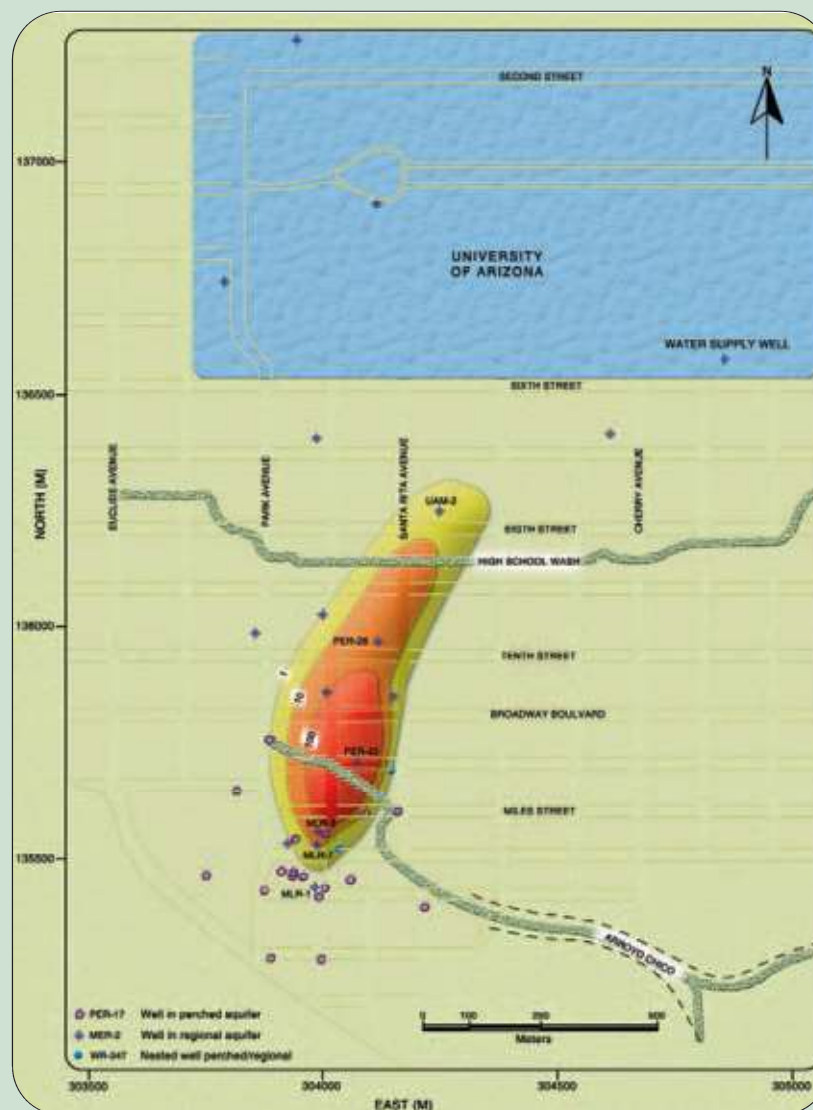


CHAPTER 17

SUBSURFACE POLLUTION

M. L. Brusseau and G. R. Tick



Groundwater contaminant plume (tetrachloroethene) contour map for a site in Tucson, Arizona.
Source: data provided by Arizona Department of Environmental Quality; drawn by Concepción Carreón Diazconti.

INFORMATION BOX 17.1

7,000-Year-Old Hand-Dug Wells in New Mexico and Texas

After the last Ice Age (about 11,000 years ago), the region encompassing western Texas and eastern New Mexico was covered by grasslands with numerous playa lakes. This region experienced a large-scale, long-term drought beginning about 7,500 years ago, resulting in the loss of the playas. It appears that the humans occupying the region adapted to this change in climate by digging wells to obtain water. Evidence of wells dating to approximately 7,000 years ago has been found at sites in New Mexico and Texas. These wells are 1–2 meters in depth, with openings of approximately 1 m in diameter. Artifacts found at the sites indicate that sticks and stones were used to excavate the wells.

Source: <http://www.mnsu.edu/emuseum/archaeology/sites/northamerica/blackwaterdraw.html>; and <http://archaeology.about.com/od/mesolithicarchaic/a/archaicwells.htm>.

17.1 GROUNDWATER AS A RESOURCE

Freshwater comprises approximately 3% of all water on Earth (see also Chapter 3). Approximately 95% of this small fraction occurs as water in the subsurface, *i.e.*, groundwater. Thus, groundwater is a critical resource throughout the world.

Groundwater is a major source of potable water, supports food and crop production, and is used for myriad industrial activities. As such, the availability, quality, and sustainability of groundwater resources are issues of great significance. We will briefly explore these issues in this chapter.

Groundwater has long been used by humankind. This likely occurred initially through the use of natural springs and later via hand-dug wells. There are numerous references to groundwater in ancient texts, such as the works of Plato and Aristotle (Fetter, 2001). Chinese archaeologists have found wells in the Hunan Province dating back to 2000 BC (Xinhua News Agency, 2002). Evidence of hand-dug wells has been found at archaeological sites thousands of years old (see Information Box 17.1).

Groundwater use has increased greatly in the past several decades. Groundwater use worldwide has tripled in the past 50 years (Figure 17.1). This is also true for the U.S. (Figure 17.2). These increases are a direct result of increases in population and economic development. A primary use of groundwater is to supply potable water for drinking and other domestic uses. Groundwater serves as a significant source of potable water throughout the world, ranging from 15% in Australia to 75% in Europe (Table 17.1). In the United States, groundwater provides approximately half of the total potable water supply. The percentage of the U.S. population relying on groundwater as their primary source of potable water varies greatly by state (Figure 17.3).

In addition to supplying potable water, groundwater is also used for many other purposes. Agricultural applications, primarily as irrigation for crops, constitute the single largest use of groundwater in the U.S. (Figure 17.4). The majority of

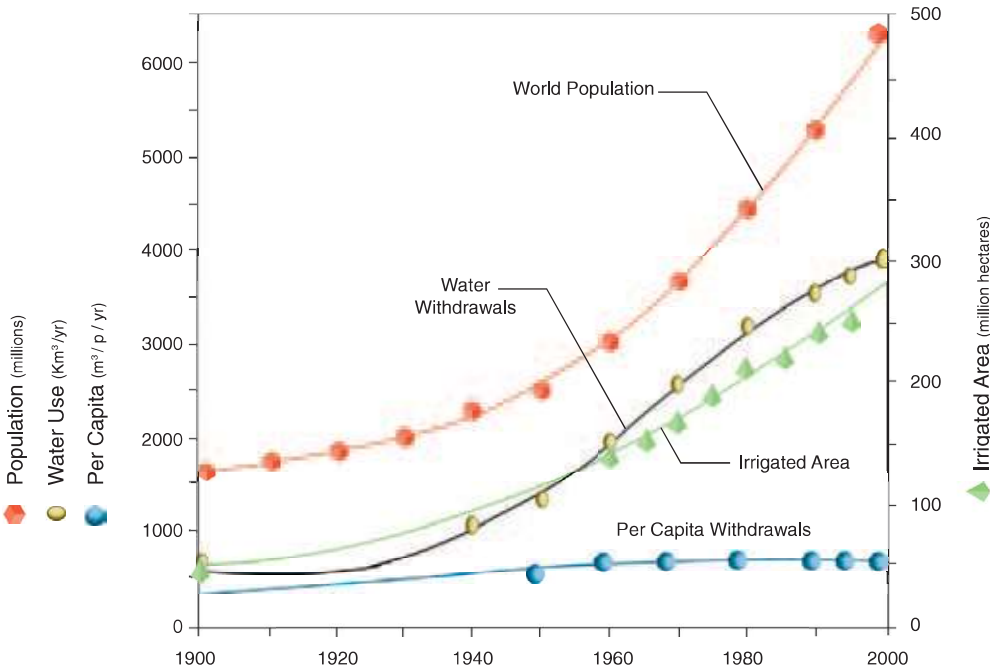


Figure 17.1 Global trends in water use. From Morris et al., 2003.

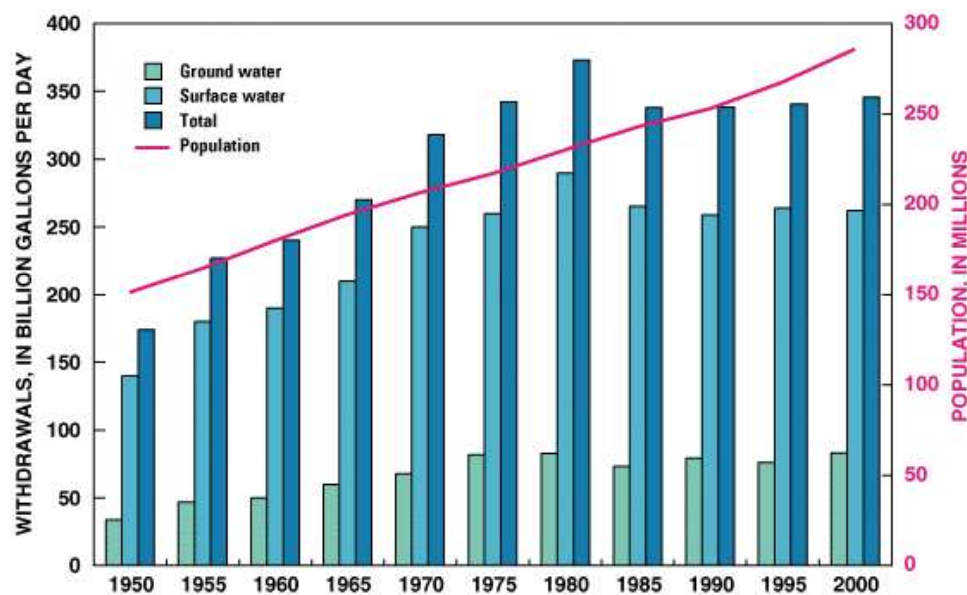


Figure 17.2 Groundwater withdrawals in the USA, 1950–2000. From <http://pubs.water.usgs.gov/circ1268/htdocs/figure13.html>.

irrigation use occurs in the semi-arid and arid regions of the U.S., as one would expect (Figure 17.5). Other uses of groundwater include industrial, mining, and power generation.

17.2 GROUNDWATER POLLUTION

Hand in hand with the use of groundwater by humans is the pollution of groundwater by humans. This pollution can occur in many forms, including hazardous industrial organic compounds, fuel components, heavy metals, agrochemicals, pathogenic microorganisms, and salinity. Groundwater can be contaminated through numerous means, as illustrated in Figure 17.6. Major sources of groundwater contamination in the U.S. are reported in Figure 17.7. There are two general categories of groundwater contamination: those produced from point sources and those that develop from diffuse or nonpoint sources. Specific examples of major groundwater pollution issues will be presented in later sections.

The growth of population centers (urbanization), with the attendant increase in population densities and industrial/

commercial development, has had an enormous impact on groundwater use and quality. Water-resource development during the evolution of an urban center follows a typical pattern, as illustrated in Figure 17.8. Generally, increasing demand for potable water that occurs as population increases results in over-pumping of groundwater from the original well field located in the city center. The amount of water being extracted is greater than the amount recharged, causing a decline in water levels. This eventually requires the city to supplement their potable water supply from other sources. An ancillary effect of the over-pumping and falling water levels is subsidence of the land surface. Another significant effect of over-pumping in coastal areas is seawater intrusion. This will be discussed in detail in a forthcoming section.

The development of high-intensity agriculture and the widespread use of fertilizers and pesticides have led to major groundwater pollution issues for rural areas. This is of particular concern because groundwater generally is the predominant source of potable water for rural areas. For example, more than 95% of the rural population of the U.S. uses groundwater as their potable water supply. Additionally, most of the potable water supply is obtained from individual or small community wells. Groundwater from these wells does not typically undergo the extensive treatment and monitoring that is prevalent for centralized urban water supply systems (see Chapter 28).

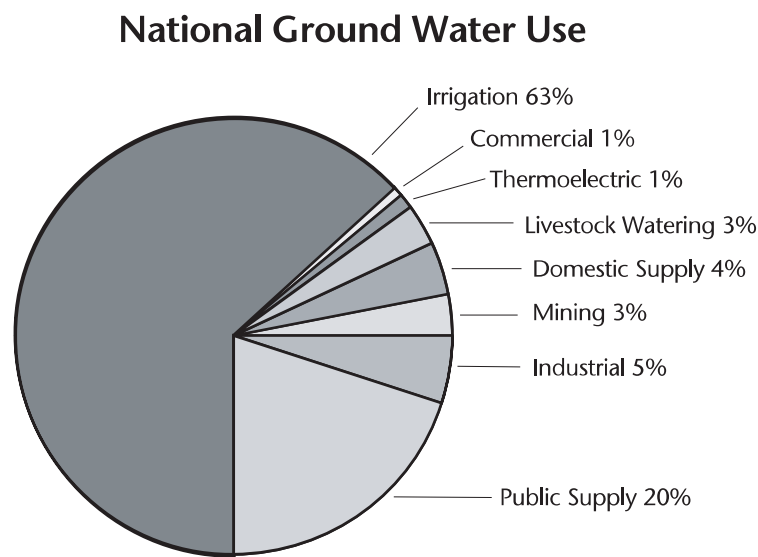
A comprehensive monitoring program is instrumental in managing and protecting groundwater resources. The U.S. Geological Survey's National Water-Quality Assessment (NAWQA) Program is a nation-wide program that is the principal source of information on groundwater quality in the United States. Under this program, the U.S. Geological Survey collects water quality data in 60 special study regions of the country, conducts retrospective analyses of existing data (such as state data), and prepares national-scale syntheses of

TABLE 17.1 Estimated percentage of potable water supply obtained from groundwater (Morris et al., 2003).

REGION	PERCENT	POPULATION SERVED (MILLIONS)
Asia-Pacific	32	1000–2000
Europe	75	200–500
Central and South America	29	150
USA	51	135
Australia	15	3
Africa	NA	NA
World	—	1500–2750

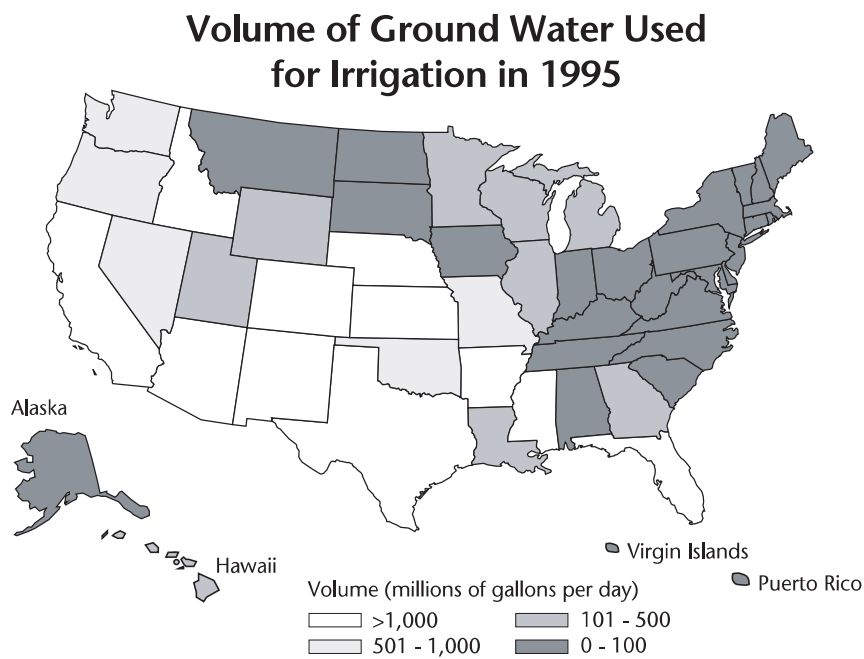


Figure 17.3 Percentage of population relying on groundwater as a drinking source. From EPA, 1999.



Source: *Estimated Use of Water in the United States in 1995*.
U.S. Geological Survey Circular 1200, 1998.

Figure 17.4 Groundwater use in the USA for 1995. From USGS, 1998.



Source: *Estimated Use of Water in the United States in 1995*.
U.S. Geological Survey Circular 1200, 1998.

Figure 17.5 Volume of groundwater used for irrigation in the USA for 1995. From USGS, 1998.

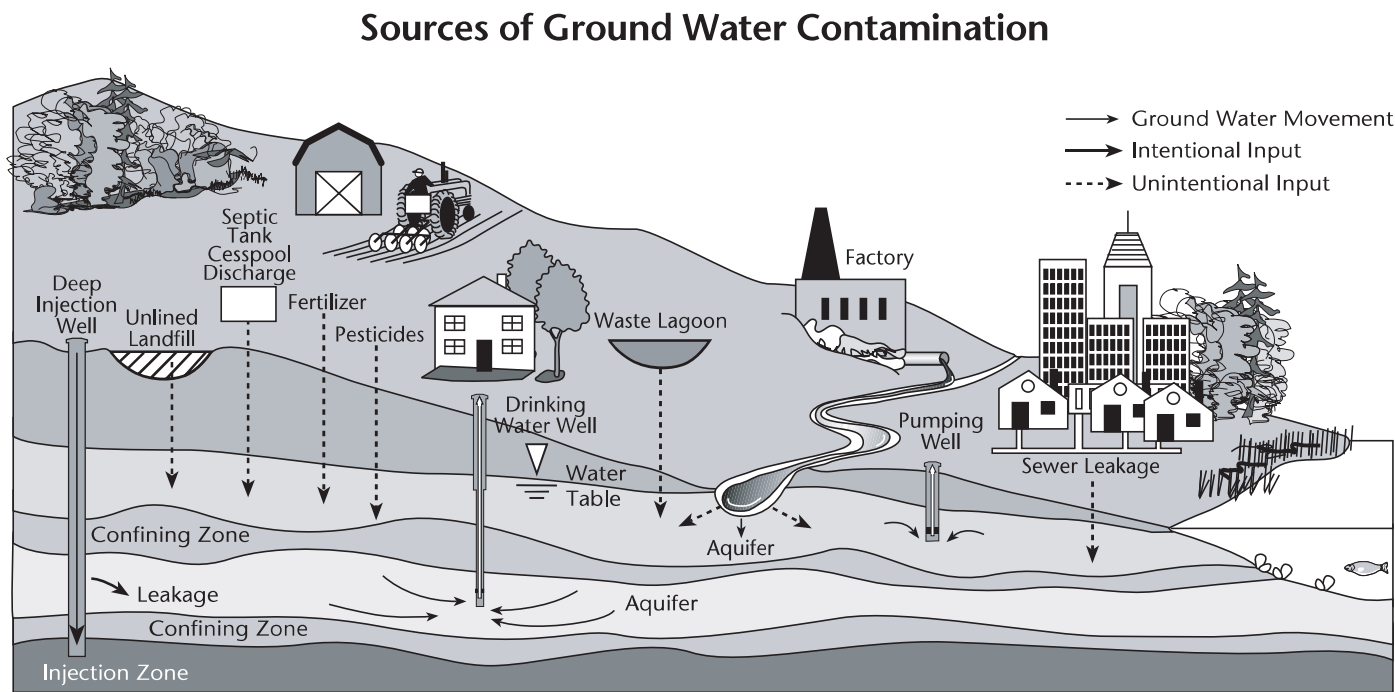


Figure 17.6 Sources of groundwater contamination. From EPA, 1998.

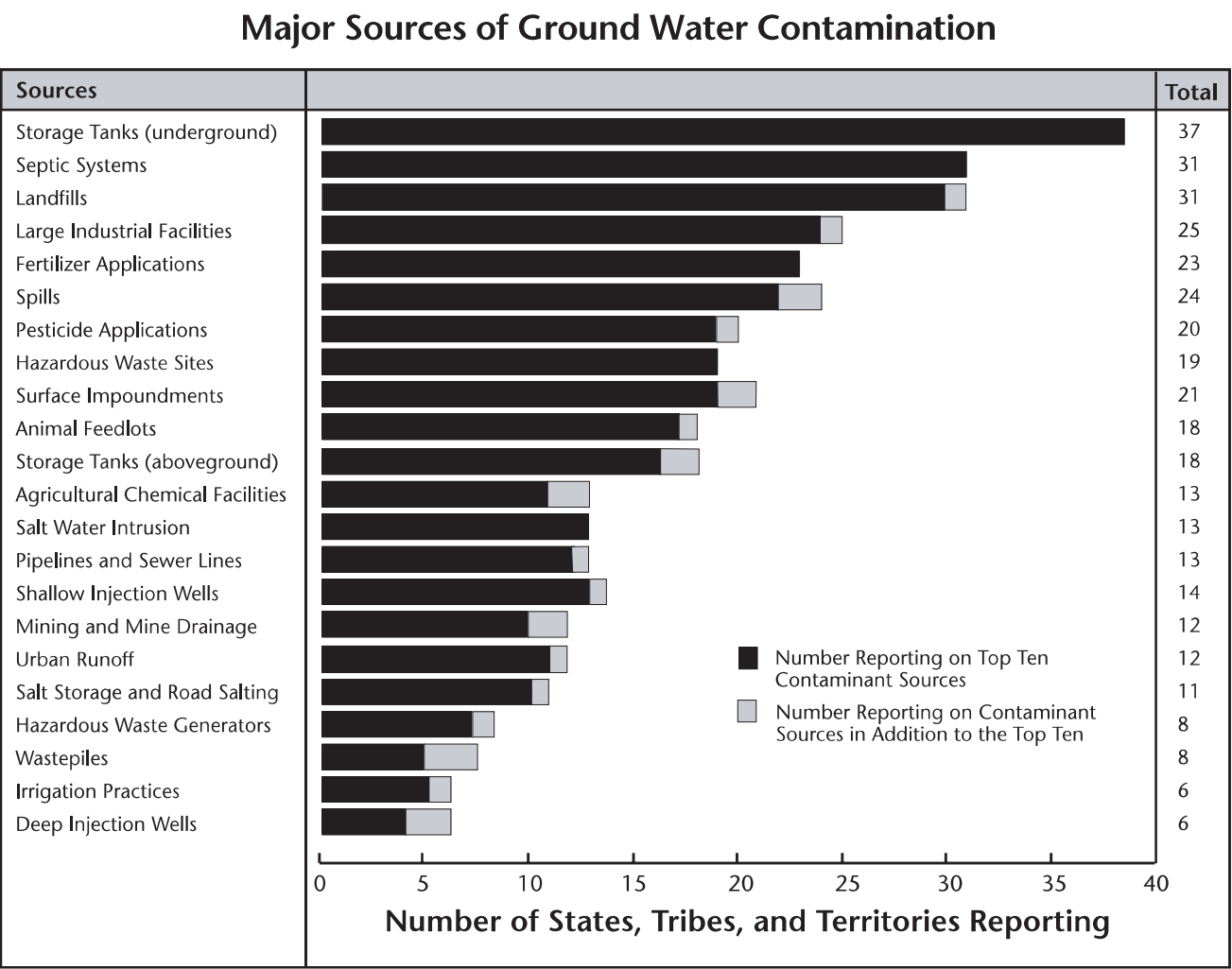


Figure 17.7 Major sources of groundwater contamination in the U.S. From EPA, 1998.

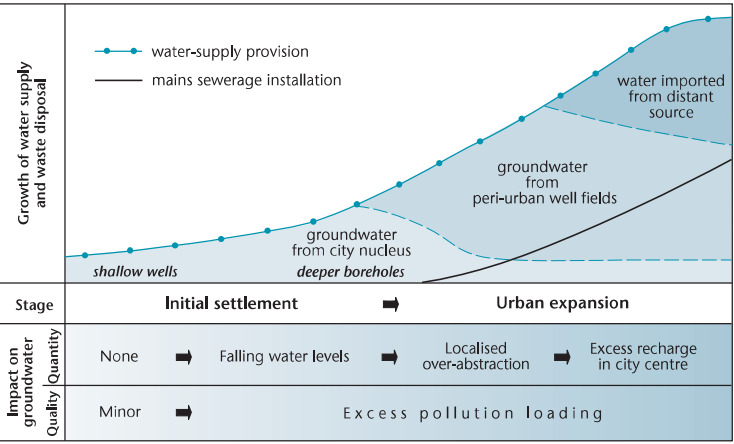


Figure 17.8 Stages in the development of water resources during evolution of an urban center. From Morris et al., 2003.

the results. In addition, many state and local governments in the U.S. carry out groundwater monitoring programs. Specialized monitoring programs are conducted in association with characterization and remediation of contaminated sites (see Chapter 12).

17.3 GROUNDWATER POLLUTION RISK ASSESSMENT

Physical properties of the subsurface result in significant differences in the behavior of groundwater compared to that of surface water. For example, residence times for groundwater range from years to hundreds of years or more; these times are much greater than those for streams. Dilution effects, either in water or the atmosphere, are much less significant for groundwater compared to surface-water systems. In addition, the absence of light eliminates the possibility of photochemical reactions, which are a major route of transformation for aboveground systems. The net result is that once groundwater and the subsurface are contaminated, it is very difficult to decontaminate (the remediation of subsurface contamination is discussed in Chapter 19). Thus, pollution prevention is critical to maintaining sustainable groundwater resources. Groundwater pollution risk assessment is a key aspect of pollution prevention.

Preventing contamination from entering the environment is the only sure way of preventing pollution. Laws and regulations promulgated during the past few decades have helped to reduce the overall contaminant load to the environment (see Chapter 15). Obviously, however, preventing all contamination from entering the environment is not possible, hence the need for groundwater pollution risk assessment, the goal of which is to evaluate the risk posed by a given activity or event to groundwater resources. Implementing risk assessments enhances the effective management of groundwater resources and helps to minimize potential contamination (see also Chapter 14).

Groundwater pollution risk is composed of two components: groundwater vulnerability and contaminant load. Groundwater vulnerability is the intrinsic susceptibility of the specific aquifer in question to contamination. Several factors affect groundwater vulnerability, as shown in Table 17.2. An aquifer that is close to ground surface, overlain by sandy soil, and located in an area with high precipitation rates would clearly be more vulnerable to contamination

than an aquifer that is hundreds of meters below ground surface and located in an area of low precipitation.

Factors involved in the contaminant load are the type of contaminant, the amount of contaminant released, the timescale of release, and the mode of release. The pollution potential of a contaminant is controlled by its transport and fate behavior, as discussed in Chapter 6. Contaminants that are transported readily (*e.g.*, those with high aqueous solubility and low sorption) and that are not transformed to any great extent (*i.e.*, are persistent) generally have greater potential to pollute groundwater. For most contamination events, the contamination enters the environment in close proximity to land surface (*e.g.*, surface spills, leaking storage tanks, and landfills). Thus, transport of contaminants from the source zone to groundwater necessitates travel through the soil and vadose zone. Attenuation processes such as sorption and biodegradation (see Chapters 6, 7, and 8) can act to reduce and limit the transport of contaminants to groundwater. For this reason, the soil and vadose zone is often referred to as a “living filter.” The degree to which contaminants will be attenuated is a function of the type of contaminant and the nature of the subsurface. General transport and attenuation properties of common subsurface contaminants are presented in Table 17.3. Generally, the greater the amount of contamination released, the greater the pollution potential. The timescale and mode of release can also affect pollution potential. For example, releases from buried storage tanks may be more prone to cause groundwater contamination than releases from tanks stored aboveground on concrete pads.

The risk of groundwater pollution results from the combination of intrinsic vulnerability and contaminant load factors. Thus, an aquifer that is very vulnerable may have little to no risk of pollution if the contaminant load remains negligible. Conversely, an aquifer that has a relatively low degree of vulnerability may have a significant pollution risk if the contaminant load factor is very high. The greatest pollution risk will be associated with locations where the aquifer has a high vulnerability and the contaminant loading is high.

In general, not much can be done to modify or change the inherent vulnerability of an aquifer. That is why it is critical to focus on controlling the contaminant load for managing and preventing groundwater pollution. This can be done through implementing land-use and facility-operation regulations. For example, aquifer vulnerability assessments can be used in the siting of new facilities that involve production, storage, or disposal of hazardous materials. Including

TABLE 17.2 Factors affecting groundwater vulnerability to contamination.

FACTOR	INCREASED VULNERABILITY	DECREASED VULNERABILITY
Depth to groundwater	Shallow	Deep
Soil type	Well drained (sandy)	Poorly drained (high clay, organic matter content)
Vadose zone physical properties	Preferential flow channels	Horizontal low-permeability layers
Recharge	High precipitation, high infiltration	Low precipitation, low infiltration
Subsurface attenuation processes	Minimal attenuation	Significant attenuation

TABLE 17.3 Transport and attenuation properties of major subsurface contaminants.

CONTAMINANT	SOURCE	ATTENUATION MECHANISM					PERMITTED DRINKING WATER CONCENTRATION	MOBILITY	PERSISTENCE	POTENTIAL TO DEVELOP EXTENSIVE GROUNDWATER PLUME
		Biochemical degradation	Sorption	Filtration	Precipitation					
Pathogens	Sewage	**	**	***	×		Very low (<1 per 100 ml)	Low	Low–moderate	Low
Nitrogen (N)	Agriculture, sewage	*	*	×	×		Moderate (10–20 mg N/L)	Very high	Very high	High
Chloride (Cl)	Sewage, industry, road deicer	×	×	×	×		High	Very high	Very high	High
Sulfate (SO ₄)	Road-runoff, industry	* 2	*	×	*		High	High	High	High
Dissolved organic carbon (DOC)	Sewage, industry (esp. food processing, textiles)	**	**	*	×		Not controlled	Moderate	Low–Moderate	Moderate
Heavy metals	Industry	×	***	* 3	**		Low (variable)	Generally low unless pH low (except Cr [VI])	High	Low
Halogenated solvents	Industry, commercial	*	*	×	×		Low (5–30 µg/L)	High	High	High
Fuels, lubricants, oils, other hydrocarbons (LNAPLs)	Fuel station, industry	***	**	×	×		Low (10–700 µg/L BTEX 4)	Moderate	Low–Moderate	Moderate
Other synthetic organics	Industry, sewage	Variable	Variable	×	×		Low (variable)	Variable	Variable	Variable

KEY = *** highly attenuated, ** significant attenuation, * some attenuation, × no attenuation
1 Ammonia is absorbed, 2 Can be reduced, 3 When it occurs as organic complexes, 4 Aromatic compounds with health guideline limits
Adapted from Morris et al., 2003.

aquifer vulnerability as a siting factor can prevent building such facilities in locations where groundwater is most susceptible to pollution. For existing facilities, operation procedures can be implemented to minimize the production and disposal of wastes (see Chapter 25).

Special procedures and tools have been developed to assess groundwater pollution risk. This is usually done by employing a geographic information system. The first step typically involves constructing an aquifer vulnerability map (Figure 17.9). This map incorporates one or more factors that influence aquifer vulnerability, such as those listed in Table 17.2. A commonly used aquifer vulnerability tool is DRASTIC (See Information Box 17.2). An example of an aquifer vulnerability map is shown in Figure 17.10. Once the vulnerability map has been created, land-use factors can be superimposed to evaluate risk. An example of a groundwater risk map is shown in Figure 17.11, which shows the nitrate contamination risk for shallow aquifers in the U.S. The map was developed using soil drainage as the aquifer vulnerability factor, and fraction of cropland acreage, population density, and nitrogen loading as the loading (land use) factors.

17.4 POINT-SOURCE CONTAMINATION

Point-source systems are characterized by very localized contamination releases. Primary examples include surface spills, leaking storage tanks, disposal pits, and waste-injection wells. The distribution of contamination at sites associated with point-source releases follows a general pattern as illustrated in Figure 17.12. The region of the subsurface where the majority of the original contamination is present is referred to as the **source zone**. It is usually in close proximity to the

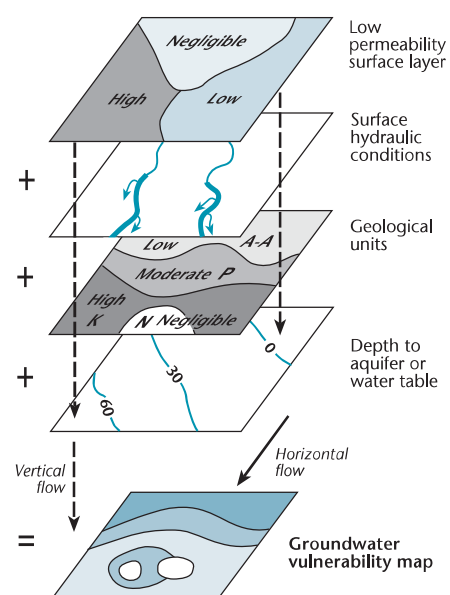


Figure 17.9 Combining factors to create a groundwater vulnerability map. From Morris et al., 2003.

INFORMATION BOX 17.2

Aquifer Vulnerability is DRASTIC

DRASTIC was developed by the EPA as a standardized system for evaluating aquifer vulnerability to pollution. The method is based on assumptions that the contaminant is released at the ground surface and that it enters the subsurface via infiltrating water. Contaminant attenuation is not considered. Thus, it may be considered to provide a conservative estimate of vulnerability for those situations where attenuation may be significant. The acronym DRASTIC is derived from the seven hydrogeologic factors considered:

1. **D**epth to groundwater
2. **R**et Recharge
3. **A**quifer media
4. **S**oil media
5. **T**opography (slope)
6. **I**mpact of the vadose zone media
7. **C**hydraulic Conductivity of the aquifer.

Each of the hydrogeologic factors is assigned a rating from 1 to 10, based on the properties of the specific site. For example, a rating of 10 is given for "depth to groundwater" if the water table is located from 0–5 feet from ground surface. A rating of 1 is given if it is more than 100 feet from ground surface. The ratings are then multiplied by a weighting coefficient ranging from 1 to 5. The most significant factors have a weight of 5; the least significant have a weight of 1. The weight factors are: D = 5, R = 4, A = 3, S = 2, T = 1, I = 5, and C = 3. The products of the rating and weighting coefficient for each factor are summed to produce the final DRASTIC score. The smallest possible DRASTIC score is 23 and the largest is 226.

The DRASTIC score represents a relative measure of aquifer vulnerability. The higher the DRASTIC score, the greater the vulnerability of the aquifer to contamination.

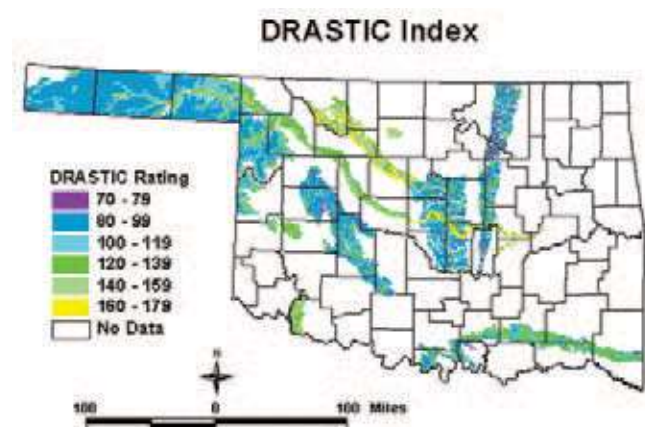


Figure 17.10 DRASTIC-based vulnerability assessment of major aquifers in Oklahoma. From Osborn et al., 1998.

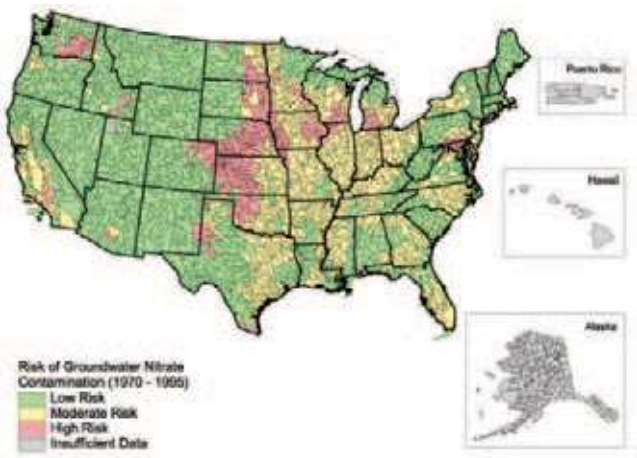


Figure 17.11 Risk of groundwater nitrate contamination for shallow aquifers in the US (< 100 feet deep). Image courtesy of USEPA; http://www.epa.gov/iwi/1999sept/iv21_usmap.html.

location of the contaminant release. The source zone generally encompasses a relatively small area and contains the majority of the contaminant mass. Conversely, the region where groundwater is contaminated by dissolved compounds originating from the source zone is referred to as a **groundwater contaminant plume**. The plume is often much larger than the source zone. However, the amount of contaminant mass associated with the plume may represent a small fraction compared to the mass in the source zone.

The configuration or “architecture” of the source zone (*e.g.*, porous-medium heterogeneity, total contaminant mass, contaminant distribution) and source-zone “dynamics” (*e.g.*, mass-transfer processes, transformation processes) is central to the pollution risk posed by the site. For example, the magnitude (size and concentration level) of the groundwater contaminant plume generated from the source zone is clearly dependent on the magnitude and rate of contaminant mass transfer from the source zone to surrounding regions (*i.e.*, the source-zone mass flux). This mass transfer will be influenced by groundwater flow patterns (which are mediated by the physical properties of the porous media), and by the type, amount, and distribution of contaminant. The groundwater contaminant plume is generally the primary source of human-health risk posed by these types of contaminated sites, as use of contaminated groundwater is usually the major route of potential exposure to subsurface contamination. Thus, it is critical to characterize source-zone and contaminant plume properties at a given site (See Chapter 19).

17.4.1 Hazardous Organic Chemicals

The contamination of groundwater by hazardous organic chemicals and the associated risk to human health and the environment is one of the primary groundwater pollution issues facing the U.S. and other industrialized countries. Major types of organic compounds that are prevalent groundwater contaminants are listed in Table 17.4. It is estimated that there are tens of thousands of sites across the U.S. where groundwater is contaminated with one or more of the

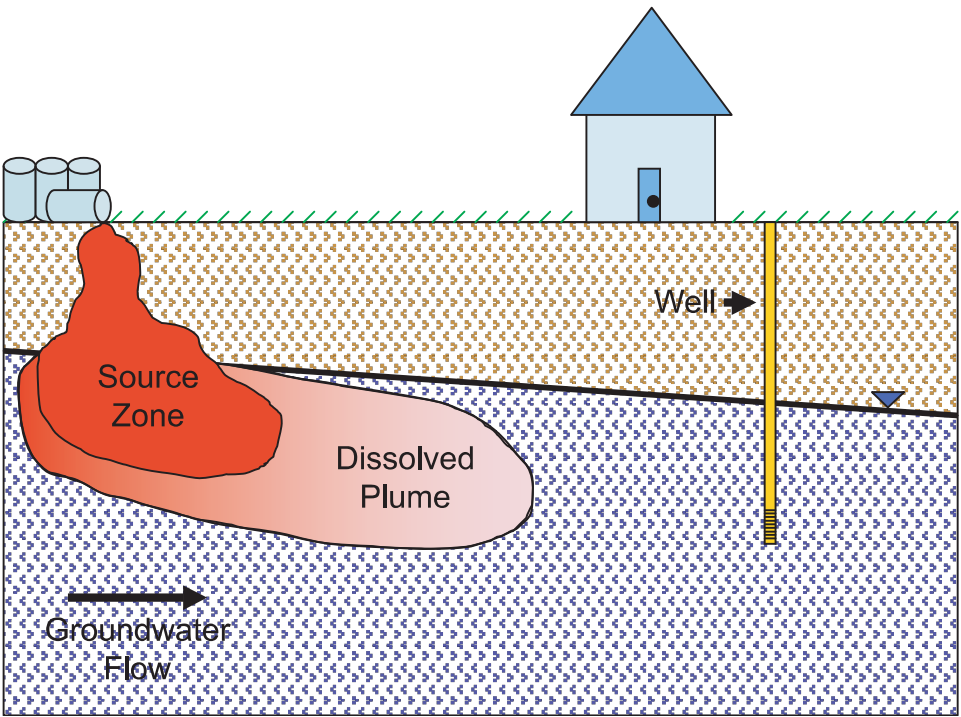


Figure 17.12 Distribution of contamination at a point-source groundwater contamination site. From C.M. McColl.

TABLE 17.4 Major classes of hazardous organic chemicals of significance for groundwater pollution.

CLASS	EXAMPLE COMPOUNDS	SOURCES/USES	PROPERTIES ¹
Chlorinated solvents	Trichloroethene Tetrachloroethene	Manufacturing Degreasing Dry cleaning	DNAPL
Coal tar, Creosote	Polynuclear Aromatic Hydrocarbons Phenols	Coal gasification Wood treatment	DNAPL
Hydrocarbon fuels	Benzene	Fuel	LNAPL
Polychlorinated Biphenyls	Aroclor	Transformer fluid	DNAPL

¹DNAPL = denser than water; LNAPL = less dense than water.

chemical classes listed in Table 17.4 (see Information Box 17.3). This contamination results from the release of the chemicals during their transport, storage, use, and disposal. For example, thousands of underground fuel storage tank releases have been confirmed for every state in the U.S. (Figure 17.13). For another example, it has been reported that up to 75% of the 36,000 active dry-cleaning facilities in the U.S. have experienced releases of tetrachloroethene or other dry-cleaning solvents (EPA, 2003a). Many of these compounds are of concern with respect to human health (*e.g.*, carcinogenic), as discussed in Chapter 13.

One of the most critical issues associated with hazardous waste sites is the potential presence of immiscible-liquid contamination in the subsurface. The chemicals listed in Table 17.4 are liquids under natural conditions, and they are immiscible with water, meaning they do not mix. Immiscible

liquids released into the subsurface become trapped in pore spaces due to capillary forces. Once entrapped, the immiscible liquid is very difficult to remove. Hence, immiscible liquids serve as long-term sources of subsurface contamination as they dissolve in groundwater or soil-pore water. The presence of immiscible liquids in the subsurface of a site can greatly impact the costs and time required for site remediation. For example, for sites contaminated by dense nonaqueous phase liquids (DNAPLs) (see Chapter 6), it is estimated that upwards of hundreds of years may be necessary to achieve health-based groundwater cleanup objectives using standard pump-and-treat systems (ITRC, 2002). This clearly illustrates the critical importance of addressing immiscible-liquid contamination when it is present at a site. Unfortunately, as is widely acknowledged, cleaning up sites contaminated by immiscible liquids is one of the greatest challenges in the field of environmental remediation. In fact, according to several reviews conducted by expert panels convened by the National Research Council, the presence of immiscible liquids is usually the single most important factor limiting the cleanup of organic-chemical contaminated sites. In addition, the presence of immiscible liquids greatly complicates site characterization and risk assessment efforts. The estimated cost to clean up the immiscible-liquid contaminated sites in the U.S. is \$100 billion or more (EPA, 2003).

The distribution of immiscible liquids in the subsurface is controlled by the physical and chemical properties of the porous media and by the properties of the chemical. A primary property of concern is the density of the immiscible liquid in comparison to that of water. In fact, this is such an important property that the immiscible liquids are classified based on whether they are more (DNAPL) or less (LNAPL) dense than water (see Table 17.4), where NAPL = nonaqueous phase liquid. Because DNAPLs are denser than water, they can sink below the water table with sufficient volume of release. A conceptual diagram of the distribution of a DNAPL in the subsurface is presented in Chapter 6 (see Figure 6.1). In contrast to DNAPLS, LNAPLS float on the water table because they are less dense than water (Figure 17.14). The distribution and amount of immiscible liquid present in the source zone has a major impact on the nature of the groundwater contaminant plume that forms at the site.

INFORMATION BOX 17.3

Chlorinated-Solvent Contamination of Groundwater in Arizona

Chlorinated solvents, such as tetrachloroethene, trichloroethene, dichloroethene, carbon tetrachloride, and vinyl chloride, are among the most common groundwater contaminants in the U.S. due to their widespread use as dry-cleaning solvents and as degreasing and cleaning agents for military, industrial, and commercial applications. In Arizona, chlorinated solvents are the primary contaminants at an overwhelming majority of both the state Superfund sites (30 out of 34) and the federal Superfund sites (13 out of 14). Hundreds of millions of dollars have been spent to date on characterization and remediation of these sites. Furthermore, additional hundreds of millions of dollars have been spent to settle toxic-tort lawsuits. In aggregate, these sites encompass hundreds of km² in land area and contain billions of liters of contaminated groundwater. As such, chlorinated solvents are a major source of groundwater contamination in Arizona and pose an immediate, significant, and continuing threat to the sustainability of the state's potable water supplies.

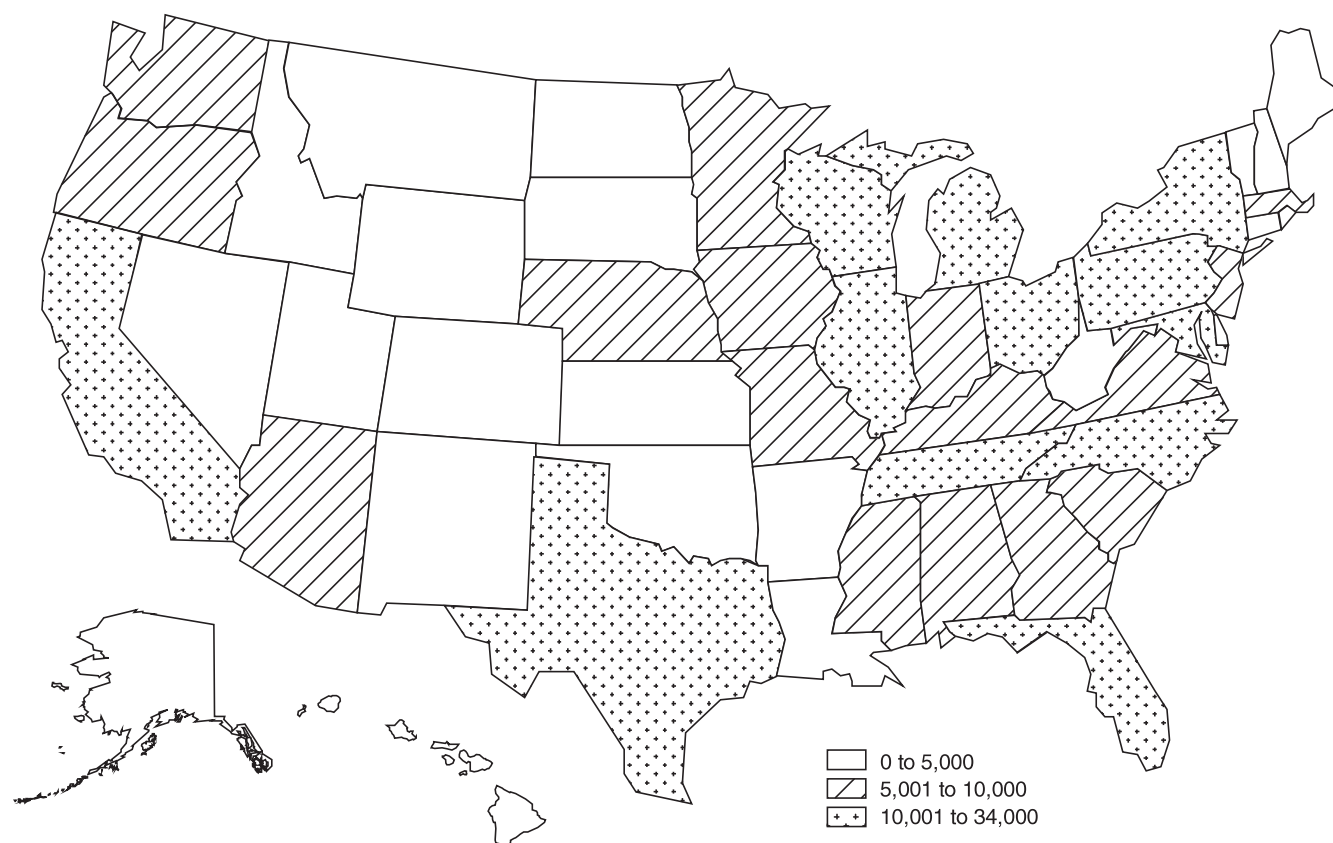


Figure 17.13 Confirmed underground storage tank releases as of February 1999. From EPA, 1999.

In addition to source-zone properties, the size of the dissolved-contaminant plume will be influenced by the nature of the chemicals and by physical, chemical, and biological properties of the subsurface. Plumes are generally relatively small for chemicals that undergo significant attenuation. Conversely, very large contaminant plumes can form for chemicals that undergo minimal attenuation. The general potential of the major classes of subsurface contaminants to

develop extensive groundwater plumes is listed in Table 17.3. For example, groundwater plumes comprised of chlorinated-solvent constituents are typically hundreds to thousands of meters long because these compounds are difficult to biodegrade and have relatively low sorption. Conversely, plumes generated from fuel hydrocarbons such as gasoline are generally much shorter, primarily because the compounds are more amenable to biodegradation.

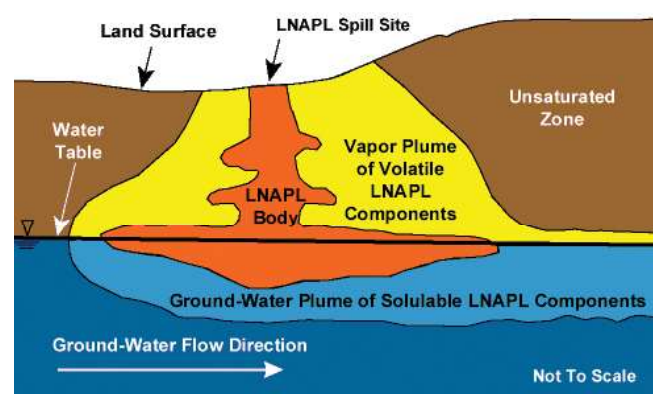


Figure 17.14 Conceptual diagram illustrating the distribution of an LNAPL in the subsurface. Image courtesy of USGS; <http://toxics.usgs.gov/definitions/lnapls.html>.

17.4.2 Landfills

The contamination of soil and groundwater from landfills is another important problem that continues to threaten groundwater resources, posing risks to human health and the environment. Chemicals, both hazardous and nonhazardous, can be leached from the materials that are disposed of in landfills (see Figure 25.7). This landfill-derived contamination or **leachate** can enter the soil and migrate through the vadose zone, eventually contaminating groundwater resources. Landfills are used for the disposal of numerous types of wastes, garbage, and materials. Thus, contamination emanating from landfills can contain mixtures of numerous types of compounds, increasing the complexity of the pollution problem (Table 17.5).

Contaminated water or leachate is produced when water (e.g., precipitation or irrigation) enters the landfill and

TABLE 17.5 Common contaminants and concentrations at landfills.

PARAMETER	"TYPICAL" CONCENTRATION RANGE	AVERAGE
BOD	1,000–30,000	10,500
COD	1,000–50,000	15,000
TOC	700–10,000	3,500
Total volatile acids (as acetic acid)	70–28,000	NA
Total Kjeldahl Nitrogen (as N)	10–500	500
Nitrate (as N)	0.1–10	4
Ammonia (as N)	100–400	300
Total phosphate (PO ₄)	0.5–50	30
Orthophosphate (PO ₄)	1.0–60	22
Total alkalinity (as CaCO ₃)	500–10,000	3,600
Total hardness (as CaCO ₃)	500–10,000	4,200
Total solids	3,000–50,000	16,000
Total dissolved solids	1,000–20,000	11,000
Specific conductance (mhos/cm)	2,000–8,000	6,700
pH	5–7.5	63
Calcium	100–3,000	1,000
Magnesium	30–500	700
Sodium	200–1,500	700
Chloride	100–2,000	980
Sulfate	10–1,000	380
Chromium (total)	0.05–1	0.9
Cadmium	0.001–0.1	0.05
Copper	0.02–1	0.5
Lead	0.1–1	0.5
Nickel	0.1–1	1.2
Iron	10–1,000	430
Zinc	0.5–30	21
Methane gas	60%	
Carbon dioxide	40%	

All values mg/L except as noted.

NA = not available

Source: Lee, G.F. and R.A. Jones (1991b) (<http://www.gfredlee.com/lf-conta.htm>).

contacts the waste materials (Figure 17.15). The infiltrating water can remove hazardous and nonhazardous chemicals, including metals, minerals, salts, organic chemicals (*e.g.*, chlorinated solvents, petroleum hydrocarbons, and pesticides), and various other toxic compounds. Millions of gallons of leachate can percolate through a landfill, depending on the size of the landfill or disposal facility. A well-designed landfill should contain the disposed materials, isolating potentially harmful leachate from the environment and specifically from groundwater and drinking water resources. However, it is impossible to contain and control all wastes produced at landfill and disposal sites. Leachate can enter groundwater systems as a result of poorly designed or improperly constructed landfills, deterioration of landfill liners, and landfills constructed without liners (*e.g.*, typically older designs).

Given that leachate is likely to leak to some degree from all landfills, it is essential to implement a well-designed monitoring scheme to help manage landfill pollution problems. For example, a series of monitoring wells can be constructed around the perimeter of the landfill. The presence of high salt concentrations (*e.g.*, Cl[−]) indicates the potential threat of contamination to groundwater. Similarly, total dissolved solids (TDS) can be used to indicate potential contamination of

groundwater by landfill leachate. Salts serve as good indicators of leachate contamination because of their high mobility and persistence (see Table 17.3), which means they usually constitute the leading (downgradient) front of the groundwater leachate plume. Monitoring pH is another means to detect potential contamination of groundwater by leachate. Generally, the pH of landfill leachate is lower than that of uncontaminated groundwater. A third method to detect potential leachate contamination of groundwater is by determining the oxidation-reduction potential. Highly reducing conditions typically indicate either low pH or high microbial degradation activity. Waste materials disposed of in landfills are often subject to microbially mediated decay and decomposition. The microorganisms consume oxygen during the degradation process, thus reducing the oxidation-reduction potential. In addition, some microorganisms can degrade waste under anaerobic conditions and in the process release methane and other gases. Thus, the presence of such gases in groundwater is another indicator of landfill-leachate contamination.

As noted above, landfill leachate comprises many compounds. Thus, the transport and fate behavior of leachate is complex and highly variable. Compounds with high mobilities and low degradation potentials (high persistence) will

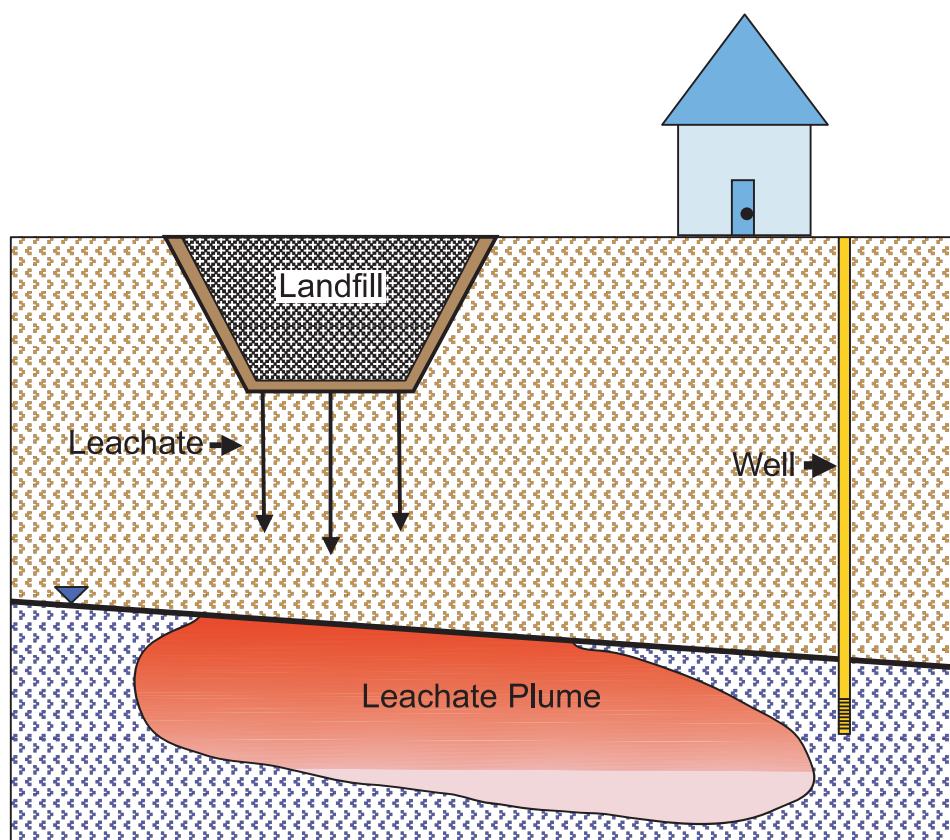


Figure 17.15 Landfill leachate plume. From C.M. McColl.

tend to be transported much further than compounds that sorb to soil and/or that are easily degraded. For this reason, it is difficult to predict the transport and fate behavior of leachate in soil and groundwater.

17.5 DIFFUSE-SOURCE CONTAMINATION

Contamination resulting from nonpoint (diffuse) sources of pollution refers to those inputs that occur over a wide area and are associated with particular land uses. This is in contrast to point-source discharges, which occur from a specific, very localized source such as a leaking fuel tank or pipe. Nonpoint sources generally encompass much larger scales (regional and even global scales) and as a result can create very large zones of pollution compared to point sources. However, the contaminant concentrations associated with nonpoint source pollution are generally lower than those associated with point sources. This section will focus on two major diffuse-source issues: agrochemical contamination and salt-water intrusion.

17.5.1 Agrochemical Pollution of the Subsurface

The advent of intensive agricultural practices during the last century and into the 21st century has greatly increased global food production. However, as discussed in Chapter 16, it has

also greatly increased the use of fertilizers and pesticides, so-called **agrochemicals** (Figure 17.16). The increasing use of these agrochemicals has led to extensive pollution of groundwater. For example, nitrate, derived from fertilizers, pesticides, and animal wastes, is one of the most widespread and pervasive groundwater contaminants in the United States

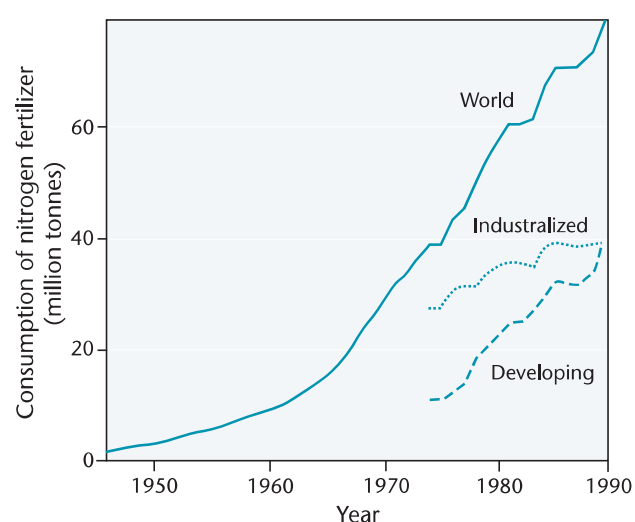


Figure 17.16 Increases in nitrogen fertilizer use in developing countries. Consumption of nitrogen fertilizer from 1946–1989. From Morris et al., 2003.

and the world. In a survey of almost 200,000 water sampling reports, the EPA found that more than 2 million people were using water from public potable-water supply systems for which nitrate standards were exceeded at least once between 1986 and 1995 (EWG, 1996). An additional 3.8 million people were using water from private wells that exceed federal drinking water standards. Researchers predict, due to past and current inputs of nitrates into the environment, that the full effect of overapplication of nitrate fertilizers will not be realized for another 30–40 years (Hallberg and Keeney, 1993). The potential impacts of nitrate contamination on human health are discussed in Chapter 13.

As we might expect, agricultural areas generally have the most significant groundwater nitrate contamination problems. For example, major agricultural regions such as the San Joaquin Valley in California and the Ogallala aquifer system extending from Minnesota to Texas are areas with high vulnerability to nitrate groundwater contamination (see Figure 17.11). In addition, these agricultural regions are also experiencing severe declines in groundwater levels as a result of excessive groundwater extraction for irrigation. It is common in agricultural areas to see the compounding effect of declining groundwater levels coinciding with high levels of nitrate contamination.

Nitrate is generally very mobile in the subsurface. This, in conjunction with the large areal extent of input, results in extensive groundwater plumes of nitrate contamination. It is difficult and expensive to clean up groundwater once it is contaminated by nitrate. For example, the costs associated with managing nitrate contamination problems in California and Iowa are estimated to exceed \$200 million per year (EWG, 1996). A standard approach for dealing with shallow groundwater nitrate contamination is to drill deeper wells. However, this can be done only a limited number of times. Another common practice is to blend contaminated water with uncontaminated water. The objective of this technique is to dilute the nitrate to concentrations below the drinking water standard. This approach increases the overall use of water resources. It

is estimated that closing down a well due to nitrate contamination, and drilling another well or blending contaminated water with cleaner supplies, can cost between \$200,000–500,000 per well (EWG, 1996). Point-of-use treatment for nitrate is also expensive, requiring methods such as reverse osmosis. A key to solving the problem of nitrate groundwater contamination is to prevent future contamination by using best management practices, as discussed in Chapter 16.

Another major class of agrochemicals, also widely used in agricultural practices, are pesticides (see Chapters 10 and 16). Pesticides are typically applied at the land surface, usually as a chemical spray. Once applied to the ground surface, pesticides can migrate downward through the vadose zone with infiltrating water and contaminate groundwater. Pesticides are used throughout the world, primarily for agriculture, to control weeds, insects, and fungal pests (Table 17.6). A study conducted between 1991 and 2001 by the U. S. Geological Survey found that 42% of wells sampled in agricultural regions across the United States contained the common pesticides atrazine and diethylatrazine. Furthermore, it was reported that about 20% of the wells sampled in major aquifer systems throughout the U.S. contained both atrazine and diethylatrazine. These results illustrate the extent of groundwater pollution by pesticides.

The majority of pesticides are organic compounds. Their transport and fate behavior in the subsurface is a function of their chemical properties (see Chapters 6 and 7). Some pesticides are relatively mobile (*e.g.*, 2,4-D), while others are highly sorbed (*e.g.*, DDT) (see Chapter 16). The classes of pesticides that were initially developed, such as DDT, are very persistent in the environment. Newer pesticides have been designed in part to be less persistent. A complicating factor in the evaluation of pesticide pollution problems is the sheer number of pesticides available for use. It is not customary to analyze for all possible pesticide compounds, their derivatives, and possible degradation products in groundwater monitoring surveys. In addition, analytical limitations have constrained detection capability. However,

TABLE 17.6 Pesticide use and occurrence in groundwater.

REGION	DOMINANT PESTICIDE USE	TYPICAL COMPOUNDS DETECTED
United Kingdom	Pre- and postemergent herbicides on cereals, triazine herbicides on maize and in orchards	Isoproturon, mecoprop, atrazine, simazine
Northern Europe	Cereal herbicides and triazines as above	As above
Southern Europe	Carbamate and chloropropane soil insecticides for soft fruit, triazines for maize	Atrazine, alachlor
Northern U.S.	Triazines on maize and carbamates on vegetables, <i>e.g.</i> , potatoes	Atrazine, aldicarb, metolachlor, alachlor and their metabolites
Southern and Western U.S.	Carbamates on citrus and horticulture, and fumigants for fruit and crop storage	Aldicarb, alachlor and their metabolites, ethylene dibromide
Central America and Caribbean	Fungicides for bananas, triazines for sugarcane, insecticides for cotton, and other plantation crops	Atrazine
South Asia	Organophosphorous and organochlorine insecticides in wide range of crops	Carbofuran, aldicarb, lindane
Africa	Insect control in houses and for disease vectors	Little monitoring as yet

From Morris et al., 2003.

recent advancements have resulted in more frequent detection of pesticide compounds in groundwater supplies.

17.5.2 Salt-Water Intrusion

Salinization of freshwater is one of the most serious and widespread groundwater contamination issues throughout the world. Areas along coasts where seas or oceans meet continental landmasses and island systems are most vulnerable to salinization of groundwater resources. In most coastal settings, groundwater beneath land surface generally exists as a lens of “freshwater.” The freshwater is separated from the denser seawater by a diffuse interface known as the freshwater/saltwater interface or zone of dispersion (Figure 17.17). The freshwater/saltwater interface typically resides at some point near where the ocean meets the land mass (coastline) and extends vertically in the subsurface, separating freshwater (inland) from high salinity water (seawater). This freshwater lens tends to become thinner as it approaches the shoreline. If recharge into the aquifer equals extraction rates due to pumping, the freshwater/saltwater interface will remain stable (Figure 17.18). However, if groundwater pumping exceeds recharge, the saline water will invade the freshwater aquifer and the freshwater/saltwater interface will progress further inland. As this zone progresses further inland, groundwater supply wells can become contaminated from the invading saltwater. This phenomenon is known as **saltwater intrusion**, and

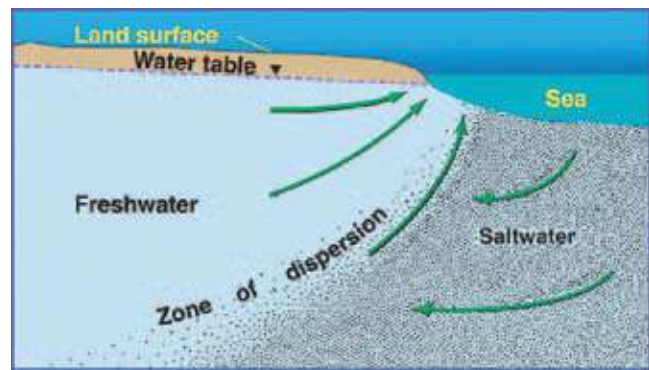
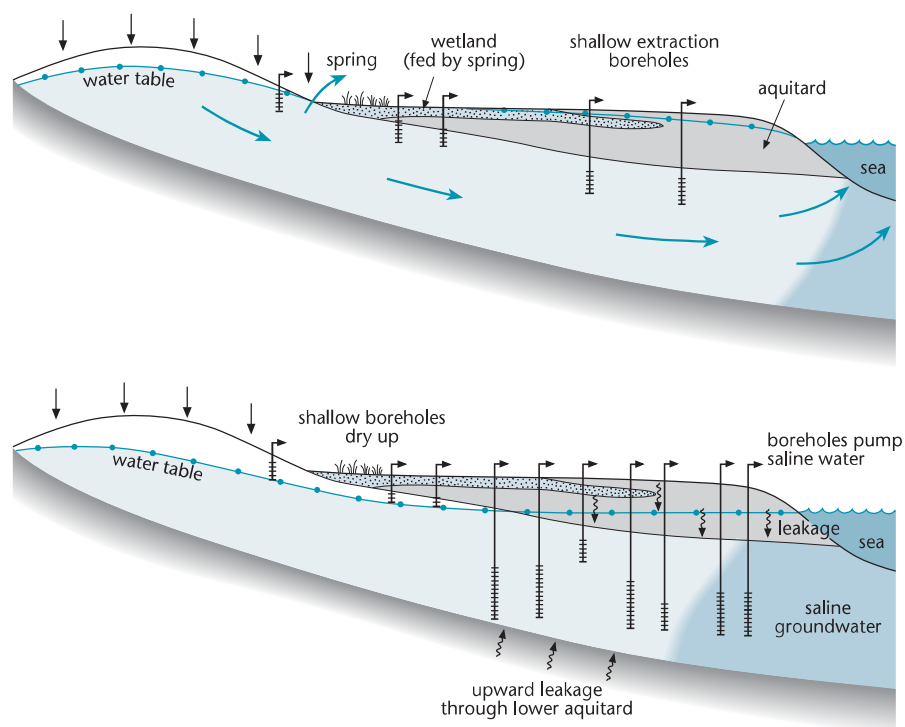


Figure 17.17 Freshwater and saltwater mix in the zone of dispersion. Figure modified from Cooper H. H. (1964). A hypothesis concerning the dynamic balance of fresh water and salt water in a coastal aquifer. U.S. Geological Survey Water-Supply Paper 1613-C, p. 1–12).

it has caused severe degradation and contamination of groundwater.

It does not take very much saltwater to contaminate a fresh groundwater supply. Only 3–4% addition of salinity can make a fresh water supply unsuitable for most uses, including drinking water and even irrigation (Morris et al., 2003). As little as 6% addition of saltwater will render a freshwater source (groundwater) unsuitable for any use except cooling or flushing purposes. Once a freshwater resource is degraded by salt contamination, it will take a very



Stage A : Initial condition

- groundwater flows from outcrop to coast
- springs help maintain wetland
- limited extraction from shallow boreholes occurs

Stage B : Groundwater extraction increases leading to:

- groundwater level decline in aquifer
- springs feeding wetland cease
- shallow wells dry up
- coastal boreholes become saline
- leakage through upper and lower aquitards (if present) begins

Figure 17.18 Saltwater intrusion: invading seawater. Top: Groundwater extraction balanced by recharge. Bottom: Groundwater extraction exceeds recharge. From Morris et al., 2003.

long time for that aquifer to recover, and if positive groundwater recharge conditions are not re-established, it may never recover. Remediation efforts are often cost-prohibitive if not impossible due to the technical constraints associated with removing or decreasing the levels of salt concentration in groundwater. The first response is often abandonment of the contaminated wells, accompanied by drilling of new wells further inland. Effectively, the freshwater resource will have been lost, and supplying new water depends on availability of groundwater supplies further inland. Furthermore, if excessive groundwater pumping continues, the saltwater will continue to invade further inland, again contaminating fresh groundwater supplies. The other option currently available is to construct a desalinization plant to treat the contaminated groundwater prior to use. Such plants are likely to increase in use in the future, as technology improves and the availability of water supplies dwindles.

Although coastal regions may be most susceptible to saltwater intrusion, many noncoastal areas are also being affected by salinization of groundwater. Many natural geologic systems can lead to the salinization of freshwater resources. Areas once occupied by deep-water oceans or seas are now part of continents. These areas, now deep within the subsurface, contain ancient geologic units that contain high concentrations of salt or brine water. These salt-containing geologic units can contaminate freshwater aquifers when over pumping occurs in the region, causing the water table to decline and encroach into the high-salinity geologic units.

Generally there are no harmful health effects associated with low concentrations of chloride in drinking water. In some cases, salt (chloride) can be harmful to people with heart or kidney conditions. The EPA has set unenforceable secondary drinking water guidelines for chloride at 250 mg/L. However, the contamination of water by saltwater intrusion will increase salt concentrations far beyond what can be tolerated by humans. The primary concern with the contamination of drinking water supplies from saltwater intrusion is the large-scale loss of water resources.

17.6 OTHER GROUNDWATER CONTAMINATION PROBLEMS

Although we have discussed some of the major groups of contaminants threatening groundwater resources, such as hazardous organic chemicals (*e.g.*, chlorinated solvents and fuel-type hydrocarbons), agrochemical pollutants (*e.g.*, nitrates and pesticides), and salinization (*e.g.*, saltwater intrusion and high-salinity groundwater), it is important to note some other contaminants that also present potential threats to the quality of groundwater supplies. We will briefly discuss some of these groundwater contaminants in the following sections.

17.6.1 Pathogen Contamination of Groundwater

Contamination of groundwater by microbial pathogens, including viruses, bacteria, and protozoa, is of significant concern throughout the world. The types of pathogens and their impact on human health were discussed in Chapter 11. The transport behavior of pathogens in the subsurface environment is discussed in Chapter 27.

Potential sources of pathogens for groundwater contamination include land disposal of sewage treatment byproducts (wastewater, biosolids), septic tank systems, and latrines. Risks posed by pathogen-contaminated groundwater are generally believed not to be significant for public supply systems, given the level of treatment applied before use (see Chapter 28). Of much greater concern is potential pathogen contamination of groundwater used for private water supplies, because water from private wells typically undergoes little or no treatment before use. Thus, residential areas with septic systems and private wells are particularly susceptible to potential effects of groundwater contamination by pathogens.

Proper siting and construction of septic and well systems is necessary to minimize potential pollution problems. So-called wellhead protection rules have been developed to prevent the siting or application of pathogen sources too close to water-supply wells. Several recent surveys of groundwater across the U.S. have shown that the incidence of human viruses in groundwater is greater than previously believed and may in part be due to septic tank systems (see Information Box 17.4).

INFORMATION BOX 17.4

Occurrence of Viruses in U.S. Groundwater

Viruses (10–100 nm) are smaller than bacteria (0.5–3 μm) and protozoa (1–15 μm), and thus viruses are generally more mobile in porous media. For example, viruses have been observed to travel more than 100 m in the subsurface. Accordingly, it would be expected that groundwater is more likely to be contaminated by viruses than by other pathogens. To this end, a large-scale study was recently instituted to evaluate the occurrence of viruses in groundwater in the U.S. Information pertaining to physical and geological characteristics of wells and associated subsurface environments, along with various microbial and physico-chemical water-quality parameters, was collected, and possible correlation with the presence of human viruses was investigated. Groundwater samples were collected from 448 sites in 35 states, and assayed for microorganisms and chemical contaminants. Infective viruses, viral nucleic acid, bacteriophages, and bacteria were present in approximately 5, 31, 21, and 15% of the samples, respectively.

Source: Abbaszadegan et al., 2003.

17.6.2 Gasoline Additive: Methyl Tertiary-Butyl Ether (MTBE)

In the mid-1990s it was discovered that methyl tertiary-butyl ether (MTBE), an additive in gasoline, had caused extensive contamination of groundwater throughout the United States (see Information Box 17.5). MTBE had been used since the early 1970s as an oxygenate to promote more efficient combustion of fuel in automobiles. Ironically, while the intended use of MTBE has in fact reduced toxic emissions (*e.g.*, carbon monoxide) released to the atmosphere from automobiles, it has contributed to the widespread contamination of groundwater resources from leaking underground fuel storage tanks, posing serious threats to the quality of drinking water supplies. The contamination of groundwater by MTBE is extensive in the U.S. The EPA reports, citing a study by Chevron, that MTBE concentrations exceeded $1000\text{ }\mu\text{g L}^{-1}$ in 47% of 251 California sites surveyed, 63% of 153 Texas sites surveyed, and 81% of 41 Maryland sites surveyed (EPA, 2004). Responding to the rising occurrences of MTBE contamination, California in 1999 became the first state to ban the use of MTBE in gasoline reformulation after 2002. The EPA has now begun regulatory action to phase out the use of MTBE in gasoline.

The primary concern associated with the release of MTBE to the subsurface environment (from spills or leaking underground fuel storage tanks) is its mobility and persistence. For example, at most fuel station sites affected by leaking storage tanks, it is commonly observed that MTBE has migrated much farther than typical gasoline contaminants (*e.g.*, benzene, toluene). Unlike these contaminants, MTBE has a relatively low biodegradation potential. The health effects associated with MTBE through human ingestion of drinking water are not well understood nor well documented. Due to a lack of appropriate data on the health effects of MTBE contamination, the EPA has been unable to define national regulatory standards based on quantitative estimates for health risks. However, the EPA has set provisional drinking water health advisory limits at $20\text{--}40\text{ }\mu\text{g L}^{-1}$.

INFORMATION BOX 17.5

The First Significant Incidence of MTBE Contamination

In 1996, it was discovered that two well fields providing drinking water to the city of Santa Monica, California, were extensively contaminated with MTBE at average levels of $610\text{ }\mu\text{g L}^{-1}$ and $86\text{ }\mu\text{g L}^{-1}$. The city of Santa Monica lost 50% of its drinking water supply when these two well fields were shut down. Enormous costs were incurred from aquifer decontamination and remediation efforts, which continue to this day. In addition, the city of Santa Monica has had to supplement its drinking water supply by purchasing replacement water from outside resources.

Source: EPA, 2003b.

17.6.3 Solvent Additives: 1,4-Dioxane

In recent years, 1,4-dioxane (dioxane) has gained considerable attention as a primary “emerging” contaminant for groundwater resources. Dioxane, like MTBE, is commonly used as an additive. It is a synthetic organic chemical used as an industrial solvent or solvent “stabilizer” that prevents the breakdown of chlorinated solvents during manufacturing processes. Dioxane is commonly added to chlorinated solvents and other solvents such as tetrachloroethene (PCE), trichloroethene (TCE), 1,1,1-trichloroethane (TCA), and paint thinners. Dioxane is also used as a solvent for the manufacturing of paper, cotton, textiles and various organic products, automotive coolant, shampoos, and cosmetics. It is estimated that TCE and TCA contain approximately 1% and 2–8% 1,4-dioxane, respectively (Mohr, 2001). It was estimated that between 10 and 18 million pounds of 1,4-dioxane were produced in the U.S. in 1990 (Mohr, 2001).

Although 1,4-dioxane has been used as a stabilizer for solvents since the 1940s, the extensive contamination of groundwater by dioxane was not documented until the mid-1990s, when improved analytical methods allowed for the detection of lower concentrations. Dioxane is a very mobile and persistent compound, and is listed as a probable human carcinogen. The EPA has not yet defined a national regulatory standard for dioxane. Action levels have been adopted by some states for 1,4-dioxane. For example, the California Department of Health Services has set an action level of $3\text{ }\mu\text{g L}^{-1}$.

17.6.4 Perchlorate in Groundwater

Perchlorate, another “emerging” groundwater contaminant, was first detected in drinking water in 1997 and has since been recognized to pose a significant threat to groundwater resources (EPA, 2005). As mentioned previously, it often requires a significant advancement in analytical capability to first observe an emerging contaminant’s presence in the environment and in particular groundwater. The development of an analytical method to detect low concentrations of perchlorate allowed for the recognition of its widespread occurrence in groundwater in the U.S. (Information Box 17.6)

INFORMATION BOX 17.6

Perchlorate Contamination in Nevada

The city of Las Vegas gained notoriety as having one of the largest known groundwater perchlorate problems in the U.S. The site of the Kerr-McGee Chemical Corporation near Las Vegas produced some of the highest perchlorate concentrations in groundwater ever reported, with $3.7\text{ million }\mu\text{g L}^{-1}$ in groundwater and $24\text{ }\mu\text{g L}^{-1}$ in drinking water. Strategies for cleanup and remediation are currently in progress and will likely continue well into the future, with incurred costs estimated into the hundreds of millions if not billions of dollars (Struglinski, 2005).

Perchlorate is an inorganic anion and is often present as a salt complex or ammonium salt as ammonium perchlorate. Perchlorate is used for numerous industrial and military purposes. For example, it is a primary constituent in the manufacturing and use of rocket propellants (solid rocket fuel) and other explosives. For this reason, much of the perchlorate contamination of groundwater is derived from military bases and installations. In fact, it is estimated that approximately 90% of perchlorate compounds are produced for use in defense activities and the aerospace industry (EPA, 2005).

Perchlorate, like many salt compounds, is extremely mobile in groundwater. In addition, perchlorate is not readily susceptible to chemical or microbial degradation and is thus extremely persistent in the environment. In studies perchlorate has been shown to interfere with the uptake of iodine by the thyroid. This can disrupt thyroid functioning, including hormone regulation, metabolism regulation, fetus development, and child development. To date, the EPA has not established a maximum contaminant level or enforceable regulatory limit for perchlorate in drinking water. A few states have adopted “action levels” or advisory levels for perchlorate, which generally range from $1 \mu\text{g L}^{-1}$ to $6 \mu\text{g L}^{-1}$.

17.6.5 Arsenic in Groundwater

Contamination of groundwater by arsenic (As) is another important groundwater contaminant problem throughout the world (see Chapter 10). The high toxicity associated with arsenic is of primary concern for human health. As a result of the high associated toxicity of arsenic, regulatory standards have recently been lowered by the EPA, from $50 \mu\text{g L}^{-1}$ to $10 \mu\text{g L}^{-1}$. The additional water-treatment costs associated with meeting the revised standard are projected to be in the billions of dollars.

The contamination of groundwater and drinking water can result from natural or human activities. Arsenic is a naturally occurring metallic element that is found in soil, rocks, air, plants, and animals. Arsenic in soil and rocks can act as sources for groundwater contamination. Through processes such as dissolution, weathering, and erosion, arsenic can be released into the environment, resulting in the contamination of groundwater and drinking water supplies. Arsenic sources associated with human activities include agriculture, use as a wood preservative, the burning of fuels and wastes, smelting and mining, paper production, glass manufacturing, and cement manufacturing. In 1997, almost 8 million pounds of arsenic were released to the environment by human activities (EPA, 2000). Extensive adverse health impacts due to arsenic contamination of groundwater have been recently documented in Bangladesh (see Chapter 10).

17.6.6 Acid-Mine Drainage

Another source of pollution that poses threats to groundwater is acid mine drainage. Highly acidic water is produced when rain or groundwater comes into contact with mine tailings or mining wastes. The highly acidic water can change

the oxidation-reduction potential in the groundwater and may cause the release of minerals and metals, serving as a source of groundwater contamination. The geology, hydrology, and mining technology employed will determine the nature of the acid mine drainage. Additional issues associated with pollution caused by mining activities are discussed in Chapter 16. Restoration of sites polluted by mining activities is discussed in Chapter 20.

17.7 SUSTAINABILITY OF GROUNDWATER RESOURCES

Clearly, the world's population is greatly dependant on groundwater for many uses. Thus, managing and protecting our groundwater resources is essential to ensuring that sufficient quantities of quality groundwater will be available for future generations. This concept is referred to as **maintaining long-term sustainability of groundwater resources**.

Ensuring groundwater sustainability requires balancing supply and demand. Hydrologic and geologic factors (climate, topography, subsurface properties) exert primary control on the intrinsic supply of groundwater. The potential impact of global climate change on the hydrologic cycle and groundwater supply is of concern. Groundwater pollution affects the fraction of the intrinsic supply that is of sufficient quality for use. Thus, it imposes a constraint on supply. The demand for groundwater is associated with land use and population density. The significant increase in groundwater use observed over the past few decades (see Figure 17.1) is a result of population growth and economic expansion.

The primary means by which to ensure long-term sustainability of groundwater resources is to manage supply and demand. The groundwater supply can be extended through moderating demand and can be supplemented with additional sources of water. Water reuse is one primary method being implemented to enhance sustainability. This includes reusing municipal wastewater directly, either as potable water or for secondary uses such as irrigation, or indirectly (*e.g.*, artificial groundwater recharge). Instituting conservation measures to reduce demand is another method. The use of external supplies is another means of supplementation. For example, the **Central Arizona Project (CAP)** provides surface water from the Colorado River to supplement groundwater resources in Arizona. The CAP canal extends 336 miles from Lake Havasu City to Tucson, and cost \$3.6 billion to construct. In Tucson, all water provided by the CAP is recharged into groundwater prior to being pumped to the surface and treated for potable use. A potential problem with using external water supplies, versus water reuse and conservation, to manage supply and demand, is that it imposes a demand on water resources at the point of origin. An example of this is, in fact, the Colorado River, which barely exists as a river close to its entry into Mexico because of its great degree of use upstream. Thus, the demand has just been shifted in part from one location to another. Changes in land use also exert an impact on supply and demand. For example, groundwater

use is now shifting from agriculture to residential as urban centers increase in size and population density.

Balancing supply and demand is encapsulated in the concept of **safe yield**. In essence, the principle of safe yield is that the amount of groundwater extracted should not exceed the amount replenished through recharge. This concept is simple in theory. Unfortunately, it is very complex in practice. A primary reason for this is that water resource issues are influenced to a great extent by nonscience factors (political, economic, societal, legal). This causes the management of demand among the competing uses prevalent in large

urban centers to be a complex and difficult task. In addition, planning for future water resource use is difficult and fraught with uncertainty. For example, there is always uncertainty in estimating the future supply of groundwater available in a region. This uncertainty is compounded by uncertainty in demand, which must be estimated based on future population growth and land-use patterns. These difficulties are exacerbated by the “invisibility” of groundwater—as opposed to surface water, it cannot be seen. The prevalent attitude of “out of sight, out of mind” often creates impediments to increasing the awareness of groundwater resource issues.

QUESTIONS AND PROBLEMS

1. What is meant by the term “safe yield”?
2. Discuss the factors that affect the supply of groundwater available in a specific location.
3. Discuss the factors that affect the demand for groundwater resources in a specific location.
4. What can be done to modify the supply and demand for groundwater resources?
5. Why is nitrate a widespread groundwater contaminant?
6. Comparing heavy metals and solvents, which would you expect to generate larger groundwater contaminant plumes? Why?
7. What is involved in conducting a groundwater pollution risk assessment? What type of information would you need?

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