Although these graphical methods were developed to study the protein surface, they should also be useful in visualizing the packing of alpha helices and beta sheets in the protein interior, simply by giving these structural elements individual surface contours. This will bring solvent-accessibility studies back full-circle to their original scientific problem, the understanding of the folding of the polypeptide chain to form protein tertiary structure.

References and Notes

1. R. Diamond, in *Computational Crystallography*, D. Sayre, Ed. (Oxford Univ. Press, Oxford, 1982), p. 318; T. A. Jones, in *ibid.*, p. 303.
2. F. P. Brooks, Jr., in *Proceedings of the 1977 International Federation of Information Processing*, B. Gilchrist, Ed. (North-Holland, Amsterdam, 1977), p. 625.
3. C. D. Barry, C. E. Molnar, F. U. Rosenberger, *Technical Memo 229* (Computer Systems Laboratory, Washington University, St. Louis, Mo., January 1976); C. D. Barry, H. E. Bosshard, R. A. Ellis, G. R. Marshall, in *Computers in Life Science Research*, W. Siler and D. A. B. Lindberg, Eds. (Plenum, New York, 1975), p. 137.
4. T. Porter, *Comput. Graphics* **12**, 282 (1978); *ibid.* **13**, 234 (1979).
5. R. J. Feldmann *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **75**, 5409 (1978).
6. K. Knowlton and L. Cherry, *Comput. Chem.* **1**, 161 (1977).
7. N. L. Max, *Comput. Graphics* **13**, 165 (1979).
8. C. K. Johnson, *Oak Ridge Natl. Lab. Tech. Rep. 5138* (1976).
9. F. M. Richards, *Annu. Rev. Biophys. Bioeng.* **6**, 151 (1977).
10. B. Lee and F. M. Richards, *J. Mol. Biol.* **55**, 379 (1971).
11. J. Greer and B. L. Bush, *Proc. Natl. Acad. Sci. U.S.A.* **75**, 303 (1978).
12. A. Shrake and J. A. Rupley, *J. Mol. Biol.* **79**, 351 (1973).
13. M. L. Connolly, thesis, University of California, Berkeley (1981).
14. ——, *QCPE Bull. 1* (1981), p. 75. The dot molecular surface program (MS) is written in Fortran and may be obtained by writing to Quantum Chemistry Program Exchange, Department of Chemistry, Indiana University, Bloomington 47405.
15. R. Huber, D. Kukla, W. Bode, P. Schwager, K. Bartels, J. Deisenhofer, W. Steigemann, *J. Mol. Biol.* **89**, 73 (1974).
16. R. N. Smith, C. Hansch, F. H. Kim, B. Omiya, G. Fukumura, C. D. Selassie, P. Y. C. Jow, J. M. Blaney, R. Langridge, *Arch. Biochem. Biophys.* **215**, 319 (1982).
17. C. Hansch, R. Li, J. M. Blaney, R. Langridge, *J. Med. Chem.* **25**, 777 (1982).
18. S. Sprang, R. Fletterick, M. Stern, D. Yang, N. Madsen, J. Sturtevant, *Biochemistry* **21**, 2036 (1982).
19. E. Goldsmith, S. Sprang, R. Fletterick, *J. Mol. Biol.* **156**, 411 (1982).
20. S. R. Sprang, E. J. Goldsmith, R. J. Fletterick, S. G. Withers, N. B. Madsen, *Biochemistry* **21**, 5364 (1982).
21. R. A. Lerner, *Nature (London)* **299**, 592 (1982).
22. A. J. Olson, G. Cohen, D. Davies, *Antibody Structure*, film available from Byron Motion Pictures, 65 K Street, NE, Washington, D.C. 20002.
23. A. J. Olson, *Virus Wars*, computer-generated film presented at the International School of Crystallography, Conference on Crystallography in Molecular Biology, Italy, June 1982.
24. R. E. Dickerson and I. Geis, *Hemoglobin: Structure, Function, Evolution, and Pathology* (Benjamin/Cummings, Menlo Park, Calif., 1983), p. 136.
25. I. D. Kuntz, J. M. Blaney, S. J. Oatley, R. Langridge, T. E. Ferrin, *J. Mol. Biol.* **161**, 269 (1982).
26. R. Langridge, T. E. Ferrin, I. D. Kuntz, M. L. Connolly, *Science* **211**, 661 (1981).
27. R. O. Fox, Jr., and F. M. Richards, *Nature (London)* **300**, 325 (1982).
28. M. L. Connolly, *J. Appl. Crystallogr.*, in press.
29. T. J. Richmond and F. M. Richards, *J. Mol. Biol.* **119**, 537 (1978).
30. C. J. Alden and S.-H. Kim, *ibid.* **132**, 411 (1979).
31. M. P. do Carmo, *Differential Geometry of Curves and Surfaces* (Prentice-Hall, Englewood Cliffs, N.J., 1976), pp. 274–276.
32. F. M. Richards, *J. Mol. Biol.* **82**, 1 (1974).
33. J. L. Sussman, S. R. Holbrook, R. W. Warrant, G. M. Church, S.-H. Kim, *ibid.* **123**, 607 (1978).
34. H. R. Drew, R. M. Wing, T. Takano, C. Broka, S. Tanaka, K. Itakura, R. E. Dickerson, *Proc. Natl. Acad. Sci. U.S.A.* **78**, 2179 (1981).
35. H. R. Drew, S. Samson, R. E. Dickerson, *ibid.* **79**, 4040 (1982).
36. T. Whitted, *Science* **215**, 767 (1982).
37. W. N. Newman and R. F. Sproull, *Principles of Interactive Computer Graphics* (McGraw-Hill, New York, 1979), pp. 367–388.
38. J. D. Foley and A. Van Dam, *Fundamentals of Interactive Computer Graphics* (Addison-Wesley, Reading, Mass., 1982).
39. M. L. Connolly, in preparation.
40. J. A. Tainer, E. D. Getzoff, K. M. Beem, J. S. Richardson, D. C. Richardson, *J. Mol. Biol.* **160**, 181 (1982).
41. H. L. Monaco, J. L. Crawford, W. N. Lipscomb, *Proc. Natl. Acad. Sci. U.S.A.* **75**, 5276 (1978).
42. J. F. Blinn, *ACM Trans. Graphics* **1**, 235 (1982).
43. T. J. O'Donnell and A. J. Olson, *Comput. Graphics* **15**, 133 (1981).
44. A. J. Olson, *Tomato Bushy Stunt Virus*, film available from Palmer Film Services, 611 Howard Street, San Francisco, Calif. 94105.
45. J. M. Blaney *et al.*, *J. Med. Chem.* **25**, 785 (1982).
46. P. K. Weiner, R. Langridge, J. M. Blaney, R. Schaefer, P. A. Kollman, *Proc. Natl. Acad. Sci. U.S.A.* **79**, 3754 (1982).
47. E. D. Getzoff, thesis, Duke University, Durham, N.C. (1982).
48. F. C. Bernstein *et al.*, *J. Mol. Biol.* **112**, 535 (1977).
49. T. Whitted, *Commun. ACM* **23**, 343 (1980).

50. I thank T. J. O'Donnell and A. J. Olson for the use of their program GRAMPS, the Brookhaven National Laboratory Protein Data Bank for x-ray coordinates (*48*). M. Pique for assistance at the Computer Graphics Laboratory, University of North Carolina at Chapel Hill (NIH RR 00898, F. P. Brooks, Jr., principal investigator), J.-P. Dumas for assistance at the Salk Institute, and the Helen Hay Whitney Foundation for a postdoctoral fellowship.

Ground Water Contamination in the United States

Veronica I. Pye and Ruth Patrick

Ground water that is used by humans consists of subsurface water which occurs in fully saturated soils and geological formations. Nearly half the population of the United States use ground water from wells or springs as their primary source of drinking water (*1, 2*); 36 percent of the municipal public drinking water supply comes from ground water (*1*); and 75 percent of major U.S. cities depend on ground water for most of their supply (*3*). Total fresh ground water withdrawals in 1980 were estimated as 88.5 billion gallons per day, of which 65 percent were used for irrigated agriculture (*4*). Although ground water contamination has occurred for centuries, increased industrialization, population density, and agricultural activities have greatly exacerbated the problem in some areas. As our dependence on ground water increases, its quality becomes an ever more important issue.

Ground water is not only important to man, it is also an integral part of the hydrologic cycle of the earth—the circulation of water between the oceans, atmosphere, and land. It constitutes approximately 4 percent of the water in the hydrologic cycle, second only to the oceans and seas, which account for about 94 percent (*5*). The volume of ground water in storage exceeds the volume of fresh surface water in lakes, streams, and rivers. Approximately 30 percent of the streamflow of the United States is supplied by ground water emerging as natural springs or other seepage areas (*2*). Ground water forms most, if not all, of the low water flow of streams during dry periods. The interrelation between surface water and ground water is further indicated by the fact that, under certain conditions, surface water may recharge ground water aquifers.

Aquifers may be composed of permeable or porous geological material, either unconsolidated sand and gravel or consolidated material such as carbonate

Veronica I. Pye is Research Director of the Environmental Assessment Council, Academy of Natural Sciences, Philadelphia, Pennsylvania 19103. Ruth Patrick is Chairman of the Environmental Assessment Council, is Senior Curator of Limnology and occupies the Francis Boyer Research Chair at the Academy of Natural Sciences, Philadelphia, and is Adjunct Professor at the University of Pennsylvania. The report on ground water on which this article is based was prepared by the Environmental Assessment Council. Council members were Robert G. Dunlop, Caryl Haskins, Richard E. Heckert, Lane Kirkland, George Lamb, Charles F. Luce, Ruth Patrick, Glen Paulson, William Reilly, Laurance S. Rockefeller, Abel Wolman, and George Wills.

rocks, volcanic rocks, or fractured igneous, metamorphic, or sedimentary rocks. Unconfined aquifers are the most susceptible to contamination (Fig. 1). They are not overlain by impermeable material and are recharged by water seeping through the soil. They may be fairly close to the land surface. Water in unconfined aquifers at the saturated-unsaturated interface is at atmospheric pressure and the volume in storage may fluctuate according to seasonal cycles of natural recharge due to precipitation and man's use of the aquifer.

Confined aquifers occur at greater depths and are bounded top and bottom by layers of relatively impermeable material called aquitards (Fig. 1). The aquitards and the depth at which they occur offer confined aquifers a certain measure of protection from contamination. Some confined aquifers have no recharge areas and may be considered a finite resource. Confined aquifers may become contaminated when they are tapped for use, when contaminating activities are sited in their recharge areas, or when water of poor quality leaks in from a shallower or deep saline or contaminated aquifer through the aquitards, which are rarely totally impermeable.

Aquifer size is very variable; many are local or regional, whereas others may underlie several states. An example of the latter is the Ogallala in the Midwest. Most occur within 2500 feet of the land surface and may be a few feet or several hundred feet thick. Estimates of ground water in storage in the United States vary from 33 quadrillion gallons (*2*) to 100 quadrillion gallons (*6, 7*).

The water contained in aquifers varies naturally in quality and may or may not be readily retrievable. However, potable ground water occurs in most areas of the United States and can often be used as a raw resource without pretreatment. Such freshwater aquifers are often underlain by deeper saline aquifers. The salinity can depend on the geologic formation through which the ground water passes and the length of time during which it is in contact with a particular deposit in its flow history. There are five types of naturally occurring ground water that often have a total dissolved solids content exceeding 10,000 parts per million. These are connate water, which was trapped in sediments at the time they were deposited; magmatic and geothermal water; intruded seawater; water affected by evapotranspiration; and water affected by salt leaching (*5*). Saline ground water is generally unusable because of its high salinity or the presence of naturally occurring toxic substances. For example, radioactivity from uranium causes problems in Texas, Oklahoma, and New Mexico (*8*). Arsenic may be a local problem in thermal springs (*9*), but it is also a widespread problem, particularly in the western United States.

Summary. Ground water contamination is of increasing concern in the United States because about 50 percent of our drinking water comes from well water. The causes of contamination stem from both point sources and nonpoint sources. Since ground water moves slowly, the contaminant may affect only a small portion of an aquifer for a considerable period of time. Deleterious effects on human health have resulted from pathogenic organisms in ground water and from its toxic chemical composition. It is difficult to estimate the extent of contamination on a national basis as the frequency of instances of contamination is very variable. Remedial actions to clean up aquifers are difficult, expensive, and sometimes not feasible. Many of the laws and regulations that control ground water contamination are designed with other main objectives.

Sources of Ground Water Contamination

Important sources of contamination include man's activities, such as waste disposal, as well as nonpoint sources. The many sources associated with waste disposal include manufacturing and service industries, agriculture, domestic waste production, and wastes resulting from government activities. Both the number of potential sources and the problems they pose vary greatly. For example, domestic waste production may include such sources as individual sewage disposal systems, land disposal of solid and liquid wastes, and the collection and treatment of municipal wastewater. Industrial activities result in sources such as industrial and other wastewater impoundments, land spreading of sludge, brine disposal associated with the petroleum industry, disposal of mine wastes, and deep well disposal of liquid wastes. Disposal of wastes from animal feedlots may contribute to ground water contamination. In addition, there is the threat posed by disposal of high- and low-level radioactive wastes resulting from a variety of activities, both private and governmental. It is often difficult to state that contamination from a particular source is the result of a particular type of activity. For example, land spreading is a technique used by farmers, municipal authorities, and industry to dispose of wastes. However, all these activities could result in natural or synthetic substances entering the ground water. Some of them are illustrated in Fig. 1.

Other sources of contamination that are direct results of human activities include such diverse events as accidental spills and leaks and the use of highway deicing salts. Agricultural activities, including the application of pesticides and fertilizers, irrigation, and practices resulting in a change in the vegetative land cover, are potential nonpoint sources of ground water pollution. Other sources unrelated to disposal activities include mining, especially dewatering and abandonment, atmospheric contaminants, infiltration from polluted bodies of surface water, and improper well construction. Poorly planned ground water development can, in fact, lead to contamination. Many coastal communities have overpumped their freshwater aquifers and caused saltwater intrusion into the aquifers, rendering the water unfit for many uses.

Factors Affecting the Characteristics of Contamination

The chemical composition of ground water may be influenced by natural processes that are responsible for its background quality. The chemical characteristics of a contaminant may change as it percolates through the soil zone before it reaches the aquifer. Attenuation of contaminants in the soil zone may occur through surface adsorption, dilution, volatilization, mechanical filtration, precipitation, buffering, neutralization, ion exchange, microbial metabolism, and plant uptake. Clay soils have a greater capacity for physicochemical attenuation of contaminants than coarse sands or fissured rocks. Deep soils may contain active organisms whose metabolism results in contaminant attenuation (*10*). Although these changes often reduce the toxicity or mobility of a contaminant, they may not always do so. At present, the biological and physicochemical changes that occur in contaminants in the unsaturated soil zone are not well understood.

Once contaminants reach the aquifer, their attenuation by biological processes is reduced, although there may still be effects due to the physicochemical processes outlined above. Radionuclides have a characteristic rate of decay dependent on their half-lives. In contrast, contaminants such as heavy metals would persist in the ground water if not precipitated or chelated.

Effect of Ground Water Movement on Dispersion of Contaminants

One of the main factors influencing the effect of a contaminant is the slow movement of ground water. Under idealized conditions, transport would result in the formation of an elliptical plume of contamination with well-defined boundaries (*1*), but often this is not the case. The pattern of flow varies in different types of aquifers, and flow rates are governed by hydraulic gradients and aquifer permeability, resulting in a range of values from a fraction of an inch to a few feet per day. The slow movement of contaminants results in a low mixing rate. This factor is important when considering the transport and persistence of contaminants. However, diffusion and dispersion in the aquifer may bring contaminants into contact with geological material that retards their progress and alters their rate of dispersion and thus their potential effect. As ground water moves slowly and the mixing rate is low, the contaminants remain localized over long periods of time and not become as rapidly diluted as they would in a body of surface water. Many contaminants have been found in higher concentrations in ground water than in surface water (*11*, *12*).

Problems Posed by Ground Water Contamination

The chemical composition of wastes legally disposed of in landfills or impoundments is usually known. However when the constituents of such wastes interact new compounds may be formed. Many industrial waste disposal practices now involve stabilization of wastes to render them chemically less active; however, leachate production may chemically alter some of the constituents. Thus it is almost impossible to accurately predict precisely what chemicals may reach an aquifer as a result of waste disposal.

The types of contaminant now found in ground water range from simple inorganic ions, such as chloride, nitrate, and heavy metals, to complex synthetic organic chemicals and pathogens such as viruses and bacteria. According to a report to the Committee on Environment and Public Works of the U.S. Senate,

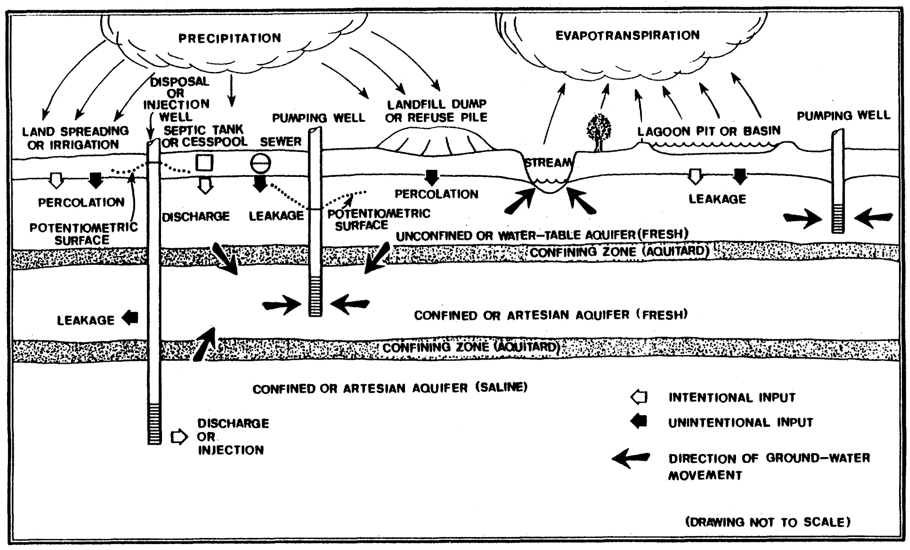

Fig. 1. How waste disposal practices can contaminate the ground water system (*37*).

requested by Senator Muskie, a study was made of 128 case histories of ground water contamination that resulted in well closings due to the following contaminants: organics, 242; insecticides, 201; chlorides, 26; nitrates, 23; and metals, 619. In the Midwest, nitrate problems are fairly common (*13*). For example, in Washington County, Illinois, 81 percent of 221 dug wells and 34 percent of drilled wells had a nitrogen concentration (as nitrate) of more than 10 mg/liter, the amount known to be toxic to humans (*14*).

The deleterious effects of contaminants vary according to the volume of contaminants discharged, their toxicity, their concentration in the aquifer, their persistence through time, and the degree of environmental and human exposure to them. Environmental effects of ground water contamination may include vegetation stress and death, bioconcentration of contaminants in the food chain of the flora and fauna of surface waters, and adverse effects on wildlife and domestic animals that drink from tainted springs. The impact of ground water contamination on humans is difficult to quantify accurately in terms of the number of people affected by well closings. In Nassau and Suffolk counties on Long Island, New York, the wells of 36 communities were closed; these were the source of domestic water for more than 2 million people (*15*). There has been no national survey of the numbers of persons affected by well closings.

Deleterious effects of contaminated ground water on human health are produced by pathogenic organisms or by its toxic chemical characteristics. Between 1945 and 1980 there were 158 outbreaks of disease with more than 31,000 cases of illness attributed to contamination of ground water by pathogenic organisms such as viruses, bacteria, or parasites (*16*). In the same period 57 cases of illness were attributed to occurrences of toxic organic chemicals (*16*). More than 300 cases of illness have been attributed to 20 occurrences of chemical contamination (excluding organic chemicals) (*17*). Outbreaks of illness attributed to waterborne agents are reported to the Centers for Disease Control (CDC) by state health departments; it is thought that only a fraction of those that occur are reported, and the efficiency of reporting varies greatly from region to region. The CDC recognizes that these figures cannot be considered definitive in terms of occurrence and etiology. Reports of the National Academy of Sciences on drinking water and health present data on the effects of ingesting low concentrations of certain chemical contaminants (such as arsenic and chloroform) in drinking water over long periods which are suggestive of links with certain diseases but are by no means conclusive (*14*, *18–21*).

Many chemicals now found in ground water have not yet been tested for health effects, and no standards exist for their maximum concentration in water. There has been no national survey of the extent of ground water contamination, probably because well drilling and sampling on such a scale would be extremely expensive and time-consuming. For those reasons, it is not possible to assess quantitatively the risks of ground water contamination. However, it should be emphasized that ground water contamination is often very localized due to the slow movement of the plume; once an incident of contamination is discovered, it does not imply that all the ground water in the area is contaminated.

Table 1. Most frequently reported sources of ground water contamination in the ten states reviewed by the environmental assessment council (*26*); mgd, million gallons per day.

State	Ground water use (mgd)	Natural quality of ground water	Source of contamination	Total number of known contamination incidents	Number affecting or threatening water supply	Number where remedial actions have been undertaken
Arizona	4,800	Generally good; mineralization problems	1. Industrial wastes 2. Landfill leachate 3. Human and animal wastes	23	23	7
California	13,400 to 19,000	Good	1. Saltwater intrusion 2. Nitrates from agricultural practices 3. Brines and other industrial and military wastes	Not known	Not known	Not known
Connecticut	116	Good to excellent	1. Industrial wastes 2. Petroleum products 3. Human and animal wastes	64	38	20
Florida	3,000	Generally good	1. Chlorides from saltwater intrusion and agricultural return flow 2. Industrial wastes 3. Human and animal wastes	92	58	42
Idaho	5,600	Good	1. Human and animal wastes 2. Industrial wastes 3. Radioactive wastes	29	28	13
Illinois	1,000	Generally good	1. Human and animal wastes 2. Landfill leachate 3. Industrial wastes	58	44	35
Nebraska	5,900	Generally good	1. Irrigation and agriculture 2. Human and animal wastes 3. Industrial wastes	35	12	11
New Jersey	790	Generally good	1. Industrial wastes 2. Petroleum products 3. Human and animal wastes	374	198	346
New Mexico	1,500	Fair to good; mineralization problems	1. Oil field brines 2. Human and animal wastes 3. Mine wastes	105	87	27
South Carolina	200	Suitable tor most uses	1. Petroleum products 2. Industrial wastes 3. Human and animal wastes	89	66	34

Extent of Ground Water Contamination

Even though no comprehensive national survey of ground water contamination has been undertaken, incidents of contamination have been reported from every state. Assessments completed by the Environmental Protection Agency (EPA) in the 1970's (*8, 9, 22–24*) indicate that problems characteristic of one area may not occur in another, but that several sources of ground water contamination occur at a high or moderate degree of severity in each area studied. The four pollutants most commonly reported—chloride, nitrate, heavy metals, and hydrocarbons—may be a reflection of the monitoring practices prevailing at the time the surveys were made. The problems given priority in the five regions studied were not selected on the basis of statistical information, as it was not available. The priorities were established empirically on the basis of the experience of the authorities and individuals who had worked in the five regions (*25*).

In our studies of the extent and severity of ground water contamination (*26*), we contacted all the states and asked them to provide information on known incidents of contamination. The information we received varied in detail. Some states have computed inventories of known and suspected incidents of contamination; others have just started or are in the process of documentation. We studied ten states in more detail because they had the greatest amounts of information available and also because they served as examples of different levels of industrialization, agricultural activity, population density, dependence on ground water, and climatic conditions. The states chosen were Arizona, California, Connecticut, Florida, Idaho, Illinois, Nebraska, New Jersey, New Mexico, and South Carolina.

The information from these ten states showed that the problems encountered to date vary from one region of the country to another (Table 1). A comprehensive national survey, if undertaken, may find a greater similarity between regions. Human and animal wastes were among the most frequently reported sources of contamination in the ten states listed in Table 1. In California and Florida, saltwater intrusion was the more important source of contamination. The industrial Northeast had problems associated with industrial wastes, petroleum products, and landfill leachate. The agricultural areas of California, Florida, and Nebraska reported problems arising from agricultural practices, and New

Mexico and California reported problems with disposal of oil field brines. The results of these studies showed that the problems depend on the type and degree of industrial and agricultural activities in a region and the population density. The information represents a "best-case" scenario, and the situation could change as new cases of contamination are discovered. The known incidents, depending on the regional or geographic density of the source, may represent single isolated plumes of contamination or many closely spaced plumes, and may fall into geographic patterns.

There have been recent estimates by Lehr (*6*) and by the EPA (*27*) of the extent of ground water contamination nationwide. The EPA (*27*) estimated that about 1 percent of the nation's usable ground water had been contaminated, based on an evaluation of contamination from primary sources (industrial impoundments, municipal and industrial landfills) and secondary sources (subsurface disposal systems, petroleum exploration and mining activities). Lehr (*6*) estimated that the extent of contamination might exceed 2 percent, based on an assumed total of 200,000 point sources of contamination in the country, including septic tanks, landfills, pits, ponds, and lagoons. These estimates cannot be considered complete since they took into account only certain point sources and disregarded nonpoint sources. On a nationwide basis the estimates mean very little, for in some areas reported contamination incidents are very few, whereas in others (more populated areas) they are often much more frequent.

Remedial Action and Aquifer Rehabilitation

When it has been discovered that an aquifer is contaminated, it must be decided what, if any, remedial action to take. Recent studies of remedial action (*28–32*) have concluded that it is complicated, time-consuming, expensive, and often not feasible, and that the best solution to ground water contamination is prevention. The suitability and effectiveness of remedial actions depend on the period over which contamination has taken place, the type and behavior of the contaminants, and the hydrogeology of the site. Often it is more cost-effective to locate a new source of water than to attempt treatment (*28*).

Shallow plumes of contamination in unconsolidated material may be controlled by excavation and removal once the problem of the final disposal method for the contaminated material has been solved. There are two other major categories of remedial actions (*31*): (i) in situ methods and (ii) conventional withdrawal, treatment, and final disposal methods. Many in situ methods are experimental and include detoxification, stabilization, and immobilization. They require the use of biological cultures, chemical reactants, or sealants. The aim is to detoxify or stabilize the contaminants, or to form a barrier around the plume to prevent migration of the contaminants.

Withdrawal, treatment, and final disposal techniques may include the use of one or more of the following: collection wells, subsurface gravity collection drains, impervious grout or slurry curtains and withdrawal wells, and cut off trenches. Methods of water treatment that might be employed include reverse osmosis, ultrafiltration, use of ion exchange resins, ozonation and ultraviolet radiation, coagulation and precipitation, aerobic biological treatment, and filtration through activated charcoal (*31*).

Costs of remedial actions must be estimated on a case-by-case basis as they are influenced by many factors specific to the site. They can range from several thousands to several billions of dollars. For most ground water pollution problems, prevention of contamination would have been preferable to curative actions.

Laws and Regulations Applicable to Ground Water Protection

At present there is no federal program dealing specifically with the problem of ground water contamination. The framework of federal laws that can be used for ground water protection is a group of statutes which are aimed primarily at other environmental problems but which touch indirectly on ground water problems. One of the principal statutes of this type is the Resource Conservation and Recovery Act of 1976, which establishes guidelines for the management of solid and hazardous wastes (*33*). The Safe Drinking Water Act of 1974 contains an underground injection control program to prevent ground water contamination by waste injection wells and to protect sole-source aquifers for drinking water. The Clean Water Act of 1977 requires the EPA to establish, equip, and maintain a water quality surveillance system for ground water as well as surface water. The Toxic Substances Control Act of 1976 and the Surface Mining Control and Reclamation Act both have provisions that could offer a measure of protection to ground water. The Comprehensive Environmental Response, Compensation and Liability Act of 1980 authorizes the federal government to clean up contamination caused by inactive waste disposal sites or spills, many of which pose immediate threats to ground water quality.

These are not the only federal statutes that could be used to protect ground water, but they are the most important ones. They have been unevenly implemented, and as a result they are, at present, not very effective in controlling and preventing ground water contamination.

The states have long been involved with ground water allocation law and water rights, but it is only in the last few years that they have made large efforts to prevent, abate, and monitor ground water pollution. The considerable variation in natural ground water quality and in the quantity used, and the regional characteristics of the major sources of ground water contamination may account for the uneven handling of these problems and the diversity of state regulatory mechanisms and organizational structures.

State regulations that may affect ground water quality fall into three main categories: (i) those dealing with particular sources of pollution such as septic tank systems and waste disposal sites, (ii) those establishing and implementing water quality standards for aquifer water, and (iii) those regulating the use of land in areas overlying critical aquifer recharge zones.

As with federal regulations, the state and local controls that effectively protect ground water often are not designed for that purpose. Even when a regulation is adopted with ground water protection in mind, this may only be one of several regulatory objectives.

EPA Policy on Ground Water Protection

In 1980, after more than a year of discussion and study, EPA proposed a national ground water strategy (*27, 34, 35*). Its goal was to prevent ground water contamination rather than provide remedial action. The suggested approach included the development of state management and protection strategies; the development of a ground water classification system; and EPA coordination of existing federal programs for ground water protection. The proposed strategy was aimed at protecting ground water quality according to its value and use, and the technical approach adopted included the use of siting and design criteria, best management practices, effluent standards, innovative and alternative technologies to achieve performance standards, and, to a lesser extent, numerical ground water quality standards and economic incentives.

In 1981, EPA was questioned by the chairman of the House Government Operations Subcommittee on Environment, Energy and Natural Resources about its lack of action on the proposed national ground water strategy. In response, EPA created two separate ground water task forces, one for policy and one for technical purposes, to develop a consistent agencywide strategy.

The EPA is now revising its ground water policy statement. The statement developed by the two task forces apparently did not resolve inconsistent regulatory issues on ground water protection (*36*) and did not set policies on state classification of ground water. Institutional relations—for example, intrastate and state and local government relations—and EPA commitment to the policy in terms of time and money were not resolved.

Conclusions

The hazards posed by contaminants of ground water vary according to the volume discharged, the toxicity of the compounds, their concentration in the aquifer, their persistence in the environment, and the degree of exposure to them. Ground water forms the base flow of streams, and therefore may contaminate the environment, causing vegetation stress and death, possible concentration of contaminants in the foodchain of surface water organisms, and possible adverse effects on wildlife and domestic animals that drink from tainted springs. The impact on man is difficult to quantify in terms of the population affected by well closings and the numbers of outbreaks of disease and cases of illness. Use of ground water contaminated by pathogens has caused disease outbreaks; there have also been cases of acute public health effects due to chemical contamination of ground water. The effect of long-term use of drinking water with low levels of chemical contamination is not known, and many chemicals now found in ground water have not yet been tested for health effects. The lack of a comprehensive national survey on the extent of ground water contamination and the fact that few contaminants have been tested for their health effects make it impossible to assess in quantitative terms the national risk of drinking contaminated ground water. Many of the data required to assess the severity of ground water contamination simply are not available.

Estimates of the extent of ground water contamination nationwide may not be realistic. The estimates that 1 to 2 percent of our usable surface water may be contaminated took into account only certain point sources and ignored nonpoint sources. Contamination has not been uniform nationwide and in areas of high usage these percentages may be excluded.

One of the major difficulties in dealing with ground water contamination is that it occurs underground, out of sight. The pollution sources are not easily observed, nor are their effects seen until damage, which is often irreversible, has been done. The tangible effects of ground water contamination usually come to light long after the incident causing the contamination occurred and the precise source of contamination may be difficult to determine. Nevertheless, although ground water contamination has occurred throughout the United States and is likely to continue to some extent in the future, we are still in a position to make choices on how best to use, manage, and protect this valuable resource. Prevention of ground water contamination is a more effective strategy than cure.

References and Notes

1. Environmental Protection Agency, *The Report to Congress: Waste Disposal Practices and Their Effects on Ground Water* (Office of Water Supply and Office of Solid Waste Management Programs, Washington, D.C., 1977).
2. Water Resources Council, *The Nation's Water Resources, 1975–2000* (Water Resources Council, Washington, D.C., 1978), vol. 1.
3. L. B. Leopold, *Water: A Primer* (Freeman, San Francisco, 1974).
4. U.S. Geological Survey (USGS), Reston, Va., preliminary unpublished data from the National Water Use Information Program (1982).
5. R. A. Freeze and J. A. Cherry, *Groundwater* (Prentice-Hall, Englewood Cliffs, N.J., 1978).
6. J. H. Lehr, *Ground Water Monit. Rev.* (Winter 1982), pp. 4–5.
7. R. H. Langford, USGS associate chief hydrologist, statement before the Subcommittee on Toxic Substances and Environmental Oversight of the Committee on Environment and Public Works, U.S. Senate (July 1982).
8. M. R. Scalf, J. W. Keeley, C. J. LaFevers, *Ground Water Pollution in the South Central States* (EPA-R2-73-268, Environmental Protection Agency, Washington, D.C., 1973).
9. F. van der Leeden, L. A. Cerillo, D. A. Miller, *Ground Water Problems in the Northwestern United States* (EPA-660/3-75-018, Environmental Protection Agency, Washington, D.C., 1975).
10. J. T. Wilson, J. F. McNab, B. H. Wilson, M. J. Noonan, *Dev. Ind. Microbiol.*, in press.
11. D. W. Miller, paper presented in a seminar on the fundamentals of ground water protection organized by Geraghty and Miller Inc. and American Ecology Services Inc., Cherry Hill, N.J., 5 and 6 October 1981.
12. G. W. Page, *Environ. Sci. Technol.* **15**, 12 (1981).
13. U.S. Library of Congress, Environment and Natural Resources Policy Division, *Resource Losses from Surface Water, Groundwater, and Atmospheric Contamination: A Catalog* (Government Printing Office, Washington, D.C., 1980).
14. National Academy of Sciences, *Drinking Water and Health* (National Academy Press, Washington, D.C., 1977), vol. 1.
15. D. E. Burmaster, *Contamination of Ground Water by Toxic Organic Chemicals* (Council on Environmental Quality, Washington, D.C., 1981).
16. Environmental Protection Agency, computer printout of disease outbreaks in the United States attributed to ground water between 1948 and 1980 (Environmental Protection Agency, Cincinnati, Ohio, 1981).
17. J. S. Hubert and L. W. Canter, *Health Effects from Ground Water Usage* (report NCGWR 80-17, National Center for Ground Water Research, Norman, Okla., 1980).
18. National Academy of Sciences, *The Geochemistry of Water in Relation to Cardiovascular Disease* (National Academy Press, Washington, D.C., 1979).
19. ———, *Drinking Water and Health* (National Academy Press, Washington, D.C., 1980), vol. 2.
20. ———, *ibid.*, vol. 3.
21. ———, *ibid.*, vol. 4.
22. D. W. Miller, F. A. DeLuca, T. L. Tessier, *Ground Water Contamination in the Northeast States* (EPA 600/2-74-056, Environmental Protection Agency, Washington, D.C., 1974).
23. J. C. Miller, P. S. Hackenberry, F. A. DeLuca, *Ground Water Pollution Problems in the Southeastern United States* (EPA-600/3-77-012, Environmental Protection Agency, Ada, Okla., 1977).
24. D. K. Fuhriman and J. R. Barton, *Ground Water Pollution in Arizona, California, Nevada, and Utah* (report 16060ERU, Environmental Protection Agency, Washington, D.C., 1971).
25. J. Keeley, personal communication.
26. V. I. Pye, R. Patrick, J. Quarles, *Groundwater Contamination in the United States*, sponsored by the Environmental Assessment Council of the Academy of Natural Sciences, Philadelphia (Univ. of Pennsylvania Press, Philadelphia, in press).
27. Environmental Protection Agency, *Planning Workshops to Develop Recommendations for a Ground Water Protection Strategy: Appendices* (EPA/ODW-2, Environmental Protection Agency, Washington, D.C., 1980).
28. D. E. Lindorff and K. Cartwright, *Ground Water Contamination: Problems and Remedial Actions* (Illinois Geological Survey, Urbana, May 1977).
29. Environmental Protection Agency, *Management of Uncontrolled Hazardous Waste Sites* (Hazardous Material Control Research Institute, Silver Spring, Md., 1980).
30. P. A. Hajali and L. W. Canter, *Rehabilitation of Polluted Aquifers* (NCGWR 80-12, National Center for Ground Water Research, Norman, Okla., 1980).
31. M. Sills, J. Struzziery, P. Silberman, in (*29*), pp. 192–201.
32. J. J. Geraghty, paper presented at a seminar on the fundamentals of ground water quality protection, organized by Geraghty and Miller Inc. and American Ecology Services Inc., Cherry Hill, N.J., 5 and 6 October 1981.
33. J. Quarles, *Federal Regulation of Hazardous Wastes: A Guide to RCRA* (Environmental Law Institute, Washington, D.C., 1982).
34. Environmental Protection Agency, *Planning Workshops to Develop Recommendations for a Ground Water Protection Strategy* (PB81-122624, Office of Drinking Water, Environmental Protection Agency, Washington, D.C., 1980).
35. Environmental Protection Agency, *Proposed Ground Water Protection Strategy* (Washington, D.C., 1980).
36. *Environ. Rep.* **13**, 907 (29 October 1982).
37. Redrawn from the Environmental Protection Agency, *The Report to Congress: Waste Disposal Practices and Their Effects on Ground Water* (Environmental Protection Agency, Washington, D.C., 1977).

38. For advice on the subject matter discussed in this article, we thank G. Wolman, S. Samuels, M. McCloskey, T. Clark, G. Paulson, D. Smith, J. Pennick, and H. Elkin. Sections of the larger report on which this article is based were reviewed by J Keeley, R. S. Kerr, R. Tucker, J. Lehr, J. Kotas, J. Aitcheson, R. Heckert, J. Geraghty, L. Canter, D. Burmaster, N. E. Armstrong, P. Buckingham, J. Bredehoeft, A. Wolman, K. Kawata, and G. Comstock. We particularly thank J. Kelley and S. Roberts for technical help. This work was made possible by the Environmental Assessment Council of the Academy of Natural Sciences in Philadelphia, a grant from the Glenmede Trust Company, and a gift from Laurance Rockefeller.