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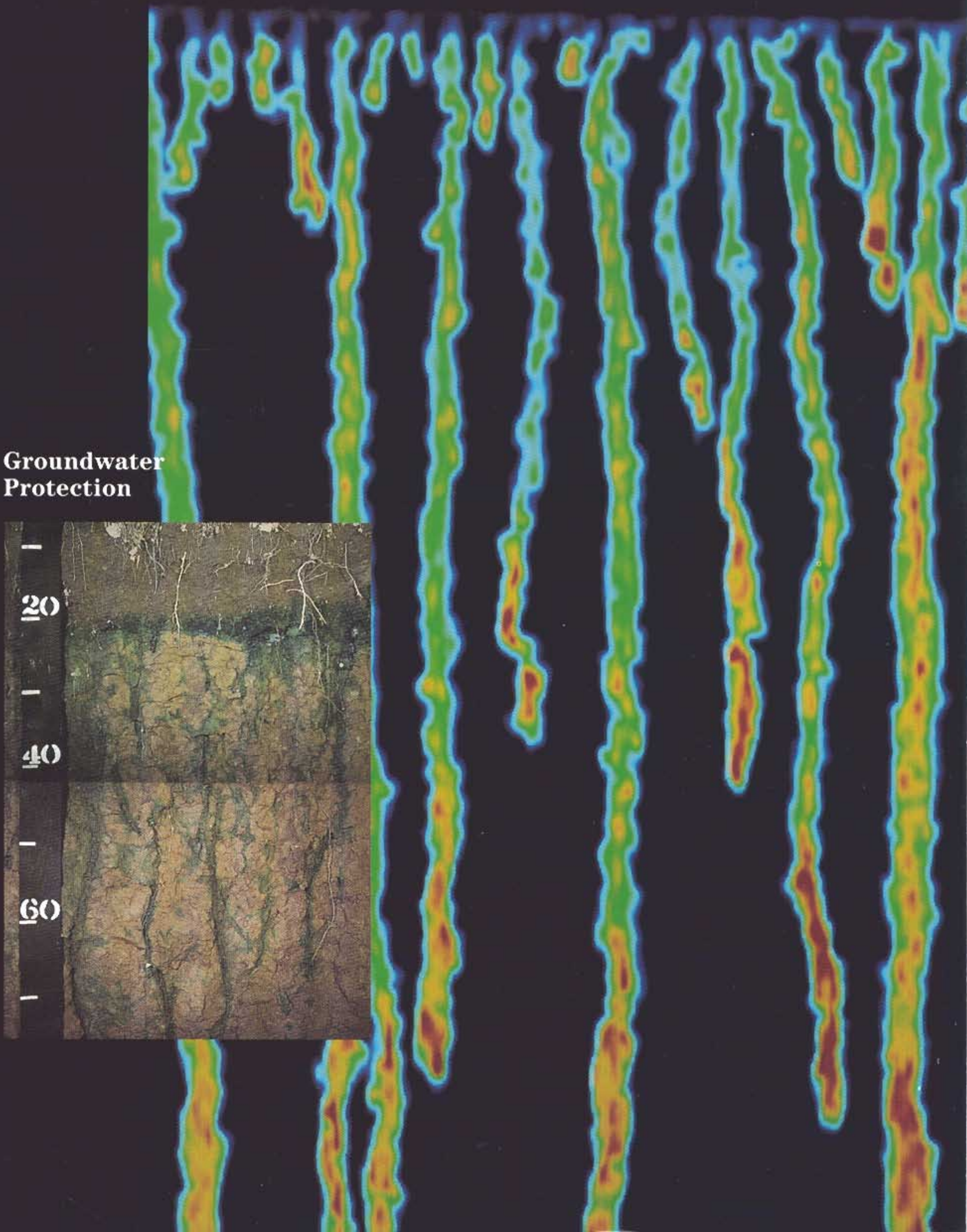

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The Flow of Pesticides through Preferential Paths in Soils

by J.-Y. Parlange, T. S. Steenhuis, R. J. Glass, T. L. Richard, N. B. Pickering, W. J. Waltman, N. O. Bailey, M. S. Andreini, and J. A. Throop.

Increasing concern about the presence of pesticides and other chemicals in the environment has led to strict regulation of their use, and in particular on their concentration levels allowable in groundwater. This in turn is forcing scientists to refine their analyses of the movement and fate of pesticides in the soil, and to consider processes which have become important because minute amounts of chemicals must be accurately accounted for.

Water is nature's primary vehicle for the transport of dissolved chemicals. It is also a valuable resource, and for this reason many hydrological models have been developed to predict, for instance, watershed yield and groundwater recharge. With few exceptions, as with movement through fissured rocks, these hydrological models do not consider explicitly preferential paths in a soil, such as cracks, macropores, worm holes, decaying roots, and so on.

Rather, transport equations are written for an "average" path which predicts average water movement for a suitable time interval. A typical error in snch averaging procedures is that the early arrival of water through preferential paths is not described. As long as this early arrival involves relatively little water, and as long as the time interval necessary to reach the average recharge is short enough, the procedure is appropriate. Indeed, this is the case for most hydrological problems.

Theory and Reality

Figure 1 illnstrates some consequences of averaging procedures by looking at fertilizer (nitrate) movement below a potato field; that is, that part of added fertilizer which reaches the water table and was not taken up by the crop roots. The experimental observations show a continuous increase over the 24-week season. An averaging (theoretical)

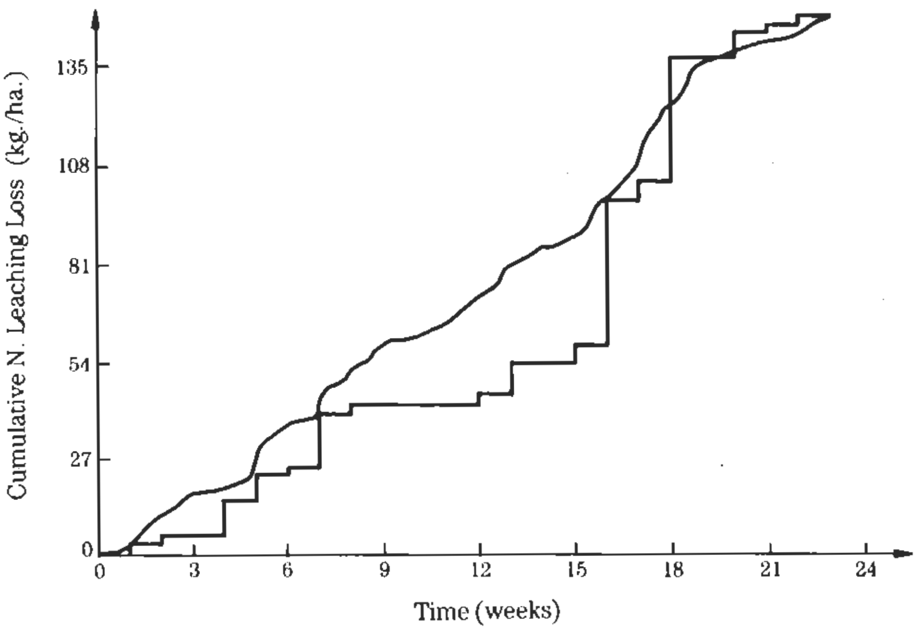


Figure 1. Cumulative experimental and predicted leaching losses from planting to season end for the Wisconsin potato crop.

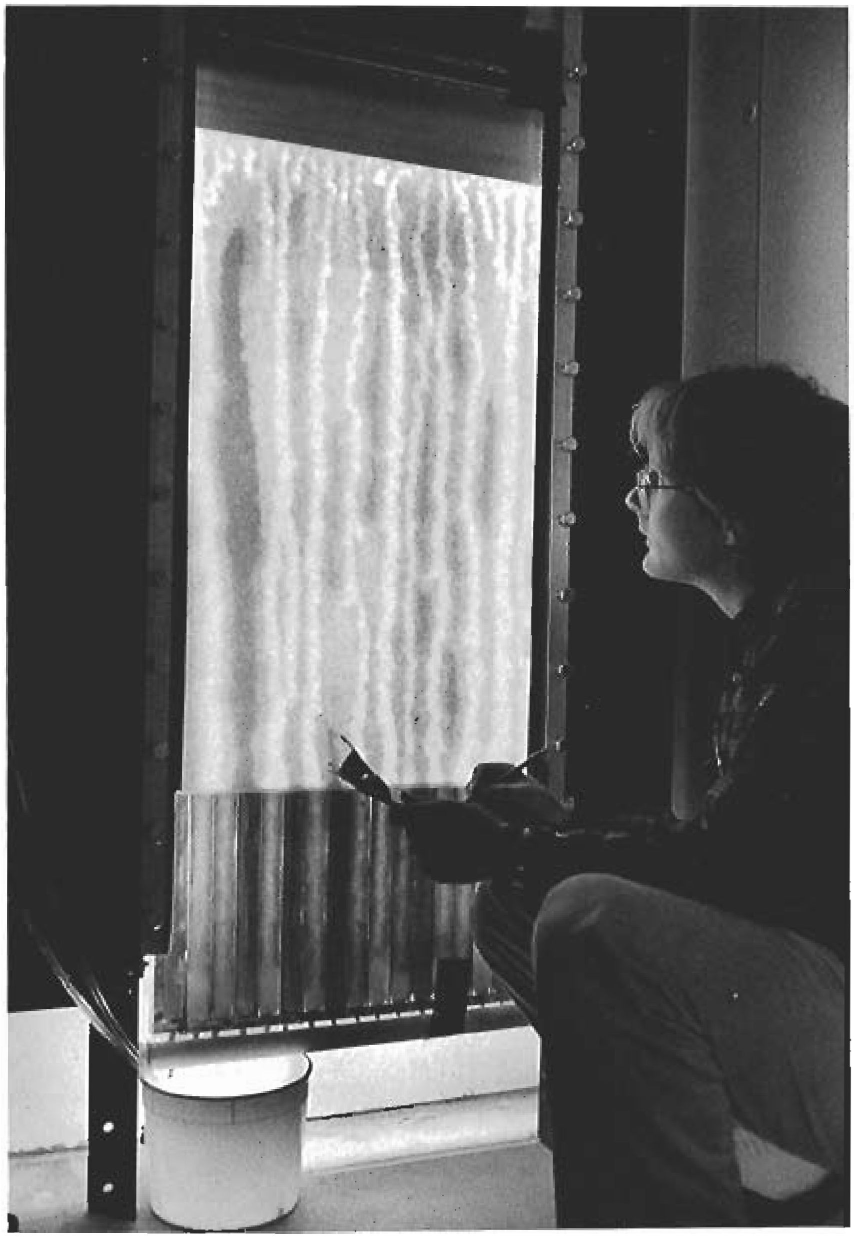
procedure, based on one-week time intervals, predicts sudden and large increases in weeks 16 and 18. The theory also predicts very little additional nitrate between weeks 7 and 16, whereas the field observations show an increase at a uniform rate.

The reason for these discrepancies is quite clear: Between weeks 7 and 16 the added water is small enough that, on the average, the water does not penetrate very far below the root zone. The theory predicts that much of the nitrate accumulates just below the root zone, then in weeks 16 and 18 sufficient water is added to flush the soil, causing large amounts of nitrate to be leached. Indeed, the "average" picture is physically misleading, since some preferential pathways do in fact carry water—and nitrate—to the water table during weeks 7 to 16.

How significant is the discrepancy? If we are trying to predict water recharge and nitrate concentrations on a weekly basis, the model is inadequate. But on the other hand, for a half-year basis it is acceptable. In terms of water recharge, the lack of accuracy on a weekly basis is probably not very important, whereas the large nitrate concentration for week 16 in the recharge water (according to the model) makes it adequate for predictive purposes.

We must stress that the requirements for nitrate prediction are far more constraining than for water: If we do not know within a couple of weeks when water reaches the water table not much harm will result, but if that water has an excessively high concentration of nitrate, it is unfit for human consumption no matter when it arrives.

How can we remedy the difficulty? Obviously, the model must be refined; talking about average soil properties is



Laboratory soil column of top soil layer over coarse sand for demonstrating formation of preferential paths. Amount of water in "fingers" determines intensity of light emerging from light box behind soil column.

Both kinds of preferential paths are able to rapidly carry small quantities of pesticides to large distances below the topsoil...

inadequate to predict nitrate movement. The remedy depends on the requirements and will be different, in general, for fertilizers and for pesticides.

Soil Studies

Instead of looking only at the average water transport, the next level of sophistication is recognizing that soil heterogeneities, i.e., the existence of different pathways, can be studied as a stochastic, or statistical, phenomenon. Thus, not only the average water flux, but the standard deviation around the mean as well, is predicted. Such an approach does not require a detailed description of the pathways, just a statistical description of soil properties.

Indeed, when such a model is applied to nitrate movement in Figure 1, the prediction of cumulative leaching is practically the same as measured, for all times. The reason for the improvement is clear: The transport of nitrate is substantial and consequently involves many pathways, even between weeks 7 and 16; and as long as a large number of them have to be considered, a statistical approach is warranted. Thus, a relatively straightforward improvement of the averaging procedure is appropriate.

These statistical improvements, however, may not be adequate in the case of pesticides and dangerous chemicals. The maximum levels of concentration acceptable in groundwater can be a thousand times lower than they are for nitrates and are expressed in parts per billion (ppb) instead of parts per million (ppm). Hence, if a thousand different pathways must be considered to explain nitrate leaching, only one might be responsible for unacceptable, toxic levels of pesticides in the aquifer.

Under such conditions no statistical description of heterogeneities, which implies that many pathways participate in the transport, is adequate. Rather, individual preferential pathways that may be responsible for the accidental transport of pesticides must be mapped and described in situ. Obviously, this would involve an enormous amount of research to determine the most efficient and economical ways to carry out such mapping, especially as pathways may change with the season and differing agricultural practices, such as tillage.

Our group uses dye tracer technique to delineate preferential pathways in a soil, as illustrated by the left photograph on the cover. It shows a plow layer with a nonadsorbing blue dye uniformly distributed (more or less) as it enters the lower layer through cracks and other preferential paths.

The pulse of dye, dissolved in water, is applied in a ring at the soil surface. The method involves two steps: First, a blue dye, as shown in the figure, is applied when steady state infiltration under ponding has been reached, to indicate all preferential paths where sampling for pesticides might be required. Not all pathways will carry water and pesticides equally to the water table, since pathway continuity is required. For instance, one pathway may terminate and carry little water once a steady state is reached. To indicate this, at the end of the experiment a pulse of a different color dye, e.g. red, is added which enters preferential paths for a short distance only to indicate the magnitude of the flow in each crack. Then a trench is dug carefully and the cracking pattern as indicated by the dyes is photographed for future analysis and characterization.

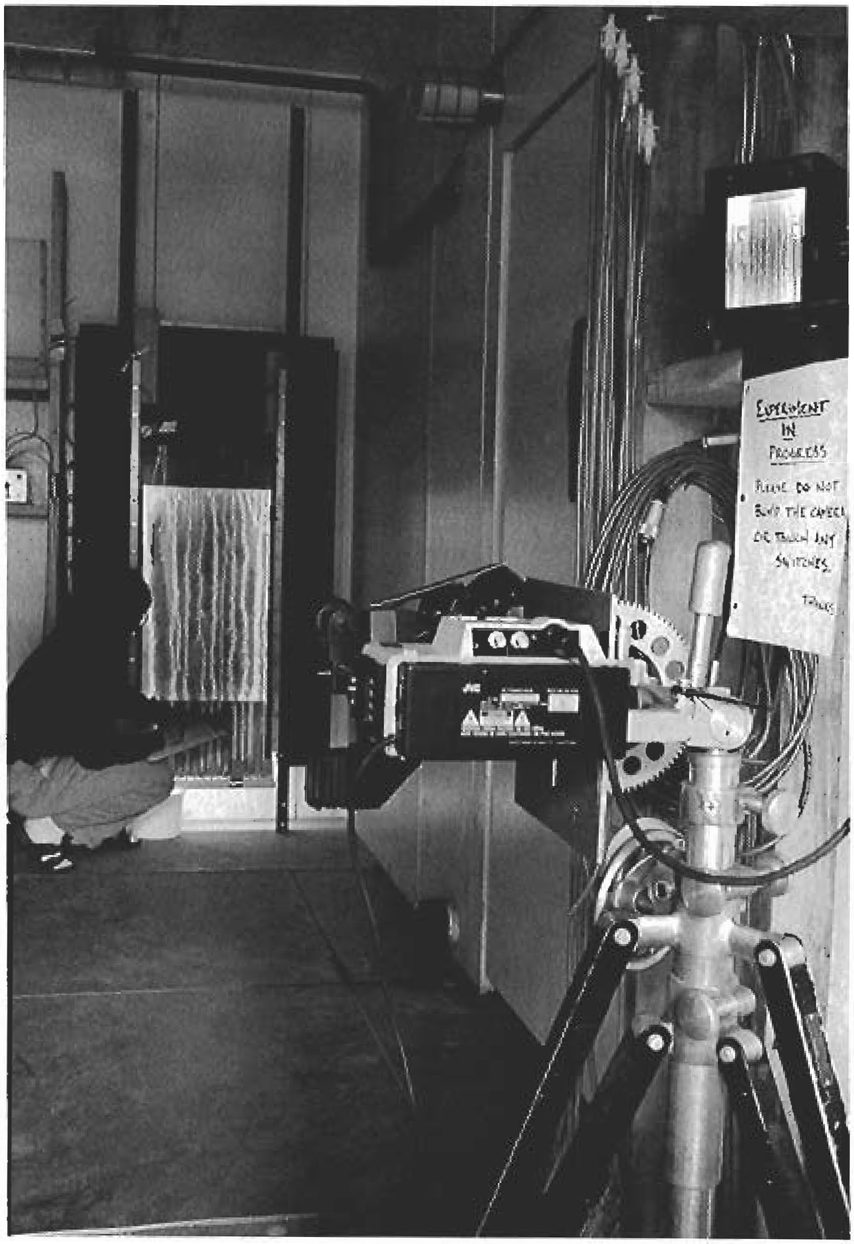
Trying to describe all soil series, even in New York State alone, is probably unrealistic. At present, we plan to analyze systematically only a dozen of the more important agricultural soils. This mechanism of transport through preferential paths is especially important for shallow soils where roots and worm holes permeate the soil layers, but we should not expect the same process to occur with deep, sandy aquifers as found on Long Island.

Characterizing Sandy Soils

For deep, sandy aquifers with little soil structure, another process takes place leading to preferential paths differing from the roots and worm holes of shallow soils—but it suggests very similar consequences. The process (right photograph on cover) is demonstrated with a two-dimensional soil column having two layers. The top layer, representing the "plow layer," is uniformly filled with water, the bottom layer is a coarse sand, uniform throughout, and yet it shows preferential paths. We have visualized this by shining a light through the column and analyzing the intensity of the emerging light. More light indicates more water and each color in the photograph is a computer equivalent of range of water content, red being the wettest and blue the least wet.

To understand the mechanism for the formation of preferential paths in a homogeneous soil, imagine the topsoil as a sponge saturated with water with drops of water hanging at the lower surface, held by surface tension and pulled by gravity. The coarse sand underneath sucks in these drops as they try to form, resulting in narrow, vertical, preferential paths, called "fingers."

Superficially, preferential paths formed by cracks and fingers may appear very different, but in fact they



As water forms preferential paths in soil column intensity of emerging light is recorded by video camera in foreground. Digitized video image can then be statistically analyzed and recreated as a computer graphic representation (see cover).

are very similar. In both cases the downward movement is caused by gravity in near-saturated cores; the width of the core is that of the crack in one case, while in the other the width is controlled by surface tension. Around the wet core, water diffuses laterally in both cases, and if pesticides are present adsorption may occur as well. Observation and characterization of fingers *in situ* has also been carried out with dyes, exactly as in the case of cracks. Both kinds of preferential paths are able to rapidly carry small quantities of pesticides to large distances below the topsoil, and in sufficient quantities to pollute our groundwater.

In conclusion, we must reiterate that stricter regulations on smaller, acceptable levels of chemicals require a more refined understanding of the physical and chemical processes involved in their transport and fate. This in turn requires additional and costly laboratory and field research. The above discussion on preferential paths concerns one such process that cannot be ignored.

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