controlled conditions. This need exists especially for the transport of surface-applied chemicals under rainfall conditions. The demand for knowledge of these processes is related to the growing practice of minimum or no tillage, which entails: (i) greater pesticide use and application of both pesticides and fertilizers on the soil surface with minimum incorporation into the soil, thus increasing soluble chemical amounts in surface flow that can enter the macropores; and (ii) enhanced earthworm activity due to plant residues on the surface, and greater numbers of worm holes and root channels staying open at the surface due to residues and no tillage (Zachmann et al., 1987; Edwards et al., 1990).

The amount of surface-applied chemical available for preferential flow during rainfall can be influenced by many factors, including soil water and soil surface conditions prior to application and rainfall. High initial soil water content decreases infiltration of water and chemical into the soil matrix and, thus, increases macropore flow and transport. Surface soil aggregation results in regions with finer pores that tend to hold back initial water and chemical in the upper layer. This greatly increases the amount of a surface-applied chemical available to be transferred to macropore flow (Heathman et al., 1992, 1995). Thus, the aggregation of field soils confounds the process of chemical transport through the soil matrix and macropores. Understanding the characteristics and magnitude of macropore transport will guide us in selecting suitable management practices to minimize adverse effects on ground or surface water.

The objective of this study was to evaluate and refine a simple model of soil matrix vs. macropore transport of a surface-applied Br\textsuperscript{–} tracer under rainfall in an initially unsaturated soil by testing against experimental data from controlled studies in soil columns reported earlier (Heathman et al., 1995). The experimental treatments consisted of two initial soil-water conditions, without and with surface aggregates, and without and with an artificial macropore. The transport model is a component of the USDA-ARS soil–plant–climate–management model called RZWQM (Root Zone Water Quality Model, RZWQM Team, 1992).

RZWQM OVERVIEW AND MODEL REVISION

The components of RZWQM dealing with water and chemical transport were described in detail in Ahuja et al. (1993). During the present study, several aspects of the model were refined to better predict the observed data. An overview of these components and revisions are summarized below.

The Green–Ampt equation is used to calculate infiltration rates into a homogenous or layered profile divided into 10-mm increments (Green and Ampt, 1911; Childs and Bybordi, 1969; Hachum and Alfaro, 1980):

\[
V = \bar{K}_s \frac{(H_e + H_a + Z_{ef})}{Z_{ef}} \tag{1}
\]

where \(V\) is the infiltration rate at any given time, \(\bar{K}_s\) is the effective saturated hydraulic conductivity of the wetted zone, \(H_e\) is the capillary drive or suction at the wetting front, \(H_a\) is the depth of surface ponding, if any, and \(Z_{ef}\) is the depth of the wetting front.

For a homogenous soil, the \(\bar{K}_s\) in Eq. [1] is commonly set equal to the field-saturated hydraulic conductivity of the soil. This conductivity is generally less than the fully saturated conductivity...
hydraulic conductivity, $K_s$, because of air entrapment. Furthermore, Morel-Seytoux and Khanji (1974) showed that in a homogeneous soil, for the Green–Ampt model to give results comparable to a more rigorous two-phase flow equation, the right-hand side of Eq. [1] should be divided by a “viscous resistance correction factor” of $\approx 1.4$ to account for the resistance of water movement due to the simultaneous movement of air. Bouwer (1969) and Brakensiek and Onstand (1977) found the effective $K_s$ to be about one-half of the fully saturated $K_s$. Under certain conditions, soil surface sealing may develop on a bare soil, which may further reduce the value of effective $K_s$. For all the above reasons, we defined

$$\overline{K_s} = \frac{K_s}{\text{VRCF}}$$  \[2\]

where VRCF is defined as the viscous resistance and entrapped air correction factor. It is essentially a reduction of the measured $K_s$ due to entrapped air, the resulting viscous resistance, and surface sealing.

The only source of water and chemicals available to and transported through the macropores is overland flow generated at the soil surface and the chemicals it picks up from the surface soil by mixing and raindrop impact. The excess rainfall or overland flow is calculated as the difference between rainfall and infiltration in each time step. The degree of mixing between rainwater and soil solution in the micro- and mesopores is assumed to be unity at the soil surface ($z = 0$) and to decrease with depth ($z$):

$$B = e^{-hc}$$  \[3\]

where $B$ represents the fraction of rainwater that mixes with soil solution at any depth, and $h$ is a parameter that depends on the soil type, surface roughness, crusting, and cover conditions. Although Ahuja (1986) found the value of $h$, integrated across 10-mm intervals, to be close to 4.4 for a number of soils, this parameter can require some calibration depending on soil conditions near the surface.

Two domains of flow, the soil matrix and macropore channels, interact through walls of the macropore channels. The solution in macropore flow is subject to lateral absorption into the soil matrix. The transient radial infiltration rate from a cylindrical macropore is calculated based on the Green–Ampt approach (Ahuja et al., 1993). Compaction along macropore walls may influence the ability of the soil to absorb water and chemicals from macropores. Under field conditions, for example, the worm holes and root channels may have their walls compacted or made impervious by some organic coating. To account for such effects, we multiplied the radial infiltration rate from the macropore by an appropriate reduction factor:

$$V_r = \text{SFCT} V_r^*$$  \[4\]

where $V_r$ is the radial infiltration rate, $V_r^*$ is the Green–Ampt radial infiltration rate, and SFCT is the absorption correction factor.

A further refinement of the macropore flow model was made after initial simulations in this study consistently underpredicted observed Br$^-$ mass in the bottom outflow out of macropores. In the original model, the macropore flow did not interact or mix with water and chemical in the soil around the macropore wall in the wetted portion of the soil profile. Better results were obtained when this flow was allowed to mix with soil solution within 0.5 mm of the macropore wall. This refinement was then incorporated permanently into the model.

For purposes of chemical transport, the soil matrix domain is further subdivided into mesopore (mobile) and micropore (immobile) zones. The mesopores are the larger, more continuous pores through which solutes are transported during infiltration. The micropores are very small pores inside soil aggregates or ped. Once wetted, the solution within these pores is assumed to take no further part in transport during infiltration. Microporosity (MICP), defined as a fraction of the total porosity, needs to be either measured somehow or calibrated from control columns. The MICP of surface aggregates is extremely important, as it greatly affects the amount of chemical in macropore outflow (Heathman et al., 1992, 1995).

At each infiltration event, the soil solution is displaced sequentially across the wetted soil increments in the manner of piston displacement. However, the water flux during an infiltration step is always less than the mesopore soil water content of a wetted 10-mm increment. Thus, the displacement and mixing of solution in this increment is only partial. The extent of this mixing, and hence dispersion, can be controlled by allowing more than one displacement step within a given time (or infiltration) increment. Thus, this process simulates miscible displacement in the mesopores. At the end of an infiltration event, when the water movement slows down, the meso- and micropore regions are allowed to equilibrate.

Between rainfall events, soil water is redistributed by a mass-conservative, finite-difference, numerical solution of the Richards equation (Celis et al., 1987, 1990). The chemicals in solution move with water from one depth increment to the other according to the Darcy flux of water. The chemicals in the meso- and micropores are assumed to be in equilibrium during redistribution and are not treated separately.

### MATERIALS AND METHODS

#### Experimental Measurements

The model described above was evaluated on experimental data from controlled studies in soil columns under simulated rainfall reported separately (Heathman et al., 1992, 1995). Surface soil from the Kirkland silt loam series (Udertic Paleustoll) was air dried, sieved through a 3.5-mm sieve, and carefully packed in sectionable Plexiglas soil columns, 150 mm in diam. and 300 mm long. A total of 16 soil columns were subject to eight treatments, each in duplicate, consisting of combinations of: a macropore vs. no macropore, a 10-mm surface layer of soil aggregates (4.5–12.5 mm in size) vs. no aggregates, and initially air-dry soil ($\theta = 0.02$ m$^3$ m$^{-3}$) vs. soil initially saturated ($\theta = 0.54$ m$^3$ m$^{-3}$) by rainfall to a depth of $\approx 70$ mm prior to the infiltration run of interest. In the columns with a macropore, an artificial hole, 3-mm in diameter, was created with a pointed steel rod all along the vertical axis of the column, open to both the soil surface and to the bottom outflow plate. Precautions were taken to stabilize the hole at the surface with a quick-setting cement to ensure that the hole stayed open during the experimental rain. The aggregates were obtained from the same soil during the process of sieving the air-dried sample through a 3.5-mm sieve.

The aggregate layer was placed on the surface after the desired initial condition was obtained but before the chemical solution was applied. Just prior to the experimental rainfall, an 18.2-mL solution of SrBr$_2$, at a concentration of 22 400 mg L$^{-1}$ Br$^-$, was uniformly sprayed on the soil surface. The rate of application was 22.4 g Br$^-$ m$^{-2}$. A simulated rainfall of $\approx 0.0236$ mm s$^{-1}$ (8.5 cm h$^{-1}$) intensity (measured before and after each run) was applied over the column. In columns without a macropore, surface runoff rates and Br$^-$ concentrations were measured. In columns with a macropore, all the overland flow generated went into the macropore, and macropore outflow rates through the column bottom and its Br$^-$ concentrations were measured. At the conclusion of rainfall,
the soil column was quickly sectioned in mostly 11.5-mm increments. Water content, bulk density, and Br⁻ concentrations of these sections were measured to obtain the distributions of water and chemicals in soil. The Br⁻ concentrations were determined using an ion-specific electrode.

Model Initialization

Initialization of the model involved setting up initial and boundary conditions, defining the soil properties, and specifying the treatment. The soil properties required by the model were the water content–suction relationship, the hydraulic conductivity–suction relationship, the factors VR CF, SFCT, and b, the microporosity of each soil horizon, the macroporosity and average radius of the macropores in each horizon, and the fraction of dead-end pores. Some of the soil hydraulic properties needed for running the model were measured independently, whereas the rest were estimated or calibrated from the control columns. The water content–suction relationship, θ(τ), of the soil was measured on triplicate samples, 75 mm in diam. and 50 mm long, packed to the same bulk density as the columns (1.26 g cm⁻³). The average θ(τ) (m³ m⁻³) was represented by a slightly modified Brooks and Corey (1964, p. 1-15) function as follows:

\[ \theta(\tau) = -0.00138\tau + 0.542494 \quad \tau \leq 22.6 \text{ cm} \]
\[ \theta(\tau) = 0.7609\tau^{-0.12748} \quad \tau > 22.6 \text{ cm} \]  

A first estimate of the K(τ) (cm h⁻¹) function was obtained from the above θ(τ) function following the Brooks and Corey (1964, p. 1-15) or Campbell (1974) approach. This estimate was then refined by inverse numerical computation with respect to experimental redistribution data on a separate column, to obtain:

\[ K(\tau) = 1.714\tau^{-0.02} \quad \tau \leq 30.0 \text{ cm} \]
\[ K(\tau) = 1491.0.15\tau^{-2.01} \quad \tau > 30.0 \text{ cm} \]

Values for the parameters for VR CF, SFCT, and b were initially calibrated on appropriate control columns. In a few exceptional cases, they were adjusted to get the best fit to the observed data for each column. The microporosity of the soil matrix was assumed to be 10⁻³. The microporosity of the aggregate layer, calibrated from control columns, was set at 0.35. A continuous macropore 1.5 mm in radius gave a macroporosity of 0.00039 in all horizons. The fraction of dead-end pores was set to 10⁻¹⁰ (essentially zero).

The initial soil water content of the dry columns was assumed to be 0.02 m³ m⁻³ (based on some initial measurements), and varied for the wet columns according to what was reported in the experimental data. Water applied with the SrBr₂ solution was assumed to add 0.10 m³ m⁻³ to the initial soil water content of the top 10-mm layer in each column. The rainfall rate was assumed to be constant during the rainfall period, but varied between columns. The actual amount of SrBr₂ applied also varied slightly between columns. The actual rainfall for each column was determined by summing the measured runoff or macropore outflow and the soil water content increase due to infiltration. This rainfall amount, divided by the observed time of infiltration, gave rainfall rates between 0.0214 and 0.0311 mm s⁻¹ (77 and 112 mm h⁻¹). These rates were, on the average, higher than the mean rainfall rate of 0.0236 mm s⁻¹ (8.5 cm h⁻¹) obtained from measurements before and after the experimental columns were in place. The difference is probably due to temporal rainfall variability during the actual experiment or possibly an underapproximation of the initial soil water contents. The actual amount of SrBr₂ applied was determined with a similar mass-balance approach. Although this method of calculating the applied rainfall rates and chemical masses resulted in application rates that differed from the reported mean experimental application, it allowed us to compare results with the same amounts of total water and Br⁻ in both observed and simulated data.

Rainfall was followed by 30 min of redistribution. A constant evaporation rate of 0 mm h⁻¹ at the soil surface was used as the upper boundary condition and a unit gradient was assumed for the bottom boundary condition.

RESULTS AND DISCUSSION

It should be stated up front that we do not consider the following results on model simulations vs. the observed data as "validation" of the model, but rather as an evaluation and refinement of the initially proposed model based on a comparison of the results. We do feel, however, that this evaluation and refinement has greatly enhanced our understanding of the macropore transport of a surface-applied chemical and the role of surface aggregates in this transport.

In Table 1, the near-optimal values of the four parameters that resulted in similar results are shown for all replicate columns. The K* needed in Eq. [1] was calibrated from the rainfall infiltration data for four control columns, the duplicate initially dry (C5 and C6) and initially wet (C41 and C42) columns (Table 1). In the rest of the six dry columns, the calibrated VR CF value of 2.03 was equally well applicable to four out of six columns. In column C16, an initially dry column with a macropore and without surface aggregates, a VR CF value of 2.41 gave better results than the calibrated value. Using a value of 2.03, the simulated infiltration was greater than the observed value by a factor of 1.19, and the simulated wetting front was deeper by ≈1 cm. Similarly, in the replicate column, C17, the wetting front depth was better simulated using a VR CF value slightly higher than 2.03, although the difference between wetting front depths using the two VR CF values was <1 cm. The remaining six initially wetted columns, except one with aggregates (C28), gave good results with the calibrated VR CF value of 2.97. The simulated wetting front depth in C28 using a VR CF of 2.97 was about 2 cm shallower than with a smaller value of 1.73.

The three deviations from the calibrated values were probably due to packing and rainfall deviations for these columns, and were within the range of common experience. We think that the time interval between initial wetting and subsequent rainfall caused the soil surface in the prewetted columns to consolidate and seal somewhat by the suction created by the gravity drainage, much like the widely reported reduction in infiltration by surge irrigation (Walker et al., 1982; Trout, 1990). Hence, the prewetted columns, in general, required a higher VR CF value, i.e., a smaller effective hydraulic conductivity, during infiltration.

In all cases but three (out of 16 cases), the surface mixing parameter b of Eq. [3] was assumed equal to the uncalibrated value of 4.4, obtained from previous experimental studies (Ahuja, 1986). In duplicate initially wet columns without macropore or aggregates, C41 and C42, a b value much higher than 4.4 was needed to...
Soil water content distributions 30 min after the end of infiltration for the initially dry soil columns, one with and one without surface aggregates but both without a macropore, indicated that the Green–Ampt model described the infiltration (Fig. 1) and runoff amounts (Table 2) reasonably well. The simulated Br\textsuperscript{−} distributions in soil for these two columns (Fig. 2) also compared well with the observed, in terms of both peak position and shape. In the column with surface aggregates (C39), however, the simulated total amount of Br\textsuperscript{−} within the soil profile was less than the observed amount, and the
decrease the amount of Br\textsuperscript{−} in runoff to observed amounts (Table 1). A value of 4.4 resulted in overestimates of ≈2.46 and 1.89 g Br\textsuperscript{−} m\textsuperscript{−2} in runoff (seven or eight times the observed amount), respectively. This discrepancy in these two wet columns may be due to a slight delay in the start of runoff after chemical application, which allowed the applied chemical to move below the soil surface and, thus, less of it transferred to runoff. The delay in the start of runoff may have been due to some time lapse between the first wetting and subsequent rainfall, which allowed the surface to drain. In the third case, a wet column with both aggregates and a macropore, b was changed only slightly and although the Br\textsuperscript{−} amount in macropore outflow was not accurately predicted, the general shape of the distribution of Br\textsuperscript{−} in the soil was improved.

In the presence of aggregates, the microporosity of the top 10 mm (MICP) was set to 0.35, based on calibration of initially dry control columns with aggregates but without macropores. Even without larger aggregates placed on the surface, the initially dry soil had some small natural aggregates. Setting MICP to 0.005 helped bring the simulated amount of Br\textsuperscript{−} in runoff in the dry columns without aggregates close to the amount observed. Using a microporosity fraction of 10\textsuperscript{−5} (essentially zero) in the surface layer of these dry, nonaggregate columns resulted in underpredicting the amount of Br\textsuperscript{−} in runoff. In initially wetted columns, this microporosity fraction was set to 10\textsuperscript{−5} (Table 1) because the micropores here were already filled with water and would not absorb much of the chemical solution applied after wetting.

The observed vs. simulated soil water and Br\textsuperscript{−} content distributions presented below for each treatment combination pertain to one of the two replicate soil columns, as identified in Table 1. The comparisons for the other replicate columns were very similar to those shown in Fig. 1 to 9.
work, including controlling both the mass and size of aggregates that were placed on the surface (done only qualitatively in this study). In any case, the total difference of $\approx 1.35 \text{ g m}^{-2}$ in runoff for column C39 is only a small percentage of the amount applied (6%).

The simulation of soil water content distribution in the initially dry column with a macropore but without aggregates (C16), including the wetting around the macropore below the main wetting front, was good (Fig. 3). The seepage (the outflow from the bottom of the macropore) amounts agreed very well, too (Table 2). The overall results were pretty good in column C30, with surface aggregates, even though the simulation did not reproduce the observed soil water content heterogeneity in this column (Fig. 3).

The simulated $\text{Br}^-$ content distribution in C16, with a macropore but without aggregates, was similar in shape to that observed, but had the center of mass moved a little deeper (Fig. 4). The $\text{Br}^-$ amount in seepage was small (Table 2), but comparable. In the column with aggregates (C30), the agreement between observed and simulated $\text{Br}^-$ distribution, including the $\text{Br}^-$ content of the wetted zone around the macropore below the main $\text{Br}^-$ pulse, was excellent. The simulated amount in seepage was a little smaller than the amount observed (reverse of the trend in columns without a macropore discussed above).
Comparison of Macropore Flow Rates

Fig. 5. Comparison of macropore flow rates for initially wet and dry soils, without and with surface aggregates. In each case, the time after the macropore flow started was considered.

such a difference in sorptivity? We do not know for certain, but a possible reason is suggested by looking at the macropore flow rates (Fig. 5). When compared at similar times after macropore flow began, the rates were higher in the initially wet columns than in initially dry columns, both with and without surface aggregates. The reason that the macropore flow rates were higher in initially wet columns is that the smaller effective $K_s$ resulted in more rainfall excess, and thus more solution available for macropore flow. Furthermore, although the rainfall rate was smaller in the dry column without aggregates than in the wetted column, the result still holds for the columns with aggregates where the rainfall rate was greater in the dry column than the wet. The need for a higher SFCT in prewetted columns might indicate that the assumed boundary condition of zero water pressure at the macropore wall, all around the pore perimeter, for lateral infiltration was satisfied more closely in initially wet columns than in initially dry columns. In initially dry columns, the macropore flow rate may not have been high enough to wet the entire perimeter and maintain zero pressure all around; i.e. the water just flowed on one side of the hole. As a result, the effective lateral absorption was lower in the initially dry columns.

The simulations of initially wetted columns without a macropore adequately reproduced the observed soil water content distributions (Fig. 6) and runoff (Table 2) in columns with and without surface aggregates. The latter column was obviously different in packing, as indicated by the heterogeneity of the observed soil water content distributions, which may explain the need for a lower VRCF value (Table 1). The $Br^-$ content distributions in soil and the amount of $Br^-$ in runoff in the wet column without macropore or aggregates, were also very closely simulated (Fig. 7, Table 2). In the column with aggregates, the simulated $Br^-$ distribution differed in shape, but was close in mass; the simulated amount of $Br^-$ in

Fig. 6. Comparison of observed and simulated soil water content distribution for initially wet columns without a macropore, with and without surface aggregates.

Fig. 7. Comparison of observed and simulated soil $Br^-$ concentration distribution for initially wet columns without a macropore, with and without surface aggregates.
runoff was only slightly less. The heterogeneity of this column could be responsible for these differences, as in the case of soil water content distribution.

Distributions of soil water in initially wetted columns with a macropore, with and without surface aggregates, showed that the simulated wetting around the macropore, below the main wetting front, was somewhat greater than that observed (Fig. 8). The position of the main wetting front and the amount of seepage (Table 2) were simulated well. The soil Br⁻ content distribution (Fig. 9) was adequately simulated in the column without aggregates (C13), but not as well in the column with aggregates (C22), although the general shape of the distributions were very similar. In the latter column, with aggregates, the amount of Br⁻ in seepage was also greatly undersimulated in a relative sense (Table 2). The smaller value for ̂ (3.0 instead of 4.4) in this column helped increase the Br⁻ amount by = 13%, but mainly it helped us simulate the observed shape of the Br⁻ distribution. A mixing factor much lower than 1.0 would be needed to increase the amount of Br⁻ in seepage to the observed amount. We cannot fully explain this undersimulation, except to note that the observed amount of Br⁻ in seepage in column C22, with aggregates, was much too high compared with all other columns with aggregates. Whether this was an experimental error in this column or macropore outflow (seepage) in Table 2 show more deviation than those for the amounts of water. However, overall the simulations are not bad, except in columns 22 and 20. Both of these columns had surface aggregates. The results for column 22, which showed the maximum deviation, have been discussed above. The role of aggregates in the partitioning of surface-applied chemical be-

**Table 2. Comparison of observed and simulated water and Br⁻ in runoff or seepage.**

<table>
<thead>
<tr>
<th>Column no.</th>
<th>Simulated water</th>
<th>Observed water</th>
<th>Simulated Br⁻</th>
<th>Observed Br⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Simulated water</td>
<td>Observed water</td>
<td>Simulated Br⁻</td>
<td>Observed Br⁻</td>
</tr>
<tr>
<td>5</td>
<td>32.42</td>
<td>30.6</td>
<td>0.004</td>
<td>0.012</td>
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<td>6</td>
<td>44.88</td>
<td>44.0</td>
<td>0.017</td>
<td>0.012</td>
</tr>
<tr>
<td>39</td>
<td>22.61</td>
<td>27.2</td>
<td>2.190</td>
<td>0.843</td>
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<td>15</td>
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<td>16.0</td>
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</tr>
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<td>18.9</td>
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</tr>
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<td>11.16</td>
<td>11.7</td>
<td>0.889</td>
<td>1.211</td>
</tr>
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<td>10.7</td>
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<tr>
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<td>8.747</td>
<td>7.24</td>
<td>1.122</td>
<td>2.832</td>
</tr>
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</table>
between infiltration and runoff or macropore flow is complex and needs further work. This further work should include controls on both the mass and size of aggregates that are placed on the surface. In this study, these variables were not strictly controlled.

CONCLUSIONS

Evaluation of a simple macropore flow and transport model against experimental data from soil columns resulted in the following findings and model refinements:

1. The viscous resistance and entrapped air correction factor, which reduces the Green-Ampt infiltration rate, may vary with the soil wetting history between about 2.0 and 3.0. Higher values for prewetted columns appear to be due to consolidation and sealing of the surface.

2. Lateral absorption of the macropore walls needs to be adjusted for compaction and air entrapment. It may need to be additionally adjusted for possible partial wetting of the macropore perimeter under small macropore flow rate conditions, which results in less lateral absorption.

3. The model now mixes macropore flow with soil solution within ≈0.5 mm of the macropore wall in passing through the upper wetted portion of the soil profile.

4. The microporosity of surface aggregates is an important factor in the partitioning and transport of a surface-applied chemical.

With the above refinements, the model gave generally good descriptions of the experimental data, considering the complexity of the processes. However, further work is needed in the following areas: (i) the role of surface aggregates in partitioning the surface-applied chemicals to infiltration and macropore flow needs to be examined more carefully, including the effects of total mass vs. the size of aggregates; and (ii) the relationship between macropore flow rates and boundary conditions on the macropore wall, for different macropore sizes, needs to be studied.

REFERENCES


