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INVESTIGATING A GROUNDWATER SOLUTE PLUME IN THREE DIMENSIONS*

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Summary

Groundwater contaminant plumes are often studied in two dimensions, but in some cases it is essential to characterize them in all three dimensions. The depth of a plume can be investigated by several methods, including completing wells at multiple depths at the same location; using inflatable packers to isolate an interval of borehole for sampling; and sampling a well at multiple depths without use of packers. A contaminant plume in the Triassic Culpeper Basin in northern Virginia was investigated using these methods. It was found to be about 12 000 feet long, up to 3000 feet wide, and as much as 1000 feet deep. Because of surface recharge and pumping from a deep well at the downgradient end of the plume, its center descended from the surface at the upgradient end, near a possible source area, to a depth of about 400 feet at the pumping well. Characterizing the plume in three dimensions greatly increased the confidence that all of the contaminant had been found, and provided valuable guidance for the design of possible remedial systems. Shallow wells installed early in the overall investigation would have given a misleading picture of the plume, since they showed much less than the actual maximum concentration at that point, if they had not been supplemented by information obtained deeper in the plume.

Why think about groundwater contamination in two dimensions

When groundwater contaminants are emitted from a source, they move down the groundwater head gradient while spreading laterally. The result is a groundwater contaminant plume. Being physical objects, contaminant plumes have length, breadth, and height; or, since they are subsurface objects, depth. We are used to seeing plumes represented as elongated areas on maps. We like to think of them as simply two-dimensional areas, partly out of habit and partly for simplicity. Since aquifers are generally horizontally stratified, and are thin relative to their lateral dimensions, thinking of them in two dimensions often seems a reasonable simplification. Consequently, we often find ourselves thinking of contaminant plumes in two dimensions, when we should be thinking of them in three.

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The dangers of two-dimensional thinking

We run considerable risks when we neglect the vertical dimension of groundwater contamination. In unfavorable hydrogeological conditions, monitoring wells installed without regard to possible contaminant depth may be too deep or too shallow, and miss the contaminants entirely. Even if the plume is detected, neglecting concentration variations with depth may cause us to misinterpret its location, or its direction of movement, or the amount of contaminant in the plume. Not knowing the depth of greatest concentration may lead to designing inefficient remedial pumping wells.

A contamination situation with depth

Since relatively few large-scale studies have characterized contaminant plumes in three dimensions, it may be of value to present the results of a large study where three-dimensional characterization of a contaminant plume was of considerable practical importance. This investigation was carried out for a private client by Dames & Moore, with the packer equipment described later supplied and supported by Earth Data, Inc. of St. Michaels, Maryland. The features of particular interest in this investigation were the large size of the plume (and in particular its great depth), the high degree of detail with which the plume was characterized, and the light that this investigation sheds on contaminant migration in certain types of fractured-rock aquifers.

The problem that we investigated concerned a plume of organic solvents dissolved in groundwater. A number of compounds were involved, but by far the most widely distributed and most concentrated was perchloroethylene (PCE) (tetrachloroethylene), so I will discuss only that compound. Similarly, I will not discuss possible sources, except to say that there appear to have been more than one. The distribution of PCE in map view, as finally determined, is shown in Fig. 1. The boundary is defined by the extent of PCE above a detection limit of 1 ppb. Since EPA has proposed a regulatory MCL (maximum contaminant level) of 5 ppb, nearly all of the plume represents groundwater having an undesirable PCE concentration.

The plume shown in Fig. 1 extended 12 000 feet between an industrial complex, located near the south end of the plume, to the vicinity of an important public supply well designated PW-07 at the north. The width of the plume is at most about 3000 feet. An area several times as large was investigated in the process of defining the limits of the plume. The figure shows selected wells used in this investigation; many of the dots actually represent clusters of two or more wells. Most of the wells shown were installed specifically for this investigation.

Previous studies had shown the presence of PCE in groundwater near the industrial complex and in well PW-07. Our task was to determine the total

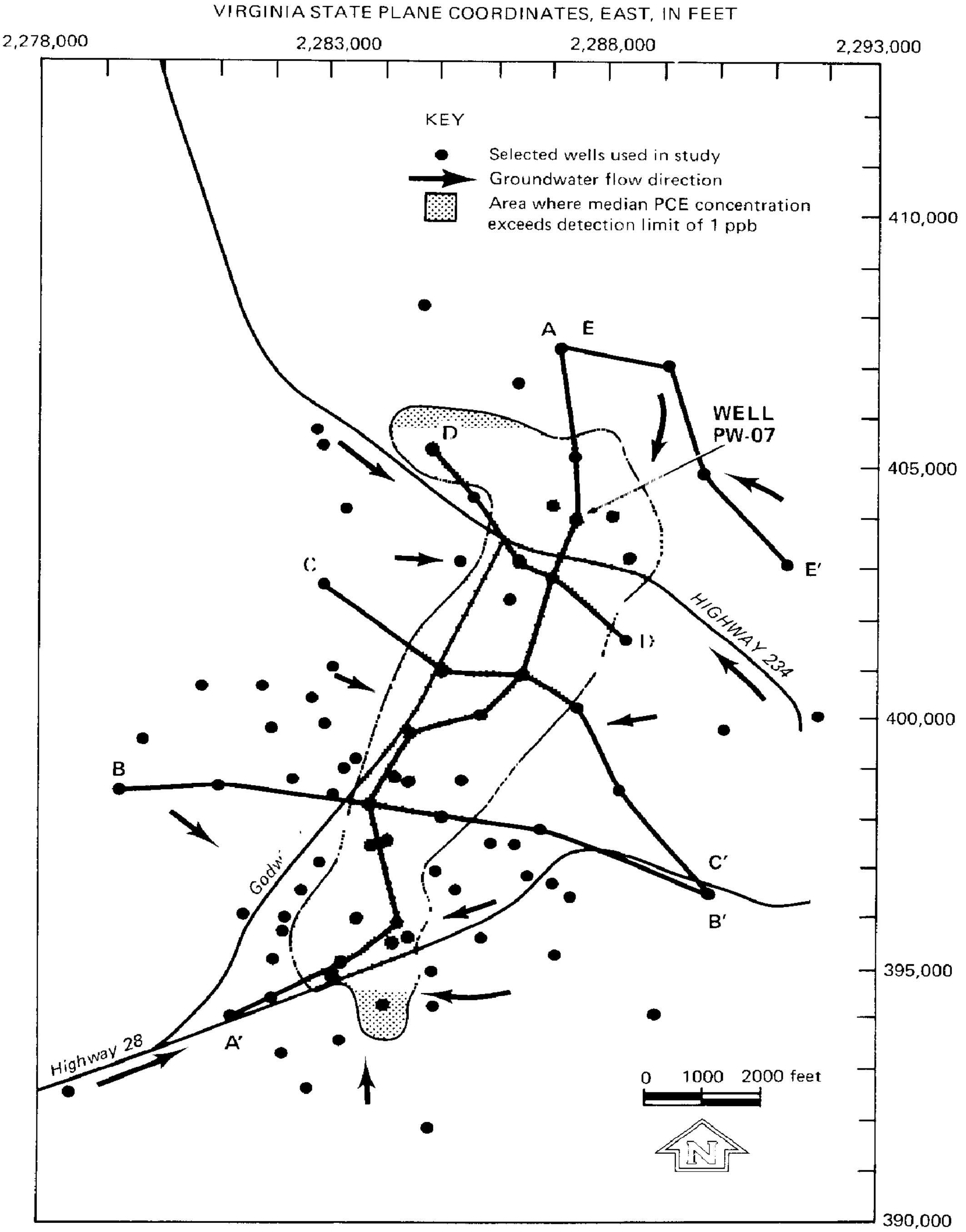

Fig. 1. Map view of contaminant plume, with locations of cross sections.

extent of the plume, both horizontally and vertically, in order to assess the risk it presented to public health, and to allow design of remedial measures. The remainder of this discussion will concentrate on how the vertical extent of the plume was investigated, and on what we found.

Hydrogeological background

The study area was in the Culpeper Basin, in and near Manassas, Virginia. The Culpeper Basin is one of the Triassic-age sedimentary basins that lie along the eastern edge of North America. Sedimentary rocks filling these basins are known collectively as the Newark Supergroup [1]. The most current geological description of the basin is by Lee [2].

The Culpeper Basin is about 92 miles long north to south, and is 15 miles at its widest. It was formed when a depression in metamorphic bedrock was filled by lake and river sediments; the depositional environment while the basin was being filled must have been something like the modern rift valley lakes of eastern Africa [3,4]. Today, the sediments occur as a complexly interlayered sequence of fractured siltstones and sandstones, mostly bright red to gray in color. Igneous rocks are associated with the sediments. Diabase intrudes the sediments in the form of large dikes, and basalt flows are interbedded with sediments near the west margin of the basin.

There are three important things to keep in mind about the rocks in the basin. First, they are very thick — more than 1000 feet in the study area, and more than 7000 feet in the deepest part of the basin [5–7]. Second, the rocks are fractured to such an extent that they transmit water fairly well, and the entire sedimentary fill of the basin behaves as a single aquifer. Third, the study area lacks extensive confining beds, that is, low-permeability layers that would impede downward movement of contaminants. Although such beds occur, they extend such small distances laterally that contaminants moving downward can easily bypass them. The second and third points are conclusions of this investigation, which involved extensive aquifer testing beyond that described in this paper.

Wells at multiple depths

The simplest and most obvious method for finding how deep a contaminant plume extends is to install wells at several different depths. This technique is rather common in investigations of shallow surface aquifers, where wells are relatively inexpensive. Seventeen pairs of 6-inch diameter wells were installed for this study, most of them with one well 200 and the other 450 feet deep. These depths were based on limited information from previous studies that suggested that a large part of the plume was likely to occur between them. The wells had steel casing extending to 50 feet from the bottom of the borehole, so groundwater could enter the deepest 50 feet of the well. Thus, we could see how PCE concentrations differed between two depths at each of the pairs of wells.

Packer testing

Completing wells at multiple depths has the advantage that samples can be taken repeatedly at the different depths. In many locations we did not, however, feel that this capability was worth the delay and expense of installing more than one well. Another method, possible only during well construction, allowed us to obtain one-time information on variation in PCE concentration with depth. Packer testing, as this method is called, was developed in the petroleum industry for somewhat different purposes. It involves temporarily sealing off a certain interval of a borehole so that water samples can be obtained from only that length. At the same time, hydraulic conductivity of the rocks outside this interval is tested in order to see how it varies with depth.

Packers are basically thick-walled, cylindrical balloons made of synthetic rubber. For most tests they were used in pairs. The equipment that went into the borehole is shown diagrammatically in Fig. 2. It consisted of the two packers, which were attached to the ends of a 50 foot steel pipe; an electric submersible pump, mounted between the packers; three electronic pressure transducers to monitor changes in hydraulic head; and a steel pipe extending to the surface that supported the packer assembly and also discharged water from the pump. At the surface were nitrogen cylinders, pressure regulators and controls, and equipment for monitoring hydraulic head. The latter consisted of a Metrosonics data logger, connected in one direction to the transducers, and in the other through a serial interface to an IBM PC Convertible portable computer. In most cases the data logger was used simply as an analog-to-digital converter, converting voltages received from the transducers to strings of characters, but in case of computer problems it could record test results (but not display them so conveniently) independently of the computer. In normal operation, a specially-written computer program polled each of the three transducers in turn, sending a command to the data logger that instructed it to read input from a specified transducer. Hydraulic head was displayed graphically as a function of time on the computer screen and simultaneously recorded on a diskette. In this way, the results of pumping could be seen as they occurred as well as analyzed conveniently later.

Packer tests were conducted in the borehole while it was open to the bedrock, after drilling but before the steel well casing was installed. To conduct a packer test using two packers, the packer assembly was lowered to the depth to be tested, then both packers were inflated using compressed nitrogen carried from surface tanks through small-diameter tubes. A pressure of a few hundred pounds was generally enough to counteract water pressure and expand the packers into a water-tight seal with the walls of the borehole. The pump was started; hy-

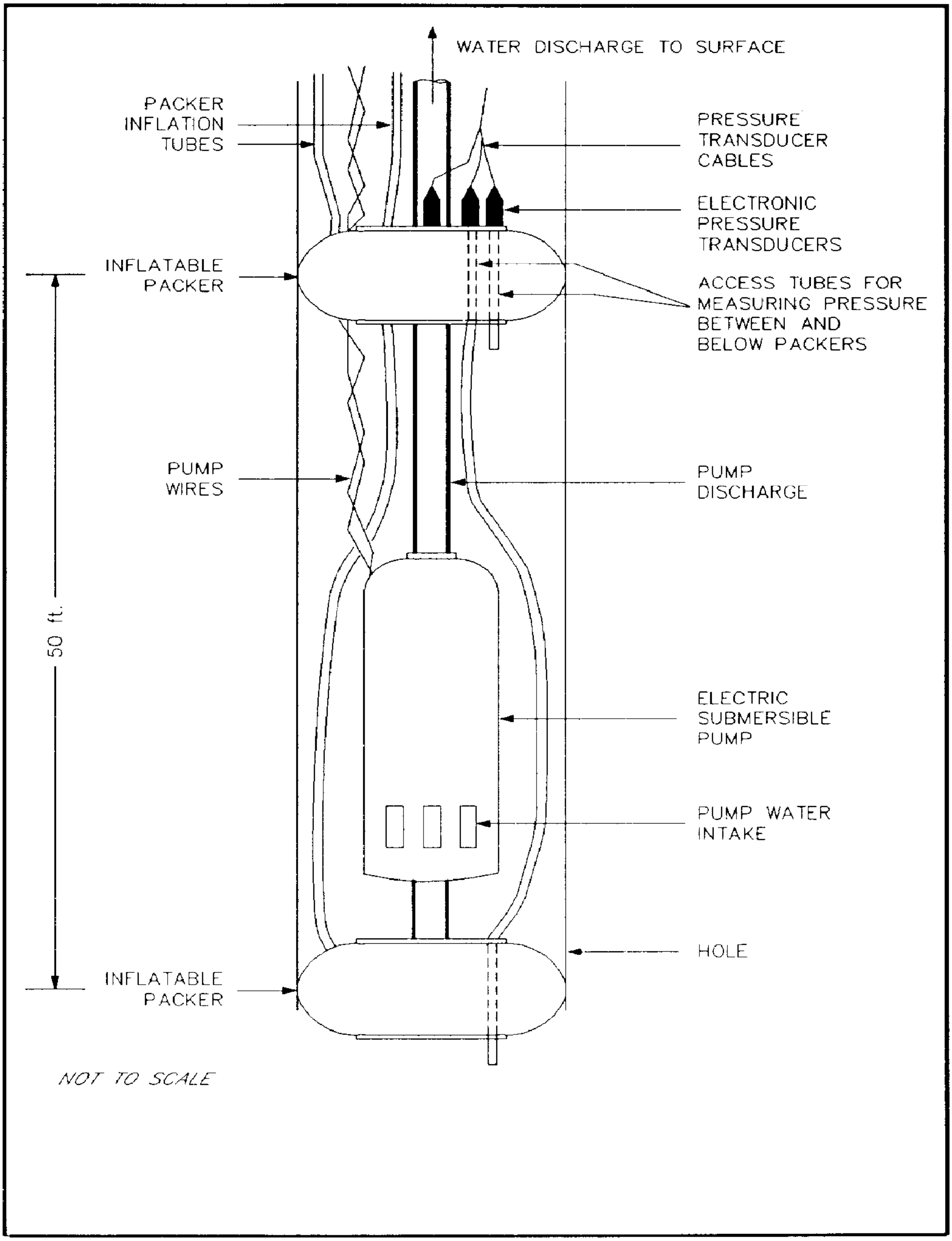

Fig. 2. Double inflatable packer/pump assembly.

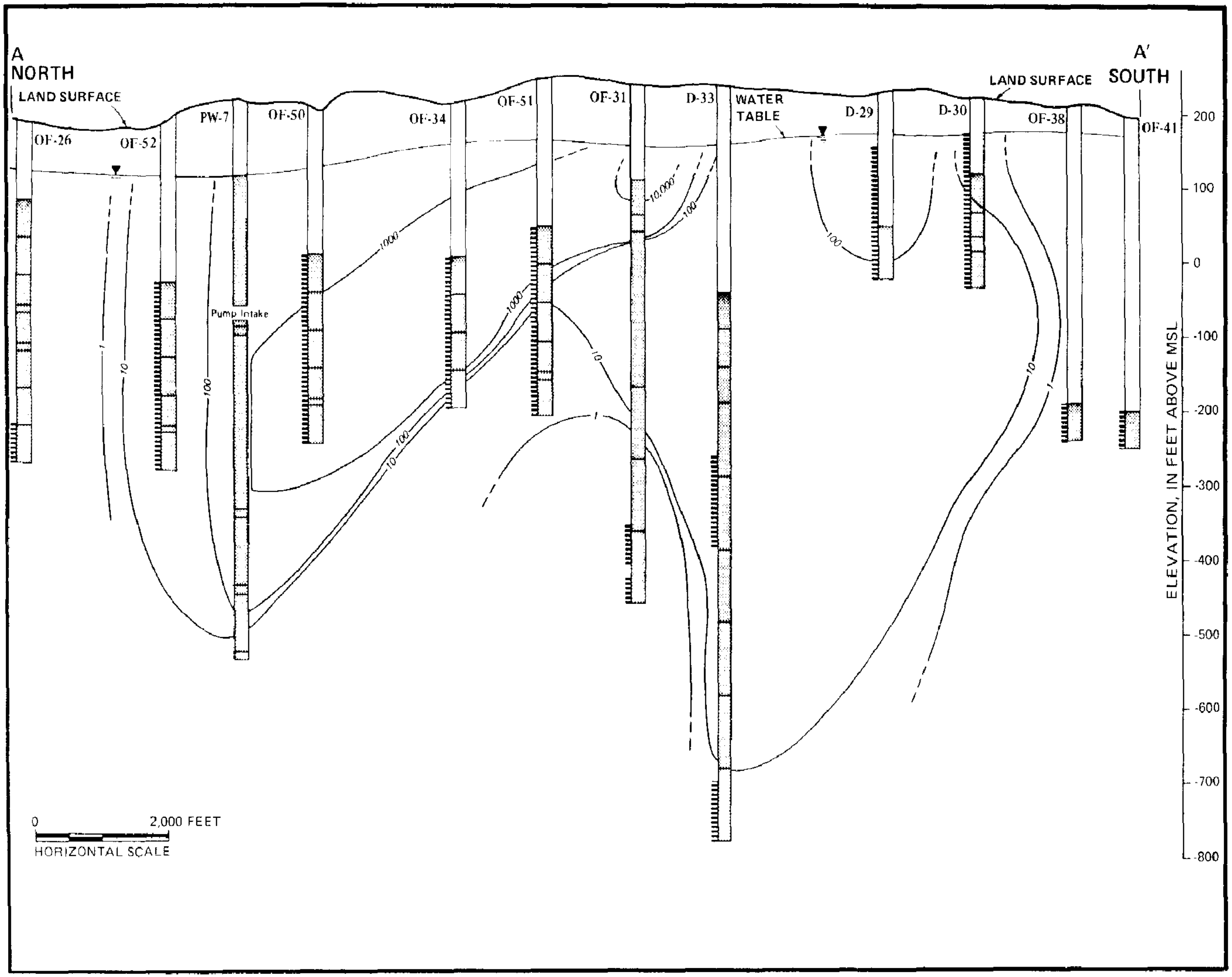

Fig. 3. Cross section A-A′ showing perchloroethylene concentrations.

draulic head between the packers fell rapidly, then stabilized at some lower level. The change between initial and stabilized head was used in calculating the hydraulic conductivity of the surrounding rock. A water sample was taken from the pump discharge, the packers were deflated, and the equipment was lowered to sample the next 50 foot interval. This method allowed water sampling for PCE from about six intervals within most wells. Under good conditions, all samples from a well could be obtained in about one day.

The tests described above were conducted in wells whose depths were preplanned. We hoped, of course, to penetrate most or all of the plume with these wells, but had no way to guarantee that this would occur. Three especially deep wells were therefore drilled specifically to determine how deep the plume really extended. A different scheme of packer sampling was used for these wells. The first step was drilling to the greatest depth that PCE was known to occur near the well: 500 feet in well D-31, 350 feet in D-33, and 450 feet in OF-09. Wells D-31 and D-33 are shown in Fig. 3. Well OF-09 is at the same location as OF-34 in the figure, but is not shown because all intervals tested (from 365 to 600 feet depth) showed no PCE. Only a single packer was used; the equipment was as shown in Fig. 2, but with the lower packer and its pipe and tubing omitted. The packer was lowered to 50 feet (or 100 feet at depths below 500 feet) above the bottom of the hole, inflated, and hydraulic testing and water sampling were performed as described above. The packer testing equipment was removed from the well, drilling was continued for another 50 or 100 feet, and the packer equipment was reinstalled. Meanwhile, the water sample was rushed to a laboratory, where special arrangements allowed PCE analysis on the same day. Thus, the field supervisor knew how the PCE concentration was changing as drilling proceeded deeper. Drilling was stopped when two successive samples showed no detectable PCE. In this way, it was determined that the plume extended to a depth of 500, 1000, and 365 feet, at the three wells, respectively. Packer sampling using this method has the great advantage of showing the total depth of contaminant penetration; it is, on the other hand, considerably slower than testing with a pair of packers because all equipment must be removed and reinstalled for each interval sampled.

Sampling a single well at multiple depths

Another approach to determining the depth of a plume is to take groundwater samples from various depths within a single well having a long open interval. This is often called "depth-discrete" sampling. In the area under investigation, water samples were obtained from well PW-07 at eleven different depth during previous investigations.

Various kinds of sampling devices can take water samples from specific depths. Elaborate electrically-operated samplers are sometimes used by well geophysics companies. Most equipment, however, is considerable simpler. The

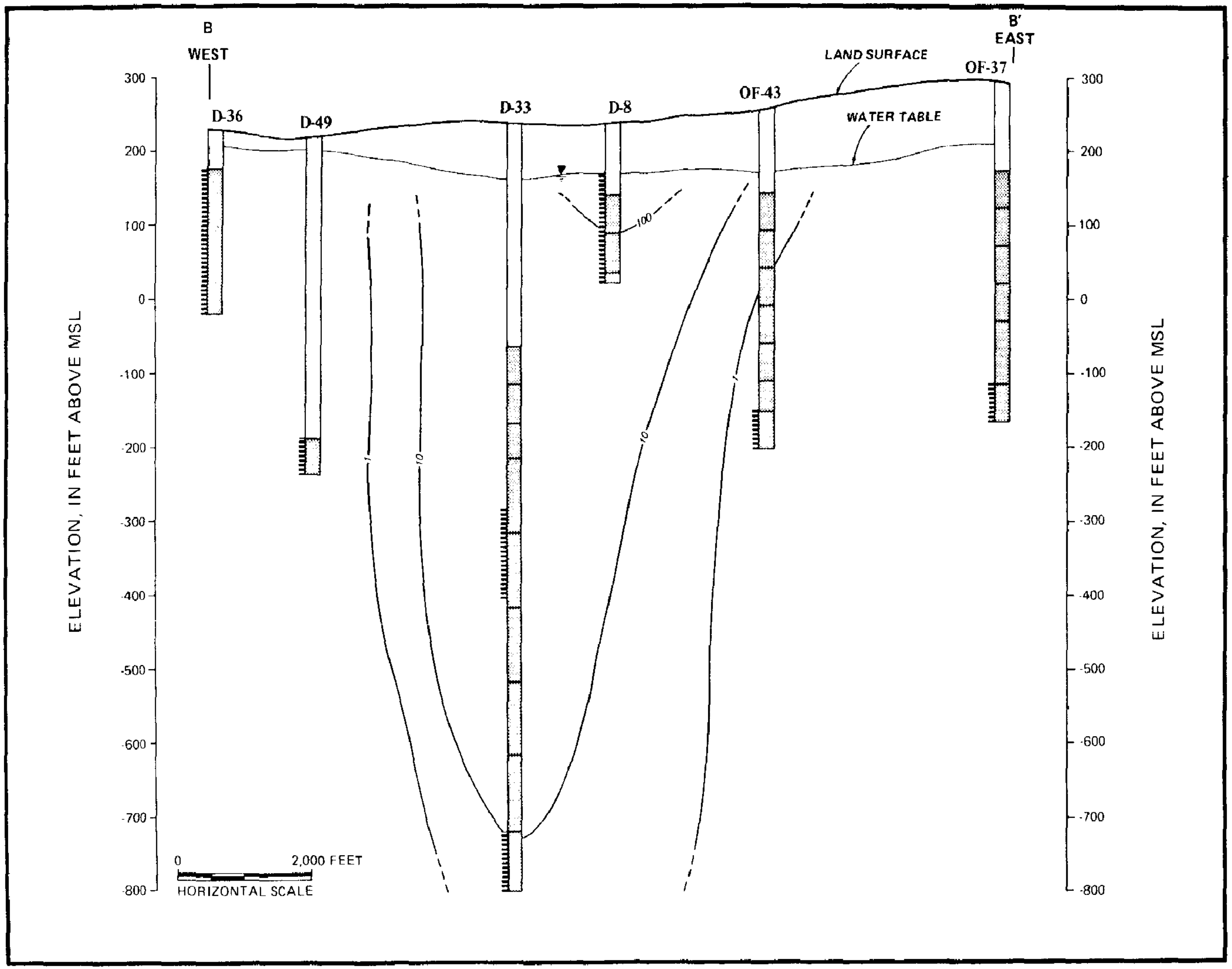

Fig. 4. Cross section B-B′ showing perchloroethylene concentrations.

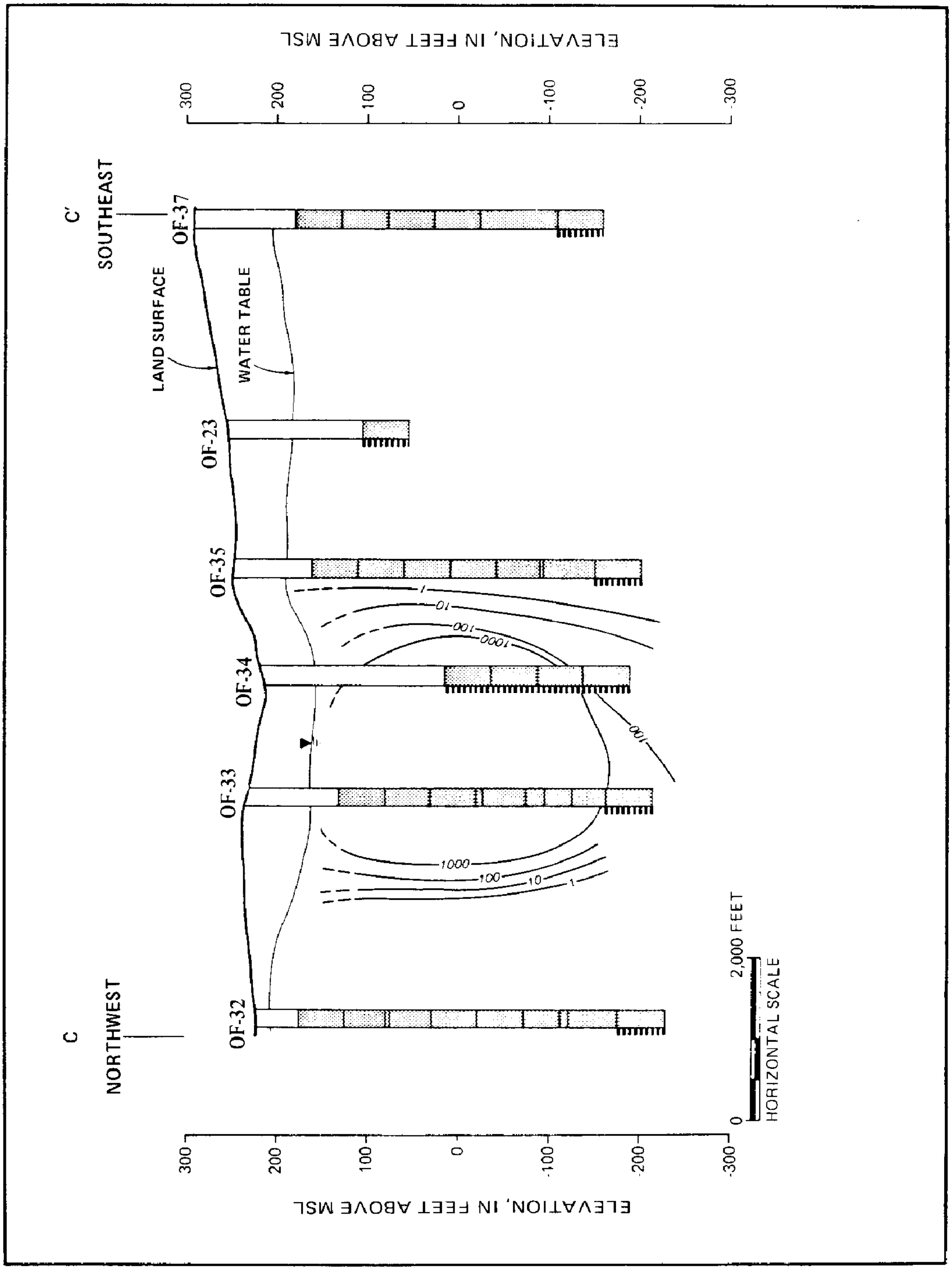

Fig. 5. Cross section C–C′ showing perchloroethylene concentrations.

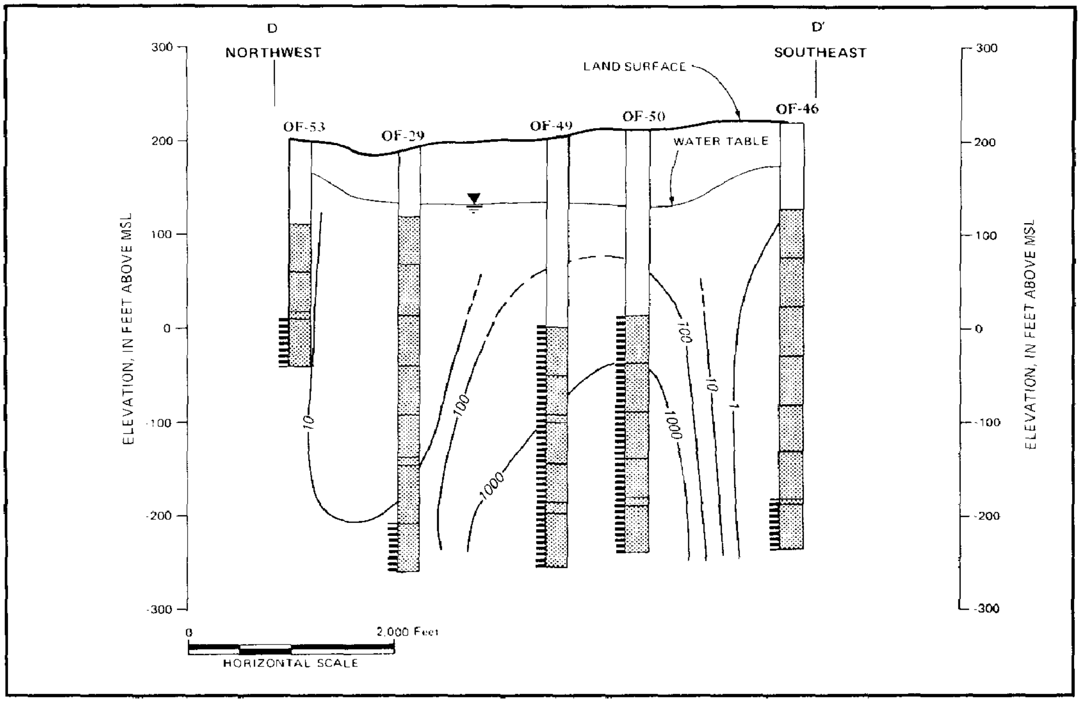

Fig. 6. Cross section D–D′ showing perchloroethylene concentrations.

commonest type is the double-ball-valve bailer [8]. This is a tube with a ball valve at top and bottom. It is lowered to the sampling depth, then moved up and down repeatedly. This motion flushes out the water inside the bailer and fills it with water from the well. It is then pulled up, with the ball valves remaining closed. Another type is the Kemmerer sampler [8], a tube with mechanically-operated valves at top and bottom. These are held open by a latch until the sampler reaches the desired depth. A "messenger" is dropped down the supporting rope; this is a small cylindrical weight with a hole down its center through which the rope passes. The messenger strikes the latch and closes both valves, trapping a water sample inside.

Sampling at specific depths in an open hole has the advantage of being relatively rapid and inexpensive. Unlike packer sampling, however, there is nothing to prevent a sample from a certain depth being contaminated by water that has moved up or down the borehole from other depths. This may be a serious problem in wells that penetrate several aquifers having different water levels. In well PW-07, however, the concentrations measured correlated well with those obtained from packer tests at similar depths in other nearby wells, so this simple method of multiple-depth sampling appears to have produced valuable results.

The extent of the plume

The size and shape of the plume, in three dimensions, are summarized in one map and five cross sections, one down the length of the plume and four cutting across it.

Figure 1 shows the plume in map view and the locations of the cross sections. It is about 12 000 feet long, and as much as 3000 feet wide. The boundaries are believed to be accurate, since a number of wells at various depths outside the indicated boundaries showed no detectable PCE.

First, consider the north-south cross section A–A′ (Fig. 3). It shows high PCE concentrations near the surface, but concentrations fall of rapidly with depth. The highest near-surface concentrations are near wells D-28 and D-29, located near what independent evidence suggests may be a possible PCE source. Northward along the section, PCE extends to progressively greater depths as far as well PW-07. At PW-07, PCE occurs in detectable concentrations to approximately 1000 feet below the surface; this represents a large fraction of the plume width. Downward migration of PCE is probably caused partly by recharge infiltrating from the land surface (thus displacing PCE-bearing water downward), and partly by pumping from well PW-07. This well pumps almost continuously at approximately 200 gal/min, and appears to capture all PCE

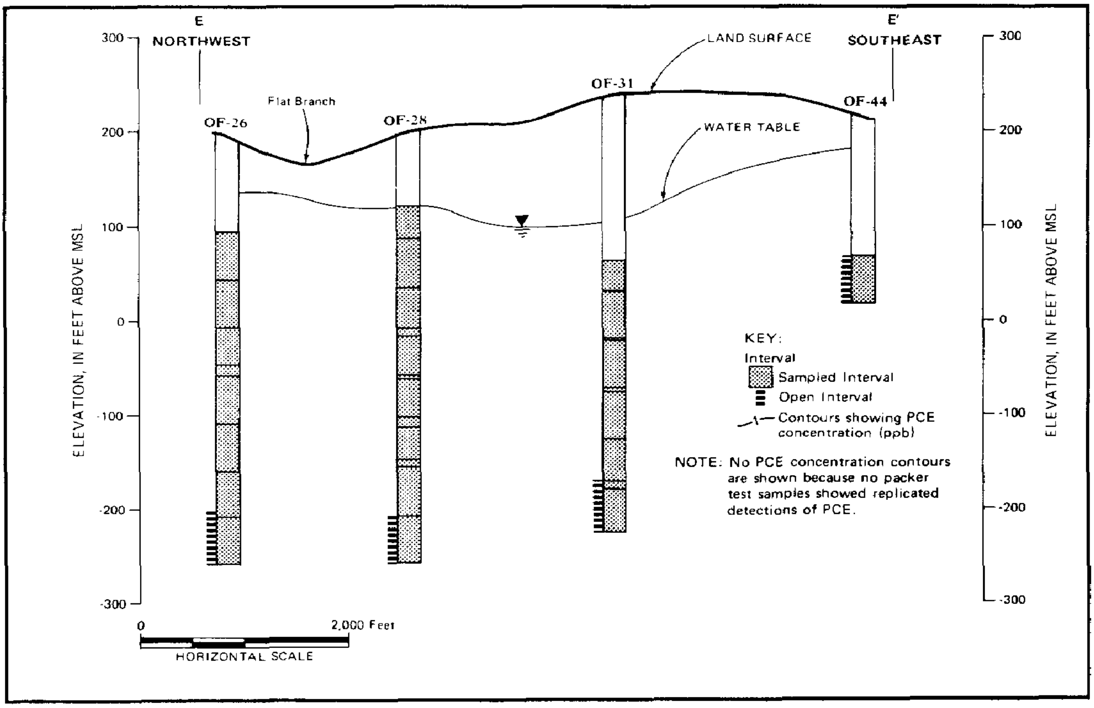

Fig. 7. Cross section E–E′ showing perchloroethylene concentrations.

migrating toward it. The PCE is removed by a carbon filtration system before the water is used.

The other cross sections, taken in order from south to north, reveal other details of the plume's geometry. Section B–B′ (Fig. 4) includes the deep well D-33, and so shows practically the entire thickness of the plume. Here it is a few thousand feet wide, and about a thousand feet deep, with highest concentrations near the surface. This cross section is located slightly south of the area showing highest concentration in cross section A–A′; in fact, concentrations are relatively modest.

In section C–C′ (Fig. 5), farther north toward well PW-07, two wells penetrate most of the thickness of the plume. Here, the depths of highest concentration are somewhere in the middle of the wells, with lower concentration near the surface and at greater depths. Wells on either side showed no detectable PCE at any depth, and thus define the lateral limits of the plume.

Section D–D′ (Fig. 6) is located where the plume has moved to greater depths, so wells intersect only the top of the main plume. Highest concentrations are near the bottoms of two of the wells.

Section E–E′ (Fig. 7) is located north of well PW-07, beyond the north end of the plume. None of the wells showed detectable PCE in any of the depth intervals sampled.

The general shape of the plume in three dimensions is thus similar to that of a cigar, with one pointed end near the surface on the south. The other end is rather more blunt, as the plume is terminated abruptly by pumping from well PW-07.

Why the vertical investigation mattered

To sum up, what of practical value did we learn from investigating the vertical dimensions of the PCE plume? The first thing that we gained was greatly increased confidence that all of the plume had been located. One of the most important objectives of this study was to completely define the extent of PCE in groundwater. We could never be confident that this had been achieved if the possibility existed that PCE was hidden at greater depths than we investigated.

An instructive example was provided by well OF-50, shown on cross section D–D′ (Fig. 6). A shallower (200 foot) well, designated MW-03, had been installed at this location during earlier investigations. PCE concentrations in MW-03 were generally less than 100 ppb, rather lower than expected considering that it was close to the estimated center line of the plume, lying between the south end of the plume and well PW-07. Furthermore, concentrations in PW-07 were considerably higher, typically several hundred ppb. We suspected that most of the plume was deeper than the bottom of well MW-03, so a deeper well was installed to investigate. Packer testing in well OF-50 was started at 200 feet (the depth of the shallower well), and proceeded downward to 450 feet. As anticipated, the highest PCE concentrations were found at greater depths, with about 1500 ppb from 250 to 450 feet. The bulk of the PCE would have been missed by relying on information only from the shallower well.

Second, we gained valuable information for design of remedial systems. This investigation showed that it is essential, within the area studied, to plan remedial pumping wells according to the actual depth of PCE occurrence. There is no simple way to do this in the area investigated; one can not, for example, simply install wells in some easily identifiable aquifer. The depth of greatest PCE concentration must be actually measured, using the methods described above, before the most effective depth for a proposed remedial well can be selected.

Third, we gained valuable insights into plume behavior in this hydrogeological setting. In particular, we found that as deep as it was investigated, the entire thickness of rocks in the Culpeper Basin appears to behave as a single aquifer. There are no extensive confining beds that prevent downward plume movement. At first, this result seems improbable, since many of the rocks are fine-grained, low-permeability shales and siltstones that would seem to transmit water poorly. The explanation is that these rocks are so well lithified that they are brittle, and have been extensively fractured; most groundwater movement is through fractures, and these fractures penetrate shales and siltstones as well as coarser-grained sandstones and conglomerates. Furthermore, the shales and siltstones occur in small, disconnected bodies that would not in any case form a continuous barrier to downward groundwater movement.

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