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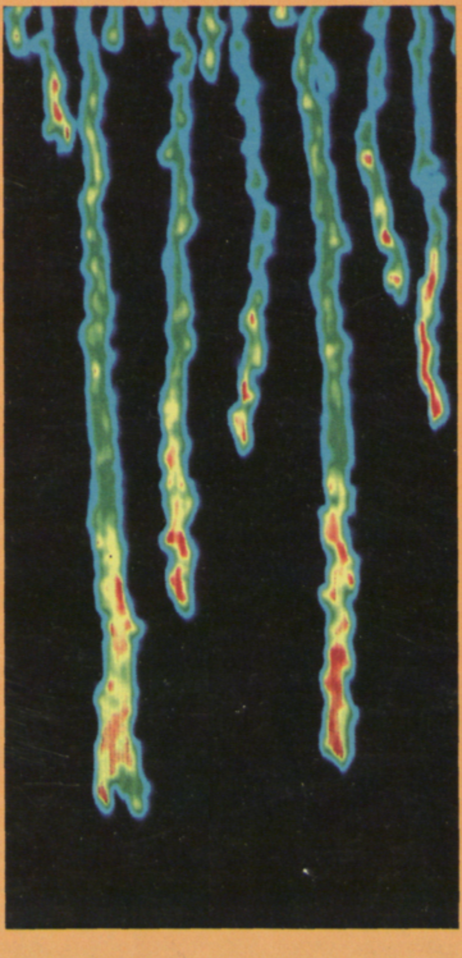

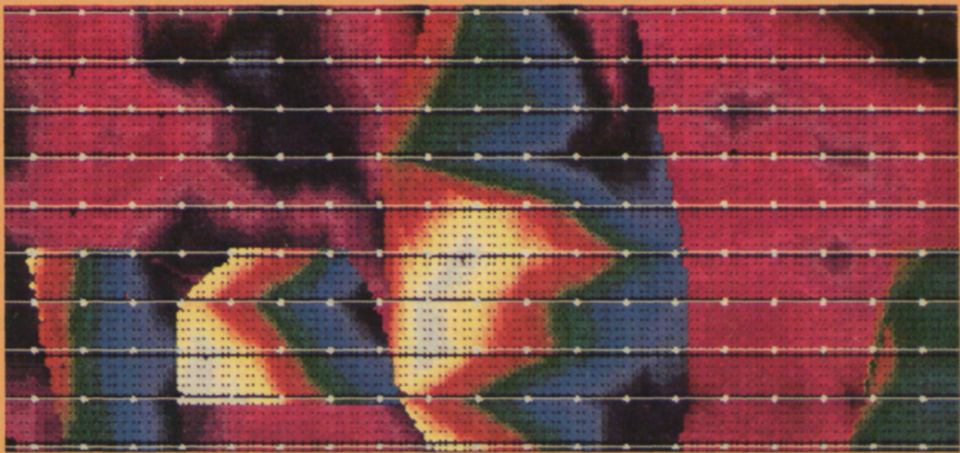

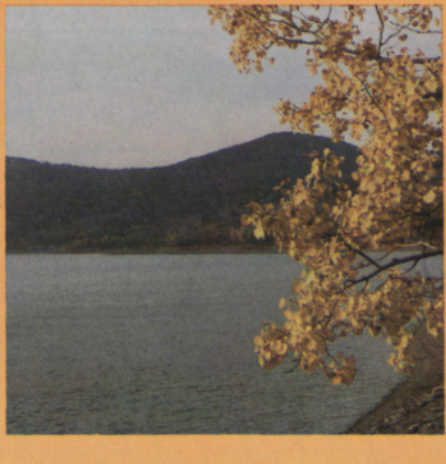

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WATER IN THE GROUND

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Outside cover illustrations, clockwise from upper left: Fingers of water infiltrating into layered sand (see page 13); a computer-generated image of a map view based on data from ground-penetrating radar signals (see the article pages 15–19); a view of Cannonsville Reservoir in New York State (see page 4).

Opposite: The valley of the West Branch Delaware River, discussed by Douglas A. Haith in his article in this issue. The view is from a hill near the town of Walton, New York.

MATHEMATICAL MODELS OF NONPOINT-SOURCE POLLUTION

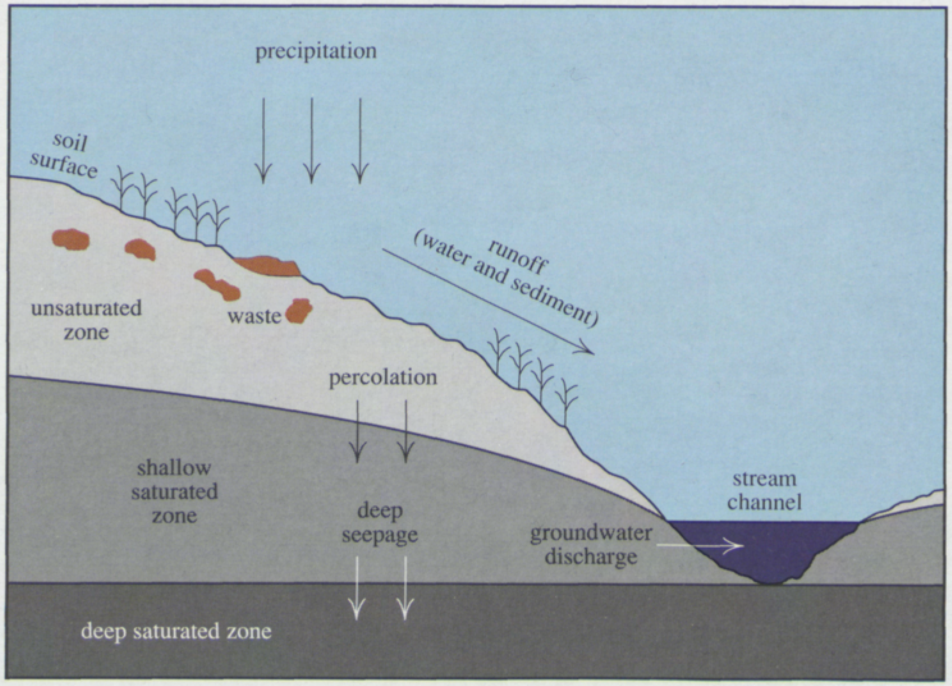
by Douglas A. Haith

A form of water pollution with the improbable name of "nonpoint-source" was placed in a regulatory spotlight by the U.S. Water Pollution Control Act Amendments of 1972. For many years engineers and planners had concentrated on sources of pollution such as municipal sewage and industrial wastes, which are discharged at particular, fixed points. But there was a growing recognition that nonpoint-source pollution also has a profound effect on the quality of the nation's water. Subsequent research has shown it to be a serious and persistent problem.

Nonpoint-source pollution is the contamination of aquifers, streams, rivers, and lakes by water that picks up harmful materials as it drains off the landscape. Precipitation in the form of rain or snow, as well as water used for irrigation, may become polluted by mixing with waste materials as it runs across the surface or percolates through the soil (see Figure 1).

Most of the wastes that become nonpoint-source pollutants are the residue of human activities. Some wastes are deliberately disposed of on the land; obvious examples are municipal and industrial wastewaters and sludges, drainage from septic tanks and dry wells, solid waste in municipal landfills, and livestock manures. Other materials become wastes inadvertently: pesticides, fertilizers, and eroded soil that wash from agricultural lands; salts and other chemicals that become concentrated in irrigation drainage; sulfates from acid rain; the accumulated litter and debris on city streets; and drainage from coal and salt storage piles.

Figure 1. A schematic view of the hydrology of nonpoint-source pollution.



"... a lake may be polluted by pesticides as a result of a particular combination of chemical applications and rainfall that is likely to occur only once in several years."

THE UTILITY OF STOCHASTIC MODELS

Nonpoint-source pollution is much more variable than pollution from point sources such as sewage-treatment plants. The many different flow paths are often difficult to identify and impossible to monitor. Furthermore, nonpoint-source pollution is initiated by random weather processes, and the major rainstorms and winter thaws that produce significant runoff and percolation are unpredictable and ephemeral.

This extreme variability in time and space complicates efforts to measure and manage nonpoint-source pollution. For example, when water from one well is sampled to detect nitrate contamination, concentrations in nearby wells may differ by a factor of ten. Equally great differences may be seen in samples from the same well taken over an interval of several months. Similarly, a lake may be polluted by pesticides as a result of a particular combination of chemical applications and rainfall that is likely to occur only once in several years. Such an episode, although brief, may be sufficient to destroy most of the aquatic life in the lake.

Because of the practical difficulties of monitoring nonpoint-source pollution, water-quality engineers have turned to mathematical models to simulate hydrologic and chemical processes and estimate the loads of nonpoint-source contaminants that can be expected in bodies of water. Since these pollution loads are stochastic—random over time—they are most realistically described by probability distributions.

Dairy farms, a major source of nonpoint-source pollution, on the West Branch Delaware River.

In simple situations, probability distributions of nonpoint-source pollution can be derived analytically. In most cases, however, the problems are sufficiently complicated to require a Monte Carlo simulation process. Probability distributions of weather variables such as temperature and precipitation are sampled to produce a long-term weather record. These data are input into a model that simulates the hydrologic and chemical processes that interact to pollute a particular body of water. The model then generates probability distributions showing the likelihood that pollution loads will exceed specified levels.

A CASE IN POINT: CANNONSVILLE RESERVOIR

This type of modeling was recently used to track fluctuations in the amount of phosphorus entering a reservoir from nonpoint sources.

The West Branch Delaware River Basin is an 850-square-kilometer watershed in a dairy-farming region east of Binghamton, New York (see Figure 2). Thirty percent of the land is used for agriculture, 67 percent is forested, and 2 percent is urban. The watershed empties into the Cannonsville Reservoir, a source of water for the city of New York. Phosphates draining from the watershed into the reservoir have caused excessive growth of phytoplankton, whose decay during the summer months uses up dissolved oxygen in water near the surface, so that deeper water becomes oxygen-starved. This process, which is known as eutrophication, has greatly diminished the reservoir's value as a municipal water supply. The U.S. Environmental Protection Agency funded a study to determine the sources of phosphorus in the watershed and evaluate possible control measures; the study was carried out by the New York State Department of Environmental Conservation and Cornell's Department of Agricultural and Biological Engineering.

A major portion of the study involved developing a model of how the plant nutri-

Figure 2

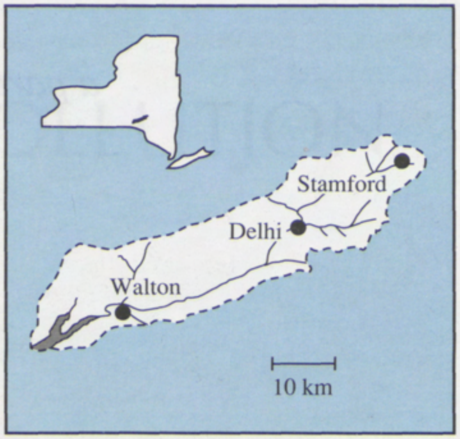


Figure 2. The West Branch Delaware River Basin, which drains into Cannonsville Reservoir. The location of the drainage basin is shown on the small map of New York State. A view of the valley appears inside the front cover.

Below: A view of Cannonsville Reservoir.

ents, nitrogen and phosphorus, were carried by water draining from the watershed. The model, which came to be known as Generalized Watershed Loading Functions (GWLF), includes representations of both dissolved and solid-phase nitrogen and phosphorus in stream flow from point sources, groundwater, rural runoff, and urban runoff. Rural runoff includes nutrient loads from forests, croplands, and barnyards. Urban runoff includes nutrients washed from streets and other solid surfaces of developed areas.

The GWLF model, which was developed with the assistance of Leslie Shoemaker, a graduate student in agricultural and biological engineering, employs mathematical descriptions of a variety of different processes. These include snow melt, evapotranspiration, groundwater discharge into streams, erosion and sediment transport, and removal of nutrients from farmers' fields and village streets. Since the reduction of these phenomena to mathematical terms involved a great many simplifying assumptions, it was important to determine whether the model is, in fact, a valid representation of the watershed.

PREDICTED AND OBSERVED LEVELS OF NUTRIENTS

Validation is an essential component of any water-quality modeling exercise. Mathematical models of water pollution are, at best, only crude approximations to reality, and it is necessary to test the accuracy of their results.

The GWLF model was tested by comparing model predictions with the actual flux of stream flow, sediment, and nutrients measured in the West Branch Delaware River Basin over a three-year period. Samples were taken and analyzed from April 1979 through March 1982. We found that the phosphorus loads predicted by the model correlate quite well with these observations (see Figures 3 and 4). This suggests that the GWLF model is a reasonably accurate means of estimating the nutrient loads of phosphorus that can be expected from a particular watershed.

The GWLF model was subsequently run in a Monte Carlo simulation to determine probability distributions of phosphorus loads and to assess the relative magnitudes of phosphorus sources. A one-hundred-year record of daily weather was input into the model to produce one hun-

Figure 3. Correlation of measured stream flow in the West Branch Delaware River (circles) with predicted values (dashed line).

Figure 4. Correlation of measured phosphorus in the West Branch Delaware River (circles) with predicted values (dashed line).

Figure 3

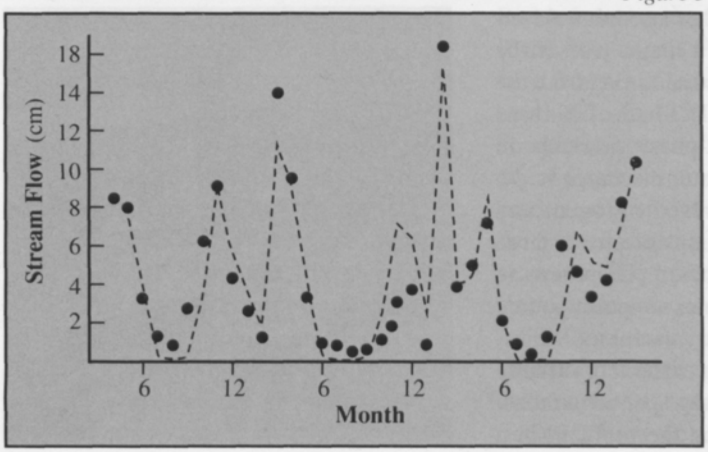


Figure 4

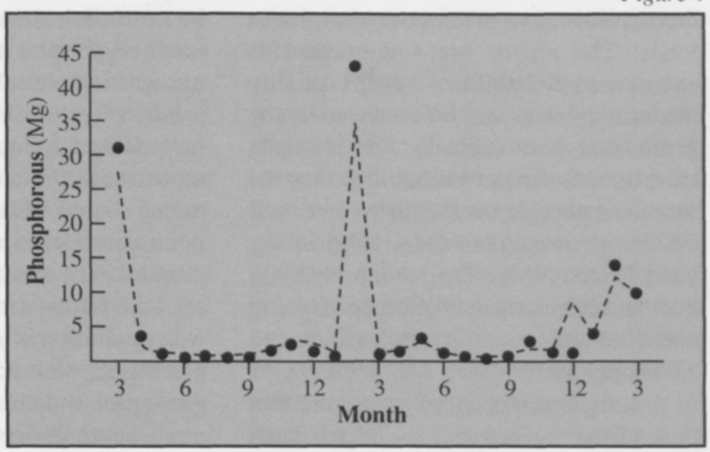


Table I.

Probability of Annual Nitrogen and Phosphorus Levels

Probability of Exceedence (percent)	Nitrogen (Mg)		Phosphorus (Mg)	
	Dissolved	Total	Dissolved	Total
50	270	350	25	53
40	285	369	26	55
30	301	389	27	58
20	322	415	28	62
10	353	453	30	68
5	318	487	31	73
2	416	529	33	79

Table II.

Magnitude of Nitrogen and Phosphorus Sources

Source	Nitrogen (percent)		Phosphorus (percent)	
	Dissolved	Total	Dissolved	Total
Agricultural runoff	37	46	41	70
Forest runoff	3	2	1	1
Urban runoff	0	5	0	2
Groundwater discharge	44	34	18	9
Point Sources	16	13	40	18

dred annual values of reservoir phosphorus loads. The results are summarized as exceedence probabilities—the probability that stated values will be exceeded in any given year (see Table I). For example, there is a 5 percent probability that the dissolved phosphorus flux in the river will exceed 31 megagrams (Mg, 10^6g) in any year. There is also a 5 percent probability that the total amount of phosphorus (both dissolved and in a solid state) will exceed 73 Mg per year.

A comparison of mean annual nutrient fluxes from various sources, as generated by the model, shows that agricultural runoff is responsible for a major part of the nitrogen and phosphorus draining from the watershed (see Table II). Much of this load is produced by solid-phase nutrients in eroded soil. Groundwater discharge is the major source of dissolved nitrogen, and point sources are responsible for a large proportion of the dissolved phosphorus.

A model that simulates nonpoint-source water pollution is a very useful tool. Inasmuch as the pollution is extremely variable over space and time, taking enough measurements to understand the problem in a particular watershed is very laborious and time-consuming. A good model obviates the necessity for much of this process. Since the GWLF model was developed and validated, it has been used by planning departments and soil- and water-conservation districts in several counties in central New York. The model software and users' manual have also been requested by engineers in other parts of the United States, Canada, and Europe.

Douglas A. Haith, a professor of agricultural and biological engineering, is a specialist in environmental systems analysis. He has also held positions as hydraulic engineer, project engineer, and senior engineer in several consulting firms.

Haith joined the Cornell faculty in 1971 after earning a doctorate here. He also holds B.S. and M.S. degrees from the Massachusetts Institute of Technology.

The American Society of Civil Engineers awarded him the Walter L. Huber Civil Engineering Research Prize in 1981 and the Wesley W. Horner Environmental Engineering Award in 1988.

In addition to professional papers, his publications include Environmental Systems Optimization, *published by Wiley in 1982.*

PREFERENTIAL FLOW IN STRUCTURED AND SANDY SOILS

by Tammo S. Steenhuis and J.-Yves Parlange

In 1980, residents of eastern Long Island were dismayed to learn that approximately a thousand wells, from which they got their drinking water, had been contaminated with Aldicarb, a pesticide used to fight the Colorado potato beetle. Regulators familiar with local conditions were as surprised as anyone, for they did not expect the pesticide to get into the groundwater so rapidly, nor in such high concentration. Their conception of the fate of pesticides was clearly inadequate.

Long Island's problem is not unique. In the United States, 95 percent of the rural population depends on groundwater for drinking, and many cities use it for all or part of their water supply. In the Third World, where there are as many as fifty thousand deaths a day from diseases carried by surface water, people are encouraged to dig wells. However, contamination of groundwater with agricultural chemicals is a serious threat. Modern agriculture relies on a broad range of fertilizers and pesticides to assure reliable crop yields, and although integrated pest management may reduce the amount of chemicals needed, a total ban is not currently feasible. A long-term hazard is involved: once the chemicals get into groundwater, they may remain there for hundreds of years.

PREDICTING SOLUTE DISTRIBUTION THE CONVECTIVE-DISPERSIVE WAY

In order to advise farmers about the relative safety of different agricultural practices, it is necessary to predict the way in which pesticides and fertilizers leach into groundwater. The best way to account for all possible soil types and climatic conditions would be to conduct field experiments on each farm, but this is manifestly impractical. So methods have been developed that simulate the way in which the water flux carries solutes into the ground.

The approach currently used by many soil scientists derives from the work of L. A. Richards, whose doctoral research, published in the first issue of *Physics* in 1931, formulated a theory of water movement in unsaturated soils. In 1956 Wiebe van der Molen combined aspects of this model with the theory of dispersive movement in an attempt to predict the course of desalinization of land in the Netherlands that had been inundated by seawater. The resulting convective-dispersive equation assumes that water and solutes follow an average path through the soil—which is to say that a given molecule, starting at the surface, is equally likely to follow any one of a multitude of available paths.

Typical of models based on the convective-dispersive equation is MOUSE (Model of Underground Solute Evaluation), which we developed in the early 1980s. It assumes an average flow path for water moving through the soil, and includes a statistical description of soil heterogeneities. MOUSE and similar models have proven quite satisfactory for predicting the overall flow of water and the transport of nitrates; in studies conducted on Long Island, the predicted values are acceptably close to values determined by sampling (Figures 1 and 2). But studies of pesticides conducted at similar sites failed to predict the speed with which the contaminants penetrated the soil (Figure 3).

The difference in predictive accuracy results from a wide disparity in the amount of chemicals that will cause health standards to be exceeded. According to limits set by the Environmental Protection Agency, nitrates are tolerable in concentrations up to 10,000 parts per billion, which are not attained unless more than 40 percent of the amount commonly applied reaches groundwater. In contrast, the maximum permissible pesticide concentration is usually below 10 parts per billion. On Long Island, a con-

Figures 1–3. Test results showing how well the convective-dispersive equation in the computer program MOUSE predicted groundwater recharge and solute transport.

Figure 1, comparing calculated values for groundwater recharge with actual movements, shows a reasonably good correlation.

As illustrated in Figure 2, an acceptable correlation was found also for the amount of nitrate showing up in groundwater in the months following surface applicaton.

The convective-dispersive equation proved unsatisfactory, however, in predicting the occurrence of a pesticide in groundwater (Figure 3). The model predicted that the pesticide atrazine would not arrive for one thousand days, but actually it began to appear after only eight days.

In the experimental studies, water-quality samples were taken from tile drainage lines.

centration of 2.5 parts per billion may be attained if just one quarter of one percent of the amount usually applied reaches groundwater. Since this limit can be exceeded if only a small amount of solute follows a non-average flow path, averaging models based on the convective-dispersive equation are too simplistic.

PREFERENTIAL FLOW IN STRUCTURED SOILS

A more sophisticated model must take preferential flow into account. It must recognize that water does not infiltrate the soil uniformly, but shows a preference for certain pathways. In clay and loam soils, for example, areas of relatively low permeability are riddled with channels consisting of cracks partially filled with sand and small stones, as well as passages formed by roots and earthworms. When it rains, water infiltrating the ground follows these channels in preference to the surrounding matrix, whose small pores are penetrated comparatively slowly (see the photograph on the opposite page). Different

Figure 1

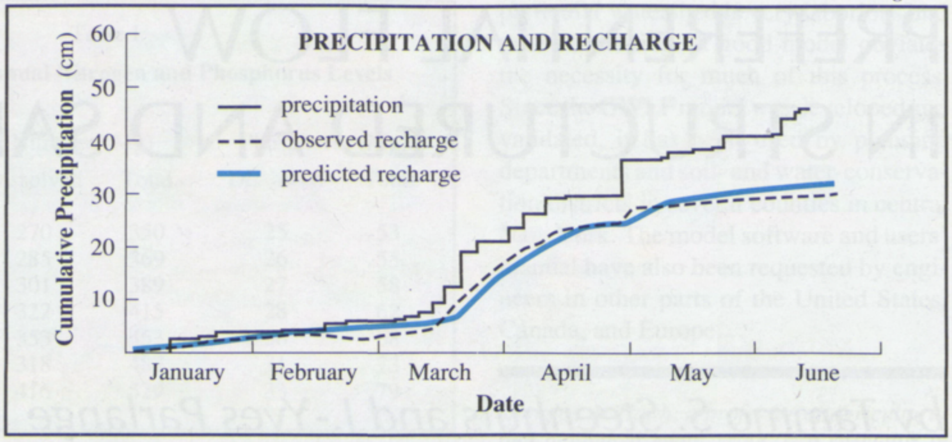


Figure 2

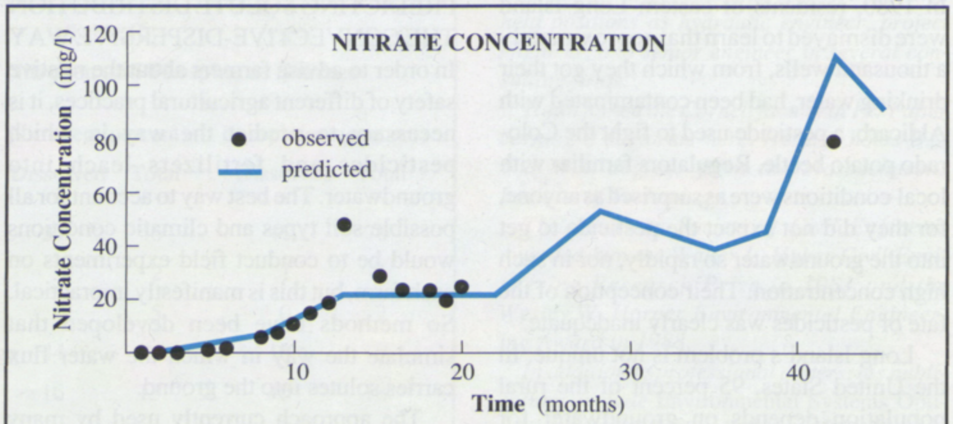
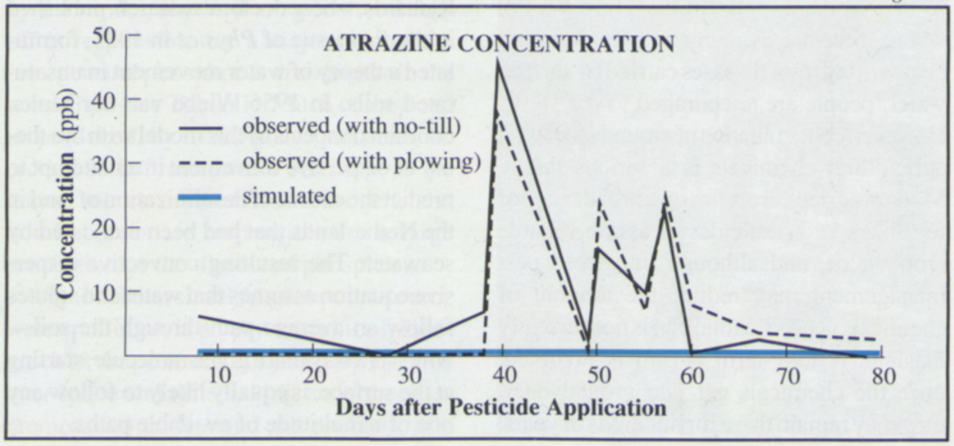
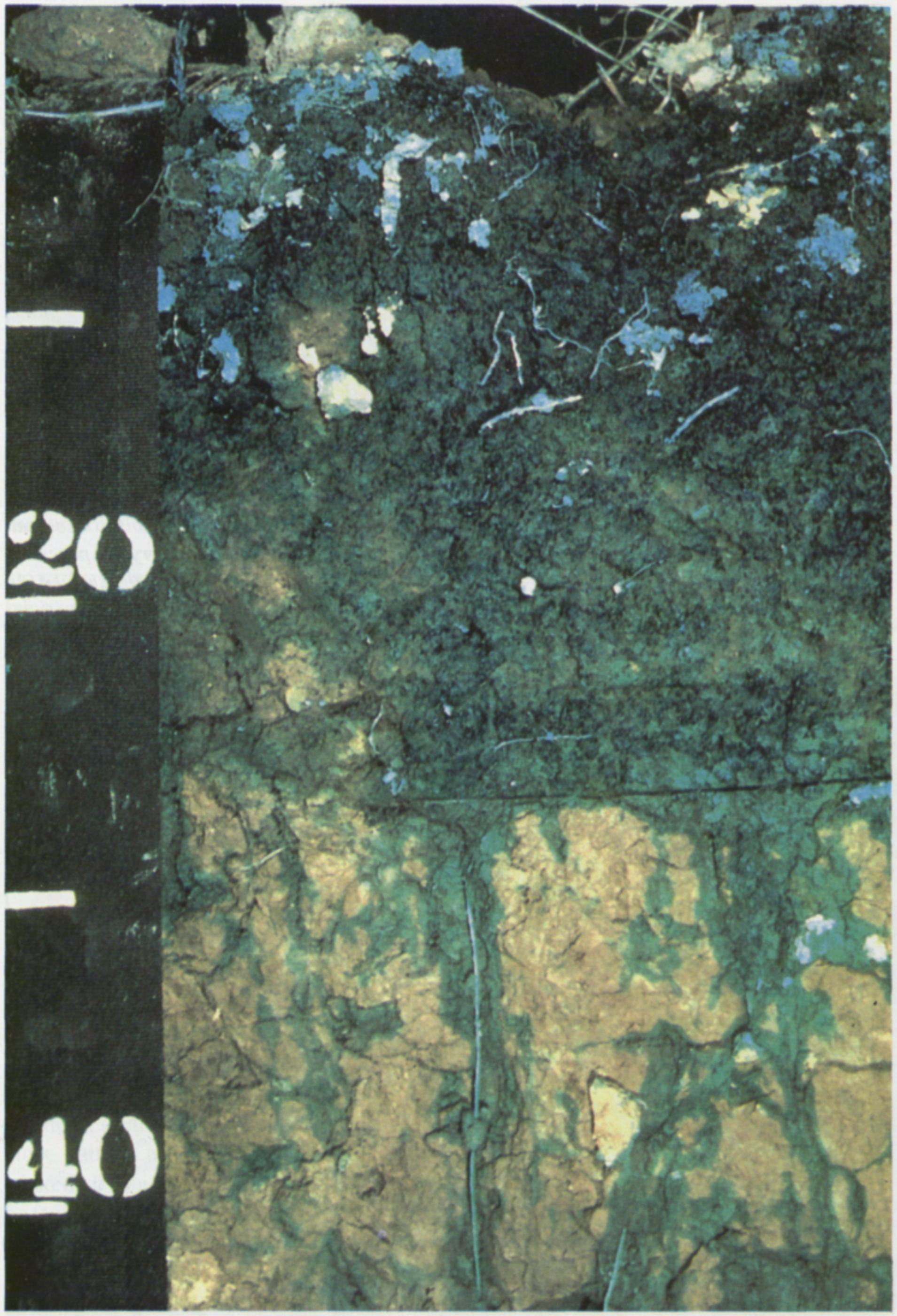


Figure 3





Preferential flow paths in a structured soil near Ithaca, New York, are colored by a blue dye. The dye, a nontoxic food coloring, infiltrated the soil from the surface.

channels sometimes cross each other, with a resultant mixing of water and solutes.

Preferential flow was described more than a hundred years ago (1882), in a landmark paper by J. B. Lawes, J. H. Hilbert, and R. Warington. The authors distinguished between preferential and matrix flow, and pointed out that the relative importance of the two kinds of drainage depends on soil type and rainfall intensity. In light soils, matrix flow predominates, while in heavy soils, preferential flow has greater importance. Moreover, the relative preponderance of one type of flow or the other affects solute transport: When salt is evenly distributed throughout the soil, the salt content of the drainage is higher for water from matrix flow than from preferential flow.

We have incorporated many of the findings of this long-neglected paper into our own model for simulating preferential flow. We begin by conceptually dividing the multitude of flow paths distributed throughout the soil into a number of different categories in accordance with the size of the "pores" through which the water moves. These categories are established by means of a piecewise linear

Figure 4

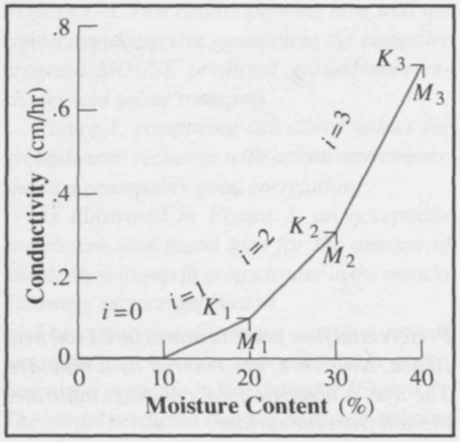
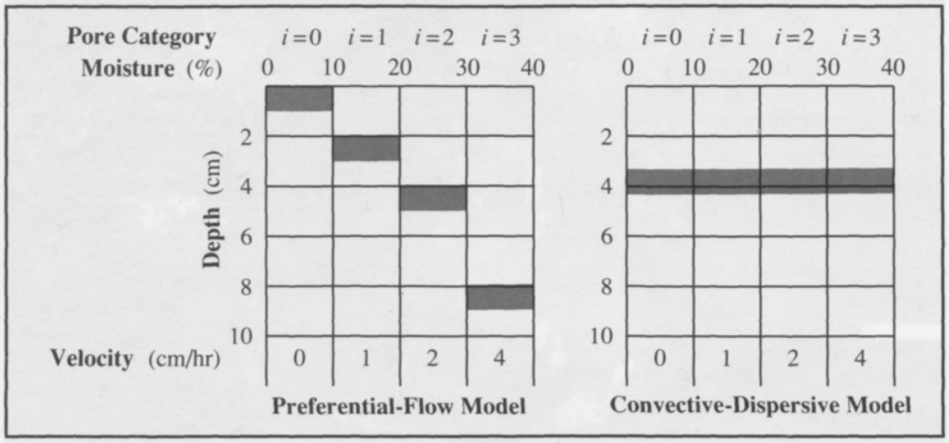


Figure 5



conductivity function (see the box). It is then possible to calculate the way water moves at different velocities through pores of different sizes. A number of rules are specified to account for mixing between pores, and finally, solute transport is superimposed on water flow.

How the model works—and how it differs from models based on the convective-dispersive equation—can be demonstrated with an example of steady-state saturated flow through a vertical column. The limiting moisture contents for each category of pores (shown schematically in Figure 5) are the moisture contents at the intersections of the conductivity function's linear pieces (as illustrated in Figure 4). For example, the limiting moisture contents for pores in the category labeled i=1 are 0.10 and 0.20 cubic centimeter of liquid per cubic centimeter of available space. Employing the equations in the box, we find that the velocity of flow for pores in categories i=0, i=1, i=2, and i=3 are 0, 1, 2, and 4 centimeters per hour, respectively. After two hours, for example, water in category i=0 pores has not moved at all, while water in category i=3 pores has moved 8 centimeters. This tells a very different story than a convective-dispersive

Figure 4. Conductivity function for pores of varying moisture content as represented in the preferential-flow model. Linear pieces are designated in accordance with the equations below.

Figure 5. Velocity of water penetration as a function of moisture content. Pore categories correspond to linear pieces in Figure 4. The preferential-flow model (left) shows that flow is faster through pores with greater moisture content. After two hours, water in category i=3 pores has penetrated 8 centimeters below the surface. In contrast, convective-dispersive averaging (right) predicts penetration to only 3.5 centimeters.

FLOW THROUGH STRUCTURED SOILS

Pores in the soil through which water can flow are divided into categories according to their size by introducing a piecewise linear conductivity function $k_i(\theta)$ for $M_{i-1} < \theta \leq M_i$ of the form

$$k_i(\theta) = K_{i-1} + (K_i - K_{i-1})\,\frac{\theta - M_{i-1}}{M_i - M_{i-1}} \qquad i = 1,2 \ldots n$$

where n is the number of pore categories with mobile water, and M_i and K_i are the upper limiting moisture content and conductivity value, respectively, of the i^{th} piece of the conductivity function (see Figure 4). For stagnant water, $0 < \theta < M_0$, $k(\theta) = 0$.

Using a modified Richards equation and the method of characteristics, we can obtain a transport model in which the fluids move with different velocities along the various preferential flow paths. The velocity of water, v_i, for the i^{th} pore category may be obtained as follows:

$$v_i = \frac{K_i - K_{i-1}}{M_i - M_{i-1}} \qquad i = 1,2 \ldots n$$

$$v_0 = 0$$

analysis based on an average flow path, which places the depth of penetration at a uniform 3.5 centimeters.

PREFERENTIAL FLOW IN SANDY SOILS

Even in homogeneous soils, water does not necessarily take an average flow path. In 1971 one of the authors (Parlange) and David Hill documented, for the first time, preferential flow in homogeneous sand at low infiltration rates. Further research has led to an understanding of many of the mechanisms involved in this phenomenon.

Our main experimental apparatus is a column that consists of a one-centimeter-thick layer of sand between two glass plates. A strong, uniform light is located at the back of the column, and water is allowed to infiltrate the sand between the plates. Since the amount of light transmitted through the sand increases with wetness, quantitative observations of the flow pattern are possible. The image is picked up by a video camera and computer software assigns different colors to different intensities of light, making differences in water content immediately apparent (Figure 6).

Figure 6

Figure 6. The way water forms fingers in homogeneous sandy soils. These images are produced by passing light through a "sand sandwich" and converting the different intensities to different colors by a computer program. Red corresponds to the wettest areas and blue to the driest. The image at left shows the extent of finger growth after 48.8 seconds; the one in the middle after 75 seconds; and the one at right after 111 seconds.

Figure 7. A three-dimensional study. Water containing a blue dye has been allowed to infiltrate sand and then frozen. When the loose sand falls away, the fingers are revealed.

Figure 7

"... water finds its way down through sandy soils in a number of channels that we call fingers."

Other experiments make use of a chamber that allows observation in three dimensions (Figure 7). Since the light-intensity method cannot be employed in this situation, flow paths are marked by water containing a blue dye. After the water has had a chance to penetrate the soil, the sample is frozen, and when the loose dry sand has fallen out, the congealed flow paths can be examined.

This line of research has shown that water finds its way down through sandy soils in a number of channels that we call *fingers.* A poorly conducting layer of topsoil at the surface produces a wetting-front instability. Gravity drives the instability and surface tension has a contrary, stabilizing effect. What happens is analogous to the dripping of water from a sponge; the pull of gravity is opposed by surface tension, which makes the drops increase in size before they fall. In the case of soils, this balance of forces determines the diameter of the fingers.

Some fingers do not carry enough water to keep growing, and the number of fingers diminishes with increasing depth. In sand that is quite homogeneous, the fingers are nearly vertical and do not merge with one another. If the sand is less homogeneous, however, the fingers deviate from a strictly

FLOW THROUGH COARSE-GRAINED SOILS

The balance between gravity, expressed as $(Q - k_w)$ cm/sec, and surface tension, expressed as $S_w^2 / (\theta_w - \theta_i)$ (cm²/sec) gives the diameter, d, of the fingers. In accordance with dimensional analysis,

$$d = \lambda \frac{S_w^2}{(\theta_w - \theta_i)(k_w - Q)},$$

where λ is a universal number, Q is the entering flux, θ_w and θ_i are the average water contents behind and ahead of the wetting front, S_w is the sorptivity, and $k_w = k(\theta_w) - k(\theta_i)$, where $k(\theta_w)$ and $k(\theta_i)$ are the soil water conductivities at their respective water contents. θ_w can be called the water-entry value.

To solve the transport equation for the fastest growing disturbance, λ is explicitly calculated with Bessel functions for three-dimensional fingers as $\lambda = 4.8$. (For two-dimensional fingers, $\lambda = \pi$.) In the field, k_w tends to be much larger than Q, and for most sandy soils the quantity $S_w^2/(\theta_w - \theta_i)\, k_w$ is only a slightly increasing function of θ_w. These fundamental properties imply that d is essentially independent of both Q and the amount of water carried by the fingers, θ_w, and is a property of the soil.

The distribution of water within a given finger is not uniform. Not only is there a sharp gradient at the fingers' surface, responsible for lateral diffusion, but even more strikingly, there is an increase of water content with depth. This variation with depth can easily be described by solving the transport equation for a constant velocity of finger growth, v, yielding:

$$\frac{k(\theta)}{\theta} = \frac{v}{1 - v^{-1}\partial h/\partial t}$$

This equation has proven very useful in measuring soil-water conductivity as a function of the matric potential, h. At a given position the value of h is measured as a function of time; v is easily measured as the velocity of the fingertip, and the equation above gives k/θ. Thus, these equations make it possible to describe the width and spatial distribution of fingers.

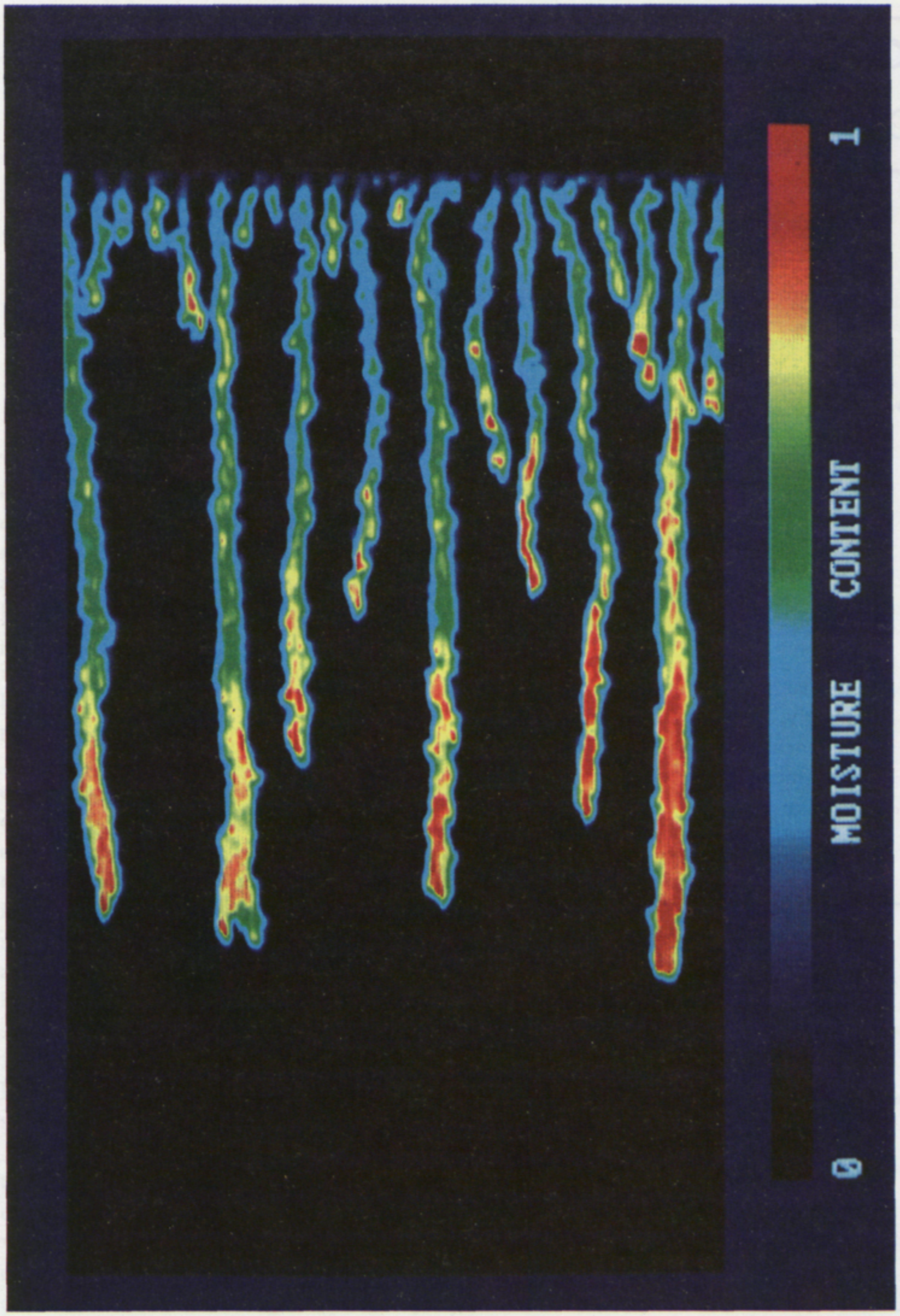


Figure 8. Fingers in layered sand. This image, produced by the same technique used for Figure 6, shows several instances of fingers merging, as well as a case of splitting.

vertical path, and can merge (Figure 8). When this happens, they do not come together on equal terms, like the arms of a Y. Instead, one finger continues on itcourse, while the other donates water as a tributary entering from the side. This results from a difference in the water content of the fingers, with capillary action pulling water from the wetter of the two and delivering it to the dryer one, which stays on course.

After a merger, the continuing finger carries considerably more water than either of the contributors, as color-coded images such as Figure 8 clearly show. Since the continuing finger is only slightly larger in diameter, the extra water increases its conductivity and, in accordance with the conservation of mass, the speed with which it grows.

In the field, where heterogeneities in the soil are far more pronounced than in laboratory experiments, most merging takes place in a shallow layer near the surface called the *induction zone*. Below the induction zone, merging is less common as long as the water flows through a relatively homogeneous medium. But further down in the soil, sloping interfaces of compositionally different layers may act as funnels. Such structures can concentrate the water from a large area into a single finger. And contrariwise, fingers may split. This is the probable outcome when a finger reaches saturation and cannot handle the imposed flow. (This is shown in Figure 8.)

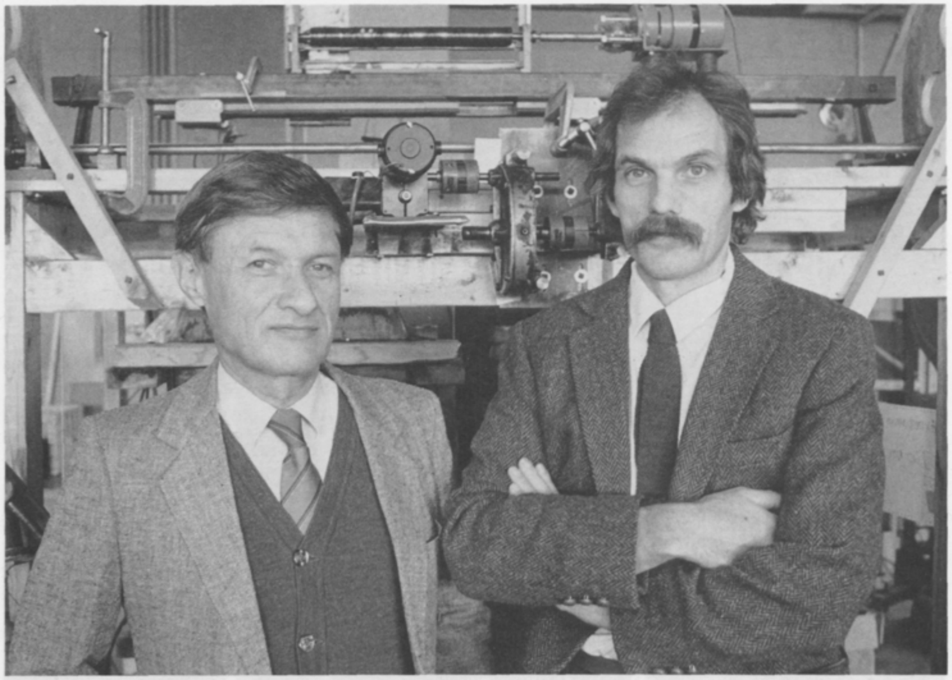
IMPLICATIONS FOR MONITORING GROUNDWATER CONTAMINATION

The effect of preferential flow on groundwater quality is much the same whether it occurs in structured soils or homogeneous sandy soils. In fact, preferential flow seems to be most common in soils at both ends of the spectrum. In dense clay soils, cracks provide the only channels through which flow can occur, and in most coarse soils (when rainfall intensity is low) instabilities resulting in preferential flow are a near certainty.

Our research is already helping to improve models of groundwater flow that are now on the market. The piecewise linear approximation to the conductivity function can give a good account of how small quantities of pesticide can move rapidly through structured soils. For sandy soils we need to have a better knowledge of depositional layers below the surface, and ground-penetrating radar may soon give us this information. (This is discussed in the article that follows.)

What we have learned about preferential flow is also being used in designing the best configuration for tailings left behind by mining operations. By including clean material at strategic places where preferential flow is directed, the toxicity of leachates can be greatly reduced.

While some of our laboratory work may seem far removed from practical concerns, it has clear implications for safeguarding the quality of groundwater. A better understanding of preferential flow points up factors that need to be studied in order to predict more accurately the likelihood that groundwater will be affected by agricultural chemicals, landfills, and industrial wastes. Ultimately, our work should lead to sounder management practices that will diminish a serious threat to one of humanity's most precious resources.



Tammo S. Steenhuis and J.-Yves Parlange are colleagues in Cornell's Department of Agricultural and Biological Engineering.

Steenhuis, an associate professor, earned B.S. and M.S. degrees at the State Agricultural University of The Netherlands and then studied at the University of Wisconsin, receiving the M.S. degree in 1975 and the Ph.D. in 1977. He joined the Cornell faculty that fall. His research concerns the interaction of water and agricultural toxic flow, management of wetlands, and the use of microcomputers in water-management design.

Parlange, a professor, earned the Dipl. Eng. at the École Nationale Superieure de l'Aeronautique in Paris in 1958, and the Ph.D. at Brown University in 1962. After earning his doctorate, he stayed on at Brown for a year as a research associate and then served two years in the French air force before joining the Yale University faculty in 1964. He worked as a research scientist at a Connecticut experimental station from 1968 to 1977, when he became a professor in the College of Forest Resources of the University of Washington. The following year he was appointed professor of applied mathematics at Griffith University in Brisbane, Australia, and in 1985 he joined the Cornell faculty.

Many graduate students, including some who have left Cornell for their first professional positions, participated in the research reported on in this article. They include Sunnie A. Aburime, Marc S. Andreini, Nathaniel O. Bailey, Jennifer L. Bell, Jan Boll, Robert J. Glass, James R. Hagerman, Yaping Liu, Nigel B. Pickering, Bruce Pivetz, Tom Richard, Sue I. Saul, and John S. Selker.

FINDING LAYERS IN THE SOIL
Ground-Penetrating Radar as a Tool in Studies of Groundwater Contamination

by Tammo S. Steenhuis, K.-J. Samuel Kung, and Lawrence M. Cathles, III

The way soil is layered makes a big difference in how water and solutes find paths down to groundwater. In penetrating the soil, water follows preferential flow paths, as described in the article by Steenhuis and Parlange (page 7). The way these flow paths merge depends on inhomogeneities in the soil, and sloping structural interfaces have a considerable effect on the degree of merging and rate of flow.

Soils deposited by ocean currents, rivers, lakes, or glaciers consist of strata laid down at different times and under different circumstances, and they differ in composition and permeability. Experiments, both in the laboratory and in the field, have shown that at low flow rates, coarse layers act as funnels, collecting water from a broad area and channelling it through a small number of drainage fingers. At higher flow rates, these coarse layers begin to leak, and the funnel effect becomes less significant (see Figure 1).

Funnel flow is an important factor in the transport of contaminants. Since the funnel effect produces a more concentrated flow, which moves faster, the time available for degradation is greatly reduced. Since the chemical is carried through a relatively small part of the soil matrix, total adsorption is also greatly reduced. Moreover, since the water and solutes flow through more widely scattered paths as they move deeper, current sampling protocols, which call for assessing the solute concentration at randomly chosen points, are inadequate.

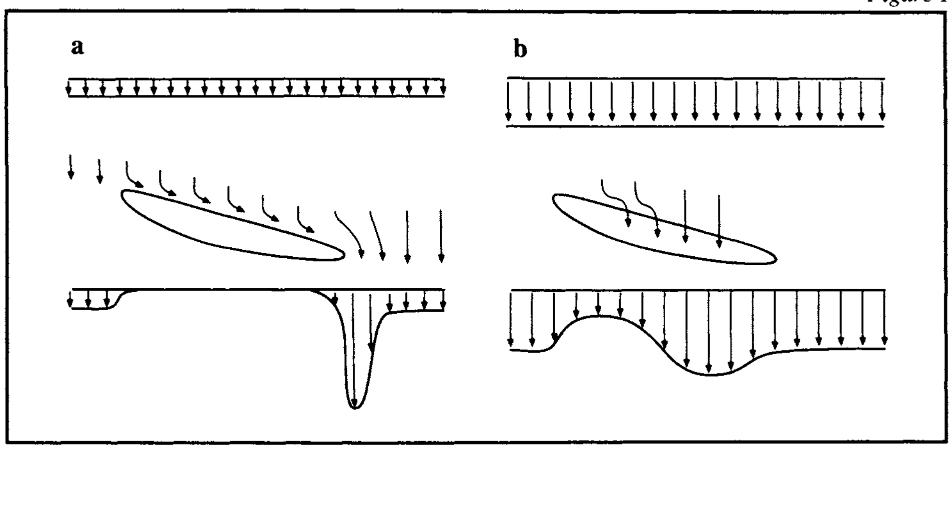
BETTER PREDICTION REQUIRES BETTER DATA

The contamination potential of a waterborne pollutant carried by funnel flow is seriously underestimated by all existing computer models. Accurate prediction of the flow pattern in layered soils requires three-dimensional data that show bedding structures and textures in the vadose zone (above the water table). Without such data, it is impossible to forecast the impact of preferential flow paths triggered by the funnel mechanism.

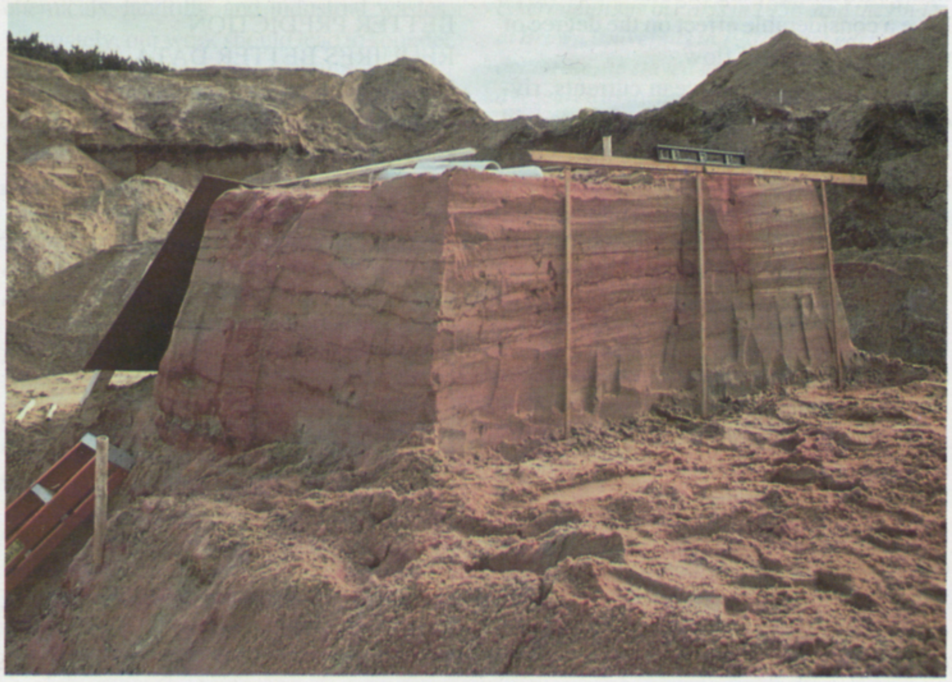
Most soil physicists and environmental engineers have approached the problem of

Figure 1. The funnel effect in sandy soil. With a relatively low flow rate (a), a fast-moving spout forms beneath the lower end of an inclined layer. Such inequalities in penetration are minimized when the flow is greater (b).

Figure 1



Top: Ground-penetrating radar is used to acquire data. The equipment can be operated by two people. One pulls the transmitter and receiver (in the big red box), and the other pulls the power supply and tape recorder, seen at left. (The round device at right is a rain gauge.)



Bottom: A nearby plot is excavated after red dye has been permitted to infiltrate the ground. The dye shows how water becomes more narrowly channeled as it flows over hidden layers.

groundwater contamination by developing computer models based on limited field observations, rather than by developing new techniques to collect essential data. We believe that it is not possible to predict how water will move through soil without knowing empirical details about the soil's structure. Hence, we are experimenting with instrumentation that will make it possible to detect and identify three-dimensional subsurface structures on a large scale.

Ground-penetrating radar has been successfully used in geophysics, archaeology, and construction engineering, as well as for mapping soil horizons. Refinements in the technology have increased the depth to which it will reach and the detail with which images can be resolved. New instruments are portable and easy to use in the field, making it possible to carry out controlled surveys under rather difficult conditions. Data are processed with state-of-the-art digital techniques.

Ground-penetrating radar works much like seismic-reflection and sonar techniques. A pulse train of electromagnetic radiation in the frequency range of 10 to 1,000 megahertz (MHz) is sent into the

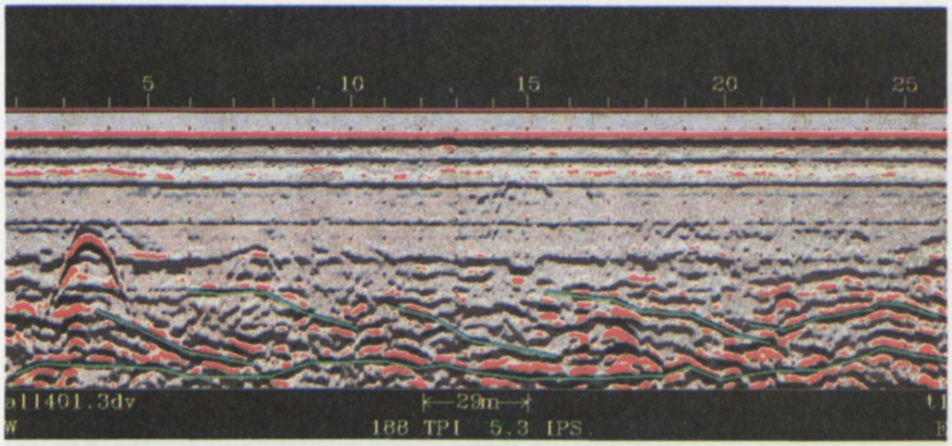


Figure 2. A cross-sectional view of soil examined with ground-penetrating radar. In the computerized processing of the data, the layers are made visible by assigning different colors to reflected signals that have different amplitudes.

ground. The depth to which it penetrates depends on the attenuation properties of the medium. The electromagnetic properties of soils are primarily controlled by the water and clay content. The radar waves are reflected differentially by subsurface structures with different dielectric properties. The returning waves are picked up by a receiver, amplified, digitized, and stored on magnetic tape for subsequent computer processing.

A DEMONSTRATION
OF THE TECHNIQUE

The potential of ground-penetrating radar for monitoring pollutants was investigated in a 24-by-24-meter plot at the Hancock Research Station in Wisconsin. The geological setting consists of interbedded layers of fine and coarse-grained sands, most of which were deposited by rivers that originated in melting glaciers, although lake and Eolian deposits may also be represented.

Ground-penetrating radar images were obtained by using a 500-MHz antenna that was towed by hand at a rate of five kilometers per hour over a series of parallel paths one meter apart. For each transect there were 1,800 to 2,300 separate scans, depending on differences in the towing rate. For each scan there were 512 data points with values ranging from –127 to +127, representing variations in the amplitude of the reflected signal. After digitizing, the data for each transect consisted of approximately four megabytes of integer ASCII numbers.

These data on reflected signals were automatically recorded on tape, and then put through a series of processing steps (see Figure 3). Eventually they were translated into a form compatible with a workstation, at Cornell's Department of Geological Sciences, that was made available by the Landmark Graphics Corporation. The program makes it possible to view the data in graphical form, and to assign different colors to specific ranges of amplitude. By choosing these colors carefully, the strongest reflections can be highlighted, making more discernible the interbedded layers in the soil (see Figure 2).

RADAR PICTURES
AND WATER PENETRATION

On two other plots, near the one mapped with radar, dye was applied and permitted

Figure 3. The sequence of processing steps in the conversion of radar signals to visual images.

Figure 3

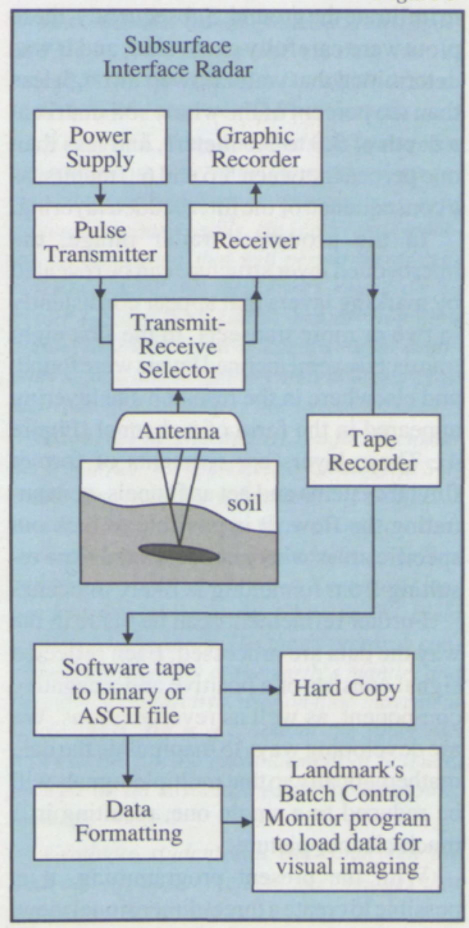


Figure 4. A computer-generated image made from radar signals. An old river bed hidden below the present surface of the ground is revealed.

Figure 5. A three-dimensional view of sloping layers.

to infiltrate the ground. Subsequently, these plots were carefully excavated, and it was determined that water flowed through less than ten percent of the whole soil matrix at a depth of 3.0 to 3.6 meters, and less than one percent between 5.6 and 6.0 meters, as a consequence of the interbedded layering.

In the processed radar image, the interbedded layer structure can be revealed by marking layers that appear consistently in two or more transects. In the first eight transects several inclined layers were found, and elsewhere in the research site layering appeared in the form of a channel (Figure 4). These layers are remnants of former fluvial systems and act as funnels, concentrating the flow. It is possible to pick out specific areas where concentrated flow resulting from funnelling is likely to occur.

Further refinements can be made in the way the data are processed. Each reflected signal consists of a positive and a negative component, as well as reverberations. We are developing ways to manipulate the data mathematically so that multiple signals will be reduced to a single one, resulting in a much cleaner picture.

With the present programming, it is possible to create a three-dimensional view,

Figure 4

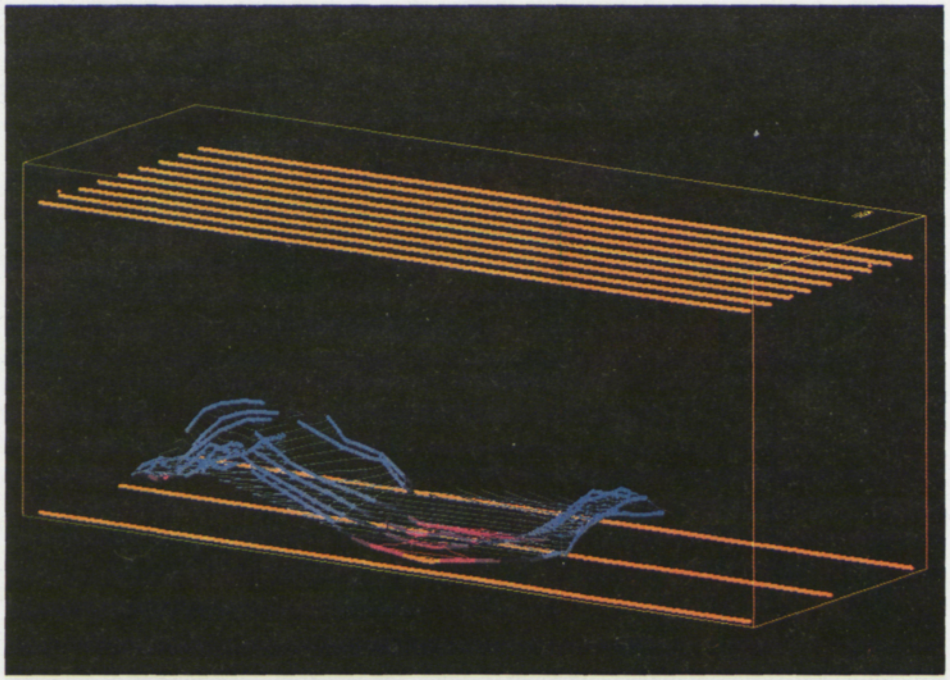
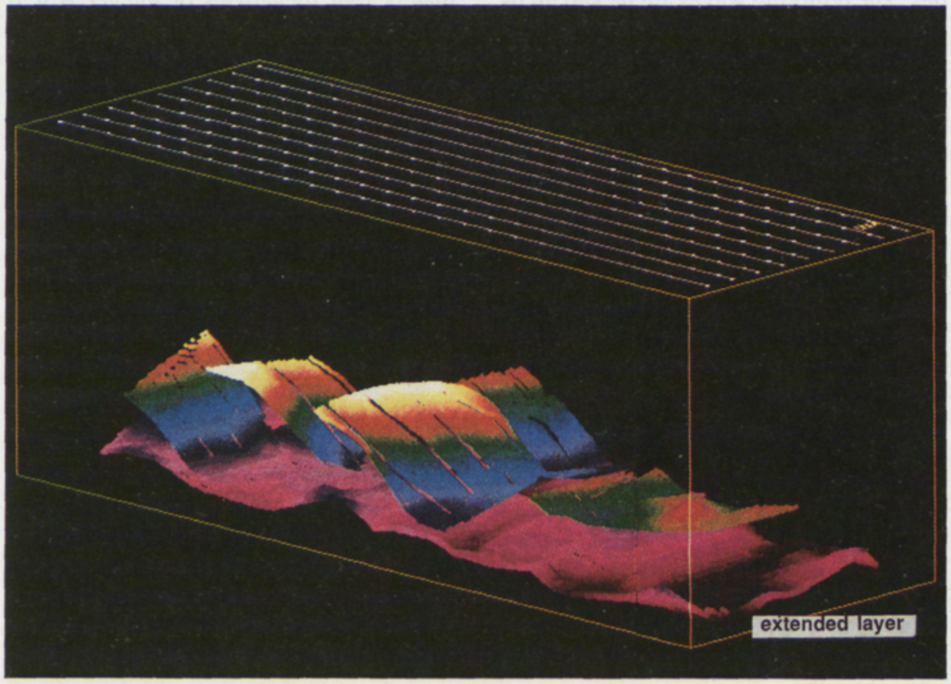
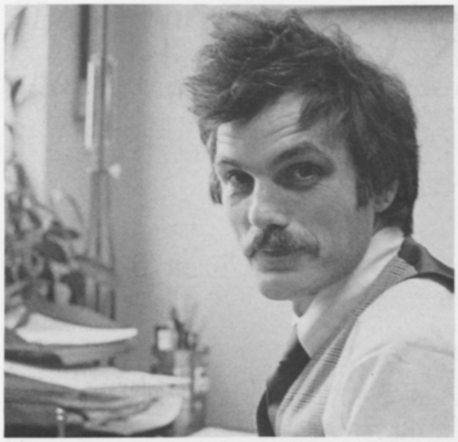


Figure 5



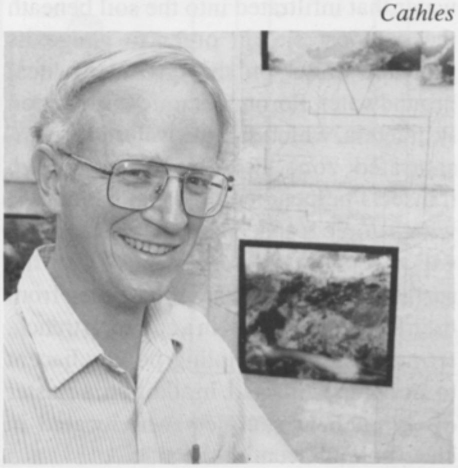
Steenhuis



“. . . ground-penetrating radar will be an invaluable tool for determining the routes that pollutants take on their way to groundwater.”

Kung

Cathles



showing the configuration of a particular stratum (Figure 5). But this is a laborious process that involves analyzing radar images from each transect separately, and then combining them. After further processing, however, it will be possible to visualize all the data as part of a single, three-dimensional cube, in which sections can be viewed from any direction or inclination. It will even be possible to look at horizontal slices through the cube.

The work done up to this point suggests that ground-penetrating radar will be an invaluable tool for determining the routes that pollutants take on their way to groundwater. The technique is currently limited to sandy or gravelly soils, but this should be a minor drawback, as these are precisely the kinds of soil in which major aquifers most commonly occur.

Tammo S. Steenhuis, an associate professor of agricultural and biological engineering at Cornell, is also a co-author of the article beginning on page 7.

K.-J. Samuel Kung is an assistant professor in the Department of Soil Science at the University of Wisconsin, where he conducts research on heat and mass transfer in unsaturated soils, and on mechanisms of soil erosion. He received M.S. (1982) and Ph.D. (1984) degrees in agricultural engineering from Cornell.

Since 1987, Kung has conducted numerous experiments to determine the mechanisms responsible for the movement of nonpoint-source pollutants in sandy soils. He is currently working on algorithms that will permit better representation of the structures revealed by ground-penetrating radar, and developing a high-resolution digital-image system to determine spatial and temporal changes in soil-pore distribution.

Lawrence M. Cathles, III is a faculty member in Cornell's Department of Geological Sciences. He received his bachelor's (1965) and doctoral (1971) degrees from Princeton University. He has spent time in industry as well as academia, with seven years at Kennecott Copper and five years at the Chevron Oil Field Research Laboratory. His thesis research concerned the viscosity of the earth's mantle, and his current research focuses on fluid movement in the crust. He is a fellow of the American Association for the Advancement of Science, as well as an associate editor of Economic Geology.

Graduate student Jan Boll analyzed the data and produced the computer images that appear in this article.

COMPOSTING AND WATER QUALITY

by Tom Richard

Composting is a good way to reduce the amount of solid waste destined for landfills and incinerators. Leaves and other yard wastes typically make up about 20 percent of the solid waste stream, and food wastes constitute another 15 percent. Some municipalities are now keeping these materials separate from other wastes and are turning them into compost. But there is concern about the impact of such composting operations on the surrounding environment—in particular, the effect that a large volume of decomposing organic matter may have on surface runoff and groundwater.

A variety of methods have been developed for composting urban wastes as well as agricultural wastes such as manure. Facilities range from simple outdoor windrow systems to sophisticated indoor vessels. While outdoor systems offer significant economic advantages, they also require more careful management to minimize their impact on the local environment. Government regulators have proposed a number of constraints, including setback distances from wells and surface waters, management restrictions, and even requirements for impermeable liners under composting sites. Such measures can be costly, so my colleagues and I have undertaken research to determine whether they are really necessary.

COMPOSTING LEAVES AT CROTON POINT

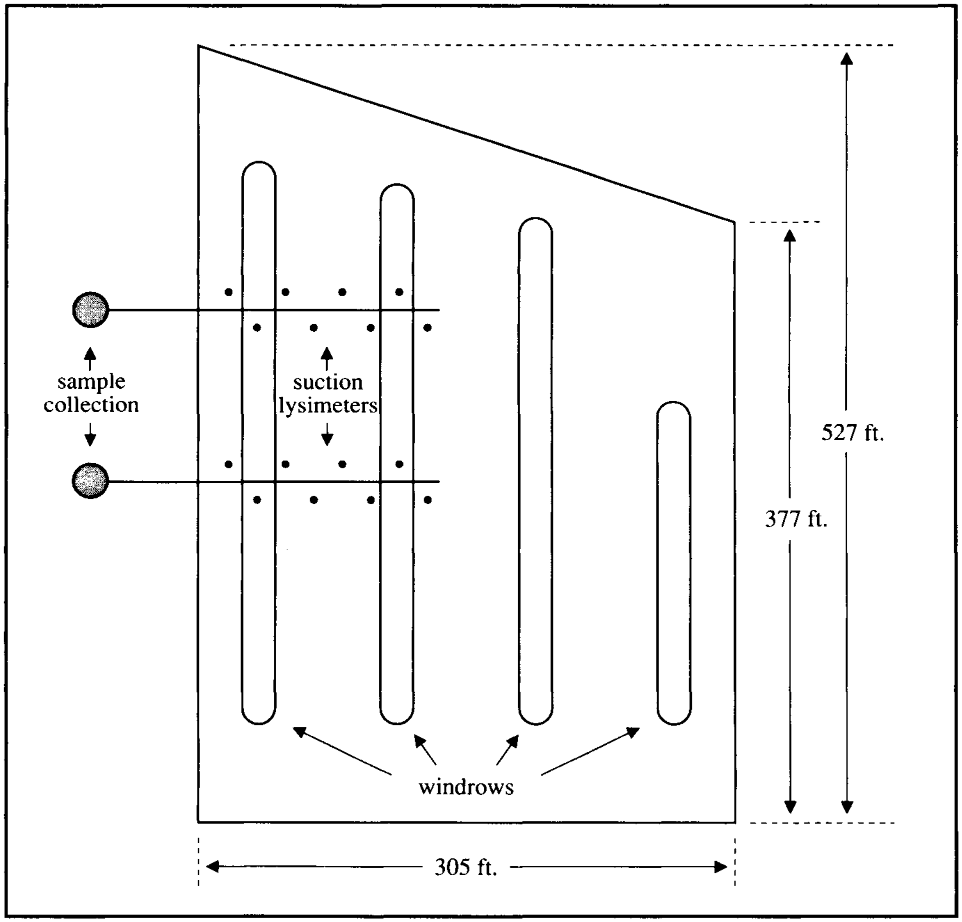
A study of leaf composting was carried out at a demonstration site located at Croton Point in Westchester County, New York. The site, which is operated by the county, is adjacent to a closed landfill on county-owned land that is bordered by a public park and a private industrial establishment. Leaves for the study were from the village of Croton-on-Hudson, a community of 7,300 people that is situated about twenty miles north of New York City. Five hundred tons of leaves—about 4,800 cubic yards—were brought to the site between mid-October and late December 1988.

The leaves were stacked in windrows approximately eight feet tall and twelve feet wide. Water was added at a rate of about four gallons per cubic yard. The windrows were turned with a front-end loader every other week, and as the volume diminished they were combined as necessary to keep them at least six feet high and twelve feet wide throughout the winter. Temperatures in the interior of the windrows ranged from 100°F to 140°F through February, and then slowly dropped to ambient temperature. By mid-June of 1989, the original 4,800 cubic yards had been reduced to only 30 percent of this volume. Some of the finished compost was distributed to interested residents, and the remainder was used by the public works department.

Extensive environmental monitoring and detailed economic analysis were carried out at the Croton Point facility. Our part of the study involved monitoring the water that infiltrated into the soil beneath the compost site in order to gauge its probable effect on the quality of local groundwater. Porous ceramic-cup suction lysimeters, which sample water in the unsaturated zone, were laid out in two transects perpendicular to the windrows, with samplers spaced at two-meter intervals, twelve to eighteen inches under the surface (Figure 1). Sampling tubes from each transect were laid in a common trench, terminating at a sampling point adjacent to the composting pad. In addition, a cluster of up-gradient samplers was located in clean soil adjacent to the site.

"Leaves and other yard wastes typically make up about 20 percent of the solid waste stream. . . ."

Figure 1. Arrangement of lysimeters under compost at the Croton Point facility.



EFFECTS OF LEAF COMPOST ON LOCAL GROUNDWATER

Samples drawn from twelve lysimeters before the leaves were delivered established background conditions for the site. A dry winter delayed additional sample collection until the beginning of May, when heavy rains permitted a complete sampling. The concentrations of various substances found in the samples were compared with background levels and with New York State's groundwater discharge standards. There were only minute traces of heavy metals, except for iron, which had a high background concentration at the site. Nitrate levels, which are frequently viewed as a major pollution threat from organic wastes, were also low. They remained well below the groundwater discharge standard of 20 milligrams per liter throughout the study, and even fell below the background values for the site. These extremely low nitrate concentrations may be attributed to the fact that leaf composting is limited by the availability of nitrogen. The composting of materials such as grass clippings, which are rich in nitrogen, would be expected to generate considerably higher nitrate levels.

Right: Installation of lysimeters at the Croton Point composting site.

Some organic constituents of the groundwater under the leaf compost were considerably elevated, however. Phenols, in particular, went from undetectable background levels to 0.18 milligram per liter, well above New York State's groundwater discharge standard of 0.002 milligram per liter. Phenols are a natural product of decomposing lignin, and thus would be expected at a leaf-composting site, much as they are found in swamps and other areas where large amounts of organic matter decompose. These natural phenols can compromise the taste and odor of drinking water, but are nontoxic—and it is important to distinguish them from industrial phenols, several of which are extremely toxic, even in low concentrations.

Biochemical oxygen demand (BOD) is the other parameter that exceeded normally acceptable levels. The BOD of three samples was above 150 milligrams per liter, the highest value that could be measured. High-BOD runoff can deplete the dissolved oxygen in lakes and streams, with negative consequences for aquatic life.

Both phenols and BOD can be substantially reduced by degradation processes that take place in the soil, and the observed levels would not be expected to contaminate groundwater supplies. They could become a threat, however, if significant quantities were released directly into lakes or streams.

EFFECTS OF MANURE COMPOST ON NITROGEN LEVELS

Another study of the effects of composting on water quality was carried out at a site where bull manure is composted in an abandoned gravel pit near Ithaca, New York. The manure is from a breeding facility where large quantities of sawdust bedding are used, and the manure, mixed with bedding material, is composted and then spread on the land as part of an ongoing reclamation program. Approximately 150 cubic yards of the manure-sawdust mixture were delivered to the site in the fall of 1988. It was piled in windrows four to five feet high and eight to ten feet wide, and was turned once a month with a tractor-mounted loader. Internal temperatures varied from 80°F to 110°F during the winter, and rose to 120°F to 130°F in the spring after the material had been macerated through a manure spreader. Temperatures dropped to ambient levels during the summer, and the compost was spread and incorporated into the soil the following fall.

Leachate samples were collected from depressions immediately adjacent to the

Left: Bull manure being composted near Ithaca, New York.

windrows, and runoff samples were collected at a shallow berm that was about thirty feet down-slope from the windrow area and had minimal intervening vegetation. Samples were taken during rainy periods and thaws in the winter and spring of 1988-89. Grab samples were analyzed for nitrates, nitrites, and ammonia, with the leachate providing an indication of undiluted nitrogen levels.

The runoff water consistently met drinking-water standards for nitrate (10 milligrams per liter), although the runoff was sometimes the color of strong tea. The manure-sawdust mixture had an initial carbon-to-nitrogen ratio of approximately fifty to one, and as a result, the composting process ran with a slight nitrogen deficit. This appears to have limited the movement of nitrogen out of the windrow. Dilution also appears to have had a considerable effect, for the concentration in the runoff was two to twenty times lower than in the leachate.

MANAGEMENT STRATEGIES
FOR MUNICIPAL COMPOSTING

These studies suggest that large-scale composting can be practiced in an environmentally sound manner. An excess of phenol, BOD, or nitrogen compounds may be produced, but these difficulties could be readily managed through proper design and operation of the facility.

While phenols and BOD are both natural consequences of decomposition, strongly affected runoff should not be discharged into surface water supplies. This is not a serious problem, however, for several simple measures will reduce the volume of runoff, lower the concentration of phenols, and lessen the biochemical oxygen demand. Diversion ditches and berms that keep excess water from running onto the site will reduce the amount of affected water that flows off the site. Locating the facility on soil of moderate to high permeability will also significantly reduce runoff. And remaining runoff can be treated with simple technologies such as soil treatment, filter strips, or recirculation.

These low-cost treatment strategies have proven effective with a variety of wastewaters and organic wastes. Soil treatment forces water to percolate through the soil profile, where organic compounds can be adsorbed and degraded. Vegetative filter strips slow the motion of runoff water so that many particles can settle out, while others are filtered out and adsorbed onto plants. Recirculation involves pumping the runoff water back onto the

windrows of compost, where organic compounds can degrade further and the heat generated by decomposition can help evaporate the water. Recirculation would be especially beneficial during the early stages of composting, when water often needs to be added, but would be inappropriate when the moisture content was already high.

While these simple measures would also be sufficient to ameliorate moderate levels of nitrogen, the best strategy is to keep high-nitrogen leachate from forming. This is not hard to do, as experience with the manure-sawdust mixture demonstrates. Microorganisms use carbon and nitrogen in an optimum ratio of between twenty-five to one and thirty to one. Starting with a mix that has a carbon-to-nitrogen ratio greater than thirty-to-one insures that almost all the available nitrogen will become bound up in microbial biomass, and the concentration of soluble nitrogen compounds will be very low. Composting in a nitrogen-limited mode also helps minimize odors, which are often related to excess nitrogen.

Many current restrictions on composting do not account for either the nature of the material composted or the system employed to manage runoff. But information acquired by monitoring large-scale composting operations should make it possible to develop guidelines that will provide greater flexibility in the siting of facilities, while protecting water quality more effectively. Communities can develop composting facilities and begin recycling their organic wastes without waiting until all the evidence is in. By incorporating relatively simple measures to protect water quality, composting facilities can operate efficiently and economically, and still be good neighbors.

Tom Richard is a senior research specialist and Ph.D. candidate in agricultural and biological engineering at Cornell. His research focuses on the beneficial reuse of organic waste materials from municipal, industrial, and agricultural sources. Current studies concern optimal process management of composting systems, land applicaton of sludges and food-processing wastes, and the fate of contaminants during land application and composting.

Richard received a B.S. degree from the University of California at Berkeley in 1978 and an M.S. from Cornell in 1987. Since then he has worked as a biological engineer in the Department of Agricultural and Biological Engineering, participating in research and extension activity in residuals management. He directs Cornell's state-wide extension program in composting.

REMOVING TOXIC ORGANICS FROM GROUNDWATER

Biological Conversion of PCE and TCE

by William J. Jewell

For over half a century, people have benefitted from the use of many chemicals whose impact on the environment remained imperfectly known. Among these chemicals are chlorinated solvents such as tetrachloroethylene (PCE) and trichloroethylene (TCE). These are excellent degreasing agents that have been widely used in industry and in the dry-cleaning business. They are not corrosive, not particularly flammable, and not highly toxic—in the short run. Unfortunately, they are associated with an increased incidence of cancer, and they remain in the environment for a long time.

Today, many such solvents are subject to rigorous regulation by the Environmental Protection Agency and are tolerated only in amounts that approach the limits of detectability. But the United States has been producing over ten million tons of chlorinated solvents per year since the early 1970s, with PCE and TCE accounting for about five percent of this total. The accidental discharge of only five gallons of these solvents can contaminate many square miles of groundwater, and thousands of different localities are already affected by billions of pounds of PCE and TCE as a result of improper disposal or accidental leakage.

TECHNIQUES FOR COPING WITH CHLORINATED SOLVENTS

Techniques presently used to keep PCE and TCE from contaminating groundwater involve vaporization or collection on materials such as activated carbon, which are then stored in special landfills designated for hazardous wastes. These are less-than-ideal ways to treat industrial waste water before discharge, and quite inadequate for cleaning up groundwater that is already polluted. In the first place, they do not really solve the problem because the pollutants are not broken down, but merely transferred from one environment to another. In the second place, these treatment techniques are expensive. Virtually all chemical companies, as well as numerous military bases and government laboratories, face billions of dollars in clean-up costs. Many companies have had to make strategic decisions about how much they can budget for clean-up without going bankrupt.

A better way to treat chlorinated solvents would be to break them down into harmless constituents. Many of humanity's traditional wastes are broken down by bacteria that occur naturally in soil and water. Such materials are said to be *biodegradable* (a term that is inappropriate for plastics that disintegrate without being chemically altered). Ten years ago, chlorinated solvents such as PCE and TCE were thought to be non-biodegradable. Recently, however, some microorganisms that can affect these compounds have been identified.

These microbes do not actually consume the chlorinated compounds, but use them in complex ways in the presence of another energy source, such as sucrose. Processes of this kind are referred to as *cometabolic*. The reactions that bring about the degradation of PCE and TCE are not yet fully understood, but it is useful to think of them as involving cometabolism, since the microbes must be supplied with all the nutrients required for growth while they attack the toxic materials.

DIFFERENT ROUTES TO BIODEGRADATION

In recent years there has been a national effort to identify new and more cost-effective technologies to purify industrial wastes and polluted groundwater. A number of research teams involved in this initiative have identified both anaerobic and aerobic bacteria that might play a part in the biodegradation of toxic materials. The anaerobic

Figure 1. Anaerobic, methanogenic systems compared with aerobic, methanotrophic systems. Collateral pathways that degrade chlorinated solvents are shown with arcs tangential to the direct, metabolic pathways.

Figure 2. Collateral pathways that degrade PCE and TCE. The sequence of breakdown products formed in anaerobic systems is shown on the left, and products formed in aerobic systems are shown on the right.

Figure 1

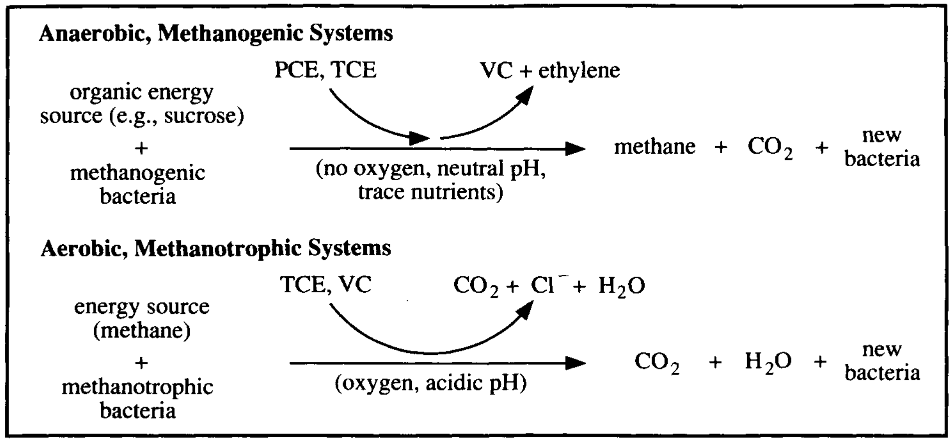
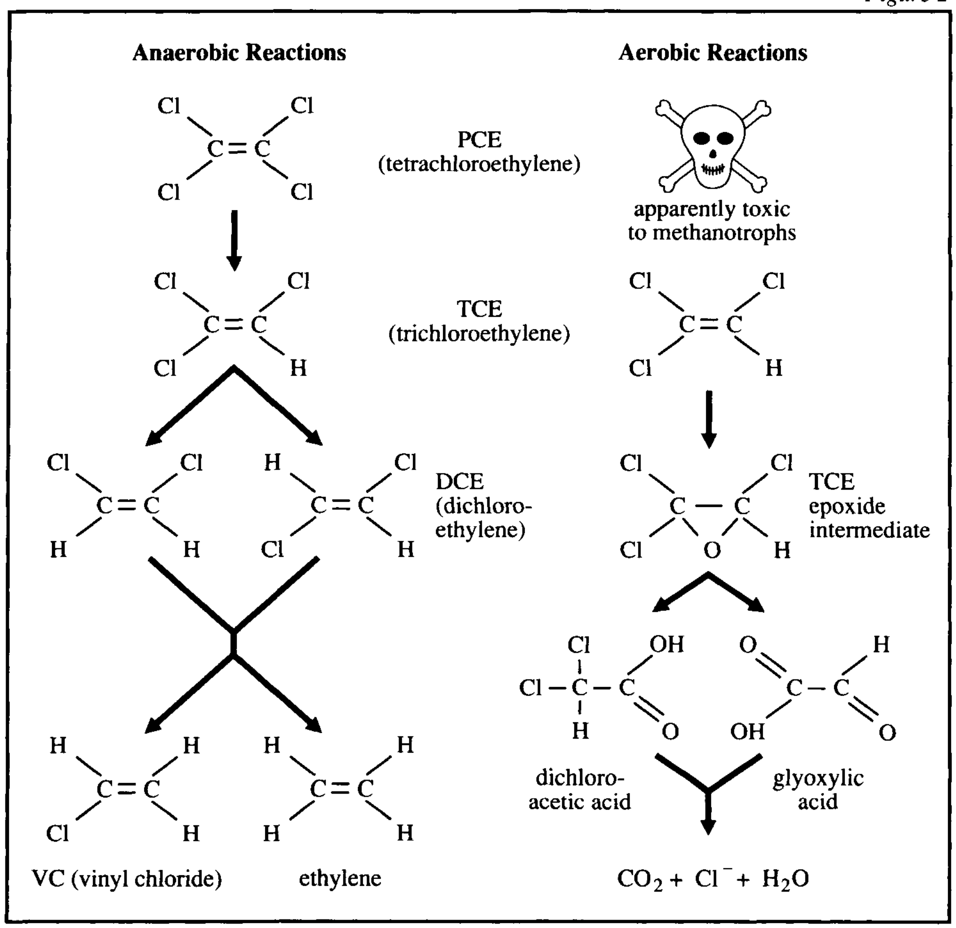


Figure 2



bacteria produce methane, and hence are called *methanogenic*; in contrast, the aerobic bacteria "eat" methane and are called *methanotrophic*.

Some of the leading work on the mechanisms by which anaerobic bacteria dechlorinate PCE, TCE, and dichloromethane was done by James M. Gossett and David L. Freedman in Cornell's School of Civil and Environmental Engineering. In the absence of oxygen, these microorganisms convert complex organics such as sucrose to volatile acids, and eventually methane and carbon dioxide are formed. A collateral pathway breaks down PCE and TCE, producing vinyl chloride (VC) and ethylene.

The aerobic bacteria of interest inject oxygen into complex organic compounds. This leads to an instability that makes these compounds susceptible to the action of heterotrophic organisms, rendering them biodegradable.

Figure 1 compares the anaerobic, methanogenic and the aerobic, methanotrophic pathways for treating PCE and TCE. These sequences of reactions are not fully understood, but in both cases an energy source and an electron or an electron-donor source appears to be necessary

Many researchers were involved in developing the system for the methanotrophic biodegradation of TCE. Behind William Jewell are (from left to right) researchers Elaine C. Rawley, Yarrow M. Nelson, Brian K. Richards, Sean R. Carter, Fred G. Herndon, Timothy D. Nock, Mark S. Wilson, Robert J. Cummings, Lois J. P. Brown, Donna E. Fennell, and Evangeline V. Baradas.

to start the process. The focus of a project in which I am involved has been to understand the kinetics of both of these systems and evaluate their potential for breaking down chlorinated solvents.

Anaerobic and areobic processes both involve a direct pathway that sustains bacterial growth as well as a collateral pathway that affects chlorinated solvents (Figures 1 and 2). In the anaerobic process, chlorinated solvents are dechlorinated one step at a time, with PCE (whose molecule has four chlorine atoms) going to TCE (with three chlorine atoms), then dichloroethylene (with two), and finally vinyl chloride (with one) and ethylene (with none). The conversion to ethylene turns out to be a bottle-neck that limits the effectiveness of the whole process. Only a quarter of the dichloroethylene goes to ethylene; the rest becomes vinyl chloride, which accumulates in the system. This is not acceptable, since vinyl chloride is more volatile than PCE and TCE, and it is just as toxic—if not more so. Thus, anaerobic reductive dechlorination, by itself, is of limited value.

In contrast, aerobic pathways are shorter, but go to a more acceptable conclusion. Methanotrophic bacteria cannot attack PCE, which seems, in fact, to be toxic to them. Apparently, when all sites are occupied by chlorine, it is not possible for the enzyme, methane mono-oxydase, to inject oxygen into the molecule. But methanotrophic bacteria *can* attack TCE, converting it, through the addition of oxygen, into an epoxide intermediate. This is rapidly broken down into compounds that can be utilized by heterotrophic organisms that degrade it to carbon dioxide, water, and the chloride ion.

GETTING THE BEST OF BOTH WORLDS

Researchers in the Department of Agricultural and Biological Engineering have developed a highly effective attached-film bioreactor that uses what is known as an expanded bed. The bacteria in this reactor are attached to small granules, which makes it possible for them to interact with a flowing stream of water without being swept away. This is an obvious improvement over reactors that utilize bacteria in suspension.

Because of our expertise in this area, we were invited to participate in a nationwide effort—involving major universities, private consultants, and the Department of Energy—that seeks to identify a new, cost-effective technology for the biological treatment of contaminated groundwater. Our work is supported by the Gas Research Institute, an organization that represents the natural gas industry. Apart from having an interest in cleaning up contamination for which its members are responsible, the institute sees methanotrophic bioreactors as a possible new market for natural gas—which is more than 99 percent methane.

Figure 3

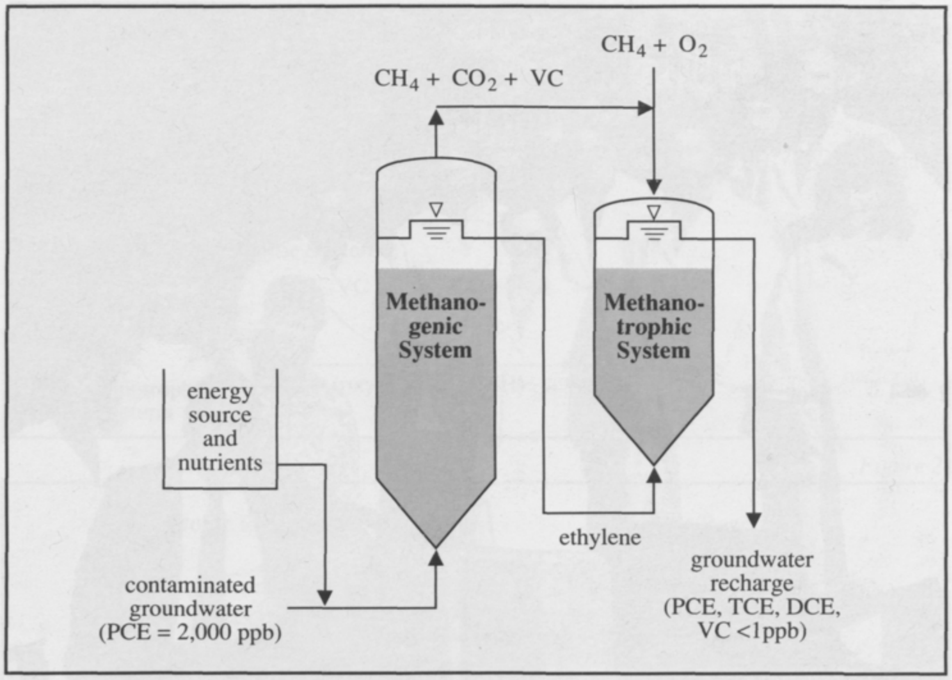


Figure 3. A hypothetical expanded-bed system for the biological treatment of common chlorinated solvents. Ratios of chemicals to water are given in parts per billion (ppb).

We began work on the project in 1987 and spent the first two years developing a methanotrophic attached-film expanded-bed (MAFEB) reactor. Because of the toxic nature of the materials involved, it was necessary to exercise extreme caution in testing and operation. Working with these materials is considerably more difficult than working with pollutants such as the organic materials found in sewage, and the cost of obtaining reasonable data is two or three times greater.

Our large team of researchers began by developing the methanotrophic kinetics for reactions involving TCE and its products at 35°C, and then began adapting the system to work at the ambient temperatures of groundwater. We found that the MAFEB reactor could utilize TCE at a rate approaching the maximum reported by microbiologists. This rate is relatively slow, however, especially when the TCE concentration is less than five hundred parts per billion.

At this point, a growing understanding of the kinetics of both anaerobic and aerobic systems sent us off in a new direction. We learned that anaerobic, methanogenic bacteria can not only degrade PCE (which methanotrophic bacteria could not), but that they are also able to degrade other, more highly chlorinated compounds more rapidly. This suggested the possibility of a hybrid system, with an anaerobic, methanogenic first stage followed by an aerobic, methanotrophic second stage.

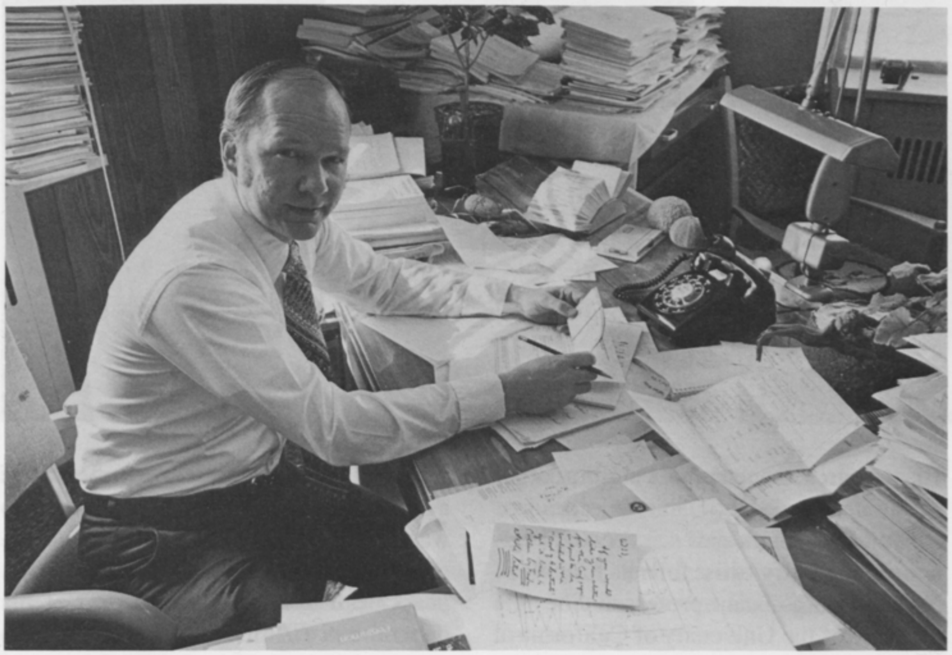
In August 1989 we began experimenting with an anaerobic attached-film expanded-bed reactor. After a short period of acclimation, anaerobic dechlorination occurred extremely rapidly and proved very efficient. Even without being optimized, the system was able to reduce the PCE concentration from 10,000 parts per billion to less than 50 parts per billion in a hydraulic retention time of under two hours. As expected, much of the PCE was broken down only to vinyl chloride.

This is where the aerobic system took over: the vinyl chloride was introduced into a second-stage, methanotrophic reactor. In early tests, the level of vinyl chloride was reduced to undetectable levels in a matter of hours.

FIRST STEPS TOWARD A PRACTICAL SYSTEM

The ideal way to conduct bioremediation of polluted groundwater would be to stimulate bacteria that are already present in the soil to degrade toxic materials. But when soil conditions do not provide the right environment for the bacteria, *in situ* treatment is not possible. Instead, an above-ground treatment system must be used. This involves pumping the polluted water up to where it can be treated, and then either returning it to the ground or discharging it.

The treatment process can be controlled much more easily in above-ground treatment than in an *in situ* operation. Because



of this, most researchers feel that initial experiments in bioremediation should be done above ground. Once a process is well understood, it may be possible to increase efficiency and reduce cost by adapting it for *in situ* application.

Our studies of the kinetics of reactions in attached-film expanded beds that utilize both anaerobic, methanogenic bacteria and aerobic, methanotrophic bacteria indicate that chlorinated solvents could be treated successfully with a hybrid above-ground reactor. The possibility of building a pilot model of such a reactor at the Department of Energy's Savannah River Laboratory in 1991 or 1992 is currently under review.

Meanwhile, the team at Cornell's Department of Agricultural and Biological Engineering continues working to define more precisely the limitations of the system. The speed with which this new technology is being developed is truly impressive. What seemed impossible just ten years ago may soon be demonstrated in the field.

William J. Jewell is a professor of agricultural and biological engineering at Cornell.

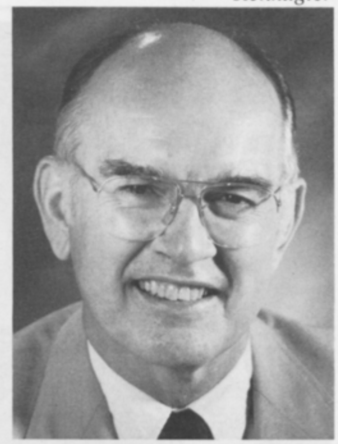
Before joining the faculty in 1973, he earned the B.S. degree at the University of Maine, the M.E. at Manhattan College, and the Ph.D. at Stanford University; did postdoctoral research at the University of London and the Water Research Center in Stevenage, England; and taught at the University of Texas and the University of Vermont.

He has been a consultant to industrial firms, the Environmental Protection Agency, the U.S. Department of Agriculture, the United Nations, and several foreign governments. He belongs to a number of professional organizations in agricultural and civil engineering and has been active in their national committee work.

". . . chlorinated solvents could be treated successfully with a hybrid above-ground reactor."

REGISTER

Rehkugler



■ Five engineering faculty appointments were made in the 1990 spring or fall terms.

T. Michael Duncan became an associate professor of chemical engineering this fall after ten years at AT&T Bell Laboratories. He holds a B.S. degree from the University of Michigan, and M.S. and Ph.D. degrees from the California Institute of Technology. His research interests include heterogeneous catalysis, solid-state nuclear magnetic resonance spectroscopy, and the development of materials.

Another appointment in chemical engineering is that of **James R. Engstrom**, who became an assistant professor in January 1990. He earned the B.Ch.E. degree at the University of Minnesota and the Ph.D. at the California Institute of Technology, and spent three years in postdoctoral research at the University of Washington. His research concerns fundamental aspects of materials processing and gas/solid interactions.

Yosef Y. Shacham-Diamand, a visiting faculty member since 1989, became an assistant professor of electrical engineering this fall. After earning three degrees at the Technion in Israel, he spent four years at the University of California at Berkeley and three years on the Technion faculty. His research is centered on ultra-large-scale integrated (ULSI) microelectronics.

New to the materials science and engineering faculty this fall is **Carol S. Nichols**, an assistant professor. She is a graduate of the University of California at San Diego, and received M.A. and Ph.D. degrees from the University of California at Davis. Subsequently, she spent eight months at the Max Planck Institute in Stuttgart, Germany, and three years at IBM in Yorktown Heights. Her research interests are in theory and computation of structure-property relationships in polycrystalline and composite materials.

Charles H. K. Williamson, an assistant professor of mechanical and aerospace engineering since January 1990, earned the B.Sc. degree at Southampton University, England, and the Ph.D. at Cambridge. He has worked for a firm involved in research on offshore platforms, as a mathematics and physics teacher in London, and as a research fellow in aeronautics at the California Institute of Technology. His research includes studies of the transition to turbulence in shear flows; it involves use of a new 22-foot computer-controlled "X-Y Towing Tank", as well as wind tunnels.

■ **Gerald E. Rehkugler**, a professor of agricultural and biological engineering, was appointed associate dean for undergraduate programs this fall. For the past six years he has served as chairman of his department.

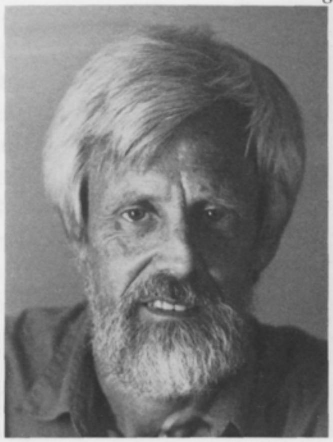
As associate dean, Rehkugler works with the faculty and its Common Curriculum Governing Board to improve undergraduate education, and he supervises the activities in the offices of admissions, the registrar, advising, and placement. He also oversees the Engineering Minority Programs, the Undergraduate Research Program, and the Engineering Communications Program.

Rehkuger earned B.S. and M.S. degrees at Cornell before joining the faculty in 1958. Beginning in 1964, he spent two years at Iowa State University, where he was a National Science Foundation faculty fellow and earned the Ph.D. degree.

His professional specialties are in the design of agricultural and food-processing machinery, food engineering, digital image processing, and vehicle dynamics. He has received four awards for outstanding publications from the American Society of Agricultural Engineers.

Cohen

Karig



Death

■ **Claude Cohen** began a term as director of the School of Chemical Engineering in July, succeeding Keith Gubbins.

After studying at the American University in Cairo as an undergraduate, Cohen earned the Ph.D. in chemistry at Princeton University. He joined the Cornell faculty in 1977 after serving as Katzir-Katchalsky fellow at the Weizmann Institute in Israel and as a research associate at the California Institute of Technology.

Cohen has served as chairman of the college's policy committee and as faculty representative of the graduate Field of Chemical Engineering. He is a member also of the graduate Field of Materials Science and Engineering. His research area is the physical properties of polymer systems and composites. He is associated with the Cornell Injection Molding Program.

■ In the Department of Geological Sciences, **Daniel E. Karig**, who had been serving as associate chairman, succeeded Donald L. Turcotte as chairman.

A specialist in marine geology and geophysics, Karig has participated in numerous oceanographic expeditions, including three cruises for the Deep-Sea-Drilling Project, and has conducted field research in Indonesia, the Philippines, Iran, Turkey, and Japan. He is a fellow of the Geological Society of America and an honorary foreign member of the Geological Society, London.

He received undergraduate and master's degrees from the Colorado School of Mines, and earned his doctorate at the Scripps Institute of Oceanography of the University of California at San Diego. Before coming to Cornell, he spent a year as a postdoctoral researcher at the Scripps Institute and two years on the faculty of the University of California at Santa Barbara.

■ The new head of the college's Office of Development and Public Affairs is **Murray Death**, a 1967 Cornell graduate, who was appointed as an assistant dean. Mary Berens, who formerly headed the office, is now director of college and unit public affairs for the university.

Death worked in Cornell's Division of Public Affairs for twenty years, serving as director of the Cornell Fund, as coordinator of regional and college development programs, and, most recently, in the Office of Special Gifts.

Another newcomer to the office is **Robin Burt**, director of alumni relations. A graduate of the University of Washington, she has had ten years of experience in the areas of public relations, promotions, special events, membership management, and organization of volunteers.

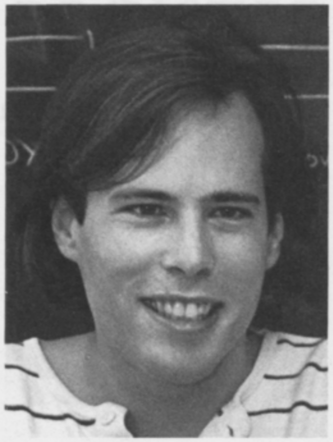
Janice Conrad, formerly director of alumni relations, is now director of leadership gifts, and **Marsha Pickens** continues as director of development.

■ **Edwin Gordon** has been named director of advising at the college. He had served for a year as assistant director. Gordon earned bachelor's and master's degrees at Baylor University and worked in the advising office there for five years. He is enrolled part-time at Cornell in a Ph.D. program in educational administration.

■ Visitors at the college this year are **Carol C. Shilepsky** in operations research and industrial engineering, **Richard Warkentin** in mechanical and aerospace engineering, and **Allan Getto** in the Engineering Minority Programs Office.

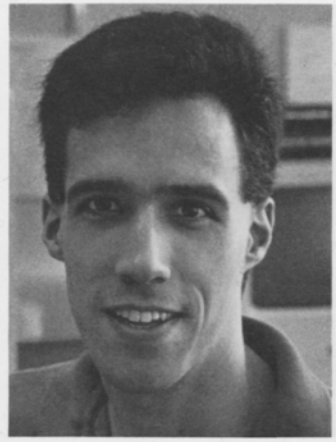
Shilepsky, a professor of mathematics and computer science at Wells College, is

Brown

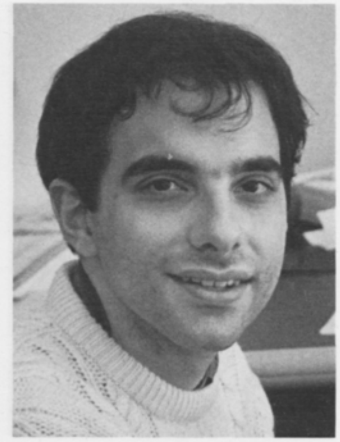


Deierlein

Huttenlocher



Vavasis



working in the area of semiconductors and artificial intelligence during her year-long visiting professorship. She was awarded an $88,000 grant from the National Science Foundation, part of an initiative to enhance the participation of women in science and engineering. She has previously held visiting and research positions at Cornell, most recently in the Mathematical Sciences Institute. She holds M.S. and Ph.D. degrees from the University of Wisconsin.

Warkentin is teaching, conducting research, and working with Associate Professor Paul Dawson in the development of experiments for the new Emerson Manufacturing Laboratory. He holds M.S. and Ph.D. degrees from Cornell and has previously held postdoctoral positions here.

Getto, a senior engineer at the IBM East Fishkill facility, is spending this academic year at the college as part of his company's executive loan program. He is focusing on the recruitment and retention of underrepresented minorities, and helping to plan and develop outreach programs. He is also counselling students, describing the corporate world in talks and feedback sessions with students, and working with the program's industrial advisory council.

■ Four of the college's assistant professors are winners of 1990 Presidential Young Investigator Awards. They are **Geoffrey M. Brown** in electrical engineering, **Gregory G. Deierlein** in civil and environmental engineering, and **Daniel P. Huttenlocher** and **Stephen A. Vavasis** in computer science.

Sponsored by the National Science Foundation, the awards provide, each year for five years, $25,000 in research funding plus $37,500 to match any outside funding, for a total value of up to $100,000 per year. Thirty-three Cornell engineering faculty members have won the prestigious awards since the program began in 1984.

Brown earned a bachelor's degree from Swarthmore College and an M.S. from Stanford University, and then worked as an electrical engineer for Motorola in Texas before studying for his Ph.D. at the University of Texas at Austin. He joined the Cornell faculty in 1987. His research interests are in hardware specification and verification, distributed systems, and computer engineering; he is currently conducting a research project on formal verification of hardware synthesis systems.

Deierlein is a 1981 Cornell alumnus who holds an M.S. from the University of California at Berkeley and a Ph.D. from the University of Texas at Austin. A registered professional engineer in New York State, he has worked as a structural engineer for Leslie E. Robertson and Associates. His research interests include the behavior and design of steel and composite structures, and computer-aided design and analysis.

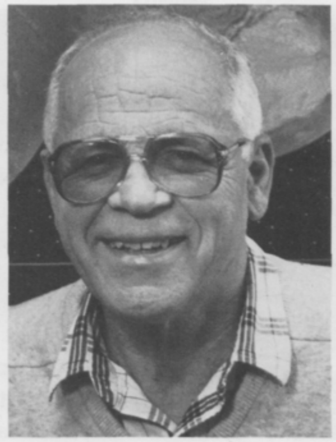
Huttenlocher holds a B.S. degree from the University of Michigan and M.S. and Ph.D. degrees fom the Massachusetts Institute of Technology. Since coming to Cornell in 1988, he has established an active research program in computer vision and geometric matching, and is developing, with a colleague, a laboratory curriculum in robotics and computer vision.

Vavasis earned a bachelor's degree summa cum laude from Princeton, was a Churchill Scholar in mathematics at Cambridge University, and received his Ph.D. from Stanford University. He is working on the formulation and analysis of algorithms for large-scale numerical problems, specifically large-scale sparse matrix problems; another area of interest is boundary-element methods for fluid flow. He joined the Cornell faculty in 1988.

■ Honors received recently by Cornell engineering professors include a number of awards from professional societies.

Fleischmann

Oliver



Hans H. Fleischmann, professor of applied and engineering physics, received one of this year's two $2,000 merit awards from the Nuclear and Plasma Sciences Society. He was cited for "pioneering and extensive contributions to the generation, physics, and technology of field-reversing electron and ion rings."

Jack E. Oliver, the Irving Porter Church Professor of Engineering, is this year's recipient of the George P. Woollard Award of the Geological Society of America. He was recognized for "major contributions to our knowledge of the Earth's crust through the application of seismic techniques." Developments in which he has played a key role include understanding the nature of seismic surface waves, acceptance of the idea of plate tectonics, and establishment of the Consortium for Continental Reflection Profiling (COCORP).

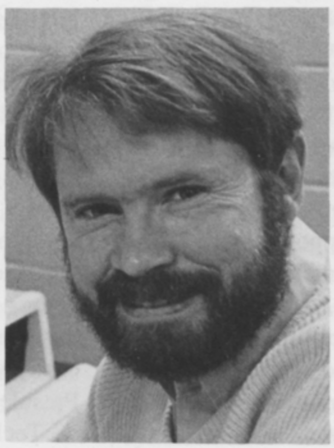
John A. Muckstadt and **Peter L. Jackson** of the operations research and industrial engineering faculty and John M. Jenner of IBM received a EDUCOM/NCRIPTAL Higher Education Software Award and an accompanying $1,000 prize. Their program, "The Manufacturing System Development Game," was cited for "distinguished curriculum innovation in engineering." The award was presented at the national EDUCOM '90 conference held in October in Atlanta.

Stephen B. Pope, professor of mechanical and aerospace engineering, and two of his former graduate students won the $25,000 first prize in an IBM-sponsored competition for a paper on supercomputing. The co-authors of the paper, "Stretching and Bending of Material Surfaces in Turbulence," are **Paul-Kuen Yeung**, now a faculty member at The Pennsylvania State University, and **Sharath S. Girimaji** of Analytical Services and Materials, Inc.

Robin O. Roundy, associate professor of operations research and industrial engineering, was awarded the $3,000 Frederick W. Lanchester Prize by the Operations Research Society of America for two papers on lot sizing. The work may "provide a paradigm for coping with classes of seemingly intractable problems," according to the citation.

Muckstadt

Jackson



Pope

Roundy

Turcotte

Webb

Mitchell

Donald L. Turcotte, the Maxwell M. Upson Professor of Engineering in the Department of Geological Sciences, will receive the Alfred Wegener Medal from the European Union of Geosciences at the sixth biennial meeting in March 1991 in Strasbourg, France. As medalist, Turcotte will give a lecture at the meeting, and over the next two years he will deliver lectures at three European universities. His specialties are geophysics, geomechanics, and mantle convection.

Watt W. Webb has been named by the American Physical Society as the 1991 recipient of the $5,000 Biological Physics Prize, which is awarded in recognition of outstanding research in that field. Webb, a professor of applied and engineering physics, was cited for seminal work on the biophysics of cell membranes and cell motility, for his training of future generations of critical biophysicists, and for longstanding contributions to the biophysics community.

■ The 1990 Excellence in Teaching Award at the college was won by **Joseph S. B. Mitchell**, an assistant professor of operations research and industrial engineering since 1986. The award, based on a student survey conducted by Tau Beta Pi, was accompanied by a $2,000 prize from the Cornell Society of Engineers.

In 1988 Mitchell received a Dean's Prize for Excellence in Teaching from the college, and also a Presidential Young Investigator Award from the National Science Foundation in support of research in applied optimization and geometry.

Mitchell holds B.S. and M.S. degrees from Carnegie-Mellon University and a Ph.D. from Stanford University. He worked for five years for the Hughes Artifical Research Center.

■ Five faculty or staff members received 1990 Dean's Prizes for contributions to the college's undergraduate program. These prizes carry awards of $1,500 each.

John C. Belina, lecturer and assistant director at the School of Electrical Engineering, was recognized for his continuing work in advising undergraduates and student organizations. He was formerly the college's director of advising.

Edwin Gordon, director of advising, received a prize for coordinating a new course, Cultural Diversity in the Workplace, in which lecturers are drawn from industry and various Cornell departments.

Richard H. Lance, professor of theoretical and applied mechanics, was recognized for planning and implementing the Freshman Tutorial Program, which promotes better interaction between underclass students and their faculty advisers.

James W. Mayer, the Francis Norwood Bard Professor of Materials Science and Engineering, was cited for developing an interdisciplinary course—Art, Isotopes, and Analysis—involving faculty members in art, archaeology, English, physics, and materials science. The course, which covers scientific techniques for the analysis of art works and rare old books, will be offered again in spring 1991 and a second-term course will be introduced next fall.

Zellman Warhaft, associate professor of mechanical and aerospace engineering, was cited for sustained excellence in teaching.

■ Two Cornell engineering alumni who have close affiliations with the college are among thirty scientists, engineers, and mathematicians who were honored recently with National Medals for research. President Bush awarded a National Medal of Technology to Greatbatch Gen-Aid, *Greatbatch*

Ingraffea

Thomas

Ltd., a firm headed and founded by **Wilson Greatbatch**. A National Medal of Science was awarded to **George Carrier**, the T. Jefferson Coolidge Professor of Applied Mathematics, emeritus, at Harvard University.

Greatbatch is an inventor and business entrepreneur whose interests center on products and electronic or medical techniques that are beneficial. Among the products his corporation has manufactured are pacemakers and a special battery for them, implantable electronic prostheses and drug-infusion pumps, and electronic instrumentation used in hospitals and space flights. Products based on research in molecular biology are a recent interest.

Greatbatch has received numerous awards and is member of the National Academy of Engineers. A Cornell electrical engineering graduate of 1950, he has been a member of the Cornell University Council and is currently an adjunct professor in the College of Engineering.

Carrier's Cornell degrees are a baccalaureate in mechanical engineering (1939) and a Ph.D. (1944). He is an emeritus member of the Engineering Advisory Council at Cornell.

■ Leaders in a new eight-university National Engineering Education Coalition, sponsored by the National Science Foundation, are Cornell faculty members **Anthony R. Ingraffea** and **Robert J. Thomas**. Ingraffea, professor of civil and environmental engineering, is the project director, and Thomas, professor of electrical engineering, heads the Cornell effort.

The coalition, which is funded by NSF at $15.3 million over a five-year period, is one of several selected on the basis of proposals. The purpose is to develop high-technology methods of teaching engineering and to increase the number of engineers, particularly women and minorities.

The Cornell-led coalition represents a diversity of location, size, mission, and institutional type. The other members are California Polytechnic State University at San Luis Obispo; the University of California at Berkeley; and Hampton, Iowa State, Southern, Stanford, and Tuskegee Universities.

The coalition's main purposes are (1) to bring more students into engineering education, (2) to improve curricula through the development of modular courseware that synthesizes curricular materials, software, and hardware, (3) to develop a delivery system involving such tools as high-tech classrooms, a courseware-development studio, and experimental laboratories, and (4) to utilize linkages between educational institutions and external constituencies.

An important project is the development of a prototype computerized library, the National Engineering Education Delivery System (NEEDS). Some materials have already been developed at Cornell and this work will continue under the direction of **Kate Mink**, coordinator of educational computing at the College of Engineering.

Cornell engineering professors who are working on various aspects of the project include **Mary Sansalone**, **Richard C. Compton**, **Richard H. Lance**, **Richard N. White**, and **Gregory Deierlein**. Also, **Helen Doerr** of the Cornell National Supercomputing Facility is leading "Supercomputing Saturdays" for high school students and teachers. **John Saylor**, head engineering librarian, is co-directing an effort, involving industries, to adopt common standards for hardware and software. The integration of NEEDS into the planned National Research and Education Network is also under study.

Above: The new Engineering and Theory Center Building is across from Hoy Field on Campus Road and is attached to Upson Hall. The towers are stairwells.

■ The $35.2-million Engineering and Theory Center Building, completed this fall, houses engineering laboratories and offices on the lower three stories and the basement. The upper four stories are occupied by the Cornell Theory Center, which operates the Cornell National Supercomputer Facility. The building provides the College of Engineering with about 50,000 square feet of usable space.

The School of Operations Research and Industrial Engineering has moved into the building, along with personnel and facilities in electrical engineering and mechanical and aerospace engineering. Included are laboratories, many of them computer-intensive, for research in automation, robotics, energy systems, manufacturing, and process control. There are also several conference rooms on the engineering floors.

■ Construction on a different scale was carried out by the student chapter of the American Society of Civil Engineers, whose community project for the year was a bicycle and pedestrian bridge linking Stewart Park and the Farmers' Market in Ithaca.

The project, coordinated by **Gregory Johnson** '90 and **Jonathan Pease** '91, began in the fall of 1989 with a preliminary design contest won by **Peter Clark**, a Ph.D. student in structural engineering, and **Catherine Olt** '90, an architecture student. Cost, ease of construction, and suitability to the site were the main considerations.

The chapter members performed site surveys and soil studies, prepared the final design for the bridge and its foundations, estimated costs, built scale models, and helped in the construction, which was directed by graduate student **Paul Crovella**. Professor **Mary Sansalone** was the faculty adviser and **Larry Fabbroni** of Ithaca's Department of Public Works served as a consultant. The $17,000 project was approved by the Ithaca City Planning Commission and was funded by the city.

Designed to resemble a nearby railroad bridge, the structure has steel I-beams, a wooden deck, and handrails made from old rails.

The 1990–91 project is a playground for the South Side Community Center.

Below: Ithaca's new pedestrian and bicycle bridge.

FACULTY PUBLICATIONS

Current research activities at the Cornell University College of Engineering are represented by the following publications and conference papers that appeared or were presented during the three-month period April through June 1990. (Earlier entries omitted from previous Quarterly *listings are included here with the year of publication in parentheses.) The names of Cornell personnel are in italics.*

AGRICULTURAL AND BIOLOGICAL ENGINEERING

Andreini, M. S., and *T. S. Steenhuis*. 1990. Preferential paths of flow under conventional and conservation tillage. *Geoderma* 46:85–102.

Aneshansley, D. J., J. Stouffer, B. Xu, Y. Lui, J. A. Throop, and *S. Berlow*. 1990. Ultrasonic images allow automated grading and inspection of beef and swine. In *Proceedings, 1990 Conference on Food Processing Automation*, ed. F. A. Payne, pp. 256–63. St. Joseph, MI: ASAE.

Datta, A. K. 1990. Heat and mass transfer in the microwave processing of food. *Chemical Engineering Progress* June, 1990:47–53.

Dean, J., D. J. Aneshansley, H. E. Edgerton, and *T. Eisner*. 1990. Defensive spray of bombardier beetle: A biological jet. *Science* 248(4960):1219–21.

Delwiche, S. R., R. E. Pitt, and K. H. Norris. 1990. Using near infrared reflectance to study water in starch and related carbohydrates. Paper read at 1990 International Summer Conference, American Society of Agricultural Engineers, 24–27 June 1990, in Columbus, OH.

Derksen, R. C., and *Z. Sagi*. 1990. Greenhouse sprayer performance evaluations—current status and needs. Paper read at 1990 International Summer Meeting, American Society of Agricultural Engineers, 24–27 June 1990, in Columbus, OH.

Eisner, T., K. D. McCormick, M. Sakaino, M. Eisner, S. R. Smedley, D. J. Aneshansley, M. Deyrup, R. L. Meyers, and *J. Meinwald*. 1990. Chemical defense of a rare mint plant. *Chemoecology* 1:30–37.

Gorewit, R. C., D. J. Aneshansley, J. Jiang, and *L. Price*. 1990. A method for identifying the vasactive response of isolated perfused arteries. *FSAB (Federation of American Society of Experimental Biologists) Journal* 4(4):A845.

McFarland, M. J., and *W. J. Jewell*. 1990. The effect of sulfate reduction on the thermophilic (55° C) methane fermentation process. *Journal of Industrial Microbiology* 5:247–58.

Pitt, R. E. 1990*a*. A model of cellulase and amylase additives in silage. *Journal of Dairy Science* 73:1788–99.

___. 1990*b*. *Silage and hay preservation*. Technical report no. NRAES–5. Ithaca, NY: Northeast Regional Agricultural Engineering Service.

Price, L. R., D. J. Aneshansley, R. C. Gorewit, and *C. S. Czarniecki*. 1990. Effects of long-term (full lactation) exposure to electrical currents in dairy cows. *Journal of Dairy Science (Supplement 1)* 73:244. Abstract no. P373.

Steenhuis, T. S., K.-J. S. Kung, *J.-Y. Parlange, J. S. Selker*, and X.-X. Chen. 1990. Flow regimes in sandy soils with inclined layers. In *American Geophysical Union Hydrology Days 1990*, ed. H. J. Morel-Seytoux, pp. 78–94. Fort Collins, CO: Hydrology Days Publications.

Steenhuis, T. S., J.-Y. Parlange, and *M. S. Andreini*. 1990. A numerical model for preferential solute movement in structured soils. *Geoderma* 46:193–208.

APPLIED AND ENGINEERING PHYSICS

Bedzyk, M. J., G. M. Bommarito, M. Caffrey, and T. L. Penner. 1990. Diffuse-double layer at a membrane-aqueous interface measured with x-ray standing waves. *Science* 248:52–56.

Clauson, E. M., Jr., J. P. Harbison, C. C. Chang, P. S. D. Line, *H. G. Craighead*, and L. T. Florez. 1990. Positive and negative "resistless" lithography of GaAs by electron beam exposure and thermal Cl_2 etching. *Applied Physics Letters* 57:1043–45.

Denk, W., and *W. Webb*. 1990. Optical measurement of picometer displacements of transparent, microscopic objects. *Applied Optics* 29:2382–91.

Flynn, T., and *D. H. Bilderback*. 1990. A ray-tracing comparison of intensity gain from x-ray mirror focussing geometries for crystallographic applications. Paper read at CHESS Users Group Meeting, 19–20 June 1990, in Ithaca, NY.

Webb, W. W., K. S. Wells, D. R. Sandison, and *J. Strickler*. 1990. Criteria for quantitative dynamical confocal fluorescence imaging. In *Optical microscopy for biology*, ed. B. Herman and K. Jacobson, pp. 73–108. New York: Wiley-Liss.

CHEMICAL ENGINEERING

Aul, R. W., and *W. L. Olbricht*. 1990. Stability of a thin annular film in pressure-driven flow through a capillary. *Journal of Fluid Mechanics* 215:585–99.

Aven, M. R., and *C. Cohen*. 1990. Polystyrene diffusion in semidilute solutions and in swollen networks of polydimethylsiloxane. *Polymer* 31:778–80.

Bringi, V., and *M. L. Shuler*. 1990. A framework for understanding the effects of immobilization on plant cells: Differentiation of tracheary elements in

tobacco. In *Physiology of immobilized cells*, ed. J. A. M. de Bont, J. Visser, B. Mattiasson, and J. Tramper, pp. 161–72. Amsterdam, The Netherlands: Elsevier.

Finn, R. K., and P. Präve, eds. (1989.) *Biotechnology focus 2*. New York: Hanser.

Gubbins, K. E. 1990. The behavior of fluids in micropores. Paper read at 3rd Liblice Conference on the Statistical Mechanics of Liquids, 28 May–1 June 1990, in Bechyne, Czechoslovakia.

Harriott, P. 1990. A simple model for SO_2 removal in the duct injection process. *Journal of Air Waste Management Association* 40:998.

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LETTERS

Editor:
The summer 1990 issue of the *Engineering: Cornell Quarterly* provided an excellent perspective on the burgeoning waste problem in this country and the ways in which research and outreach efforts are attempting to deal with it. Regrettably, the list of external research awards of the Solid Waste Combustion Institute which we submitted for inclusion on page 3 of that issue omitted the excellent work of Dr. Richard I. Dick, the Joseph P. Ripley Professor of Civil and Environmental Engineering at Cornell.

The objective of Professor Dick's project, "Improvement of Sludge Combustion Properties," is to improve our fundamental understanding of the physical characteristics of municipal wastewater sludges so that water may be removed economically. In particular, to the extent that the efficiency of mechanical dewatering processes can be improved, sludge might be incinerated without absorbing a significant fraction of its heating value to vaporize water. The importance of this research was also underscored by John Martin's article, which identified a number of factors that will lead to significant changes in sludge disposal practices.

Steven W. Kulick, Research Coordinator
Solid Waste Combustion Institute

Editor:
I would like to offer my congratulations on the Summer 1990 issue. I found it unusually interesting and, more to the point, the best concise presentation that I have read or seen on the subject of waste management and disposal and their effects on the environment.

I have spent forty-odd years in facilities management, for the Navy, several universities (including Cornell), and the State of Alabama, and have spent much time and energy trying to solve problems relating to waste disposal. During the last ten years, I have been especially interested, though not directly involved, in Alabama's situation of being a net importer of waste, especially toxic wastes, and our efforts to evolve satisfactory policies and practices to deal with the resulting problems.

The articles in your publication provided a succinct and balanced outline of the alternatives available for dealing with solid wastes and of the costs of their use and non-use. After reading many of the diatribes prepared for the reading public, I found it refreshing (and enlightening) to find a document that described the problems, discussed solutions and related research techniques and findings, and neither preached salvation nor threatened instant damnation to unbelievers. I plan to provide copies to the Alabama Department of Environmental Management and to others who would profit from reading it.

Thanks for an unusually good issue of your excellent publication.

Cushing Phillips, Jr.
Civil Engineering, Class of 1944
Montgomery, Alabama

Editor:
This letter is in reference to the Summer 1990 issue, "Dealing with Waste". . . . The accepted philosophy for waste disposal is (1) not in my back yard, and (2) zero impact on people's health or the environment. But we need to recognize that contamination levels cannot continue to be set at values that will protect the most susceptible persons with a factor of safety. As population increases and medical advances are able to keep more fragile people alive, there is a likelihood that tighter standards will be required. . . . Also, contamination hazards, such as from PCBs, may be overblown. Years ago, those of us who worked with oil in transformers and circuit breakers (many of whom I still hear from) suffered no ill effects. . . .

I believe that waste disposal should be studied on a cost/benefit basis. . . . For instance, not permitting recycled plastics in food-contact applications should be reviewed: how many deaths are predicted if this regulation were revoked? To prevent the once-in-years contamination of foods and medicines by criminals, we have added many tons to the waste stream, and more fuel is burned by trucks used to transport the excess material.

Richard L. Katzenstein, P.E., M.E.'35
Boca Raton, Florida

Asked to comment on Richard Katzenstein's letter, Richard E. Schuler, director of the Cornell Waste Management Institute, gave the following reply.

While opinions similar to Mr. Katzenstein's are held by many, we live in a democratic society in which a majority of the electorate seems to be willing to err on the side of an extra margin of safety and environmental precaution. Admittedly, those safety measures have their costs in terms of reduced economic growth, narrowly defined, and it is the Institute's responsibility to advise the public about the magnitude of the tradeoffs where good data are available—which is not the case in some of the examples cited by Mr. Katzenstein.

Editor:
I am writing to thank you for *Engineering: Cornell Quarterly*. It is well read here and inspires much debate on the topics raised and American engineering enterprise in general.

John Vickers, Chairman
Cambridge University Engineering Society
Engineering Department
Cambridge, U.K.

GROUNDWATER

Rain that percolates down through the soil to a point where the earth is completely saturated becomes groundwater. The residence time of water in the atmosphere is only eleven days, and lakes and streams are constantly renewed through the hydrological cycle of evaporation and precipitation. But because it cannot evaporate easily, groundwater has an average residence time of four thousand years. The groundwater we drink today contains rain that fell when Agamemnon's troops were laying siege to Troy. Groundwater is, for all practical purposes, a nonrenewable resource.

Groundwater provides one-fifth of the fresh water used in the United States. It is the source of half the drinking water supplied to cities and over 80 percent of the water used by rural families and their livestock. Elsewhere in the world, groundwater is the principal source of fresh water for Denmark, Cyprus, and Malta, and the sole supply of drinking water for more than 60 percent of the towns in the Soviet Union.

Groundwater reserves are being contaminated by the disposal of sewage, solid wastes, municipal waste water, industrial waste water, sludge, brine from the petroleum industry, mining wastes, deep-well disposal of liquid wastes, animal feedlot waste, and radioactive wastes. Groundwater is also affected by accidental spills, agricultural activities, mining, road salt, acid rain, and salt-water infiltration. In the United States an estimated one-third of all underground fuel tanks leak, 58 percent of industrial hazardous wastes are disposed of by injection into deep wells, and leachates from a thousand abandoned waste dumps are slowly percolating down to groundwater. Water from up to 2 percent of the aquifers in the United States may already be unfit for drinking.

Worldwide, aquifers are being depleted far faster than they are being recharged. Beijing's groundwater is being withdrawn four times faster than it is being replaced. In the Tamil Nadu region of India, the withdrawal of water for agriculture has lowered the water table 25 to 30 meters in just ten years. In the United States, one-fifth of the water pumped out of the ground each year is nonrenewable; in California's San Joaquin Valley, an area of 6,200 square kilometers has sunk as much as nine meters since 1930; and half the water in the Ogallala Aquifer, which serves one-fifth of the nation's cropland (from Nebraska to Gaines County, Texas), has already been used up.

People at Cornell are working on some of these problems. The Water Resources Institute, part of the Center for Environmental Research, focuses on research and outreach in the areas of agricultural chemicals and groundwater, nonagricultural contaminants, mathematical models, and water supply. Engineering faculty members who are concerned with water resources (in addition to those whose articles appear here) include Michael F. Walter, in the Department of Agricultural and Biological Engineering, and James J. Bisogni, Jr., Wilfried H. Brutsaert, Richard I. Dick, Leonard B. Dworsky, Gerhard H. Jirka, Philip L.-F. Liu, Daniel P. Loucks, Christine A. Shoemaker, and Jery R. Stedinger in the School of Civil and Environmental Engineering. Their research can help identify ways of protecting and conserving the world's supply of fresh water. But only a serious public commitment can assure the continued availability of this most precious resource to future generations.—*DP*

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