INCORPORATING PREFERENTIAL FLOW AND HERBICIDE FATE AND TRANSPORT INTO THE *DRAINAGE* MODEL

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ABSTRACT. *The DRAINAGE model was modified by incorporating a pesticide component and a preferential flow component in order to simulate pesticide concentrations in subsurface drain flows. Field data on subsurface drain flows and their atrazine concentrations were used to calibrate and validate the enhanced DRAINAGE model for growing seasons of 1990, 1991, and 1992. Simulated subsurface drain flows and their atrazine concentrations were compared with the measured values. Predicted daily flows by the modified DRAINAGE model were close to the observed values (difference over all years + 6.3%). Overall mean difference (M_d) and correlation coefficient (R^2) were + 0.1 mm and 0.70, respectively.*

The predicted atrazine concentrations in subsurface drainage water followed the observed trends well except in 1992. The overall timings of pesticide appearance in the drain water were predicted well by the model. The annual atrazine losses with subsurface drain flows predicted by the model were also in close agreement with the observed losses for 1990 and 1991 (with 1.1% difference). The results of this study indicated that the modified DRAINAGE model has good potential for simulating atrazine concentrations for normal rainfall years when a substantial amount of pesticides may be lost in the subsurface drainage water (overall M_d = 2.03 μg/kg and R^2 = 0.58).

Keywords. *Subsurface drain flow, Atrazine, DRAINAGE Model, Simulations.*

Considerable public concern has been expressed about the use of herbicides in agricultural production systems and their effects on water quality. The USEPA estimated that at least 19 herbicides have been detected in groundwater in 24 states as a result of normal agricultural practices (USEPA, 1989). Approximately 98% of the corn and soybean hectares receive herbicides in Iowa (Wintersteen and Hartzler, 1987). Atrazine (2-chloro-4-ethylamino-6-isopropylamino-1,3,5-trazine) is one of the widely used herbicides in corn production in Iowa. Because leaching of herbicides to groundwater through the root zone is a major concern for groundwater quality, understanding the processes and fate of surface applied herbicides is an important issue. Although point source contamination has been well documented (Long, 1987; Fawcett, 1989), the extent of herbicide leaching from normal field use is still uncertain and complex.

There is a growing body of evidence that herbicides are leached below the root zone generally as a result of preferential flow (flow through large cracks, root channels, and worm holes in structured soils). Preferential flow bypasses the soil matrix and thus is able to transport surface applied chemicals rapidly to groundwater (Beven and Germann, 1982; Smettem et al., 1983; Bowman and Rice, 1986; Priebe and Blackmer, 1989; Steenhuis et al., 1994). Short circuiting to groundwater through macropores is of serious concern at present. This concern has been exacerbated by the growing practice of minimum or no tillage for two reasons: (1) this practice entails greater pesticide use and both pesticides and fertilizer chemicals are applied on the soil surface with minimum incorporation into the soil, thus increasing the soluble chemical amounts in surface flow that can enter macropores; and (2) plant residues on the surface and no tillage enhance worm activity and allow worm holes and other channels to stay open at the surface. In the recent past, an attempt has been made to incorporate preferential movement of chemicals into various models (Ahuja, 1991; Chen and Wagenet, 1992; Workman and Skaggs, 1990).

Subsurface drainage is a common agricultural water management practice in areas with shallow groundwater or seasonally perched water tables. The study of chemical composition of subsurface drainage water may enable the scientists to identify the direct threat of pollution to groundwater and surface water due to agricultural chemicals. As suggested by Hallberg et al. (1986), subsurface drainage studies can be a useful tool for assessing the impact of agricultural management practices on groundwater because they integrate the effects of spatial variability on a field scale and are better tools than many other measurement methods such as suction cups and soil cores (Richard and Steenhuis, 1988). However, field studies are limited to specific sites and require large amount of data before any concrete conclusions can be drawn.

Several computer simulation models have been developed in the past to study the fate and transport of herbicides through the root zone (CREAMS: Knisel, 1980;

Article was submitted for publication in November 1996; reviewed and approved for publication by the Soil & Water Div. of ASAE in April 1997. Presented as ASAE Paper No. 96-2060.

Journal paper no. 16839 of the Iowa Agricultural and Home Economics Experiment Station, Ames, Iowa. Project No. 3289. This study was partially supported with funds provided by the EPA, USDA-CSRS, and the Iowa Experiment Station.

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PRZM: Carsel et al., 1985; LEACHMP: Wagenet and Hutson, 1987; RZWQM: USDA-ARS, 1992; GLEAMS: Leonard et al., 1987). However, most of these models lack the capability of simulating pesticides in tile water. Several analytical models are also available to simulate preferential transport of pesticides in the soils, but these analytical models have not been incorporated into large field scale models for simulating overall subsurface drain flows and their pesticide concentrations. Several researchers have reported the difficulty in predicting pesticide concentrations without a preferential flow component (Ahuja et al., 1991; Sichani et al., 1991). There is a need to develop the capability of existing field scale models to simulate the preferential transport of pesticides in the subsurface drainage water. Also, very few studies have been conducted to compare the field observed tile water pesticide concentrations with the model predicted values. Therefore, the main objective of this study was to develop preferential flow and pesticide components and incorporate them into the DRAINAGE model (Kanwar et al., 1983) to simulate pesticide concentrations in subsurface drainage waters. The original DRAINAGE model (Kanwar et al., 1983) simulates water and nitrate-nitrogen (NO_3-N) transport to subsurface drains and requires relatively few input data. The specific objectives of this study were to:

1. Develop a pesticide component, based on the GLEAMS model, and integrate it with the subsurface drainage hydrology component of the DRAINAGE model.
2. Develop a field scale preferential flow component, based on the theory given by Workman and Skaggs (1990), and incorporate it into the DRAINAGE model.
3. Validate and evaluate the performance of the modified DRAINAGE model in simulating subsurface drain flows and their atrazine concentrations using three years (1990-1992) of field data from a water quality research site in Iowa.

MODEL DESCRIPTION

The DRAINAGE model (Kanwar et al., 1983) was developed to simulate the subsurface drain flows and their NO_3-N concentrations in a typical agricultural field. The DRAINAGE model was modified by incorporating a nitrogen component based on GLEAMS for improving its predictions of NO_3-N concentrations in subsurface drain flows (Kumar and Kanwar, 1997). In this model, the soil profile was divided into 30 layers of 5 cm each plus a layer that extends from 150 cm to the impermeable layer of the soil profile. It was assumed that soil properties do not vary within each of the layers. As modified, the DRAINAGE model consists of three major components: (1) a hydrology component (simulates subsurface drain flows); (2) a nitrogen (N) component (simulates NO_3-N concentrations and losses in the subsurface drainage waters); and (3) a pesticide component.

The hydrology component of the DRAINAGE model has been modified by changing the infiltration processes to incorporate the preferential flow component in the model. The following sections of this article will describe the modified hydrology component (including preferential flow) and pesticide components in detail. The DRAINAGE model simulates the major water-transport processes at the soil surface and in the soil profile. It calculates the daily water-table depth, drainage into subsurface drains, surface runoff, and evapotranspiration as the major output parameters.

SURFACE HYDROLOGY

In the DRAINAGE model, the processes are simulated in the following order: (1) infiltration; (2) preferential flow; (3) runoff; and (4) subsurface drainage. The water balance at the soil surface over the unit area for the time increment, Δt, can be written as:

$$R = F + PF + \Delta S + RO \tag{1}$$

where
R = rainfall (cm)
F = infiltration (cm)
PF = preferential flow (cm)
ΔS = change in the storage on the surface (cm)
RO = runoff (cm)

Infiltration. The modified DRAINAGE model calculates infiltration during short durations of rainfall (Kumar, 1996). The SCS type II rainfall distribution curve was used to divide daily rainfall into 15-min rainfall intensities. The modified form of the Green-Ampt-Mein-Larson function was developed to estimate infiltration. For a given time period, all the water supply at the soil surface is assumed to infiltrate if the calculated time of ponding is longer than the time period used in the model simulation. Ponding time is estimated by using the equation derived from the Green-Ampt equation presented by Mein and Larson (1973) as:

$$t_p = K\Psi\Delta\theta/[i(i - K)] \tag{2}$$

where
t_p = ponding time (h)
K = the average hydraulic conductivity of soil (cm h^{-1})
Ψ = wetting front capillary pressure head (cm)
$\Delta\theta$ = difference between initial and final volumetric water content of the soil
i = rainfall intensity (cm h^{-1})

Otherwise, if ponding occurs, infiltration is estimated using the Green-Ampt infiltration function, which is expressed in quadratic form as:

$$F_2^2 \frac{1}{\Delta t} - F_2\left(\frac{F_1}{\Delta t} + K + \frac{K\Delta\Psi\Delta\theta}{2F_1}\right) - \frac{K\Delta\Psi\Delta\theta}{2} = 0 \tag{3}$$

where F_2 is the cumulative infiltration at the end of time period (cm) and F_1 is the cumulative infiltration at the beginning of the time increment (cm). The difference between F_2 and F_1 is the potential amount of infiltration that can occur during that time period. The actual infiltration may be less if the supply of water at the surface is less than the potential amount of infiltration. The difference between supply of water at the surface and potential amount of infiltration was defined as the amount of surface storage available for preferential flow during a given time period.

Preferential Flow. The preferential flow component was developed to simulate the saturated and unsaturated movement of water from the soil surface into and through the soil profile above the water table. The network of macropores that contribute to the faster movement of water in the soil are not uniform in size and location. A macroscopic viewpoint developed by Workman and Skaggs (1990) was adopted to simulate the contribution of preferential flow to the movement of water into the soil between subsurface drains.

Macroporosity is calculated as a percentage of the surface area between drains, and when the percentage of macroporosity (pm) is known, the equivalent macropore area per square cm of surface area can be estimated as:

$$\pi r^2 = pm/100(1.0\ cm^2) \qquad (4)$$

where r is the effective radius of the representative macropore in cm.

The transport of water through the pore network is assumed to be a function of the transmitting properties of the pore. Poiseuille's equation (Childs, 1969) was used to estimate the potential volume of preferential flow for a given representative macropore radius, and is described as:

$$Q_p = \frac{\pi\ \rho\ g}{8\ \mu}\ r^4 \qquad (5)$$

where

Q_p = volume flux ($cm^3\ s^{-1}$)
ρ = density of water ($g\ cm^{-3}$)
g = acceleration due to gravity ($cm\ s^{-2}$)
μ = dynamic viscosity ($g\ cm^{-1} s^{-1}$)
r = pore radius (cm)

The movement of water through the pore will also depend on the lateral adsorption of water by the soil matrix. However, for simplifying the modeling process, no interaction between preferential flow and the soil matrix was assumed. After calculating the potential preferential flow using equation 5, the actual preferential flow was calculated based on available surface storage.

Surface Storage and Runoff. The runoff was calculated for each time period separately and was summed at the end of each day. Runoff occurred only when there was more excess water than the maximum allowable surface storage after calculating preferential flow. The surface storage was calculated as the difference between the rainfall at the surface and the matrix infiltration for a given time period during simulation. A 3.0 mm maximum allowable surface storage was allowed to accumulate at the surface before any runoff took place. The difference between surface storage and maximum allowable surface storage was taken out of the system as runoff.

PROFILE HYDROLOGY

A water balance scheme is also used to account for all the water moving into and out of the vertical section of the soil profile during each time increment as:

$$\Delta SS = F + PF - DR - ET \qquad (6)$$

where

ΔSS = change in the storage within the soil profile (cm)
DR = subsurface drainage via matrix (cm)
ET = evapotranspiration (cm)

The time step used in the model simulations was 0.25 h. The evapotranspiration in the DRAINAGE model was calculated on a daily basis and was divided equally for each time step.

Once the preferential flow was calculated, water was redistributed by adding preferential flow in the water table, and the water table depth was updated according to the water in that layer. A water routing procedure (based on generalized threshold values such as field capacity and wilting point) is used to redistribute the matrix infiltration. The subsurface drainage was calculated using Hooghoudts steady state equation as modified by Bouwer and Van Schilfgaarde (1963).

PESTICIDE COMPONENT

A simple representation of all the processes of the pesticide component is illustrated in figure 1. The pesticide processes considered in the DRAINAGE model are: degradation, runoff extraction, percolation, pesticide losses with evapotranspiration, pesticide adsorption and desorption, pesticide losses to the subsurface drainage, and preferential transport of pesticides. The pesticide processes are described in detail by Leonard et al. (1987). All processes are not described here due to lack of space. Those processes dealing with preferential transport of pesticides and pesticide losses to subsurface drainage are described below.

Pesticide Transport with Preferential Flow. Since the hydrology component of the DRAINAGE model considers the movement of water flow through macropores, the pesticide mass moved with preferential flow was estimated. The pesticide mass in the mixing layer (layer 1) is available for transport with preferential flow. The pesticide mass, P_M, lost with preferential flow was estimated as:

$$P_M = C_{w(1)}\ P_F \qquad (7)$$

where $C_{w(1)}$ is the pesticide concentration in the solution in the mixing layer and P_F is the mass of water percolated through macropores. Since macropores were assumed to be continuous to the water table and lateral flow of macropore water from its walls was not considered, the pesticide movement with preferential flow is added to the pesticide mass in the layer which contains the water table. The pesticide mass that percolated through macropores is subtracted from the available pesticide mass for percolation in layer 1. After preferential flow, the pesticide transport can move upward if the water table rises due to the addition of preferential flow into the water table. The pesticide mass which moves up is subtracted from the total pesticide mass of layer i, P_{MI} (layer which contains water table):

$$P_{MI} = P_{MI} - E_M\ C_{wi} \qquad (8)$$

and is added to layer i–1:

$$P_{MI-1} = P_{MI-1} + E_M\ C_{wi} \qquad (9)$$

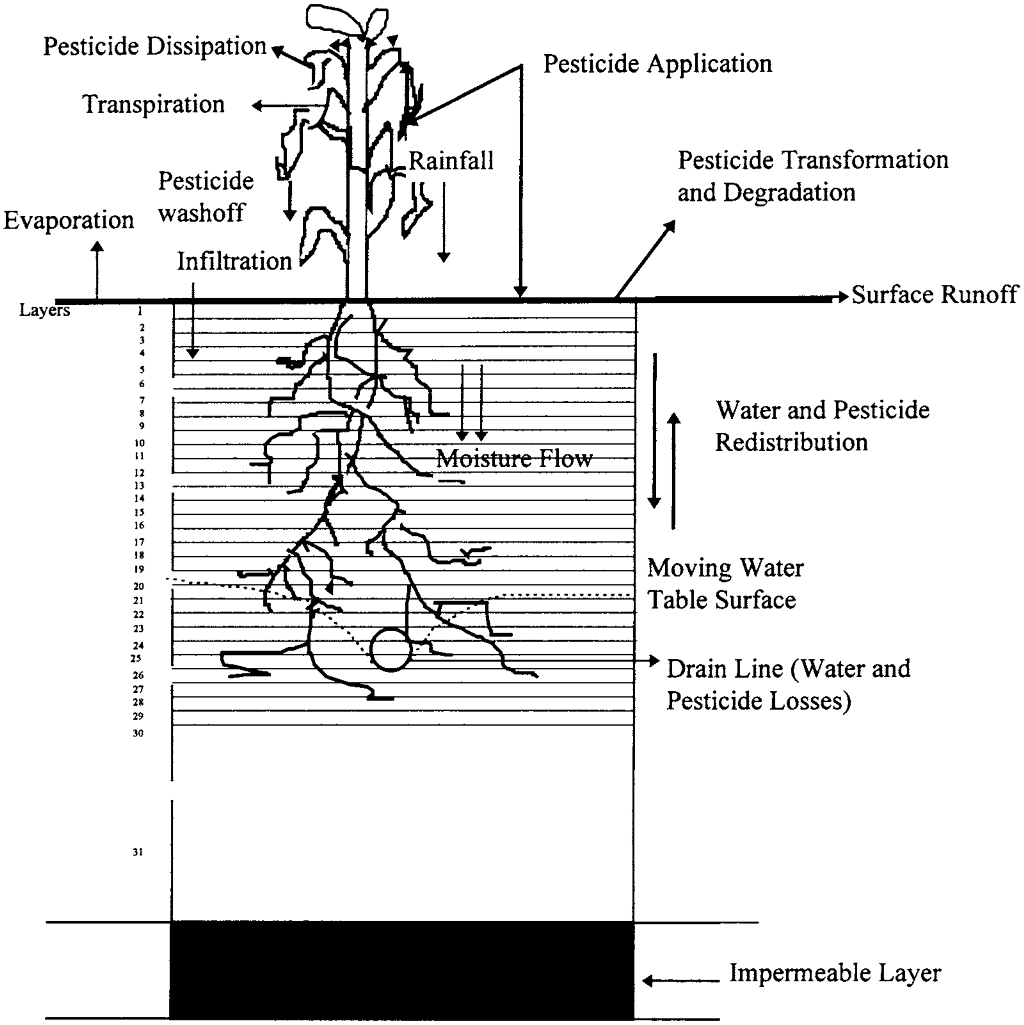

Figure 1–The physical system and pesticide processes represented in the DRAINAGE model.

where E_M is the excess water (total soil water minus water at saturation) and C_{wi} is the pesticide concentration in layer i.

Pesticide Concentrations in Subsurface Drainage Water. Pesticide concentrations in the subsurface drainage water are estimated as a function of pesticide concentrations in the saturated soil profile. For each time step of model simulation, the same amount of water is drained from each layer in the saturated part of the soil profile. The total mass of pesticide lost with drainage is estimated as:

$$P_{MD} = \sum_{i=1}^{N} C_{wi}\left(\text{Sliver}\right) \qquad (10)$$

where P_{MD} is the total pesticide mass loss in drainage from saturated profile and Sliver is the amount of water contributed to subsurface drainage from each saturated layer. The pesticide concentration in subsurface drainage water for a given day is estimated as:

$$P_C = P_{MD}/F_L \qquad (11)$$

where P_C is the daily pesticide concentration in the drainage water and F_L is the total daily drain flow. Once the pesticide concentrations in drainage water are estimated, the pesticide mass in all soil layers is updated as:

$$P_{Si} = P_{Si} - P_{MDi} \qquad (12)$$

The brief discussion on preferential flow and pesticide components provided above represents the concepts from Workman and Skaggs (1990) and Leonard et al. (1987), respectively. The detail discussion can be found from the above cited literature.

METHODS AND MATERIALS

FIELD EXPERIMENT SITE AND SAMPLING PROCEDURE

Field experiments for this study were conducted at Iowa State University's Northeast Research Center (NERC) near Nashua, Iowa (Kanwar et al., 1993). The experimental site is located on Kenyon and Floyd soils with 3 to 4% organic matter. The study site consists of 36 plots of 0.4 ha each. Each plot is drained by a single drain line installed at the 1.2 m depth. The drains were spaced at 28.5 m apart. These drain lines discharge to individual sumps to study water quality and quantity issues related to subsurface drainage.

A detailed discussion on the automatic subsurface drain monitoring system is provided by Kanwar et al. (1993). Data on subsurface drainage outflows, and NO_3-N and pesticide concentrations in drain water are available for this site. For pesticide sampling, composite subsurface drain water samples were taken weekly and after every major rainfall (greater than 25.4 mm) within 60 days of pesticide application. For the remainder of the year, drain water sampling frequency did not exceed more than once a week when drain lines were flowing. The data on subsurface drain flows and atrazine concentrations in subsurface drain flows, collected from no-till (NT) plots under continuous corn production for the years 1990 to 1992 were used in this study to evaluate the DRAINAGE model. The data set used in this study represents the average value for three replications.

CROP AND CHEMICAL MANAGEMENT

Tillage and planting activities were carried out on the field as soon as the soil conditions permitted each year. Continuous corn received 200 kg-N/ha during each year before planting. The continuous-corn treatment receive alachlor + atrazine and terbufos for rootworm control. Dates of major field operations are provided in table 1. Tillage comprised the use of a field cultivator in NT plots. Corn was planted in rows with rows parallel to drain lines (Kanwar et al., 1993).

Pesticides were applied to the soil during the planting operation as a tank mix sprayed over the entire surface area. The characteristics of the pesticides and the application rates are shown in table 2.

MODEL INPUT PARAMETERS

Daily rainfall data collected from the study site were used as input to the model and converted to 15 min rainfall intensity as explained in the model description section of this article. Other data including open pan evaporation, wind velocity, air temperature, and soil temperature were also collected at the study site. Daily pan evaporation data are needed to calculate the evapotranspiration rates for corn. A detailed procedure to calculate ET by the DRAINAGE model is described by Kanwar et al. (1983).

Table 1. Data on N fertilization, tillage, pesticide application, planting, and harvesting for Nashua, Iowa

	Year		
Treatment	1990	1991	1992
Nitrogen (202 kg/ha)	23 April	14 May	2 May
Pesticides* and planting	2 May	28 May	6 May
Tillage	26 May	20 June	5 June
Harvesting	1 October	8 October	16 October

* Alachlor, Atrazine and Cyanazine were applied.

Table 2. Pesticide characteristics and application rates at the experimental site*

Common Name	Trade Name	Water Solubility (µg/g)	Half Life (d)		Washoff Fraction	K_{OC}	Application Rate (kg/ha)
			Soil	Foliar			
Alachlor	Lasso	242	18	3	0.4	190	2.2
Atrazine	Aatrex	33	60	2	0.5	160	2.8
Cyanazine	Bladex	165	14	2	0.6	168	2.8

* Columns 1 through 7 taken from *GLEAMS User Manual*, Version 2.0, Knisel et al., 1990. Column 8 reported by Kanwar et al., 1993.

The data on initial soil water content, field capacity ($\Theta_{1/3\ bar}$), wilting point (Θ_{15bar}), diffusivity, saturated hydraulic conductivity (Ksat), lateral saturated hydraulic conductivity (LKsat), and initial water table depth are required as inputs to the model. Wilting point and field capacity values were taken from Sharpley and William (1990). The Ksat value was determined by calibration because the modified model requires only matrix Ksat while field measured values of Ksat represent both matrix and macropore conductivites.

The planting and harvesting dates for corn, distribution of the corn root system as a function of time, the crop development ratios, and crop stress factors as a function of soil water are required as input to the model and were taken from Kanwar et al. (1983).

Initial atrazine concentrations in the soil profile are required as input data for the model simulations. Field observed initial concentrations in the soil profile at the study site were used as input to the model.

MODEL CALIBRATION

The hydrology component of the modified DRAINAGE model was calibrated by using observed subsurface drain flows for 1990. The criteria used for model calibration was to minimize the difference between the measured and predicted cumulative daily subsurface drain flows for the growing season of 1990 (1 April to 30 Nov). Importance was also given to matching the predicted drain flow peaks to the observed peaks. A trial and error procedure was used to determine the best possible values of various parameters that are used in the model simulations including saturated hydraulic conductivity, lateral saturated hydraulic conductivity, and soil macroporosity. Each parameter was varied within a reasonable range (within 10% of measured value for similar conditions) while all other parameters were kept constant. This procedure was followed for each parameter. A list of calibrated and measured parameters is given in table 3.

There is generally a good agreement between simulated and observed subsurface drain flows for 1990 except in the beginning of the season when the model overpredicted the flows (fig. 2). The reason for overpredicting the flows in the beginning could be due to drier soil profile in the field. The initial soil water contents for unsaturated soil layers were set at field capacity, however the actual water contents could have been lower than field capacity. Also, annual predicted subsurface drain flows were close to the observed values (table 4). Annual preferential flow, runoff and subsurface drain flows are given in table 4. Data in table 4 indicates that running the model with preferential flow simulated higher subsurface drainage as compared

Table 3. Summary of input parameters for subsurface drain system design and hydraulic properties

Parameter	Calibrated or Known Value
Drain spacing	28.50 m
Depth	1.20 m
Actual depth from drain to impermeable layer*	1.52 m
Equivalent depth from drain to imp. layer*	1.30 m
Macroporosity*	0.02%
Lateral hydraulic conductivity*	2.3E-6 m/s
Saturated hydraulic conductivity*	2.3E-6 m/s

* Calibrated values.

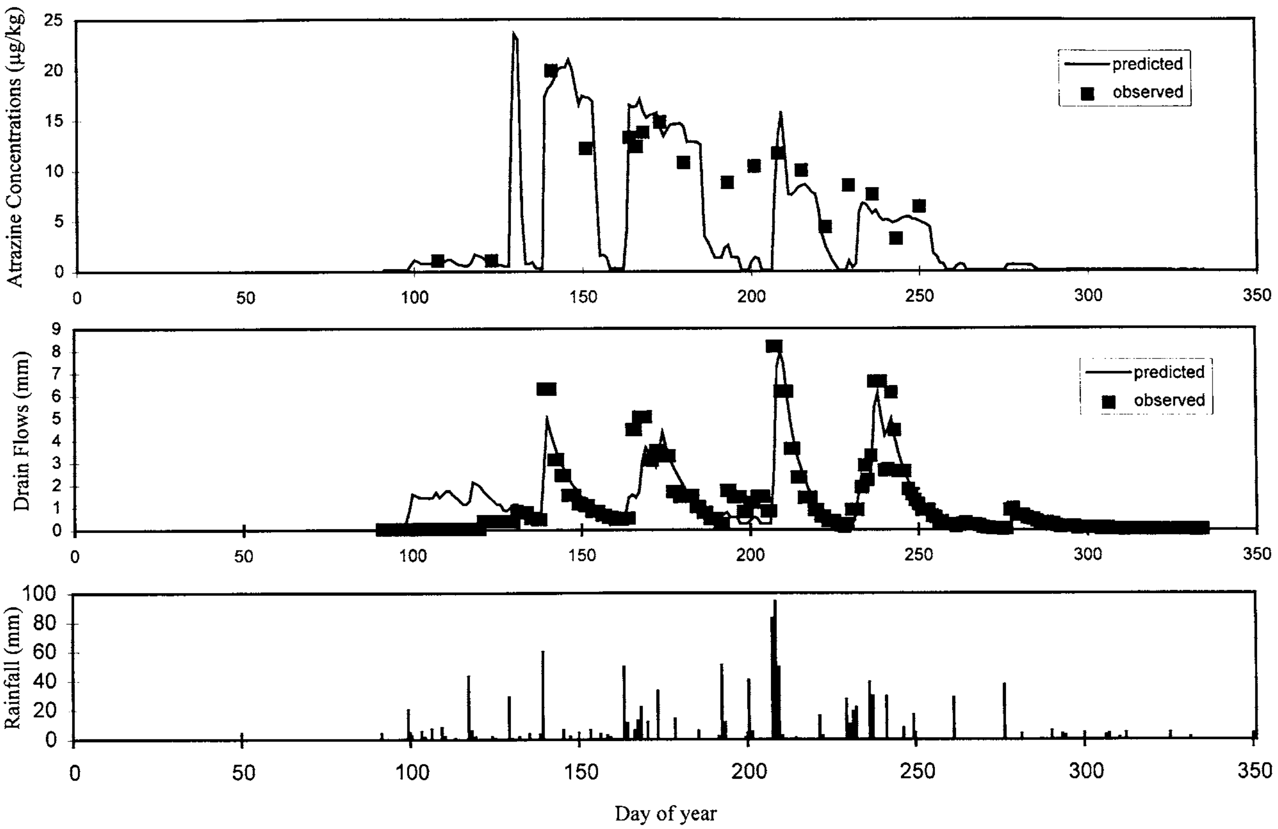

Figure 2–Daily rainfall and observed (average of three replications) and predicted subsurface drain flows and atrazine concentrations in drainage water for no-till plot for the year 1990.

Table 4. Summary of seasonal total predicted runoff, subsurface drain flow, and preferential flow and observed subsurface drain flow for the no-till plots for 1990, 1991, and 1992 with 0.02% macroporosity

Year	Rainfall (mm)	Observed* Subsurface Drainage (mm)	Predicted Runoff (mm)	Predicted Subsurface Drainage (mm)	Predicted Preferential Flow (mm)
1990	1050.0	275.0	197.0 (238.0)†	305.0 (263.0)	82.0
1991	854.0	288.0	87.0 (117.0)	294.0 (279.0)	73.0
1992	720.0	104.0	37.0 (71.0)	110.0 (81.0)	69.0

* Average of three replicates.

† Values in parentheses indicate predictions calculated by running the model without preferential flow.

with model simulations without preferential flow. When the model is run with preferential flow, part of the surface storage becomes available for infiltration through macropores and thus lower surface runoff is predicted. Given the fact that a number of uncertainties exist in the deterministic, physically based models due to inadequate or faulty representation of the hydrologic system, model predictions of subsurface drain flows in 1990 were reasonably good (% difference = 10.9). The percentage difference was calculated as (predicted – observed)/ observed.

MODEL EVALUATIONS

Both graphical and statistical methods were used for the model evaluations. Statistical methods suggested by Addiscott and Whitmore (1987) were used to evaluate the simulation capability of the model. The statistical parameters used in this study were correlation coefficient (R^2) between predicted and observed values and the mean difference (M_d) between predicted and observed values which is calculated as $M_d = \Sigma(\text{predicted} - \text{observed})/$ number of observations. A non-significant M_d and higher R^2 would indicate the satisfactory predictions of the model. A t-test was used to determine whether M_d was significantly different from zero (Addiscott and Whitmore, 1987). To simulate the atrazine concentrations in subsurface drain flows, macroporosity of 0.02% was used. All other parameters used to simulate atrazine concentrations were taken from the GLEAMS User Manual (table 2). The performance of the model for simulating subsurface drain flows and their atrazine concentrations was evaluated by comparing the simulated atrazine concentrations with the observed concentrations for 1990 to 1992.

RESULTS AND DISCUSSION

SUBSURFACE DRAIN FLOWS

To test the ability of the model to predict subsurface drain flows, model simulations were conducted for 1991 and 1992 using the calibrated parameters. Daily predicted subsurface drain flows matched well with the observed values (figs. 3-4). Although there were some discrepancies, the overall timings and levels of flows were close to the observed values. Predicted annual subsurface drain flows (table 5) compared exceptionally well with observed flows (% difference = 6.3). The mean difference (M_d) and correlation coefficient (R^2) were calculated for individual years and for the overall data for three years (table 6). The overall R^2 value of 0.70 and a lower M_d value of + 0.1 mm indicate satisfactory model predictions of subsurface drain flows.

ATRAZINE CONCENTRATIONS IN SUBSURFACE DRAIN FLOWS

Total seasonal atrazine losses were computed by summing daily pesticide losses over the entire growing season. Simulated atrazine losses were computed by the model and observed seasonal losses were calculated by multiplying the daily flows by atrazine concentrations. Atrazine concentrations were assumed to vary linearly between two available values from the field (note that atrazine concentrations are not available for each day).

Annual atrazine losses with subsurface drain flows (table 5) were close to the predicted atrazine losses by the DRAINAGE model for 1990 (calibration year) and 1991 but were overpredicted for 1992. Model predictions of atrazine concentrations in subsurface drainage water followed the observed trend reasonably well for 1990 (fig. 2). The model also showed the effects of preferential transport of atrazine in the beginning of growing season, especially immediately after the pesticide application, even though the model showed a decreasing trend of atrazine concentrations in the drain flows as a function of time.

The model overpredicted atrazine concentrations in subsurface drainage water for 1991 and 1992 (figs. 3 and 4). As indicated by figure 3, the predicted peak of atrazine concentrations on day 162 was much greater than the observed value. This was due to the fact that a major rainfall occurred on day 162, just 14 days after pesticide application (pesticide was applied on day 148), and transported a significant amount of atrazine with subsurface drain flows. However, the timings of peak concentrations for observed and simulated values occur at the same time with few exceptions. A simple analysis of figure 4 indicates that only a few drain water samples were collected for atrazine concentrations in 1992 because of lack of drain flow producing rainfall events making the comparison between observed and predicted values of atrazine concentrations in subsurface drain flows more difficult.

Considering all three years of simulation (table 6), it can be concluded that the modified DRAINAGE model does a good job of predicting atrazine concentrations in subsurface drainage water (M_d = 2.03 μg/kg and R^2 = 0.58). Although the value of M_d was significantly different from zero, a satisfactory R^2 indicated reasonable model predictions considering the complexities involved in pesticide transport processes.

SUMMARY AND CONCLUSIONS

The DRAINAGE model was modified to simulate pesticide concentrations in the subsurface drainage water by incorporating the pesticide component from the GLEAMS model (Leonard et al., 1987) and a preferential flow component based on theory given by Workman and Skaggs (1990). The modified DRAINAGE model was calibrated and evaluated by comparing the predicted subsurface drain flows and their atrazine concentrations

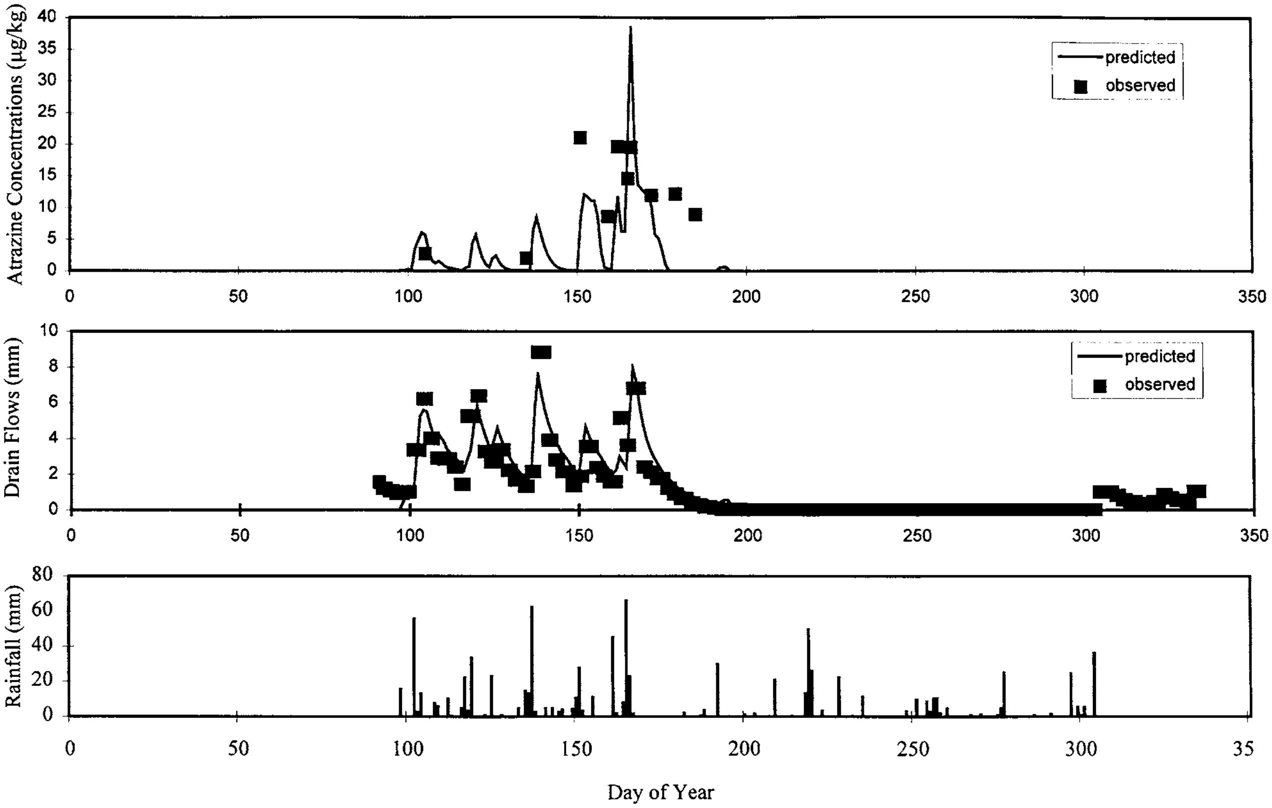

Figure 3–Daily rainfall and observed (average of three replications) and predicted subsurface drain flows and atrazine concentrations in drainage water for no-till plot for the year 1991.

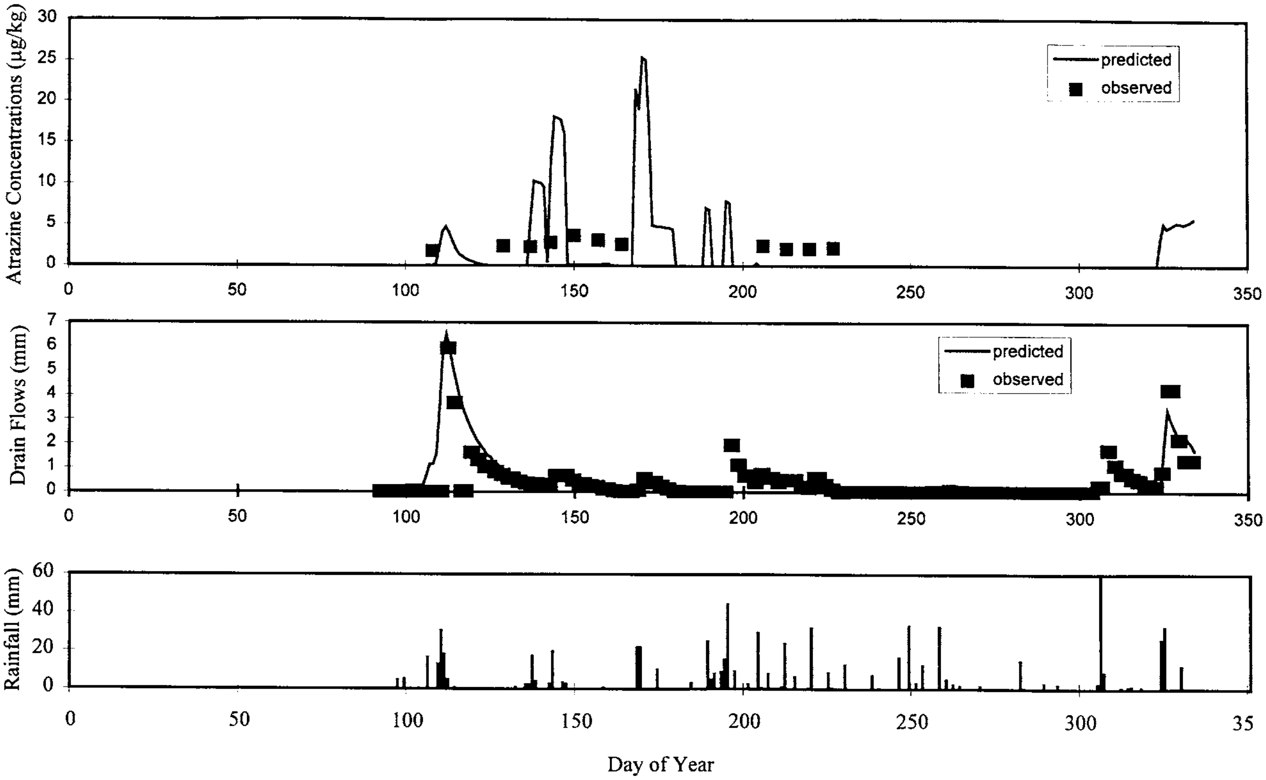

Figure 4–Daily rainfall and observed (average of three replications) and predicted subsurface drain flows and atrazine concentrations in drainage water for a no-till plot for the year 1992.

Table 5. Total seasonal (between DOY* 91-334) predicted and observed subsurface drain flows and atrazine losses for 1990, 1991, and 1992

Year	Precipitation (mm)		Drain Flows (mm)	Atrazine Losses (g/ha)
1990	1050.0			
		Observed†	275.0	26.9
		Predicted	305.0	26.0
		% Difference	+10.9	–3.3
1991				
	854.0			
		Observed†	288.0	16.1
		Predicted	294.0	17.0
		% Difference	+2.1	+5.6
1992				
	718.0			
		Observed†	104.0	0.2
		Predicted	110.0	4.0
		% Difference	+5.8	

* Day of the year.
† Average of three replications.

Table 6. Statistical comparison between simulated and observed values of subsurface drain flows and atrazine concentrations in the drainage water for years 1990 to 1992*

		Statistical Parameters	
Year	Parameters	M_d	R^2
1990	Flows (mm)	+0.2	0.70
	Atrazine conc. (μg/kg)	1.40†	0.61
1991	Flows (mm)	+0.1	0.79
	Atrazine conc. (μg/kg)	3.55†	0.42
1992	Flows (mm)	+0.1†	0.52
	Atrazine conc. (μg/kg)	1.77	0.07
Three years combined	Flows (mm)	+0.1†	0.70
	Atrazine conc. (μg/kg)	2.03†	0.58

* Statistical analysis is based on daily values.
† Significantly different from zero at the 0.05 probability level.

with the observed values for three years (1990-1992) from the Nashua Water Quality Site of Iowa State University.

Predicted subsurface drain flows for 1990, 1991, and 1992 compared reasonably well with measured flows. Peaks of the measured and predicted flows were not exactly the same at all times (figs. 2-4). Simulated seasonal subsurface drain flows were in close agreement with the observed values (overall average percentage difference being within + 6.3%). Overall, a small mean difference (M_d = + 0.1 mm) and a satisfactory correlation coefficient (R^2 = 0.7) also indicate the accuracy of predictions.

The predicted atrazine concentrations in subsurface drain flows generally followed the observed trend reasonably well for all years except 1992. Total predicted seasonal losses of atrazine with subsurface drain water were close to the observed losses for 1990 and 1991 (table 5). Discrepancies between predicted and observed atrazine concentrations indicated a further need for better knowledge of atrazine fate and transport processes. Also, atrazine losses were predicted really well by the model for three years. Results of statistical analysis (table 6) clearly indicate that the modified model is capable of simulating atrazine concentrations and losses reasonably well.

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