UNDERSTANDING GROUNDWATER MONITORING

Increasing attention is focusing on the composition and migration of groundwater at plantsites. Here is a guide to the various monitoring techniques, and what a sampling program should involve.

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Someone accuses your plant of contaminating the drinking-water supply of a town three miles away: How do you prove that the plant is not at fault? Or is it? What are those geologists doing driving all over your site, towing a downward-looking radar unit, pounding stakes into the ground, and drilling all those expensive groundwater-monitoring wells?

Here, we will answer those questions. We will look at the reasons for monitoring groundwater, how it moves, how contaminants move in it, what tools geologists use to investigate it and, finally, how to manage a groundwater-monitoring program.

Why monitor groundwater?

Groundwater monitoring is increasingly becoming a prime focus of environmental efforts.

In the U.S., to operate or close a surface impoundment or a landfill, or to carry on other hazardous-waste-disposal activities, groundwater monitoring is required by the Resource Conservation and Recovery Act.

Federal UST (underground storage tank) regulations, prompted by increasing concern over leakage from underground tanks, are imposing a whole new class of groundwater-monitoring requirements.

Very small leaks from such tanks are almost impossible to detect by conventional testing methods; indeed, an underground tank that has been tested and found not to be leaking can still lose up to 1.2 gal/d. Such a leak could easily contaminate an entire aquifer — leading to several hundred thousand dollars in cleanup costs. This leakage may be detected by groundwater monitoring, which can provide an early warning, so as to prevent big costs later. (For more perspective on underground storage tanks, see *Chem. Eng.*, Mar. 16, pp. 61–69.)

In addition to the federal requirements, several states have passed or are passing groundwater-monitoring and UST laws. California, for example, now requires a hydrogeologic assessment to be performed on all surface impoundments, even if they do not contain hazardous wastes. Another bill, also in California, would require monitoring and testing of all underground tanks.

Groundwater monitoring is sometimes performed as a defensive measure by companies, to establish background or existing conditions. This can be important in real-estate acquisition or new-plant construction — as part of environmental-impact filings, or for aquifer development to supply cooling or drinking water to a process plant.

Also, corporations are becoming aware of the need to monitor to establish their innocence against potential charges of groundwater pollution. In some cases, good corporate citizenship prompts an effort to discover what may be in the groundwater so that preventive actions can be initiated to head off environmental problems.

Groundwater movement

Groundwater always flows in the direction of decreasing hydraulic gradient — i.e., downhill. That much about its movement is straightforward. However, determining the extent and travel speed of groundwater contaminants is considerably more complex. These parameters are controlled by geologic characteristics, which include clay layering, nonisotropic conditions in soil, fracturing in rock, and reactive conditions between the contaminants and soils. The seasonal fluctuation of the groundwater will also influence the direction and speed that groundwater and contaminants travel. In addition, pumping-wells, lakes, rivers and streams can play a significant role.

The basic equation governing groundwater movement is expressed by Darcy's Law:

$$V = -K\, dh/ds$$

where V is the velocity, K is the coefficient of hydraulic conductivity, and dh/ds is the hydraulic head gradient.

Darcy's law can be developed from the Bernoulli equation by neglecting its velocity term because it is so very small. In groundwater, flow regimens are laminar, usually with Reynolds numbers much less than 1.

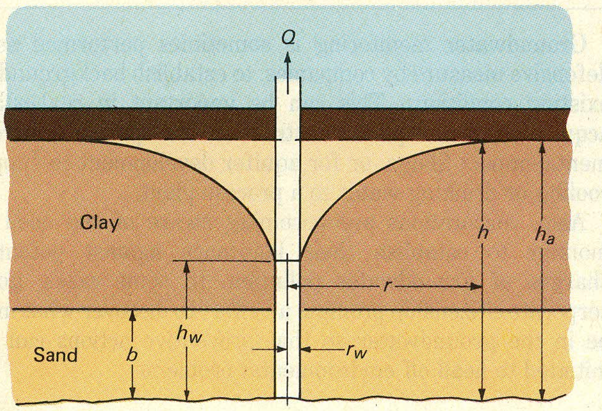
Groundwater flow is not constant with time or with direction in the ground. A more general description of the flow regimen requires a Laplace equation. When this equation has been transformed to cylindrical coordinates and integrated, it takes the form shown in Fig. 1.

Contaminants in the groundwater may or may not move at the same rate as the groundwater. In addition, they may interact with soil or rock, changing form or chemical composition as they move along, or they may disappear entirely.

Fig. 2 illustrates the difficulty in predicting the movement and behavior of chemical contaminants in groundwater. In this relatively simple case, the groundwater is in a confined layer moving through a porous medium — sand — at a small velocity, v_x. The initial concentration of the contaminant is C_i, and, at some point x downstream, C_x is zero. Yet, the equation required to model the flow is complex.

In using such a model, data constraints can be very great and, sometimes, the best models cannot accurately approximate the physical situation because not enough information is available.

Models, however, are only one of the tools used by geologists to try to understand and predict the movement of contaminants, as we shall discuss later.



r_w = Radius of well

K = Coefficient of permeability

h_w = Height of water in the well being pumped

b = Thickness of aquifer

h_a = Hydraulic head at nonpumping conditions

Q = Pumping rate

$$Q = 2\pi rbK\frac{dh}{dr}$$

$$h - h_w = \frac{Q}{2\pi Kb}\ln\frac{r}{r_w} \text{ or } h - h_w = \frac{Q}{2\pi T}\ln\frac{r}{r_w}$$

Figure 1 — These equations provide a basic representation of groundwater flow

The "Rooftop" model

The following analogy frequently helps explain some of the problems associated with the conducting of a subsurface investigation:

Let us suppose that you are on the roof of a large building, and you want to find out what is going on in the building. The roof has its own terrain — it may be flat, irregular, or have terraces, gables, and steeply sloping areas where it might not be possible to stand.

Let us also assume that your funds are somewhat limited, and you cannot, or do not want to, rip up the entire roof to see what is going on below. But you can take all the subsurface measurements you like, and can drill holes to the limit of your budget.

Your subroof exploration will yield greatly different results, depending upon how deep you go and where on the roof you are. The location of the kitchen on one floor may correspond to that of a den or bathroom on another level, and to that of an equipment room or a broom closet on still another floor. As you explore the building, you might even find the elevator shaft or a swimming pool — big discontinuities, which, if taken by themselves, could lead to false conclusions about the contents or activity within the building.

Locating and describing the subsurface activity and geology at a plantsite can be just as tough as describing what is going on below the roofline.

Geologists and geophysicists have developed a variety of instruments that can reduce the overall cost of subsurface exploration. These devices can provide some interesting information about what is underground, even if they cannot always substitute for a borehole.

Ground-penetrating radar

This works much the same way as airborne radar, except that signals in the ground travel at a slower rate, depending upon the dielectric properties of soils. The depth that a unit can probe the ground, and the resolution of the image, depend upon the frequency of the radar. Most commercial units operate at three or more frequencies, usually 120, 350 and 700 MHz. Instruments commonly used can "see" into the ground from several feet in wet clays to one hundred feet or more in dry sand.

A unit can survey up to 90,000 ft^2 from one site, or, moved around, it can profile a mile or more per day.

Ideal uses for ground-penetrating radar include locating buried tanks, trenches, pits, pipes, and the top of shallow rock or groundwater. Radar can also find voids beneath concrete slabs, provided that reinforcing bars in the concrete do not interfere with the signal.

However, ground-penetrating radar is blind in highly conductive soils and salt water.

Electromagnetic and electrical surveys

Both of these techniques (see Fig. 3) measure the electrical properties of soil. Electromagnetic (EM) equipment assesses relative conductivity via an induced electromagnetic field. Because an EM unit does not require direct contact with the ground, it can generate subsurface profiles very quickly.

EM equipment is useful in locating drums, metallic objects and other buried items, up to a distance of about 30 feet — or deeper, if power lines, chain-link fences and other objects do not interfere.

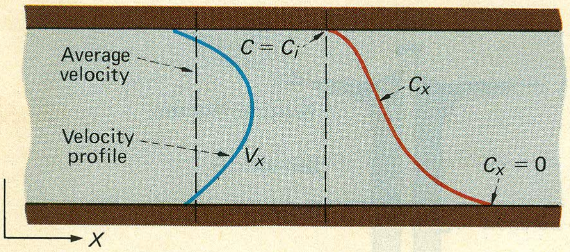
Electrical-resistivity surveys apply a current between two points on the ground, and then measure the voltage difference between them. Varying the electrode spacing and the strength of the applied electrical field will permit deeper "soundings" of the subsurface to be developed. The resistivity measurements can also be used for profiling.

Electrical surveys take longer to conduct than EM ones because they require conductive spikes to be driven into the ground before measurements are made. Also, resistivity measurements are slower, but they can give results where EM equipment cannot.

Seismic profiling

One of the most familiar subsurface-exploration techniques is seismic profiling.

Seismic techniques use an array of geophones to measure the ground vibration from an acoustic source (see Fig. 4). Often, this sound is provided by an explosion, but, for shallow work, it may even be from a mallet strike. The sound travels outward from the source, and is reflected and refracted at interfaces and returned to the surface. There, the geophones record the time and frequency of the wave.



Advection and dispersion equation:

$$\frac{\delta C}{\delta t} = D\delta^2 C - V\frac{\delta C}{\delta x}$$

Where
D = dispersion coefficient $[L^2/T]$
C = concentration

When this equation is rearranged and solved for the concentration:

$$\frac{C}{C_i} = 1/2\left[\text{erfc}\left(\frac{1-\xi}{2V\xi\eta}\right) + \exp\left(\frac{1}{\eta}\right)\text{erfc}\left(\frac{1+\xi}{2V\xi\eta}\right)\right]$$

where $\xi = \frac{Vt}{x}$ and $\eta = \frac{D}{rx}$ and erfc is an error function

Source: "Fluid Movement in Earth Materials", by A. Ogata and R. B. Banks, U. S. Geological Survey Paper #411—A, 1961.

Figure 2 — Even for a confined porous layer, a model of contaminant travel is complex

In an area of a plant where heavy machinery is employed, or where ground vibration is a factor, the use of seismic profiling may be restricted.

Seismic techniques are not suited for locating buried drums or defining plumes of contaminated groundwater, but they can provide a lot of useful information about the depth and location of major subterranean features, including the groundwater table.

Drilled-well techniques

A drilled borehole, properly logged, can tell a geologist a great deal about subsurface conditions beneath your site. In addition to the borehole, the geologist uses a number of instruments to log the well and provide further information about the geology. The porosity, permeability and density of the soil and rock layers are often indicators of the way in which water and pollutants will move through an area.

The borehole is expensive to drill, though, and provides information about only a very small area.

Various techniques can be used with boreholes.

Electrical-resistivity measurements are made on wet uncased holes, using a meter and a portable generator that provides both alternating and direct current. By comparing the direct-current specific potential to the alternating-current resistivity, a picture of the subsurface lithology (rock-formation characteristics) and an estimate of groundwater quality can be obtained.

Nuclear logging, via gamma rays or neutrons, also can be employed. When used with other techniques and with core samples, these logs can provide fairly accurate information about the subsurface lithology.

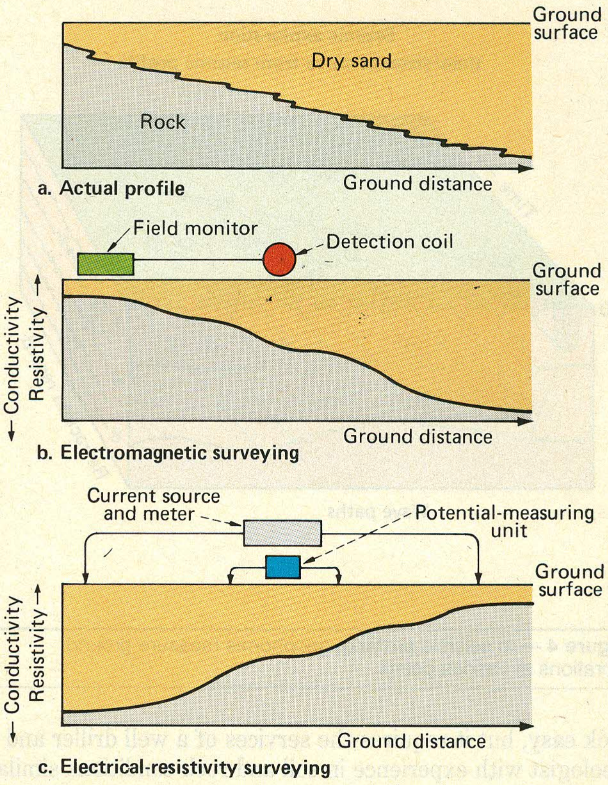


Figure 3 — Electromagnetic and electrical-resistivity surveys provide mirror-image profiles

Gamma-ray logging is particularly suited for locating clay layers, since they have a higher level of Potassium 40 than do rock formations. Backscattered gamma-ray logging can determine the density and porosity of the soil or rock near the well. Backscattered neutron logging is primarily applied to measure the porosity of the subsurface formations.

Groundwater-monitoring wells

A drilled well is one of the most common methods of getting water out of the ground. Fig. 5 depicts three types of wells.

The Type I well is the simplest to construct. It generally is of small diameter because it is primarily used to determine the depth of the groundwater in a shallow formation. The backfill around the well casing is usually soil or, occasionally, a bentonite clay.

The Type II well is more expensive to drill. It is grouted around the casing so as to prevent vertical migration of contaminants between distinct lithologic zones — e.g., the soil and underlying rock formations.

The Type III well is the most expensive to drill. This is because it is double drilled, to prevent contamination from an upper zone from going into a lower one. A larger-diameter well is first drilled, cased and grouted through the contaminated zone(s). Then, a second well is drilled inside the casing of the first well.

Development of a good monitoring well is an art. It may look easy, but it requires the services of a well driller and a geologist with experience in soil and rock conditions similar to those found at your site. An improperly constructed well can permit cross-aquifer contamination — allowing dirty water to pollute clean formations, indicating the existence of a problem where none exists, or creating a new and bigger groundwater problem.

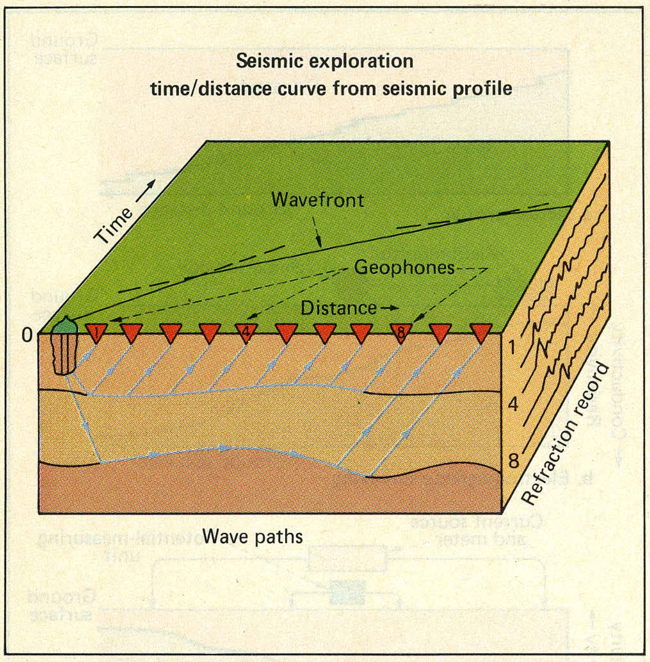


Figure 4 — In seismic profiling, geophones measure ground vibrations at various points

The materials used in monitoring wells have to be carefully selected. Polyvinyl chloride is subject to attack by some chemicals, especially aromatic organics and solvents; polyethylene may absorb certain organics; galvanized steel pipe's coatings may dissolve in acidic waters, releasing zinc and cadmium, which may contaminate the water samples.

Wells for water-level measurements are usually 2 in. dia., and cased with PVC pipe. These wells are generally used for groundwater sampling because they are inexpensive to drill. A 4-in.-dia. well is the most common for low-volume groundwater pumping.

Setting up a sampling and analysis program

After monitoring wells have been installed around your plant, you will be facing one of the most difficult challenges — setting up a sampling program. It can literally make or break your facility. The results of your sampling probably will become public knowledge, and the program and analysis will likely receive high-level scrutiny within your company.

So, you must know why you are monitoring, and what results must be reported and to whom, before the first sample is taken.

Currently, there are at least three separate series of analyses conducted on groundwater: for pollutants covered by the Resource Conservation and Recovery Act (RCRA); for Priority Pollutants, as defined by the Environmental Protection Agency; and for Drinking Water Standards compliance.

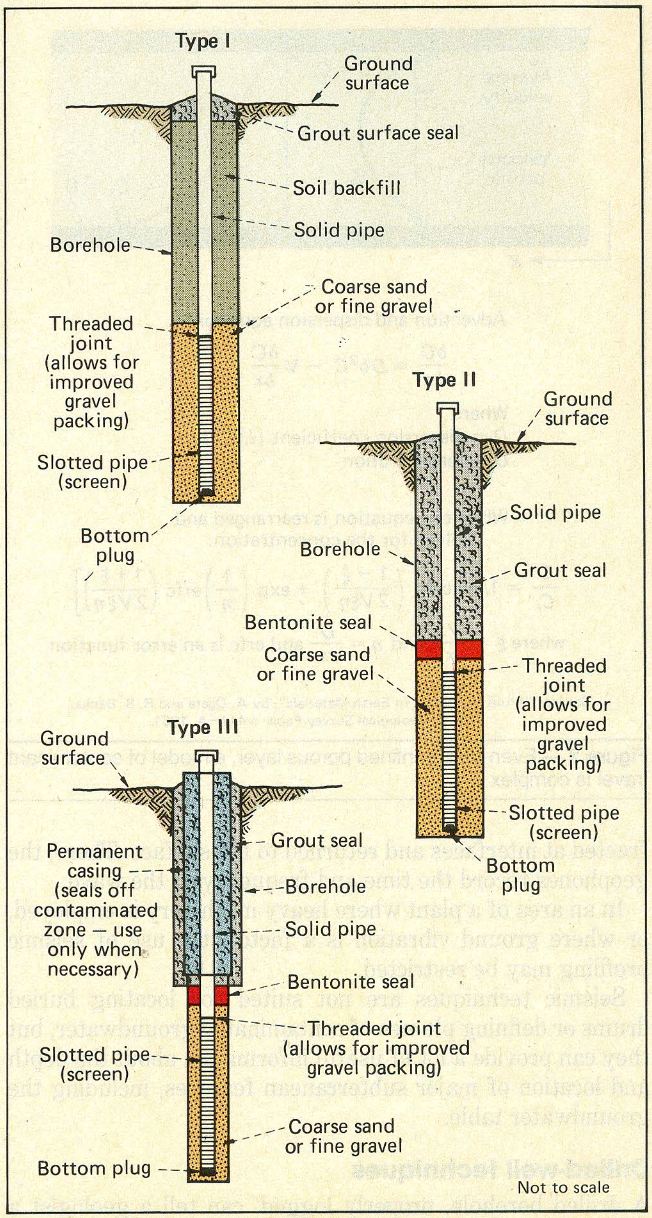


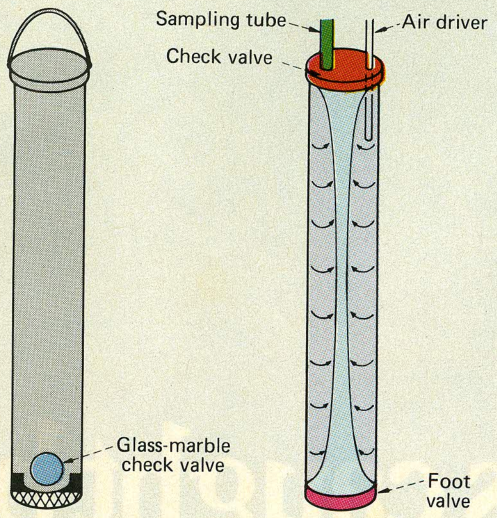
Figure 5 — Three types of boreholes provide different levels of protection against contaminant migration

It is not uncommon to find laboratory fees of around $3,000/sample for RCRA Appendix VIII analysis, $800 for Priority Pollutant analysis, and $200 for Drinking Water Standards analysis. Unfortunately, it is too common to find an incomplete or suspect analysis because of poor sampling techniques, laboratory contamination, or lack of planning.

Political considerations — A sampling-and-analysis program should be set up with the idea that all data generated may become public knowledge and may, in turn, be scrutinized by the press, the public, and regulatory agencies. Unfavorable publicity may prompt investigations of the plant by government agencies.

So, a company must be prepared to deal with unpleasant results, and must be committed to spending the money necessary to resolve or correct any problems unearthed.

Technical factors — Misleading or inaccurate data are dangerous. They may result in unnecessary monitoring for pollutants that really are not present, or lead to ignorance of actual regulatory violations. Getting valid analysis requires the use of appropriate techniques by a competent laboratory.



a. Manual — Bailer is lowered into water and then withdrawn

b. Air-actuated — Air tube pressurizes housing, forcing sample up the sampling tube

Figure 6 — Bailers to take groundwater samples come in manual and automatic versions

New and improved analysis methods and equipment have lowered the detection threshold for many compounds by several thousandfold over the past ten years: A compound not detectable ten years ago often can be measured to three significant places now. Thus, a "below detection limit" or "not detected" notation on an analysis is meaningless unless it is referenced to a specific method, a detection limit, and a specific piece of analytical apparatus.

Look carefully at the credentials and reputation of your prospective laboratory — as well as at its price list. Just because the laboratory has a lot of fancy and expensive equipment is no indication that someone there knows how to properly use it.

Is the laboratory certified by regulatory agencies to do the required tests? Has it routinely done, or is it now doing, the type of analysis you want? Inspect the laboratory, or have someone who is qualified inspect it for you. Obtain a copy of its quality-assurance program, and determine in advance whether or not it meets minimum EPA and State requirements. Discuss the types of samples that will be sent, and clearly state your objectives and expectations from the laboratory. Agree in advance how the sample is to be handled, what analyses are to be performed, and how the results are to be reported.

Remember: reliable data are your best ally, while unreliable data are your worst enemy!

(For more details on obtaining reliable analyses, see *Chem. Eng.*, Apr. 30, 1984, pp. 54–60.)

Decide in advance whether or not you want all the calculations or just data summaries, and obtain definite commitments on when the results are to be delivered. Be aware that laboratories performing RCRA analysis for Appendix VIII compounds may have a three-month backlog.

A sample for laboratory analysis is covered by "chain of custody protocols," which must be followed, even if this requires special arrangements to be made for sample transportation.

As part of the overall chain of custody, you will want to know how and where the samples will be disposed of when the analyses are completed.

Getting good samples

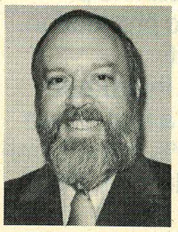
Samples are taken from wells by bailers, such as those shown in Fig. 6. At least five well volumes should be removed before the actual sample is collected. The bailer must be carefully decontaminated between well samplings, to avoid residuals showing up in the analyses.

Before beginning bailing, make sure that a sufficient number of containers and sample bottles are on hand, and that enough bailer-decontamination supplies are available. Also, be sure to take water-level measurements from the well, and determine how to dispose of the water you are bailing from the well. Finally, check all protective and safety equipment.

Each sample taken from a well has preservation and holding requirements; these may require rapid transport and analysis.

Some measurements need to be made in the field. Temperature, atmospheric pressure, the concentration of dissolved gases and pH can all change by the time the sample is received at the laboratory — e.g., the release of dissolved CO_2 may change the pH.

***Mark D. Rosenzweig**, Editor*



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