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**Chapter 2**  
**Groundwater Contamination**  
**and Its Impacts**

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# Groundwater Contamination and Its Impacts

## CHAPTER OVERVIEW

Groundwater is an increasingly important resource in the United States—it is relied on for about 50 percent of drinking water supplies; it is used to supply water for almost 80 percent of rural domestic and livestock needs, about 40 percent of irrigation needs, many commercial activities, and almost 25 percent of self-supplied industrial needs (other than thermoelectric power); it is used for stream flow maintenance and as a barrier to salt-water intrusion; and it is both an intentional and unintentional depository for society's waste and non-waste products (USGS, 1983a).

The degree of reliance on groundwater varies significantly around the Nation. For example, groundwater withdrawals for public water supplies vary from 11 percent in the Great Lakes region to 75 percent in the Rio Grande region, for rural uses from 12 percent in the Upper Colorado to 100 percent in New England, and for irrigation from 1 percent in the Upper Colorado to over 90 percent in the Upper Mississippi.

Contamination of the Nation's groundwater resource has recently become an issue of widespread public concern. This chapter analyzes current knowledge about the nationwide extent of contamination, the substances known to occur in groundwater and their associated impacts, and known sources of contamination. Specific topics addressed are:

- the extent of groundwater contamination and difficulties in its assessment;
- substances known to occur in groundwater and their uses;
- health impacts of contamination;
- non-health impacts of contamination (e. g., economic and environmental impacts);

- concentration and frequency of compounds in groundwater;
- potential but as yet undetected substances in groundwater;
- types of sources and their associated substances;
- factors influencing a source's potential to contaminate groundwater (including estimates of numbers of sources and amounts of material flowing through or stored in sources); and
- the potential for sources to contaminate groundwater.

Major conclusions drawn from this information are summarized below.

The portion of the Nation's groundwater resources that is contaminated is believed by experts to be small. No matter how small, this portion is nevertheless significant because of its location near heavily populated areas and because of the many uses of and increasing dependence on groundwater. The site-to-site variability of contamination, combined with the expense and time required to investigate potential contamination problems, means that a detailed nationwide description of groundwater quality may never be attainable.

A variety of adverse impacts due to groundwater contamination is possible—including effects on public health, the environment, agricultural productivity (e. g., due to increased salinity in irrigation water), and on the output of industries requiring high-quality water. Public attention has focused primarily on the potential for health effects; because little information is available on other impacts, this chapter focuses on potential damage to human health.

Even if a comprehensive description of groundwater quality were available, the magnitude and exact nature of public health effects resulting from contamination could not be estimated with confidence. At best, evidence would involve the documentation of effects attributable to contamination,

<sup>1</sup>Substance is defined in this study as any organic or inorganic chemical, micro-organism, radionuclide, or other material (e. g., sediments). Whether or not a substance is a 'contaminant' depends on its association with adverse impacts and on other site-specific factors (e. g., hydrogeology).

with predictions regarding the magnitude and types of future effects. This type of information is typically obtained from risk assessment analyses, wherein data on: 1) the adverse effects and 2) toxicity (i. e., dosage levels at which adverse effects are observed) of substances are linked with 3) exposure data to identify probabilities of adverse impacts on human health.

Data limitations preclude a risk assessment of the magnitude of public health risks from groundwater. Some of the data required for risk assessment analysis of groundwater contamination are available, primarily regarding known or possible hazards and known toxicities, but much of this information is not precise enough. Almost no data are available on human exposure to the substances of concern. These types of data are not likely to be obtainable in sufficient detail in most cases because of the inherent limitations of epidemiological investigations. For example, data would be needed—and, again, are probably unattainable—on the amount of exposure to substances from only groundwater (e. g., as opposed to exposure to the same substances from other media such as air and surface water), on the number of people exposed to various concentrations, and on interactions among substances when more than one substance is present.

Although the magnitude of the impacts of groundwater contamination cannot be estimated with confidence, the *nature* of many impacts is known. There is also a substantial body of indirect evidence indicating the large *potential* for groundwater contamination and subsequent health effects. Over 200 substances have already been detected in groundwater—substances that are used throughout society

in a multiplicity of commercial, industrial, and household activities. For some, but not all, of these known substances, information is available about their adverse effects on laboratory animals and humans, toxicity levels, and the range of concentrations found in groundwater. Many of the substances present in groundwater can cause liver and kidney damage, damage to the central nervous system, cancers, and eye and skin irritation.

The pathways by which substances eventually enter groundwater are diverse and extremely complex—i.e., they can enter during production, handling, storage, processing, disposal, transport, and use. One focal point along these pathways, which Congress has started to address in recent legislation, is the *sources* from which contaminants enter groundwater. Sources of contamination are convenient for assessing possible detection, correction, and prevention actions. At least 33 major sources are known. There is a vast diversity among sources in terms of their associated substances, release characteristics, amounts of materials, geographic location, and role in society.

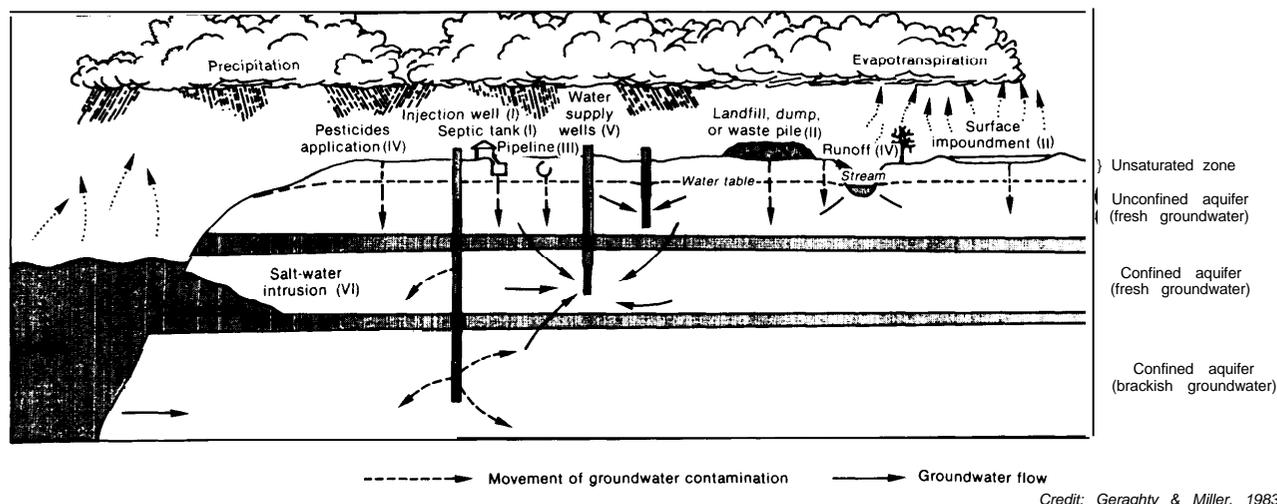
So far, most attention given to sources has concerned waste discharges (particularly hazardous wastes) from point sources. As shown by OTA'S analysis, many potential sources of contamination also are associated with both non-hazardous wastes and non-waste products; and contaminants can enter groundwater from both point and non-point sources. Important advances have been made in the information base concerning sources since the U.S. Environmental Protection Agency's 1977 Report to Congress on waste disposal practices (EPA, 1977),

## EXTENT AND NATURE OF GROUNDWATER CONTAMINATION

### *Assessing the Nationwide Extent of Groundwater Contamination*

Although contamination of surface water has long been of concern to the public and to Congress—as demonstrated by passage of the Federal Water Pollution Control Act (the Clean Water Act)

and the Safe Drinking Water Act—groundwater contamination has historically received little attention at the national level. One major reason was the common belief that groundwater was pristine, i.e., that potential contaminants percolating through the subsurface would adhere to the soil or be degraded by natural processes and, therefore, would



Pathways of groundwater contamination vary depending on the source. Examples of sources are shown here for each of OTA'S six source categories (I-VI) (see the section on Types of Sources and Associated Substances, below).

not enter or greatly affect groundwater quality. Thus the subsurface, and groundwater, had been regarded as a safe and convenient depository for the wastes and non-waste byproducts generated by society.

But there is a growing consensus that the quality of groundwater is in decline. Incidents of contamination are being reported with increasing frequency and have now occurred in every State. Although the activities and practices that cause contamination are varied and were often begun many years ago, groundwater contamination recently has come to the attention of the public, primarily in the context of threats to human health. Most of the attention has focused on sources associated with hazardous wastes (e. g., landfills, surface impoundments, and waste piles) because of the severity of their impacts on surrounding populations and environments—groundwater has been seriously contaminated by toxic chemicals associated with these sources in at least 34 States (CEQ 1981). However, non-hazardous wastes and non-wastes also contribute to the contamination of groundwater.

A small amount of the Nation's groundwater is generally believed to be contaminated (estimates range from about 1-2 percent). Although this portion may seem very small, it is significant because

contamination is often near heavily populated areas and groundwater is being increasingly relied on for a variety of uses.

The extent of groundwater contamination is also likely to be greater than 1-2 percent. Descriptions of groundwater quality problems often include anecdotal or non-comparable data, making them difficult to interpret and analyze. In addition, much of the current information on the extent and magnitude of contamination reflects only the nature of investigations—where and which substances have been looked for and where they have been found. For example, groundwater that is not used for public drinking water supplies is not always tested, and more information is generally available about hazardous waste sources than about non-point sources and sources with non-hazardous wastes and non-waste products. Further, substances known to contaminate groundwater are used throughout society; thus, more widespread detection of contamination can be expected as efforts increase to monitor known, as yet undetected, and potential problems. Little is known about how much contamination is reversible and how rapidly new sites and sources of contamination are being created.

A complete description of contamination would require detailed information about groundwater



Photo credit: State of Florida Department of Environmental Regulation

Thirty-four of the 100 largest cities in the United States rely completely or partially on groundwater.

quality on a site-by-site basis throughout the Nation and about associated site-specific hydrogeologic conditions (e. g., the vulnerability of groundwater to the entrance of substances). A difficulty in assessing the extent of groundwater contamination is that not all substances entering groundwater may have adverse impacts. Whether the presence of substances in groundwater results in a contamination problem depends on site-specific hydrogeology, the potential for adverse impacts (health, economic, environmental, and social), current and future groundwater use patterns, the exposure of humans to the substances, the availability of alternative water supplies, and the feasibility of corrective measures including management alternatives.

The lack of data about groundwater quality stems from the technical complexity of groundwater. Groundwater and associated problems often cannot be directly observed and are not easily meas-

ured, and the behavior of substances in groundwater is not well understood—the movement of substances varies temporally and spatially in different hydrogeologic environments, and chemical and biological processes can alter the nature and subsequent behavior of substances. For these reasons, groundwater contamination problems are highly site-specific. Given this complexity and the costs and time that would be needed to gather data, a complete description of groundwater quality may never, for all practical purposes, be attainable.

### ***Substances Known to Occur in Groundwater***

As part of the OTA study, information was gathered that documents the presence of over 200 substances known to occur in the Nation's groundwater. Specific substances detected in groundwater

thus far, and examples of major uses of these substances, are shown in table 1. These substances include about 175 organic chemicals, over 50 inorganic chemicals (metals, non-metals, and inorganic acids), biological organisms, and radionuclides.

The presence of substances in groundwater and an understanding of how, why, and where they are present are directly related to their use and/or disposition. As shown in table 1, many substances found in groundwater are widely used by industry, agriculture, commerce, and households. Potential contaminants can thus enter groundwater at numerous points as materials flow through society. Although most points-of-entry are associated with particular sources, the sources themselves are not the only places for controlling the entry of substances to groundwater (preventive strategies are discussed in chs. 11 and 12). However, focusing on sources is convenient to assess how substances enter groundwater. The relationship between substances and specific sources is discussed below in *Types of Sources and Associated Substances*.

Detection of substances in groundwater is biased not only by sampling and analytical limitations (see ch. 5) but also by the circumstances that prompted detection and reporting. There appear to be two major circumstances under which substances are being detected in groundwater: 1) as the result of planned activities (e. g., regulatory compliance, analysis and data management activities, routine monitoring, research, and liability protection); and 2) in response to apparent impacts (e. g., citizen complaints stemming from the observable or feared presence of substances, accidents, and aerial photography) (University of Oklahoma, 1983). The two most frequently cited reasons for detection of substances are regulatory compliance as a planned activity and response to public complaints. Reliance on public observation probably will not lead to the detection of many substances—most substances of concern are odorless, colorless, and otherwise unobservable without use of special analytical equipment.

## HEALTH IMPACTS

### *General Issues*

Many naturally occurring and synthetic substances can cause biological injury, disease, or death under certain conditions of exposure. Whether injury or illness occurs depends on many factors, including properties of the substance, dosage of and exposure to the substance, and characteristics of the individuals exposed. Many of the diseases and effects associated with groundwater contaminants are discussed below; however, data are insufficient for determining the relative importance of these contaminants in causing various effects.

Relationships between health impacts and different groups of substances—organic and inorganic chemicals (non-radioactive), micro-organisms, and radionuclides—are not understood with the same degree of knowledge and certainty. For example, there is a long history of public health efforts to un-

derstand and address micro-organisms, albeit primarily in surface water, and many sources of data are available. Radionuclides have been studied extensively since the 1940s, and much is *now* known about their health impacts, although not often at low concentrations. In contrast, health effects resulting from exposure to many chemicals are not well understood, in large part because of the relatively recent occurrence of and exposure to certain chemicals in the environment. Health effects of chemicals are of the greatest concern because chemicals are pervasive and persist in the environment.

Assessing risks from substances in groundwater requires information about adverse effects, toxicity, and exposure (extensive details on risk assessment are available in NAS, 1983, and Environ Corp. , 1983; a brief summary is presented in app. A. 1.); and available data are often insufficient to conduct such an assessment. Thus human health impair-

**Table 1.—Substances Known to Occur in Groundwater, Ranges of Detected Concentrations, Exceeded Standards, Examples of Uses, and Quantitative Estimates of Carcinogenic Potency and Noncarcinogenic Toxicity<sup>a</sup>**

Contaminant	Concentration <sup>b</sup> (parts per billion)	Standard <sup>c</sup>	Examples of uses <sup>d</sup>	Carcinogenicity <sup>e,f</sup>	Noncarcinogenic toxicity <sup>e,g</sup>
<b>Aromatic hydrocarbons</b>					
Acetanilide-			Intermediate manufacturing, pharmaceuticals, dyestuffs		
Alkyl benzene sulfonates		•	Detergents		
Aniline			Dyestuffs, intermediate, photographic chemicals, pharmaceuticals, herbicides, fungicides, petroleum refining, explosives		
Anthracene	1 <sup>8</sup>		Dyestuffs, intermediate, semiconductor research		
Benzene	0.6-20,230	*	Detergents, intermediate, solvents, antiknock gasoline	Low	
Benzidine			Dyestuffs, reagent, stiffening agent in rubber compounding	High	
Benzyl alcohol			Solvent, perfumes and flavors, photographic developer inks, dyestuffs, intermediate		
Butoxymethylbenzene			NA <sup>i</sup>		
Chrysene	10		Organic synthesis		
Creosote mixture			Wood preservatives, disinfectants		
Diben[a.h.]anthracene			NA <sup>i</sup>		
Di-butyl-p-benzoquinone			NA <sup>i</sup>		
Dihydrotrimethylquinoline			Rubber antioxidant		
4,4-Dinitrosodiphenylamine			NA <sup>i</sup>		
Ethyl benzene	0.9-4,000	*	Intermediate, solvent		Low
Fluoranthene	31	•	NA <sup>i</sup>		
Fluorene			Resinous products, dyestuffs, insecticides		
Fluorescein			Dyestuffs		
Isopropyl benzene	290		Solvent, chemical manufacturing		
4,4'-Methylene-bis-2-chloroaniline (MOCA)			Curing agent for polyurethanes and epoxy resins	Low	
Methylthio benzothiazole			—		
Naphthalene	6.7-82	•	Solvent, lubricant, explosives, preservatives, intermediate, fungicide, moth repellent		Low
o-Nitroaniline			Dyestuffs, intermediate, interior paint pigments, chemical manufacturing		
Nitrobenzene			Solvent, polishes, chemical manufacturing		Moderate
4-Nitrophenol			Chemical manufacturing		
n-Nitrosodiphenylamine			Pesticides, retarder of vulcanization of rubber		
Phenanthrene	18-471 <sup>h</sup>		Dyestuffs, explosives, synthesis of drugs, biochemical research		
n-Propylbenzene			Dyestuffs, solvent		
Pyrene	48		Biochemical research		Low
Styrene (vinyl benzene)		•	Plastics, resins, protective coatings, intermediate		Low
Toluene	0.1-6,400	*	Adhesive solvent in plastics, solvent, aviation and high octane blending stock, diluent and thinner, chemicals, explosives, detergents		
1,2,4-Trimethylbenzene			Manufacture of dyestuffs, pharmaceuticals, chemical manufacturing		
Xylenes (m,o,p)	0.07-300	•	Aviation gasoline, protective coatings, solvent, synthesis of organic chemicals		Low
<b>Oxygenated hydrocarbons</b>					
Acetic acid			Food additives, plastics, dyestuffs, pharmaceuticals, photographic chemicals, insecticides		Low

**Table 1.—Substances Known to Occur in Groundwater, Ranges of Detected Concentrations, Exceeded Standards, Examples of Uses, and Quantitative Estimates of Carcinogenic Potency and Noncarcinogenic Toxicity<sup>a</sup>—continued**

Contaminant	Concentration <sup>b</sup>	Standard <sup>c</sup>	Examples of uses <sup>d</sup>	Carcinogenic potency <sup>e,f</sup>	Noncarcinogenic toxicity <sup>e,g</sup>
<b>Oxygenated hydrocarbons (cent'd) (parts per billion)</b>					
Acetone	10-3,000		Dyestuffs, solvent, chemical manufacturing, cleaning and drying of precision equipment		Low
Benzophenone			Organic synthesis, odor fixative, flavoring, pharmaceuticals		Low
Butyl acetate			Solvent		
n-Butyl-benzylphthalate	10-38		Plastics, intermediate		
Di-n-butyl phthalate	470	•	Plasticizer, solvent, adhesives, insecticides, safety glass, inks, paper coatings		Low
Diethyl ether			Chemical manufacturing, solvent, analytical chemistry, anesthetic, perfumes		
Diethyl phthalate		•	Plastics, explosives, solvent, insecticides, perfumes		
Diisopropyl ether	20-34		Solvent, rubber cements, paint and varnish removers		
2,4-Dimethyl-3-hexanol			Intermediate, solvent, lubricant		
2,4-Dimethyl phenol			Pharmaceuticals, plastics, disinfectants, solvent, dyestuffs, insecticides, fungicides, additives to lubricants and gasolines		
Di-n-octyl phthalate	23		Plasticizer for polyvinyl chloride and other vinyls		
1,4-Dioxane	2,100		Solvent, lacquers, paints, varnishes, cleaning and detergent preparations, fumigants, paint and varnish removers, wetting agent, cosmetics		
Ethyl acrylate			Polymers, acrylic paints, intermediate		
Formic acid			Dyeing and finishing, chemicals, manufacture of fumigants, insecticides, solvents, plastics, refrigerants		
Methanol (methyl alcohol)			Chemical manufacturing, solvents, automotive antifreeze, fuels		High
Methylcyclohexanone			Solvent, lacquers		
Methyl ethyl ketone			Solvent, paint removers, cements and adhesives, cleaning fluids, printing, acrylic coatings		
Methylphenyl acetamide			Na		
Phenols (e.g., p-Tert-butylphenol)	10-234,000	•	Resins, solvent, pharmaceuticals, reagent, dyestuffs and indicators, germicidal paints		
Phthalic acid			Dyestuffs, medicine, perfumes, reagent		
2-Propanol			Chemical manufacturing, solvent, deicing agent, pharmaceuticals, perfumes, lacquers, dehydrating agent, preservatives		
2-Propyl-1-heptanol			Solvent		
Tetrahydrofuran			Solvent		
Varsol			Paint and varnish thinner		
<b>Hydrocarbons with specific elements (e.g., with N, P, S, Cl, Br, I, F)</b>					
Acetyl chloride			Dyestuffs, pharmaceuticals, organic preparations		
Alachlor (Lasso)	190-1,700	•	Herbicides		Moderate
Aldicarb (sulfoxide and sulfone; Temik)	38-405	•	Insecticide, nematocide		High
Aldrin		•	Insecticides	High	
Atrazine		•	Herbicides, plant growth regulator, weed control agent		Moderate
Benzoyl chloride		•	Medicine, intermediate		
Bromacil	72-110		Herbicides		Moderate
Bromobenzene	1.9-5.8		Solvent, motor oils, organic synthesis		Moderate

**Table 1.—Substances Known to Occur in Groundwater, Ranges of Detected Concentrations, Exceeded Standards, Examples of Uses, and Quantitative Estimates of Carcinogenic Potency and Noncarcinogenic Toxicity<sup>a</sup>—continued**

Contaminant	Concentration <sup>b</sup>	Standard <sup>c</sup>	Examples of uses <sup>d</sup>	Carcinogenic potency <sup>e,f</sup>	Noncarcinogenic toxicity <sup>e,g</sup>
<b>Hydrocarbons with specific elements</b>					
(e.g., with N,P,S,Cl,B;I,F) (cent'd)	(parts per billion)				
Bromochloromethane	—		Fire extinguishers, organic synthesis		Low
Bromodichloromethane	1.4-110	*	Solvent, fire extinguisher fluid, mineral and salt separations		
Bromoform	2.4-110		Solvent, intermediate		Moderate
Carbofuran	4-160	*	Insecticide, nematocide		Moderate
Carbon tetrachloride	0.3-18,700	*	Degreasers, refrigerants and propellants, fumigants, chemical manufacturing	Moderate	
Chlordane		•	Insecticides, oil emulsions		
Chlorobenzene	2.7-41	•	Solvent, pesticides, chemical manufacturing		Moderate
Chloroform	1.4-1,890	*	Plastics, fumigants, insecticides, refrigerants and propellants		
Chlorohexane	—		NA <sup>i</sup>		
Chloromethane (methyl chloride)	44		Refrigerants, medicine, propellants, herbicide, organic synthesis		Low
Chloromethyl sulfide			NA <sup>i</sup>		
2-Chloronaphthalene	83		Oil: plasticizer, solvent for dyestuffs, varnish gums and resins, waxes wax: moisture, flame, acid, and insect-proofing of fibrous materials; moisture- and flame-proofing of electrical cable; solvent (see oil)		
Chlorpyrifos			NA <sup>i</sup>		
Chlorthal-methyl (DCPA, or Dacthal)			Herbicide		
o-Chlorotoluene	2.4		Solvent, intermediate		
p-Chlorotoluene	—		Solvent, intermediate		
Dibromochloromethane	2.1-55		Organic synthesis		
Dibromochloropropane (DBCP)	1-137	*	Fumigant, nematocide		
Dibromodichloroethylene	—		NA <sup>i</sup>		
Dibromoethane (ethylene dibromide, EDB)	35-300	*	Fumigant, nematocide, solvent, waterproofing preparations, organic synthesis		
Dibromomethane	44.9		Organic synthesis, solvent		
Dichlofenthion (DCFT)	—		Pesticides		
o-Dichlorobenzene	2.7	•	Solvent, fumigants, dyestuffs, insecticides, degreasers, polishes, industrial odor control		Moderate
p-Dichlorobenzene	0.6-0.7	*	Insecticides, moth repellent, germicide, space odorant, intermediate, fumigants		Moderate
Dichlorobenzidine			Intermediate, curing agent for resins	Moderate	
Dichlorocyclooctadiene			Pesticides		
Dichlorodiphenyldichloroethane (DDD, TDE)			Insecticides		Low
Dichlorodiphenyldichloroethylene (DDE)	0.01-0.8		Degradation product of DDT, found as an impurity in DDT residues		
Dichlorodiphenyltrichloroethane (DDT)	0.05-0.22	•	Pesticides	High	
1,1-Dichloroethane	0.5-11.330		Solvent, fumigants, medicine		Low

**Table 1.—Substances Known to Occur in Groundwater, Ranges of Detected Concentrations, Exceeded Standards, Examples of Uses, and Quantitative Estimates of Carcinogenic Potency and Noncarcinogenic Toxicity<sup>a</sup>—continued**

Contaminant	Concentration <sup>b</sup>	Standard <sup>c</sup>	Examples of uses <sup>d</sup>	Carcinogenic potency <sup>e,f</sup>	Noncarcinogenic toxicity <sup>e,g</sup>
<b>Hydrocarbons with specific elements (e.g., with N,P,S,Cl,Br,I,F) (cont'd)</b>					
1,2-Dichloroethane	(parts per billion) 250–847	*	Solvent, degreasers, soaps and scouring compounds, organic synthesis, additive in antiknock gasoline, paint and finish removers	Low	
1,1-Dichloroethylene (vinylidene chloride)	1.2–4,000	*	Saran (used in screens, upholstery, fabrics, carpets, etc.), adhesives, synthetic fibers	Moderate	
1,2-Dichloroethylene (cis and trans)	0.2–323		Solvent, perfumes, lacquers, thermoplastics, dye extraction, organic synthesis, medicine		
Dichloroethyl ether	1,100		Solvent, organic synthesis, paints, varnishes, lacquers, finish removers, drycleaning, fumigants		
Dichlorodimethane	2.8–4.1		NA <sup>i</sup>		
Dichloroisopropylether (= B chloroisopropylether)			Solvent, paint and varnish		
Dichloromethane (methylene chloride)	4–8,400		Solvent, plastics, paint removers, in foams		
Dichloropentadiene	0.0		NA <sup>i</sup>		
2,4-Dichlorophenol	1–85,000	•	Organic synthesis		
2,4-Dichlorophenoxyacetic acid (2,4-D)		•	Herbicides		Moderate
1,2-Dichloropropane	46–60	•	Solvent, intermediate, scouring compounds, fumigant, nematocide, additive for antiknock fluids		
Dieldrin		•	Insecticides	x	
Diiodomethane	2.0	•	Organic synthesis		
Disopropylmethyl phosphonate (DIMP)	—	•	Organic synthesis		
Dimethyl disulfide	—		NA <sup>i</sup>		
Dimethylformamide	—		Solvent, organic synthesis		
2,4-Dinitrophenol (Dinoseb, DNBP)	124–400		Herbicides		Moderate
Dioxins (e.g., TCDD)	—		Impurity in the herbicide 2,4,5-T	High	
Dodecyl mercaptan (lauryl mercaptan)	—		Manufacture of synthetic rubber and pharmaceuticals, insecticides, fungicides		
Endosulfan	0.0	•	Insecticides		
Endrin	—	•	Insecticides		
Ethyl chloride	—		Chemical manufacturing, anesthetic, solvent, refrigerants, insecticides		
Bis-2-ethylhexylphthalate	12–170		Plastics	Low	
Di-2-ethylhexylphthalate		•	Plasticizers		
Fluorobenzene	67		Insecticide and larvicide intermediate		
Fluoroform	3.5		Refrigerants, intermediate, blowing agent for foams		
Heptachlor	—	•	Insecticides		Moderate
Heptachlorepoxyde	—	•	Degradation product of heptachlor, also acts as an insecticide		
Hexachlorobicycloheptadiene	2.2		NA <sup>i</sup>		
Hexachlorobutadiene	2.53		Solvent, transformer hydraulic fluid, heat-transfer liquid		

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Contaminant	Concentration <sup>b</sup>	Standard <sup>c</sup>	Examples of uses <sup>d</sup>	Carcinogenic potency <sup>e,f</sup>	Noncarcinogenic toxicity <sup>e,g</sup>
<b>Hydrocarbons with specific elements (e.g., with N,P,S,Cl,Br,I,F) (cont'd)</b>					
α-Hexachlorocyclohexane (= Benzenehexachloride, or α-BHC)	6	•	Insecticides		
β-Hexachlorocyclohexane (β-BHC)	3.8	•	Insecticides		
γ-Hexachlorocyclohexane (γ-BHC, or Lindane)	0.5-43	•	Insecticides		Moderate
Hexachlorocyclopentadiene			Intermediate for resins, dyestuffs, pesticides, fungicides, pharmaceuticals		
Hexachloroethane	4.6		Solvent, pyrotechnics and smoke devices, explosives, organic synthesis	Low	
Hexachloronorbomadiene			N A		
Kepone		•	Pesticides		High
Malathion		•	Insecticides		
Methoxychlor		•	Insecticides		Moderate
Methyl bromide	7.4		Fumigants, pesticides, organic synthesis		
Methyl parathion	4.6	•	Insecticides		
Parathion	—	•	Insecticides		High
Pentachlorophenol (PCP)	—	•	Insecticides, fungicides, bactericide, algicides, herbicides, wood preservative		Moderate
Phorate (Disulfoton)		•	Insecticides		
Polybrominated biphenyls (PBBs)			Flame retardant for plastics, paper, and textiles		Low
Polychlorinated biphenyls (PCBs)	8-40	•	Heat-exchange and insulating fluids in closed systems	Moderate	
Prometon	—		Herbicides		
RDX (Cyclonite)	3,400	•	Explosives		
Simazine		•	Herbicides	Moderate	
Tetrachlorobenzene	5,-m	•	N A		
Tetrachloroethanes (1,1,1,2 & 1,1,2,2)	4	•	Degreasers, paint removers, varnishes, lacquers, photographic film, organic synthesis, solvent, insecticides, fumigants, weed killer	Moderate	
Tetrachloroethylene (or perchloroethylene, PCE)	717-2,405	•	Degreasers, drycleaning, solvent, drying agent, chemical manufacturing, heat-transfer medium, vermifuge	Low	
Toxaphene	1-570	•	Insecticides	Moderate	
Triazine	2		Herbicides		
1,2,4-Trichlorobenzene	37		Solvent, dyestuffs, insecticides, lubricants, heat-transfer medium (e.g., coolant)		
Trichloromethanes (1,1,1 and 1,1,2)	0.2-26,000	•	Pesticides, degreasers, solvent	Low	
1,1,2-Trichloroethylene (TCE)	210-37,000	•	Degreasers, paints, drycleaning, dyestuffs, textiles, solvent, refrigerant and heat exchange liquid, fumigant, intermediate aerospace operations	Low	
Trichlorofluoromethane (Freon 11)	26		Solvent, refrigerants, fire extinguishers, intermediate		Moderate
2,4,6-Trichlorophenol	—		Fungicides, herbicides, defoliant		Low
2,4,5-Trichlorophenoxyacetic acid (2,4,5-T)	—	•	Herbicides, defoliant		Moderate

**Tab 1.—Substances Known to Occur in Groundwater, Ranges of Detected Concentrations, Exceeded Standards, Examples of Uses, and Quantitative Estimates of Carcinogenic Potency and Noncarcinogenic Toxicity<sup>a</sup>—continued**

Contaminant	Concentration <sup>b</sup>	Standard <sup>c</sup>	Examples of uses <sup>d</sup>	Carcinogenic potency <sup>e</sup>	Noncarcinogenic toxicity <sup>e,g</sup>
<b>Hydrocarbons with specific elements (e.g., with N,P,S,Cl,Br,I,F) (cont'd)</b>					
2,4,5-Trichlorophenoxypropionic acid (2,4,5-TP or Silvex)	—	•	Herbicides and plant regulator		High
Trichlorotrifluoroethane	35-135		Drycleaning, fire extinguishers, refrigerants, intermediate, drying agent		
Trinitrotoluene (TN <sup>+</sup> )	620-12,600	*	Explosives, intermediate in dyestuffs and photographic chemicals		
Tris-(2,3-dibromopropyl) phosphate	50-740	•	Flame retardant		
Vinyl chloride	—	•	Organic synthesis, polyvinyl chloride and copolymers, adhesives	Low	
<b>Other hydrocarbons</b>					
Alkyl sulfonates	—		Detergents		
Cyclohexane	540		Organic synthesis, solvent, oil extraction		
1,3,5,7-Cyclooctatetraene	—		Organic research		
Dicyclopentadiene (DCPD)	—		Intermediate for insecticides, paints and varnishes, flame retardants		
2,3-Dimethylhexane	—		NA <sup>1</sup>		
Fuel oil	2,000-9,000	*	Fuel, heating		
Gasoline	—		Fuel		
Jet fuels	—		Fuel		
Kerosene	243,000		Fuel, heating, solvent, insecticides		
Lignin	7,500 <sup>1</sup>		Newsprint, ceramic binder, dyestuffs drilling fuel additive, plastics		
Methylene blue activated substances (MBAs)	11	•	Dyestuffs, analytical chemistry		
Propane	—		Fuel, solvent, refrigerants, propellants, organic synthesis		
Tannin	7,500		Chemical manufacturing, tanning, textiles, electroplating, inks, pharmaceuticals, photography, paper		
4,6,8-Trimethyl-1-nonene	—		NA <sup>1</sup>		
Undecane	—		Petroleum research, organic synthesis		
<b>Metals and c: b</b>					
Aluminum	(parts million) 0.1-1,200	*	Alloys, foundry, paints, protective coatings, electrical industry, packaging, building and construction, machinery and equipment	High	Moderate
Antimony	—		Hardening alloys, solders, sheet and pipe, pyrotechnics		
Arsenic	0.01-2,100	*	Alloys, dyestuffs, medicine, solders, electronic devices, insecticides, rodenticides, herbicide, preservative	High	
Barium	2.8-3.8	•	Alloys, lubricant		
Beryllium	less than 0.0 <sup>1</sup>	†	Structural material in space technology, inertial guidance systems, additive to rocket fuels, moderator and reflector of neutrons in nuclear reactors	Moderate	
Cadmium	0.01-180	*	Alloys, coatings, batteries, electrical equipment, fire protection systems, paints, fungicides, photography		High
Calcium	0.5-225		Alloys, fertilizers, reducing agent		

**Table 1.—Substances Known to Occur in Groundwater, Ranges of Detected Concentrations, Exceeded State Quantitative Estimates of Carcinogenic Potency and Noncarcinogenic Toxicity<sup>a</sup>—c**

Contaminant	Concentration <sup>b</sup>	Standard <sup>c</sup>	Examples of uses <sup>d</sup>
<b>Metals and cations (cent'd)</b>	(parts per million)	(parts per million)	
Chromium	0.06-2,740	0.06-2,740	Alloys, protective coatings, paint, High temperature research
Cobalt	0.01-0.18	0.01-0.18	Alloys, ceramics, drugs, paint, electroplating, lamp filaments
Copper	0.01-2.8	0.01-2.8	Alloys, paints, electrical wiring materials, electroplating, paint
Iron	0.04-6,200	0.04-6,200	Alloys, machinery, magnets
Lead	0.01-5.6	0.01-5.6	Alloys, batteries, gasoline additives, radiation shielding
Lithium	—	—	Alloys, pharmaceuticals, coolants
Magnesium	0.2-70	0.2-70	Alloys, batteries, pyrotechnic mirrors
Manganese	0.1-110	0.1-110	Alloys, purifying agent
Mercury	0.003-0.01	0.003-0.01	Alloys, electrical apparatus, pigments, mildew-proofing, pesticides
Molybdenum	0.4-40	0.4-40	Alloys, pigments, lubricant
Nickel	0.05-0.5	0.05-0.5	Alloys, ceramics, batteries, pigments
Palladium	—	—	Alloys, catalyst, jewelry, protective equipment
Potassium	0.5-2.4	0.5-2.4	Alloys, catalyst
Selenium	0.6-20	0.6-20	Alloys, electronics, ceramics
Silver	9-330	9-330	Alloys, photography, chemical tronic equipment, jewelry, ticals
Sodium	3.1-211	3.1-211	Chemical manufacturing, catalysts for highways, laboratory reagents
Thallium	—	—	Alloys, glass, pesticides, pharmaceuticals
Titanium	—	—	Alloys, structural materials, pigments
Vanadium	243	243	Alloys, catalysts, target materials
Zinc	0.1-240		Alloys, electroplating, electronics, automotive parts, fungicides, roofing, cable wrappings, nutrition
<b>Nonmetals and anions</b>			
<b>Ammonia</b>	1-900		Fertilizers, chemical manufacturing, refrigerants, synthetic fibers, fuels, dyestuffs
Boron	—		Alloys, fibers and filaments, semi-conductors, propellants
Chlorides	1,0-49,500		Chemical manufacturing, water purification, shrink-proofing, flame-retardants, food processing
Cyanides	1.05-14		Polymer production (heavy duty tires), coatings, metallurgy, pesticides
Fluorides	0.1-250		Toothpastes and other dentrifices, additive to drinking water
Nitrates	1.4-433		Fertilizers, food preservatives
Nitrites			Fertilizers, food preservatives
Phosphates	0.4-33		Detergents, fertilizers, food additives
Sulfates	0.2-32,318		Fertilizers, pesticides
Sulfites	—		Pulp production and processing, food preservatives

**Table I.—Substances Known to Occur in Groundwater, Ranges of Detected Concentrations, Exceeded Standards, Examples of Uses, and Quantitative Estimates of Carcinogenic Potency and Noncarcinogenic Toxicity<sup>a</sup>—continued**

Contaminant	Concentration <sup>b</sup>	Standard <sup>c</sup>	Examples of uses <sup>d</sup>	Carcinogenic potency <sup>e,f</sup>	Noncarcinogenic toxicity <sup>e,g</sup>
<b>Micro-organisms</b>	(parts per million)				
Bacteria (coliform)	—	•			
Viruses					
<b>Radionuclides</b>	(picocuries per milliliter)				
Cesium 137	—		Gamma radiation source for certain foods		
Chromium 51			Diagnosis of blood volume, blood cell life, cardiac output, etc.		
Cobalt 60	6.4		Radiation therapy, irradiation, radiographic testing, research		
Iodine 131			Medical diagnosis, therapy, leak detection, tracers (e.g., to study efficiency of mixing pulp fibers, chemical reactions, and thermal stability of additives to food products), measuring film thicknesses		
Iron 59	—		Medicine, tracer		
Lead 210	—		NA <sup>i</sup>		
Phosphorus 32	—		Tracer, medical treatment, industrial measurements (e.g., tire tread wear and thickness of films and ink)		
Plutonium 238, 243			Energy source weaponry		
Radium 226	0.8-25		Medical treatment, radiography		
Radium 228	12.5		NA <sup>i</sup>		
Radon 222	—	•	Medicine, leak detection, radiography, flow rate measurement		
Ruthenium 106	—		Catalyst		
Scandium 46	—		Tracer studies, leak detection, semi-conductors		
Strontium 90	0.817	•	Medicine, industrial applications (e.g., measuring thicknesses, density control)		
Thorium 270	—		NA <sup>i</sup>		
Tritium	150-353	•	Tracer, luminous instrument dials		
Uranium 238	10-500	•	Nuclear reactors		
Zinc 65	—		Industrial tracer (e.g., to study wear in alloys, galvanizing, body metabolism, function of oil additives in lubricating oils)		
Zirconium 95	—		NA <sup>i</sup>		

<sup>a</sup>Based on Abrams, et al., 1975; Bryant, et al., 1983; Harris, et al., n.d.; O'Brien and Fisher, 1983; Tucker, 1981; University of Oklahoma, 1983; Hawley, 1977; Considine and Considine, 1983; Lewis and Tatken, 1980; and Windholz, et al., 1982.

<sup>b</sup>Concentrations represent single reported concentrations or ranges of reported groundwater or domestic well concentrations from references surveyed; they generally do not include concentrations at hazardous waste sites. Dash (—) indicates contaminant detected but concentration not reported. Note that units differ among categories; units are defined at the beginning of each contaminant category.

<sup>c</sup>Solid bullet means that at least one type of standard exists for the substance. Asterisk means that at least one standard is known to have been exceeded. Note that these refer to standards for individual substances; standards for groups of substances or other measurements such as BOD are listed in app. C.

<sup>d</sup>Listed uses are primarily industrial applications. Some substances occur naturally in groundwater and may not be a result of human activities.

<sup>e</sup>Absence of an entry does not necessarily mean that no adverse health effects are associated with that substance; rather, entries reflect data available to OTA. In addition, if a value was found for carcinogenic potency of a substance, no search for non-carcinogenic toxicity of that substance was made.

<sup>f</sup>Carcinogenic potency is measured either according to unit risks developed by EPA Carcinogen Assessment Group or according to estimated unit risk based on assessment by EPA Office of Pesticides and Toxic Substances (as reported in Environ Corp., 1983); carcinogens are listed only if peer-reviewed unit risk data are available. Unit risk = risk per unit of exposure, where unit of exposure is defined as lifetime average daily intake. Estimates of lifetime risk are obtained by multiplying unit risk by actual exposure. Potency categories are defined as (Environ. Corp., 1983):

High potency = unit risk greater than 5 (mg/kg/day)<sup>-1</sup>

Medium potency = unit risk equal to 0.1–5 (mg/kg/day)<sup>-1</sup>

Low potency = unit risk less than 0.1 (mg/kg/day)<sup>-1</sup>

<sup>g</sup>Noncarcinogenic toxicity is measured by Minimum Effective Dose (MED, the minimum dose known to cause adverse impact; Environ Corp., 1983):

High = MED less than 10 mg/kg body weight/day

Moderate = MED 10–100 mg/kg body weight/day

Low = MED greater than 100 mg/kg body weight/day.

<sup>h</sup>Value for combined anthracene and phenanthrene.

<sup>i</sup>NA — Information on use not available in standard references that were consulted.

<sup>j</sup>Value for combined lignin and tannin.

ment is not easily linked to substances found in groundwater. Adverse effects and toxicity are discussed below. With respect to exposure, five possible pathways of human exposure have been identified (Environ Corp., 1983):

1. direct ingestion through drinking;
2. inhalation of contaminants (e. g., during showering);
3. skin absorption from water;
4. ingestion of contaminated food; and
5. skin absorption from contaminated soil.

Except for drinking water containing known levels of substances, there appear to be no general models available for estimating exposure through these routes.

### ***Adverse Impacts of Chemicals***

Many of the chemicals detected in groundwater are known or suspected to cause a variety of adverse health effects, including depression of central nervous system functions, liver and kidney damage, and eye and skin irritation. Some of these chemicals are known or suspected human carcinogens. The discussion below summarizes the known adverse effects of individual chemicals found in groundwater; the data upon which the summary is based are shown in appendix A.2.

Much of the data reviewed below concerning the effects of chemicals is derived from experimental studies on laboratory animals, but some information (e. g., acute effects such as eye and skin irritation, some cancers) is based on studies of human populations. The inference of human health effects from animal studies is controversial and is reviewed elsewhere (Environ Corp., 1983). However, for many chemicals, data from laboratory studies are the only means available for assessing potential impacts upon humans. Although there is usually no direct, conclusive evidence that these effects are induced at the concentrations at which these chemicals are detected in groundwater, a variety of information— qualitative human health studies conducted at sites of groundwater contamination (e.g., at Hardeman County, TN; Harris, et al., no date), data on human health impacts of specific chemicals (whether studied directly in humans or in-

directly in laboratory animals), and much anecdotal information— suggests that the consumption of groundwater contaminated with chemicals can result in acute, subchronic, and chronic human health impacts. An important recent study shows a statistically significant relationship between two wells contaminated with chloroform and TCE and elevated leukemia and birth defect rates in Woburn, MA (reported in Science News, 1984).

Apart from the controversial nature of laboratory data, the information in appendix A.2 is a limited data base because:

- not all chemicals have been tested for all impacts,
- documentation is not available for cases in which specific impacts were *not* observed during studies of specific chemicals,
- chemicals that dominate the list of potential health effects are the ones that have been most thoroughly studied, and
- the data were obtained from secondary sources.

Thus the purpose of appendix A.2 is not to establish either that effects will be realized with certainty in exposed human populations or the probability of their occurrence. Rather, the information shown should be viewed as an indication of the nature of potential human health impacts from substances in groundwater.

A given effect can be caused by numerous chemicals (see app. A. 2). The effects associated with the largest numbers of chemicals include (in decreasing order of the number of chemicals known to cause these effects): eye and skin irritation, effects on the central nervous system, liver damage, lung and respiratory tract effects, kidney damage, cancers, and genetic mutation. Of these effects, and depending on dosage, central nervous system (CNS) damage, liver and kidney damage, and cancers may be the most commonly expected serious forms of adverse health impacts associated with known groundwater chemical contaminants (Environ Corp. , 1983). More specifically:

1. Liver, kidney, and CNS toxicants include ethylbenzene and toluene (alkyl-substituted benzenes); carbon tetrachloride, chloroform, and TCE (halogenated aliphatic hydrocarbons); bromobenzene, PBBs, and PCBs (halo-

genated aromatic hydrocarbons); chlordane, DDT, and toxaphene (chlorinated hydrocarbon pesticides); and some heavy metals.

2. Known or suspected carcinogens listed in table 1 include 32 of the organic chemicals—chlorinated aliphatic hydrocarbons and chlorinated hydrocarbon pesticides—and 5 of the heavy metals (3 of which may be active only via inhalation). The evidence for human carcinogenicity of some substances has been obtained from human studies and is quite strong. There is very little doubt that benzene, benzidine, inorganic arsenic, vinyl chloride, chromium, and nickel are human carcinogens (the latter two, however, are not likely to be present in groundwater in their carcinogenic forms).

Studies of experimental animals where the predominant effect is on the rodent liver provide the main evidence for carcinogenicity of chlorinated aliphatic hydrocarbons (e. g., carbon tetrachloride, chloroform, TCE, PCE, and others; note from above that vinyl chloride is an exception) and chlorinated hydrocarbon pesticides (e. g., aldrin, chlordane, DDT, dieldrin, heptachlor, toxaphene, and others). It is also possible that nitrates are transformed into nitrosamines, which are carcinogenic in laboratory animals (NAS, 1977).

In a review of 31 substances commonly found in groundwater (Crump, et al., 1980, cited in Harris, 1983), two compounds with known human carcinogenic effects were documented. In addition, 12 compounds (including six chlorinated aliphatic hydrocarbons and four chlorinated hydrocarbon pesticides) had carcinogenic effects in at least one laboratory animal species and two compounds had effects suggestive of carcinogenicity. Despite some scientific debate on the biological relevance of these findings for humans (Environ Corp., 1983), Federal regulatory agencies consider many of these substances potential human carcinogens. One compound had no observable effects in preliminary tests, and 14 chemicals had not even been tested in animal experiments.

3. Only a few compounds are known to be capable of damaging the reproductive system or causing birth defects, but some of them are widely used throughout society. The major

substances in this category are DBCP, vinyl chloride, EDB, benzene, toluene, and xylene (Harris, 1983) and selected chlorinated ethanes and phthalate esters, PCBs, and the chlorinated dibenzo-p-dioxins (Environ Corp., 1983).

4. Skin and eye irritation, particularly during showering and bathing, might be expected when chemicals are found in groundwater. Data suggest that these effects are reversible upon cessation of exposure.

### ***Potential Toxicity or Potency of Chemicals***

In addition to requiring information on the general adverse effects of groundwater contaminants, a standard risk assessment analysis requires information on the non-carcinogenic toxicity and carcinogenic potency of the chemicals. That is, adverse effects are associated with certain chemicals, but they are elicited at only certain dosages and/or exposure levels—and different chemicals have different abilities to elicit those effects. As part of OTA's study, chemicals found in groundwater were ranked according to their relative degree of non-carcinogenic toxicity and carcinogenic potency using dose-response data when available (see table 1; Environ Corp., 1983).<sup>2</sup> Three broad categories are defined: 'high,' 'moderate,' and 'low'; note that the definitions shown in table 1 are different for non-carcinogenic toxicity and carcinogenic potency.

Based on these broad rankings, the following general conclusions are drawn (Environ Corp., 1983):

1. Some chemicals are of high toxicity and can elicit non-carcinogenic responses (e. g., liver, kidney, and CNS damage) at relatively low doses and/or exposure levels. These chemicals include endosulfan, endrin, and kepone (pesticides), and heavy metals (see table 1).
2. Many other chemicals with potential to affect the liver, kidney, and CNS are of low to moderate toxicity and thus require higher doses and/or exposure levels to elicit these effects.

<sup>2</sup>The susceptibility of humans to various substances is also variable among individuals and is affected by factors such as age, general health, and genetic background.

These chemicals include trichlorofluoromethane, bromochloromethane, chloromethane, and 1,1 -dichloroethane (halogenated aliphatic hydrocarbons), bromobenzene and dichlorobenzene (halogenated aromatic hydrocarbons), and ethylbenzene and toluene (alkyl-substituted benzenes).

3. Substances with high to moderate carcinogenic potency can elicit carcinogenic responses at relatively low doses and/or exposure levels. These chemicals include aldrin, DDT, dieldrin, and chlordane (pesticides), carbon tetrachloride, chloroform, and 1,1 -dichloroethylene (halogenated aliphatic hydrocarbons), benzidine (an aromatic amine), and PCBs (halogenated aromatic hydrocarbons).

There are substantial numbers of chemicals known to occur in groundwater for which no toxicity or potency data are available (beyond some acute effects). Approximately two-thirds of the organic chemicals and one-half of the inorganic chemicals listed in table 1 may not have associated toxicity or potency data.<sup>3</sup> In addition, substances not generally thought of in terms of toxicity or potency (e. g., salt water, micro-organisms, or nitrates) can also contaminate aquifers, causing both health and non-health impacts.

<sup>3</sup>Data may be available for these substances in sources not reviewed by OTA.



Photo credit: State of Florida Department of Environmental Regulation

Research on health impacts will provide information now lacking about many groundwater contaminants.

## ***Interactions Among Multiple Chemicals***

One of the potentially most important, and as yet relatively unexplored, health issues of groundwater contamination is that contaminated aquifers usually contain more than one substance. Knowledge is almost totally lacking about possible interactions among combinations of substances. Such interactions, in which subsequent impacts are qualitatively and quantitatively different than expected (and usually greater—i.e., synergistic), are common in many chemical and biological processes (Odum, 1971).

At least one type of synergistic interaction has been identified that is of potential importance in groundwater: the liver toxicity of carbon tetrachloride, TCE, and 1,1,1-trichloroethane (halogenated aliphatic hydrocarbons) is known from animal experiments to increase greatly in the presence of alcohol. This effect has been confirmed in human case studies for carbon tetrachloride and TCE (Radike, et al., 1977; EPA, 1980a and b). Liver toxicity of TCE and PCE is also affected by Aroclor 1254, a polychlorinated biphenyl (PCB) (see NRDC, 1982; EPA, 1980c).

## ***Biological Substances***

Pathogenic biological organisms that have been found in groundwater include:

1. bacteria (e. g., typhoid, bacillary dysentery, cholera, gastroenteritis, and tuberculosis);
2. viruses (e. g., enteroviruses and hepatitis); and
3. parasites (e. g., protozoa, worms, and fungi).

The micro-organisms most frequently found in groundwater are bacteria that inhabit the gastrointestinal tract, and the most common category of disease resulting from micro-organisms in groundwater is gastrointestinal. Contaminated groundwater was identified as the cause of approximately one-half of all outbreaks of acute waterborne disease occurring in the United States from 1971 to 1977, and bacterial contamination has been the most frequently identified source of groundwater-related disease outbreaks (e. g., EPA cites 94 such outbreaks between 1945 and 1980; see Environ Corp., 1983). The potential for bacterial contami-

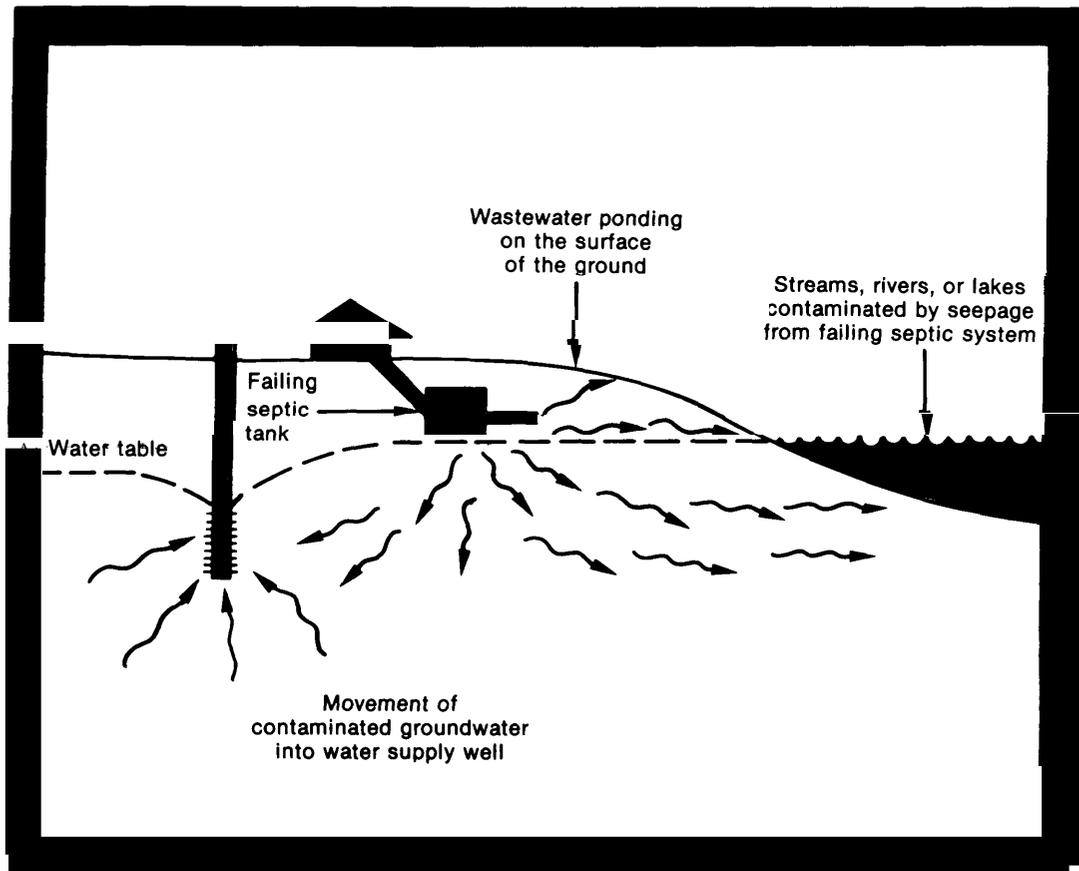
nation of groundwater depends on both the survival rate of the species and characteristics of the subsurface (e. g., moisture content, pH, and temperature). Bacterial contamination most commonly results from the introduction of human (or animal) fecal material, usually when septic tanks or cesspools leak or overflow (Environ Corp., 1983).

Viruses and parasites have been implicated in groundwater contamination incidents in relatively few instances. The low rate for viruses may be attributed to limitations in detection methods (Environ Corp., 1983). The analytical limitations regarding detection of viruses, coupled with estimates by the World Health Organization that about 60 percent of the cases of waterborne disease reported in the United States are caused by unrecognized or unknown agents, suggest that viral contamina-

tion of drinking water (including groundwater sources) may be of greater significance than has been recognized (Environ Corp., 1983). The principal sources of viruses in groundwater are sewage effluent (e. g., from septic tanks, cesspools, and land application practices), animal feedlots, and dairies. The factors that affect the occurrence of viruses in groundwater are complex and poorly understood; it is likely that they are similar to those for bacteria.

### ***Radioactive Substances***

Most groundwater contains trace levels of naturally occurring radioactive substances or their by-products. The types and levels vary from area to area, depending principally on subsurface materials. In addition to natural radiation, radioactive



*Credit: Southeast Michigan Council of Governments, 1982*

Septic systems can cause both biological and chemical contamination of groundwater and surface water.

substances in groundwater can result from human activities. These sources include radioactive waste disposal sites, waste tailings and piles, and mine drainage related to uranium mining.

Health protection from radiation is a highly developed science, and data accumulated over many years link adverse health effects and exposure. Importantly, health effects are generally understood only at high exposure levels; only in isolated circumstances are these levels of radioactivity likely to occur in groundwater. The National Academy of Sciences, in its discussion of the health risks of radioactive drinking water (NAS, 1977), estimated total average body exposure from drinking contaminated water at less than 1 percent of total average yearly background radiation exposure received by the population (total exposure is approximately 100 mrem/year). The risk of cancer from total average natural background radiation is estimated at 4.5 to 45 fatalities per million persons per year (estimates depend on particular assumptions; NAS, 1977), including 0.6 fatal cases of bone cancer per million persons per year.

Because radioactive content can vary from average conditions, there can be situations in which

doses are significantly greater than average. For example, in areas with high groundwater radium levels (e. g., 25 pCi/liter of Ra<sup>226</sup> and 12.5 pCi/liter of Ra<sup>228</sup>), exposure of the human skeleton could be as much as a sixfold increase (up to 600 mrem/year) over that from all natural background sources. Radiation in groundwater could thus be a serious problem in localized areas, e.g., parts of New England (Harris, 1984; Duncan, et al., 1976, cited in Prichard et al., 1983). Under the "high" groundwater radium levels mentioned above, the risk of fatal bone cancer could increase to an estimated 4.2 fatalities per million persons per year.

Radiation exposure can also cause developmental or teratogenic effects; the lowest dose at which any developmental or teratogenic effect has been reported is 1,100 mrem/year. Under 'average' conditions, doses received by the population are so small that no measurable developmental or teratogenic effects from drinking radioactive groundwater would be found, even during the sensitive period of gestation (NAS, 1977).

## NON-HEALTH IMPACTS

There is a general absence of both methodological experience and data on evaluating the non-health impacts—economic, environmental, and social—of groundwater contamination. Examples of these impacts are shown in table 2. Because available data are insufficient for quantifying or otherwise comparing most of these impacts, this section focuses on the nature of non-health impacts and the difficulties in their assessment.

### *Economic Impacts*

Data about various types of economic impacts associated with groundwater contamination are generally not available (University of Oklahoma, 1983). The data that are available tend to be the direct costs of corrective action; and they either encompass such a broad range that they are difficult

to interpret apart from site-specific conditions (e. g., corrective actions can cost tens of millions of dollars or more depending on site conditions), or they lack sufficient documentation (e. g., in terms of describing site conditions) for subsequent comparison and analysis. Some data may also be unobtainable because of their proprietary nature or use in litigation.

In addition to empirical difficulties, there are methodological difficulties in assessing the value of groundwater quality in terms of both the costs of contamination and the benefits of protection. Few studies are available that systematically approach an assessment of economic impacts (see Raucher, 1983; Sharefkin, et al., 1983; Reitman, 1982). These conceptual difficulties, some of them common to the assessment of impacts on other environmental media (e. g., surface water and air), include:

**Table 2.—Examples of Economic, Environmental, and Social Impacts Resulting from Groundwater Contamination**

<b>Economic impacts</b>	
Industry	<p>Higher operation/maintenance or capital costs (e.g., for accelerated repair or replacement of damaged equipment or materials)</p> <p>Lost output from downtime during repairs, during the search for alternative water supplies, and during relocation</p> <p>Relocation costs</p> <p>Decreases in property value</p> <p>Decreases in revenue if quantity of products sold or their prices fall as a result of lower product quality</p> <p>Secondary costs (e.g., incurred by suppliers to inputs to the industry or by receivers of the output such as by processors or marketing agents)</p> <p>Legal and administrative costs</p> <p>Costs of detection, correction, and prevention activities</p>
Agriculture	<p>Higher operation/maintenance or capital costs (e.g., for accelerated repair or replacement of damaged equipment or materials)</p> <p>Loss of output due to damage to productivity of land (also reflected in decreases in property value)</p> <p>Lost revenue from discarding of food products unsuitable for consumption</p> <p>Loss of output due to injury or death to perennial plants and trees</p> <p>Decreases in livestock productivity, including illness and death</p> <p>Secondary costs (e.g., incurred by suppliers of inputs to agriculture or by receivers of output)</p> <p>Legal and administrative costs</p> <p>Costs of detection, correction, and prevention activities</p>
Households	<p>Higher operation/maintenance or capital costs (e.g., for cleaning, replacement, and/or rehabilitation of damaged pipes, plumbing, appliances)</p> <p>Decreased value of residential property</p> <p>Relocation expenses, including search costs, higher purchase prices, higher interest rates and fees, and moving costs</p> <p>Secondary costs (e.g., contraction or expansion of commercial activities)</p> <p>Loss of income due to sickness</p> <p>Legal costs</p> <p>Costs of detection, correction, and prevention activities (e.g., pre-treatment and purchase of bottled water)</p>
Municipalities	<p>Lost receipts from property, sales, or income taxes</p> <p>Re-allocation of additional resources to provide emergency services</p> <p>Costs of procuring alternative supplies</p> <p>Legal and administrative costs</p> <p>Detection, correction, and prevention activities</p>
<b>Environmental impacts</b>	
Aesthetics	<p>Odor</p> <p>Taste</p> <p>Appearance</p>
Surface water contamination by groundwater	
Biota	<p>Damage to vegetation, waterfowl, and aquatic life</p> <p>Contamination of fish</p>
Air pollution	
Soil contamination	
Social impacts	
Psychological stress	
Inconvenience	
Social disruption	

SOURCE Off Ice of Technology Assessment

- determination of the effects of various activities and practices on groundwater quality;
- determination of the effects of changes in groundwater quality on groundwater use;
- lack of a perfectly competitive economic marketplace for valuing groundwater quality;

- selection of an appropriate time horizon for the analysis and an appropriate discount rate for the time value of money; and
- assessment of the cost and effectiveness of various approaches to detection, correction, and prevention of groundwater contamination.

The economic damages resulting from groundwater contamination shown in table 3 illustrate the types and magnitude of documented costs. Data are easiest to obtain for perceptible, short-term effects on users that are reflected in the marketplace. Importantly, although the real value lost to the Nation from any one incident may not be significant compared to, say the gross national product, the economic costs of groundwater contamination are significant if the costs for all incidents are combined and if the time over which these costs will be incurred is considered. In addition, the costs to the Nation associated with the contamination of many aquifers may well exceed the sum of the costs associated with individual aquifers—e. g., if there is widespread loss of potable drinking water or of agricultural produce. Further, the economic damages from any one incident may be significant from the perspective of the populations and users affected. For example, cash-flow imbalances or other dislocations (e. g., layoffs) can result, especially during emergencies when impacts may not be anticipated or planned for.

### ***Environmental and Social Impacts***

Contaminated groundwater causes diverse environmental and social impacts; they are generally not quantifiable and little documentation is available.

Because groundwater provides a significant portion of baseflow to streams, the potential for adverse impacts on surface water quality may be large, especially during periods of low rainfall when dilution is minimal. Changes in the quantity of groundwater also influence the quality of groundwater (e. g., the pumping of groundwater can induce the migration of contaminants). The extent of other environmental impacts is unknown; some cases document damage to fish, vegetation, and wildlife. The potential for groundwater contaminants (e. g., volatile organics) to enter the atmosphere in the vicinity of certain sources (e. g., landfills) or from volatilization during showering has now been recognized.

Social impacts are related largely to the anxiety caused by fear and uncertainty about exposure to contaminants. Exposure can occur unknowingly because many contaminants are odorless, colorless, and tasteless. Exposure to contaminants occurs over many years and via many pathways, including drinking contaminated water, eating foods that have been in contact with contaminated groundwater, bathing in contaminated water, and breathing contaminants when they volatilize in the shower. Social impacts also arise from decreased property values, and from lost income because of illness, relocation, and inconvenience (e. g., in procuring alternative water supplies).

## **CONCENTRATION AND FREQUENCY OF SUBSTANCES FOUND IN GROUNDWATER**

### ***Concentration of Substances in Groundwater***

A substance is 'detected' or 'reported' if its concentration sufficiently exceeds the detection limits of sampling and measurement equipment so that its presence is verifiable. Detection limits (typically referred to as "trace levels" imply that values below the measurement threshold will not be reported as positive even if substances are in fact present at lower concentrations.

A wide range of concentrations of various substances has been found in groundwater (table 1). The most important conclusions about the concentration data are:

- . concentrations of substances in groundwater are site-specific and thus are highly variable spatially;
- . concentrations are highly variable temporally—they may fluctuate at a particular site by a factor of 10 during the course of a year (Har-

**Table 3.—Examples of Economic Costs Resulting From Contaminated Groundwater<sup>a</sup>**

Location	Contaminants	Nature of costs	Direct costs incurred	Documentation
Canton, CT	Carbon tetrachloride, methylethylketone, trichloroethylene, chloroform	Well closings; extension of water lines to affected areas	<b>\$145,000-379,000</b>	CRS, 1980a
Oscoda MI	Trichloroethylene	Well closings; provision of new source of water	\$140,000	CRS, 1980a
South Brunswick, NJ	Chloroform, toluene, xylene, trichloroethane, trichloroethylene	Well closings; extension of municipal water lines to affected area	<b>300,000</b>	CRS, 1980a
Cohansey Aquifer, NJ	Wastes from manufacture of organic chemicals, plastics, resin	Well closings(148); removal of drums; interim emergency water supply (via tanker trucks); drilling of new wells; extension of public water supply (60% of total monetary costs)	\$417,000 (Residential cost of water increased from an average of \$45/year to \$75/year)	U.S. EPA, 1976 CRS, 1980b
Miller County, AR	Brine contamination from oil and gas activities	Loss of irrigation well Partial rice crop loss Estimated loss in profits for changing from irrigated to nonirrigated crops	\$4,000 \$36,000 <b>\$150/acre/year for rice</b> <b>\$35/acre/year for cotton</b> <b>\$20/acre/year for soybeans</b>	Fryberger, 1972
38 communities in 11 Midwestern States <sup>b</sup>	Mineral content	Reduced service lives of household plumbing and appliances	<b>Increased annual capital cost per household of 40% as total dissolved solids increase from 250 ppm to 1,750 ppm</b>	Patterson, et al., 1968
Atlantic City, NJ	Chemical wastes (Price's Landfill)	Estimated cost of new well field to replace contaminated wells	<b>\$2 million</b>	As reported in Sharefkin, et al., 1983
Orange County, CA <sup>c</sup>	Mineral content	Cost of alternative water supply to 35 private residences	\$250,000	Orange County Water District, 1982
		Estimated cost of reduced service lives of household plumbing and appliances	\$6.5 million total annual capital cost	
		Estimated average annual cost of water softeners or increased cost of cleaning products	\$12.3 million	
Montana	Salinity	Loss of farm income	\$5 million per year	Miller, 1980
San Joaquin Valley, CA	Salinity	Loss of farm income	\$31.2 million per year	Sheridan, 1981
Auburn, MA	Unspecified chemicals	Alternative water supply for affected area	\$180,000	U.S. House of Representatives, 1980
Lathrop, CA	Pesticides	Purchase of water by residents	\$3-5 per 5 gallons	CRS, 1980b
		Connection to district water supply	\$150 per connection, monthly operating costs of \$4-10	
Jackson Township, NJ	Chloroform, methyl chloride benzene toluene, trichloroethylene, ethylbenzene, acetone	Costs of planned water system to replace closing of 100 wells	\$1.2 million	CRS, 1980a

<sup>a</sup>Based on University of Oklahoma, 1983.

<sup>b</sup>Costs shown are not comparable because they are not measured in constant dollars.

<sup>c</sup>Almost all these communities obtain their primary water supply from groundwater.

<sup>d</sup>Costs are those associated with using higher salinity (surface) water from the Colorado River as opposed to water from the State Water Project.

SOURCE: Office of Technology Assessment.

ris, et al. , no date), and they may vary from day to day (Harris, 1984);

- concentrations of substances are often many times higher in groundwater than in surface water; and
- higher concentrations of substances are typically found near the site of their release (Westerhoff, et al., 1982), especially if that site contains concentrated amounts of the substance, sources are numerous, and/or the site is characterized by relatively permeable soils.

A number of surveys focusing on public drinking water wells have been conducted by the States and the Federal Government in the last 10 years—including the early Environmental Protection Agency (EPA) National Organics Reconnaissance Survey (NORS) and National Organics Monitoring Survey (NOMS) and, more recently, the Community Water Supply Survey (CWSS) and Ground Water Supply Survey (GWSS).<sup>4</sup> Efforts in these studies were oriented toward detection of volatile organic chemicals (VOCs), as opposed to non-VOCs (NAS, 1977). These studies show that volatile organic compounds are frequently present at detectable concentrations in public drinking water wells.<sup>5</sup> The studies also reveal that concentrations of compounds in groundwater are often much higher than in surface water; for example, TCE, toluene, and 1,1,1-trichloroethane are up to 1,000 times more concentrated in groundwater than in surface water (Burmester, et al. , 1982).<sup>6</sup>

The National Inorganic and Radionuclides Survey (NIRS) is an ongoing EPA study of ground-

<sup>4</sup>The National Statistical Assessment of Rural Water Conditions (EPA, 1984) is EPA's response to a congressional mandate under Section 3(a) of the Safe Drinking Water Act, for a one-time evaluation of characteristics of drinking water supplies, including water quality, in rural households. This is the first national sampling of private water supplies.

Results suggest water quality problems of greater magnitude and prevalence (especially for metals) than had generally been expected, based on data from monitoring community water systems and from other studies. Bacterial contamination was the most prevalent problem. Water quality sampling for organic substances was restricted to substances covered under National Interim Primary Drinking Water Regulations: Lindane, Methoxychlor, Toxaphene, 2,4-D, and 2,4,5-TP. No significant problems were detected from organic substances.

<sup>5</sup>Projections of the number of groundwater and surface water systems in the United States that have concentrations of individual VOCs exceeding 5 µg/l are also available (Coniglio, 1982).

<sup>6</sup>This may not be true for the trihalogenated methanes (THMs; Harris, 1983)—chloroform, bromoform, bromodichloromethane, dibromochloromethane.

water-supplied community water systems; 38 inorganic (26 of which have already been detected in groundwater), 4 radionuclides (all previously detected in groundwater), and 2 common measures of radioactivity are the focus of this investigation.

Because of the site-specific nature of groundwater contamination, it is not possible to draw more detailed conclusions about or to predict typical contaminant concentrations. At best, concentration data indicate the severity of site-specific contamination problems and immediate local risks to public health and the environment (see the sections on Standards and Health Impacts). Such data are also essential to determine the suitability of alternative corrective actions (see ch. 8).

Generalizations about concentration data at any level more aggregated than at an individual site are highly tentative. Systematic collection of data in space or time can show how concentrations vary in an area and can provide historical information, thus establishing contamination trends for a particular source and/or type of hydrogeologic setting. In all cases, however, the concentration data are snapshots at one point in time and thus do not take into account the dynamics of system behavior.

### ***Frequency of Occurrence of Substances in Groundwater***

Frequency of occurrence generally refers to the number of positive samples (i. e., number for which the substance of concern is detected) in the total number of samples tested. Like concentration data, frequency data can be biased by sampling procedures and analytical detection limits (University of Oklahoma, 1983; Westrick, et al., 1983). In addition, data are not usually collected with sufficient detail for frequency analysis (e. g., detection limits of the measuring instrumentation are often not specified), and there may be no information available on frequency distributions. Most importantly, there is often no attempt to link frequency data with concentration data; thus a 'positive' sample implies that the substance is detectable, but it does not indicate the concentration.

Interpretation of frequency data is more meaningful if information is also available about such factors as historical land uses and sources. At least

at the site-specific level, frequency data can give an impression of the pervasiveness of substances in groundwater. From a regional or national perspective, however, interpretation of frequency data becomes much more difficult. Nationwide frequency studies would require extensive sampling (hundreds to thousands of sites) and, like concentration studies, would provide only snapshots.

With these limitations in mind, data concerning the frequency of occurrence for specific chemicals are summarized in appendix A.3. The national surveys listed in the section on *Concentration of Substances in Groundwater* (NORS, NOMS, CWSS, GWSS), the National Screening Program for Organics in Drinking Water (NSP), and some State surveys have all yielded data on the frequency of organic chemicals in groundwater-supplied drinking water. Information on the percentage of total groundwater samples in Federal surveys which contained detectable levels of VOCs is summarized by Coniglio (1982).

General conclusions about the frequency data are:

- several organic chemicals associated with chlorinated solvents, especially TCE and PCE, have frequently been detected in groundwater contamination incidents;
- public drinking water systems relying on groundwater are frequently contaminated with VOCs; and
- two or more VOCs are frequently detected simultaneously in groundwater supplies.

In studies of drinking water wells conducted by 18 States, frequencies of detection of various VOCs were compiled for both random and non-random samples (CEQ 1981). For the most common chemicals in the random samples, frequency of detection ranged among the States from 1.7-11.3 percent for TCE and from 3.6-4.5 percent for 1,1-dichloroethane. Random samples both are more indicative of general conditions and generate more conservative estimates than non-random samples.

The two most recent Federal studies (CWSS and GWSS) provide much information regarding frequency of VOCs in groundwater. Information from the CWSS indicated that 15 percent of public water systems relying on groundwater contained at least

one VOC; VOCs were detected in 45 percent of the public water systems serving more than 10,000 people and in 12 percent of the more numerous public water systems serving fewer than 10,000 people. Because the samples were 1-2 years old at the time of analysis, some VOCs may have degraded; thus, these percentages are regarded as minimum estimates (Brass, et al., 1981, cited in NRDC, 1982).

The GWSS (Westrick, et al., 1983) provides information on the frequency with which one or more VOCs were detected in groundwater samples. In the GWSS, random samples of groundwater supplies from public water systems were collected from 466 randomly selected communities. The percentage of random samples with one or more VOCs detected was 16.8 percent for small systems (serving fewer than 10,000 people) and 27.9 percent for large systems (serving more than 10,000 people). TCE and PCE were detected in 3.2 percent and 4.6 percent of the random samples from small systems, respectively, and both were detected in 11.3 percent of the random samples from large systems. More importantly, the percentage of random samples with two or more VOCs present was 6.8 percent for small systems and 13.4 percent for large systems. An additional part of the survey focused on non-random supplies selected by State agencies.

### ***Concentration and Frequency Data in Relation to Governmental Standards***

Evaluation of health risks associated with groundwater contamination requires, among other things, information concerning both frequency and concentration of substances—specifically, the frequency with which groundwater contains one or more substances at concentrations exceeding levels that are considered unsafe. Standards promulgated by government agencies specify those limits above which the presence of a substance is considered unsafe; they thus serve as a gauge of the potential impacts of contamination. Concentration data alone can reveal potential problems, but only if they can be compared with standards or health impact data related to those specific concentrations.

No Federal standards have been developed specifically for substances found in groundwater. But

various Federal standards and guidelines—some developed for drinking water—have been applied to groundwater. These include National Interim Drinking Water Regulations (Primary and Secondary), Health Advisories, and Ambient Water Quality Criteria. In addition, individual States have developed standards which they are applying to groundwater, including State drinking water standards and State groundwater standards (see chs. 3 and 4 and app. C. 3 for additional information related to standards).

Standards or guidelines of some type (State or Federal) have been promulgated for less than one-half the substances that have been detected in groundwater (refer to table 1). Although Federal standards or guidelines exist for over 60 substances, there are only 22 enforceable standards (established by the National Interim Primary Drinking Water Regulations) and of these, 18 are for individual substances. An additional six Federal standards are non-enforceable under the Secondary Relations; remaining standards or guidelines are Health Advisories or Ambient Water Quality Criteria. Over 150 substances and other quality indicators have State standards; less than one-half of them also have some type of Federal standard or guideline.

Because there is no consistent approach to the development of standards, because different standards are used by different Federal and State agencies, and because standards do not exist for many substances, people in different States do not receive a uniform level of health protection against groundwater contaminants. For example, some States (especially in the Northeast, but also in other parts of the country) have closed contaminated drinking water wells in order to prevent human exposure to specific chemicals (e. g., TCE, PCE, dichloroethane, benzene, chloroform, toluene, and vinyl chloride; Environ Corp., 1983). Concentrations of the chemicals in the closed wells almost always exceeded Ambient Water Quality Criteria, but the levels at which the wells were closed varied greatly from State to State. For example, wells in New York, Rhode Island, and Massachusetts were closed at levels of tetrachloroethylene ranging from 1-61 parts per billion (Ambient Water Quality Criterion = 0.8 ppb); and wells in New York and Rhode Island were closed at levels of 1,1,1-trichloroethane ranging from 3-1400 ppb (Ambient Water



*Photo credit: State of Florida Department of Environmental Regulation*

About one-half of the Nation's population depends on groundwater for drinking, and the level of health protection against groundwater contaminants varies from State to State.

Quality Criterion = 18.4 ppb). Although these data indicate the levels at which wells were closed, they do not indicate the minimum threshold concentrations that would have elicited well-closing decisions (Environ Corp., 1983).

Theoretically, frequency data could be linked with concentration data and various standards to ascertain the percentage of contamination incidents in which some type of standard is exceeded. If the standard reflects an exposure level that could result in adverse health effects, then this type of analysis would yield information on the frequency with which the public is exposed to unsafe concentrations of contaminants in groundwater. In general, both concentration and frequency data are usually not reported in enough detail for such an analysis.

OTA's study attempted such an analysis, as a first approximation, for examples with sufficient data. Documentation showed 38 organic chemicals, 25 inorganic chemicals, and two radionuclides for which concentrations in at least one groundwater sample are known to have exceeded one or more of the above types of standards or guidelines (see app. A.4 for details of which standards or guidelines have been exceeded). Of these 65 substances, 14 (3 organics, 10 inorganics, and 1 radionuclide) involve National Interim Primary Drinking Water Regulations, and an additional 5 inorganic chemicals involve Secondary Regulations. In most cases where standards or guidelines were exceeded, State

standards or Ambient Water Quality Criteria were involved.

Frequency and concentration data are available for 13 of the 38 organic chemicals known to exceed some standard or guideline in at least one sample; for none of these 13 compounds have the National Interim Primary or Secondary Drinking Water Regulations been promulgated. Calculations indicate that 4 of the 13 compounds are known to exceed at least one type of standard or guideline in .5-10 percent of groundwater contamination incidents (the type of standard or guideline exceeded is shown in parentheses in the following list):

1. carbon tetrachloride (State groundwater and Ambient Water Quality);
2. 1,1-dichloroethylene (Ambient Water Quality);
3. tetrachloroethylene (Ambient Water Quality); and
4. trichloroethylene (Ambient Water Quality).

This list is not intended to be exhaustive; rather, it documents situations where substances are known to exceed specified standards or guidelines frequently.

## POTENTIAL BUT AS YET UNDETECTED SUBSTANCES IN GROUNDWATER

Many substances have the potential to enter groundwater because of their molecular properties and association with sources (see the section on *Association of Substances Found in Groundwater With Sources*, which follows); they may already be present in groundwater but have not yet been detected. This study has been unable to determine whether these substances have not yet been detected because they are not being looked for, or are being looked for but have not been found. A num-

ber of them are known or are suspected to exhibit toxic properties. Table 4 presents some generalizations about potential groundwater contaminants that could have serious health effects; these generalizations are derived primarily from animal experiments. Table 4 should not be viewed as either exhaustive or definitive. It appears that some, but not all, of the contaminants of potential concern can be detected with standardized analytical methods (Environ Corp., 1983).

## TYPES OF SOURCES AND ASSOCIATED SUBSTANCES

### *Types of Sources*

The quality of groundwater is altered by a wide variety of human activities and naturally occurring situations. Sources are points along the pathways that substances travel as they flow through society, where the substances can be released into groundwater. To illustrate, substances can be stored in or flow through sources in a variety of ways, from the storage of raw materials (e. g., materials stockpiles) to manufacturing (e. g., product storage) to distribution (c. s., pipelines) to use (e. g., pesticide applications) to disposal (which can take place almost anywhere in the process).

OTA's study has identified 33 sources known to have contaminated groundwater and has categorized them based on the nature of their release of substances to groundwater (table 5). It is important to note that these categories are for the convenience of discussion. Depending on emphasis, a source could be categorized in another way. For example, non-waste injection wells (for enhanced recovery and artificial recharge) could be placed in Categories I or V. In addition, sources interact with each other—a leak from an above ground storage tank could result in substances entering groundwater directly (Category II) or entering urban runoff and, subsequently, groundwater (Category IV).

**Table 4.—Potential Groundwater Contaminants Displaying Serious Adverse Health Effects<sup>a</sup>**

Compound or class	Potential effects
Acrylonitrile	Carcinogenicity
Alkyl lead compounds	Neurotoxicity; damage to kidneys and hematopoietic system
Alkylamines and alkanolamines (alkyl polyamides, secondary amines)	Allergic sensitization; liver and kidney injury; potential to form carcinogenic N-nitrosamines
Carbon disulfide	Neurotoxicity
Dimethyl sulfate	Carcinogenicity; mutagenicity
n-Hexane	Neurotoxicity
Mercaptans	CNS depression; liver and kidney damage
N-Nitrosamines	Carcinogenicity
Pesticides which are not included in Table 1.1	Neurotoxicity; enzyme inhibition
Phenols which are not included in Table 1.1	Neurotoxicity; variety of systemic effects
Propylene oxide	Suspect carcinogenicity; mutagenicity

additional details in Environ Corp., 1983.

SOURCE: Office of Technology Assessment

Other categorization schemes are also possible (e.g., according to the nature of the user: agricultural, industrial, domestic, and municipal; or the physical location of the source: above the land surface, below the land surface and above the groundwater table, and below the groundwater table). However, classification based on discharge characteristics has the advantage of identifying and characterizing the entry of substances into the groundwater system. The points-of-entry, in turn, are places where actions can be taken to discover and alter the entry—i.e., to detect, correct, and prevent contamination.

Three general conclusions can be reached from this categorization:

1. There is a great diversity of sources, and they are associated with a broad range of industrial, agricultural, commercial, and domestic activities. Both wastes and non-wastes are potential contaminants of groundwater. However, most attention has been focused on wastes, particularly hazardous wastes, from point sources or clusters of point sources. (A "point" source is an easily identified facility, such as a landfill or impoundment.)

2. Only a few source types (Category I) are specifically designed to discharge substances (i. e., wastes) into the subsurface.
3. Non-waste releases result from some sources designed to retain non-waste products (Categories II and III) and as a consequence of other activities (Category IV) or altered flow patterns (Category V).

### ***Association of Substances Found in Groundwater With Sources***

The occurrence of substances in groundwater and an understanding of how, why, and where they are present are directly related to their use and/or disposition. One way of approaching this topic is to examine the association of various substances with specific sources.

Rather than examine all substances shown in table 1 individually, this study relates nine general classes of substances to specific sources<sup>7</sup> (table 6). Classes of substances with the *potential* to be found in association with a source are also indicated. Table 6 does not represent a comprehensive survey of the literature, even though one was attempted. New information about actual contamination incidents is being obtained continually, especially as the States survey their groundwater resources or

<sup>7</sup>The selection of the nine groupings is based on three fundamental features exhibited by all molecules (Woodward-Clyde Consultants, 1983): 1) elemental composition (i.e., elements and their frequency of occurrence in a molecule); 2) functional group (i.e., the arrangement of elements into stable combinations); and 3) structure (i.e., the spatial arrangement of elements).

A substance, in turn, is placed in a grouping if two conditions are met: first, at least a piece of the substance must possess the composition, function, and structure of the grouping, and second, that piece of the substance must be the most readily discernible by measurement techniques (see ch. 5). Thus, a highly complex chemical compound (e.g., multifunctional organic) could be placed into several groupings on the basis of the first condition but, if there are such ambiguities, the following hierarchy would be followed for its categorization based on the second condition: element-containing dominates aromatic, aromatic dominates oxygenated, and oxygenated dominates other hydrocarbons. In addition, biologicals and radionuclides are listed as separate groupings since these properties in themselves are sufficient for their detection; these groupings would dominate all other groupings in the hierarchy. The groupings shown deviate from conventional approaches to contaminant categorization: these groupings are based on molecular properties as well as detectability; conventional categories are based strictly on molecular properties (and thus tend to be more detailed).

Table 5.—Sources of Groundwater Contamination

<p><b>Category I—Sources designed to discharge substances</b></p> <p>Subsurface percolation (e.g., septic tanks and cesspools)</p> <p>Injection wells</p> <ul style="list-style-type: none"> <li>Hazardous waste</li> <li>Non-hazardous waste (e.g., brine disposal and drainage)</li> <li>Non-waste (e.g., enhanced recovery, artificial recharge, solution mining, and in-situ mining)</li> </ul> <p>Land application</p> <ul style="list-style-type: none"> <li>Wastewater (e.g., spray irrigation)</li> <li>Wastewater byproducts (e.g., sludge)</li> <li>Hazardous waste</li> <li>Non-hazardous waste</li> </ul> <p><b>Category 11—Sources designed to store, treat, and/or dispose of substances; discharge through unplanned release</b></p> <p>Landfills</p> <ul style="list-style-type: none"> <li>Industrial hazardous waste</li> <li>Industrial non-hazardous waste</li> <li>Municipal sanitary</li> </ul> <p>Open dumps, including illegal dumping (waste)</p> <p>Residential (or local) disposal (waste)</p> <p>Surface impoundments</p> <ul style="list-style-type: none"> <li>Hazardous waste</li> <li>Non-hazardous waste</li> </ul> <p>Waste tailings</p> <p>Waste piles</p> <ul style="list-style-type: none"> <li>Hazardous waste</li> <li>Non-hazardous waste</li> </ul> <p>Materials stockpiles (non-waste)</p> <p>Graveyards</p> <p>Animal burial</p> <p>Aboveground storage tanks</p> <ul style="list-style-type: none"> <li>Hazardous waste</li> <li>Non-hazardous waste</li> <li>Non-waste</li> </ul> <p>Underground storage tanks</p> <ul style="list-style-type: none"> <li>Hazardous waste</li> <li>Non-hazardous waste</li> <li>Non-waste</li> </ul> <p>Containers</p> <ul style="list-style-type: none"> <li>Hazardous waste</li> <li>Non-hazardous waste</li> <li>Non-waste</li> </ul>	<p>Open burning and detonation sites</p> <p>Radioactive disposal sites</p> <p><b>Category III—Sources designed to retain substances during transport or transmission</b></p> <p>Pipelines</p> <ul style="list-style-type: none"> <li>Hazardous waste</li> <li>Non-hazardous waste</li> <li>Non-waste</li> </ul> <p>Materials transport and transfer operations</p> <ul style="list-style-type: none"> <li>Hazardous waste</li> <li>Non-hazardous waste</li> <li>Non-waste</li> </ul> <p><b>Category IV—Sources discharging substances as consequence of other planned activities</b></p> <p><b>Irrigation practices (e.g., return flow)</b></p> <ul style="list-style-type: none"> <li>Pesticide applications</li> <li>Fertilizer applications</li> <li>Animal feeding operations</li> <li>De-icing salts applications</li> <li>Urban runoff</li> <li>Percolation of atmospheric pollutants</li> <li>Mining and mine drainage</li> <ul style="list-style-type: none"> <li>Surface mine-related</li> <li>Underground mine-related</li> </ul> </ul> <p><b>Category V—Sources providing conduit or inducing discharge through altered flow patterns</b></p> <p><b>Production wells</b></p> <ul style="list-style-type: none"> <li><b>Oil (and gas) wells</b></li> <li><b>Geothermal</b> and heat recovery wells</li> <li>Water supply wells</li> <li>Other wells (non-waste)</li> <li>Monitoring wells</li> <li>Exploration wells</li> <li>Construction excavation</li> </ul> <p><b>Category VI—Naturally occurring sources whose discharge is created and/or exacerbated by human activity</b></p> <p><b>Groundwater—surface water interactions</b></p> <p><b>Natural leaching</b></p> <p><b>Salt-water intrusion/brackish water upconing (or intrusion of other poor-quality natural water)</b></p>
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SOURCE Office of Technology Assessment.

respond to contamination incidents, inventory sources, and monitor supplies, and as efforts are undertaken to recover and/or remove substances prior to their entry into the groundwater.

Four general conclusions can be drawn from this table:

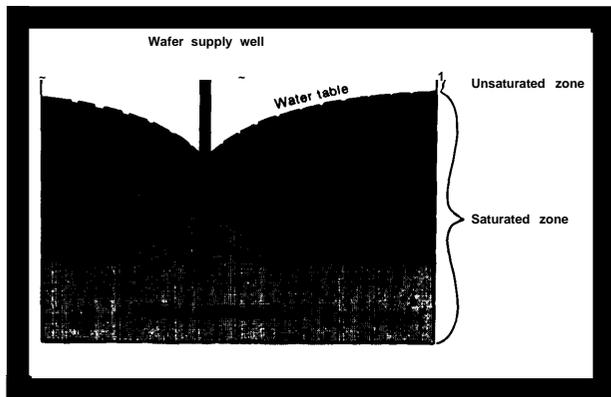
1. A diversity of classes of substances is associated with known sources of contamination. The most common are the metals/cations and non-metals/anions, followed by hydrocarbons with specific elements (e. g., pesticides and

chlorinated solvents), miscellaneous hydrocarbons (e. g., fuels), and radionuclides.

2. The association of substances with specific sources often varies according to the nature of the use and disposal of substances by different segments of society. For example, pesticides may enter groundwater from the storage tanks of manufacturers, from aerial spraying during agricultural operations, and from residential disposal in backyards. In contrast, because of their design and operating constraints (see app. A.5), radioactive disposal



Photo credit: State of Florida Department of Environmental Regulation



Credit: USGS, 1483b

Poorly constructed and maintained or abandoned wells can provide a conduit for the introduction of contaminants into groundwater because of, for example, the migration of water through corroded casings. In this case, uncontrolled discharge from an artesian well is causing brackish water upconing.

sites are not likely to contain many organic chemicals. In addition, substances associated with a source are not necessarily found at every facility of a given source type, and they can vary from facility to facility and over time at a given facility. The essential conclusion is that generalizations about the association of substances with sources are not possible — specific substances associated with a single source depend on past and present uses, and thus the association of substances with sources is highly site-specific.

3. Almost all sources are likely to release simultaneously a number of substances with very different properties. Eight sources (subsurface percolation, disposal wells, land application, landfills, open dumps, residential disposal, surface impoundments, and underground storage tanks) have already been associated with substances from five or more classes, and an additional nine sources have a similar potential (table 6). Even if only one class of substances is involved in a particular situation, many individual substances within that class could be present, and their properties (e. g., toxicity) could vary.
4. For sources associated with particular activities (e. g., agricultural practices and materials storage), fewer classes of substances are likely to be found combined. Even then, however, a broad range of substances may be present in groundwater, depending on past and present land uses.



Photo credit: U.S. Environmental Protection Agency

Residential disposal as a source of groundwater contamination involves the indiscriminant disposal of household products.

## FACTORS INFLUENCING A SOURCE'S POTENTIAL TO CONTAMINATE GROUNDWATER

The extent to which a source has the potential to contribute to groundwater contamination depends on factors that characterize both the general type of facility or activity (e. g., all landfills) and the particular facility or activity of concern (e. g., a specific landfill). These factors include:

- design, operation, and maintenance characteristics;
- release characteristics;
- geographic location (pervasiveness and regionality);
- number of sources and amounts of material flowing through or stored in sources; and
- hydrogeology.

Design, operation, and maintenance can influence a source potential to contribute substances to groundwater through faulty operation and maintenance procedures or through mechanical failure or deterioration; these factors are relatively random. Release characteristics, pervasiveness and regionality, and the number of sources and amounts of

material are described in this section. (For general descriptions of sources and details of calculations, see app. A.5. )

Hydrogeology is site-specific, and it influences the potential contribution of individual facilities or activities primarily by affecting the movement of substances into and within groundwater. (See ch. 5 for a discussion of hydrogeologic factors and investigative techniques. )

### *Release Characteristics*

Potential sources of groundwater contamination are highly variable in the spatial (areal) pattern of their releases (table 7). These releases can be: 1) discrete releases, where substances emanate from a single identifiable unit; 2) *diffuse* releases over a large area, so that substances cannot be traced to a single identifiable source; or 3) *frontal* or boundary releases, which may or may not emanate

Table 6.—Sources and Classes of Associated Substances<sup>a</sup>

	Organic chemicals				Inorganic chemicals			Biological	Radionuclides
	Aromatic hydrocarbons	Oxygenated hydrocarbons	Hydrocarbons with specific elements	Other hydrocarbons	Metals/cations	Nonmetals/anions	Inorganic acids		
Category I									
Subsurface percolation	■	■	■	■	■	■		■	
Injection wells	▲	▲	■	▲	■	■		■	■
Land application <sup>b</sup>									
a Wastewater				■	■	■		■	
b Wastewater byproducts				■	■	■		■	▲
c. Hazardous waste	■		■		▲	▲			
Category II									
Landfills	■	■	■	■	■	■	■	▲	▲
Open dumps	■	■	■	■	■	■	■	■	▲
Residential disposal	■	■	■	■	■	■	■	■	
Surface impoundments	■	■	■	■	■	■	■	■	■
Waste tailings					■	■	■		■
Waste piles					■	■	■		■
Materials stockpiles					▲	▲			
Graveyards					■	■		■	
Animal burial					▲	▲		▲	
Above-ground storage tanks	▲	▲	▲	■	▲	▲	▲	▲	▲
Underground storage tanks	■	■	■	■	■	■	■	■	■
Containers	▲	▲	▲	▲	▲	▲	▲	▲	▲
Open burning and detonation sites					▲	▲			
Radioactive disposal sites									
Category III									
Pipelines	▲	▲	▲	■	▲	▲	▲	▲	
Materials transport and transfer operations	▲	■	■	■	▲	▲	▲	▲	▲
Category IV									
Irrigation practices					■	■			
Pesticide applications			■						
Fertilizer applications			■		■	■		▲	
Animal feeding operations					■	■		▲	
De-icing salts applications					▲	▲			
Urban runoff	▲	▲	■	▲	■	■	▲	■	
Percolation of atmospheric pollutants					■	■			
Mining and mine drainage					■	■	■		■

Key:  
 ■ Contaminant in class has been found in groundwater associated with source  
 ▲ Potential exists for contaminant in class to be found in groundwater associated with source.

Table 6.—Sources and Classes of Associated Substances—Continued

	Organic chemicals				Inorganic chemicals			Biologicals	Radionuclides
	Aroma- tic hydro- carbons	Oxy- genated hydro- carbons	Hydro- carbons with specific elements	Other hydro- carbons	Metals/ cations	Nonmetals/ anions	Inorganic acids		
Category V									
Production wells									
a 011	▴								
b Geothermal and heat recovery									▴
c Water supply									▴
Other wells					—		—		▴
Construction excavation									▴
Category VI									
Ground Water surface water									▴
Interactions									▴
Natural leaching									▴
Salt water Intrusion									▴

<sup>a</sup>Based primarily on University of Oklahoma, 1983. Additional information from Colton, et. al., 1979; Metropolitan Area Planning Council, 1982; Ridgley, et. al., 1982; San Francisco Bay Regional Water Quality Control Board, 1983; and Kaplan, et. al., 1983.

<sup>b</sup>Documentation was not available on the land application of non-hazardous wastes.

SOURCE: Office of Technology Assessment

from a single source but which generally impact groundwater along a front or boundary.

The first pattern, discrete releases, is typical of point sources; diffuse and frontal release describe non-point sources. But there are exceptions. For example, point sources may be so densely situated (e. g., oil production fields) that substances are released in an essentially diffuse pattern, and no single source can be identified. If numerous different types of point sources are located in an area (e. g., urban area), the specific source of the substances found in groundwater may also be obscured. For these reasons, the categorization of a source according to spatial release patterns is often site-specific and thus not rigid.

Sources also vary in the temporal pattern of potential releases (table 7). Some sources that are active year-round are influenced by seasonal patterns of rainfall and recharge (e. g., subsurface percolation, materials stockpile runoff, and natural leaching). Other year-round sources are not affected by the elements because their associated materials are enclosed or otherwise protected from climate (e. g., storage tanks and containers); in these cases, releases are random with respect to season. Some sources are active only at certain times of the year

(e. g., agricultural activities and de-icing salts applications).

The age of an individual facility may also influence temporal release patterns. For example, more concentrated levels of substances may be released during the active years of a facility's operations, or if there is increasing mechanical failure or deterioration over time. Salinity from irrigation flow (a Category IV source, which is seasonal in intensity) may also be age-dependent in salts built up in the soil over time.

### ***Geographic Location: Pervasiveness and Regionality***

Sources of groundwater contamination are either widespread throughout the Nation, located in a few concentrated areas or regions, or extremely localized (table 7). The majority of widespread sources are point sources; they are numerous but also tend to be concentrated in heavily populated areas. Most point sources are Category II sources and are waste-related (e.g., landfills and surface impoundments). Some non-waste point sources (e. g., storage tanks and water supply wells) and, importantly, some non-point sources (e. g., pesticide applications and

Table 7.—Summary of Source Characteristics

	Individual facility/activity			Aggregate of facilities/activities			
	Purpose <sup>a</sup>	Spatial release pattern <sup>b</sup>	Temporal release pattern <sup>c</sup>	Pervasiveness <sup>d</sup>	Diversity of known contaminants <sup>e</sup>	Numbers <sup>f</sup>	Amounts of material <sup>g</sup>
<b>Category I</b>							
Subsurface percolation . . . . .	W	P <sup>h</sup>	Y <sup>i</sup>	R	High	High	High
Injection wells . . . . .	W/NW	P	Y <sup>i</sup> ,S	R	Moderate	High	High
Land application . . . . .	W	D,P	S	R	Moderate	Moderate	Low
<b>Category II</b>							
Landfills . . . . .	W	P <sup>h</sup>	S <sup>i</sup>	W	High	High	Moderate (High?)
Open dumps . . . . .	W	P <sup>h</sup>	S <sup>i</sup>	W	High	Moderate ?	Moderate ?
Residential disposal . . . . .	W	P <sup>h</sup>	S <sup>i</sup>	W	High	?	?
Surface impoundments . . . . .	W	P <sup>h</sup>	S <sup>i</sup>	W	High	High	High
Waste tailings . . . . .	W	P <sup>h</sup>	S <sup>i</sup>	R	Moderate	?	High
Waste piles . . . . .	W	P <sup>h</sup>	S <sup>i</sup>	R	Moderate	?	High
Materials stockpiles . . . . .	NW	P <sup>h</sup>	S <sup>i</sup>	W	Low	?	High
Graveyards . . . . .	W	P <sup>h</sup>	S <sup>i</sup>	W	Moderate	?	?
Animal burial . . . . .	W	P <sup>h</sup>	S <sup>i</sup>	L	Low	?	?
Aboveground storage tanks . . . . .	W/NW	P <sup>n</sup>	R	W	Low	?	?
Underground storage tanks . . . . .	W/NW	P <sup>h</sup>	R	W	Moderate	High	Moderate
Containers . . . . .	W/NW	P <sup>h</sup>	R	W	Low	Moderate (?)	Moderate
Open burning and detonation sites . . . . .	W	P	S	L	Low	Low (?)	Low
Radioactive disposal sites . . . . .	W	P	Y,S,R, <sup>i</sup>	L	Low	Low	Low
<b>Category III</b>							
Pipelines . . . . .	W/NW	P <sup>h</sup> ,F	R	W	Low	Moderate	High
Materials transport and transfer operations . . . . .	W/NW	P <sup>h</sup> ,F	R	W	Moderate	Moderate	Moderate
<b>Category IV</b>							
Irrigation practices . . . . .	NW	D	S <sup>i</sup>	R	Low	Moderate	Moderate
Pesticide applications . . . . .	NW	D	S <sup>i</sup>	W,R	Low	High	Low
Fertilizer applications . . . . .	NW	D	S	W,R	Moderate	High	Moderate
Animal feeding operations . . . . .	w	P <sup>h</sup>	Y	W	Low	Moderate	LOW
De-icing salts applications . . . . .	NW	F	S	R	Low	?	Moderate
Urban runoff . . . . .	w	P,D,F	S	W	Moderate	Moderate	?
Percolation of atmospheric pollutants . . . . .	w	D	S	W	Low	?	?
Mining and mine drainage . . . . .	w	P,D,F	S <sup>i</sup>	R	Moderate	High	Low (?)
<b>Category V</b>							
Production wells . . . . .		P	Y <sup>i</sup>	R	Moderate	High	Moderate
Other wells . . . . .	NW	P	Y <sup>i</sup>	W	Low	?	?
Construction excavation . . . . .	w	P,D,F	S	W	Low	?	Moderate
<b>Category VI</b>							
Groundwater-surface water interactions . . . . .	w	F	S	W	Low	NA	?
Natural leaching . . . . .	NW	D,F	Y,S	L	Moderate	NA	?
Salt-water intrusion . . . . .	NW	D,F	s	R	Moderate	NA	?

<sup>a</sup>Purpose: W = waste; NW = non-waste.  
<sup>b</sup>Spatial Release Pattern: P = point; D = diffuse; F = frontal.  
<sup>c</sup>Temporal Release Pattern: Y = year-round; S = seasonal; R = random.  
<sup>d</sup>Pervasiveness: W = widespread; R = regional; L = local.  
<sup>e</sup>Diversity of known contaminants (based upon Table 1.4): Low = 1-2 associated classes; Moderate = 3-5 associated classes; High = 6-8 associated classes.  
<sup>f</sup>Number (based upon Table 1.6): Low = < 1,000 facilities; Moderate = 1,000-25,000 facilities, 10-20,000 spills, 100,000-1,000,000 miles, or 10-100 million acres; High = 725,000 facilities or > 100 million acres; ? = unable to obtain sufficient information; NA = not applicable.  
<sup>g</sup>Amounts (based upon Table 1.6): Low = < 10 billion gallons, < 10 million tons, < 10 million cubic yards, < 1 billion barrels, or < 100 million acres; Moderate = 10-250 billion gallons, 10-250 million tons, 10-100 million cubic yards, 1-10 billion barrels, or 10-250 million acres; High = > 250 billion gallons, > 250 million tons, or > 10 billion barrels; ? = unable to obtain sufficient information.  
<sup>h</sup>Point sources, but typical dense concentration leads to a diffuse problem (individual sources are not traceable).  
<sup>i</sup>Release characteristics are also a function of age.

SOURCE: Office of Technology Assessment.

urban runoff) are also widespread. But widespread point sources may be of greater concern in some regions than in others because of variations in hydrogeology or the level of dependence on groundwater.

Regional sources tend to be associated with heavily populated areas or major economic activities; often they are numerous or have large amounts of material associated with them. They include sources in Categories I, II, V, and VI. For example, septic tanks are relatively more concentrated in California and the Northeast, fertilizers and pesticides are applied primarily in the West and Midwest, brine disposal wells are located primarily in the Southwest, and mine drainage is found mostly in the East, Midwest, and Southwest. A regional source such as salt-water intrusion is naturally limited to certain coastal areas. In addition, because the distribution of sources is dynamic (e. g., industrialization is increasing in the South, and energy development is increasing in Appalachia and in the Midwest), sources related to previous land uses, rather than present-day activities, may be responsible for the contamination.

The regional nature of some activities does not preclude their associated substances from becoming widespread. For example, only a few manufacturers are primary producers of the active ingredients in pesticides, but their products are used by intermediate manufacturers, small industries, residential households, and agricultural operations throughout the country.

Maps could be used to show the predominance of sources on a regional scale as well as the pervasiveness of sources nationwide. Maps are not included in this report for two major reasons:

1. Available maps generally refer to one source or to several related sources. Because the information contained on different maps involves different assumptions and levels of detail, the relative importance of different sources is difficult to ascertain.
2. Most importantly, site-specific conditions (including hydrogeology), which are essential for any conclusions or predictions about groundwater contamination, are not included on these maps. Relationships would need to be established between source locations and hydrogeologic areas most vulnerable to the entrance and subsequent movement of substances in groundwater and source locations.

### ***Numbers of Sources and Amounts of Material Flowing Through or Stored in Sources***

Current estimates of the number of sources and the amounts of materials flowing through or stored in these sources are presented in table 8. As can be seen, many of the estimates in the 1977 Report to Congress (EPA, 1977; Miller, 1980) are updated, and initial estimates for many additional sources have been developed in OTA's analysis. Details of the calculations are in appendix A.5.

At least four limitations are inherent in these estimates:

1. The estimates are specifically for the amounts of material flowing through or stored in the source and are not estimates of the amounts of material actually reaching the groundwater (unless otherwise indicated). Thus the estimates suggest only the maximum potential for groundwater contamination.
2. An estimate of the amount reveals nothing about the nature and concentration of substances in that material. Industrial and municipal sludge provides an example. The amount of industrial sludge used in land applications is roughly 7 percent of that used from municipal systems, yet often the chemical compounds or their concentrations in industrial sludge (e. g., inorganic acids and higher concentrations of hydrocarbons) pose greater health threats than the chemical compounds found in municipal sludge.
3. Accuracy of the quantitative estimates varies considerably from source to source, depending on the underlying assumptions and completeness of the data. This study has attempted to address this problem by indicating the range of values within which the true value probably falls (see app. A.5 for details), but even this approach is arbitrary. It is important to remember that there is a high degree of uncertainty underlying the estimates and that

Table 8.—Numbers of Sources and Amounts of Material Flowing Through or Stored in Sources<sup>a</sup>

Source	OTA Update			1977 Report	
	Approximate number of facilities	Approximate amount of material <sup>b</sup>	Possible uncertainty in number estimate <sup>c</sup>	Possible uncertainty in amount estimate <sup>c</sup>	Approximate amount of material
<b>Category I</b>					
Subsurface percolation					
Domestic. . . . .	16.6 -19.5 million	820-1,460 bgy	< 2 x	< 2 x	800 bgy
Industrial . . . . .	25,000	1-2 bgy	>10 x	> 10x	1.2 bgy
Injection wells					
Hazardous waste . . . . .		8.6 bgy <sup>d</sup>	<10 x	< 10x	
Drainage, etc. . . . .	350,000	?	< 10x	?	
Brine . . . . .		525 bgy	<10 x	<10 x	<b>460 bgy</b>
Non-waste (enhanced oil recovery) . . . . .	140,000	<b>24.5 bgy</b>	?	< 10x	
Non-waste (solution, in-situ) . . . . .	12,000	?	?	<10 x	0.3 mt
Land application					
Municipal sludge . . . . .	2,500	<b>3-4 mty (dry)</b>	< 10x	< 10x	<b>4 mty</b>
Industrial hazardous waste . . . . .	70	<b>0.10 bgy<sup>d</sup></b>	<10 x	< 10x	
Spray irrigation . . . . .	485	?	>10 x	?	
<b>Category II</b>					
Landfills					
Industrial hazardous waste. . . . .	199	0.81 bgy <sup>d</sup>	< 10x	>10 x	50 bgy
Industrial non-hazardous waste. . . . .	75,700	40-140 mty (wet)	<10 x	>10 x	
Utility. . . . .	?	30 mty (wet)	?	> 10x	
Municipal . . . . .	15-20,000	138 mty	<2X	< 2 x	90 bgy
Open dumps. . . . .	2,400	10 bgy	>10 x	>10 x	
Residential disposal sites . . . . .	?	?	?	?	
Surface impoundments. . . . .					
Hazardous waste . . . . .	1,078	35.8 bgy <sup>d</sup>	< 10x	< 10x	
Non-hazardous waste. . . . .	180,000	1,800 bgy <sup>e</sup>	< 2 x	<10 x	161 bgy
Waste tailings. . . . .	?	580 mty	?	<2X	—
Waste piles					
Hazardous waste . . . . .	174	<b>0.4 bgy</b>	> 10 x	> 10x	
Non-hazardous waste. . . . .	?	<b>1,730 mty</b>	?	< 2 x	
Materials stockpiles . . . . .	?	<b>700 mty</b>	?	< 10x	
Graveyards. . . . .	?	?	?	?	
Animal burial . . . . .	?	?	?	?	
Aboveground storage tanks . . . . .	?	?	?	?	
Underground storage tanks . . . . .					
Hazardous waste . . . . .	2,031	13.8 bgy	< 10x	<10 x	
Non-hazardous waste. . . . .	2.5 million	25 bg	< 2 x	<10 x	
Non-waste . . . . .	?	7	?	?	
Containers					
Hazardous waste . . . . .	3,577	<b>0.16 bgy<sup>d</sup></b>	>10 x	>10 x	
Non-hazardous waste. . . . .	?	?	?	?	
Non-waste . . . . .	?	?	?	?	
Open burning and detonation sites . . . . .	?	?	?	?	
Radioactive disposal sites . . . . .	31'	3.7 million cubic yards	< 2 x	<2X	
<b>Category III</b>					
Pipelines					
Hazardous waste . . . . .	?	?	?	?	
Non-hazardous waste. . . . .	700,000 miles	<b>280 bgy<sup>e</sup></b>	< 10x	>10 x	<b>250 bgy</b>

Table 8.—Numbers of Sources and Amounts of Material Flowing Through or Stored in Sources<sup>a</sup>—continued

Source	OTA Update			1977 Report	
	Approximate number of facilities	Approximate amount of material <sup>b</sup>	Possible uncertainty in number estimate <sup>c</sup>	Possible uncertainty in amount estimate <sup>c</sup>	Approximate amount of material
<b>Category III—continued</b>					
<b>Non-waste</b> . . . . .	175,000 miles	10 billion barrels	?	?	—
Materials transport and transfer operations					
Hazardous waste . . . . .	16,000 spills	14 mty	<10 x	>10 x	
Non-hazardous waste . . . . .		?	?	?	
<b>Category IV</b>					
Irrigation practices . . . . .	50-60 million acres	169 million acre-feet	< 2 x	< 2 x	
Pesticide applications . . . . .	280 million acre-treatments	0.26 mty active ingredients	< 2 x	< 2 x	
Fertilizer applications . . . . .	229 million acre-treatments	42 mty	< 2 x	< 2 x	
Animal feeding operations . . . . .	1,935	8 mty	< 2 x	< 10 x	
De-icing salts applications . . . . .	?	10-12 mty	?	< 2 x	
Urban runoff . . . . .	21.2-32.6 million acres	?	< 2 x	?	
Percolation of atmospheric pollutants . . . . .	NA		?	?	
Mining and mine drainage					
Surface . . . . .	15,000 active	4 million acres;	< 10x	< 10x	108 billion gallons
Underground . . . . .	67,000 inactive	0.36-1.0 mty acid			
<b>Category V</b>					
Production wells					
Oil wells . . . . .	548,000 activity 2 million abandoned	g	<10 x	< 10x	
Geothermal, heat recovery . . . . .	32	?	?	?	—
Water supply . . . . .	350,000	?	?	?	—
Other wells (non-waste)					
Monitoring . . . . .	?	?	?	?	—
Exploration . . . . .	?	?	?	?	—
Construction excavation . . . . .	?	45 mty	?	> 10 x	—
<b>Category VI</b>					
Groundwater-surface water interactions . . . . .	NA	?	NA	?	—
Natural leaching . . . . .	NA	?	NA	?	—
Salt-water intrusion . . . . .	NA	?	NA	?	—

<sup>a</sup> ? = OTA unable to obtain sufficient information to develop estimate.

— = No estimate presented in 1977 report (EPA, 1977).

NA = Not applicable.

<sup>b</sup> mty = million tons per year.

bg = billion gallons per year.

bg = billion gallons.

<sup>c</sup> Confidence in estimates is defined as follows (see app. A.5 for more details):

< 2x = estimate considered correct within 100%.

< 10 x = estimate considered correct within one order of magnitude.

> 10 x = estimate could be incorrect by more than one order of magnitude.

<sup>d</sup>Note that this figure refers to hazardous wastes regulated under RCRA (see app. A.5)

<sup>e</sup> Estimate of actual amount of leachate.

<sup>f</sup> Excludes nuclear reactors.

<sup>g</sup> See estimate for brine injection (app. A.5).

SOURCE: Office of Technology Assessment.

**they are best used to indicate the most numerous and most material-intensive sources.**

4. Comparing estimates is difficult because they are expressed in different units of measurement. The units cannot be converted into a common base unit; thus only simple categorizations of large versus small numbers or amounts can be made. (See the section on *Identifying Sources With "Significant" Potential To Contribute Substances to Groundwater*, where this problem is encountered again, for more details, )

Given these caveats, table 8 is still useful in at least two ways:

1. It indicates sources which are numerous and/or have large amounts of associated materials.
2. Table 8 shows that non-point **sources (e.g., Category IV, including fertilizer and pesticide applications) and sources dealing with non-waste products (e. g., Category II, including underground storage tanks) and with non-hazardous wastes (e. g., Category 1, including brine disposal wells) are often as important—in terms of numbers or amounts of material as defined in table 7—as point sources or hazardous waste sources.** Many of the non-point sources have associated with them chemicals that are highly toxic (e. g., pesticide applications) or very diverse (e. g., underground storage tanks); see the previous section on *Association of Substances Found in Groundwater With Sources*).

Quantitative estimates of the numbers of sources are available at least in part for 19 sources. The contribution of some sources to groundwater contamination is difficult to measure (e. g., salt-water intrusion), and data are incomplete for others. Of equal importance, estimates of amounts do not exist for 11 sources and are incomplete for seven others. For some sources, amounts are technically difficult to measure (e. g., drainage wells and residential disposal); for others, local information is available but is difficult to compile on a national level (e. g., non-waste containers and water supply wells). With increased time and effort, investigators can proba-

bly improve estimates for some sources (e. g., industrial subsurface percolation and hazardous waste containers) and possibly obtain sufficient information to generate first estimates for some of the sources for which there are no estimates (e. g., spray irrigation).

The most numerous sources include: subsurface percolation (domestic), injection wells (brine disposal and drainage), industrial landfills, surface impoundments, underground storage tanks, pipelines, irrigation practices, pesticide applications, fertilizer applications, mine drainage, and oil wells.

The largest amounts of material apparently flow through or are stored in the following sources: subsurface percolation (domestic), brine disposal wells, industrial and municipal landfills, surface impoundments, waste tailings and piles, materials stockpiles, and pipelines. **Much of the material that enters groundwater comes from non-point sources**, such as applications of pesticides and fertilizers, especially in particular regions of the country. Non-waste sources such as injection wells, storage tanks, and many agricultural activities, and non-hazardous waste, and/or non-waste sources contribute large amounts of material.



Photo credit: Paula Stone, Office of Technology Assessment

Of an **estimated 2.4 million steel underground storage tanks** in the United States, as many as one-fourth may be used by farmers; other important users include service stations (using an estimated 50 percent) and government agencies (using an estimated 5-6 percent) (see app. A.5).

## POTENTIAL FOR SOURCES TO CONTRIBUTE SUBSTANCES TO GROUNDWATER

Determining the contribution of any source to groundwater contamination depends on understanding a broad range of technical, economic, and social factors. Economic and social factors affect where sources are located, how they are used, and what they are used for. The actual contribution of substances by any source will depend on such technical factors as biodegradation rates, surface and subsurface hydrology (e. g., percolation and adsorption rates), the amount and type of wastes, release patterns, number of sources, and source characteristics (condition, maintenance, and operation procedures).

Two basic approaches are discussed below for identifying which sources have the potential for contributing significant amounts of substances to groundwater. One approach involves the use of physical and mathematical models to predict when and which sources release substances to groundwater and what happens to the substances once they enter groundwater. This approach can also involve record-keeping at individual facilities. In the second approach, descriptive criteria are developed in order to generate lists of important sources (as defined on the basis of those criteria).

### *Modeling the Potential of Sources To Contaminate Groundwater*

Efforts to protect groundwater would be aided by a priori information on when an individual facility or activity will release substances with the potential to enter groundwater, and by estimates of what portion of these substances will actually enter groundwater.

Little work has been done to develop measures of the potential for sources to contribute substances to groundwater. In general, the site-specific nature of hydrogeology and the varying characteristics of individual sources have precluded development of predictive models. One existing model for steel underground storage tanks uses tank age and local soil condition data to generate predictions about the situations in which tanks will develop leaks (Rogers, no date). If an inventory of underground

storage tanks (including specific age data) were available, at-risk situations identified by the model could be investigated. Apparently this type of modeling has not been developed for other sources and is limited by data availability.

Physical and mathematical models are available that predict the behavior and movement of substances once they enter groundwater. (See app. A.5 for references.) Most of the models yield a temporally varying description of the spatial distribution of a substance in an aquifer (see ch. 5). Input requirements generally relate to underlying soils and other hydrogeologic features and the amount or rate at which the aquifer is receiving the substance. If existing contamination and aquifer characteristics are known, some models can be run in reverse to determine the amount of the substance that must have been released from its source to produce the given conditions. These models rely on empirical measurements for input; the value of their output, therefore, is highly dependent on both the underlying assumptions and the quality of the input data.

Measuring contamination potential thus also involves record-keeping at individual facilities. Losses caused by leakage or infiltration of leachate can be estimated via water balance, injected waste leakage, or back-calculation procedures (University of Oklahoma, 1983). However, these procedures are basically empirical or bookkeeping for an individual facility, and the information gained is used to estimate leachate generation or the amount of contaminated recharge at that particular facility. Applicability of these prediction methods to other similar facilities is limited. Historic flow records could contribute to crude predictions, but the records are generally not available.

### *Identifying Sources With “Significant” Potential To Contribute Substances to Groundwater*

OTA's analysis attempted to develop objective criteria that could be used to identify and list im-

portant sources, i.e., sources with a “significant potential to contaminate groundwater. However, in the course of developing these lists, a number of problems became apparent that severely limited the usefulness of the lists.

Developing a single unambiguous set of objective criteria is not a simple task. One investigator might believe that amounts of material are a sufficient indicator of importance, and others might be concerned with the diversity of substances associated with various sources. Groups of criteria might be used, but the lists of important sources will differ depending on which sets of criteria are selected, as shown below.

An additional problem concerns comparisons of different units of measurement for a single criterion. For example, suppose that the amount of material handled by a source is the criterion under consideration. In table 7, amounts of material are measured in gallons, tons, cubic yards, barrels, acres, and acre-feet. Definition of a “large” versus “small” amount is arbitrary because of the inability to make comparisons among different units of measurement. In addition, documentation or estimation of large amounts of material (using any definition of large) does not necessarily mean that large amounts of substances will be released into the groundwater; estimates of large amounts should be viewed only as upper bound indicators of the potential for contaminant release.

To illustrate some of the above problems and to indicate the context in which such lists could be used, listing is examined in detail. As an example, one set of criteria was selected, comprised of four characteristics described in the section on *Factors Influencing a Source's Potential To Contaminate Groundwater*: number, amounts of material, diversity of substances, and pervasiveness. Although these criteria might seem to be relatively objective, all entail arbitrary definitions of low (or small), moderate, and high (or large). The definitions thus determine the evaluations made in any list.

Information is even more subjective or sparse for other possible criteria, such as the degree to which source control (of operating and maintenance procedures) is required to prevent the release of substances, the potential of the source to introduce new substances into groundwater, the toxicity of

associated substances, and the nature of release characteristics. These criteria are useful in characterizing sources, but they are more difficult to interpret when considering the question of the potential of any particular source to contaminate groundwater. For example, the release of substances with any of the spatial or temporal release patterns discussed above could result in little to significant contamination.

Using the above four criteria, several lists of sources were generated by using different groupings of the criteria and different levels of importance for particular criteria (e. g., use of high numbers in one list, moderate to high numbers in another list). A selection of these lists is presented in table 9. Although some sources fit into many of these lists, a major conclusion is that the exact listing changes as different criteria are selected. For example, if regulatory authorities are interested in groundwater contaminated by a high diversity of substances, there are five important sources (subsurface percolation, landfills, open dumps, residential disposal, and surface impoundments) and, of these, the most important source would be surface impoundments (based on table 6). If the number of facilities alone is important (e. g., as a gauge of regulatory efforts required for control), nine sources are of primary interest and, of these, the most important source would be subsurface percolation (based on table 8).

Among the first nine lists in table 9, seven sources appear on more than one-half the lists: subsurface percolation, injection wells, landfills, open dumps, surface impoundments, underground storage tanks, and fertilizer application. Of all sources, only the surface impoundment source is widespread and has a “high” ranking for the other three criteria (see table 7). Additional criteria could justify the inclusion of specific sources. For example, it is known that a high percentage of underground storage tanks are leaking gasoline and causing a number of contamination incidents (see app. A. 5). Location over vulnerable aquifers (e. g., sole-source aquifers) would be another reason for including surface impoundments and other sources on a list.

The first nine lists are based exclusively on the above four criteria, which tend to be quantitative; quantitative criteria will generally bias a list toward

**Table 9.—“Important” Sources of Groundwater Contamination Based on Selected Sets of Criteria<sup>a</sup>**

Sources/criteria <sup>b</sup>	1 — diversity	2 H amounts	3 H numbers	4 H numbers M–H diversity	5 M–H numbers M–H amounts H diversity	6 M–H numbers M–H amounts Widespread or Renormal	7 M–H numbers M–H amounts Widespread or Renormal	8 Same as 7 but H diversity only	9 Same as 7 but at least one H ranking diversity	10 Proximity
Subsurface percolation . . . . .	X		X	X	X	X	X	X	X	
Injection wells . . . . .		X	X	X	X	X	X	X	X	
Land application . . . . .										
Landfills . . . . .		X	X	X	X	X	X	X	X	
Open dumps . . . . .	X	X								
Residential disposal . . . . .	X									
Surface impoundments . . . . .	X	X	X	X	X	X	X	X	X	
Waste tailings . . . . .	X	X	X	X	X	X	X	X	X	
Water piles . . . . .		X	X	X	X	X	X	X	X	
Materials stockpiles . . . . .		X	X	X	X	X	X	X	X	
Aboveground storage tanks . . . . .										
Underground storage tanks . . . . .				X	X	X	X	X	X	
Containers . . . . .			X	X	X	X	X	X	X	
Pipelines . . . . .		X								
Materials transport . . . . .										
Pesticides applications . . . . .			X	X	X	X	X	X	X	
Fertilizer applications . . . . .			X	X	X	X	X	X	X	
Mining . . . . .			X	X	X	X	X	X	X	
Production wells (oil) . . . . .			X	X	X	X	X	X	X	

<sup>a</sup>Abbreviations: H = High, M–H = Moderate to High.  
<sup>b</sup>Other sources listed in table 5 do not meet any of the selected criteria.  
 SOURCE: Office of Technology Assessment.

point sources, because point sources are relatively easy to identify and count or measure (note that of the above seven sources, only fertilizer applications is a non-point source). In contrast, suppose toxicity, a criterion that is more descriptive of the potential health effects of substances and is not biased toward point sources, is selected. Then the list (see the toxicity column in table 9) would include pesticide applications, open dumps, residential disposal (e. g., TCE and other halogenated aliphatic hydrocarbons), open dumps, and the facilities/activities of each source type that deal with hazardous wastes. Although this list does focus on hazardous waste sources, it also includes several non-point sources (pesticide applications, residential disposal, land application, pipelines, and materials transport). Other criteria that could be used

in this manner include economic impacts and environmental impacts.

This exercise illustrates the difficulty in identifying one single list of sources that would satisfy all sets of criteria—**the list of sources generated depends on the criteria selected for identifying "important" sources.** In addition, groundwater contamination problems differ from region to region and from site to site, thereby making national lists somewhat tenuous. Listing the sources is not as important as recognizing that materials flow through society; that problems involve non-point, non-hazardous, and non-waste sources; that problems vary from region to region; and that groundwater contamination is highly site-specific.

## CHAPTER 2 REFERENCES

- Abrams, E. F., D. Derkics, C. V. Fong, D. K. Guinan, and K. M. Slimak, "Identification of Organic Compounds in Effluents From Industrial Sources," NTIS PB-241641, 1975.
- Bryant, C. T., F. P. Lyford, K. L. Stafford, and D. M. Johnson, "Hydrology of Area 42, Western Region, Interior Coal Province, Arkansas," U.S. Geological Survey, Little Rock, AR, Water-Resources Investigations, Open-file Report 82-636, 1983.
- Burmester, D. E., and R. H. Harris, "Groundwater Contamination: An Emerging Threat," *Technology Review* 85(5):50-62, 1982.
- Cohen, S. F., S. M. Creeger, R. F. Carsel, and C. G. Enfield, "Potential for Pesticide Contamination of Ground Water Resulting From Agricultural Uses," to be published in the American Chemical Society Symposium Series: *Treatment and Disposal of Pesticide Wastes*, in press.
- Colton, D., O. C. Braids, D. R. MacCallum, D. W. Miller, and J. P. Sgambat, "Supplemental Report to the Nassau-Suffolk Regional Planning Board on the Current Status of Ground-Water Investigations for Organic Chemicals in the Nassau-Suffolk Area," prepared by Geraghty & Miller, Inc., Port Washington, NY, 1979.
- Congressional Research Service, *Resource Losses From Surface Water, Groundwater, Atmospheric Contamination: A Catalog*, prepared for the Committee on Environment and Public Works, U.S. Senate, 1980a.
- Congressional Research Service, *Six Case Studies of Compensation for Toxic Substances Pollution: Alabama, California, Michigan, Missouri, New Jersey, and Texas*, prepared for the Committee on Environment and Public Works, U.S. Senate, 1980b.
- Coniglio, W., "Criteria and Standards Division Briefing on Occurrence/Exposure to Volatile Organic Chemicals," Office of Drinking Water, U.S. Environmental Protection Agency, 1982.
- Considine, D. M., and G. D. Considine (eds.), *Van Nostrand's Scientific Encyclopedia*, 6th ed. (New York: Van Nostrand Reinhold, 1983)
- Council on Environmental Quality, "Contamination of Ground Water by Toxic Organic Chemicals," Washington, DC, 1981.
- Environ Corp., "Approaches to the Assessment of Health Impacts of Groundwater Contaminants," draft report prepared for the Office of Technology Assessment, August 1983.
- Fryberger, J., "Rehabilitation of a Brine-Polluted Aquifer," Office of Research and Monitoring, U.S. Environmental Protection Agency, 1972.
- Geraghty & Miller, Inc., "The Fundamentals of Ground-water Quality Protection," New York, 1983.
- Harris, R. H., "The Health Risks of Toxic Organic Chemicals Found in Groundwater," Princeton University/Center for Energy and Environmental Studies, Report No. 153, 1983.

- Harris, R. H., Center for Energy and Environmental Studies, Princeton University, personal communication, January 1984.
- Harris, R. H., J. V. Rodricks, R. K. Rhamy, and S. S. Papadopoulos, 'Adverse Health Effects at a Tennessee Hazardous Waste Disposal Site, draft manuscript, Fourth Annual Symposium on Environmental Epidemiology, University of Pittsburgh, no date.
- Hawley, G. G., *The Condensed Chemical Dictionary*, 9th ed. (New York: Van Nostrand Reinhold, 1977).
- Kaplan, E. M. G., B. Royce, E. F. Riedel, and J. Sathaye, 'Assessment of Environmental Problems Associated With Increased Enhanced Oil Recovery in the United States: 1980 -2000,' Brookhaven National Laboratory 51528 UC-92a, under U.S. Department of Energy contract No. DE-AC02-76CH00016, 1983.
- Lewis, R. J., and R. L. Tatken (eds. ), *Registry of Toxic Effects of Chemical Substances*, 1979 ed., U.S. Department of Health and Human Services (Washington, DC: U.S. Government Printing Office, September 1980).
- Metropolitan Area Planning Council, "A Guide to the Safe Use and Disposal of Hazardous Household Products, Boston, MA, 1982.
- Miller, D. W. (ed.), *Waste Disposal Effects on Ground Water* (Berkeley, CA: Premier Press, 1980).
- National Academy of Sciences, *Drinking Water and Health* (Washington, DC: National Academy Press, 1977).
- National Academy of Sciences, *Risk Assessment in the Federal Government: Managing the Process* (Washington, DC: National Academy Press, 1983).
- Natural Resources Defense Council, "Comments of the Natural Resources Defense Council, Inc. on National Revised Primary Water Regulations, Volatile Synthetic Organic Chemicals in Drinking Water, Advanced Notice of Proposed Rulemaking, 47 Federal Register, 9350-9358 (Mar. 4, 1982), " Sept. 30, 1982.
- O'Brien, R. P., and J. L. Fisher, 'There is an Answer to Groundwater Contamination," *WATER\Engineering and Management*, p. 30ff, May 1983.
- Odum, E. P., *Fundamentals of Ecology*, 3d ed. (Philadelphia: W. B. Saunders Co., 1971).
- Orange County Water District, "Water Quality and Consumer Costs, " 1972.
- Patterson, W. L., and R. F. Banker, "Effects of Highly Mineralized Water on Household Plumbing and Appliances, ' paper presented at the Annual Conference, American Water Works Association, June 1968.
- Prichard, H. M., and T. F. Gesell, "Radon-222 in Municipal Water Supplies in the Central United States, *Health Physics* 45:991-993, 1983.
- Radike, M. J., K. L. Stemmer, P. G. Grown, E. Larson, and E. Bingham, 'Effect of Ethanol and Vinyl Chloride on the Induction of Liver Tumors: Preliminary Report, *Environmental Health Perspectives* 21:153-155, 1977.
- Raucher, R. L., "A Conceptual Framework for Measuring Benefits of Groundwater Protection, *Water Resources Research* 19:320-326, 1983.
- Reitman, F., "Costs and Benefits in Aquifer Protection, *New England Journal, Business and Economics* 19(1), 1982.
- Ridgley, S. M., and D. V. Galvin, 'Summary Report of the Household Hazardous Waste Disposal Project, Toxicant Control Planning Section, Water Quality Division, Municipality of Metropolitan Seattle, WA, 1982.
- Rogers, W., "Tank Integrity Program, Warren Rogers Associates, Inc., Newport, RI, no date.
- San Francisco Bay Regional Water Quality Control Board, "Underground Tank Leak Detection Program Status Report, ' 1983.
- Science News, vol. 125, No. 104, Feb. 18, 1984.
- Sharefkin, M. F., M. Schechter, and A. V. Kneese, "Impacts, Costs, and Techniques for Mitigation of Contaminated Groundwater, pp. 93-126 in Papers for and a Summary of a Workshop on Groundwater Resources and Contamination in the United States (Washington, DC: National Science Foundation, PRA Report 83-12, August 1983).
- Sheridan, D., "Desertification of the United States' (Washington, DC: Council on Environmental Quality, 1981).
- Southeast Michigan Council of Governments, "Public Review Summary Draft: Genoa Township Policy Plan for Groundwater Protection, March 1982.
- Tucker, R. K., "Groundwater Quality in New Jersey: An Investigation of Toxic Contaminants, New Jersey Office of Cancer and Toxic Substances Research, 1981.
- U.S. Environmental Protection Agency, "Hazardous Waste Disposal Damage Reports, " No. 3, 1976.
- U.S. Environmental Protection Agency, 'The Report to Congress; Waste Disposal Practices and Their Effects on Ground Water, " 1977.
- U.S. Environmental Protection Agency, "Ambient Water Quality Criteria for Carbon Tetrachloride, NTIS PB81-117376, 1980a.
- U.S. Environmental Protection Agency, "Ambient

- Water Quality Criteria for Trichloroethylene," NTIS PB81-117871, 1980b.
- U.S. Environmental Protection Agency, "Ambient Water Quality Criteria for Tetrachloroethylene," NTIS PB81-117830, 1980c.
- U.S. Environmental Protection Agency, "National Statistical Assessment of Rural Water Conditions," June 1984.
- U.S. Geological Survey, "Estimated Use of Water in the United States in 1980," USGS Circular 1001, 1983a.
- U.S. Geological Survey, "National Water Summary 1983—Hydrologic Events and Issues," Water-Supply Paper 2250, 1983b.
- U.S. House of Representatives, 96th Cong., 2d sess., Hearing before a Subcommittee of the Committee on Government Operations, Toxic Chemical Contamination of Groundwater: EPA Oversight, 1980.
- University of Oklahoma, "Groundwater Contaminants and Their Sources," draft report prepared for the Office of Technology Assessment, August 1983.
- Westerhoff, G. P., and V. W. Uhl, Jr., "Control Measures for Groundwater VOCs," *WATER/Engineering and Management*, pp. 30-33, July 1982.
- Westrick, J. J., J. W. Mello, and R. F. Thomas, "The Ground Water Supply Survey: Summary of Volatile Organic Contaminant Occurrence Data," Technical Support Division, Office of Drinking Water, U.S. Environmental Protection Agency, Cincinnati, OH, 1983.
- Windholz, M., S. Budavari, R. F. Blumetti, E. S. Otterbein (eds.), *The Merck Index—An Encyclopedia of Chemicals, Drugs, and Biologicals*, 10th ed. (Rahway, NJ: Merck & Co., Inc., 1983).
- Woodward-Clyde Consultants, Inc., "Groundwater Contaminants and Their Measurement," draft report prepared for the Office of Technology Assessment, October 1983.