Comparison of Lumped and Distributed Models for Chemical Transport by Surface Runoff

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ABSTRACT

A simple, complete mixing model is used to evaluate the degree of distortion involved in modeling chemical exchange and transport at the soil surface as a lumped rather than a distributed process. A complete mixing model was coupled to the kinematic cascade model, KINEROS, to provide a distributed representation of chemical exchange and transport. A lumped model was developed by ignoring spatial variations of chemical concentration in overland flow and in the mixing zone. Chemical concentration and transport predicted by the alternative approaches were evaluated for total transport, arrival time, peak concentration time, and peak concentration. Total chemical transport was virtually unaffected by model form. However, significant differences were found in arrival and peak concentration times as well as peak concentrations when chemical was placed only in the upper plane of a two plane cascade. The lumped model predicted significantly lower peak chemical concentrations and arrival times that were too short. A lumped model provides a good approximation for transport from a single plane, but caution should be used when a lumped model is used to describe chemical exchange and transport on a cascade of planes.

SIGNIFICANT QUANTITIES of chemicals and nutrients may be transported to receiving waters by surface runoff. The exchange and transport process at the soil surface is extremely complex and has been discussed by Ahuja (1986) and Bailey et al. (1974). Bailey et al. (1974) described four important mechanisms in the pickup of chemicals by overland flow during a runoff-producing rainfall event. They include the following mechanisms:

1. Diffusion and turbulent transport of a dissolved chemical species by movement of soil water into the overland flow
2. Desorption of the chemical species from soil particles into the soil water or directly into overland flow
3. Dissolution of solid phase chemical into the soil water or overland flow
4. Scouring of solid phase chemical or soil particles by hydraulic forces with subsequent transport and dissolution or adsorption-desorption while in transport

The importance of each of these transport mechanisms is determined by the chemical under consideration, the method of application, soil characteristics, vegetation, and recent hydrologic history.

Because of the complexity of the exchange and transport process, many simplifications have been made in model development (Frere et al., 1975, 1980; Donigian et al., 1977; Leonard et al., 1979; Ingram and Woolhiser, 1980; Ahuja, 1982; Ahuja and Lehman, 1983; Heathman et al., 1985, 1986). One widely used simplification is based on the concept of a thin soil surface zone that interacts with the surface runoff water (Steenhuis and Walter, 1980; Ahuja, 1982; Ahuja and Lehman, 1983; Heathman et al., 1985; Snyder and Woolhiser, 1985). Donigian et al. (1977) used the concept of a thin zone at the soil surface in which complete and instantaneous mixing between rainwater and soil solution occurs. Ahuja and Lehman (1983) tested Donigian's model under free infiltration conditions with Br as a tracer and found it able to predict runoff concentrations fairly accurately. Ingram and Woolhiser (1980) applied conservation of mass equations for water and chemical to differential components of overland flow and to a conceptual mixing zone to derive a more general exchange model described by partial differential equations. Experimental measurements in a flume using $CaSO_4$ as a tracer showed that concentrations in surface runoff increased down the flume and that concentrations in surface runoff were much lower than in the near surface zone of the porous medium.

With the exception of the work by Ingram and Woolhiser (1980), all chemical transport models have been lumped. That is, the equations describing chemical exchange and transport are ordinary differential equations rather than partial differential equations. Although the lumped models appear to have some predictive capability when the parameters are estimated by fitting experimental data, questions arise regarding the interpretation of the parameters and use of the equations in other field situations. The objective of this paper is to examine the degree of distortion involved in modeling a distributed system as a lumped system. Although a completely mixed reactor model may be a gross oversimplification of the chemical exchange process, we use it in our comparison of lumped and distributed models for mathematical convenience. This presupposes that conclusions regarding lumped vs. distributed models would not change due to the type of exchange model used.

MODEL DERIVATION

The derivation of a complete mixing chemical transport model is based on the following assumptions:

1. The chemical available for surface exchange and transport is soluble and there is no adsorption or desorption. However, equilibrium adsorption-desorption could easily be included.
2. A finite soil mixing depth exists in which chemical in the soil interacts with the surface runoff water.
3. Chemical from the water in the soil mixing depth, from surface runoff, and from rainfall mix completely and instantaneously in the mixing zone. The mixing zone includes the surface runoff and soil mixing depth water. Therefore, the surface runoff and soil mixing depth water always have the same chemical concentrations.
4. There is no diffusion or dispersion of chemical within or into the mixing zone from below the soil mixing depth.
5. Infiltration rate is spatially uniform, but unsteady.
6. The kinematic wave approximation is valid for surface runoff.

Lumped, Complete Mixing Model

The lumped, complete mixing (completely mixed reactor) model can be described by equations of continuity for water and a chemical species on a plane element of unit width. The continuity equation for water is

$$dS / dt + dV / dt = R - I - Q_o + Q_b \quad [1]$$

where S is the volume of water on the soil surface per unit width, $S = \int_0^L h \, dx$; h is local depth of water on the soil surface; L is the length of the plane element; x is distance on the plane element; V is the volume of water in the soil mixing depth (ϵ) per unit width,

$$V = \int_0^L \phi\epsilon \, dx$$ or the product of the porosity of the soil

(ϕ), the soil mixing depth (ϵ), and the length of the plane (L); R is the input rainfall rate (units L^2/T)

$$R = \int_0^L r \, dx,$$ r is the rainfall rate (units L/T); I is the

infiltration rate (units L^2/T), $I = \int_0^L i \, dx$, i is the infiltration rate (units L/T); Q_o is the runoff rate (units L^2/T); Q_b is the volume running onto the plane element from the plane above (units L^2/T); and t is time. The continuity equation for chemical is

$$d(SC_a) / dt + d(VC_a) / dt$$
$$= RC_{ar} - IC_a - Q_oC_a + Q_bC_{ab} \quad [2]$$

where C_a is the concentration of chemical A in the mixing zone; C_{ar} is the concentration of chemical A in the rainfall; C_{ab} is the concentration of chemical A in the water running onto the element from above. Equations [1] and [2] may be combined to obtained

the equation,

$$dC_a / dt = [R(C_{ar} - C_a) + Q_b(C_{ab} - C_a)] / (S + V) \quad [3]$$

The storage, S, is obtained by an analytical or numerical solution of the kinematic wave equation,

$$\partial h / \partial t + \partial Q_o / \partial x = r - i \quad [4]$$

where Q_o is a function of h;

$$Q_o = \alpha h^m \quad [5]$$

The h values are then integrated from 0 to L to obtain the storage at each time increment. For laminar flow $\alpha = 8gs/Kv$ where g is the acceleration due to gravity, s is the slope, K is a parameter related to surface roughness, v is kinematic viscosity of water, and $m = 3$.

Distributed, Complete Mixing Model

The distributed, complete mixing model is described by the kinematic wave Eq. [4] and [5], combined with an equation for advective transport of chemical to yield Eq. [6].

$$\partial(hC_a) / \partial t + \partial(\epsilon\phi C_a) / \partial t + \partial(Q_oC_a) / \partial x = rC_{ar} - iC_a \quad [6]$$

Equations [4] and [6] can be combined to obtain Eq. [7].

$$(h + \epsilon\phi)(\partial C_a / \partial t) + Q_o\partial C_a / \partial x = r(C_{ar} - C_a) \quad [7]$$

Note that the term $\partial(\epsilon\phi) / \partial t$ obtained by expanding the second term in Eq. [6] is equal to zero.

At the upper boundary ($x=0$), h and Q_o are both zero, hence Eq. [7] reduces to the ordinary differential equation,

$$dC_a / dt = [r(C_{ar} - C_a)] / \epsilon\phi \quad [8]$$

For the initial condition we have

$$C_a(x,0) = C_{ao} \quad [9]$$

where C_{ao} is the initial concentration of the chemical in the soil mixing zone.

Equations [4] through [8] can be solved analytically for certain special cases and may be solved numerically in general. Note that the coefficients h and Q_o in Eq. [7] are obtained from the solution of Eq. [4]. Therefore, any inaccuracies in the numerical solution for h will be reflected in the numerical solution for $C_a(x,t)$.

NUMERICAL AND ANALYTICAL SOLUTIONS

Numerical solutions to Eq. [4] were obtained by the four-point implicit scheme

$$\frac{h_{j+1}^{i+1} + h_j^{i+1} - h_{j+1}^i - h_j^i}{2\Delta t} + \frac{\omega[\langle\alpha h^m\rangle_{j+1}^{i+1} - \langle\alpha h^m\rangle_j^{i+1}]}{\Delta x}$$
$$+ (1 - \omega)\frac{[\langle\alpha h^m\rangle_{j+1}^i - \langle\alpha h^m\rangle_j^i]}{\Delta x} = r - i \quad [10]$$

where the superscript i refers to the time step, the subscript j refers to the distance step, and ω is a

weighting function $(0.5 < \omega < 1.0)$. Prior to ponding the infiltration rate i is equal to the rainfall rate. After ponding, it is given by the Smith and Parlange (1978) Eq. [11],

$$i = \frac{[K_s \exp(F/B)]}{[\exp(F/B) - 1]} \qquad [11]$$

where K_s is the saturated hydraulic conductivity, F is the accumulated infiltration depth; B is given by the expression

$$B = G \phi (S_{max} - S_i) (1 - V_r) \qquad [12]$$

where G is the effective net capillary drive, ϕ is porosity, S_{max} is the maximum relative saturation under imbibition, S_i is the initial saturation, and V_r is the relative volume of rock in the soil matrix.

The lumped model chemical concentration Eq. [3] was solved by the finite difference formulation, with the storage calculated by the kinematic wave model, for the upper and lower planes separately as follows:

$$\frac{C_a^{i+1} - C_a^i}{\Delta t} = \frac{R\left(C_{ar} - \dfrac{C_a^{i+1} + C_a^i}{2}\right)}{0.5(S^{i+1} + S^i) + V}$$

$$+ \frac{\left(\dfrac{Q_b^{i+1} + Q_b^i}{2}\right)\left[\left(\dfrac{C_{ab}^{i+1} + C_{ab}^i}{2} - \dfrac{C_a^{i+1} + C_a^i}{2}\right)\right]}{0.5(S^{i+1} + S^i) + V} \qquad [13]$$

The distributed complete mixing model chemical transport Eq. [6] was solved with the implicit finite-difference formulation as follows:

$$\langle C_a h \rangle_j^{i+1} + \langle C_a h \rangle_{j+1}^{i+1} - \langle C_a h \rangle_j^i - \langle C_a h \rangle_{j+1}^i$$

$$+ \epsilon\phi[C_a^{i+1}j + C_a^{i+1}j+1 - C_a^i j - C_a^i j+1]$$

$$+ \omega \frac{2\Delta t}{\Delta x}(\langle C_a Q_o \rangle_{j+1}^{i+1} - \langle C_a Q_o \rangle_j^{i+1})$$

$$+ (1 - \omega)\frac{2\Delta t}{\Delta x}(\langle C_a Q_o \rangle_{j+1}^i - \langle C_a Q_o \rangle_j^i)$$

$$= 2\Delta t\, r C_{ar} - \frac{\Delta t}{2}(\langle i\, C_a \rangle_j^{i+1} + \langle i\, C_a \rangle_{j+1}^{i+1}$$

$$+ \langle i\, C_a \rangle_j^i + \langle i\, C_a \rangle_{j+1}^i) \qquad [14]$$

These finite difference formulations are of first-order accuracy and some numerical dispersion is introduced in regions where the second derivatives of h or C_a are large. The accuracy of the numerical solutions can be determined by comparing them to analytical solutions for special cases. Equations [4] and [7] can be written in the characteristic form for the kinematic wave equations (Miller, 1984) as follows:

$$dh / dt = r - i \qquad [15a]$$

$$dx / dt = \alpha m\, h^{m-1} \qquad [15b]$$

and for the advective transport equation:

$$dC_a / dt = [r(C_{ar} - C_a)]/(h + \epsilon\phi) \qquad [16a]$$

$$dx / dt = Q_o/(h + \epsilon\phi) \qquad [16b]$$

The ordinary differential Eq. [15a] and [16a] are valid

along the characteristic ground curves given by Eq. [15b] and [16b], respectively.

The solution domain is shown in Fig. 1. If we consider the flow characteristic curve beginning at (0,0) we can integrate Eq. [15a] to obtain Eq. [17]:

$$h = (r - i)t = qt \qquad [17]$$

if r and i are constant and q is rainfall excess. By substituting this expression into Eq. [15b] and integrating, we obtain Eq. [18];

$$x = \alpha (r - i)^{m-1} t^m \qquad [18]$$

the characteristic curve dividing the solution domain into the unsteady but spatially uniform region shown as A and a steady but spatially varied region shown as B in Fig. 1.

Within region A (Fig. 1) Eq. [16a] can be written as

$$dC_a / dt = -rC_a / (qt + \epsilon\phi) \qquad [19]$$

if $C_{ar} = 0.0$ Integrating Eq. [19] yields

$$C_a = [C_{ao} (\epsilon\phi)^{r/q}] / [(qt + \epsilon\phi)^{r/q}] \qquad [20]$$

which is valid within the region enclosed by the line $t = 0.0$, the curve $0\text{-}t_e$, and $x = L$. In the same region Eq. [16b] becomes

$$dx/dt = [\alpha(qt)^m] / (qt + \epsilon\phi) \qquad [21]$$

with solution upon integration for the special case of laminar flow $(m = 3)$

$$x = x_o + (\alpha q^2 t^3 / 3) + (\alpha\epsilon\phi/q)$$

$$\{\epsilon\phi qt - (q^2 t^2/2) - (\epsilon\phi)^2 \ln[(\epsilon\phi + qt)/\epsilon\phi]\} \qquad [22]$$

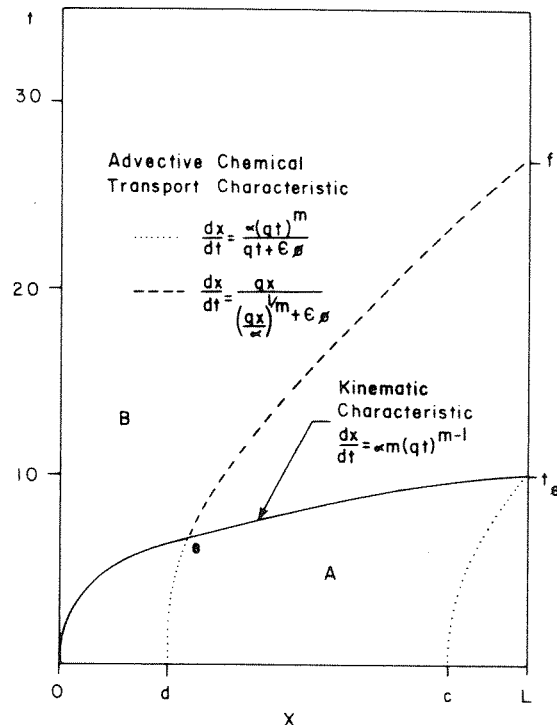where x_o is the value of x at $t = 0.0$.

Fig. 1. Solution domain for x and t in the unsteady, uniform region (A) and steady, nonuniform region (B) separated by characteristic $0 - t_e$.

In region B (Fig. 1) the solution of the kinematic wave equation is

$$\alpha h^m = Q_o = qx \qquad [23]$$

and Eq. [16a] can be divided by Eq. [16b], if $C_{ar} = 0.0$ and written as

$$dC_a / dx = -rC_a / qx \qquad [24]$$

which upon integration yields

$$C_a = C_{al} \, x_o^{r/q} \, x^{-r/q} \qquad [25]$$

where C_{al} is the solution to Eq. [20] along the characteristic Eq. [16b] when it intersects the kinematic characteristic given by Eq. [15b] (i.e., on the boundary between regions A and B).

The equation of the chemical advective characteristic ground curve can be written as

$$dx / dt = qx / [(qx/\alpha)^{1/m} + \epsilon\phi] \qquad [26]$$

and upon integration yields

$$t = t_o - (\epsilon\phi/q) \ln x_1 + \{[mq^{(1/m)-1}]/\alpha^{1/m}\}$$
$$(x^{1/m} - x_1^{1/m}) + (\epsilon\phi/q) \ln x \qquad [27]$$

where t_o and x_1 are t and x values when the characteristic Eq. [26] starts on the boundary between region A and B (Fig. 1).

The concentration at the upper boundary is obtained by integrating Eq. [8] to yield

$$C_a(0,t) = C_{ao} \exp(-rt/\epsilon\phi) \qquad [28]$$

where $C_{ar} = 0.0$.

Solutions for C_a as a function of t at the downstream boundary can be found analytically at a finite number of points by solving along a set of characteristics such as c-t_c, d-e-f, etc. (Fig. 1). Note that characteristic ground curves for chemical transport emanating from the line $(0,0)$—$(0,L)$ completely fill the solution plane (See Fig. 1 and Eq. [21]).

MODEL CASES EVALUATED

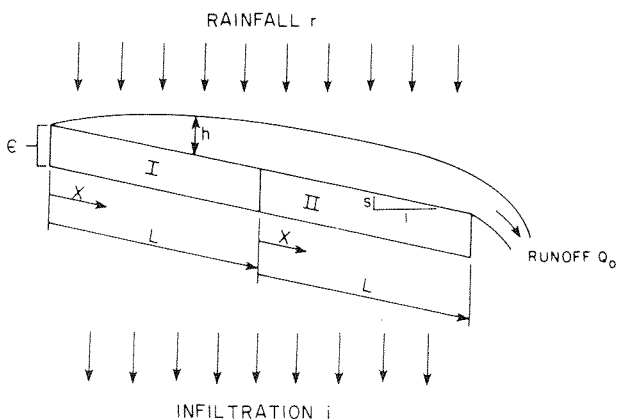The physical setup for all cases evaluated consists of two planes each 15.25 m long (L) with a 3% slope

(s) and unit width (Fig. 2). The surface exchange soil had a porosity of 30%, 20% rock fragments > 2.0 mm, 20% initial relative saturation, and final infiltration rate (i) of 2.54 mm/h (infiltration and percolation below the soil mixing depth were assumed equal). The simulated rainfall events had a duration of 60 min at a rate (r) of 25.4 mm/h. The soil mixing depth (ϵ) was 10.0 mm with an initial chemical concentration of 1.0 mg/L. Overland flow was assumed to be over a relatively smooth surface with K (as a part of Eq. [5]) set to 700. Cases with chemical in the rainfall had a concentration, $C_{ar} = 0.1$ mg/L.

The evaluation of the lumped and distributed form of the complete mixing model required that the hydraulic routing be the same in all cases. The implicit finite-difference model described above from the kinematic cascade model KINEROS was used to obtain consistent kinematic routing for all cases evaluated and storage, S, for the lumped model. The runoff hydrograph is shown in Fig. 3.

Six cases of chemical placement were evaluated for differences in runoff concentration, timing of peak concentration, and total chemical transport between the lumped and distributed model forms. The six cases were:

1. Chemical on both planes and none in rainfall
2. Chemical on both upper and lower planes and in rainfall
3. Chemical on lower plane and none in rainfall
4. Chemical on lower plane and in rainfall
5. Chemical on upper plane and none in rainfall
6. Chemical on upper plane and in rainfall

These cases represented the most common chemical placement situations encountered in surface exchange and transport modeling.

Two special cases were also evaluated to compare analytical and numerical solutions for the distributed form of the complete mixing model. The physical setup was the same as described above, except overland flow was restricted to be laminar. To obtain analytical solutions, it was necessary that rainfall and infiltration rates were constant, no chemical in the rainfall, and laminar flow.
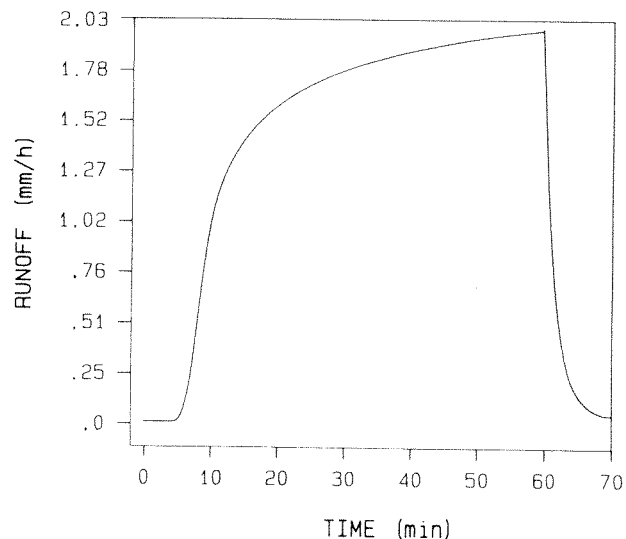

Fig. 2. Schematic drawing of overland flow planes, where r is the rainfall rate; ϵ is the soil mixing zone depth; h is the surface runoff water depth, s is the slope of the planes; I and II are the upper and lower planes; Q_o is the runoff rate; L is the length of the planes; x is a distance down the plane; and i is the infiltration rate.

Fig. 3. Runoff hydrograph for cases evaluated.

RESULTS AND DISCUSSION

Analytical and numerical solutions obtained from the two special cases of the distributed form of the complete mixing model were used to evaluate the finite difference formulation. For case one the chemical was present only in the soil mixing depth of the lower plane. Analytical and numerical solutions for this case are shown in Fig. 4. We note very close agreement until $t = 15$ min, when the numerical solution drops below the analytical solution. The analytic solution shows a sudden drop in concentration (from 0.25 to 0.0) at $t = 18$ min. This is the result of the chemical free runoff from the upper plane arriving at the lower boundary as a concentration "shock." This rapid change in concentration is smoothed by numerical diffusion in the finite difference model. For the second case, chemical was present only in the upper plane. Numerical and analytical solutions for the concentration leaving the lower plane are presented in Fig. 5.

We note that in the analytical solution there is a delay of 18 min before the arrival of the chemical as a shock and that the chemical has been considerably diluted by rainfall and infiltration as it passed over the lower plane so that the peak concentration is about 0.25. Again, the finite difference solution shows numerical dispersion, which leads to an earlier arrival time and a significantly lower peak concentration. We concluded that the finite difference approximation is adequate to examine the degree of distortion involved in modeling a distributed system as a lumped system. We recognize also that the finite difference solutions show numerical dispersion that smooths out abrupt changes in concentration. Such smoothing is actually more representative of actual surface runoff concentrations. Chemical dispersion and diffusion were not included in the complete mixing model, but they would smooth abrupt changes in surface runoff concentration. Therefore, using the numerical formulation to solve for C_a adds quasichemical dispersion and diffusion into the model that is not explicitly accounted for.

Figure 6 shows the mixing zone chemical concentration vs. time at the lower plane edge for the case of chemical on both planes. No difference was found in the predicted mixing zone concentration at the lower plane edge for the two forms of the complete mixing model. The concentration decreased from the initial concentration (1.0 mg/L) to near zero in about 50 min. For both forms of the model, 21% of the chemical was transported to the edge of the lower plane by the surface runoff and 79% percolated below the soil mixing depth. The chemical concentration decreased at a slower rate with chemical in the rainfall until it reached the input rainfall concentration of 0.1 mg/L and remained constant.

It is of interest to note that the solution for concentration as a function of time at the downstream boundary, Eq. [20], differs from that proposed by Ahuja and Lehman (1983). Ahuja and Lehman's equation is identical to our equation for the upstream boundary (Eq. [28]), which is not surprising since they assumed negligible surface water storage. However, Eq. [20]
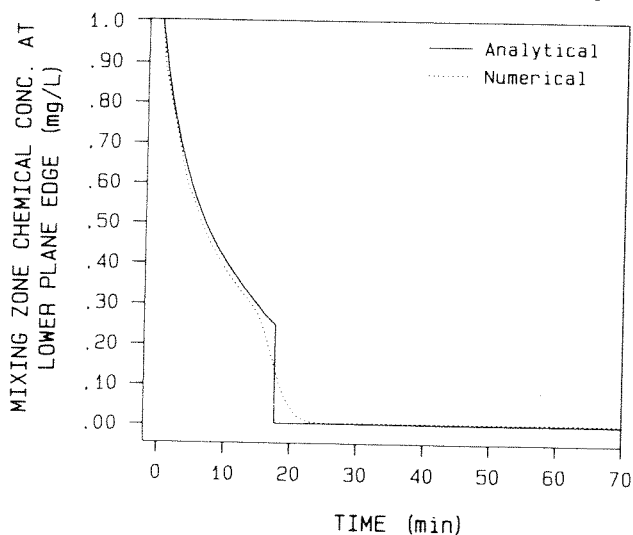

Fig. 4. Concentration vs. time for the analytical and numerical solutions to the distributed form of the model with chemical in lower plane.
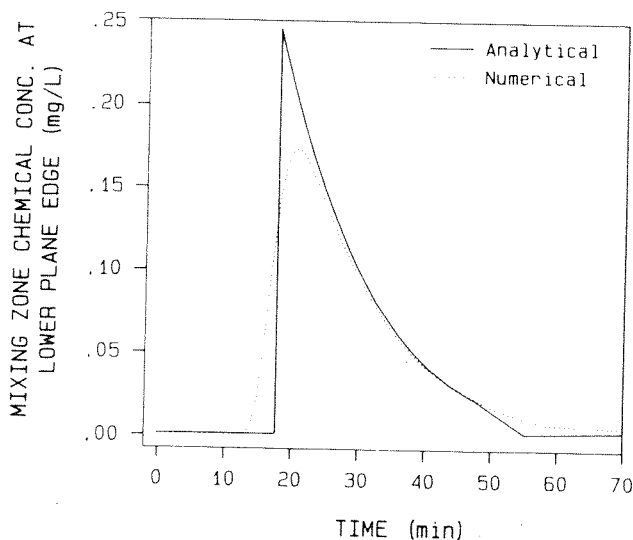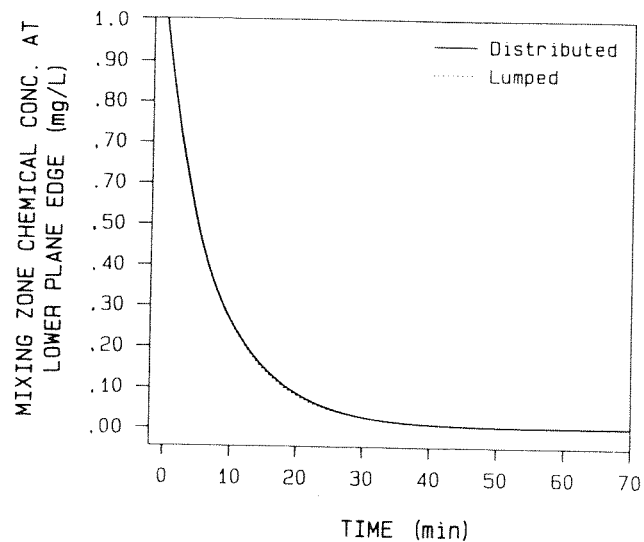

Fig. 5. Concentration vs. time for the analytical and numerical solutions to the distributed form of the model with chemical in upper plane.

Fig. 6. Concentration vs. time for chemical in both planes.

contains the infiltration rate i as a parameter as well as the rainfall rate and $\epsilon\phi$. Therefore, for a given rainfall rate and mixing zone depth, $\epsilon\phi$, there will be a family of curves depending on the infiltration rate $i = r - q$. Furthermore, for a single plane, it can be shown that the chemical concentration in the runoff at the lower boundary at any time will be higher than at the upstream boundary (i.e., for all positive values of r, q, ϵ, ϕ, and t C_a in Eq. [20] is $\geq C_a$ in Eq. [28].

Figure 7 shows the mixing zone chemical concentration vs. time at the lower plane edge for chemical on the lower plane. The distributed model had slightly higher concentrations starting at about 8 min into the event until about 18 min. After 18 min the concentration became lower than the lumped and finally both model versions approached zero at 35 min. The higher initial concentrations of the distributed model were attributed to the translocation of chemical down the lower plane. This translocation depleted the chemical from the upslope areas sooner than with the lumped model, causing the concentration to drop below the lumped concentration until they merged at zero. The concentration difference was reflected in a slight increase in the runoff transport percent from 26 for the lumped model, to 28 for the distributed model. Percolation below the soil mixing depth removed 72 and 74% of the chemical from the mixing zone for the distributed and lumped form, respectively. Including chemical in the rainfall and chemical in the lower plane produced results similar to those without chemical in the rainfall. The rate at which the chemical concentration decreased was slower and remained constant after reaching the rainfall concentration.

The mixing zone chemical concentration vs. time at the lower plane edge for the case of chemical in the upper plane is plotted in Fig. 8. The two forms of the model had significantly different peak concentration times and peak concentrations. Solute was present in the runoff from the lumped model at the same time runoff started from the planes (Fig. 3). This "accelerated" model transport is much faster than particle transport over the lower plane would be and is unrealistic. The lumped model also predicted that the peak concentration would occur earlier in the event.
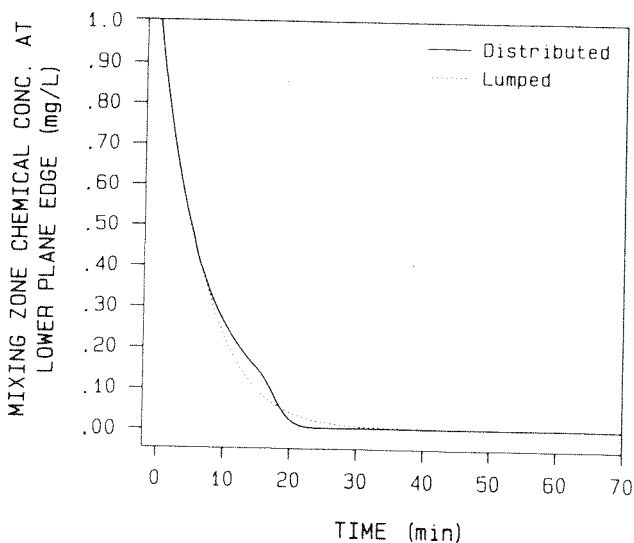
The peak concentration for the distributed model was 35% higher than for the lumped model. Differences in peak concentrations were attributed to the translation of chemical down the lower plane as a chemical front in the distributed model and the additional dispersion induced by the lumped model.

The solute concentrations for the case with chemical in the upper plane were much lower than the case with chemical in the lower plane. This illustrates what Ahuja (1986) has discussed, that in a cascade of planes the lower plane without chemical can serve as an effective filter to lower surface chemical transport and peak concentrations. Sixteen percent of the chemical was transported to the lower plane edge in the surface runoff when it was applied only on the upper plane, as opposed to a average 27% when it was applied only to the lower plane. The remaining percentage for both cases was removed from the mixing zone by percolation.

The chemical concentration in the mixing zone vs. time for the case of chemical on the upper plane and in rainfall is plotted in Fig. 9. There were significant
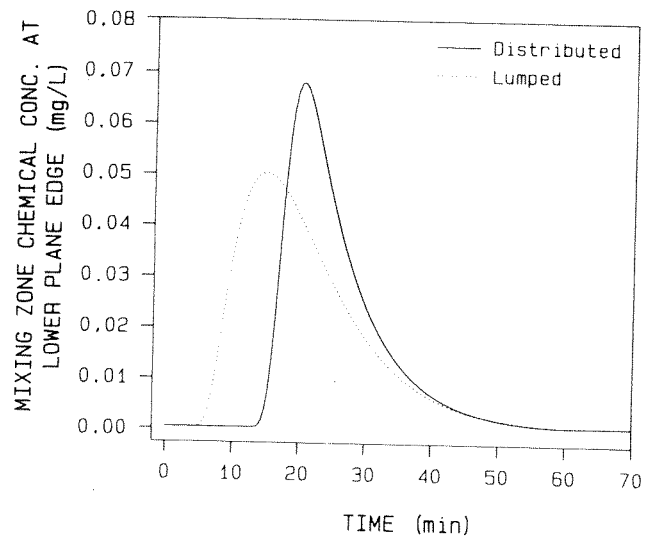
Fig. 8. Concentration vs. time for chemical in upper plane.

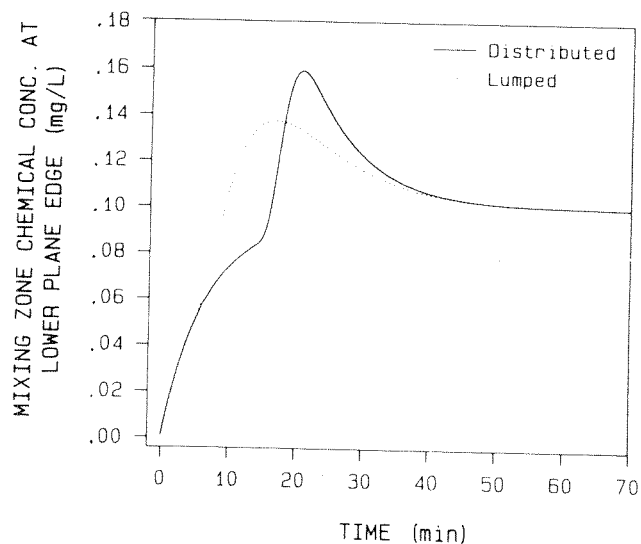Fig. 7. Concentration vs. time for chemical in lower plane.

Fig. 9. Concentration vs. time for chemical in upper plane and rainfall.

differences in the time and concentration of peaks for the two models. The two predictions were identical until runoff started. Then as runoff started, the accelerated transport from the lumped model influenced the mixing zone concentration at the lower edge of the lower plane (Fig. 3). The influence of the upper plane in the distributed model was delayed until the chemical could be translocated down the lower plane. The advective transport in the distributed model is conceptually closer to the actual process than the lumped approach to transport on a cascade of planes. The accelerated transport also caused the lumped model peak concentration to occur sooner. The peak concentration predicted by the distributed model was 15% higher than the lumped model peak. After the peaks, the predicted chemical concentrations for the two models merged to the rainfall concentration.

The simple complete mixing model used to describe the surface exchange process is independent of the surface transport process. The distributed model has an advective transport component (the term $\partial Q_o C_a / \partial x$ in Eq. [6]) and disturbances propagate at the characteristic velocity $dx / dt = Q / (h + \epsilon\phi)$. For the lumped model, solute introduced at the upper end of a plane is propagated instantaneously to the lower boundary. Other surface exchange models and associated assumptions that are incorporated into lumped and distributed transport models would only influence the magnitude of the difference that we found with the simple complete mixing model. The influence of advective and accelerated transport would always remain.

SUMMARY AND CONCLUSIONS

A simple complete mixing model was used to examine the degree of distortion introduced by modeling chemical exchange and transport as a lumped rather than a distributed process. All cases evaluated used a cascade of two planes with chemical placement on the planes in various combinations. The kinematic cascade model KINEROS was used to produce a consistent hydraulic routing for all cases with time varying infiltration.

The total chemical transport predicted by the lumped model was almost identical to that predicted by the distributed model for the cases evaluated. However, placement of chemical in the upper plane produced significant differences in chemical arrival time, peak concentration time, and peak concentrations. The lumped form of the model predicted shorter arrival

and peak concentration times, and lower peak concentrations. A lower plane without chemical provides a filter to reduce surface transport and runoff concentrations. For the case with chemical placed only in the lower plane there was little difference between concentrations predicted by the lumped model and those predicted by the distributed model.

A lumped model structure should be used with caution for modeling chemical exchange and transport over a cascade of planes as it produces an unrealistic accelerated transport and over-dispersion. A lumped or distributed model structure would have a small effect on the results from modeling surface exchange and transport on a single plane or element.

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