2

Water Quality Status and Trends in the United States

Matthew C. Larsen*, Pixie A. Hamilton, William H. Werkheiser

U.S. GEOLOGICAL SURVEY, RESTON, VA, USA

CORRESPONDING AUTHOR

CHAPTER OUTLINE

2.1 Introduction

National interest in water quality issues culminated in the 1972 enactment of the Clean Water Act (CWA) [1]. This law was passed in response to public concerns about burning rivers and dead lakes and a national consensus built over the previous 60 years that pollution of our rivers and lakes was unacceptable. Control of point-source

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contamination, traced to specific "end of pipe" points of discharge, or outfalls, such as factories and combined sewers, was the primary focus of the CWA. Significant progress toward cleaner water resulted through actions, such as implementing changes in manufacturing processes and wastewater treatment.

Water-quality challenges are now increasingly complex. The majority of water-quality problems are caused by diffuse nonpoint sources from agricultural land, urban development, forest harvesting, and the atmosphere (Table 2-1). These nonpoint-source contaminants are more difficult to effectively monitor, evaluate, and control than those from point sources (for example, discharges of sewage and industrial waste). We need improved quantification and understanding of human activities associated with nonpoint sources and how those human activities take place on the landscape—primarily information on how we use and dispose of chemicals, how we convert land over time, our use of water, and our land-management practices.

Several factors add to this complexity. First, the amount of pollution from nonpoint sources varies over short periods—hourly to seasonally—making it difficult to monitor and quantify the sources over time. Single or periodic measurements are not adequate to characterize water-quality conditions. Measurements are needed over seasons, hydrologic and meteorological events, and in real time.

We face large water-quality challenges because of the increasingly complex and emerging diversity of issues. When the CWA was passed, the dominant concern was the sanitary quality of rivers and streams. The focus was on temperature, salinity, bacteria counts, oxygen levels, and suspended solids, in large part, collected for day-to-day evaluations of compliance or permitting decisions.

While these remain important, there are now hundreds of synthetic organic compounds (such as pesticides and volatile organic compounds in solvents and gasoline) that are introduced into the environment every day. Improved laboratory techniques have led to the identification of microbial and viral contaminants, pharmaceutical compounds, and endocrine disruptors in our waters that were not previously measured. We are also finding that many contaminants, such as arsenic and radon, can originate

Table 2-1 The Changing National Focus on Water-Quality Challenges

Past Focus	Present and Future Focus
Point sources	Nonpoint sources
End-of-pipe approach	Watershed approach (landscape, human activities)
One-time, periodic reporting	Seasonal, hydrologic events, continuous, real time
Nutrients, dissolved oxygen, bacteria	Organic compounds
Single pollutants	Mixtures
Surface water	Total resource
Chemistry	Chemistry, biology, habitat, hydrology, landscape
Short-term monitoring	Long-term monitoring
Monitoring	Monitoring and prediction

from a wide range of natural sources and are of potential concern with respect to human health, even in relatively undeveloped settings that are perceived as less vulnerable to contamination. This is a critical concern with respect to the quality and safety of water from domestic or "private" wells, which are a source of drinking water for about 40 million people or 15% of the U.S. population, many of whom are based in rural and less-developed settings [2]. Domestic wells are not regulated under the federal Safe Drinking Water Act (SDWA) and are the responsibility of the homeowner. Natural and organic contaminants often end up in our waters as complex mixtures of organic compounds; many of these can, even at very low concentrations, potentially affect the health of humans and/or the reproductive success of aquatic organisms in our waters.

Our understanding of water-quality challenges has expanded with our understanding of the importance of the hydrologic cycle for water-quality conditions. Whereas our concerns were focused mainly on streams and rivers, we now recognize water-quality issues as part of an integrated hydrologic system. For example, groundwater and surface water are highly inter-related; reduced base flow from groundwater pumping often results in increased stream temperatures, drying wetlands, and habitats unsuitable for fish and other aquatic species [3]. The historic approach was to look at quality mostly in terms of concentrations independent of hydrology; however, concentrations and types of contaminants and their potential effects on ecosystems and drinking water supplies vary over time and depend largely on the amount of water flowing in streams and the amounts and directions of groundwater flow.

Other natural processes, including geology and geomorphology, also control the timing and amount of surface and groundwater flow and the transport of waterborne constituents and contaminants. Furthermore, natural complexity is increasing because of changes in climate, resulting in new patterns of seasonal precipitation, runoff, and the spatial and temporal distribution of snow versus rain [3–6]. Unfortunately, there is a continuing high degree of uncertainty in climate model predictions [7,8]. This set of challenges will continue and probably intensify as both nonclimatic and climatic factors, such as predicted rising temperature and associated changes in runoff, continue to develop [9–12].

Water-quality challenges extend beyond chemistry. We now realize that water quality, habitat disturbances, streamflow alterations, biological systems, and ultimately, ecosystem health are all closely interconnected. Meaningful water-quality assessments must therefore integrate biological monitoring and ecosystem health, such as inclusion of benthic invertebrates and other biological indicators as critical tools to understanding water quality [13–15].

Given our improved understanding of the spatial and temporal complexities in water quality and its numerous natural and human causes, the importance of long-term monitoring is increasingly clear. Comparable data must be collected over time if long-term trends are to be distinguished from short-term fluctuations and if natural fluctuations are to be distinguished from the effects of human activities. Long-term tracking is particularly critical for groundwater and sediment because slow flow paths and long residence times may not allow water quality issues to appear for years or even decades.

Monitoring alone does not provide understanding of the causes of water-quality conditions, given the complex interrelations among water quality, natural changes, and human actions over time and space. Furthermore, federal and state resources are increasingly limited, so we cannot expect to monitor water resources in all places and at all times. The value of data collected at individual sites is enhanced by applying assessment tools, including models that use monitoring data in conjunction with our understanding of the hydrologic and aquatic systems, the natural landscape, and human activities to develop more generalized knowledge of the status, trends and causes of these conditions for broader areas, including entire stream reaches and aquifers, large river basins, ecoregions, the states, and the nation as a whole. The integration of monitoring and assessment with modeling and predictive tools is the strategy needed to provide comprehensive statewide, regional, and national water-quality assessments. This strategy also will provide the needed national "water census" of water-quality status and trends and an increased ability to anticipate conditions in the future [16].

The brief overview below of water-quality status and trends in the United States is based largely on the past two decades of work accomplished by U.S. Geological Survey (USGS) scientists and is funded by USGS programs (principally the Cooperative Water- Groundwater Resources- Hydrologic Research and Development-, National Water Quality Assessment-, and Toxic Substances Hydrology Programs). These congressionally supported programs are a key part of the larger USGS portfolio of science and information aimed at informing decision makers at all levels in the United States [17].

2.2 Monitoring and Assessments of Complex Water Quality Problems

The USGS strives to continually improve and enhance science to provide unbiased information to decision makers and the public [18]. Goals of USGS programs have been adapted to the evolving complexity of water-quality challenges to track the status and trends of five priority water-quality issues across the nation: nutrients, pesticides, organic wastewater compounds, sediment-bound compounds, and mercury.

2.2.1 Nutrients

According to the U.S. Environmental Protection Agency (USEPA), nutrient pollution has for decades ranked as one of the top three causes of degradation in U.S. streams and rivers, and the concern is expected to continue for the foreseeable future. Since the 1990s the USGS has placed a major focus on studies of nutrients (Figure 2-1) [19] to provide the most comprehensive national-scale assessment of two key nutrients, nitrogen and phosphorus, in our streams and groundwater. In this study, water samples were collected

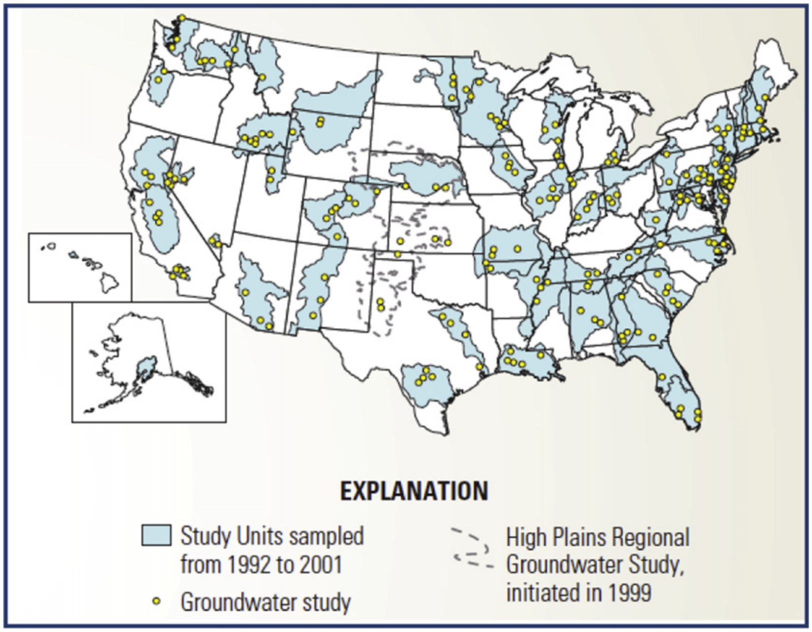

FIGURE 2-1 USGS assessments of nutrients followed a nationally consistent approach in 51 of the nation's major river basins and aquifer systems during 1992–2001. *From Ref. [20].* (For color version of this figure, the reader is referred to the online version of this book.)

from 499 stream sites monthly and during periods of high and low streamflow, usually for a minimum of 2 years. Biological communities were assessed at about 1400 stream sites. Groundwater samples were collected from 5101 wells, including domestic and public-supply wells. Trends in nutrient concentrations in streams were assessed at 171 and 137 stream sites, for phosphorus and nitrogen respectively, sampled from 1993 to 2003. Changes in nitrate concentrations in groundwater were assessed by measuring concentrations in 495 wells from 1988 to 1995, then again from 2001 to 2004. Most water samples were analyzed for five measures of nitrogen- and phosphorus-containing nutrients: total nitrogen, nitrate, ammonia, total phosphorus, and orthophosphate. The study provides improved science-based explanations of when, where, and how elevated concentrations reach streams, aquifers, and nearshore areas, and how they affect aquatic life and the quality of drinking water.

Findings [19] show that despite major federal, state, and local effort and expenditure to control the sources and movement of nutrients within our Nation's watersheds, national-scale progress is limited. For example, USGS findings show that widespread concentrations of nitrogen and phosphorus remain two to ten times greater than levels recommended by the USEPA to protect aquatic life. Most often, these elevated levels were found in agricultural and urban streams. These findings show that continued reductions in nutrient sources and implementation of land-management strategies for reducing nutrient delivery to streams may be needed to meet USEPA-recommended levels in most regions.

Elevated concentrations of nutrients, particularly nitrate, in drinking water may have both direct and indirect effects on human health. The most direct effect of ingestion of high levels of nitrate is methemoglobinemia, a disorder in which the oxygen-carrying capacity of the blood is compromised; the USEPA maximum contaminant level (MCL) of 10 milligrams per liter (mg/L) for nitrate in drinking water was adopted to protect people, mainly infants, against this problem. High nitrate concentrations in drinking water have also been implicated in other human health problems, including specific cancers and reproductive problems [21], but more research is needed to corroborate these associations. The indirect effects of nutrient enrichment of surface waters on human health are many and complex, including algal blooms that release toxins and the enhancement of populations of disease-transmitting insects, such as mosquitoes [22].

Nitrate concentrations in streams across the nation seldom exceeded the USEPA MCL of 10 mg/L as nitrogen; nitrate exceeded the MCL in 2% of 27,555 samples, and in one or more samples from 50 of 499 streams [19]. Most streams with concentrations greater than the MCL drained agricultural watersheds; these streams were particularly common in the upper Midwest where the use of fertilizer and (or) manure is relatively high and tile drains are common. Nearly 30% of agricultural streams had one or more samples with a nitrate concentration greater than the MCL, compared to about 5% of the streams draining urban land. None of the samples from streams draining undeveloped watersheds had a concentration greater than the MCL. For perspective on the relevance of these findings to surface water used for drinking water supplies, 12% of the Nation's 1679 public water-supply intakes withdraw water from streams that drain watersheds with predominantly agricultural land, whereas most water-supply intakes are in watersheds draining undeveloped land [19].

Nitrate concentrations greater than the MCL are more prevalent and widespread in groundwater than in streams. Concentrations exceeded the MCL in 7% of about 2400 private wells sampled by the USGS. Contamination by nitrate was particularly severe in shallow private wells in agricultural areas, with more than 20% of these wells exceeding the MCL. Elevated nitrate follows distinct geographic patterns—mostly related to land use. Elevated concentrations of nitrate were largely associated, for example, with intensively farmed land, such as in parts of the Midwest Corn Belt and the California Central Valley [2]. The quality and safety of water from private wells (which are a source of drinking water for about 40 million people or 15% of the U.S. population) are not regulated by the SDWA and are the responsibility of the homeowner [2,19].

Concentrations exceeding the MCL were less common in public-supply wells (about 3% of 384 wells) than in private wells. The lower percentage in public wells reflects a combination of factors, including (1) greater depths and hence age of the groundwater; (2) longer travel times from the surface to the well, allowing denitrification and/or attenuation during transport; and (3) the location of most public wells near urbanized areas where sources of nitrate generally are less prevalent than in agricultural areas [19,23].

A USGS national statistical model of the vulnerability of relatively deep groundwater (more than 164 feet below land surface) estimated that almost 500,000 people live in areas where nitrate concentrations are predicted to be greater than the MCL, and more than 1.2 million people live in areas predicted to have nitrate concentrations between 5- and 10 mg/L. A similar model suggests that the number of people exposed to nitrate concentrations greater than the MCL would be 14% greater if they obtained their water from shallow wells (33 feet or less) rather than deep wells (164 feet or greater) [19].

Nitrate concentrations are likely to increase in deep aquifers typically used for drinking water supplies despite nutrient-reduction strategies, as shallow groundwater with high nitrate concentrations moves downward to deeper aquifers. USGS findings show that the percentage of sampled wells with nitrate concentrations greater than the USEPA drinking water standard, increased from 16% to 21%, starting in the early 1990s [19,24]. Similarly, the probability of nitrate concentrations exceeding the MCL has increased from less than 1% in the 1940s to greater than 50% by 2000 for young groundwater in agricultural settings [19,24].

A 60-year record of nitrate concentrations at a public-supply well in Nebraska provides a local example of the long response time in groundwater (Figure 2-2). Nitrate concentration in shallow groundwater decreased after implementation of fertilizer-management strategies starting in the 1980s. This decrease was not noted in the deeper groundwater, where concentrations continued to increase for 25 years before beginning to decrease in 2005 (Figure 2-2). Consistent and systematic long-term monitoring is critical, especially for groundwater, when evaluating the effectiveness of environmental and land-management strategies, because of the slow response of groundwater to changes in chemical use or land-management practices [25].

The USGS generally does not assess nutrients in estuarine waters or the effects of nutrients on levels of dissolved oxygen and hypoxia; however, the USGS does assess the downstream transport of nutrients from major rivers to major receiving waters, such as

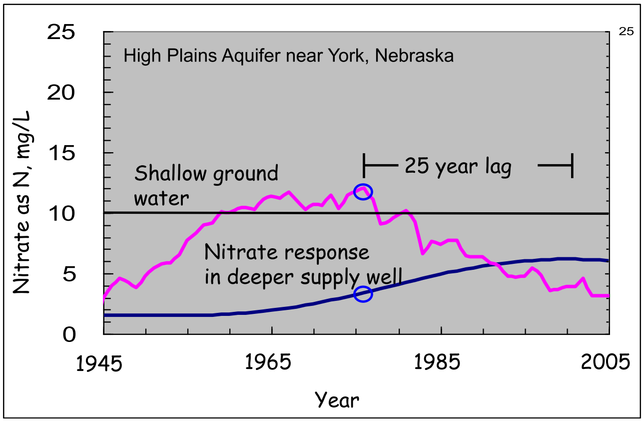

FIGURE 2-2 Nitrate concentration in a public-supply well. *From Ref. [25].* (For color version of this figure, the reader is referred to the online version of this book.)

the Gulf of Mexico and the Chesapeake Bay, as described below (Figure 2-3). Hypoxia, such as in the northern Gulf of Mexico, is caused by excess nutrients delivered from the Mississippi River in combination with seasonal stratification of Gulf waters [26]. Excess nutrients promote algal growth. When the algae die, they sink to the bottom and decompose, consuming available oxygen. Stratification of fresh and saline waters prevents mixing of oxygen-rich surface water with oxygen-depleted bottom water. Immobile species such as oysters and mussels are particularly vulnerable to hypoxia and become physiologically stressed and die, if exposure is prolonged or severe. Fish and other mobile species can avoid hypoxic areas, but these areas still impose ecological and economic costs, such as reduced growth in commercially harvested species and loss of biodiversity, habitat, and biomass [27]. Fish kills can result from hypoxia, especially when the concentration of dissolved oxygen drops rapidly.

A USGS hybrid statistical/mechanistic watershed model, known as Spatially Referenced Regression On Watershed attributes (SPARROW), is used to relate in-stream nutrient loads to upstream nutrient sources and record watershed characteristics affecting transport. SPARROW also provides information on the delivery of nitrogen and

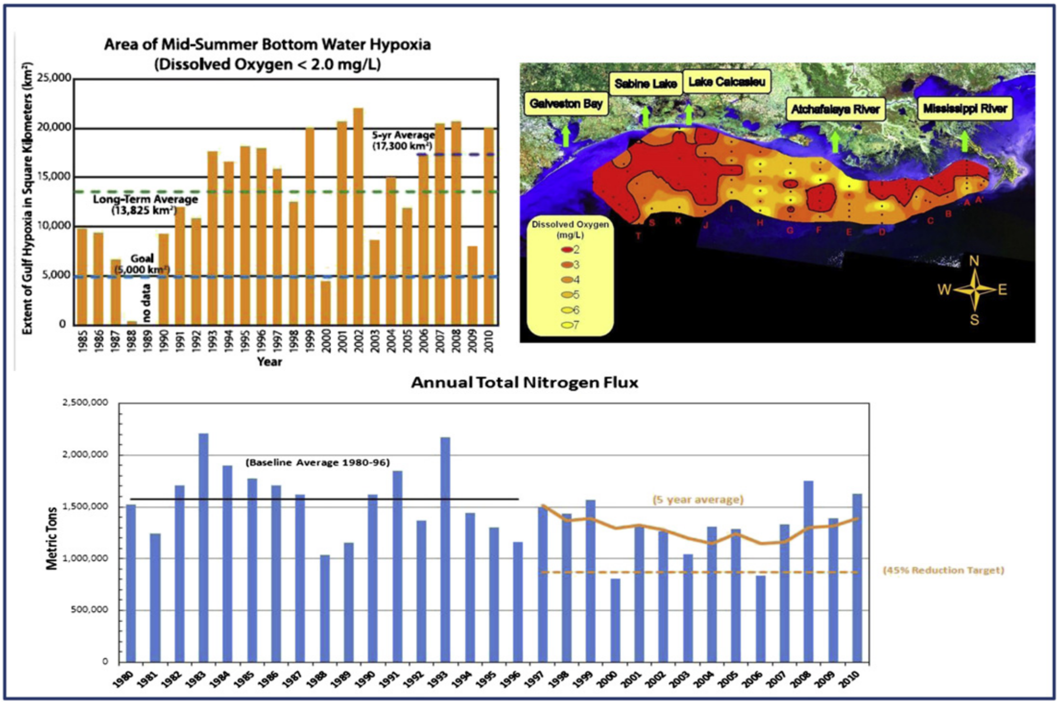

FIGURE 2-3 Areal extent of Gulf of Mexico hypoxic zone (top chart and map) and Mississippi River nitrogen flux (bottom chart). *Sources: Charts from Aulenbach and associates report [28] and Aulenbach written communication (2011); map of the 2010 Dead Zone from Ref. [29] with a larger image available at http://www.noaanews.noaa.gov/stories2010/images/dissolved_o2_day7.jpg.* (For color version of this figure, the reader is referred to the online version of this book.)

phosphorus from 62,000 stream reaches to the Nation's major rivers and estuaries [30]. Modeled findings show, for example, that the cultivation of corn and soybeans was the largest contributor of nitrogen to the Gulf of Mexico, whereas animal manure on pasture, rangelands, and corn and soybean cultivation were the largest contributors of phosphorus. In addition, modeled findings showed that large rivers contribute a larger percentage of their nitrogen to downstream receiving water bodies than small streams, in large part because nitrogen removal in streams rapidly declines as water depth and stream size increase [30].

Robertson et al. [31] used the SPARROW model to identify watersheds with the highest nutrient yields delivered to downstream waters. The watershed results provided information for management strategies to reduce the hypoxic zone and improve the water quality of rivers and streams. Additionally, the results were used to develop a statistically-reliable method for identifying high-priority areas for management, based on a probabilistic ranking of delivered nutrient yields from watersheds throughout a basin [31]. The method was designed to be used by managers to prioritize watersheds where additional stream monitoring and evaluations of nutrient-reduction strategies could be undertaken [31]. The study identified 150 watersheds having the highest delivered nutrient yields to the Gulf of Mexico; these were in the Central Mississippi, Ohio, and the Lower Mississippi River Basins.

USGS trend analyses suggest that despite major federal, state, and local nonpoint source, nutrient-control efforts for streams and watersheds across the nation, limited national progress has been made in reducing the impact of nonpoint sources of nutrients. Instead, concentrations have remained the same or increased in many streams and continue to pose risks to aquatic life and human health. For example, nitrate transport to the Gulf of Mexico during the spring, is one of the primary determinants of the size of the Gulf hypoxic zone. During high streamflow in spring in the period studied, the concentration of nitrate decreased at the study site near where the Mississippi River enters the Gulf of Mexico, indicating that some progress has been made in reducing nitrate transport during high flow conditions. However, during times of low to moderate spring streamflow, concentrations increased. The net effect of these changes is that nitrate transport to the Gulf was about 10% higher in 2008 than in 1980. This increase in nitrate transported to the Gulf can be attributed primarily to the upstream nitrate increases in the Mississippi River Basin above the Clinton (Iowa) monitoring site and in the Missouri River Basin [32]. There are some exceptions elsewhere in the nation to the findings in the Mississippi. For example, recent findings show decreased nutrient concentrations in the Susquehanna and Potomac rivers since 2000; but increasing concentrations in the Rappahannock and James rivers [33].

2.2.2 Pesticides

About 1×10^9 pounds of conventional pesticides are used annually in the United States to control weeds, insects, and other pests. The use of pesticides has a range of benefits, including increased food production and the reduction of insect-borne disease, but also has adverse effects on water quality. A USGS national assessment indicates that pesticides are widespread, albeit often at low concentrations, in river basins and aquifer systems across a wide range of landscapes and land uses [34]. Overall, at least one pesticide was found in about 95% of water samples and in 90% of fish samples from streams in agricultural and urban areas and in about 55% of shallow wells sampled in agricultural and urban areas [34].

Pesticide occurrence is closely linked to land use (Figure 2-4). For example, insecticides such as diazinon, carbaryl, chlorpyrifos, and malathion were detected more frequently and usually at higher concentrations in urban streams than in agricultural streams (Figure 2-5). Many herbicides (most commonly atrazine and its breakdown product deethylatrazine (DEA), metolachlor, alachlor, and cyanazine) were generally detected more frequently and usually at higher concentrations in streams and shallow groundwater in agricultural areas than in urban areas [35]. Some herbicides detected in urban areas, such as simazine and prometon, are those with substantial nonagricultural uses, such as weed control in commercial areas, golf courses, and along roadsides. The same relative patterns of different compounds were observed in groundwater, but at much lower detection frequencies [34].

These USGS findings provide a “signature” of what can be expected in streams and groundwater influenced by land use. This signature can be used by water managers to identify and anticipate types of contaminants, leading to better management of the use of chemicals.

It should be noted that detection does not necessarily translate to risk. The USGS intentionally analyzed for very low levels, sometimes 10–100 times lower than guidelines or standards established to protect drinking water. The intent of the low-level analysis is

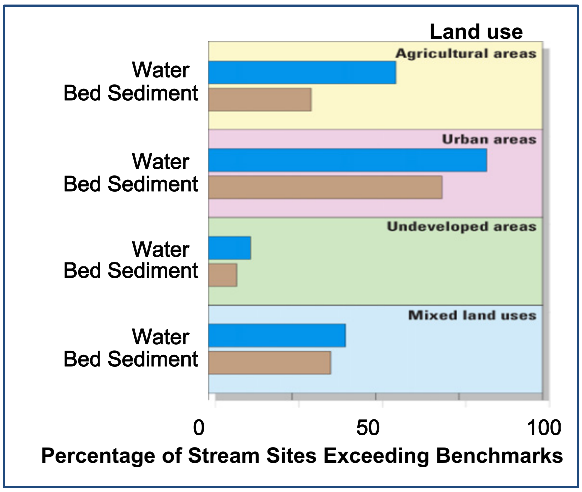

FIGURE 2-4 Pesticides and their significance to aquatic life. *From Ref. [34].* (For color version of this figure, the reader is referred to the online version of this book.)

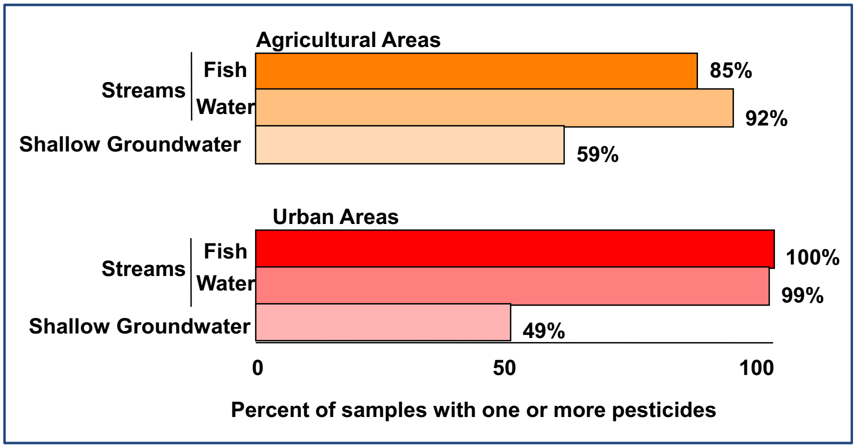

FIGURE 2-5 Pesticides in streams and shallow groundwater. In agricultural areas, these commonly include atrazine, [deethylatrazine], metolachlor, cyanazine, and alachlor. In urban areas, common pesticides found include diazinon, carbaryl, malathion, chlorpyrifos, atrazine, simazine, prometon, 2,4-D, and diuron. *From Ref. [34].* (For color version of this figure, the reader is referred to the online version of this book.)

to detect and evaluate emerging problems, as well as to track contaminant levels over time.

Nationally, the USGS findings show that pesticides are seldom present at concentrations likely to affect humans, but do occur in many streams, particularly those draining urban and agricultural areas, at concentrations that may affect aquatic life or fish-eating wildlife [34]. Concentrations of pesticides were greater than water-quality benchmarks for aquatic life and (or) fish-eating wildlife, in more than half of the streams with substantial agricultural and urban areas in their watersheds. Of the 178 streams sampled nationwide that have watersheds dominated by agricultural, urban, or mixed land uses, 56% had one or more pesticides in water that exceeded at least one aquatic-life benchmark. Urban streams had concentrations that exceeded one or more benchmarks at 83% of sites (mostly of the insecticides diazinon, chlorpyrifos, and malathion) although frequencies of exceedance declined during the study period. Concentrations exceeded benchmarks in 95% of urban streams sampled during the period 1993–1997 and in 64% of streams sampled during the years 1998–2000. Agricultural streams had concentrations that exceeded one or more benchmarks at 57% of sites—most frequently by chlorpyrifos, azinphos-methyl, atrazine, *p,p'*-DDE, and alachlor. As the use of alachlor declined through the study period, its benchmark exceedances also declined, with none during the last 3 years of study [34].

Aquatic-life benchmarks for organochlorine pesticide compounds in bed sediment also were frequently exceeded in urban areas (70% of urban stream sites). Most compounds that exceeded aquatic-life benchmarks for sediment were derived from organochlorine pesticides that had not been used since before the study began, such as DDT, chlordane, aldrin, and dieldrin. In agricultural streams, aquatic-life benchmarks were exceeded at 31% of sites (most often by DDT compounds and dieldrin) [34]. Federal regulation on the use of DDT and other organochlorine pesticides clearly has resulted in decreased contaminant levels; however, the slow rate of decreasing trends for DDT and the continuing concern for human exposure indicate that organochlorine pesticides will remain a concern.

Pesticides are most commonly detected as mixtures of multiple compounds, rather than individually, including degradates resulting from the transformation of pesticides in the environment. Streams in agricultural and urban areas almost always contained complex mixtures of pesticides and degradates. In more than 90% of cases, water samples from streams with agricultural-, urban-, or mixed land-use watersheds contained two or more pesticides or degradates, and in about 20% of cases they had 10 or more complex mixtures. Mixtures were less common in groundwater. Nevertheless, about half of the shallow wells in agricultural areas and about a third of shallow wells in urban areas contained two or more pesticides and degradates—less than 1% percent had 10 or more. The herbicides atrazine (and its degradate, deethylatrazine), simazine, metolachlor, and prometon were common in mixtures found in streams and groundwater in agricultural areas. The insecticides diazinon, chlorpyrifos, carbaryl, and malathion were common in mixtures found in urban streams [34].

The widespread abundance of pesticide mixtures, particularly in streams, means that the total combined toxicity of pesticides in water and other media often may be greater than that of any single pesticide compound that is present. Continued research is needed on the potential toxicity of pesticide mixtures, including degradates, to humans, aquatic life, and wildlife. USGS data on the presence and characteristics of mixtures and degradates is helping to target and prioritize toxicity assessments.

USGS studies continue to track pesticides over time. One such study in the Midwest Corn Belt, based on the analysis of 11 pesticides for 31 stream sites, showed that concentrations of several major pesticides mostly declined or stayed the same in rivers and streams from 1996 to 2006 [36]. Pesticides included in the trend analyses were the herbicides atrazine, acetochlor, metolachlor, alachlor, cyanazine, S-Ethyl dipropylthiocarbamate (EPTC), simazine, metribuzin and prometon, and the insecticides chlorpyrifos and diazinon. Declines in pesticide concentrations closely followed declines in their annual applications (generally within 1–2 years) indicating, not surprisingly, that reducing pesticide use is an effective and reliable strategy for reducing pesticide contamination in streams. Only one pesticide in the [36] study—simazine, (which is used for both agricultural and urban weed control) increased in the years from 1996 to 2006. Concentrations of simazine in some streams increased more sharply than its trend in agricultural use, suggesting that non-agricultural uses of this herbicide, such as for controlling weeds in residential areas and along roadsides, increased during the study period.

A key finding of the [36] study is that elevated concentrations can affect aquatic organisms in streams as well as the quality of drinking water in some high-use areas where surface water is used for municipal supply. Four of the 11 pesticides evaluated for trends were among those most often found in previous USGS studies at levels of potential

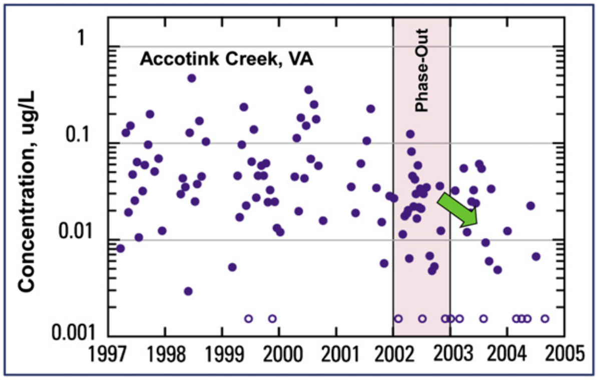

FIGURE 2-6 The concentration of diazinon at a stream in Virginia shows a downward trend following the phaseout of this chemical. *From Ref. [34].* (For color version of this figure, the reader is referred to the online version of this book.)

concern for healthy aquatic life. Atrazine, the most frequently detected, is also regulated in drinking water.

Trends in pesticide detection have been demonstrated in parts of the nation outside of the Midwest Corn Belt; these trends are also tied to use and regulations. Concentrations of diazinon, for example, show reductions beginning in 2002 in Accotink Creek, an urban stream in Virginia (Figure 2-6). Most urban uses of diazinon, such as on lawns and gardens, have been phasedout since 2001 [34].

Declines from 2000 to 2006 in concentrations of the insecticide diazinon correspond to the USEPA national phaseout of non-agricultural uses. Similarly, declines in concentrations of agricultural herbicides cyanazine, alachlor, and metolachlor show the effectiveness of USEPA regulatory actions, as well as the influence of new pesticide products. The USGS works closely with the USEPA, which uses USGS findings on pesticide trends to track the effectiveness of changes in pesticide regulations and use.

Although overall use is the most dominant factor driving changes in concentrations, other factors controlling declines may be related to improved management practices. This is suggested by rapid declines (even more rapid than their estimated use) in concentrations of atrazine and metolachlor in some streams that were sampled by the USGS in a Midwest Corn Belt study. The steeper declines in these instances may be caused by agricultural management practices that have reduced pesticide transport. However, data on management practices are not adequate to definitively draw this conclusion [36].

2.2.3 Mixtures of Organic Wastewater Compounds

Improved sampling and laboratory methods enable documentation of many compounds (known as emerging contaminants) in the Nation's waters (Table 2-2). Several national assessments have documented the presence of many commonly used substances, such as caffeine, personal use products, pharmaceuticals, and hormones (generally called

Table 2-2 Principal Organic Compounds Detectable in U.S. Wastewater (Described in Ref. [37] as Emerging Contaminants)

Antibiotics	Fragrances
Antioxidants	Fumigants
Detergents	Hormones
Disinfectants	Insecticides/repellants
Drugs	Plastics
Fire retardants	Steroids

organic wastewater compounds) in surface water and groundwater. In a landmark study, the USGS sampled 139 streams in 30 states; sampling sites represented “worst case” situations, purposely selected downstream from wastewater treatment plants, domestic septic systems, industrial discharge, animal feeding lots, and aquaculture [37]. The study showed that at least one organic wastewater compound was found in 80% of sampled streams and that 82 of the 95 targeted compounds were detected at least once. Fortunately, measured concentrations generally were low—only 5% were greater than 1 ppb (equivalent to a drop of water in an Olympic-sized swimming pool). However, detections of multiple compounds were common, with as many as 38 compounds in one sample. Nearly 35% of the samples contained more than 10 compounds. The mixtures resulted in high total concentrations in some samples, as high as 80 ppb.

Complex mixtures of organic wastewater compounds can, even at very low concentrations, adversely affect the health or reproductive success of aquatic organisms. Barber et al. [38] studied the North Shore Channel of the Chicago River (Chicago, Illinois) and determined that these waters contained mixtures of natural and anthropogenic chemicals that persisted through the water-treatment processes. They noted that aquatic organisms such as fish (largemouth bass and carp, in this study) are continuously exposed to biologically active chemicals throughout their life cycles. More than 100 organic chemicals were measured in the study, and 23 compounds were detected in all of the water samples analyzed. The majority of male fish exhibited vitellogenin induction, a physiological response consistent with exposure to estrogenic compounds.

2.2.4 Trends in Selected Sediment-Bound Compounds in Lakes and Reservoirs

Sediment cores from urban and agricultural reservoirs and lakes are used by USGS scientists to track changes in sediment-bound compounds over long periods [39,40]. The cores provide a measure of trends, make use of the watershed effect of integration of hydrologic inputs over space and time, and permit evaluation of many sediment-bound contaminants such as lead, chlordane, DDT, zinc, and polycyclic aromatic hydrocarbons (PAHs).

Findings showed a striking national reduction in concentrations of lead, which began to decrease after it was removed from gasoline in the 1970s (Figure 2-7). Specifically,

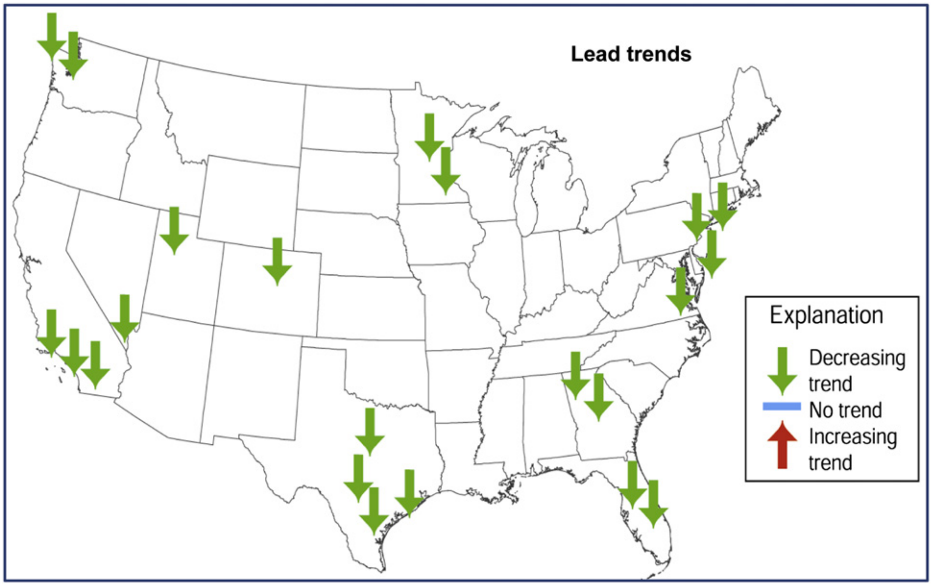

FIGURE 2-7 Samples taken from reservoir sediment cores show a decline from 1975 to 1997 in lead concentration. *From Ref. [42].* (For color version of this figure, the reader is referred to the online version of this book.)

trends in lead concentrations in sediment cores in nearly 85% of 35 sampled reservoirs and lakes in urban and reference areas, showed decreasing trends. This marks a positive environmental advancement resulting from the federal-led regulation, although concentrations are not yet back to background levels [41].

The USGS–reconstructed, water-quality histories for 38 urban and reference lakes across the United States for organochlorine compounds, showed significant trends in DDT, *p,p*'-DDE (a degradation, or breakdown product of DDT), and total polychlorinated biphenyls (PCBs). Similar to lead, the decreases reflect positive advancements resulting from federal regulations (Figure 2-8). Trends in chlordane were split evenly between upward and downward directions in concentration [43].

In contrast, trends were not so encouraging with PAHs, formed by the incomplete combustion of hydrocarbons (coal, oil, gasoline, and wood), resulting in many urban sources including industrial and power-plant emissions, home heating, car exhaust, tires, and asphalt in roads, roofs, and driveways (Figure 2-9). PAHs have increased in the majority of urban lakes sampled across the United States since about 1970 [43].

In more recent USGS work, coal-tar-based pavement sealant was determined to be the largest source of PAHs to 40 urban lakes [44,45]. On average, coal-tar-based sealcoat accounted for half of PAHs in the lakes, while vehicle-related sources accounted for about one-quarter. Elevated concentrations are generally associated with lakes receiving a large contribution of PAHs from sealcoat, in many cases at levels that can be harmful to aquatic life. Historical trends for a subset of studied lakes indicate that sealcoat use has been the

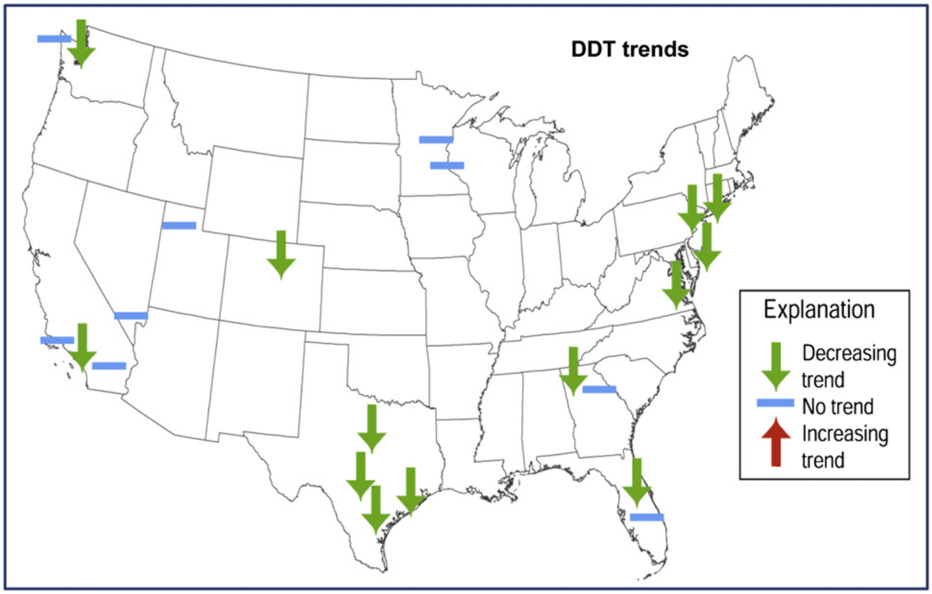

FIGURE 2-8 DDT trends from 1965 to 1997 are identified using sediment cores from reservoirs. *From Ref. [39].* (For color version of this figure, the reader is referred to the online version of this book.)

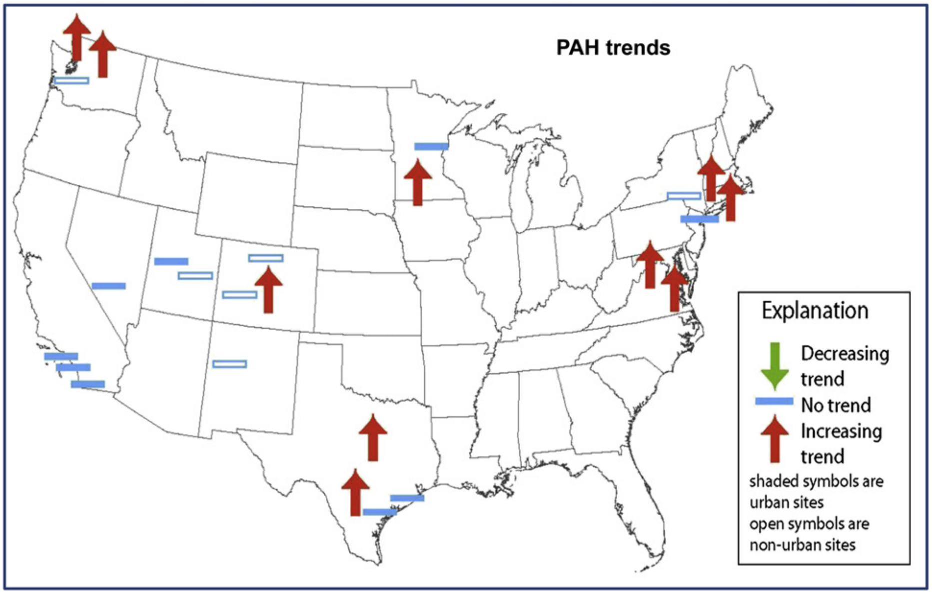

FIGURE 2-9 Polyaromatic hydrocarbon (PAH) trends from 1975 to 2000. *From Ref. [40].* (For color version of this figure, the reader is referred to the online version of this book.)

primary cause of increases in PAHs since the 1960s. These findings have led to local legislation, including a ban of coal-tar sealants, by the cities of Austin, (Texas) and Madison (Wisconsin), and in the state of Washington.

2.2.5 Mercury

Mercury, a neurotoxin, is one of the most hazardous contaminants to threaten the quality of our nation's waters. The USGS assessed mercury contamination in fish, bed sediment, and water in nearly 300 streams across the nation (Figure 2-10). The study revealed mercury contamination in fish sampled in the nearly 300 streams nationwide [46]. Sources of mercury (mostly from atmospheric deposition) are not uniform in their effects or distribution. Watershed characteristics make some streams more vulnerable to mercury deposition than others. In general, the presence of wetlands, organic material, and large amounts of dissolved organic carbon enhance the process of converting total mercury to methylmercury, the most toxic form of mercury and the form readily taken up by fish.

These factors are highlighted in a USGS study of total mercury in sediment in urban watersheds in the Boston metropolitan area, in which concentrations were highest in areas with many urban sources, including historical point-source discharges, nonpoint sources, and atmospheric deposition (Figure 2-11). Concentrations were lowest in sediment in watersheds with more forest cover in Maine and New Hampshire [47]. In

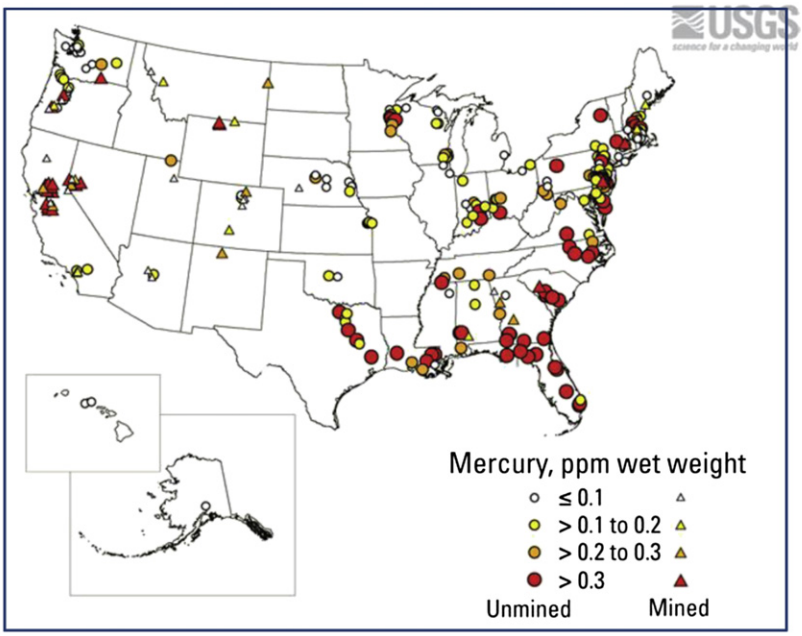

FIGURE 2-10 Spatial distribution of total mercury concentrations in game fish, 1998–2005. *From Ref. [46].* (For color version of this figure, the reader is referred to the online version of this book.)

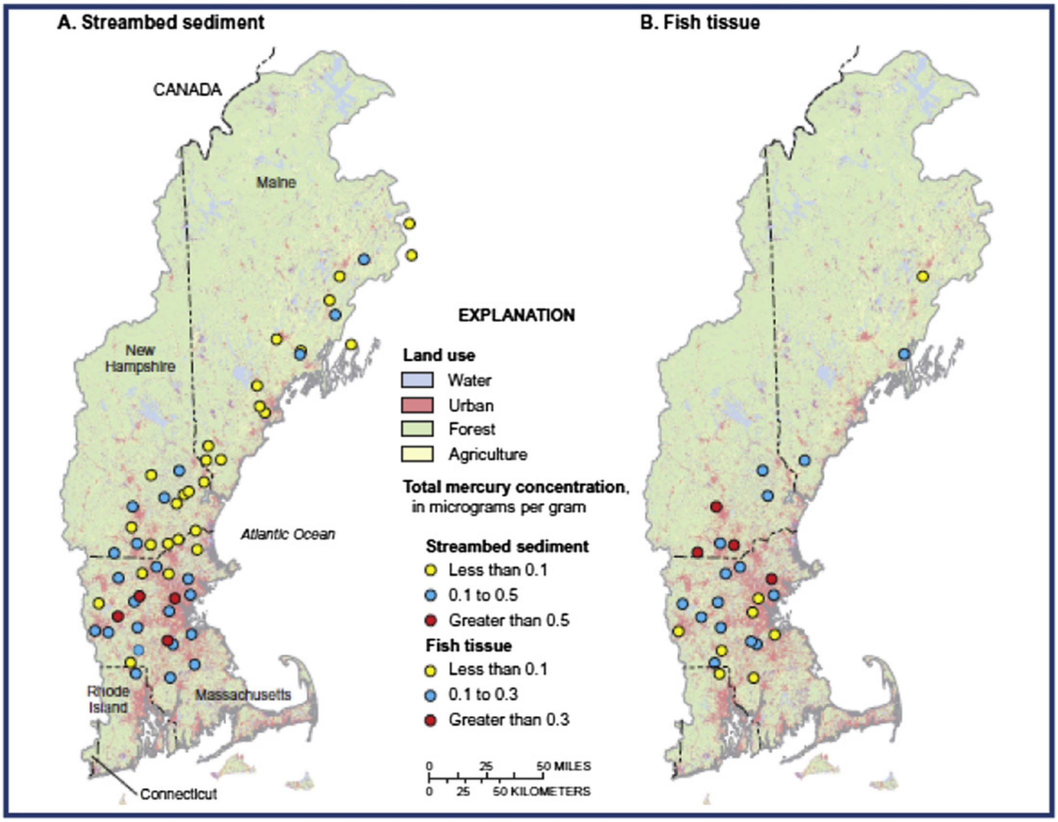

FIGURE 2-11 Mercury in fish varies by environmental setting. *From Ref. [47].* (For color version of this figure, the reader is referred to the online version of this book.)

contrast, concentrations of total mercury in fish (more than 95% of which is methylmercury) were higher in the forested watersheds near the Boston metropolitan area than in fish in the more urban watersheds. Elevated concentrations in fish in the forested watersheds result largely from natural factors, such as the presence of wetlands in these forested watersheds—an environment that enhances the process of converting total mercury to methylmercury [47].

In another study, the USGS assessed trends in mercury levels in fish, using a compilation of state and federal fish-monitoring data from 1969 to 2005 in U.S. rivers and lakes [48]. Findings showed significant decreases in fish mercury concentration at 22 of 50 sites sampled across the nation from 1969 to 1987, whereas only four sites showed increases. In those areas of decreases, mercury concentrations in fish decreased rapidly in the 1970s and more gradually or not at all during the 1980s. Most waters examined during this time period were medium to large rivers, draining areas of mixed land use. Trends were more variable from 1996 to 2005, during which time data were assessed for six states in the

Southeast and Midwest. More upward mercury trends in fish were documented in the Southeast compared to the Midwest. Upward mercury trends in fish in the Southeast were associated with increases in wet mercury deposition found at sites in the region that are part of the Mercury Deposition Network (a network of stations within the USGS National Atmospheric Deposition Program). Upward trends may, in part, be attributed to a greater influence of long-range global mercury emissions in the Southeast. In general, however, mercury concentrations in fish did not change in most aggregated state data from 1996 to 2005.

2.3 USGS Strategies to Assess Status and Trends

The USGS uses targeted designs and assessments to assess the status and trends of water quality and relations between water-quality conditions and natural and human factors that cause those conditions. These assessments consider the water-quality effects of human activities, such as agriculture and urban development, across different landscapes, geologic and hydrologic conditions, and during different seasons as well as over long periods of time.

This USGS approach is intended to answer questions such as: What are water-quality conditions? What are the contributing factors, and when do changes occur? Do certain natural features, land uses, or human activities and management actions affect the occurrence and movement of certain contaminants? Do water-quality conditions change over time?

USGS monitoring sites are not selected randomly, such as within a grid. Rather, sites are selected because they represent certain human activities, environmental settings, or hydrologic conditions during different seasons or times of year. For example, sites may be selected to assess the effects of agriculture and urban development on pesticide and nutrient contamination in streams.

2.3.1 Water Quality and the Natural Landscape

About 105 million people, or more than one-third of the Nation's population, receive their drinking water from one of the 140,000 public water systems across the United States that rely on groundwater pumped from public wells. Several USGS studies complement the extensive monitoring of public water systems that is routinely conducted for regulatory and compliance purposes by federal, state, and local drinking-water programs. USGS findings assist water utility managers and regulators in making decisions about future monitoring needs and drinking-water issues.

The natural landscape and geologic setting can be a source of natural contamination in our waters, such as with radon in groundwater (Figure 2-12). Radon is a naturally-occurring and soluble compound derived from uranium, and the USEPA classifies it as a human carcinogen. Uranium-bearing minerals are present in granite, pegmatite, and their derivative metamorphic rocks and sediments [2].

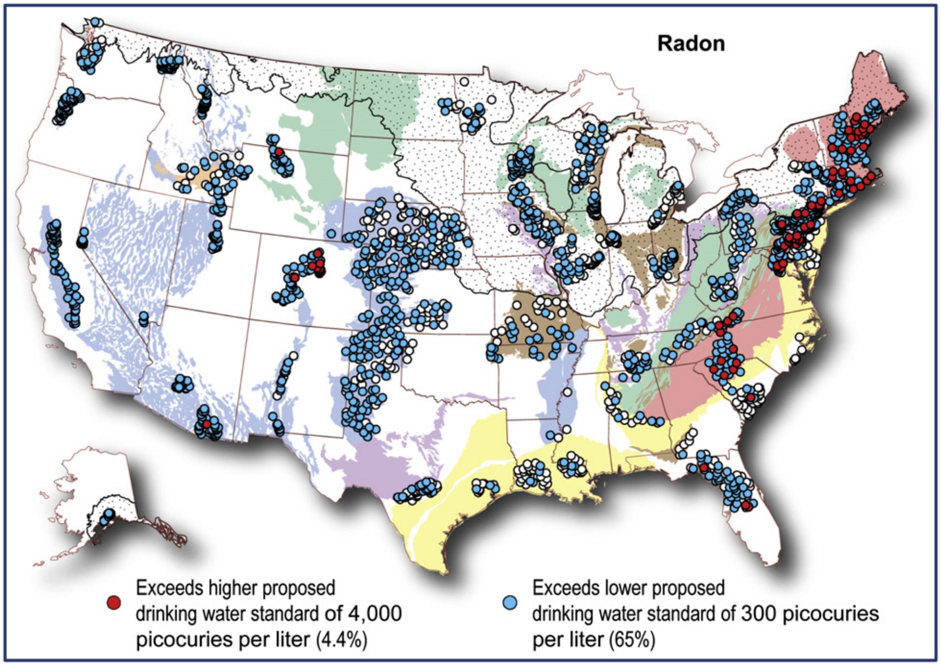

FIGURE 2-12 Radon concentrations in groundwater. Sampling sites reflect data from approximately 2000 private wells in 48 states. Regional coloring shows the extent of 30 principal aquifers sampled. Circles show radon concentrations; white circles show sites with concentrations below 300 picocuries per liter. *From Ref. [2].* (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this book.)

Radon levels are elevated throughout much of the nation. A USGS national assessment of about 2100 domestic wells showed that concentrations of radon, greater than the lower USEPA-proposed MCL of 300 picocuries per liter (pCi/L), were found in 65% of the wells sampled across the nation, which were located in all 48 states and in parts of 30 regionally extensive principal aquifers [2]. Concentrations greater than the higher proposed MCL of 4000 pCi/L, were found in 4.4% of domestic wells. The standard is still under development by the USEPA (http://water.epa.gov/lawsregs/rulesregs/sdwa/radon/index.cfm).

Areas with elevated radon concentrations are controlled in large part by geology, generally associated with crystalline-rock aquifers located in the northeast, the central and southern Appalachians, and central Colorado [2]. The results of this study are important because they show that a large number of people may be unknowingly affected by exposure to radon. About 43 million people (or 15% of the nation's population) use drinking water from private wells, which are not regulated by the SDWA. Private well owners are responsible for testing the quality of their well water and for any water treatment that may be necessary.

A national assessment of radon was also conducted on public-supply wells located in 41 states and in parts of 30 regionally extensive, principal aquifers. Radon concentrations greater than the higher proposed MCL, were present in less than 1% of more than 900 sampled public-supply wells (generally located in deeper parts of the aquifers than domestic wells), and greater than the lower proposed MCL in 55% of the sampled wells. Public wells yielding water with radon concentrations greater than 300 pCi/L, were geographically distributed across the United States. Radon generally was lowest in public wells in the central states and in a few smaller sampled areas, such as eastern North Carolina. Similar to domestic wells, elevated radon was most common in crystalline-rock aquifers located in the Northeast [23]. Elevated concentrations of naturally occurring trace elements in groundwater are also widespread across the United States [49]. About 20% of untreated water samples from selected public, private, and monitoring wells across the nation contain concentrations of at least one trace element at levels of potential health concern. The trace elements in groundwater that most frequently exceeded USEPA human-health benchmarks were arsenic, uranium, and manganese. Patterns of trace element occurrence relate to factors associated with the geologic sources of trace elements and to features that affect their mobility, such as climate, land use, and geochemistry.

The landscape can also be a natural geologic source of contamination to surface water. The USGS reports, for example, that naturally occurring geologic sources of phosphorus contribute to elevated levels of streambed-sediment phosphorus levels in many watersheds in Florida, Kentucky, and Tennessee [50]. This USGS study characterizes the potential contributions of phosphorus to streams from naturally occurring geologic materials, based on the spatial distribution of phosphorus levels in streambed sediment from 5560 sampling sites in small, relatively undisturbed basins throughout the southeastern United States.

An important finding is that more than 75% of the phosphate ore mined in the United States comes from the southeastern United States [50]. Understanding the spatial variation in potential watershed contributions of total phosphorus from geologic materials, can assist water resource managers in developing nutrient criteria that account for natural variability in phosphorus contributions from weathering and erosion of surficial geologic materials.

2.3.2 Water Quality in Urban Areas

Water quality varies among different land uses, including agricultural, urban, and pristine land-use settings. USGS assessments show that water quality varies among the different settings; insecticides, for example, are more frequently detected at higher concentrations in urban streams than in agricultural streams. Water conditions also vary among settings with different land-use practices; phosphorus, sediment, and selected pesticides, for example, are at higher concentrations in streams draining agricultural fields with furrow irrigation than in agricultural fields with sprinkler irrigation [34,51–54].

A study by Cuffney et al. [55] examined the effects of urbanization on algae, aquatic insects, fish, habitat, and aquatic chemistry in urban streams in nine metropolitan areas across the country: Boston (Massachusetts), Raleigh (North Carolina), Atlanta (Georgia), Birmingham (Alabama), Milwaukee-Green Bay (Wisconsin), Denver (Colorado), Dallas-Fort Worth (Texas), Salt Lake City (Utah), and Portland (Oregon). Study findings showed that even at low levels of development (levels often considered protective for stream communities) the number of native fish and aquatic insects, especially those that are pollution sensitive, showed declines in urban and suburban streams. Specifically, the study reported that in watershed areas with impervious cover of 10%, many types of pollution-sensitive aquatic insects declined by as much as one-third, compared to streams in undeveloped forested watersheds. As such, even minimal or early stages of development can negatively affect aquatic life in urban streams [55]. The declines are in part related to rapid rises and falls of streamflow and changes in temperature during storms and high runoff. Stormwater from urban development can also contain fertilizers and insecticides that have been used along roads and on lawns, parks, and golf courses, which can be harmful to aquatic organisms.

Comparisons among the nine areas show that stream response to urban development varies across the country [56,57]. Differences occur mostly because stream quality and aquatic health reflect a complex combination of land and chemical use, land and stormwater management, population density and watershed development, and natural features, such as soils, hydrology, and climate. For example, aquatic communities in urban streams in Denver, Dallas-Fort Worth, and Milwaukee did not decline in response to urbanization because the aquatic communities were already degraded by previous agricultural land-use activities. In contrast, aquatic communities declined in response to urbanization in metropolitan areas, where forested land was converted to urban land—areas such as Boston and Atlanta.

These USGS studies represent an integrated approach to understanding the physical, chemical, and biological water-quality effects associated with urbanization. This integration is critical for prioritizing strategies for stream protection and restoration and in evaluating the effectiveness of those strategies over time. Stream protection and management is a top priority of state and local officials, and the findings are valuable in recognition of the unintended consequences that development can have on aquatic resources. The information is useful to predict and manage the future impacts of urban development on streams and reinforces the importance of having a green infrastructure to control stormwater runoff and protect aquatic life.

2.3.3 Water Quality in Agricultural Settings

The effects of the use of agricultural chemicals and other practices associated with agriculture on the quality of streams and groundwater are well known; however, less is known about how those effects may vary across different geographic regions of the nation. USGS studies on the transport and fate of agricultural chemicals in agricultural settings across the country, using comparable and consistent methodology and study designs, highlight how environmental processes and agricultural practices interact to affect the movement and transformation of agricultural chemicals in the environment [35,58–61]. The studies address major hydrologic compartments, including surface water, groundwater, the unsaturated zone, the streambed, and the atmosphere, as well as the pathways that interconnect these compartments. The study areas represent major agricultural settings, such as irrigated diverse cropping in the West and corn and soybean row cropping in the Midwest, and therefore, findings are relevant throughout much of the nation.

Findings from these studies show how environmental processes and agricultural practices act together to determine the transport and fate of agricultural chemicals in the environment. For example, agricultural chemicals were transported more quickly in areas of hydrologic and landscape modifications, such as those associated with irrigation, tile drains, and drainage ditches. In addition, rates of movement of agricultural chemicals over the land surface to groundwater, depended on the characteristics of the chemical (such as solubility, sorption characteristics, and susceptibility to biochemical transformation), the timing of chemical application relative to irrigation and precipitation, and the volume of water inputs relative to evapotranspiration rates. Instream processes such as photosynthesis and respiration can change nitrate loads in surface water, while nitrate attenuation in groundwater depends on flow rates, the value of water moving through reactive zones, and the presence of organic substrates needed to support biological processes.

2.3.4 Water Quality as Related to Land- and Water-Management Practices

Water quality and the ecologic productivity of streams are highly interconnected with hydrology and the amount and timing of water flowing in a stream. A recent national study by the USGS assessed relations between water quality, aquatic health, and streamflow alterations, [62] identified over 1000 unimpaired streams, to use as reference points to create streamflow models. The models were applied to estimate expected flows for 2888 additional streams where the USGS had streamgages from 1980 to 2007. The estimated values for the 2888 streams were compared to actual, measured flows to determine the degree to which streams have been altered.

Findings show the pervasiveness of streamflow alteration resulting from land and water management across the United States, the significant impact of altered streamflow on aquatic organisms, and the importance of considering this factor for sustaining and restoring the health of the Nation's streams and ecosystems [62]. Specifically, the amount of water flowing in streams and rivers has been significantly altered in nearly 90% of waters that were assessed in the study. Flow alterations are a primary contributor to degraded river ecosystems and loss of native species.

Flows are altered by a variety of land- and water-management activities, including reservoirs, diversions, subsurface tile drains, groundwater withdrawals, wastewater inputs, and impervious surfaces, such as parking lots, sidewalks, and roads. Altered river flows lead to the loss of native fish and invertebrate species whose survival and reproduction are tightly linked to specific flow conditions. These consequences can also affect water quality, recreational opportunities, and the maintenance of sport-fish populations. For example, in streams with severely diminished flow, native trout, a popular sport fish that requires fast-flowing streams with gravel bottoms, is replaced by less desirable non-native species, such as carp. Overall, the work by Carlyle et al. [62] indicated that streams with diminished flow contained aquatic communities that preferred slow-moving currents more characteristic of lake or pond habitats.

Understanding the ecological effects of these flow alterations helps water managers develop effective strategies to ensure that water remains sufficiently clean and abundant to support fisheries and recreation opportunities, while simultaneously supporting economic development. Annual and seasonal cycles of water flows (particularly the low- and high flows) shape ecological processes in rivers and streams. An adequate minimum flow is important to maintain suitable water conditions and habitat for fish and other aquatic life. High flows are important because they replenish floodplains and flush out accumulated fine sediment in channels that can degrade habitat.

Carlyle et al. [62] showed that the severity and type of streamflow alteration varies among regions as a result of varying natural landscape features, land practices, degree of development, and water demand. Differences are especially large between arid and wet climates. In wet climates, watershed management is often focused on flood control, which can result in lower maximum flows and higher minimum flows. Extremely low flows are the greatest concern in arid climates, in large part due to groundwater withdrawals and high water use for irrigation.

Salinity-control projects have been implemented since the mid-1970s by the Bureau of Reclamation, U.S. Department of Agriculture, and the Bureau of Land Management to control the salinity of water delivered to Mexico, per the 1974 Colorado River Basin Salinity Control Act. A landmark USGS study by [63] showed the positive effect that this type of informed-management strategy can have in improving water quality. The study, based on USGS salinity monitoring in streams and groundwater in the Southwest during more than 30 years, used the SPARROW model to relate the salinity to natural and human factors. The study describes salinity levels in streams and groundwater in parts of Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming, and concludes that although salinity varies widely throughout the region levels have generally decreased in many streams [63]. Specifically, findings showed that dissolved solids decreased from 1989 through 2003 at all sites downstream from salinity-control projects, and that the decreases were greater than decreases upstream from projects. For example, estimated annual loads of dissolved solids in the Gunnison River in the Upper Colorado River Basin decreased by about 162,000 tons per year downstream from the lower Gunnison salinity-control unit, in contrast to a decrease of only 2880 tons per year upstream from the unit. This net decrease is about 15% of the annual load in the lower Gunnison River.

This example shows how changes in land and water use, reservoir management, transbasin exports, and the implementation of salinity-control projects, including using low water-use irrigation systems and the redirection of saline water away from streams, has improved water quality in the Colorado River Basin by lowering salinity.

The USGS study also documents the variability of salinity throughout the region, from 22 to 13,800 mg/L in streams. Finally, the study shows that both natural factors and human activities affect salinity. Through new geostatistical modeling techniques, the USGS was able to show that land- and water-use activities, primarily associated with pasture and cultivated land, contribute more than half (56%) of the salinity to streams, whereas natural geologic materials provide the remaining 44% [63].

2.3.5 Water Quality and Seasonal Variation

Water quality issues, regardless of land use, management practices, or natural geographic variability, as described above, are complicated by seasonal variations. These seasonal variations are associated with climate and human factors, such as irrigation. For example, at many sites studied by the USGS in the eastern United States, total nitrogen concentrations were highest in the spring when streamflow is highest and when fertilizer is applied, while total phosphorus concentrations were highest in the summer and autumn when streamflow is lowest and less water is available to dilute effluents from point sources. At other sites, particularly in the upper Midwest, both nitrogen and phosphorus concentrations were greatest during high streamflow in the spring. In the western states, seasonal patterns were less distinct due to the highly variable topography and climate and the widespread use of dams, reservoirs, and canals [19].

USGS pesticide assessments also reveal effects of seasonality, generally showing low concentrations of pesticides in streams for most of the year—lower than most standards and guidelines established to protect aquatic life and human health [34]. However, in the case of the insecticide diazinon in a California stream, the assessments also showed pulses of elevated concentrations that exceeded standards and guidelines during times of the year associated with rainfall and applications of chemicals (Figure 2-13). Domagalski et al. [64] examined concentrations of diazinon over a 2-year period from 1996 to 1998 relative to a guideline for the protection of aquatic life (shown on Figure 2-13; guideline set by the International Joint Commission). No local water districts draw water directly from this creek, but the levels were frequently high enough to be toxic to water insects that are essential food for fish. These types of data demonstrate the need for targeted sampling over seasons to determine when peak contaminant concentrations may affect drinking-water supplies and critical life stages of aquatic organisms.

2.3.6 Water Quality Over the Long Term

A critically important reason for any governmentto sustain a scientific mission, such as the USGS, is its ability to collect and interpret water-quality data across many decades using equivalent techniques, so that the data can be compared. A classic example was

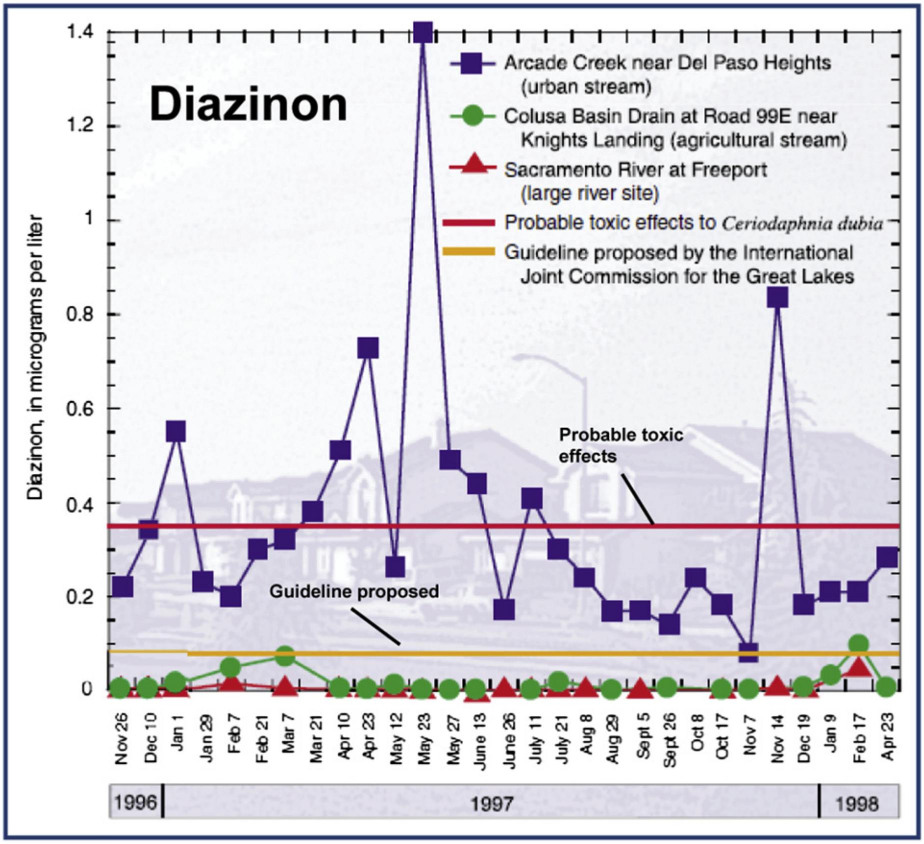

FIGURE 2-13 Pulses of elevated concentrations show the importance of tracking seasonal variation. *From Ref. [64]*. (For color version of this figure, the reader is referred to the online version of this book.)

published by Goolsby and Battaglin [65]. They described nitrogen in the Mississippi River, principally nitrate and organic nitrogen (dissolved and particulate). Nitrate is the most soluble and mobile form of nitrogen. Using USGS historical records dating back as early as 1903, the authors showed that the average concentrations of nitrate in the Mississippi River and some of its tributaries increased several fold after the early 1900s, in parts of Iowa, Illinois, Indiana, Minnesota, and Ohio. They noted that concentrations increased by a factor of about 2.6 between 1905 and 1907 and 1980 and 1996, and that most of the increase in the lower Mississippi River main stream occurred between the late 1960s and the early 1980s. During that period, the average annual nitrate concentration in water flowing to the Gulf of Mexico more than doubled.

As this example indicates, without comparable data collected over time, assessments cannot distinguish long-term trends from short-term fluctuations—nor can natural fluctuations be distinguished from the effects of human activities. USGS assessments show that water quality continually changes. The changes can be relatively quick—within days, weeks, or months, such as in streams in the Midwest where types of herbicides used on corn and soybeans have changed; or changes can be relatively slow, such as in groundwater beneath the Delmarva Peninsula where nitrate concentrations are beginning to decrease after 10 years of improved management of nitrogen fertilizers [34,66].

The need for long-term data is well demonstrated in the High Plains aquifer, also known as the Ogallala aquifer, which is the Nation's most heavily used groundwater resource. Most of the extracted water is used for irrigation, but nearly 2 million people also depend on the aquifer as a source of drinking water. The eight states that use water from the High Plains aquifer are Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. Nebraska hosts the largest areal extent of the water source.

USGS findings show that heavy use of water for irrigation and public supply, as well as leakage down inactive irrigation wells, are resulting in long-term gradual increases in concentrations of contaminants (such as nitrate and dissolved solids) from the water table to deeper parts of the High Plains aquifer where drinking-water wells are screened [67].

USGS scientists analyzed water for more than 180 chemical compounds and physical properties in about 300 private domestic wells, 70 public-supply wells, 50 irrigation wells, and 160 shallow, monitoring wells sampled between 1999 and 2004. The study, by Gurdak et al. [67] also assessed the transport of water and contaminants from land surface to the water table and deeper zones used for supply, to predict changes in concentrations over time.

Water produced by the High Plains aquifer is generally acceptable for human consumption, irrigation, and livestock watering. However, the increase in contaminant concentrations over time has important implications for the long-term sustainability of the High Plains aquifer as a source of drinking water. Once contaminated, the aquifer is unlikely to be remediated quickly because of slow rates of contaminant degradation and slow groundwater travel times in the aquifer; deep water in some parts of the aquifer is about 10,000 years old [67].

2.3.7 The Value of Water Quality Modeling

Models are essential if we are to better understand the status and trends of chemical and other constituents in the environment and to forecast future conditions. Models, integrated with monitoring, help us to apply our understanding of water quality, the hydrologic system, and the landscape to broader areas, including entire stream reaches and aquifers, large river basins, ecoregions, states, and the nation [30]. A map showing the distribution of average atrazine concentrations at USGS stream sites and the intensity of its use on crops, illustrates this point (Figure 2-14). The highest concentrations were found in the Midwest Corn Belt where use is most intense (data from Gilliam et al. [34]).

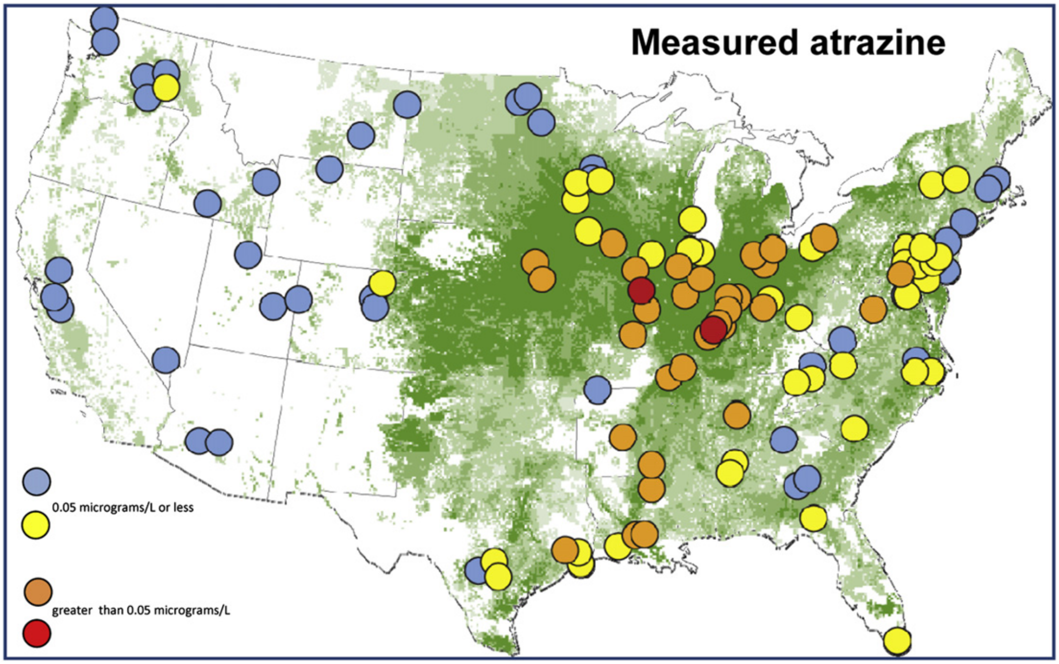

FIGURE 2-14 Atrazine measured in streams, 1992–2001. Blue and yellow circles are streams with low concentrations—0.05 μg/L or less; orange and red circles have higher concentrations—0.05 to greater than μg/L. Green shading indicates the intensity of atrazine use on crops. *From Ref. [34].* (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this book.)

To extend monitoring data to a more complete national assessment, USGS scientists developed a statistical model that uses the measured data collected in streams (e.g., Figure 2-14) with information on pesticide use and land use, climate and soil characteristics, and other watershed characteristics to predict concentrations for streams that have not been sampled. This statistical model allows scientists to map predicted average atrazine concentrations for more than 60,000 streams nationwide (Figure 2-15). The development of this type of predictive method allows scientists and resource managers to extend information from relatively few sites with direct measurements to the rest of the nation, and it is used by regulatory agencies such as USEPA and state equivalents to anticipate elevated concentrations of atrazine in streams.

Models have also been developed to better understand sources and transport of contaminants. One such example, noted earlier, is SPARROW, a spatially explicit, data-driven model that relates major pollutant sources to instream measurements [30]. At the national scale, SPARROW includes agricultural land uses and nutrient inputs (including those from the atmosphere), treated sewage, and crop and livestock production. It also includes watershed characteristics that control transportation, such as stream size, soils, and slope.

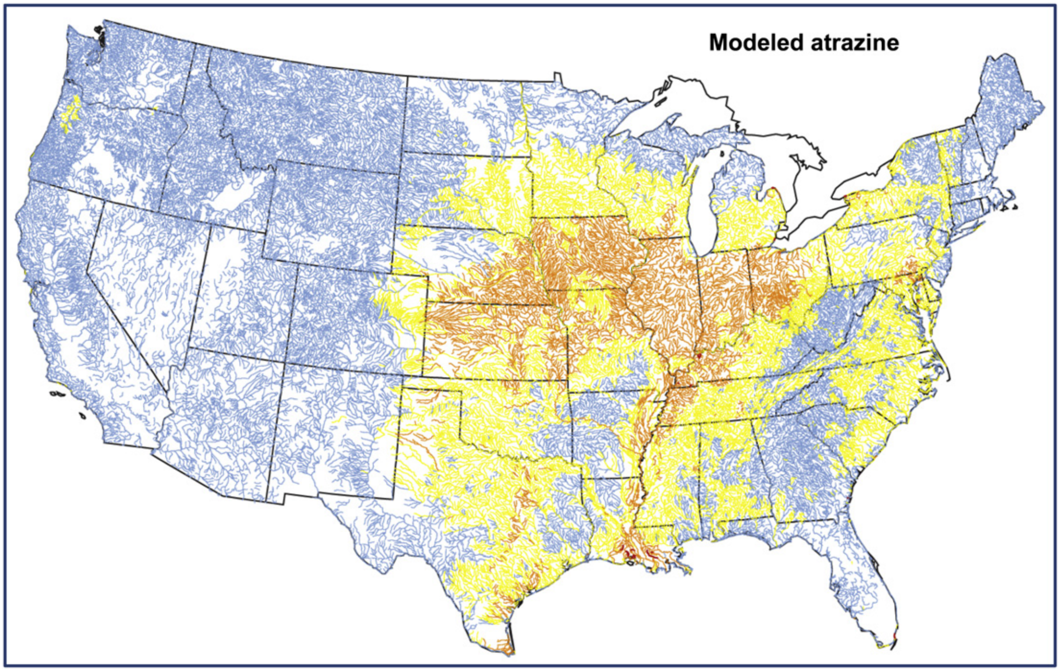

FIGURE 2-15 Prediction of atrazine in streams. Blue and yellow streams (most of the U.S. outside of the larger channels in the Mississippi River watershed) indicate low concentrations; red (mainly the Mississippi River and principal tributaries) indicates high concentrations. (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this book.)

SPARROW was used by USGS scientists to show the major source areas and delivery of phosphorus from the Mississippi River Basin (an area including 31 states) to the Gulf of Mexico (Figure 2-16). The results indicated that a considerable amount of phosphorus delivered to the Gulf originates in distant watersheds, such as in the Ohio and Tennessee Rivers [30]. Similar findings are evident for nitrogen delivery. As discussed above (Figure 2-3), USEPA, the U.S. Department of Agriculture (USDA), states, and other members of the Gulf Hypoxia Task Force use this information to identify priority watersheds and agricultural management practices in the watersheds delivering the most nutrients to the Gulf [31].

The USGS has developed a regionally focused set of SPARROW water-quality models to assist with the interpretation of water-resources data and provide predictions of water quality in unmonitored streams. These regional SPARROW models incorporate geospatial data on the geology, soils, land use, fertilizer, manure, wastewater-treatment facilities, temperature, precipitation, and other watershed characteristics derived from USGS, USEPA, USDA, and the National Oceanic and Atmospheric Administration. These data are then linked to measurements of streamflow from USGS streamgages and water-quality monitoring data from approximately 2,700 sites operated by 73 monitoring agencies [68].

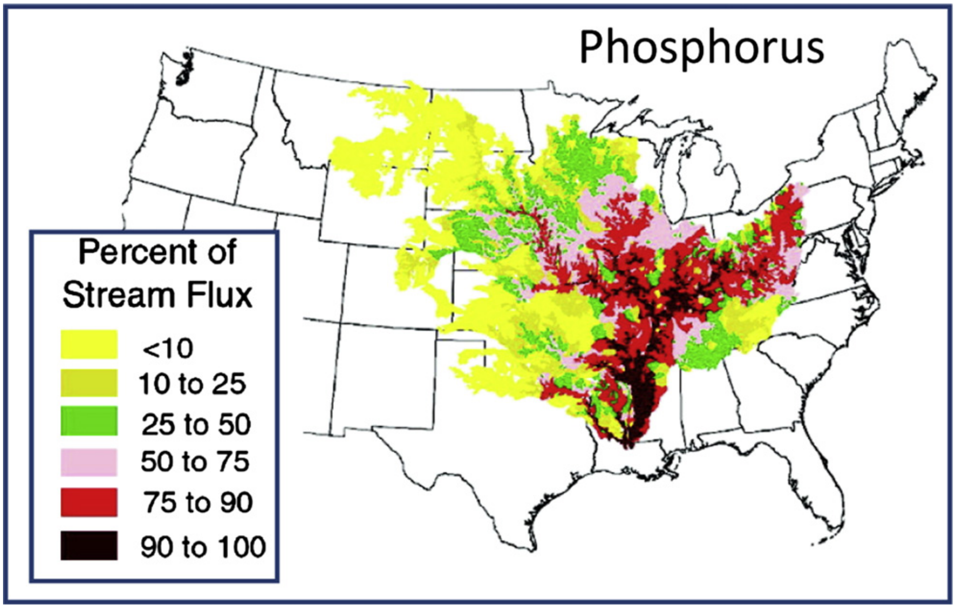

FIGURE 2-16 Estimated delivery of phosphorus from the Mississippi River Basin to the Gulf of Mexico. *From Ref. [30]* (For color version of this figure, the reader is referred to the online version of this book.)

Six USGS regional models were developed in the Northeast, Southeast, Upper Midwest (Great Lakes), Missouri River, Lower Midwest (Gulf of Mexico), and Pacific Northwest, using the national SPARROW modeling framework. Results detailing nutrient conditions in each region and description of a support system for decision making are published in a set of papers [68,69]. These authors indicate that each region and locality has a unique set of nutrient sources and characteristics that determine how those nutrients are transported to streams. For example, based on the six regional model results, wastewater effluent and urban runoff are significant sources of nutrients in the Northeast and Mid-Atlantic, while agricultural sources like farm fertilizers and animal manure contribute heavily to nutrient concentrations in the Midwest and the central regions of the nation. Atmospheric deposition is the largest contributor of nitrogen in many streams in the eastern United States, and naturally occurring geologic sources are a major source of phosphorus in many areas. Additionally, the six models show that the amount of nutrients transported varies greatly among the regions; for example, nutrients can be removed in reservoirs or used by plants before they reach downstream waters. Temperature and precipitation variations across the country also affect the rates of nutrient movement and nutrient loss on the land and in streams and reservoirs.

Using a web-based support system for decision making built on these models, users can evaluate combinations of source-reduction scenarios that target one or multiple sources of nutrients and see the change in the amount of nutrients transported to downstream waters—a capability that has not been widely available in the past. For example, the web-based support system for decision making indicates that reducing wastewater discharges throughout the Neuse River Basin in North Carolina by 25% will reduce the amount of nitrogen transported to the Pamlico Sound from the Neuse River Basin by 3%, whereas a 25% reduction in agricultural sources, such as fertilizer and manure, will reduce the amount of nitrogen by 12%.

Similar models are applied to assess groundwater quality problems and to predict the vulnerability of groundwater, across the nation, to nitrate [66]. The concentration of nitrate contamination in shallow groundwater and in drinking-water wells across the country can be predicted on the basis of (1) nitrate concentrations measured by the USGS at nearly 2000 wells, and (2) national data sets on sources of nitrogen. The model prediction demonstrates moderate to severe nitrate contamination (greater than the drinking water standard of 10 mg/L, as indicated in red on Figure 2-17) at locations in the High Plains, Mid-Atlantic region, and California. The high concentrations are generally related to high nitrogen inputs, high water input, well-drained soils, fractured rocks or those with high effective porosity, and lack of attenuation processes. The estimated number of people served by wells with nitrate concentrations severely contaminated by nitrate greater than 10 mg/L is about 467,000 in the United States. The model predicts that exposure risk is reduced by seeking deeper water supplies.

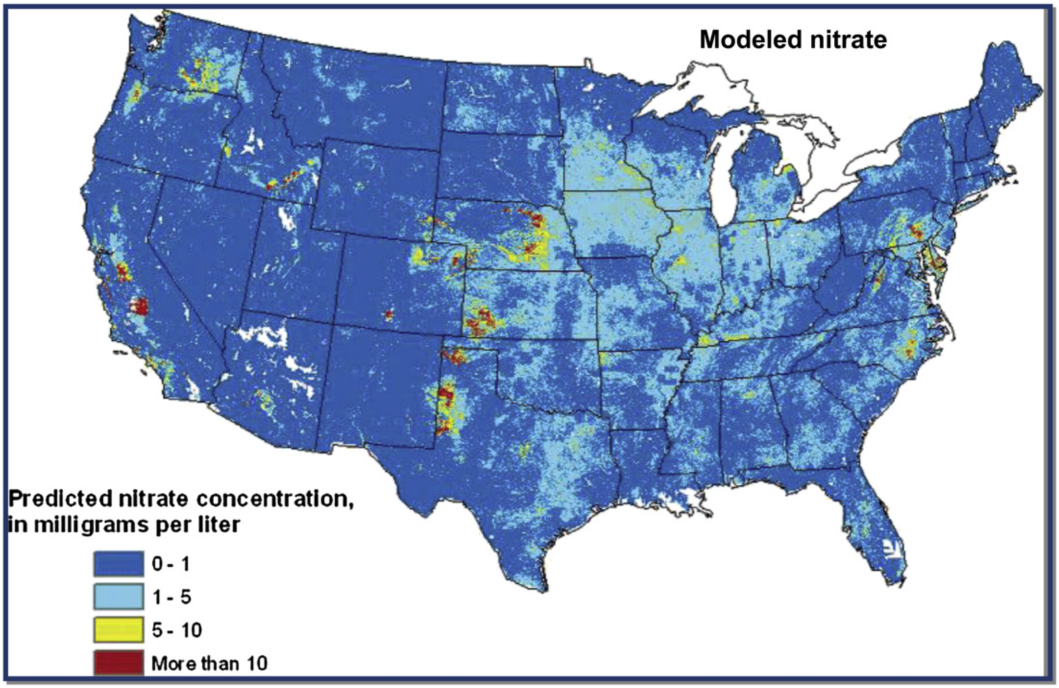

FIGURE 2-17 Vulnerability of shallow groundwater and drinking-water wells to nitrate contamination. *From Ref. [66].* (For color version of this figure, the reader is referred to the online version of this book.)

2.3.8 Water Quality and Climate Change

Climate change is a major challenge for global water-resources management [70]. Furthermore, climate change is increasingly recognized as a factor not only in water availability, but also in the quality of water [6,62]. Although numerous impacts are anticipated for the future, climate change is already affecting water resources in a variety of ways [3–5,11]. According to Dettinger [71]; “earlier spring snowmelt has been well documented in the western US. Warmer winters and springs in the Western United States have contributed to widespread hydrologic changes, including trends toward more precipitation as rain rather than as snow, less snowpack overall, earlier greening of vegetation, and earlier snowmelt” (Figure 2-18). These types of annual and decadal changes in precipitation can lead to long-term changes in surface runoff or instream dilution, contributing to long-term changes in nutrient concentrations in streams [71]. A few additional examples of water quality impacts already observed and documented, as well as others that are predicted, are described below.

Increased frequency of heavy rainfall is an expected outcome of a warmer atmosphere [9,73]. Storm rainfall is a water-treatment challenge because it increases sediment and pathogen loads, urban stormwater runoff, and combined sewer overflows [74]. Droughts are also expected to be more common and intense and to last longer [73]. A drought followed by runoff associated with heavy precipitation results in higher concentrations of contaminants and increased nutrient loads [75]. These higher levels of nutrients, in turn, increase the potential for algal blooms and the associated taste- and odor- and algal-toxin

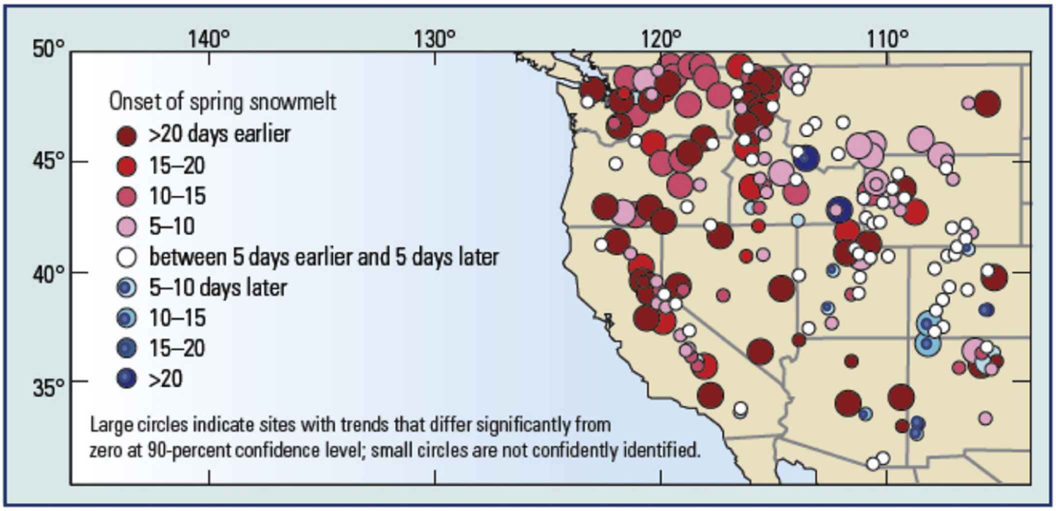

FIGURE 2-18 Trends for the onset of spring snowmelt are shown for the western United States. This is the date on which snowmelt runoff adds large water volume to rivers—the onset occurs 1 week to almost 3 weeks earlier now than in the middle of the twentieth century [71,72]. Changes in the timing of streamflow have implications for agricultural water management and hence nutrient transport. (For color version of this figure, the reader is referred to the online version of this book.)

problems [75,76]. As such, the quality of source water is expected to be affected by more frequent algal blooms, changes in types and abundance of watershed vegetation, and increased water temperature, particularly in riparian areas [74].

In their review of potential impacts of climate change on groundwater resources Earman and Dettinger [3], state that “changes in the Earth’s climate have the potential to affect both the quality and quantity of available groundwater, primarily through impacts on recharge, evapotranspiration and (indirectly) on pumpage and abstraction.”

A well-documented aspect of the impact of climate change on water quality pertains to saline intrusion in coastal aquifers. Globally, sea levels have risen by about 22 centimeters in the twentieth century. It is expected that sea level will continue to rise in response to global warming, as ocean waters warm and expand and major ice sheets melt into the seas. In coastal areas, these higher sea levels are likely to increase the potential for the intrusion of ocean water into freshwater aquifers, increasing groundwater salinity [3].

One impact of changing patterns of precipitation on small streams is that they are sustained through substantial parts of the year by groundwater flow [3]. These streams are relatively shallow compared to the depth of the aquifers that supply the groundwater inflow, and consequently receive inflows mainly from the uppermost parts of the contributing aquifers. As groundwater recharge decreases, water tables drop and contribution to streamflow declines [3].

The effects of reduced groundwater inflow on water quality and ecosystems have also been described. One effect is the reduced dilution of contaminants and warmer stream temperature. Groundwater is typically cooler than streamflow [3] because surface water has traveled overland to (and through) stream channels. Warmer stream temperatures are likely to have significant impacts on species viability, as described in two examples below.

Surface temperatures of rivers and oceans have all increased significantly [4,9]. Warmer streamflow is a stressor on many endemic species and facilitates colonization by introduced species. Additionally, spring warming of temperate lakes disrupts the timing between zooplankton and the phytoplankton food supply [4].

Model projections by Cloern [4] suggest that “climate-driven changes to the San Francisco Estuary-Watershed could lead to a diminishing water supply, continued shifts toward wetter winters and drier summers, sea level rising to higher levels than were projected only a few years ago, salt water intrusion, reduced habitat quality for native aquatic species.” Warmer water temperature has had a negative effect on fish endemic to the Sacramento Delta, such as the Delta Smelt [4]. These fish are adapted to cool, turbid, low-salinity habitats and as delta waters warm and become more saline, their already-compromised habitat may be further degraded.

Twentieth century warming has already affected the Salmonid habitat, with unfavorable changes to thermal and hydrologic properties of aquatic systems, according to a study of risks to coldwater fish as a result of climate change [77]. In their work on Native Trout and Grayling within 11 western states, the authors note that climate model output

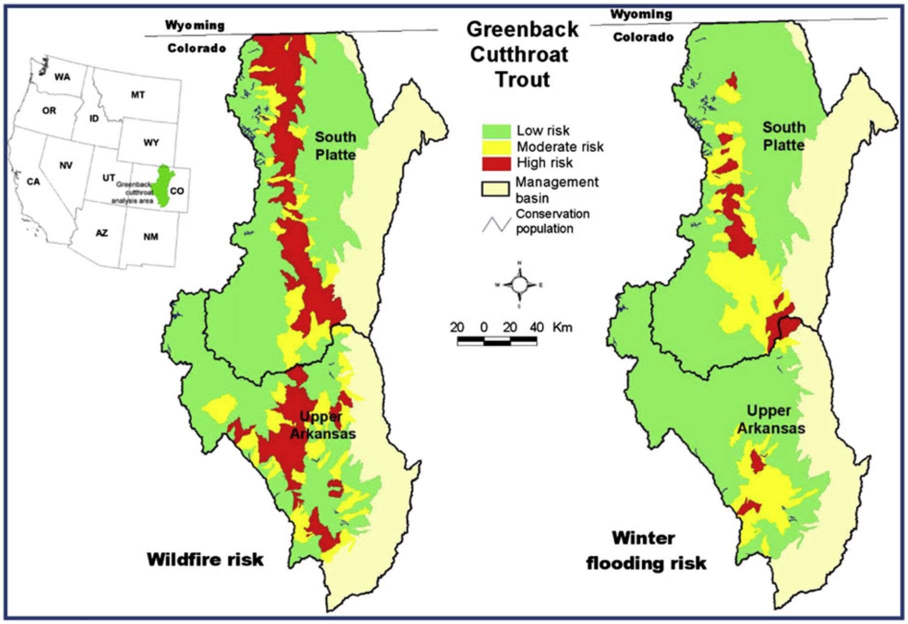

FIGURE 2-19 Risk of summer temperature increases and drought for greenback cutthroat trout in their current range in the drainages of the South Platte Basin and the Upper Arkansas Basin in Colorado. *From Ref. [77].* (For color version of this figure, the reader is referred to the online version of this book.)

indicates that these trends will continue and even accelerate until at least the middle of the twenty-first century [77]. Drought is the most pervasive threat, with 40% or more of the historic range of seven taxa at high risk. Greenback cutthroat trout are an example, in Colorado, where population pressure and land-use change have eliminated the fish from much of its former habitat, and most of the remaining populations are found in higher-elevation streams and lakes [77]. Drought is a relatively high-risk factor for this fish; additionally, increasing summer temperature and wildfire are also higher risks within its historic habitat in the South Platte Basin as compared to where they are found now (Figure 2-19) [77].

2.4 Conclusions

This brief set of mainly USGS-derived examples of water-quality status and trends in the United States indicates that to sustain water supplies of high quality to meet human and ecological needs, a continual advance in our understanding of an increasingly complex set of underlying controlling factors is required. Furthermore, constant development of new analytical tools and models to inform our approach will be essential. Lastly, the scientific community needs to synthesize and translate the results of this work so that resource managers and decision makers can effectively use the scientific information that we provide.

Water-quality issues facing the United States have changed since the implementation of the CWA and are in large part, focused on nonpoint sources of pollution and other environmental stressors. A major challenge for the monitoring of water-quality status and trends is to improve understanding of the many nonpoint-related sources and stresses that affect water quality, now and over the long term. This requires credible, objective, and interdisciplinary data on, and interpretation of, the physical, chemical, and biological conditions of water bodies and the natural landscape; and also of natural factors such as climate, climate change, and human activities, that may contribute to those conditions.

The water quality issues highlighted here are complex, and explanations for degraded water quality include interactions among the natural environment, climate change, and human land and water use that vary spatially and temporally over a variety of scales. These complexities present challenges to scientists and policy makers who are trying to understand and manage water-quality issues such as: changing patterns in flow conditions; increasing water temperature and salinity; and increases in contamination from a variety of naturally occurring and man-made chemicals. Complex mixtures of organic compounds, such as pesticides, pharmaceuticals, and hormones, can, even at very low concentrations, adversely affect the health or reproductive success of aquatic organisms; and nutrient enrichment can lead to algal blooms, low oxygen, and impaired ecosystems.

Given these complexities, achieving sustainable high-quality water across the nation to meet human and ecosystem needs requires sustained and comprehensive efforts in several key areas:

- Understanding the relations between water quality and the natural landscape, hydrologic processes, climatic variability, and human activities;
- Evaluating water quality in the context of physical, chemical, and biological systems;
- Monitoring over short-term and long-time scales;
- Integrating modeling with monitoring to help apply our understanding of water-quality conditions and hydrologic systems to unmonitored, yet comparable areas.

Such commitments and investments will continue to provide the critical and improved scientific basis for decision makers to effectively manage and protect our waters across the United States and in specific geographic areas, now and in the future. Science will help to sort out and prioritize the multitude of decisions involving competing demands for safe drinking water, irrigation, sustainable ecosystems, energy development, and recreation.

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