Influence of Subsurface Anomalies on Vadose Zone Transport [1 2 3]

Abstract

Pesticide leaching to ground water is a potential problem in agricultural production areas of South Georgia where sandy soils are prominent. A procedure to identify and sample preferential pathways in root and vadose zones using non-destructive methods, thereby reducing the expense of water quality sampling, has been established. Detailed investigations were conducted on a 1 ha conventionally managed corn field near Tifton, Georgia. Soil-solution samples collected using suction lysimeters from January 1993 to September 1996 following the application of commercial fertilizer, the herbicide atrazine, and the insecticide carbofuran indicate significant vadose zone transport. Samples indicate high pesticide concentrations (296 ppb of carbofuran) in the vadose zone and significant concentrations in the ground water at 12 m (7 ppb of carbofuran). Because of the difficulty associated with collecting the types of field data necessary to quantify mass transport in the vadose zone, and in particular those related to preferential pathways, a two-dimensional simulation model (VS2DT) was used to further analyze the process. Data and simulation results indicate clay lenses induce ponded water in the vadose zone and impact flow and transport. While point observations of solute concentration of flows to ground water increase in some positions under the clay lens, the composite effect may decrease overall groundwater contamination. Simulations indicate that clay lenses increase the period over which the solutes are delivered to the water table, effectively decreasing the concentration in ground water under the plot at any one time.

Keywords: water quality, pesticides, modeling, preferential transport

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[1] Contribution from the USDA Agricultural Research Service, Southeast Watershed Research Laboratory, PO Box 946, Tifton, GA USA 31793, in cooperation with Univ. of Georgia Coastal Plain Exp. Stn.

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[3] ASAE Paper 992143. David D. Bosch, Research Hydraulic Engineer, Clint C. Truman, Soil Scientist, and Frank M. Davis, Computer Specialist, Southeast Watershed Research Laboratory, USDA Agricultural Research Service, PO Box 946, Tifton, Georgia USA 31793. Contact author (dbosch@tifton.cpes.peachnet.edu).

Introduction

Transport of agricultural chemicals from the root zone results in decreased effectiveness, economic losses, and adverse environmental impacts. Transport of agrichemicals depends on rainfall amount, intensity, and duration; chemical solubility and degradation properties; soil properties; biological processes; and management practices. An additional characteristic which has been found to affect this transport process is soil variability. Studies have shown that macropores and spatial variability within the root zone can dramatically increase the transport rate out of the root zone (Singh and Kanwar, 1991; Birkholzer and Tsang, 1997).

At field and watershed scales, soil properties affecting flow and transport are highly variable in space and time. Layering, aggregation, and macroporosity cause the soil profile to be highly variable. Soil and geologic heterogeneity play a significant role in groundwater contamination. While many studies have focused upon the impact of macropores and preferential flow paths within the root zone, few have studied preferential transport in deeper vadose zone profiles. Horizontally layered areas of reduced conductivity restrict vertical transport and concentrate moisture and solutes, funneling the solute plume. It is hypothesized that preferential pathways in the vadose zone lead to unexpected groundwater contamination in areas where matrix flow, or flow through the bulk soil, would not.

The objectives of this research were to: 1) develop non-destructive methods for interpreting preferential flow pathways within and through root and vadose zones, 2) quantify the concentration of agrichemicals flowing in deep vadose zones containing sub-surface anomalies, 3) develop computer simulations which represent actual field conditions of preferential flow induced by clay lenses, and 4) use the collected data and computer simulations to examine the influence of the preferential pathways on the overall transport rate to the aquifer.

Materials and Methods

Site Description

The site used for this analysis was a 1 ha field located near Plains, Georgia USA. The water-table was approximately 10 m below ground surface. The surface soil is composed of a high permeability loamy sand (Bosch and West, 1998; Shaw, 1998). Soil cores were collected throughout the plot for physical property and hydraulic characterization. The mean sea level elevation of the plot ranges from 132 m on the north side of the plot to 130 m on the south side. The average ground slope is 1.2%.

The field was in a cropping sequence of summer corn (Zea Maize L.) and winter wheat (Triticum aestivum L.) from 1993 through 1995. The corn was planted in March or April of each year. Following harvest in August or early September, wheat was planted as a winter crop in late November to early December. Conventional agricultural management practices were followed. The plot was fertilized each spring and fall. The herbicide atrazine and the insecticide carbofuran were applied separately by a tractor-mounted sprayer each year just prior to planting. The pesticides were surface applied and incorporated to approximately 50 mm.

Identification of Preferential Flow Paths

Site investigations using ground-penetrating radar (GPR) were conducted in 1992 in order to identify subsurface anomalies which could impact agrichemical transport (Truman et al., 1999). GPR provides a continuous, non-destructive profile of the features being investigated (i.e. soil horizons, water tables, clay lenses, geologic strata, etc.) in a relatively short time. A grid was laid out encompassing the entire plot. Subsurface anomalies were identified from GPR charts and hand auger samples were used to verify the soil texture.

While samples were collected throughout the plot, the focus here will be on deep lysimeter samples collected along the southern edge of the plot. Fifteen sites were identified for installation of suction lysimeters within the deep vadose zone. Suction lysimeters were installed along the upper and lower ends of an identified sloping lens (fig. 1) and at equivalent depths for comparison. Groundwater wells were installed throughout the site. The screened intervals were approximately from 9 to 10 m and from 10 to 11 m from the soil surface. Monthly soil-water samples were collected using these suction lysimeters and wells.

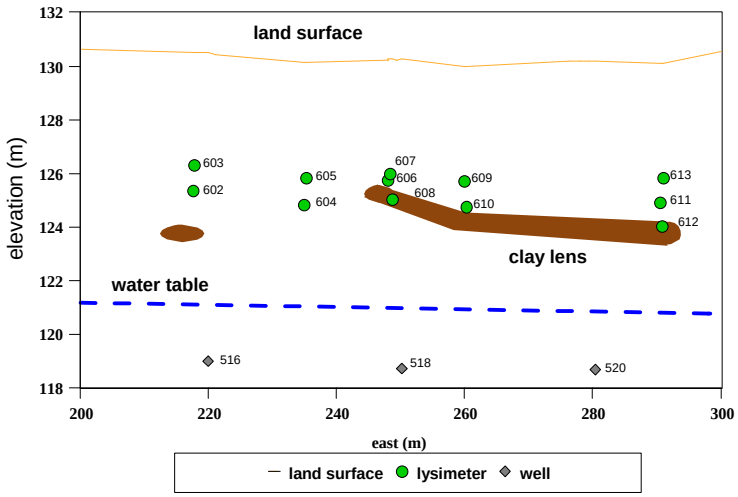

Figure 1. Vertical cross-section of lysimeter locations and wells.

Analytical Methods

All samples were analyzed for nitrate nitrogen (NO_3^- N), chloride (Cl^-), atrazine, and carbofuran. NO_3^- N and Cl^- were analyzed using standard colorimetric methods on a Lachat[4] flow injection system. Ohmicron Corporation enzyme-linked immunosorbent assay (ELISA) methods were used to screen water samples for atrazine and carbofuran concentration. All positive atrazine samples were also analyzed using capillary column gas chromatography (GC).

Numerical Simulation

The Variably Saturated Two Dimensional Transport (VS2DT) simulation model, was used to simulate transport through the vadose zone (Lappala et al., 1987, Healy, 1990). VS2DT is a finite difference program that solves Richards' equation for saturated and unsaturated flow and the advection-dispersion equation for chemical transport. The model was used to gain insight into the transport process, not to make exact comparisons to observed data.

In order to evaluate the effects of the clay lens, two representations were simulated. The first case represented a heterogeneous vadose zone with layering parallel to the soil surface. The profile was divided into 12 horizons with horizon bottoms at 0.25, 0.5, 1.0, 1.25, 1.75, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, and 10 m. The top layer was a sand, the next three loamy sands, the next three clays, and the final five sands. These layers correspond to the layering found on the western side of the field. The simple case represented the portions of the field without the clay lens. Bosch and West (1998) and Shaw (1998) collected hydraulic conductivity and soil-water release data and parameters were derived for the van Genuchten hydraulic functions (van Genuchten, 1980). Hydraulic and transport parameters are reported in table 1.

To examine the impact of the clay lens, a second simulation grid was established which contained a low density clay lens within the vadose zone extending from x, y coordinates 5 m, 4.5 m to 45 m, 6 m (fig. 2). The slope of the lens was varied to approximate actual conditions. The thickness of the clay lens was assumed to be uniform and equal to 1 m. The hydraulic and transport characteristics of the clay lens are listed in table 1. Aside from the clay lens, the layering was assumed to be the same as in the simple case.

[4] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the products listed by USDA.

Table 1. Hydraulic and transport simulation parameters for the simulated profile.

layer number	saturated hydraulic conductivity ($mm\,hr^{-1}$)	porosity	residual moisture content	beta	van Genuchten alpha (mm^{-1})	dispersivity (mm)	bulk density ($\mu g\ mm^{-3}$)
1	66.00	0.32	0.05	1.75	0.0039	20	1710
2	48.00	0.37	0.08	2.03	0.0046	40	1670
3	12.10	0.30	0.04	1.60	0.0052	40	1610
4	11.20	0.37	0.08	1.94	0.0042	30	1650
5	4.80	0.32	0.09	1.45	0.0026	70	1690
6	6.30	0.32	0.11	1.61	0.0040	70	1730
7	3.00	0.32	0.10	1.53	0.0033	70	1710
8	35.30	0.37	0.08	2.03	0.0046	20	1710
9	28.40	0.37	0.08	2.03	0.0046	20	1710
10	431.00	0.37	0.08	2.03	0.0046	20	1710
11	40.00	0.37	0.08	2.03	0.0046	20	1710
12	200.00	0.37	0.08	2.03	0.0046	20	1710
clay lens	0.1	0.37	0.1	1.53	0.0033	70	1710

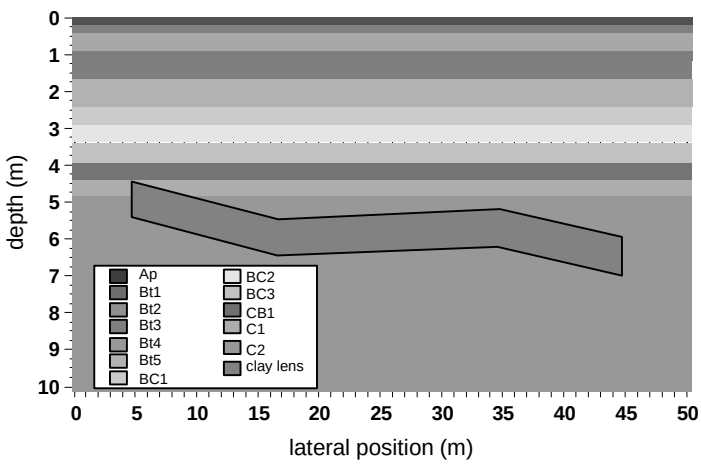

Figure 2. Simulation grid illustrating soil layering.

Both simulation grids were set up to represent a 2-D plane through the plot which was 50 m wide and 10 m to the water table. The horizontal node spacing was set at 1000 mm and the vertical node spacing was set at 31.25 mm. Space and time centering were used. Linear adsorption with Fruendlich n equal to 1 was assumed. Other constants included an anisotropy ratio of 1, specific storage of $1x10^{-7}$ mm^{-1}, molecular diffusion of 1 mm^2 hr^{-1}, decay constant of 0 hr^{-1}, and an equilibrium constant of 0.

A steady state inflow of precipitation equal to 0.14 mm hr^{-1} at the soil surface was assumed. This approximated the average annual precipitation rate of 1200 mm yr^{-1}. Evapotranspiration at the soil surface was ignored for these simulations. No flow boundary conditions were used for the sides and a constant pressure head equal to 0 was assumed for the water table. For the transport component, a pulse input of a conservative tracer at a concentration of 2009 mg L^{-1} for a period of 80 hrs was simulated. This constitutes a total applied mass of 1125 mg over the 50 m wide by 1 mm unit area, equivalent to an application of 225 kg ha^{-1}. After steady state conditions were established in each grid, the tracer was introduced for the 80 hr duration and then allowed to flow through the grid.

Results and Discussion

Vadose Zone Observations

During installation of the suction lysimeters, zones of saturation were observed just above the clay lens, indicating ponding in these areas due to the low hydraulic conductivities of the lens. A second indication of ponding was the

frequency of successful samplings for each lysimeter. Because of the sandy texture, there were times throughout the course of the study where the soil was not holding enough water to facilitate a sample. The areas directly above the clay lens were frequently saturated and we were seldom not able to capture a sample with these lysimeters. These are indirect indications that the clay lens was restricting vertical flow of water and enhancing lateral flow.

Increases in NO_3^- N and Cl^- in the vadose zone lysimeters were first observed in May 1994, approximately 420 days after first application. The first vadose zone observation of pesticide concentrations above the 0.5 ppb detection limits was made in July 1994 at lysimeters 604 and 609. The following month, atrazine was detected in all lysimeter samples. The greatest observed concentration of carbofuran was 296 ppb, observed at lysimeter 605 which was at 4.3 m, collected in July 1995.

Soil-water samples from lysimeters at 4.3 m indicated elevated concentrations of NO_3^- N, Cl^-, atrazine, and carbofuran along the west side of the main transect. These elevated concentrations appeared to be related to the texture of the surface soil. The texture of the surface soil (top 2 m) was coarser on the west side of the plot than on the east. This appeared to facilitate more rapid transport of agrichemicals on this side. Similar results were found when samples from the lysimeters at 5.2 m were compared.

Groundwater Observations

The first observations of pesticides in ground water at the site were made in April 1994 (fig. 3), approximately 370 days after the first application. The first increases in NO_3^- N and Cl^- were observed in December 1994. The greatest increases in chemical concentration have been observed on the west side of the plot, in well 516. Concentrations up to 75 ppm of NO_3^- N and up to 7 ppb of carbofuran have been observed at this well. Pesticide concentrations peaked in December 1994 while NO_3^- N concentrations did not peak until December 1995. Comparisons of data from wells 516, 518, and 520 indicate elevated NO_3^- N and pesticide concentrations on the west side of the plot. Concentrations also appear to peak later on the west side of the plot.

Vadose Zone Modeling Simulations

VS2DT simulations were used to enhance our interpretation of the vadose zone observations. For the simple case (soil layering only without the clay lens), simulated pressure heads varied from 0 at the water table to -800 mm in layer 12. Simulated moisture contents varied from 15 to 37 %, with the least moisture in layer 12. Since this is essentially a 1-D case, steady state flow rates were constant and equal to the input flow rate, 0.14 mm hr^{-1}. For the simple case, significant levels of the tracer were first simulated at the water table 417 days after application, with all transport to the water table completed by 833 days after application (fig. 4). The mass balance for this simulation accounted for 100.6 % of the introduced tracer out of the grid bottom.

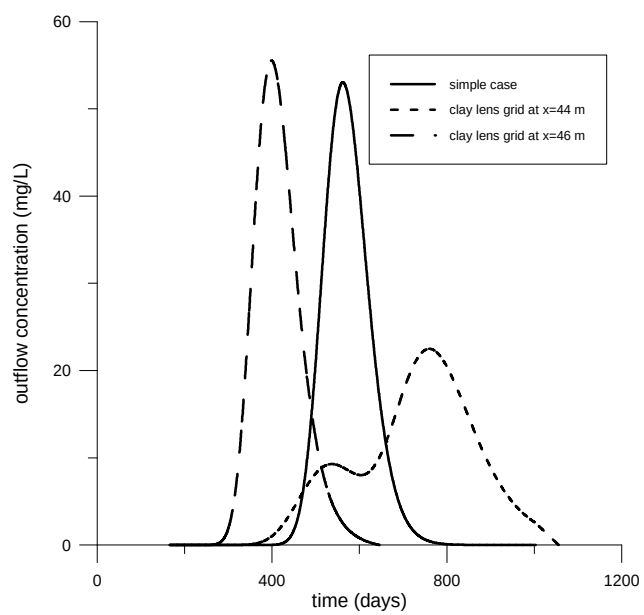

Figure 3. Simulated outflow concentrations for the simple case and the clay lens grid at two positions.

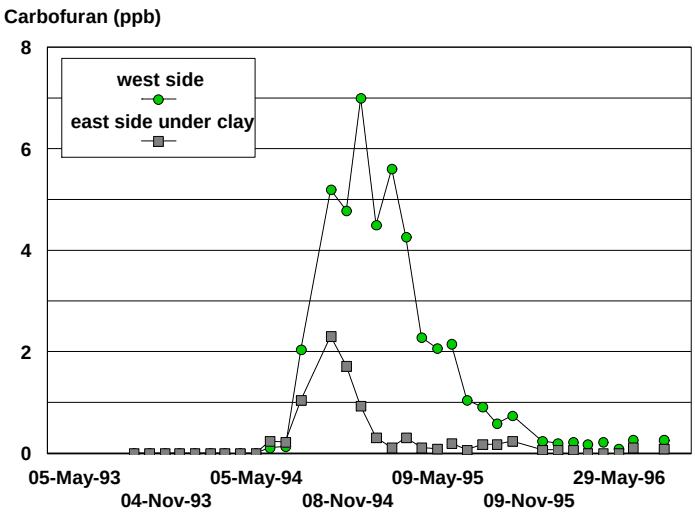

Figure 4. Carbofuran concentrations observed in the plot wells.

The clay lens simulation illustrated several differences to the simple case. Simulated pressure heads varied from 0 to -800 mm, however, ponding was simulated above and saturation within the clay lens. Flow rates ranged from 0 to 126 mm hr^{-1}, with the greatest flows simulated within and near the clay lens. Flow rates were greatest just above the clay lens, where the sandier textured layers become saturated due to the lens. A lateral flow component was induced by the clay lens, with flow driven downslope along the clay.

Significant levels of the conservative tracer were first simulated at 292 days after application (fig. 4). Peak concentrations of 55 mg L^{-1} of the tracer were simulated at 46 m along the x axis. Large concentrations were also simulated from 0 to 4 m, the area not significantly influenced by the clay lens. Loading in this area was similar to the simple case. An interesting phenomenon was simulated at 44 m. At this position two pulses of the tracer were simulated (fig. 4), likely a consequence of flow which by-passed the clay lens on the east side and flow re-directed by the clay lens. This is illustrated somewhat by the histogram of the accumulated mass outflow along the lower boundary (fig. 5). The greatest outflow mass occurs from 45 m to 48 m, followed by the area from 0 to 4 m. There is also significant loading beneath the clay lens, influenced by flow around the lens itself. The total outflow mass accounted for was 1116 mg, or 99% of the input.

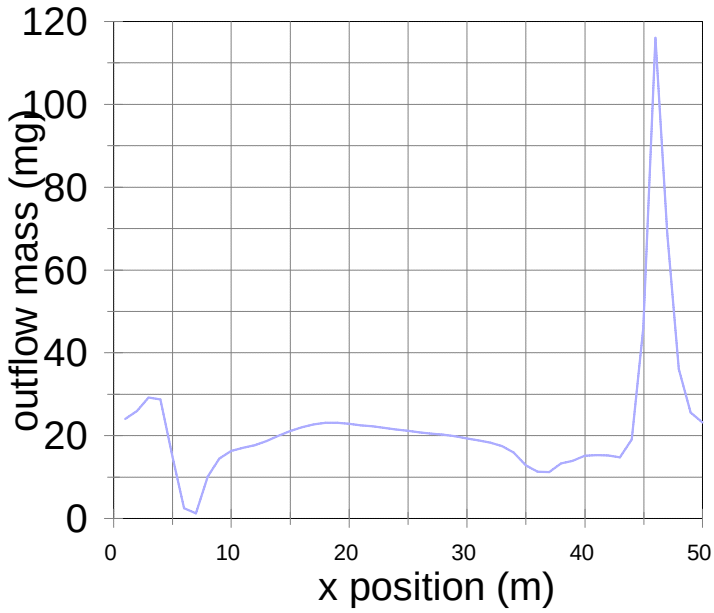

Figure 5. Simulated accumulated mass outflow for the clay lens grid.

Conclusions

The data and computer simulations indicate that clay lenses are impacting flow and transport within the vadose zone. Groundwater data indicate that loading is significantly less under the clay lens (fig. 3). Lower concentrations were observed at the well that was located around 10 m from the end of the clay lens, or at x=35 m on the simulation grid, than at the well located to the west of the clay lens. Interestingly, x=35 m is approximately the point at which the lowest mass loading occurred for the clay lens simulation (fig. 5).

Computer simulations indicate that the lenses can impact groundwater quality, although not in the manner we had expected. Concentrations and mass loadings are affected. The lens channels the flow and transport toward the downgradient end of the lens. However, the lenses do not appear to be having the concentrating effect on the solute transport that we had hypothesized. Because

the time at which the solute is delivered to the water table is spread out by the effects of the lens, the actual concentration in the ground water may be less. While the concentration at individual points may be higher, the concentration over larger areas will be lower because the solute is delivered over greater durations. For the clay lens case, the tracer transport to the water table is spread out over 1,125 days in contrast to a total time of 400 days for the non-lens case. The overall impact thus appears to be to dilute the overall loading to the water table by spreading out the delivery rate.

Our computer simulations appear to match the observed delivery times fairly well. The simulation predicted that the solute would reach the water table earlier on the east side of the plot which was impacted by the clay lens than on the west side which was not impacted. This is supported by our groundwater observations (fig. 3). Approximately 370 to 700 days lapsed between the time of first fertilizer application to the time it was observed at the water table. Our simulations indicate a travel time of 290 to 600 days depending on the configuration with the clay lens.

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