

Recognizing Emerging Environmental Problems

The Case of Chlorinated Solvents in Groundwater

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Chemicals used in contemporary technological processes, in particular chlorinated compounds including degreasing solvents and chlorofluorocarbon (CFC) refrigerants, have, until recently, proven to be an elusive quarry. Chlorinated compounds lack the telltale characteristics—smoke, smog, taste, and odor—that earlier identified and brought other, more obvious, pollutants to the attention of the public, the scientific community, regulatory agencies, and environmental historians.¹ Moreover, their public health consequences, cancer in particular, become evident only long after exposure.

In this article I employ an old theoretical construct, Thomas Kuhn's scientific paradigm, as an aid to understanding the difficulties involved in recognizing one class of chlorinated compounds: the ubiquitous degreasing solvents used in machine shops and factories small and large across the industrialized landscape of twentieth-century North America and Europe. While Kuhn's conception of scientific paradigms has taken its share of scholarly critique in the four decades since *The Structure of Scientific Revolutions* first appeared in print, one central element of Kuhn's book promises to shed considerable light on the recognition of degreasing solvents as threats to public health and environmental quality. Kuhn argues that a scientific paradigm—a focused worldview about a given theory and its related

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1. See Joel Tarr, *The Search for the Ultimate Sink: Urban Pollution in Historical Perspective* (Akron, Ohio, 1996), and Joel A. Tarr and Jeffrey K. Stine, "At the Intersection of Histories: Technology and the Environment," *Technology and Culture* 39 (1998): 601–40.

methodology—is only as powerful as the level of consensus about the validity of both the methodology and the theory on which it is based.²

A paradigm governing views of degreasing solvents as environmental hazards would require consensus among environmental scientists about contaminant pathways, the physical-chemical processes occurring along their length, accepted modes of measurement, and the biomedical effects of the contaminants on public health. A new paradigm of this sort would not necessarily replace an existing one; rather, it would explain the contamination by reference to theory, experimentation, and field measurement, and then identify potentially effective remedial actions. The act of understanding is most likely linked to a modern chemical method of analysis that makes the otherwise invisible contamination apparent; hence the absence of any prior paradigm and of any “paradigm shift.”³ Rather than recognizing a fait accompli that has occurred because of unanticipated events, scientific paradigms that incorporate environmental pathways, processes, and instrumentation provide the means of anticipating environmental problems and perhaps mitigating their biomedical consequences if there is consensus on the validity of the paradigm. An absence of consensus may inhibit the formulation of effective public policy.

This study describes the delayed recognition of the widespread contamination of American groundwater by chlorinated degreasing solvents that was discovered in the late 1970s. In 1982, when the controversial actions of the Environmental Protection Agency (EPA) under Anne Gorsuch and frequent accounts of newly discovered toxic waste sites had brought the problem to the forefront politically, Harvey Brooks of Harvard University characterized the inaction of earlier years as a failure of public policy: “Why did we not begin to accumulate the basic knowledge and techniques fifteen or twenty years ago which would have enabled us to plan and execute the necessary applied R&D

2. Thomas S. Kuhn, *The Structure of Scientific Revolutions* (Chicago, 1962).

3. Edmund Russell III has described one such case of delayed policy formulation involving DDT, a chlorinated pesticide, which was suspected by entomologists of being environmentally harmful when it was first marketed commercially in 1945; see “The Strange Career of DDT: Experts, Federal Capacity, and Environmentalism in World War II,” *Technology and Culture* 40 (1999): 770–96. A lack of evidence concerning ecological damage and strong promotion by the chemical industry meant that federal regulations were not developed until 1972, by which time environmental damage was apparent. The ubiquity of chlorinated pesticides in ecosystems was measurable during the 1960s, thanks to the introduction of the electron-capture detector fitted to a gas chromatograph; see James Lovelock, *Homage to Gaia: The Life of an Independent Scientist* (Oxford, 2000), chap. 7. In both the cases described in this article—the CFC/ozone and solvents-in-groundwater issues—scientific paradigms were created to explain potential or real problems. No paradigm shifts occurred because prior paradigms did not exist. In the words of Alexander Bird, “the immature science of competing schools is preceded by no paradigm at all, perhaps no science at all, for the phenomena of interest may previously have been unknown or ignored”; *Thomas Kuhn* (Princeton, N.J., 2000), 32.

for assessment and disposal today?” This article seeks to answer Brooks’s question and explain why the necessary research and development by industry, government, and academia—not to mention the basic monitoring of groundwaters and soils that was so clearly lacking and which Brooks identified as a sign of failure in science policy—was undertaken so belatedly.⁴

I have described elsewhere the particular failure of groundwater hydrologists in California to anticipate this contamination despite their concern for the protection of their aquifers—those bodies of water-saturated sand and gravel that form the basins where most Californians live and work.⁵ Notwithstanding the alertness of this community of scientists and engineers, widespread contamination of Californian and other aquifers throughout the southwest United States occurred in the mid-twentieth century.⁶ By 1981 it was clear that this was a national problem, which the Council on Environmental Quality described as “the recent, and seemingly sudden, appearance of toxic organic chemicals in drinking water wells.”⁷

Four factors account for the failure of hydrologists, regulators, and industry in mid-twentieth-century California to anticipate and therefore prevent groundwater contamination by these solvents.⁸ First, these chemicals were perceived as merely workplace hazards, so that the vapors on the factory floor were the only cause of concern. Second, hydrologists and others did not have the means to sample and analyze the dissolved components of these solvents in groundwater before they reached water-supply wells. Third, there was no guiding scientific paradigm that explained the environmental migration of solvents disposed of following the practices recom-

4. Harvey Brooks, “Science Indicators and Science Priorities,” *Science, Technology and Human Values* 7 (1982): 14–31. On page 28, he notes: “Several case examples from the past suggest that existing systems of research planning tend to undervalue systematic and well-planned monitoring, data collection, empirical testing, and localized environmental characterization.” Groundwater contamination was one such case.

5. Richard E. Jackson, “Anticipating Ground-Water Contamination by New Technologies and Chemicals: The Case of Chlorinated Solvents in California,” *Environmental and Engineering Geoscience* 5 (1999): 331–38.

6. Richard E. Jackson, “The Migration, Dissolution, and Fate of Chlorinated Solvents in the Urbanized Alluvial Valleys of the Southwestern USA,” *Hydrogeology Journal* 6 (1998): 144–55.

7. Council on Environmental Quality, *Contamination of Ground Water by Toxic Organic Chemicals* (Washington, D.C., 1981), vi. On page iv, the council noted that “in the past 3 years, newspapers have carried stories of a new and insidious type of ground water contamination in many parts of the country. These incidents involve discoveries—sometimes completely accidental—of high concentrations of synthetic organic chemicals in a community or private drinking water well. It is now evident that hundreds of drinking water wells affecting the water supplies of millions of people have been closed because of the contamination by toxic organic chemicals.”

8. Jackson, “Anticipating Ground-Water Contamination.” “Hydrologists” here refers to those who identify themselves as groundwater hydrologists or hydrogeologists and who might be engineers or geoscientists by training.

mended by industrial and insurance associations. Fourth, these three factors interacted in a way that inhibited inquiry—and therefore paradigm creation—by research scientists and engineers who might otherwise have considered the migration and fate of solvents in the subsurface a suitable subject of research. Recognition of the problem occurred when hydrologists, using new chemical methods, sought to detect different but similar contaminants that were suspected of having a deleterious effect on public health. The critical difference between anticipation and recognition of emerging environmental problems is the ability to forestall or mitigate the seriousness of anticipated emerging problems, as contrasted to the reactive response that follows the recognition of a fully realized problem.

The chemical industry of the twentieth century introduced many chlorinated products for a wide variety of purposes. The detrimental effects on wildlife of one class of these chemicals—chlorinated pesticides, such as DDT—prompted the development of the environmental movement in the United States and led to their regulation by the federal government.⁹ This article focuses on two other classes of chlorinated hydrocarbon compounds, degreasing solvents and CFC refrigerants, which were introduced in the 1920s and 1930s by DuPont and other chemical companies. Despite the progressive environmental policy of DuPont, dating to the 1930s, these compounds now confront industrial societies with the persistent environmental contamination of the stratosphere (ozone depletion due to CFCs) and regional groundwaters.¹⁰ What distinguishes these two issues, which developed contemporaneously, is the role of scientific paradigms in setting the stage for problem identification and remedial action. Stratospheric-ozone depletion had been anticipated by the publication of a scientific paradigm eleven years before the demonstration in 1985 of the seriousness of the problem.¹¹ Groundwater contamination by solvents was recognized in the closure of water-supply wells across the United States and in Europe in the late 1970s. But it was not until 1988 that research was translated from the German and published in English explaining why and how the problem was occurring. Only then could effective remedial actions be implemented on the basis of an increasingly sophisticated paradigm.¹²

9. Rachel Carson, *Silent Spring* (New York, 1962); see also Russell (n. 2 above).

10. Mack McFarland, "Chlorofluorocarbons and Ozone," *Environmental Science and Technology* 23 (1989): 1204–5. The policy commits DuPont to "determine that each product can be made and disposed of safely and consistent with appropriate safety, health and environmental quality criteria." McFarland states that this environmental policy was "adopted in the late 1930s."

11. Harvey Brooks, "Stratospheric Ozone, the Scientific Community, and Public Policy," in *Stratospheric Ozone and Man*, vol. 2, ed. Frank A. Bower and Richard B. Ward (Boca Raton, Fla., 1982). Richard C. J. Somerville, *The Forgiving Air: Understanding Environmental Change* (Berkeley, Calif., 1998). Edward A. Parson, *Protecting the Ozone Layer: Science and Strategy* (Oxford, 2003).

12. A committee of the National Research Council reported that estimated spending on environmental remediation in 1996 was \$9 billion. At least one half of this sum is due

The Emergence of Solvent Degreasing

Metal surfaces that are to be painted, machined, welded, heat-treated, assembled, electroplated, or packaged first require removal of machining and cooling oils and grease from prior handling. The most efficient method is vapor-phase degreasing, in which the solvent is heated to its boiling point and the workpiece is immersed in the vapor cloud so that the condensing vapors remove the oil and grease by solubilization and drainage. Trichloroethylene (TCE) is an excellent solvent for vapor-degreasing purposes and became the solvent of choice in the 1930s, shortly after vapor degreasing was adopted by U.S. industry in 1928.¹³

A “vapor degreaser” is basically a tank with a heat source to boil the solvent and a cool surface to condense the vapor in the upper section. The metal parts contaminated with oil and grease are suspended in this zone of solvent vapor. The hot vapor condenses onto the cooler parts, dissolving the oils and greases and continuously rinsing them in clean solvent. The cooled solvent returns to the boiling sump where it is heated and re-vaporized. The Detroit Rex Company (now the Detrex Corporation) was probably the first U.S. company to develop a comprehensive line of vapor degreasing equipment.¹⁴ Others, such as Blakeslee of Cicero, Illinois, and Phillips of Chicago, grew to prominence in the 1930s and 1940s.

It is probably no coincidence that the Detroit Rex Company developed where it did. The Ford Motor Company alone owned some forty-three thousand machine tools by the late 1920s. General Motors also invested heavily in new machinery at this time as it began production of the very successful new Chevrolet in 1929.¹⁵ In that same year, the United States produced over 4.5 million motor vehicles.¹⁶ Thus, the growth and increased sophistication of automotive manufacturing technology during the inter-war years stimulated the development of vapor-degreasing technology.¹⁷

to cleanup of solvent-contaminated sites. National Research Council, *Innovations in Ground Water and Soil Cleanup: From Concept to Commercialization* (Washington, D.C., 1997).

13. Electrochemicals Department, E. I. Du Pont de Nemours and Co., *Chlorinated Hydrocarbons: Properties, Specifications and Uses* (Wilmington, Del., 1944). A. L. Horvath, *Halogenated Hydrocarbons: Solubility-Miscibility with Water* (New York, 1982). W. W. Davidson, “Solvent Degreasing,” *Transactions of the Electrochemical Society* 72 (1938): 413–27. Ralph A. Van Fossen, *Vapor Degreasing: Questions and Answers—A Handbook for Engineers, Production Men and Students* (Chicago, 1944). D. W. F. Hardie, “Trichloroethylene,” *Kirk-Othmer Encyclopedia of Chemical Technology*, 2d ed. (New York, 1964), 5:183–95.

14. Davidson, “Solvent Degreasing.” Davidson was vice president of the Detroit Rex Company.

15. David A. Hounshell, *From the American System to Mass Production, 1800–1932: The Development of Manufacturing Technology in the United States* (Baltimore, 1984), chap. 7.

16. Walt W. Rostow, *The World Economy: History and Prospect* (Austin, Tex., 1978).

17. The first U.S. patent for a “degreasing apparatus” may have been that granted to

By 1943 there were twenty-five thousand to thirty thousand vapor degreasers in operation in the United States. World War II and the associated federal specifications for aircraft components and other military equipment stimulated further demand for vapor degreasing of metal surfaces. Following World War II, a Detroit Rex official estimated that about twenty thousand vapor degreasers were in operation in the country in the 1950s, and Dow Chemical technologists estimated the number to be over twenty-five thousand by the 1970s.¹⁸

Solvent Vapors as Atmospheric and Workplace Contaminants

The initial environmental concern with solvents was related to their role in urban smog formation, not groundwater pollution. On 28 July 1966, representatives of the Los Angeles County Air Pollution Control District (APCD) appeared before the county's Air Pollution Control Board to present their case that a stringent new regulation, Rule 66, was required to control atmospheric emissions of organic solvents in the county. Louis J. Fuller, the air pollution control officer for the county, pointed out that organic solvents were instrumental in causing "the photochemical air pollution which plagues this area." He asserted that some of the solvents that were to be controlled were "more reactive than gasoline in producing the manifestations of air pollution, i.e., reduced visibility, eye irritation, and damage to vegetation."¹⁹ Scientists and engineers speaking on behalf of the APCD also spoke in favor of the regulation, as did representatives of manufacturing industry and of the Chamber of Commerce. The intent of Rule 66 was to decrease the 590 tons per day of solvent emissions in the county by 200 to 300 tons per day. Most of these emissions originated at facilities involved with paint and lacquer spraying and baking, although 88 tons of chlorinated hydrocarbons were emitted each day from degreasing operations and these emissions were a special target of the APCD.²⁰

By Rule 66, the APCD identified TCE as a smog-causing agent and placed

Maurice Hirst in March 1931 (U.S. patent 1,795,170). At least twelve other U.S. patents were awarded during the 1930s for "degreasing."

18. C. E. Kircher, "Solvent Degreasing—What Every User Should Know," *ASTM Bulletin*, January 1957, 44–49. L. Skory, J. Fulkerson, and D. Ritzema, "Vapor Degreasing Solvents: When Safe?" *Products Finishing*, February 1974, 64–71.

19. Louis J. Fuller, testimony regarding Rule 66, presented before the Air Pollution Control Board, Los Angeles, 28 July 1966, records of the Air Pollution Control District of the County of Los Angeles, South Coast Air Quality Management District, Diamond Bar, California.

20. R. G. Lunche, testimony regarding Rule 66, presented before the Air Pollution Control Board, Los Angeles, 28 July 1966. Lunche was director of engineering for the APCD. Air Pollution Control District, County of Los Angeles, *Effectiveness of Organic Solvents in Photochemical Smog Formation: Solvent Project, Final Report* (Los Angeles, 1966).

such onerous restrictions on its use that when the rule came into effect in 1967 other chlorinated solvents replaced TCE almost overnight in Los Angeles County.²¹ The *Chemical and Engineering News* reported that the consumption of TCE in Los Angeles County “plummeted from a 40,000 ton-per-year level” as the aerospace and electronics industries sought replacements for TCE.²² Dow Chemical was quick to send personnel to Los Angeles County to recommend the use of Dow’s Chlorothene, a solvent comprised mainly of 1,1,1-trichloroethane, which is known as TCA, as a substitute for TCE.²³

Rule 66 proved effective in reducing TCE vapor emissions in the Los Angeles Basin. A team from the California Institute of Technology measured atmospheric chlorinated compounds throughout the Los Angeles Basin in the autumn of 1972 and could only identify traces of TCE in the lower atmosphere.²⁴ Rule 66 served as a template for the 1970 amendments to the Federal Clean Air Act, while cities such as Philadelphia also adopted similar statutes that caused further changes in solvent use by industry throughout the nation.²⁵

Workplace exposure regulations established by the Occupational Safety and Health Act of 1970 further reduced TCE use. Considerable evidence had accumulated during the 1950s and 1960s of the toxicity of TCE to the central nervous system of vapor degreaser operators and other industrial workers.²⁶ Photometric and other means of vapor analysis had been developed in the 1940s to measure such exposure.²⁷ Dow Chemical, a major producer of chlorinated solvents, in particular TCA, studied worker exposure at nearly three hundred vapor degreasers. Dow’s study determined that if

21. “Proposed Rule 66, Information concerning proposed rules 66, 66.1, and 66.2, Control of organic solvents,” Louis J. Fuller to the Honorable Board of Supervisors of the County of Los Angeles, 28 June 1966, “Additions and Revisions to the Rules and Regulations of the Air Pollution Control District,” records of the Air Pollution Control District of the County of Los Angeles.

22. Richard J. Seltzer, “Reactions Grow to Trichloroethylene Alert,” *Chemical and Engineering News*, 19 May 1975, 41–43.

23. Skory, Fulkerson, and Ritzema (n. 18 above).

24. P. G. Simmonds, S. L. Kerrin, J. E. Lovelock, and F. H. Shair, “Distribution of Atmospheric Halocarbons in the Air over the Los Angeles Basin,” *Atmospheric Environment* 8 (1974): 209–16. This team used Lovelock’s newly developed electron-capture detector in a gas chromatograph to measure PCE, TCA, and trichlorofluoromethane in quantifiable amounts, as opposed to TCE.

25. J. A. Mertens, “Trichloroethylene,” in *Kirk-Othmer Encyclopedia of Chemical Technology*, 4th ed. (New York, 1993) 6:45–46. Wesley L. Archer, “Selection of a Proper Vapor Degreasing Solvent,” in *Cleaning Stainless Steel* (Philadelphia, 1973), 54–64. G. M. Rekstad, “Upheaval in Vapor Degreasing,” *Factory*, January 1974, 27–32.

26. E. M. Waters, H. B. Gerstner, and J. E. Huff, “Trichloroethylene 1: An Overview,” *Journal of Toxicology and Environmental Health* 2 (1977): 671–707.

27. E. W. McGovern, “Chlorohydrocarbon Solvents,” *Industrial and Engineering Chemistry* 35 (1943): 1230–39. Morris B. Jacobs, *The Analytical Chemistry of Industrial Poisons, Hazards and Solvents* (New York, 1941).

the anesthetic effects of solvents were any indication of damage to human health, the greatest measure of safety was provided by TCA.²⁸ Consequently, there was a rapid decrease in TCE production and sales during the 1970s as TCA and other chlorinated solvents replaced TCE because of concerns for both worker safety and atmospheric pollution. From 1970 to 1976, U.S. demand for TCE declined 8.9 percent per year, while demand for TCA increased 6.8 percent per year.²⁹

However, TCA itself, along with a number of other chlorinated substances, would soon be identified as a cause of the depletion of stratospheric ozone.³⁰ The identification of this threat to the stratosphere in 1974 was based upon the hypothesis that CFCs may drift into the stratosphere, become dissociated into chlorine atoms and other fragments, and then react with and break down the stratospheric ozone that shields the biosphere from ultraviolet radiation.³¹ In 1985 British scientists as well as data from the National Aeronautics and Space Administration confirmed the validity of the hypothesis by identifying the Antarctic “ozone hole.”³² In September 1987, the details of an international agreement were defined—the Montreal Protocol on Substances that Deplete the Ozone Layer—which controlled the production, consumption, and phaseout of CFCs, TCA, and other chlorinated compounds, but not TCE. Later agreements accelerated the phaseout of CFCs and TCA to 1 January 1996.

Thus, in a remarkable period of just twenty-two years, a group of chlorinated compounds—CFCs—were identified as environmental contaminants and then regulated out of use in the United States and the developed world. New analytical methods had been introduced to measure their concentrations and international data collection had demonstrated the reality of the threat they posed. The speed with which the issue developed and was addressed internationally stands in marked contrast with that of ground-water contamination by chlorinated degreasing solvents.

Chlorinated Hydrocarbons as Groundwater Contaminants

In the United States, chlorinated hydrocarbons in general were identified as groundwater contaminants twenty years before Rule 66 addressed their role as atmospheric contaminants. However, effective regulatory and remedial action was delayed by the lack of methods and instruments to

28. Skory, Fulkerson, and Ritzema (n. 18 above).

29. Wesley L. Archer, “Chlorocarbons and Chlorohydrocarbons,” in *Kirk-Othmer Encyclopedia of Chemical Technology*, 3rd ed. (New York, 1979), 5:669.

30. The banned chemicals, such as CFCs, TCA, and carbon tetrachloride, were ethanes and methanes but not ethenes like TCE and PCE.

31. F. S. Rowland and M. J. Molina, “Chlorofluoromethanes in the Environment,” *Reviews of Geophysics and Space Physics* 13 (1975): 1–35.

32. Parson (n. 11 above), 84.

analyze dissolved chlorinated hydrocarbons, such as biocides and solvents, in groundwater until the 1960s and by the absence of scientific knowledge of their migration as immiscible liquids and fate in the subsurface until the 1980s.

The first recorded case of groundwater contamination by chlorinated hydrocarbons in the United States appears to have been the release of 2,4-dichlorophenol (an intermediate in the production of the herbicide 2,4-D) from a chemical plant in Alhambra, California, to a sewer in the summer of 1945. The chemical passed through a sewage-treatment plant and was discharged into the San Gabriel River. It then traveled three miles down river and seeped into the aquifer supplying the Montebello well field, shutting down eleven municipal wells serving twenty-five thousand people and requiring special treatment for four to five years. The taste and odor that the chemical imparted to the Montebello groundwater indicated its presence, and there is no indication that chemical analysis was attempted to determine its concentration in the aquifer.³³

In 1949, two British chemists reported two instances of TCE contamination of groundwater in the Thames Valley, apparently identified as anomalous by the odor coming from contaminated wells. They noted that “from these two cases it is evident that contamination by compounds of this nature is likely to be very persistent and there is some evidence of toxicity at very low concentrations.”³⁴ This appears to be the earliest recorded account of groundwater contamination by a chlorinated degreasing solvent. The first brief mention of TCE in U.S. groundwaters did not appear until 1961, when a paper delivered at a symposium on ground water contamination in Cincinnati, Ohio, identified TCE as an organic contaminant of groundwater.³⁵

Another case was associated with the migration of the herbicide 2,4-D

33. H. A. Swenson, “The Montebello Incident,” pt. 2, *Society for Water Treatment and Examination* 11 (1962): 84–88.

34. F. A. Lyne and T. McLachlan, “Contamination of Water by Trichloroethylene,” *Analyst* 74 (1949): 513. They used the 1914 Fujiwara colorimetric method, which has a detection limit of approximately 1 part per million (i.e., 1 milligram of TCE per liter of groundwater). This method was incapable of distinguishing one chlorinated solvent from another; F. D. Schaumburg, “Banning Trichloroethylene: Responsible Reaction or Overkill?” *Environmental Science and Technology* 24 (1990): 17–22. Lyne and McLachlan had been informed that TCE had been spilled at the two sites they tested, and the odor of the chemical was apparent. Such methods predated gas chromatographic ones. This article appears to have been unknown in the United States until well into the 1990s; it was not cited, for example, by James F. Pankow, Stan Feenstra, John A. Cherry, and M. Cathryn Ryan, “Dense Chlorinated Solvents in Groundwater: Background and History of the Problem,” chap. 1 of *Dense Chlorinated Solvents and Other DNAPLs in Groundwater*, ed. James F. Pankow and John A. Cherry (Portland, Ore., 1996).

35. M. Middleton and G. Walton, “Organic Chemical Contamination of Ground Water,” in U.S. Public Health Service, *Ground Water Contamination: Proceedings of the 1961 Symposium, Cincinnati, Ohio* (Cincinnati, 1961), 50–56.

“or a closely related compound” in the 1950s from waste-disposal basins at the Rocky Mountain Arsenal on the outskirts of Denver, Colorado.³⁶ The aqueous wastes were the result of the production of chemical warfare agents and herbicides at the arsenal from 1943 to 1957. The wastes were transported 11 kilometers (7 miles) by groundwater in a northwesterly direction beyond the arsenal’s boundary and damaged irrigated crops in the area between the site boundary and the South Platte River. The indicator of groundwater contamination in this case was crop damage. It was the one case of groundwater contamination to be mentioned by Rachel Carson in *Silent Spring*.³⁷

Lacking a means of directly measuring 2,4-D in the groundwater samples collected from wells on and off the Rocky Mountain Arsenal site, a University of Colorado team, funded by the U.S. Army Chemical Corps to study the problem, chose a biological assay to measure the toxicity of the samples. Thus, “water samples from selected wells throughout the area were used to irrigate test plants grown in University greenhouses.”³⁸ Direct chemical analyses in the 1970s indicated the presence of several chlorinated pesticides as well as a nerve-gas by-product in the groundwaters down-gradient of the waste-disposal basins.³⁹ By 1974, organic contamination was detected 1.6 kilometers (1 mile) from two municipal wells in the town of Brighton.⁴⁰

The seriousness of contamination of U.S. groundwaters by chlorinated hydrocarbons was not nationally recognized until 1981, when the Council on Environmental Quality reported on the presence of dissolved solvents in U.S. groundwaters and considered the public health risks from drinking contaminated groundwater.⁴¹ The events from the 1950s to the 1981 CEQ report constitute the first stage in the recognition of the problem, in that by 1981 it was clear that dissolved chlorinated hydrocarbons such as TCE were major contaminants of U.S. groundwaters.⁴²

36. T. R. Walker, “Ground-Water Contamination in the Rocky Mountain Arsenal Area, Denver, Colorado,” *Geological Society of America Bulletin* 72 (1961): 489–94. (2,4-D is 2,4-dichlorophenoxyacetic acid.)

37. Carson (n. 9 above), 42–44.

38. Walker, 491.

39. L. Konikow and D. W. Thompson, “Groundwater Contamination and Aquifer Reclamation at the Rocky Mountain Arsenal, Colorado,” in National Research Council, Panel on Groundwater Contamination, *Groundwater Contamination* (Washington, D.C., 1984), chap. 6.

40. S. G. Robson, “Computer Simulation of Movement of DIMP-Contaminated Groundwater near the Rocky Mountain Arsenal, Colorado,” in *Permeability and Groundwater Contaminant Transport*, ed. T. F. Zimmie and C. O. Riggs (Philadelphia, 1981), 209–20.

41. Council on Environmental Quality, *Contamination of Ground Water by Toxic Organic Chemicals* (n. 7 above).

42. Pankow et al., “Dense Chlorinated Solvents in Groundwater: Background and History of the Problem” (n. 34 above).

Groundwater contamination in the Thames Valley, at Montebello, and northwest of the Rocky Mountain Arsenal became evident in the 1940s and 1950s because of odor, taste, and crop damage, respectively. These isolated incidents fit no pattern that warned groundwater hydrologists of a larger problem. The recognition that the problem was widespread in the United States and in Europe would not occur until improved methods of analytical chemistry provided direct evidence of contamination.⁴³ However, because the threat to groundwaters by chlorinated solvents was unanticipated, there was little or no motivation to develop analytical instrumentation and protocols or monitor-well networks; neither was there much possibility of federal or state funding for such an effort.⁴⁴ The impetus to develop such methods came from an increasing awareness of the public health issues associated with the presence of other chlorinated hydrocarbons in drinking water and the political effect that such issues caused. Groundwater contamination from chlorinated degreasing solvents was then detected quite accidentally as a result of this new environmental concern over the potential presence of other chlorinated hydrocarbons in drinking water.

The Safe Drinking Water Act

By 1970 it had become clear to the nascent environmental community that chlorinated-pesticide residues were ubiquitous in U.S. surface waters.⁴⁵ Concern grew with the discovery of the contamination of the New Orleans water supply, drawn from the Mississippi River, and eventually led to the passage of the Safe Drinking Water Act of 1974.⁴⁶ In 1975, as the act was being implemented throughout the nation, the National Cancer Institute issued a “memorandum of alert” concerning the potential carcinogenicity of TCE.⁴⁷ This announcement had no immediate effect on the groundwater community because there was no reliable information on TCE contamination of groundwater. Furthermore, its uses as an anesthetic in England and the U.S., in extracting caffeine from coffee beans, and in food production through the 1970s diverted suspicion from TCE as a drinking-water contaminant.⁴⁸

43. Schaumburg (n. 34 above). R. D. Mutch and W. W. Eckenfelder Jr., “Out of the Dusty Archives,” *Hazmat World*, October 1993, 59–68. Pankow et al., “Dense Chlorinated Solvents in Groundwater: Background and History of the Problem.”

44. Jackson, “Anticipating Ground-Water Contamination” (n. 5 above).

45. American Chemical Society, Committee on Environmental Improvement, *Cleaning Our Environment: A Chemical Perspective*, 2nd ed. (Washington D.C., 1978), 336.

46. J. M. Symons et al., “National Organics Reconnaissance for Halogenated Organics,” *Journal of the American Water Works Association* 67 (November 1975): 634–47.

47. Seltzer (n. 22 above). U.S. Public Health Service, *Carcinogenesis Bioassay of Trichloroethylene* (Washington, D.C., 1976).

48. J. Searles and H. A. McPhail, “Trichloroethylene,” in *Kirk-Othmer Encyclopedia of*

The Safe Drinking Water Act identified national interim primary drinking water standards for six chlorinated-hydrocarbon pesticides and ten inorganic contaminants, which were to go into effect in June 1977. The installation of very sophisticated analytical instruments at EPA laboratories and other facilities across the United States made it possible to detect trace concentrations of dissolved chlorinated hydrocarbons. These gas chromatography–mass spectrometer systems (GC/MS) were coupled to minicomputers that could accurately identify trace organic compounds in water.⁴⁹

In February 1978, the EPA extended the drinking water standards to include a group of volatile organic chemicals known as trihalomethanes, or THMs. It was known that THMs were created in drinking water by the reaction of natural dissolved organic matter present in river and lake waters with chlorine used as a water purification chemical by municipalities. The 1978 amendment required that the concentration of total THMs be limited to 100 parts per billion.⁵⁰ Therefore, the standards were extended to include a suite of volatile organic chemicals as well as the semivolatile chlorinated pesticides, all of which were suspected of being carcinogenic. Moreover, the purge-and-trap method developed by the EPA in 1974 provided a means to concentrate volatile chlorinated hydrocarbons (for example, TCE) in water samples and to introduce them into a GC/MS system.⁵¹ This allowed a thousandfold improvement in the detection of each volatile chlorinated hydrocarbon.

Thus, the Safe Drinking Water Act, by mandating both the testing of potable waters and the protection of groundwater supplies used as drinking water sources, had set the regulatory stage for the testing of groundwater supplies throughout the United States. Therefore, while a municipality might collect a sample for chemical analysis of THMs in fulfillment of the requirements of the act, testing might reveal the presence of other volatile chlorinated hydrocarbons as well, such as TCE.

Solvents as Groundwater Contaminants

As soon as American municipalities moved to implement the act in the late 1970s and test for contaminants in aquifers, the scale of contamination by dissolved chlorinated hydrocarbons became apparent. Extensive testing in New York and Massachusetts revealed widespread contamina-

Chemical Technology, 1st ed. (New York, 1947), 3:788–94; T. C. Gregory, *Uses and Applications of Chemicals and Related Materials* (New York, 1939), 611–13; Schaumburg.

49. S. R. Heller, J. M. McGuire, and W. L. Budde, "Trace Organics by GC/MS," *Environmental Science and Technology* 9 (1975): 210–13.

50. American Chemical Society, *Cleaning Our Environment*, 200–201.

51. J. P. Mieure, "Determining Volatile Organics in Water," *Environmental Science and Technology* 14 (1980): 930–35.

tion on Long Island and in the manufacturing towns surrounding Boston. In 1978 the New York State Department of Health analyzed some five hundred wells in Suffolk and Nassau Counties and closed thirty-six municipal wells, affecting two million people.⁵² Trichlorethylene had been widely used on Long Island in septic tank cleaning as well as metal degreasing. Many towns in Massachusetts, including Bedford, North Reading, and Woburn, found their sole source of water supply contaminated by chlorinated hydrocarbons released by manufacturing plants.⁵³ In Woburn, the infamous wells G and H were closed in May 1979 after being “shut down for a number of years due to taste and odor problems.” The state closed these wells when chemical analysis revealed the presence of TCE and chloroform.⁵⁴ North of Boston, the municipal well for the town of Rowley was closed when analysis for pesticides, as required by the Safe Drinking Water Act, indicated the presence of TCE.⁵⁵ Table 1 lists some of the well closures of that period.

As the Council on Environmental Quality reported in January 1981, groundwater contamination by chlorinated hydrocarbons associated with the use of solvents was widespread in the United States. The number of documented cases grew rapidly throughout the 1980s as new federal legislation led to a massive assessment of the subsurface at industrial and waste-disposal sites throughout the country.

High-technology industries were often the source of the solvent-induced contamination. An IBM plant in South Brunswick Township, New Jersey, was identified as the source of TCA and perchloroethylene (PCE) that caused the shut down of the municipal well field of Dayton.⁵⁶ Similarly, in Los Angeles County, California, numerous well fields were identified during 1979–81 as contaminated by solvents released in the San Gabriel and the San Fernando Valleys. Releases by the aerospace and electronics industries caused well closures in these valleys affecting more than one million people.⁵⁷ In all cases, chlorinated hydrocarbons dissolved from solvents

52. Council on Environmental Quality, *Contamination of Ground Water by Toxic Organic Chemicals* (n. 7 above).

53. “Chemical Contamination,” working paper for the Water Quality Task Force of the Special Legislative Commission on Water Supply, prepared by the Department of Environmental Quality Engineering and U.S. EPA Region 1, Boston, 1979.

54. *Ibid.*, 29.

55. *Ibid.*, 27.

56. The South Brunswick Township well field has proven to be one of the more carefully studied cases of groundwater contamination by chlorinated hydrocarbons. See P. H. Roux and W. F. Althoff, “Investigation of Organic Contamination of Ground Water in South Brunswick Township, New Jersey,” *Ground Water* 18 (1980): 464–71. Stan Feenstra and John A. Cherry, “Diagnosis and Assessment of DNAPL Sites,” in Pankow and Cherry (n. 34 above), 462–69.

57. EPA Region 9 (San Francisco), *San Gabriel Valley Superfund Sites*, Fact Sheet Issue 3, September 1987, and *Groundwater Cleanup Studies Continue in the San Fernando*

TABLE 1

SELECTED MUNICIPAL WELL CLOSURES DUE TO CONTAMINATION BY DISSOLVED CHLORINATED HYDROCARBONS, 1977–79.

	<i>Year of Discovery</i>	<i>Municipal Wellfield</i>	<i>Population Supplied</i>	<i>Yield (mgd)</i>	<i>Principal Contaminants</i>
JANUARY	1977	South Brunswick Township, N.J.	4,400	1.6	TCA, PCE
2004	1977	Bedford, Mass.	~10,000	1.36	Dioxane, TCE
VOL. 45	1978	Rowley, Mass.	4,400	0.4	TCE
	1978	Stickney wells 3 & 4, North Reading, Mass.	~4,000	0.2	TCE
	1979	Valley County Water District, Azusa, San Gabriel Valley, Calif.	~100,000	—	TCE
	1979	Dedham wells 3 & 4, Westwood, Mass.	43,500	2.5	TCA
	1979	Wells G & H, Woburn, Mass.	9,000	1.7	TCE, PCE
	1979	San Fernando Valley, Calif.	>100,000	—	TCE, PCE

Note—Yield is given in millions of gallons per day (mgd) and may represent both drinking water and industrial supply. The chemicals are trichloroethylene (TCE), 1,1,1-trichloroethane (TCA), and perchloroethylene (PCE).

Sources—Environmental Protection Agency, *Evaluation of Ground-Water Extraction Remedies*, vol. 2, Case Studies 1–19, Interim Final, EPA/540/2-89/054b (Washington, D.C., 1989). Massachusetts Department of Environmental Quality Engineering and U.S. EPA Region 1 (Boston), “Chemical Contamination,” working paper for the Water Quality Task Force of the Special Legislative Commission on Water Supply, 1979. EPA Region 9 (San Francisco), *San Gabriel Valley Superfund Sites*, Fact Sheet Issue 3, September 1987, and *Groundwater Cleanup Studies Continue in the San Fernando Valley Basin*, Fact Sheet Number 5, July 1990.

that had been spilled or disposed and had penetrated the subsurface—dense, nonaqueous phase liquids, or DNAPLs—were responsible for the well closures.

During the same period, environmental scientists in Switzerland and West Germany began to document contamination of groundwater supplies by TCE and PCE.⁵⁸ At the prestigious Swiss Federal Institute for Water Resources and Water Pollution Control outside Zurich, chemists identified PCE in the groundwater supply of the laboratory. This contamination, of which they had been unaware but which prevented them from obtaining a

Valley Basin, Fact Sheet Number 5, July 1990. These are examples of public information documents, distributed to libraries in the neighborhood of hazardous waste sites, that recount administrative and technical progress toward cleanup of the sites. Also see Jackson, “Anticipating Ground-Water Contamination” (n. 5 above) and “Migration, Dissolution, and Fate” (n. 6 above).

58. European Chemical Industry Federation, “The Occurrence of Chlorinated Solvents in the Environment,” *Chemistry and Industry* (1986): 861–69.

zero background in their chemical analysis of chlorinated hydrocarbons in Swiss waters, originated at a dry cleaning establishment.⁵⁹

The association of the dissolved-phase contamination with the presence in the subsurface of trapped and slowly dissolving solvents was identified as the second stage of the solvent problem, that is, the identification of the problem's cause, which was revealed during the 1980s.⁶⁰ Figure 1 shows a conceptual model of the processes involved. Spilled solvents penetrate the subsurface due to their density and are retained by forces exerted by the soil grains and groundwater and by impermeable layers. These DNAPLs slowly dissolve to produce plumes of contaminated groundwater that may be pumped from water-supply wells.

A Paradigm for Solvents in the Subsurface

It was not until 1984 that the federal government prohibited the land disposal of hazardous wastes, such as spent solvent, on site property or in landfills.⁶¹ This loophole in previous legislation had allowed industry to continue land disposal in a manner that had been recommended for many years by industrial trade groups and even the American Insurance Association, which represented those firms that insured corporations and their property. Typical of recommendations on the disposal of waste chlorinated degreasing solvents was that of the American Society for Metals in 1964, the professional society for industrial metallurgy: "In the absence of clearly defined ordinances, the sludge is usually poured on dry ground well away from buildings, and the solvents are allowed to evaporate."⁶² The annual

59. Walter Giger and Eva Molnar-Kubica, "Tetrachloroethylene in Contaminated Ground and Drinking Waters," *Bulletin of Environmental Contamination and Toxicology* (1978): 475–80.

60. Pankow et al., "Dense Chlorinated Solvents in Groundwater: Background and History of the Problem" (n. 34 above).

61. The Resource Conservation and Recovery Act (RCRA) of 1976 and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 were the regulatory means by which the EPA investigated subsurface conditions at operating (RCRA) and abandoned (CERCLA) hazardous-waste sites. CERCLA, or "Superfund," in particular, was a response to the evidence of the health hazards of numerous waste-disposal sites, such as Love Canal, that were revealed in the late 1970s. RCRA was intended to ensure "cradle-to-grave" control of such hazardous substances as chlorinated solvents. The Federal Hazardous Waste and Solid Waste Amendments to RCRA of 1984 closed the loophole in the disposal of solvents.

62. Schaumburg (n. 34 above) and Pankow et al., "Dense Chlorinated Solvents in Groundwater: Background and History of the Problem," have both observed that no ordinances against solvent dumping existed. Rule 66, enacted in 1967, appears to have been the first such ordinance. Rule 66.2 on the Disposal and Evaporation of Solvents, prepared by the APCD of the County of Los Angeles in June 1966, provided advice to users on the disposal of solvents on the ground. It indicated (p. 10) "only 1½ gallons of organic solvents may be discarded in any one day in a manner which will allow the sol-

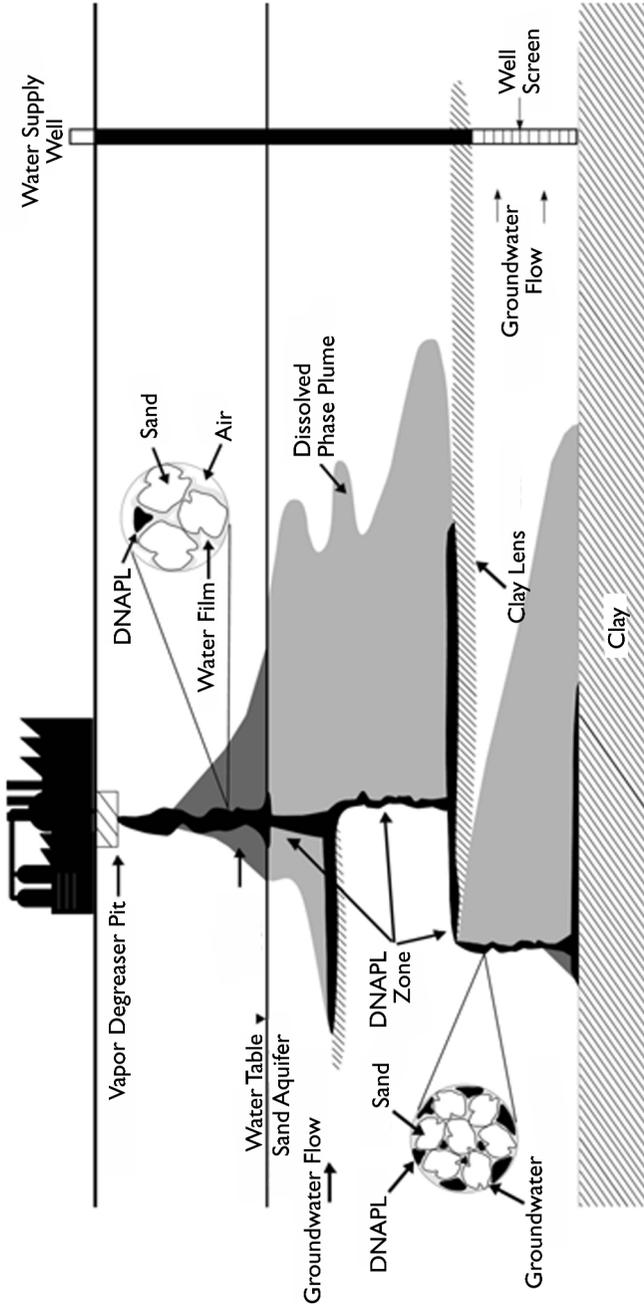


FIG. 1 Migration of DNAPL in a sand aquifer and the development of DNAPL and dissolved contamination zones.

U.S. sales of TCE, PCE, and TCA reached a total of 800,000 metric tons in 1973.⁶³ The EPA estimated that in 1974 approximately 300,000 tons of waste solvent was generated.⁶⁴ While much of this total was sent to landfills, incinerators, or solvent-recycling operations, significant volumes of waste solvent were no doubt disposed of on the grounds of industrial plants in the manner recommended by the American Society of Metals.⁶⁵ Thus, the “land ban” of 1984 was a first step in remedying the problem, but it was too late to prevent the widespread and continuing contamination of ground-water by solvents that had previously been spilled.

Consequently, during the 1980s EPA-instigated investigations detected numerous plumes of dissolved-phase contamination migrating away from industrial facilities and landfills. In a few cases the “remedial investigation” revealed the presence of pools of solvents in the subsurface. In the case of Love Canal and the hazardous waste sites associated with the Hooker Chemical Company in Niagara Falls, New York, these pools had become trapped by impermeable layers of clay or shale in the shallow subsurface (see fig. 1). Where the volume of solvent was small compared with the volume of the porous subsurface into which it could drain, the solvent would be retained

vent to evaporate into the air.” “Heat Treating, Cleaning and Finishing,” in *Metals Handbook* 8th ed. (Metals Park, Ohio, 1964), vol. 2. The American Insurance Association, in its *Chemical Hazards Bulletin* of March 1972, echoed this advice, and further recommended that after disposal on sand, ashes, or the like the waste be “cautiously ignited.” Given the nonflammability of chlorinated degreasing solvents, this is a particularly ironic piece of advice from an insurance organization whose members have paid out billions of dollars in claims in recent years to industrial clients seeking compensation for multimillion dollar remediation costs associated with groundwater contamination by chlorinated solvents and other toxic organic chemicals; see Mutch and Eckenfelder (n. 43 above).

63. J. J. McKetta, ed., *Encyclopedia of Chemical Processing and Design*, vol. 8 (New York, 1979), 7.

64. J. W. Mercer and R. M. Cohen, “A Review of Immiscible Fluids in the Subsurface: Properties, Models, Characterization and Remediation,” *Journal of Contaminant Hydrology* 6 (1990): 107–63.

65. Craig E. Colten has argued that industrial waste managers were aware before 1960 that the disposal of organic chemical wastes on the land surface would cause groundwater contamination over large distances; “Groundwater Contamination: Reconstructing Historical Knowledge for the Courts,” *Applied Geography* 18 (1998): 259–73. The quoted advice of the American Society of Metals and, in particular, of the American Insurance Association contradicts Colten’s argument. The insurance industry has paid billions of dollars to policyholders who followed the AIA’s advice and were later identified as “potentially responsible parties” under CERCLA (Superfund) litigation. I have argued elsewhere that Colten’s argument is incorrect; see Richard E. Jackson and Michael Bonchonski, review of *The Road to Love Canal: Managing Industrial Waste before EPA*, by Craig E. Colten and Peter N. Skinner, *Ground Water* 36 (1998): 393. My rebuttal is based upon the primitive state of analytical chemistry before 1960 and upon the absence of any stated perception at the time that immiscible wastes such as chlorinated solvents might be sufficiently soluble to be groundwater contaminants; see Jackson, “Anticipating Ground-Water Contamination” (n. 5 above).

as globules trapped between soil grains, like water in a wet sponge. But once in contact with groundwater, the solvent- or DNAPL-contaminated soil would act as a persistent source of contamination as it dissolved.

Friedrich Schwillie and his colleagues at the Federal Institute of Hydrology in Koblenz, West Germany, developed the conceptual model of the migration and fate of DNAPL shown in figure 1.⁶⁶ Their 1984 report on laboratory experiments concerning the migration and fate of dense chlorinated solvents established the principal features of the paradigm, including rules and experiments that hydrologists and others would subsequently follow. They showed the patterns of migration and trapping of solvents in sands of varied particle size and the retention of this DNAPL by these same sands above and below the water table. Furthermore, they demonstrated the solubilization of the DNAPL to form dissolved-phase plumes and the importance of the volume of solvent spilled and the geometrical arrangement of zones of differing permeability in determining the spatial distribution of DNAPL in the subsurface. The general acceptance of the paradigm by academic groundwater hydrologists was indicated by the 1988 publication of the English translation of Schwillie's 1984 report and the presentation of the conceptual model in the 1990 edition of a new text on groundwater hydrology.⁶⁷

66. Friedrich Schwillie et al., *Leichtfluchtige Chlorokohlenwasserstoffe in porösen und klüftigen medien: Modellversuche* (Koblenz, 1984), translated into English by James F. Pankow as *Dense Chlorinated Solvents in Porous and Fractured Media: Model Experiments* (Chelsea, Mich., 1988). Schwillie wrote: "On the other hand, investigations of spill situations seldom indicated the presence of the pure phase [i.e., DNAPL]. Rather, only the dissolved form was mainly found" (p. 1). Schwillie presented his results in North America in June 1985 at the Second Canadian-American Hydrogeology Conference, Banff, Alberta. Elements of this paradigm appeared in English in Friedrich Schwillie, "Groundwater Pollution in Porous Media by Fluids Immiscible with Water," *The Science of the Total Environment* 21 (1981): 173–85. A much more detailed synopsis was published by Schwillie as "Migration of Organic Fluids Immiscible with Water in the Unsaturated Zone," in *Pollutants in Porous Media: The Unsaturated Zone between Soil Surface and Groundwater*, ed. B. Yaron, G. Dagan, and J. Goldshmid (Berlin, 1984), 27–48. Neither article has been cited frequently by hydrologists, although Pankow's 1988 translation has been widely read.

67. Patrick A. Domenico and Franklin W. Schwartz, *Physical and Chemical Hydrogeology* (New York, 1990). Increasingly explicit descriptions of the Schwillie paradigm appeared in two reviews published in *Environmental Science and Technology*. The first acknowledged Schwillie's finding that chlorinated degreasing solvents are retained in significant quantities in the subsurface and act as long-term subsurface sources of contamination; Douglas M. Mackay, Paul V. Roberts, and John A. Cherry, "Transport of Organic Contaminants in Groundwater," *Environmental Science and Technology* 19 (1985): 384–92. The second described the Schwillie paradigm in much greater detail and how it negatively affected attempts to restore contaminated groundwater to pristine conditions by "pump-and-treat" methods, i.e., pumping contaminated groundwater to the surface for removal of the dissolved-phase contamination; Douglas M. Mackay and John A. Cherry, "Groundwater Contamination: Pump-and-Treat Remediation," *Environmental Science and Technology* 23 (1989): 630–36.

Recognizing the Effect of Solvents

The Council on Environmental Quality began its 1981 report by noting that 50 percent of all Americans relied on wells for their water supply.⁶⁸ However, there was little significant research into the organic contamination of groundwaters before 1981.⁶⁹ Research hydrologists in the 1950s and 1960s had been absorbed by the development of the theory and the implications in the area of first well-field hydraulics and then regional groundwater flow.⁷⁰ In the 1970s their focus shifted to the problems of gasoline spills, sanitary landfills, nitrate residues from fertilizers, and radioactive waste migration.⁷¹ The U.S. Atomic Energy Commission and Atomic Energy of Canada had enrolled them in very expensive studies of radioactive-waste storage and migration. No such funding by chemical manufacturers was forthcoming for studies on the fate of chlorinated degreasing solvents, despite the environmental policies of companies such as DuPont and the recommendations of industrial groups such as the Manufacturing Chemists Association, the American Society of Metals, and the American Insurance Association.⁷²

Thus, where groundwater pollution by chlorinated hydrocarbons had been detected before the 1970s, whether by odor, taste, or crop damage, neither federal nor state agencies nor chemical manufacturers pursued the problem. Nor did research hydrologists consider the problem until the 1980s, by which time events dictated that it could no longer be ignored.⁷³

68. Council on Environmental Quality, *Contamination of Ground Water by Toxic Organic Chemicals* (n. 7 above).

69. The earliest paper in the journal of the National Ground Water Association (*Ground Water*) on chlorinated hydrocarbon contamination of water supply wells was that by Roux and Althoff (n. 56 above).

70. Patrick A. Domenico, *Concepts and Models in Groundwater Hydrology* (New York, 1972).

71. R. Allan Freeze and John A. Cherry, *Groundwater* (Englewood Cliffs, N.J., 1979), chap. 9.

72. McFarland (n. 10 above), 1204.

73. The primitive understanding that North American hydrologists had of the migration, dissolution, and fate of chlorinated degreasing solvents and other DNAPLs in the subsurface is evident in the published proceedings of two major conferences held in late 1981. David W. Miller, a leading consulting hydrologist, made reference to “the density of contaminated fluids” in “Chemical Contamination of Ground Water,” in *Ground Water Quality*, ed. C. H. Ward, W. Giger, and P. L. McCarty (New York, 1985), 39–52, which is the proceedings of the First International Conference on Ground Water Quality Research, held at Rice University, Houston, Texas, in October 1981. Various chlorinated hydrocarbons were discussed in three papers at a meeting of the American Geophysical Union in San Francisco in December 1981. In one of these, groundwater hydrologists from the University of Waterloo discussed the behavior of dissolved organic contaminants in groundwater; John A. Cherry, Robert W. Gillham, and James F. Barker, “Contaminants in Groundwater: Chemical Processes,” in National Research Council, Panel on Groundwater Contamination (n. 39 above), 46–64. However, only Miller’s paper, pre-

Therefore, the migration, trapping, and dissolution of DNAPLs, such as TCE, were outside the scope of hydrology until the 1980s.⁷⁴

Between 1961 and 1981, only the U.S. Geological Survey (USGS), the dominant research agency for groundwater hydrology in the United States and the agency charged with monitoring national groundwater quality, had a program addressing the general issue of organic contamination of groundwater. But it did not pursue the question of the migration of chlorinated solvents, in particular, into the subsurface and their dissolution into groundwater. The agency's Organics in Water Project, which was begun at its Menlo Park, California, research center in 1961, addressed problems associated with chlorinated pesticides, munitions wastes, and wood-preserving chemicals, but not chlorinated degreasing solvents.⁷⁵ While atmospheric scientists were quick to use Lovelock's electron-capture detector to measure chlorinated compounds in the atmosphere, hydrologists with the Organics in Water Project used it to investigate a pesticide waste dump in Tennessee but not to study chlorinated degreasing solvents in groundwaters.⁷⁶ In the absence of a research program into their fate in the subsurface, there could be little hope for the prevention or remediation of groundwater contamination by chlorinated solvents before the 1980s. Given what is now known about the numerous releases of chlorinated degreasing solvents in nearby Silicon Valley, the USGS appears to have been remiss in its duties to safeguard American water resources.⁷⁷

sented at the Rice University conference, indicated an understanding that DNAPL might persist undissolved in the subsurface for a long time and act as a continuing source of groundwater contamination (Miller, 45 and fig. 4.7).

74. The migration of immiscible liquids was perceived by hydrologists as an issue of petroleum migration rather than groundwater contamination; see Roger J. M. De Wiest, *Geohydrology* (New York, 1965), 287–95, and Stanley N. Davis and Roger J. M. De Wiest, *Hydrogeology* (New York, 1966), 229–37.

75. Donald F. Goerlitz, "A Review of Studies of Contaminated Groundwater Conducted by the U.S. Geological Survey Organics Project, Menlo Park, California, 1961–1990," in *Groundwater Contamination and Analysis at Hazardous Waste Sites*, ed. Suzanne Lesage and Richard E. Jackson (New York, 1992). The USGS did use the electron-capture detector to study chlorinated pesticides from a dump site in Tennessee in 1967, but it did not undertake a study of the subsurface migration and fate of chlorinated solvents. Goerlitz states that GC/MS was "not available at this time."

76. Simmonds et al. (n. 24 above).

77. Tekla S. Perry, "Cleaning Up," *IEEE Spectrum*, February 1993, 20–26. The USGS was not the only federal agency that failed to address the DNAPL problem of chlorinated degreasing solvents before 1981. The EPA did not release its first advisory documents on the matter until the early 1990s; Pankow et al., "Dense Chlorinated Solvents in Groundwater: Background and History of the Problem" (n. 34 above), 47. It is a matter of further concern that both agencies also failed to protect groundwater resources from contamination by the gasoline additive methyl tertiary-butyl ether (MTBE), which came into widespread use following the 1990 Clean Air Act Amendments. MTBE has proven to be an important groundwater contaminant; "MTBE Detected in Survey of Urban Groundwater," *Environmental Science and Technology* 29 (1995): 305A. Given the fre-

The failure of groundwater hydrologists to undertake research into this problem drew criticism from two eminent scientists, James Pankow of the Oregon Graduate Institute and John Cherry of the University of Waterloo, whose names are closely associated with the recognition of this issue. Referring to the emergence of the problem ten years before, they wrote in 1988: “The fact that groundwater contamination by halogenated solvents has come as a surprise is regrettable; much of the problem could have been avoided. Indeed, we realize in retrospect that information has long been available that pointed to the potential that these chemicals have for causing rapid and extensive contamination.”⁷⁸ However, it is worth recalling the conclusion of Christopher Sellers, of the State University of New York at Stony Brook, concerning the development of industrial hygiene: “[S]pecialization among scientific professionals has at once enhanced and impeded our understanding of environmental problems.”⁷⁹

It is improbable that the successful creation and testing of scientific paradigms for contamination of large-scale environmental systems, such as groundwater basins and the stratosphere, can occur in the absence of both generous research funding and appropriate analytical instrumentation.⁸⁰ Furthermore, paradigms are essential for effective corrective action. This became apparent in 1991, when Timothy Fields Jr., the EPA’s deputy director of the Superfund program, disputed one of the more important conclusions of the Schuille paradigm, arguing that the simple act of pumping groundwater from contaminated aquifers would restore them to a pristine state in short periods of time.⁸¹

quent problems that occurred with the leakage of gasoline from service station storage tanks—the journal *Ground Water* published an article on the topic as early as November/December 1971—this is an environmental problem that could have been anticipated by both federal agencies.

78. James F. Pankow and John A. Cherry, foreword to Pankow’s translation of Schuille et al. (n. 66 above).

79. Christopher Sellers, “Factory as Environment: Industrial Hygiene, Professional Collaboration, and the Modern Sciences of Pollution,” *Environmental History Review* (spring 1994): 55–83. This issue of specialization by academic discipline and its inhibiting effects on problem resolution was noted by Schuille in his 1985 address to the Canadian-American Conference on Hydrogeology (n. 66 above), when he called on petroleum and chemical engineers to assist in interdisciplinary research into the DNAPL problem.

80. Harvey Brooks, in a letter to the author, 28 February 2000, noted that with regard to ozone depletion by CFCs and groundwater contamination by solvents, “the big difference [is] that the measurement tools necessary to bring the problem to closure were much more available in the stratospheric ozone case, thanks largely to the high political salience of the SST debate.”

81. David Stipp, “Throwing Good Money at Bad Water Yields Scant Improvement,” *Wall Street Journal*, 15 May 1991. The argument of the EPA’s deputy director of Superfund contradicted the findings of not only Mackay and Cherry’s 1989 article “Groundwater Contamination: Pump-and-Treat Remediation” (n. 67 above) but also EPA’s own study of nineteen Superfund sites; *Evaluation of Ground-Water Extraction Remedies*, vol.

Anticipating the Effects of CFCs

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New technologies introduced in the twentieth century were often based on the functional properties of innovative chemicals. It later became known that some of these chemicals are toxic to humans or can cause environmental effects that may damage human health. The use of CFCs, commonly known by their DuPont name as Freon, for refrigeration and air conditioning and in aerosol propellants is one example. In 1974 two chemists from the University of California at Irvine, Sherwood Rowland and Mario Molina, hypothesized that, once released to the atmosphere, CFCs would eventually cause depletion of stratospheric ozone by their catalytic action.⁸² Atmospheric chemists not only had a guiding paradigm but also had a powerful new tool with which to measure chlorinated compounds: the electron-capture detector fitted to a gas chromatograph, which had been developed by James E. Lovelock for medical purposes.⁸³ By 1971 Lovelock had moved to the California Institute of Technology and had begun measuring atmospheric concentrations of CFCs, which in turn prompted Rowland and Molina to consider the atmospheric fate of CFCs.⁸⁴ The publication of their physical-chemical paradigm for ozone depletion in June 1974 led six months later to the first of many congressional hearings.

The depletion of stratospheric ozone as a possible result of the effect of nitrogen oxide emissions from a hypothetical fleet of supersonic transport (SST) aircraft had already been brought before the Senate. In those hearings, it had been pointed out that ozone depletion might cause an increased incidence of skin cancers in the light-skinned human population because of the resulting increased ultraviolet radiation. Industrial scientists argued against premature regulation of CFCs in the absence of reliable scientific data, which the federal government set out to obtain. However, the government banned the use of CFCs in aerosol propellants in 1978 on the grounds

2, EPA/540/2-89/054b (Washington, D.C., 1989), case studies 1-19. Schulle, *Dense Chlorinated Solvents* (n. 66 above), 112, clearly indicated that solvents might remain at the base of aquifers "for time periods ranging between several months to decades." This appears to be more of a case of an uninformed Washington official defending his agency, which had advocated large-scale pumping and treating of contaminated groundwater at Superfund sites, than an EPA official supporting industry. By this time, several chemical and manufacturing companies with significant numbers of Superfund sites (e.g., Dow Chemical, General Electric) were funding the "Solvents Consortium" of Pankow and Cherry to study the problem.

82. M. J. Molina and F. S. Rowland, "Stratospheric Sink for Chlorofluoromethanes: Chlorine Atom-Catalyzed Destruction of Ozone," *Nature* 249 (1974): 810-12.

83. James E. Lovelock, "Electron Absorption Detectors and Technique for Use in Quantitative and Qualitative Gas Chromatography," *Analytical Chemistry* 35 (1963): 474-81. A history of this device is presented by Lovelock in his autobiography, *Homage to Gaia* (n. 2 above).

84. McFarland (n. 10 above).

that there were suitable substitutes and therefore CFCs were “nonessential.” In 1985, when industry held the political advantage against further regulation, new scientific data validated the prediction of environmental damage in the form of the Antarctic ozone hole.⁸⁵ The National Aeronautics and Space Administration quickly confirmed this phenomenon, and the political momentum changed.⁸⁶

Regulations governing the use of CFCs for purposes for which no substitutes existed, as in commercial and industrial refrigeration, were promulgated in 1988, one year after the signing of the Montreal Protocol on Ozone Depleting Substances.⁸⁷

Producing a Scientific Consensus

The difficulties of regulating environmental problems are many. When a new technology is introduced, the human toxicity and environmental effects of the chemicals used may be unknown to the industry that introduces the technology and unsuspected by the agencies that protect the environment and public health. Furthermore, the association of toxic effects on human or ecological health requires clear causative evidence relating the chemicals to the observed health effects. This implies that the prevention or remediation of these effects is also dependent on this association of cause and effect. However, the health effects on humans—such as cancer—may have a long latency period. Finally, the evidence I have presented indicates that regulatory protection from hazards cannot occur until a scientific paradigm that describes the environmental fate of the chemical of concern and its biomedical action producing the adverse health effect is proposed and then confirmed.

It is worth noting that in the case of chlorinated solvents no scientific “revolutions” were required to effect change and no “paradigm shifts” occurred because no preexisting paradigm was responsible for the failure to anticipate the emerging crisis. New science emerged, guided by a paradigm and made possible by new instrumental methods of chemical analysis, and suggested remedial approaches that in turn stimulated the development of new remedial technologies. While the introduction to this article indicated that the invisibility of the contamination, whether by CFCs or chlorinated degreasing solvents, sets this matter apart from earlier issues examined by environmental historians, there are historical similarities in microbiology.

85. Brooks, letter to the author, 28 February 2000: “It is also interesting to note that, thanks to the British work (i.e., the discovery of the Antarctic ozone hole by the British Antarctic Survey in 1985), the political salience of the CFC problem seemed to be on the decline just before the ozone hole burst on the scene.”

86. Somerville (n. 11 above) and Parson (n. 11 above).

87. W. H. Lambricht, “NASA, Ozone, and Policy-Relevant Science,” *Research Policy* 24 (1995): 747–60.

The scientific paradigm embodied in Robert Koch's germ theory of disease—aided by improved optical microscopes and laboratory culture methods—provided Walter Reed and other U.S. Army scientists with the necessary guidance to identify the mosquito as the carrier of the virus causing yellow fever, to isolate the virus, and then to develop a vaccine. Prior to this time (1900), the origin of yellow fever was a subject of much speculation, partly because of its invisibility.⁸⁸

The development of sampling equipment and analytical instrumentation to study environmental processes, the demonstration of environmental effects, and the creation of scientific paradigms all require funding and integration on a large scale. But research-funding agencies have priorities associated with known problems, not with hypothetical, unsubstantiated ones. Why should such agencies fund hypothetical and unsubstantiated research on a generous scale when sufficient real and immediate projects beg for support?

How then does an advanced technological society ensure that it anticipates and thus prevents severe environmental damage by the introduction of new technologies and the chemicals associated with them when their human-health effects are latent and their environmental fate is governed by processes that are particularly complex? In the exemplary case of the anticipation of ozone depletion by CFCs, the ongoing research program that addressed the existing concern over ozone depletion by SST aircraft aided the scientific community.⁸⁹ Research into ozone-depleting substances did benefit from federal funding—albeit funding for research into the potential effects of an SST aircraft on the stratosphere rather than the fate of CFCs in the stratosphere (for which funding was granted later).

The success of the atmospheric scientists and the failure of the groundwater hydrologists in the 1970s and 1980s indicate the importance of use-inspired basic research for paradigm creation in the anticipation of emerging environmental problems in the twenty-first century. The Rowland-Molina paradigm of 1974 told atmospheric scientists what to look for, and

88. Michael B. A. Oldstone, *Viruses, Plagues and History* (Oxford, 1998). In *Yellow Fever in the North* (Madison, Wisc., 1987), William Coleman describes the confusion over the appearance of yellow fever in European ports in the 1860s, some twenty years prior to the development of the germ theory of disease that eventually allowed the causal agent, disease-carrying mosquitoes from Caribbean forests, to be identified. T. D. Brock has written: "At all stages of its history, the science of microbiology has taken the greatest steps forward when better microscopes have been developed"; *Biology of Microorganisms* (Englewood Cliffs, N.J., 1970), 5. I am indebted to one of the *T&C* referees for pointing out this interesting analogy.

89. Parson, 24–25. In personal correspondence (28 February 2000), Harvey Brooks commented that there was a "high level of activity in stratospheric chemistry that had been generated by the SST debate in the early 1970s. Over 50 million dollars had already been spent, and numerous Congressional hearings had been held on the subject before there was any hint of the fluorocarbon problem."

in 1985 they found conclusive proof of its prediction. Two years later, after ten years of deadlock and two critical scientific assessments, effective public policy became possible through the agreement known as the Montreal Protocol.⁹⁰ Hydrologists, on the other hand, were not looking for solvent contamination in groundwaters when they first found it in the late 1970s. Remedial action and effective public policy were retarded by the absence of a guiding paradigm until 1988. As with that of Rowland and Molina for CFCs, paradigms will not go unchallenged. However, their “focusing effect” is essential in producing a scientific consensus, without which effective regulatory and remedial action is delayed.⁹¹

90. Parson states the assessments were the critical element in achieving agreement.

91. The words are those of D. A. Hollinger: “Kuhn emphasized the power of pre-conceived ideas to control the observations of scientists, and insisted that without the focusing effect of these ideas investigators would not be able actually to see the phenomena the explanation of which was essential to the creating of new knowledge.” “Paradigms Lost,” *New York Times Sunday Book Review*, 28 May 2000, 28.