Nutrient Cycling in Agroecosystems **50:** 91–97, 1998.

Mapping and interpreting soil textural layers to assess agri-chemical movement at several scales along the eastern seaboard (USA)

Tammo Steenhuis[1*], Kathy Vandenheuvel[1], Kirk W. Weiler[1], Jan Boll[1], Jayaram Daliparthy[2], Stephen Herbert[2] & K.-J. Samuel Kung[3]
[1]*Department of Agricultural and Biological Engineering Riley-Robb Hall Cornell University Ithaca, NY 14853 USA;* [2]*Department of Plant and Soil Sciences University of Massachusetts Amherst, MA 01003 USA;* [3]*Department of Soil Science University of Wisconsin Madison, WI 53708, USA (* corresponding author: phone: (607)255-2489, fax:(607)255-4080, email:tss1@cornell.edu)*

Key words: funnel flow, unsaturated flow, layered soils, preferential flow, ground penetrating radar, groundwater contamination

Abstract

Despite numerous cases of groundwater contamination with agricultural chemicals on layered sandy soils, monitoring and prediction of the fate of these chemicals in the vadose zone has eluded researchers and bureaucrats alike so far. To aid in a better understanding of this phenomena, the movement and fate of agricultural chemicals were assessed at different scales for the (sandy and layered) floodplain soil occurring along the Eastern Seaboard. At the point and field scale ground penetrating radar was used to locate the coarse sand lenses and tracer experiments were initiated to study the flow pattern of the chemicals. Results show that water and solutes moved over the coarse layers and were funneled into fingers bypassing most of the soil matrix and reaching the groundwater much faster than when the solute would move evenly through the vadose zone. At field scale a computer simulation indicated that the exact location of the layers does not have to be known for calculating travel times, indicating that pedo-transfer functions could be developed for calculating groundwater pollution potential for different combinations of soil and chemicals. In the future, groundwater pollution on a regional scale can be predicted by using these pedo-transfer functions in a Geographic Information System.

Introduction

Soil surveys have been completed in many countries and can be reliably used for qualitative interpretations of the suitability of a site for different land uses. Relying on soil survey data to assess the danger of groundwater pollution, however, is more complicated and requires a quantitative approach based, in part, on the soil survey data [2]. This quantitative approach can vary in scale and complexity. The scales, as defined by Hoosbeek and Bryant [8] vary from molecular scale (-5) to the continental scale (+5). Scale 0 is the pedon or plot. The complexity ranges from relatively simple assessments (level 1), expert knowledge (level 2), to simulation methods of various degrees (levels 3, 4, and 5). Groundwater contamination can be transient and, thus, a variable for time needs to be included in the quantitative approach. Although groundwater models introduce time varying values, these changing parameter values can also be obtained by monitoring. Whereas the latter is a more direct way of obtaining these values, monitoring is not without complication either as we will see later from the field site in Massachusetts where we measured solute concentrations.

The case study for this paper is groundwater pollution from agricultural chemicals in the region along the Eastern Seaboard of the United States where much of the productive agricultural land can be found. Scales of interest are point or horizon (-1), plot or pedon (0), polypedon or field (1), watershed or catena (2), county (3), or regional (4). The spatial terminology we will use throughout the paper (i.e., point, plot, and field) has been chosen because it is more consistent with the terminology in other solute movement studies. In the next sections we will discuss the groundwater quality findings in the Eastern Seaboard region followed by field and/or smaller scales for an experimental area in Massachusetts where we have carried out several experiments.

Regional scale problem definition and scale selection

The soils along the Eastern Seaboard are deposited by post-glacial rivers and have a texture ranging mostly from sand to sandy loam. As a result of the deposition process, these soils are characterized by layers of coarse and fine sand. Many primary aquifers are located in this area and some, such as on Long Island, can serve as the sole water supply of some 10 million people. In the rural areas many farm wells directly extract water from the aquifer without any pretreatment. The contamination of groundwater in this region is, therefore, a subject of great concern.

Many cases of groundwater pollution with agricultural chemicals have been reported in the Eastern Seaboard region. The first publicized occurrence of the pesticide aldicarb (and other carbamates) in groundwater occurred in the sandy soils of Long Island. Since that time, researchers from the Northeastern United States have reported that sandy (and gravelly) deposits are the most vulnerable soils to the leaching of pesticides, nitrates and other substances to the groundwater: Massachusetts [3, 6]; Connecticut [7, 19]; New Jersey [15]; New York [17]; New Brunswick [16]; and in the Delmarva Peninsula [11]. Interestingly, the depth of contaminant detection was positively correlated with the historical land use pattern. Nitrates, which use clearly predates that of pesticides, were found deepest in the aquifers [11].

Selection of scale for fate of agricultural pollutants

For studying the fate of agricultural chemicals, a scale size of the field or smaller is the most appropriate. In almost all cases, the groundwater pollution can be traced back to a specific location or field in the landscape. An excellent example of this relation between origin of contamination and the present location of the plume is the TCE pollution from dry cleaning stores on Long Island. By obtaining the location and the dates of operation of the dry cleaning store from old air photographs and knowing the velocity and the direction of the groundwater, the contaminant plume can usually be found without difficulty. Another example is where the Army dumped toxics in the 1950's with the thought: out of sight out of mind. Thirty years later, by tracking the movement of the chemicals, the culprits were identified.

Unlike the Army's dumping of chemicals or the TCE added from dry cleaning stores, models (levels 3, 4, and 5) that rely on the convective-dispersive equation have shown that application of agricultural chemicals to agricultural land should not cause any groundwater problems. However, as we have seen above, expert knowledge (level 2) based on monitoring at plot and field scales (0 & 1) has shown quite the opposite along the Eastern Seaboard region.

Problem definition at the field (and smaller) scales

At the field, plot, and point scales there are two issues in groundwater contamination: The first is how the contamination is measured and the second is prediction of the degree of contamination at the various scales. These two issues will be illustrated for the Massachusetts site.

Massachusetts site

The location of the experimental site is on the banks of the Connecticut River in Deerfield, MA at the University of Massachusetts Research Farm, and is typical for other sites in river valleys and along the coast. The experimental site is positioned on a primary high yielding aquifer surrounded by an area of intensive farming activity. The soil at the site is classified as a fine sandy loam (coarse, mixed, mesic Fluventic Dystrochrept) whose description, according to the soil survey, is given in Table 1. Its upper 0.6 m is homogeneous, overlaying inclined layers of coarse and fine material until a depth of approximately 2 m where the profile becomes more silty. It should be noted that the soil survey data was based on one pit. We found considerable variance, especially in the depth of the silt layer throughout the field.

Initial experiment

To determine the effect of nitrate leaching under manured alfalfa plots, an experiment was initiated in 1990 with the surface application of liquid dairy manure on a one-year-old alfalfa stand. Treatments for alfalfa consisted of a control (zero N), low manure-N (112 kg N ha^{-1} yr^{-1}), high manure-N (336 kg N ha^{-1} yr^{-1}), low fertilizer N (112 kg N ha^{-1} yr^{-1} from $NH_4 \cdot 12NO_3$), and high fertilizer N (336 kg N ha^{-1}

Table 1. Soil profile description of the South Deerfield site.

Depth from Surface (cm)	Soil Horizon	Soil Texture	Remarks
0–22	Ap	fine sandy loam	crumbs, friable
22–75/90 (wavy)	C1	fine sandy loam	massive, friable
75/90–150+	C2	fine sand with silt lenses	massive, friable
150+ and deeper	C3	silt	

yr^{-1} from $NH_4 \cdot 12NO_3$). The experimental design was a randomized complete block with four replications. Individual plot sizes were 3 by 6 m with a border of 0.9 m. For each plot, porous cup samplers at 0.3, 0.6, 0.9, and 1.2 m and wick pan samplers at 1.2 m were installed to study the fate of the applied nitrogen in this soil.

Results of initial experiment

In general, nitrate concentration was low under alfalfa plots [4, 5] and the quantification of the alfalfa's effect was hampered by a large amount of variability in the collected data. The concentration profiles for the porous cup samplers (point measurements) indicated that solute movement occurred along different flow paths. At the 0.6 m depth, relatively high nitrate concentrations were unexpectedly found in the control plot (Figure 1), where no manure or fertilizer was applied. As we shall explain later, this indicates a possible horizontal movement of nitrate from a neighboring plot. High NO_3-N concentrations were detected in one plot with a low fertilizer application, which was also puzzling since in the two other plots NO_3-N was almost absent (Figure 1a). In the manure plots, the peak NO_3-N concentration arrived earlier at 1.2 m than at 0.9 m, and showed that both high and low manure applications could result in high concentrations at the 1.2 m depth (Figure 1b). The wick samplers, however, did not collect any water during the growing season. Only in early spring, after heavy rainfall, did five out of 28 samplers collect water. Unlike the porous cup samplers at 1.2 m, the samples taken from the wick samplers were found to have a low nitrogen concentration. Thus, two sampling methods, proven to be very reliable under other circumstances [1], gave highly different results at the South Deerfield site: the suction cup samplers indicated that nitrogen moved down under the different treatments, while the wick samplers did not indicate a possible groundwater pollution problem.

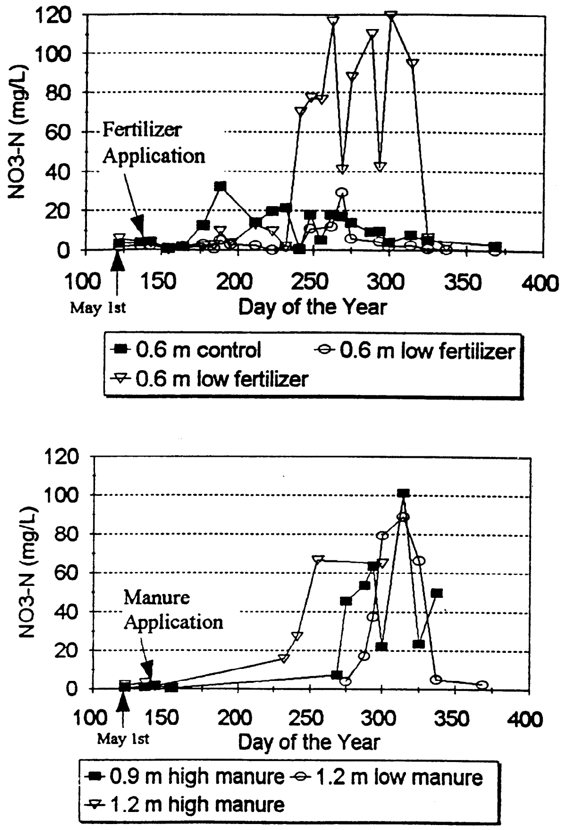

Figure 1. NO_3-N concentration data of porous cups: a. Three cups at 0.6 m depth; b. One cup at 0.9 m depth and two at 1.2 m depth.

Formulation of a hypothesis

Based on the above results, a hypothesis must be formulated that accounts for the large amount of variance seen at a point scale in the initial alfalfa experiment. One hypothesis that begins to explain this variance is that preferential (funnel) flow is the main mechanism for solute transport at the Massachusetts site. By using appropriate simulation methods, scaling from point scale to field or larger scale is possible. The effect of spatial variable chemical input concentrations is not likely to affect the funnel flow concentration and is, therefore, not considered.

Preferential flow in layered soils

For soils which contain horizontal layering in the vadose zone, as is the case at the Massachusetts site, preferential flow may occur in either the form of fingers or funnels. Finger flow occurs when the wetting front reaches the interface between a fine soil overlying a coarse soil [17]. If these coarse layers are inclined, then funnel flow occurs [12]. In unsaturated flow, it is often the case that the wetting front which reaches the coarse layer will be at too high of a tension to enter into the layer. As a result, a capillary fringe will begin to develop and flow will move laterally along the layer until the pressure exceeds the water entry value of the coarse layer. At that point, breakthrough will occur. Because this flow causes solutes to move in a nonuniform wetting front, most one-dimensional models, which assume equal horizontal solute concentrations, are invalid.

Selection of a research method

Upon formulating a hypothesis a research method must be selected that can test the hypothesis and provide answers at point, plot, and field scales to the following questions: point scale: 'Which, if any, of the two sampling methods was correct?'; plot scale: 'Can soil layering explain the high nitrate concentrations in the control, low manure, and low fertilizer plots?'; field scale: 'How can we scale up the point and plot measurements to field scale?'; and regional scale: 'How can average groundwater loadings be simulated?'

To answer these questions for the plot and field scale the following methods were selected: surveying the site with ground-penetrating radar (GPR) [1] to inspect and find the structure of the subsurface layering of the field, performing experiments with dye to visualize the flow paths at a point, and adding a chloride pulse to study the solute movement on a plot scale. For the field scale we used the results of a simulation study by Ju and Kung [10].

GPR survey

In order to properly predict funnel flow we must precisely map field layer geometries [9]. GPR is the only non-destructive method to do this in situ.

A PulseEKKO 1000 GPR system, manufactured by Sensors and Software (Mississauga, Ont., Canada), was used to find the layer structure. The 450 Mhz center frequency antenna of the radar allowed for a resolution of approximately 20 cm in the vertical direction and a depth penetration of 1.5 m. We surveyed the area of the 1990 experiment and also the plots for the chloride and dye studies discussed hereafter.

Dye study

Using ground-penetrating radar to locate a suitable layer, a field site was chosen in which the coarse sand layering occurred at approximately 75 cm in depth. In order to visualize the flow paths of water in the soil profile, 10–20 ml of red dye was injected in the beginning of September at 6 points 25 cm apart at a depth of 45 cm and approximately 20 cm above the coarse layer. Measurements were taken four months after application from a dug trench by shaving away the soil profile to expose the dye's movement.

Chloride experiment

The field site used in this study bordered the initial experiment site. Four subplots were chosen, but only one will be discussed here as an illustration of the processes occurring. Calcium chloride was surface applied to the field at the beginning of October, 1994. The calcium chloride was applied at a rate of 0.070 kg/m of Cl_{-} as $CaCl_2 \cdot 6H_20$. Beginning in late March 1995, soil samples were taken on a transect at 0.5 m horizontal intervals for a total of 5 m and at 20 cm depth intervals to a maximum of 140 cm to determine chloride mass balances and chloride breakthrough points on the coarse sand layers. The soil samples were diluted with 20 ml of deionized H_20 and chloride content in the soil solution was then determined using a digital chloridometer made by Buchler Instruments.

Results and data interpretation

Dye movement

Figure 2 shows the layer configuration and the dye movement four months after the dye application. The coarse layer was slanted slightly upwards with a slope of 3 degrees for 110 cm, where it ended. A fine sand intrusion of 5 cm in width occurred at 85 cm along the layer. The dye measurements show that plumes from the first three injection points situated above the coarse layer have a considerable lateral flow component over the coarse sand layers, while greater vertical movement is seen from points above or near the fine sand. Flow occurred through the fine sand intrusion into the coarse layer. There was also some evidence that dye was starting to move under the layer from the streamlines of sites five and six.

By comparing the 10–15 cm of downward flow from the first two injection sites to the 75 cm of downward flow at site six it is evident that the coarse sand lens acts as a barrier to flow at the point scale. Several other studies have also confirmed that water and solutes in sandy soils can be funneled into finger-type flow paths [12, 13, 14].

Chloride experiments

The soil sampling that was done near the end of the experiment shows indications of funnel flow on a plot scale. The general trend seen in chloride recovery for plot 1 (Figure 3) as well as for the other plots (not shown) is high recovery rates at the downdip ends of the layers or where the layer slope suddenly levels. In plot 1 the chloride found at the end of the layer was approximately four times the amount that was originally applied. Flow above this layer directs the chloride movement down and across the layer, thus, the high chloride content at the end of the layer is to be expected. The portion of the soil not affected by the layer shows a uniform chloride content (approximately equal to the amount applied), which is also to be expected. The data from these soil samples show remarkably similar trends to the moisture data seen by Weiler et al. [22], with higher values at the downdip locations on the layers.

Model selection, aplication and evaluation

Plot scale

Model selection: Many models have been proposed for the mathematical formulation of funnel flow [13, 18, 21]. These models primarily focus on determining the breakthrough point on the layer, which is the location at which the capillary barrier can no longer divert the incident water flux [18].

Steenhuis et al. [21] proposed the following equation for the maximum length to leakage on a coarse sand lens:

$$L = \tan\phi[1/\alpha(K_s/q_v - 1) + K_s/q_v(h_e - h_w)] \quad (1)$$

where ϕ is the slope of the coarse sand layer, $(1/\alpha)$ is the capillary length (cm), K_s is the saturated conductivity (cm/day) of the fine overlying sand, q_v is the incident vertical flux (cm/day), h_e is the air entry value (cm) of the fine sand and h_w is the water entry value (cm) of the coarse sand. Equation (1) tends to underpredict the breakthrough length because of its assumption that no water flows over the high point of the layer [23].

Model evaluation: Based on the information gained in the dye experiment and the chloride study we can now better explain the spatial distribution of the 1990 experiment. A GPR transect of the 1990 experiment is shown in Figure 3. The vertical axis shows the depth and the horizontal axis the distance along the soil surface. The coarse layer indicated on the image (and verified by excavation) was at its highest point where the wick pan samplers were installed and funneled water away from the wick pan samplers. The distance that the finger moves over the layer depends on the recharge rate (Eq. (1)). Hence, the five wick samplers intercepted fingers only in spring during a high recharge rate. In contrary to the wick samplers, porous cup samplers attract preferential flow paths in the vadose zone above the capillary fringe, as was shown in Connecticut on a similar soil [19]. Also, in Delaware [20] we found clear evidence of the same phenomena. Consequently, it is very likely that the porous cups overpredicted the amount of nitrate moving down while, due to the experimental layout, the wick samplers underpredicted the amount.

Chloride breakthrough lengths were calculated for the 1994–1995 experiment using Eq. (1), in order to determine its validity. Weiler et al. [22] calculated, based on an in situ instantaneous profile method (point measurement), that the fine sand has a saturated moisture content of 0.57 cm^3/cm^3, a saturated conductivity of 0.007–0.015 cm/min, a capillary length of 63 cm and an air entry value of 40–60 cm. The coarse sand has a water entry value of 17 cm. The slope of the layer in plot 1 was 6% and the recharge rate with the sprinkler irrigation on was approximately 0.6 cm/day. Based on Eq. (1), the maximum calculated breakthrough length is 225 cm, while the layer length is 250 cm. Thus, the observed breakthrough at the end of the layer is in accordance with the conservative estimate of 225 cm with Eq. (1). Also, in the other three plots, although the data was quite variable, Eq. (1) predicted the breakthrough length in almost all cases [23].

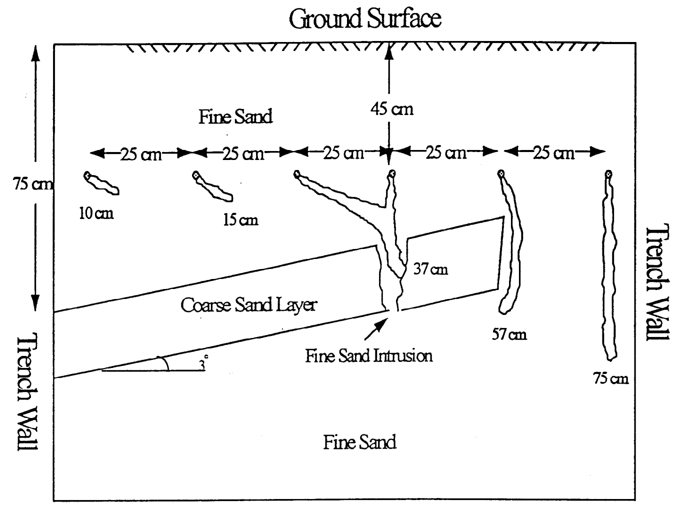

Figure 2. Pattern of dye movement four months after application. Distances below dye plumes indicate maximum vertical movement.

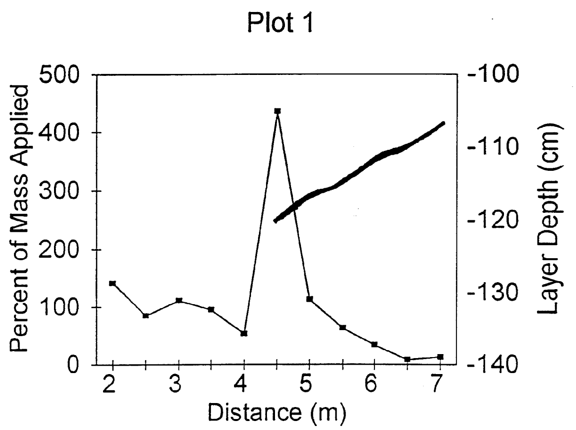

Figure 3. Layer configuration and percent chloride recovered in soil cores in a transect in plot 1. Dark solid line indicates the layer location. Solid squares and line is the percent of the chloride recovered from the application.

Field scale

Knowledge of unsaturated flow regimes is crucial in modeling and sampling for groundwater solutes. From all the experiments carried out, it is evident that preferential flow takes place in the areas where the coarse sand lenses are located and should be taken into account when scaling up from point measurements. Standard soil survey data, as expected, does not provide enough detail for this and additional information about the textural composition and location of the layers need to be known. We have found that GPR with a 450 MHz antenna could be used to find the location of the layers.

With precise information about layering, soil properties, and downward fluxes, it is possible to use simulation models, such as developed by Ju and Kung [9] to predict the exact location of the preferential flow paths for different rainfall rates on a plot scale. It is, however, unrealistic to expect that we can survey the Eastern Seaboard with GPR to find the layering structure and predict flow paths. A different method needs to be found to predict the fate of agricultural chemicals on a field or larger scale. Recently, Ju and Kung [10] used a finite difference computer model to model water and pesticides in a layered soil profile under a wide variety of water fluxes and soil properties including the number of coarse sand layers. They found that the shape of the solute breakthrough curve as function of cumulative recharge was independent of the actual layer structure below approximately 10–15 coarse sand lenses. They found that the water then moved in only 10–15% of the soil profile. Although Ju and Kung's study was specifically for a profile with rather small coarse sand lenses, a similar simulation can be performed for longer sand lenses. The important finding of Ju and Kung's work is that the exact location of the sand lenses does not have to be known to obtain a breakthrough curve on a field scale. This allows us, then, to use the models to develop pedo-transfer functions for a characteristic soil along the Eastern Seaboard region which translates water input rate to travel time. In this way, we have only to perform GPR surveys for a subset of all soils. By superimposing the chemical and biological characteristics the concentration in the groundwater can be calculated. Clearly, more research has to be performed

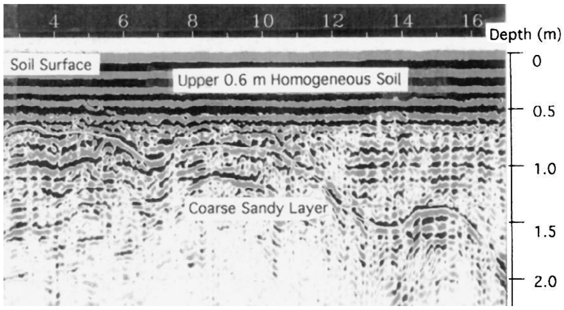

Figure 4. GPR transect for the 1990 nitrate leaching experiment at the South Deerfield site showing the presence of the coarse sandy layer between 0.6 and 1.5 m depth. The sampler is located at left-hand side where the layer is the most shallow.

to find the pedo-transfer function for the different layered soil profiles.

Model selection – regional scale

Once pedo-transfer functions have been developed, a Geographic Information System (GIS) could then predict groundwater loadings on a county or regional scale. As long as the pedo-transfer function and the chemicals spread on the land are not known we cannot predict the large scale groundwater loading realistically yet.

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