The Quality of Our Nation's Waters

Ecological Health in the Nation's Streams, 1993–2005

National Water-Quality Assessment Program

Circular 1391

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COVER
Background: Lake Fork River, Utah (U.S. Geological Survey photo by Daren Carlisle); upper photo: damselflies (photo courtesy of Jeremy Monroe, Freshwaters Illustrated); lower photo: mottled sculpin *(Cottus bairdii)* (photo courtesy of Ben Holcomb, Utah Department of Environmental Quality).

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By Daren M. Carlisle, Michael R. Meador, Terry M. Short, Cathy M. Tate, Martin E. Gurtz, Wade L. Bryant, James A. Falcone, and Michael D. Woodside

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FOREWORD

The United States has made major investments in assessing, managing, regulating, and conserving natural resources such as water, minerals, soils, and timber. Sustaining the quality of the Nation's water resources and the health of our ecosystems depends on the availability of sound water-resources data and information to develop effective, science-based policies. Effective management of water resources also brings more certainty and efficiency to important economic sectors. Taken together, these actions lead to immediate and long-term economic, social, and environmental benefits that make a difference to the lives of millions of people (http://water.usgs.gov/nawqa/applications/).

Two decades ago, Congress established the U.S. Geological Survey's National Water-Quality Assessment Program (NAWQA) to meet this need. Since then, it has served as a primary source of nationally consistent information on the quality of the Nation's streams and groundwater; how water quality changes over time; and how natural features and human activities affect the quality of streams and groundwater. Objective and reliable data, water-quality models and related decision support tools, and systematic scientific studies characterize where, when, and why the Nation's water quality is degraded—and what can be done to improve and protect it for human and ecosystem needs. This information is crucial to our future because the Nation faces an increasingly complex and growing need for clean water to support population, economic growth, and healthy ecosystems. For example, two-thirds of estuaries in the United States are impacted by nutrients and dead zones that no longer fully support healthy fish and other aquatic communities. Forty-two percent of the Nation's streams are in poor or degraded condition compared to reference conditions. Eighty percent of urban streams have at least one pesticide that exceeds criteria to protect aquatic life. Groundwater from about 20 percent of public and domestic wells—which serve about 150 million people—contains at least one contaminant at a level of potential health concern.

This report presents a national assessment of stream health based on the condition of biological communities in relation to important physical and chemical factors, such as the degree of hydrologic alteration and concentrations of nutrients and other dissolved contaminants. Algae, macroinvertebrates, and fish provide a direct measure of stream health because they live within streams for weeks to years, therefore integrating through time the effects of changes to their chemical and physical environment. This report is one of a series of publications, *The Quality of Our Nation's Waters*, which describes major findings of NAWQA on water-quality issues of regional and national concern. Other reports in this series focus on the occurrence and distribution of nutrients, pesticides, and volatile organic compounds in streams and groundwater; the effects of contaminants and streamflow alteration on the condition of aquatic communities in streams; and the quality of untreated water from private domestic and public supply wells. Each report builds toward a more comprehensive understanding of the quality of regional and national water resources (http://water.usgs.gov/nawqa/nawqa_sumr.html). All NAWQA reports are available online at http://water.usgs.gov/nawqa/bib/.

The information in this series is intended primarily for those interested or involved in resource management and protection, conservation, regulation, and policymaking at regional and national levels. In addition, the information should be of interest to those at a local level who wish to know more about the general quality of streams and groundwater in areas near where they live and how that quality compares with other areas across the Nation. We hope this publication will provide you with insights and information to meet your needs, and will foster increased citizen awareness and involvement in the protection and restoration of our Nation's waters.

William H. Werkheiser
Acting Deputy Director,
U.S. Geological Survey

Acknowledgments

A report that spans multiple decades of data collection and synthesis owes many debts to many people—too numerous to thank in this small space. Nevertheless, the authors want to highlight the contributions of a few who notably assisted in unique ways. First, Bill Wilber's (U.S. Geological Survey, USGS) vision and persistence, from the very beginnings of the National Water-Quality Assessment Program (NAWQA), helped guide these ecological investigations and ensured their integration with other components of the program. Keith Slack's innovative approaches to field methods led to a collection device for macroinvertebrates that allowed comparable methods to be used in the broadest possible array of stream habitats. Carol Couch (now at Commonwealth Scientific and Industrial Research Organisation of Australia) envisioned and led the initial national synthesis efforts. Steve Moulton (USGS) provided key leadership during the early stages of this report. Frank Ippolito's artistic talents and scientific interests fostered the creation of illustrations that help tell the stories of natural aquatic systems and how human interactions alter and shape the environment in which we live; Dennis Roehrborn provided a farmer's perspective that added a key element of realism to the agricultural stream diagram. Jeff Martin (USGS) provided his expertise in the analysis of pesticides and stream biota. Pixie Hamilton (USGS) provided crucial guidance in the early development of this report; Kelly Ruhl (USGS) supported data management. Lisa Nowell (USGS), Terry Maret (USGS), Steve Paulsen (U.S. Environmental Protection Agency), and Judy Meyer (University of Georgia) provided thoughtful reviews at a critical stage in the life of this document. We also thank the many individuals from the USGS and other agencies who participated in the collection of thousands of samples and other field data, and in the management of those data; these form the scientific foundation that makes reports like this possible. And finally, NAWQA's many partners in governmental and nongovernmental sectors helped guide scientific efforts and ensure that NAWQA information meets the needs of local, State, tribal, regional, and national stakeholders.

Contents

Chapter 1 Overview of Findings and Implications

Nearly 4 million miles of streams and rivers are woven through the landscape of the United States. This immense natural resource provides many societal benefits. Streams and rivers provide water for cities and farms; they provide recreational, cultural, and aesthetic benefits valued by many people; and they nourish a diverse array of plant and animal species. Changes in land use and increasing demands for freshwater pose risks to the health of streams and rivers and to the benefits they provide to society.

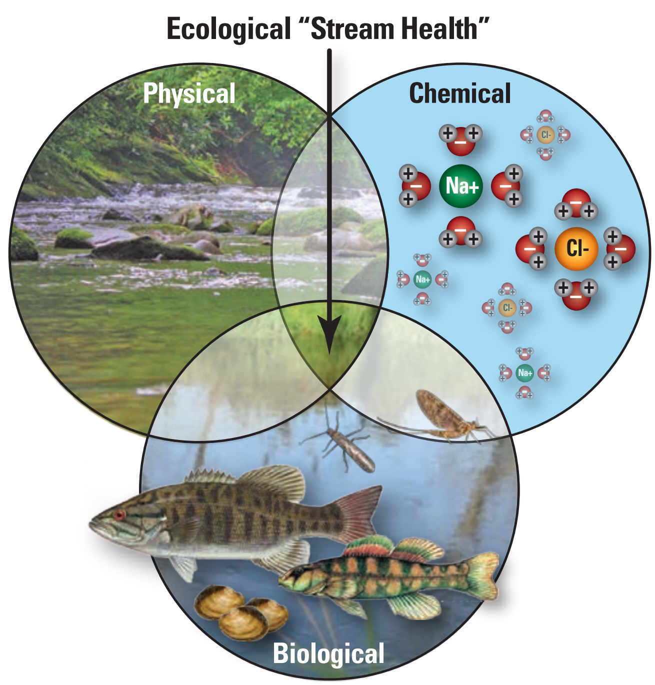
U.S. Geological Survey photo by Daren Carlisle.

The condition of biological communities—which are collections of aquatic organisms—provides a direct measure of stream health.

Introduction

This report summarizes a national assessment of the ecological health of streams done by the U.S. Geological Survey's (USGS) National Water-Quality Assessment Program (NAWQA). Healthy functioning stream ecosystems provide society with many benefits, including water purification, flood control, nutrient recycling, waste decomposition, fisheries, and aesthetics. The value to society of many of these benefits is substantial; for example, sportfishing in the United States generates an estimated annual economic output of $125 billion, including more than 1 million jobs (National Research Council, 2005; American Sportfishing Association, 2008). Continued monitoring and assessment of the Nation’s streams is needed to support informed decisions that will safeguard this important natural and economic resource.

The quality of streams and rivers is often assessed with measures of the chemical or physical properties of water. However, a more comprehensive perspective is obtained if resident biological communities are also assessed. Guidelines to protect human health and aquatic life have been established for specific physical and chemical properties of water and have become useful yardsticks with which to assess water quality. Biological communities provide additional crucial information because they live within streams for weeks to years and therefore integrate through time the effects of changes to their chemical or physical environment. In addition, biological communities are a direct measure of stream health—an indicator of the ability of a stream to support aquatic life. Thus, the condition of biological communities, integrated with key physical and chemical properties, provides a comprehensive assessment of stream health.



As this simple diagram shows, a stream’s ecological health (or “stream health”) is the result of the interaction of its biological, physical, and chemical components. Stream health is intact if (1) its biological communities (such as algae, macroinvertebrates, and fish) are similar to what is expected in streams under minimal human influence and (2) the stream’s physical attributes (such as streamflow) and chemical attributes (such as salinity) are within the bounds of natural variation. Although the condition of biological communities is a crucial indicator of stream health, a more holistic approach includes assessments of key physical and chemical characteristics of streams. This is NAWQA’s approach to assessing stream health.

Highlights of Major Findings and Implications

- The presence of healthy streams in watersheds with substantial human influence indicates that it is possible to maintain and restore healthy stream ecosystems. Such streams can also offer insights into how stream health can be maintained amid anticipated changes in land use or restored when stream health has deteriorated as a result of human actions.
- Assessments that are limited to a single biological community are likely to underestimate the effects of land and water use on stream health. Assessments of multiple biological communities increase our ability to detect streams with diminished health and provide a more complete understanding of how land and water use influence stream health.
- Water quality is not independent of water quantity because flows are a fundamental part of stream health. Because flows are modified in so many streams and rivers, there are many opportunities to enhance stream health with targeted adjustments to flow management.
- Efforts to understand the causes of reduced stream health should consider the possible effects of nutrients and pesticides, in addition to modified flows, particularly in agricultural and urban settings.
- Stream health is often reduced due to multiple physical and chemical factors. Assessments and restoration efforts should therefore take a multifactor approach, wherein a number of factors—and their possible interactions—are considered. Understanding how these multiple factors influence biological communities is essential in developing effective management strategies aimed at restoring stream health.

U.S. Geological Survey photo by John Wilson.

This photograph of stream runoff going through a cornfield in Hancock County, Indiana, illustrates that stream health can be influenced by multiple factors. For example, runoff from some land-use practices may contain nutrients, sediments, and pesticides, which can be transported to local streams and potentially affect biological communities.

U.S. Geological Survey photo by Daren Carlisle.

Extreme low-water conditions shown in this photograph of a California stream illustrate the necessity to balance societal needs for water withdrawal with the needs to maintain stream health. Understanding relations among biological communities and manmade modification to streamflow is essential to informing decisions needed to achieve this balance.

At least one biological community—algae, macroinvertebrates, or fish—was altered in 83 percent of assessed streams.

Biological Condition and Land Use

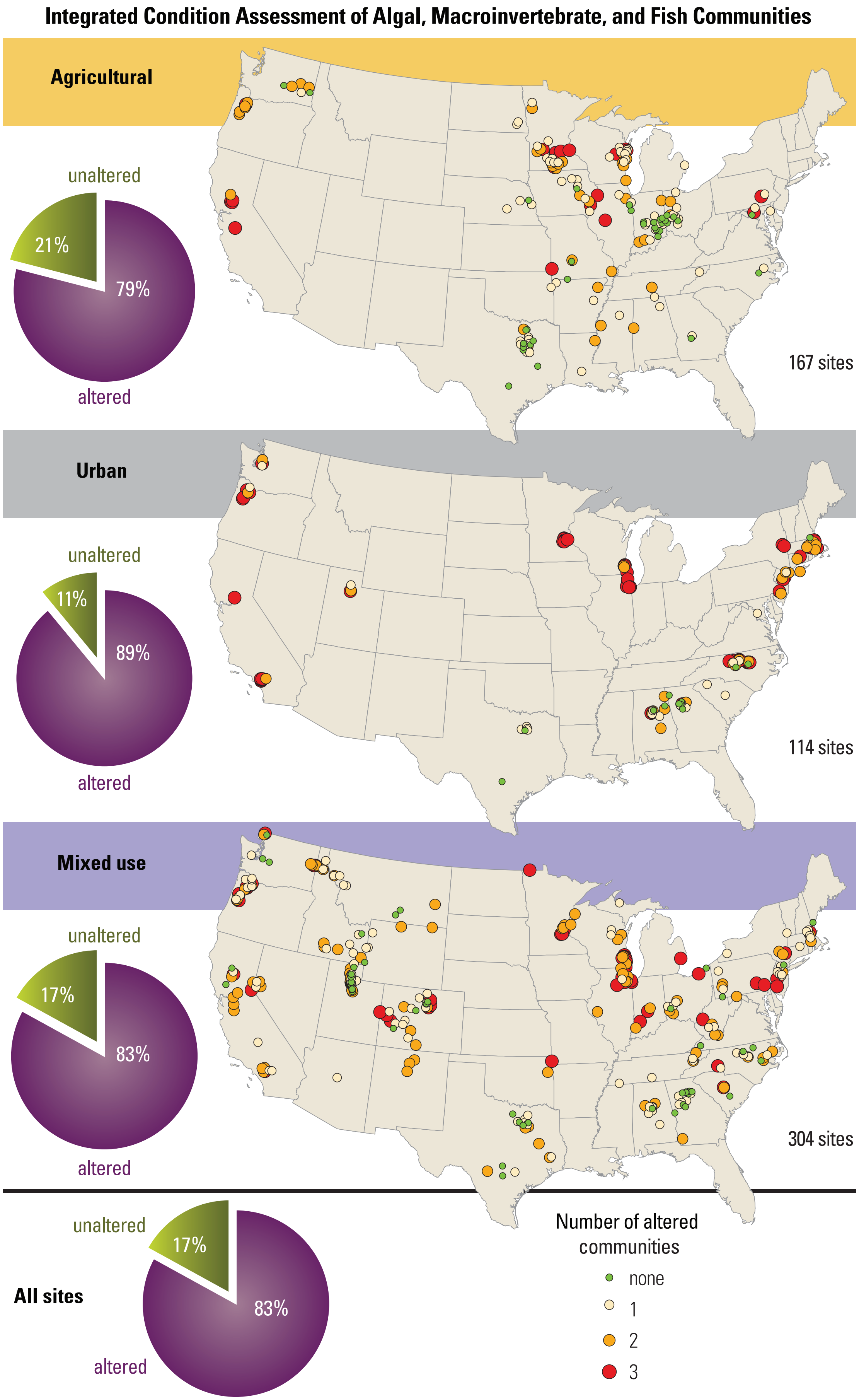
Across all land-use settings at least one biological community—algae, macroinvertebrates, or fish—was altered in 83 percent of assessed streams. In urban settings, 89 percent of sites assessed by NAWQA had at least one altered biological community, compared with 79 percent of sites in agricultural settings and 83 percent of sites in mixed-use settings. All three biological communities were altered in 22 percent of assessed streams. A community was classified as altered if the numbers and types of organisms in it were substantially different from its natural potential, as estimated from regional reference sites (chapter 3). This high incidence of altered biological communities suggests that stream health is threatened by a wide variety of land- and water-management activities across the Nation (chapter 5).

Unaltered biological communities were present in 17 percent of assessed streams. The presence of unaltered biological communities in agricultural and urban watersheds suggests that it is possible to maintain stream health in the midst of substantial human influence. In addition, a wide range in the severity of biological alteration was found among streams within each land-use setting (chapter 5), which indicates that the influences of land and water management on stream health differ widely across the Nation.

Integrated assessments of algal, macroinvertebrate (such as insects and snails and clams), and fish communities revealed twice as many altered streams in some land-use settings compared to single-community assessments (chapter 5). Multicommunity assessments increase the likelihood of detecting reduced stream health because species in different communities have unique vulnerabilities to manmade changes in their physical and chemical surroundings. This finding suggests that assessments limited to a single biological community are likely to underestimate the influence of land and water management on stream health.

Background illustration by Frank Ippolito/www.productionpost.com.

As shown in this illustration, living components of stream ecosystems include a complex and varied array of biological communities, including algae, macroinvertebrates (such as aquatic insects and snails and clams), and fish.



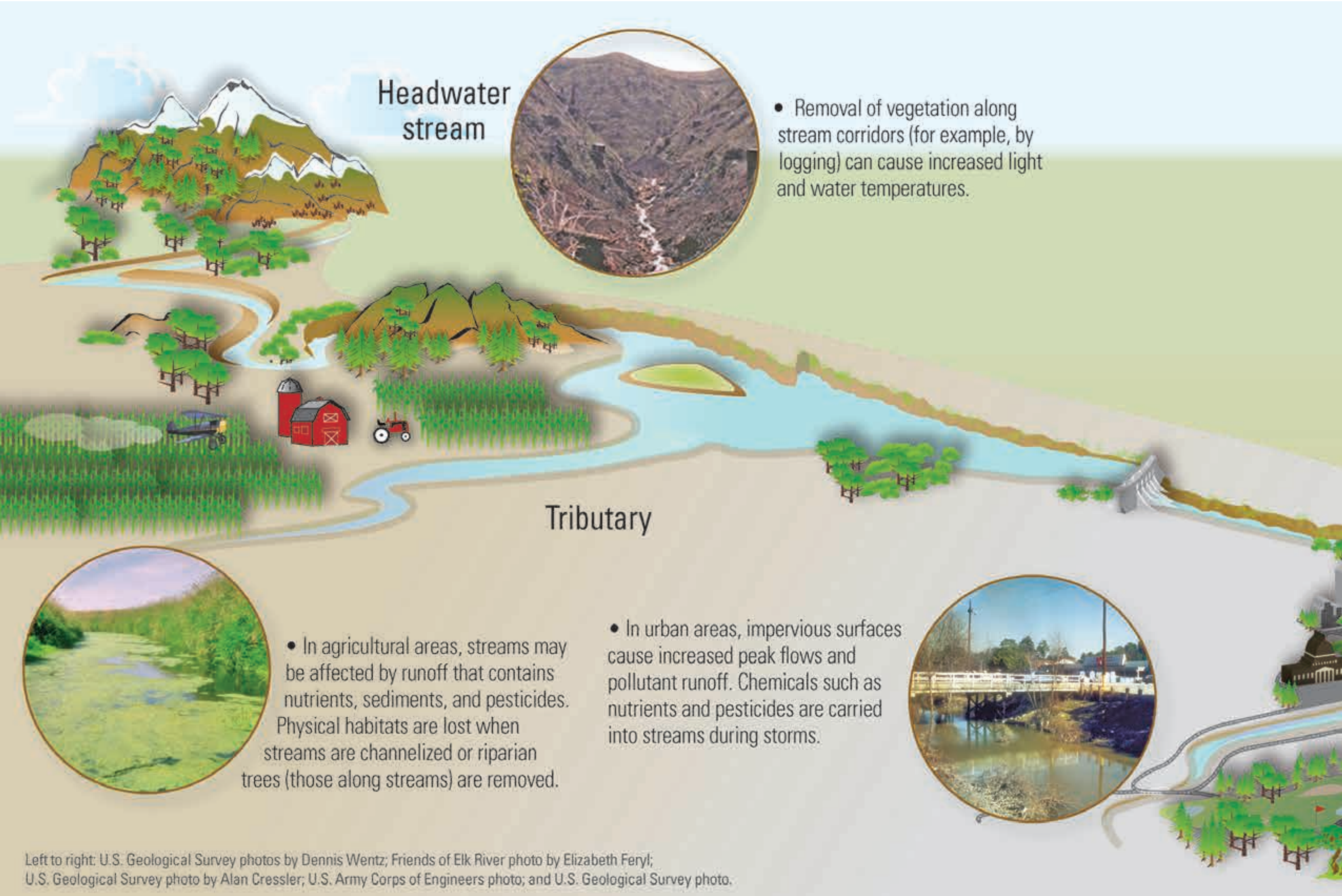
As shown in this diagram, regardless of land-use setting, at least one biological community (algae, macroinvertebrates, or fish) was altered, relative to regional reference conditions, at 83 percent of the 585 streams in the conterminous United States where NAWQA performed integrated assessments of multiple biological communities. (%, percent. Labels for individual States are shown on the map on page 22.)

Reduced stream health was associated with manmade modifications to physical and chemical factors that often result from land and water management.

Factors Associated with Stream Health

When assessments reveal that biological communities are altered—which indicates that stream health is diminished—scientists and managers must determine which physical or chemical factors have been modified by human activities sufficiently to alter biological communities. This information is essential to identifying and implementing appropriate management practices aimed at restoring stream health (chapter 6).

Reduced stream health is associated with manmade modifications to the physical and chemical properties of streams, which are a consequence of land and water management. Maintenance of stream health requires that physical and chemical properties of streams remain within the bounds of natural variation. When manmade disturbances push these characteristics beyond natural ranges, such as might occur from increased fluctuation in streamflows or excess nutrients, vulnerable aquatic species are eliminated—ultimately reducing stream health. Manmade modifications to key physical and chemical factors that control stream health are extensive, occurring in all types of land-use settings (chapter 4).

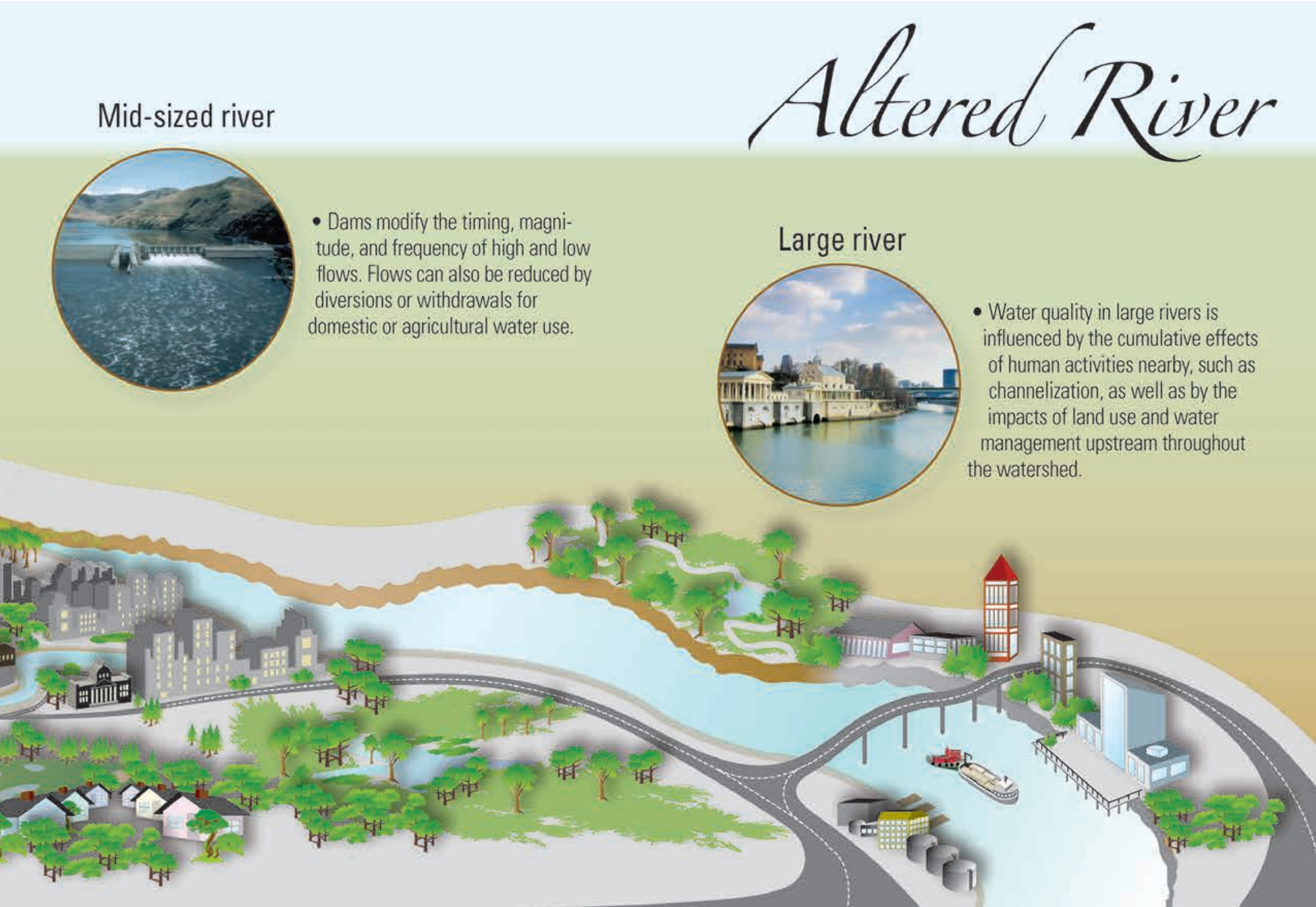


Left to right: U.S. Geological Survey photos by Dennis Wentz; Friends of Elk River photo by Elizabeth Feryl; U.S. Geological Survey photo by Alan Cressler; U.S. Army Corps of Engineers photo; and U.S. Geological Survey photo.

Alteration of biological communities and reduced stream health in a given stream are often related to modifications of multiple physical and chemical factors. A major challenge to understanding why stream health is reduced is unraveling the effects of many interacting natural and human-caused factors (chapter 6). In addition, factors associated with altered biological communities often differ among algal, macroinvertebrate, and fish communities, because each has unique requirements for survival and vulnerability to changes in their environment (chapters 5 and 6). Finally, factors associated with reduced stream health often differ among geographic regions (chapter 6). These findings suggest that management strategies aimed at restoring stream health should take a multifactor approach that is tailored to the geographic setting and the biological communities that have been altered.

Several physical and chemical factors that are known to be widely altered as a result of land and water management have the potential to alter stream health. These are briefly summarized in the pages that follow but do not represent all the possible factors that contribute to reduced stream health across the Nation.

No single physical or chemical factor was universally associated with reduced stream health across the Nation.

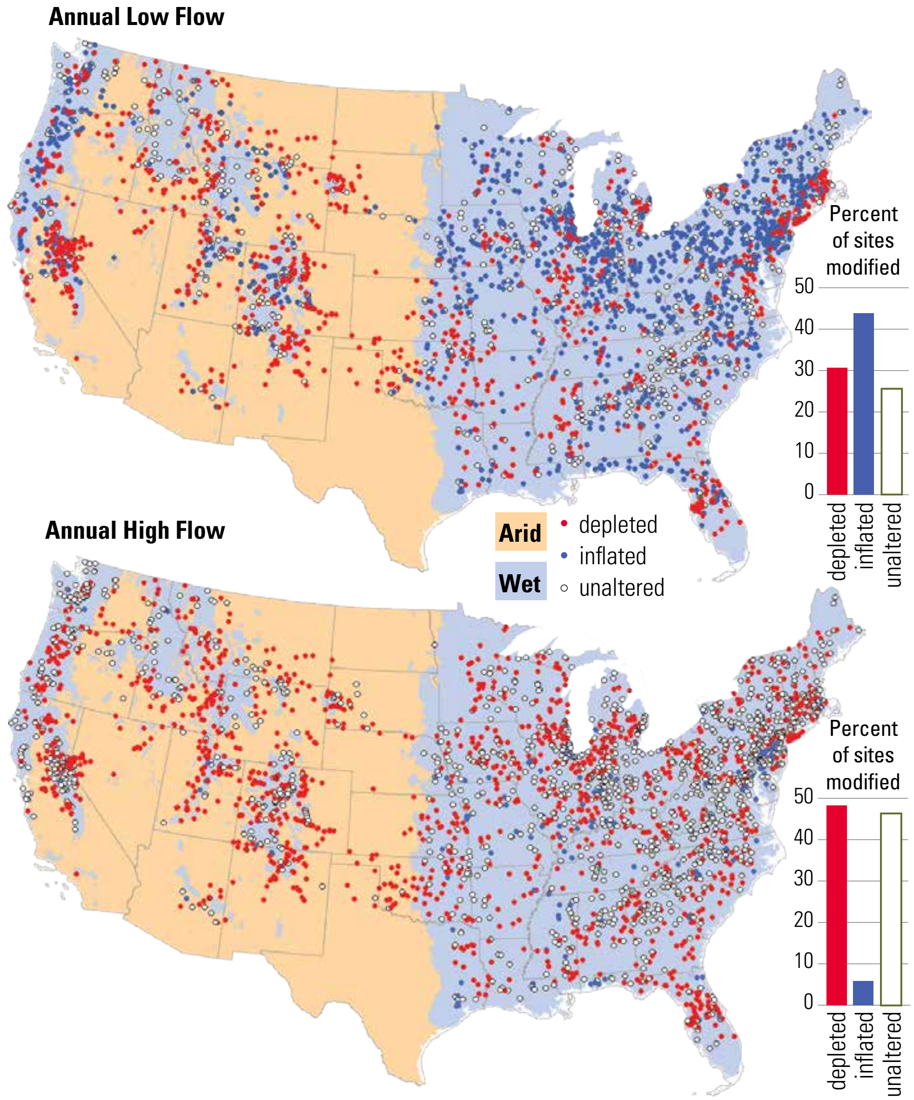


Annual low or high flows were modified in 86 percent of the almost 3,000 assessed streams.

Streamflow Modification

Flowing water is the defining feature of streams, yet streamflows across the Nation have been modified by land and water management, leading to reduced stream health. Annual high or low flows were modified in 86 percent of the almost 3,000 streams assessed by NAWQA across the Nation (chapter 4). Streamflows are modified by a variety of land- and water-management activities, including reservoirs, diversions, subsurface tile drains, groundwater withdrawals, wastewater inputs, and removal of vegetated land cover in the watershed.

Differences in streamflow modification are especially large between arid and wet climates. In wet climates, watershed management is often focused on flood control, which can result in depleted high flows and inflated low flows. In contrast, extremely low flows are a larger concern in arid climates, in part due to groundwater withdrawals and high water use for irrigation.

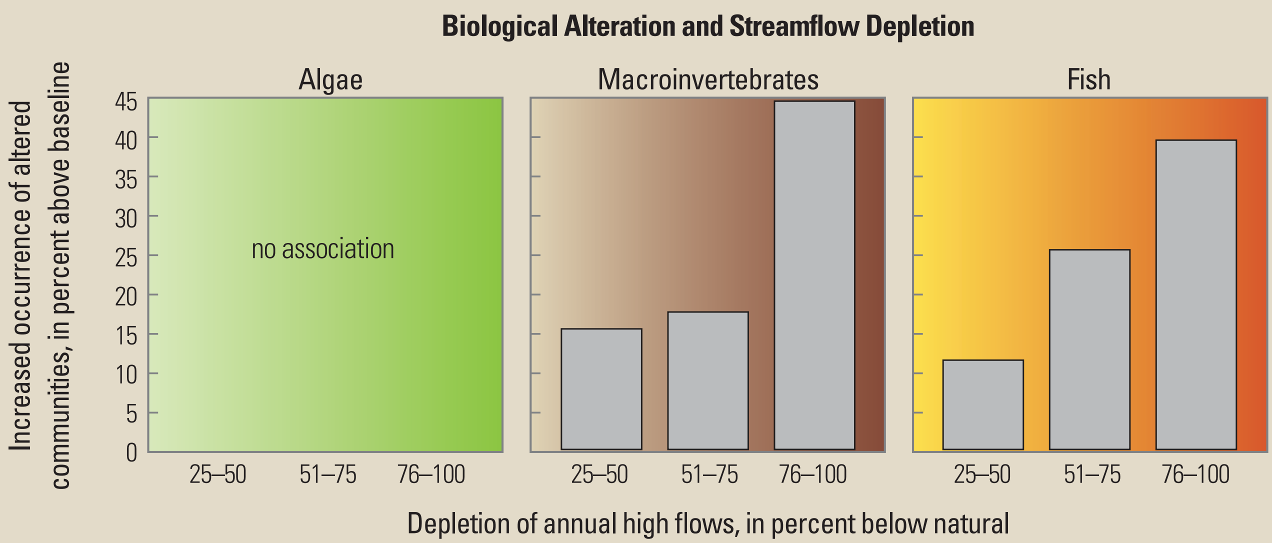


As shown in this diagram, annual high or low streamflows were modified in 86 percent of stream sites assessed across the Nation by NAWQA. Streamflow modification was depleted (less than), inflated (more than), or unaltered relative to expected natural magnitudes. Although high flows were depleted throughout the United States, low flows tended to be depleted in arid regions and inflated in wet regions. These results highlight the value of long-term streamflow data collected by the U.S. Geological Survey in cooperation with numerous local, State, and Federal partners.

Biological communities were more frequently altered in streams with modified flows (chapter 6). With increasing manmade depletion of annual high flows, the incidence of altered communities increased from 16 to 45 percent for macroinvertebrates and from 12 to 40 percent for fish. Similar patterns were observed for depletion of annual low flows. These associations between biological alteration and streamflow modification were evident even after controlling for the influence of other factors that affect biological communities such as nutrients, salinity, and land cover (Carlisle and others, 2011). Algal community condition, in contrast, was unrelated to streamflow modification.

Macroinvertebrate and fish communities were frequently altered as streamflow modification increased.

Understanding the relations between streamflow modification and biological condition is essential to make informed decisions about tradeoffs between water use and the maintenance of stream health (Postel and Richter, 2003; Poff and others, 2010). NAWQA findings provide a national-scale perspective on the importance of natural streamflow to the maintenance of biological communities and stream health and provide water managers a much-needed perspective on the pervasiveness and severity of streamflow modification.



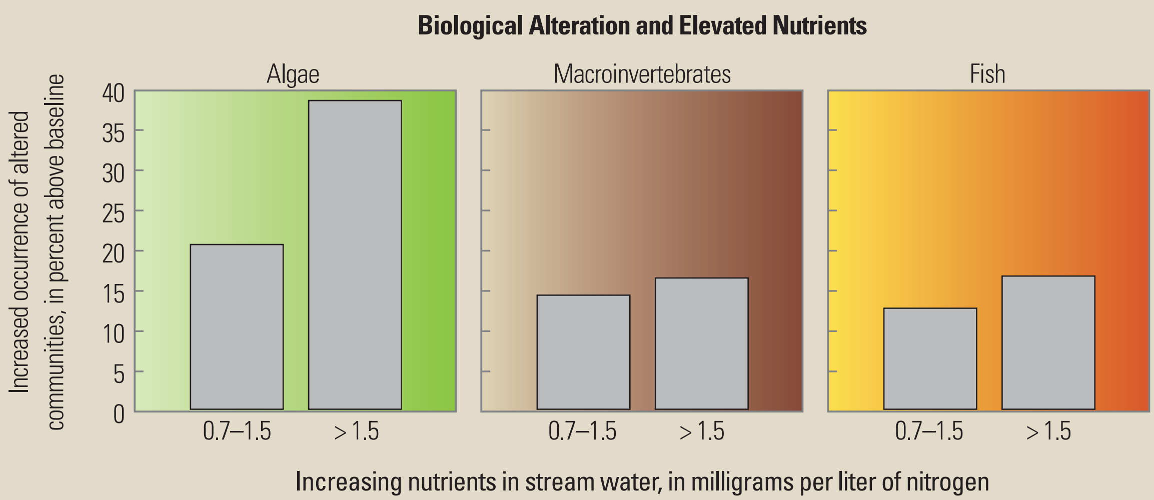
NAWQA studies found that macroinvertebrate and fish communities in the Nation's streams were more frequently altered in streams with increasingly severe flow depletion (bar graphs above). Algal community alteration was not related to flow depletion. Reservoirs, diversions, and other manmade changes to streams and their watersheds modify natural streamflows that are crucial to the life cycles of aquatic organisms. Baseline is the occurrence of altered communities in approximately 60 streams with annual high-flow depletion less than 25 percent.

Biological communities, particularly algae, were more frequently altered in streams with elevated nutrients.

Elevated Nutrients

Excess concentrations of nutrients are widespread in the Nation’s streams and rivers and are associated with altered biological communities (U.S. Environmental Protection Agency, 2006a). A national NAWQA assessment of nutrients (Dubrovsky and others, 2010) reported that concentrations of nitrogen and phosphorus—important plant nutrients—exceeded predicted natural levels in streams and rivers and in all types of land-use settings throughout the Nation. A variety of sources can contribute nutrients to streams, including wastewater and industrial discharges, fertilizer applications to agricultural and urban lands, and atmospheric deposition.

Biological communities, particularly algae, were more frequently altered in streams with elevated nutrients (chapter 6). With increasing nutrient concentrations in stream water, the incidence of altered biological communities increased from 21 to 39 percent for algae, from 15 to 17 percent for macroinvertebrates, and 13 to 17 percent for fish. Changes in biological alteration associated with nutrient levels were most pronounced for algal communities, likely because of the direct link between nutrient availability and algal growth and reproduction.



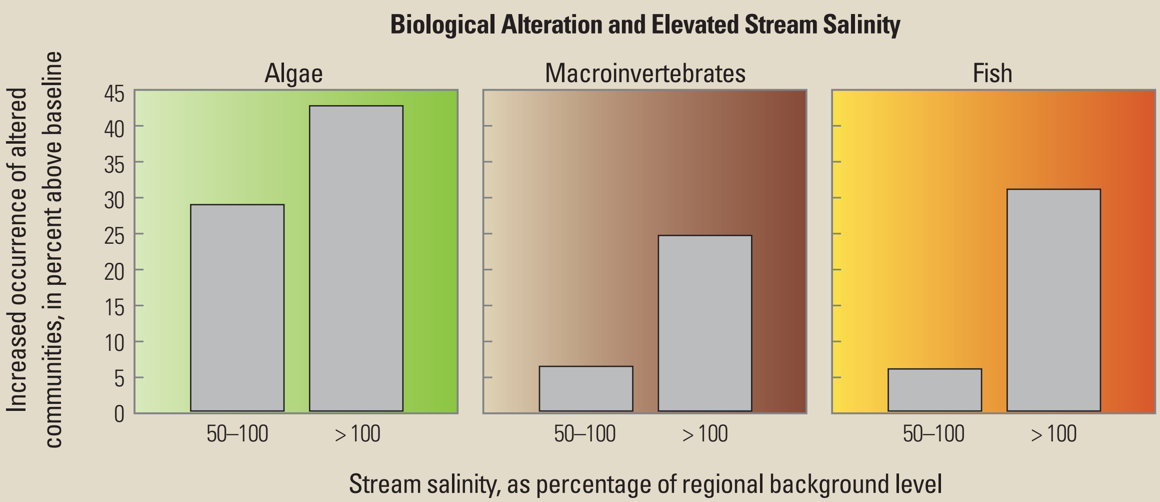
NAWQA studies found that biological communities, particularly algae, in the Nation’s streams were more frequently altered in streams with elevated levels of the nutrient nitrogen (bar graphs above). Algae that flourish in streams with excess nutrients can become prolific and consume the oxygen in water, often leading to the death of aquatic animals. Baseline is the occurrence of altered communities in approximately 400 streams with total nitrogen concentrations less than 0.7 milligram per liter. (>, greater than; 1 milligram per liter = 1 part per million.)

Elevated Salinity

Biological communities were more frequently altered in streams with increasingly elevated salinity relative to background levels.

Streams with elevated salinity occur in urban and agricultural land-use settings throughout the Nation (Mullaney and others, 2009). Elevated salinity in urban settings is most prevalent in northern States that receive relatively high snowfall, which suggests that road de-icing is a major salt source (chapter 4). Other sources of salinity in urban streams include wastewater effluent and faulty septic systems. Elevated salinity in agricultural streams occurs throughout the Nation. The largest sources of excess salinity in agricultural streams include fertilizer applications and irrigation wastewater (Mullaney and others, 2009).

Biological communities were more frequently altered in streams with increasingly elevated salinity levels (chapter 6). In streams with increasingly elevated salinity above regional background levels, the incidence of altered communities increased from 29 to 43 percent for algae, 7 to 25 percent for invertebrates, and 6 to 31 percent for fish. Excess salinity in stream water disrupts the balance of salts and fluids between the tissues of aquatic organisms and the surrounding water, which often leads to death and, ultimately, the loss of vulnerable species.



NAWQA studies found that algal, macroinvertebrate, and fish communities in the Nation's streams were more frequently altered in streams with increased salinity over natural background levels (bar graphs above). Land-use practices such as irrigation and road-salt application can lead to excess salinity in stream water, which disrupts the balance of salts and fluids in aquatic organisms, often leading to death. Baseline is the occurrence of altered communities in approximately 500 streams with salinity levels less than 50 percent of regional background levels. (>, greater than.)

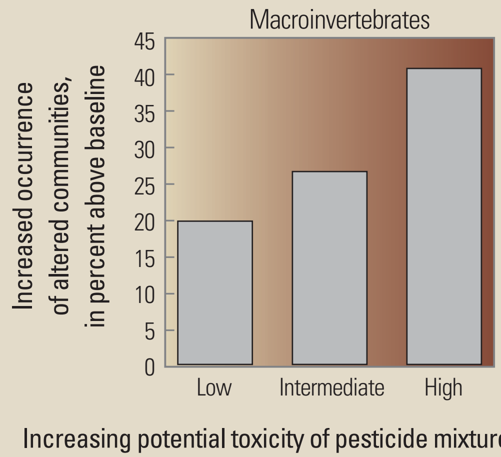
Macroinvertebrate communities were more frequently altered in streams containing pesticide mixtures with higher potential toxicity.

Contaminant Toxicity in Stream Water and Sediments

Across the Nation, contaminant mixtures in stream water and sediments contribute to diminished stream health. A national NAWQA assessment of pesticides (Gilliom and others, 2006) reported that dissolved pesticide concentrations were greater than benchmarks established for aquatic life by the U.S. Environmental Protection Agency in more than half of assessed streams in agricultural and urban settings and therefore have the potential to adversely affect aquatic organisms. Importantly, pesticides commonly occur as mixtures of multiple chemical compounds, rather than individually. As a consequence, aquatic organisms are typically exposed to complex mixtures of multiple compounds, and the total combined toxicity of these mixtures may be greater than that of any single compound present.

Macroinvertebrate communities were more frequently altered in streams with elevated concentrations—and potential toxicity—of pesticides (chapter 6). Specifically, the incidence of altered macroinvertebrate communities increased from 20 to 42 percent as the potential toxicity of pesticide mixtures increased. Insecticides commonly used in agricultural and urban areas (chlorpyrifos, carbaryl, and diazinon) were among the most frequently detected—and potentially toxic—pesticides in stream water and were associated with the alteration of macroinvertebrate communities across the Nation, even after controlling for other natural and manmade factors (chapter 6). These findings indicate that nationwide some of the reduction in stream health in agricultural and urban areas can be attributed to elevated levels of dissolved insecticides. Diazinon

Macroinvertebrate Community Alteration and Potential Toxicity of Pesticides



NAWQA studies found that macroinvertebrate communities in the Nation's streams were more frequently altered in streams with increasing levels of pesticides, as measured by the potential toxicity of pesticide mixtures (bar graph above). Insecticides, which are designed to kill insects, were the most frequently detected and potentially toxic pesticides and were found in stream water in agricultural and urban settings. Baseline is the occurrence of altered communities in 132 streams with no pesticide detections.

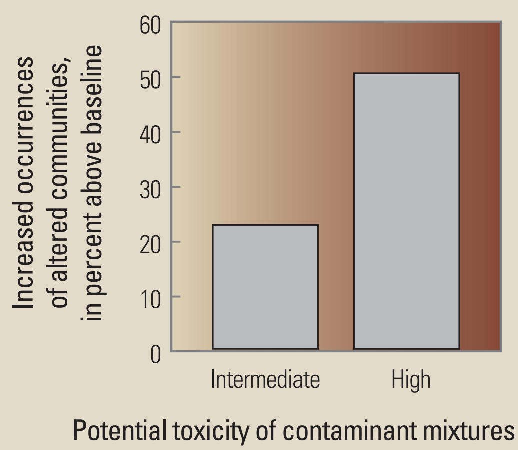
sales for residential use were phased out beginning in 2000, and it has since been replaced by other products.

Contaminants associated with streambed sediments also were frequently present at concentrations that may adversely affect stream health. A national NAWQA assessment of the occurrence and distribution of contaminants in streambed sediments reported that U.S. Environmental Protection Agency Aquatic-Life Benchmarks for pesticide compounds were exceeded at 70 percent of assessed streams in urban settings and 30 percent of streams in agricultural settings (Gilliom and others, 2006). As with dissolved pesticides, sediment contaminants generally occurred in complex mixtures of multiple compounds.

Macroinvertebrate communities were more frequently altered in streams with greater potential toxicity of sediment contaminant mixtures (chapter 6). Specifically, the incidence of altered macroinvertebrate communities increased from 23 to 51 percent as the potential toxicity of sediment contaminants increased. The sediment contaminant mixtures examined in this report include organochlorine pesticides such as dichlorodiphenyltrichloroethane (DDT), polycyclic aromatic hydrocarbons (PAHs) such as benzene, and trace metals such as mercury. In urban areas, high potential toxicity was mostly the result of elevated concentrations of PAHs, many of which are known to be highly toxic to aquatic life (Albers, 2003). In agricultural areas, high potential toxicity was largely the result of elevated concentrations of legacy organochlorine compounds, such as DDT. Collectively, these findings show evidence that elevated concentrations of dissolved pesticide mixtures in stream water and contaminant mixtures in stream sediments have a high potential to diminish stream health across the Nation.

Macroinvertebrate communities were more frequently altered in streams with greater potential toxicity of sediment contaminant mixtures.

Macroinvertebrate Community Alteration and Potential Toxicity of Sediment Contaminants



NAWQA studies found that macroinvertebrate communities in the Nation's streams were more frequently altered in streams with increasing concentrations and potential toxicity of contaminants in streambed sediments (bar graph above). Sediment-bound contaminants in streams typically include polycyclic aromatic hydrocarbons in urban settings and persistent pesticides in agricultural settings. Baseline is the occurrence of altered communities in 132 streams within the lowest category of potential toxicity.

Priorities for Filling Information Gaps for Understanding the Ecological Health of Streams

As present-day knowledge is brought to bear on decision making, there is a continuing need to improve the data and scientific understanding required for future decisions on the biological health of the Nation’s streams. Some of the most important steps needed to fill these information gaps are outlined below:

- **Reference sites—**Improve understanding of natural variability in physical, chemical, and biological characteristics at streams with minimal human influences. The ability to quantify manmade modifications requires an understanding of the natural variability in physical, chemical and biological characteristics of streams. An expanded network of reference sites, particularly in regions that have widespread landscape modification, will be necessary to improve understanding of natural variability.

- **Predicting baseline conditions—**Synthesize existing State and Federal monitoring data to develop models that predict expected baseline conditions of key physical and chemical factors in streams, such as salinity, sediment, and water temperature. Greater use of the water-quality data portal (http://waterqualitydata.us) would increase access to State and Federal monitoring data and enhance the ability to synthesize large amounts of data for model development.

- **Understanding multiple factors—**Improve assessment and understanding of the effects of the interactions of multiple manmade factors on biological communities. A major challenge to understanding why biological communities are altered is the ability to unravel the effects of many interacting natural and manmade factors. New studies are needed to specifically assess the interactions of multiple factors on stream health.

- **Tools for decision making—**Improve the availability of tools useful for decision making. Increased understanding of the ways in which land and water management modify key physical and chemical characteristics of streams—and in turn influence stream health—should be accompanied by decision-support tools that allow predictions of the effects of alternative management actions.

- **Long-term monitoring—**Sustain and expand long-term monitoring for trends in the ecological health of streams. Long-term, consistent data for assessing trends is essential for tracking biological responses to management practices, as well as to natural and human-influenced variation in climate.

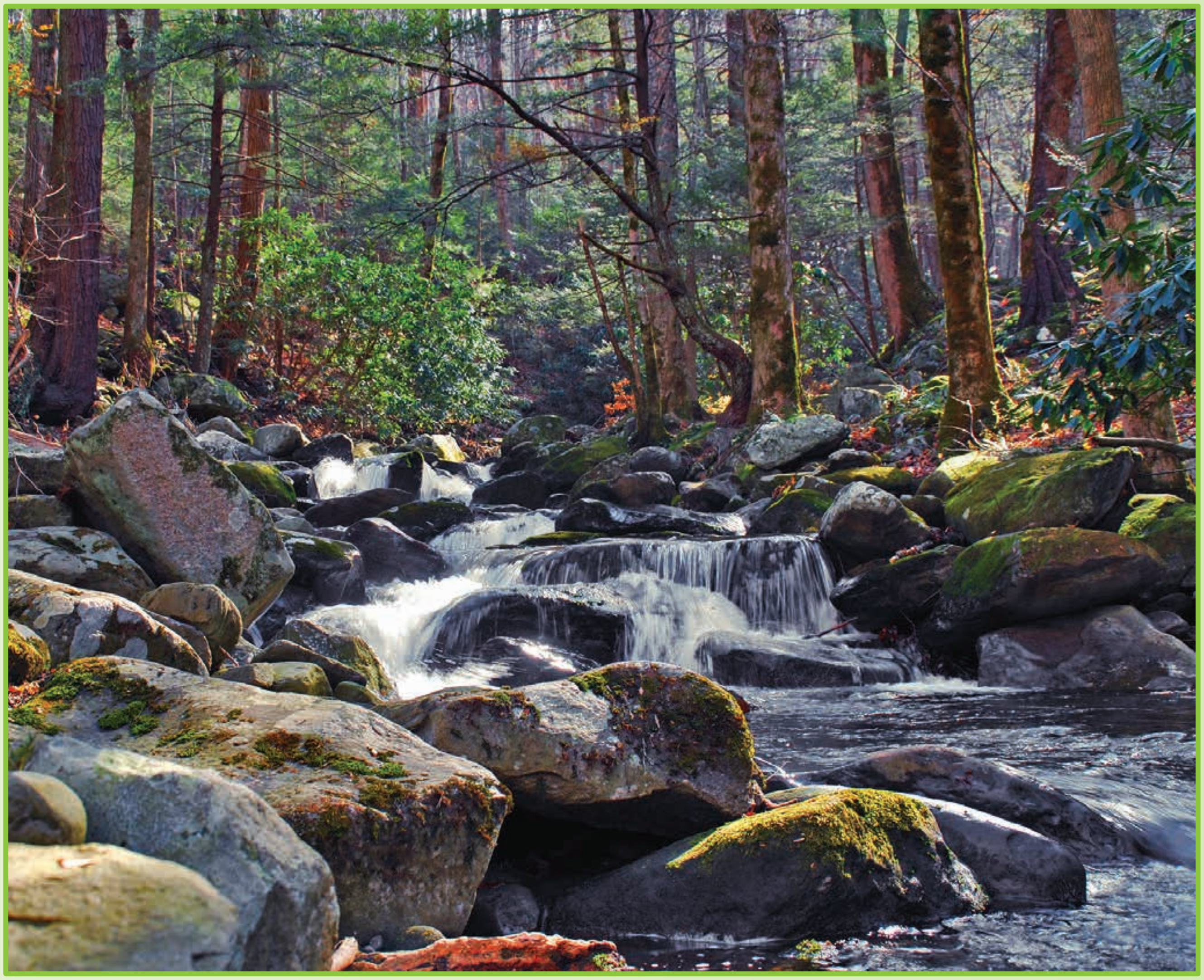
Society benefits in many ways from healthy streams and rivers, including recreational fishing, as shown in this photograph on the White River, Indiana.

U.S. Geological Survey photo by Joe Fenelon.

Chapter 2

Stream Ecology Primer

This chapter serves as a foundation for understanding important factors that can affect biological condition in streams—topics that are examined in subsequent chapters. Biological condition is a measure of the overall health of a stream ecosystem, defined as the degree to which the characteristics of biological communities differ from their natural state. The characteristics of biological communities can vary among different regions and environmental settings because of human activities, as well as natural factors related to hydrologic, climatic, and other watershed and stream properties.



U.S. Geological Survey photo by William Cannon.

Algal, macroinvertebrate, and fish communities provide unique and complementary information to assessments of biological condition.

Biological Communities and Water Quality

Historically, water quality in streams, lakes, and wetlands has been assessed using measures of the chemical or physical properties of water. However, a more comprehensive perspective is obtained if chemical and physical measures are integrated with assessments of resident biological communities. Guidelines to protect human health and aquatic life have been established for many physical and chemical properties of water and are useful yardsticks with which to assess water quality. Biological communities provide even more crucial information because they live within the aquatic environment and therefore integrate through time the effects of manmade changes to their surroundings. In addition, biological communities are a direct measure of the ability of a water body to support aquatic life and healthy ecosystems—which is a fundamental goal of water-quality management.

Living components of stream ecosystems include a complex and varied array of biological communities—from microscopic bacteria and algae to flowering plants, macroinvertebrates, fish, and other vertebrates. These groups of organisms interact with each other and with their ever-changing chemical and physical surroundings. Algae, macroinvertebrates, and fish are the biological communities most often evaluated in water-quality assessments by local, State, and Federal authorities. Each of these communities represents a different functional role in the ecosystem, responds in different ways to manmade environmental change, and thus provides different and complementary perspectives on water quality and stream health.

Because species within biological communities have different roles in ecosystems and widely varying traits, the most complete assessments of stream health make use of several communities, each offering complementary information. For example, algae are primary producers with short lifespans and therefore respond more rapidly than other communities to changes in chemical factors such as nutrient concentrations. Macroinvertebrates are commonly examined during water-quality assessments because they inhabit a specific stream for many months and therefore are good indicators of environmental conditions over relatively long periods of time. Fish offer advantages to those making assessments because they often migrate throughout a watershed and are therefore exposed to a wide array of environmental changes caused by human activities. In addition, many fish species are of economic importance as a food source or for recreation. Although any single biological community can provide information about water-quality conditions, assessments of two or more communities increases the potential to detect the scope of ecological change potentially caused by human activities.

Table showing the different roles of algae, macroinvertebrates, and fish in ecosystems and the traits that allow each to make a unique but complementary contribution to water-quality assessments.

Attributes	Algae	Macroinvertebrates	Fish
Primary roles in ecosystem	Primary producers; source of food for many species	Primary consumers of algae and other organic matter; source of food for many species	Primary consumers of macroinvertebrates and algae; source of food for aquatic and terrestrial species
Time scale	Lifespans of days to weeks; may respond rapidly to changes in environment	Lifespans of months to years; sensitive life stages respond quickly to environmental stress, but overall community responds more slowly	Lifespans of years; may take longer to respond to, or recover from, change
Spatial scale	Indicators of localized, site-specific conditions; organisms mostly sessile (attached to substrates)	Indicators of drainage-basin and stream-reach conditions; organisms range from mostly sessile to relatively mobile	Indicators of watershed and stream-network conditions; some are highly mobile
Sensitivity	Many species sensitive to nutrients, salinity, and other chemical factors	Sensitive to wide range of factors; may be specifically vulnerable to insecticides	Sensitive to changes in habitat such as hydrologic alteration, including manmade changes in streamflow
Societal relevance	Nuisance algal blooms, taste and odor effects on drinking water, and toxic species	Important food source for sport fisheries; high biodiversity	Economic and recreational importance

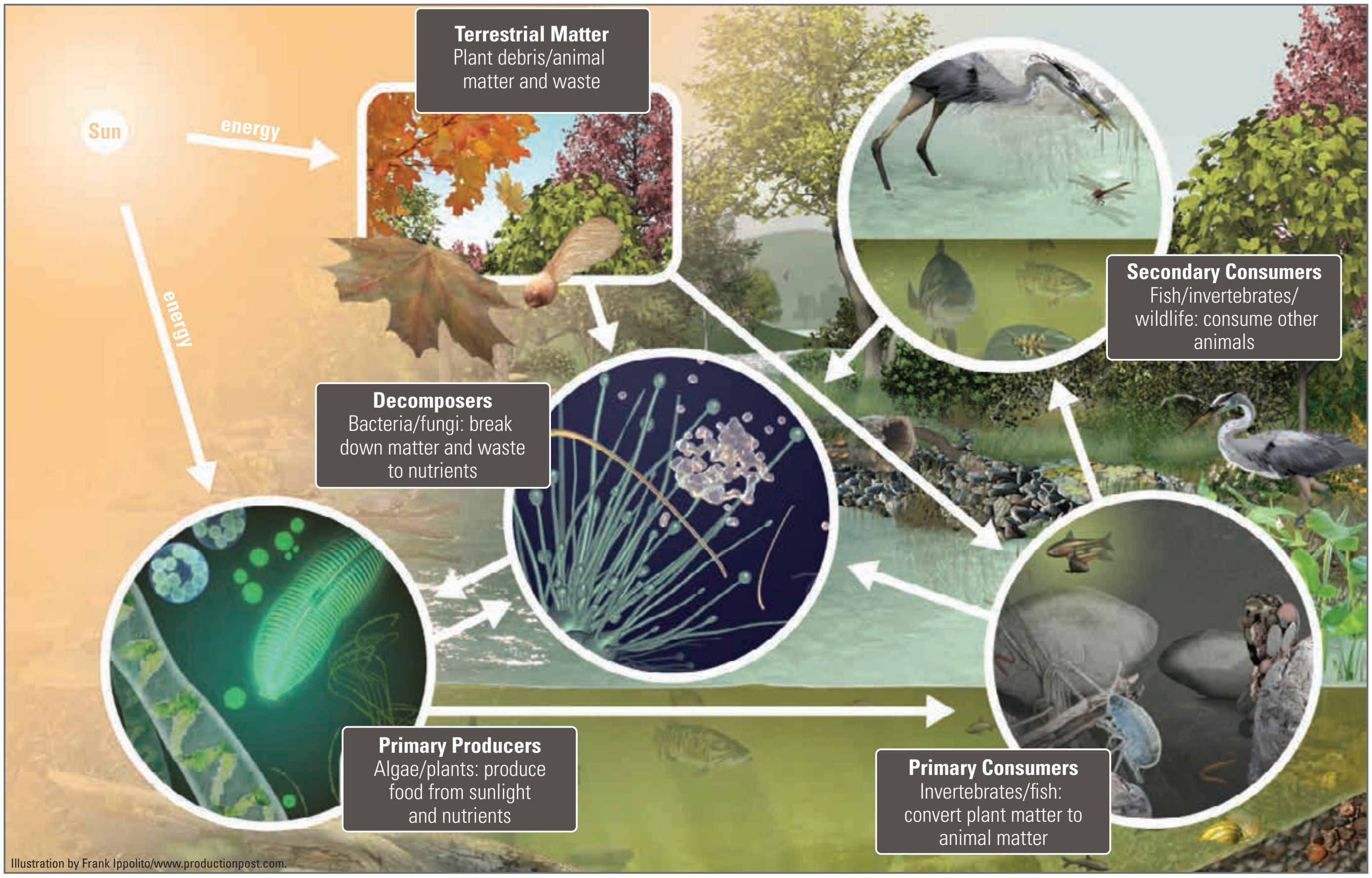


Illustration of a simplified food web in a stream ecosystem, showing the interrelations among major biological communities and their physical and chemical environment. Energy originating from sunlight and through photosynthesis in primary producers (such as algae and plants) becomes available to a wide variety of primary consumers such as insects, fish, and other animals. In turn, secondary consumers, such as fish and birds, prey on the primary consumers. Decomposers such as bacteria and fungi, are organisms that process and recycle dead and decaying organic material.

As the key living components of ecosystems, biological communities also provide an indication of ecosystem health, which is the ability of an ecosystem to support its full complement of native species and natural processes. Naturally functioning aquatic ecosystems support countless species—which adds to the Nation's biological diversity—and provide a wealth of services to society, including water purification, flood control, nutrient recycling, waste decomposition, fisheries, and aesthetics. The value to society of many of these benefits is substantial; for example, sportfishing in the United States generates an estimated annual economic output of $125 billion, including more than 1 million jobs (National Research Council, 2005; American Sportfishing Association, 2008). Another example is the maintenance of pure drinking water for the more than 8 million residents of New York City. The city invested in a long-term comprehensive watershed protection program that uses corrective and protective initiatives to ensure that watersheds and stream ecosystems retain their ability to provide high-quality water (http://www.nyc.gov/html/dep/html/watershed_protection/about.shtml, accessed January 11, 2013), which was ultimately billions of dollars less expensive than the construction and maintenance of water-purification facilities (Chichilnisky and Heal, 1998).

A stream is considered healthy if it is capable of supporting its full complement of native species and natural processes.

Algae respond rapidly to changes in water quality because of their short lifespans.

Algae

Algae are plant-like, photosynthetic aquatic organisms that range in size from single cells to giant kelps. Algal communities in rivers and streams are generally attached to hard surfaces, such as rocks and twigs, as well as to fine-grained sediments such as sand and silt. Algae are also an important food source for many aquatic organisms. Often the most abundant and diverse algal group in streams is diatoms, which are single-celled algae with elaborate silicon skeletons (see sidebar below). In general, algal populations in streams respond rapidly to changes in the environment because of their short (for example, days to weeks) lifespans and fast growth rate. As a result, algae (and diatoms in particular) are often used in biological condition assessments because they are found in streams of all sizes and are widespread.

Under certain environmental conditions, algal populations can become extremely dense. When these dense growths die and decompose, they reduce the dissolved oxygen levels in water, leading to suffocation of fish and other aquatic organisms. Some algae (cyanobacteria; sometimes called blue-green algae) produce chemicals that can cause taste-and-odor problems in drinking water, even though the organisms themselves can be removed in water-treatment processes. Some algae therefore increase the cost of water treatment or limit recreational activities.

U.S. Geological Survey photo by Nara Souza.

Under certain environmental conditions, the abundance of some species of algae, such as shown by the bands of green scum on the pond in this photograph, can reach nuisance levels that interfere with recreational, industrial, and other uses of streams and rivers.

Diatoms

Diatoms (photo at right) are a group of mostly single-celled, microscopic algae that have elaborate silica (glass) skeletons and are found in streams, rivers, lakes, and oceans. There are an estimated 100,000 living species of diatoms throughout the world. Diatoms are often the most abundant and diverse types of algae in streams and rivers.

Diatoms are photosynthetic and provide an important food source for aquatic animals such as invertebrates and fish in streams. They are therefore an important foundation of the aquatic food web. Diatoms are easily collected, and many species respond quickly and predictably to changes in water chemistry, which makes diatoms useful in water-quality assessments.

Photo from Archives of the Academy of Natural Sciences.

Macroinvertebrates

Macroinvertebrates are animals without backbones that can be seen with the unaided eye and include insects, mollusks (such as snails and clams), worms, and crustaceans (such as crabs, shrimp, and crayfish). In contrast to algae, macroinvertebrates have longer lifespans, ranging from months to years. Most macroinvertebrate species in streams are immature stages of insects that spend most of their lives in the aquatic environment and a relatively short period as terrestrial adults (see sidebar below).

Macroinvertebrates are found in a wide variety of stream habitats but primarily inhabit benthic (stream bottom) substrates such as rocks and woody debris. Macroinvertebrates are important consumers of algae (see above) and terrestrial plant material that falls into streams—especially that from seasonal leaf fall in temperate climates. Many macroinvertebrates also prey on other species, and many are an important food source for waterfowl, amphibians, and fish.

Some macroinvertebrate species can negatively affect natural ecosystems, particularly when introduced into waterways outside their native ranges or when they become unnaturally abundant in human-modified environments. For example, after colonizing the Great Lakes, populations of the zebra mussel *(Dreissena polymorpha)*—which is native to central Asia—rapidly expanded into other streams and rivers.

National Oceanic and Atmospheric Administration photo.

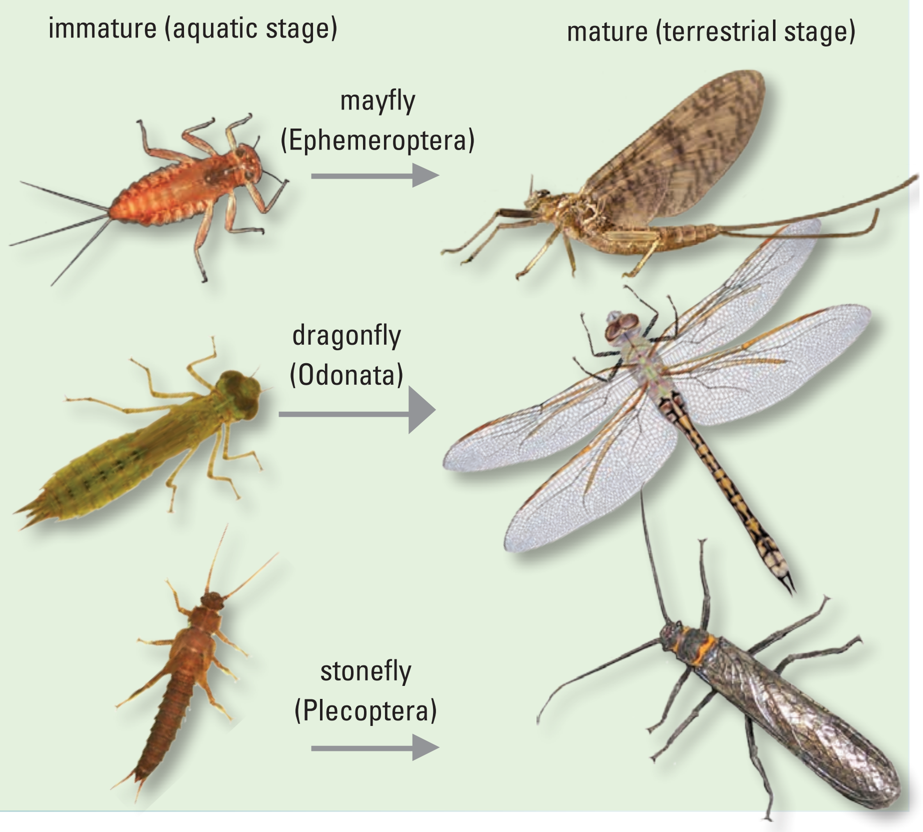
Zebra mussels attach themselves to any stable structure, as shown in this photograph. In some cases, population densities become so dense that all submerged objects are completely covered—hindering operations of water intakes, dams, and shipping.

Macroinvertebrates are sensitive indicators of changes in water quality and habitat.

Aquatic Insects

More than 90 percent of the Earth's species are invertebrates—meaning they lack backbones. The immature stages of insects are generally the most diverse group of macroinvertebrates in rivers and streams, with more than 5,000 species known in North America. Aquatic insects spend most of their lives within the stream, usually in an area of just a few square yards, then emerge from the aquatic environment and live a few days as winged terrestrial adults, as shown for mayflies, dragonflies, and stoneflies.

Aquatic macroinvertebrates are easily sampled and identified and possess a wide range of tolerances to environmental changes. Consequently, they are the most commonly used biological community in water-quality assessments.



Fish are indicative of water quality across river networks because of their long lifespans and mobility.

Fish

Fish occupy many roles in stream ecosystems. Some species are predators that eat macroinvertebrates and other fish; other species are herbivores; others feed by filtering small organisms or plant material from stream bottoms. Fish also are an important food source for wildlife, as well as for humans, and support substantial economic activity related to sport fishing. Fish communities in some geographic areas are rich in species diversity, such as in the Southeastern United States (see sidebar below), whereas the Western United States has very few native species.

Relative to macroinvertebrates and algae, fish have longer lifespans (years), and some species can migrate long distances throughout river networks. Whereas algae and macroinvertebrates are found in streams of almost any size, fish may be naturally absent from some small streams, where habitat and food resources are limited.

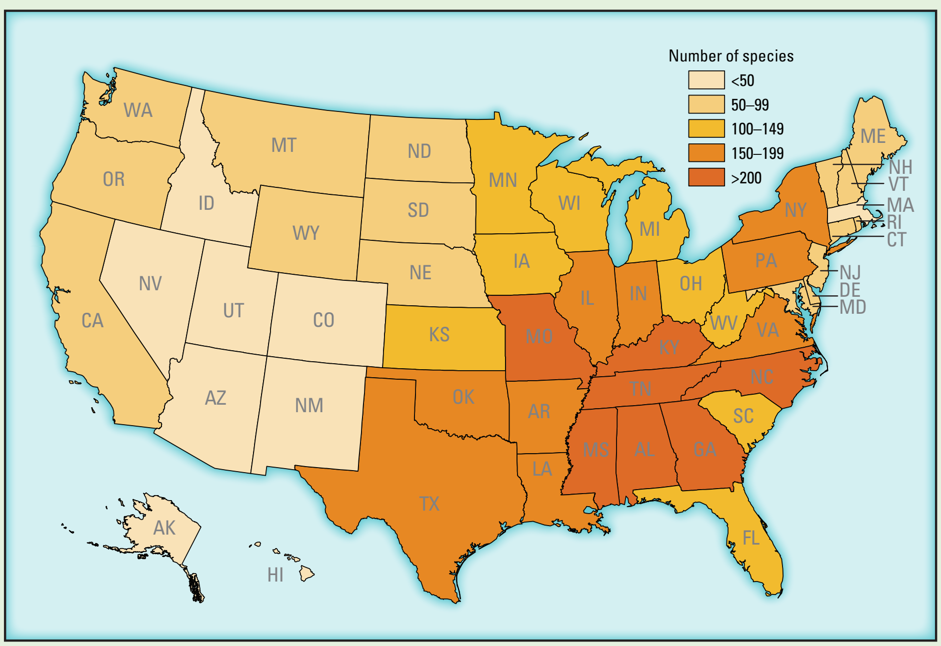
Unlike algae and macroinvertebrates, the populations of many fish species are actively managed. In fact, many species have been actively or accidentally moved to waters outside their native range, becoming invasive to resident fish communities.

Photo from asiancarp.org.

Asian carp, such as the one in this photograph, escaped from fish farms in the 1990s, spread throughout the Mississippi River, and now threaten the Great Lakes. "Asian carp" is used to refer to several species of carp (Cyprinidae) originally native to Asia; these fish are prolific and compete with native fish for food and habitat.

Fish Species Diversity

Fish are the most diverse group of vertebrates, with more than 31,000 species described throughout the world. More than 1,000 fish species are native to North America, and the Southeastern United States supports the most species (see map). Many fish species have extremely limited geographic distributions, and others have specific habitat requirements for survival and reproduction and are therefore important sentinels of manmade environmental changes. Indeed, recent estimates (Jelks and others, 2008) show that the number of imperiled North American fish species has increased from 219 to 539 since the 1980s.

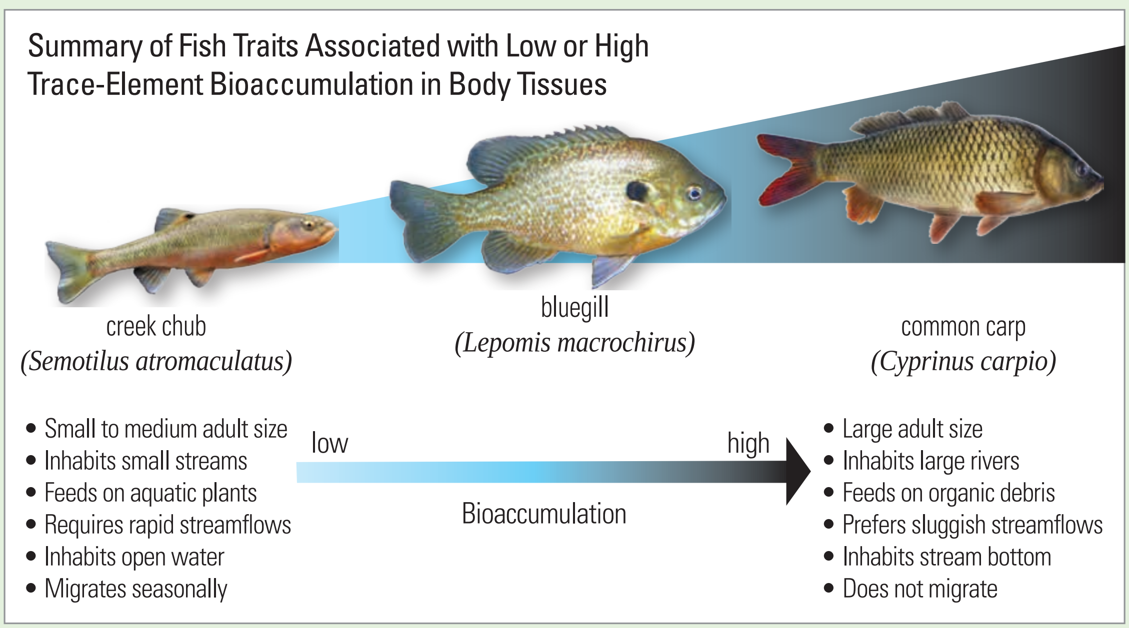


As this map shows, the natural diversity of fish species varies greatly across the United States, being lowest in the interior West and highest in the Southeast. Low species diversity in the West is thought to be a result of limited aquatic habitat in arid environments. (<, less than; >, greater than. States are identified by U.S. Postal Service abbreviations. Alaska and Hawaiʻi not shown to scale.)

Species Traits Influence Exposure to Chemical Contaminants

Biologists often catalogue facts on plant and animal species, organizing their traits into categories including physical appearance, habitat, behavior, and food requirements. A species' response to changes in its environment depends in large part on its traits, which influence where it can survive, grow, and successfully reproduce. Manmade changes to the environment eliminate only species that are most sensitive to those changes, whereas tolerant species may thrive. Changes in the relative abundance of different species in a community therefore provide important clues of the well-being of the ecosystem.

A species' traits also influence its exposure to chemical contaminants. Aside from the physical properties of chemical contaminants and their concentrations in the environment, an organism's exposure to contaminants depends largely on its habitat, living habits, food preferences, and other traits. This principle is illustrated in a NAWQA study evaluating the relation among the traits of fish species and the bioaccumulation of trace elements in their body tissues (Short and others, 2008). The accumulation of trace elements in body tissues varied among fish species largely due to differences in their traits. Specific trait characteristics were identified that were least and most strongly associated with trace-element bioaccumulation. For example, fish species that attain large adult body size typically had greater trace-element bioaccumulation than small-bodied species. One explanation for this pattern is that large-bodied species are typically longer lived than smaller size species (Wooton, 1998) and therefore have a longer lifetime exposure to environmental contaminants.



Streams and rivers typically undergo noticeable natural changes from headwaters to mouth.

Environmental Factors that Influence Stream Biological Communities

The abundance and types of species in streams are influenced by many factors, including streamflow, water and sediment chemistry, and physical habitats. Many of these factors are influenced by the properties of the watershed, a geographic area where rainfall and (or) snowmelt drain into a common body of water. Most of these factors change naturally from a river's headwaters to its mouth; this continuum of change influences the numbers and types of species present in biological communities, as well as the ecological processes that these species control. In addition, these factors vary naturally among geographic regions (see sidebar on opposite page). Land- and water-management practices in a watershed can modify these factors outside their natural ranges or to levels that affect the growth, survival, and reproduction of individual species. The fundamental principles of these changes are described on this page and shown later in this chapter in the two-page sidebar "Natural River/Altered River."

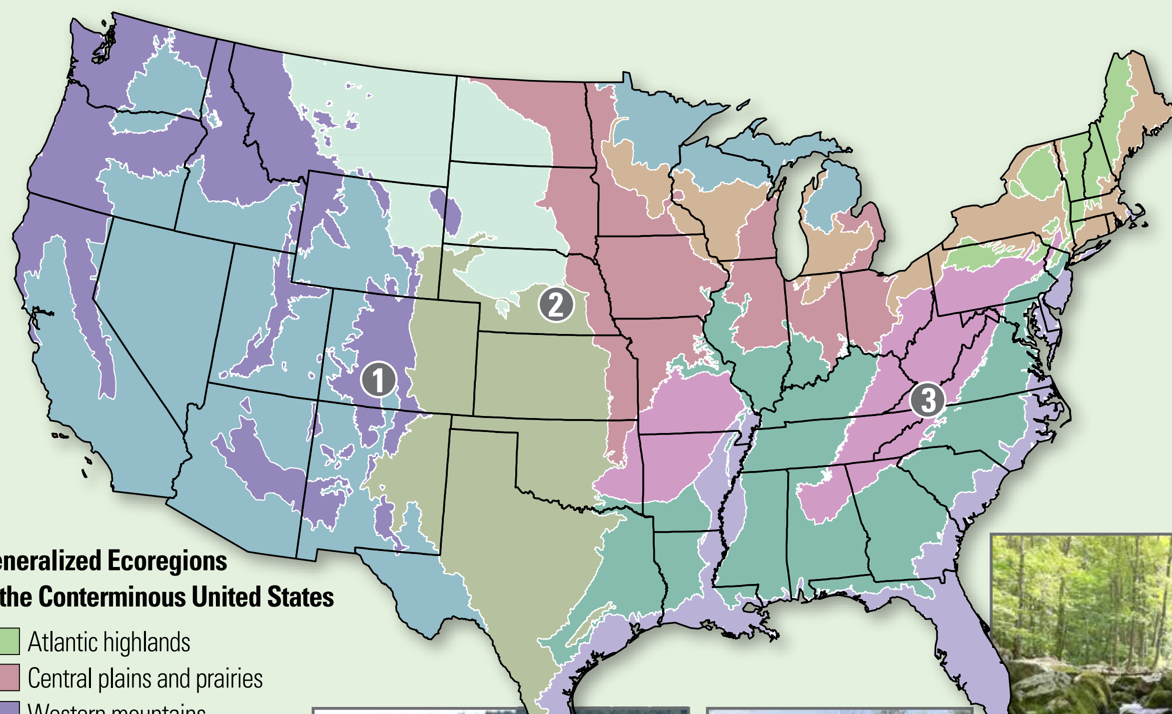
Streams and rivers typically undergo noticeable natural changes from headwaters to their mouths (see Natural River). Headwater streams are typically small and shaded by streamside vegetation, which influences water temperature and other physical characteristics. Food webs in headwater streams are often supported by decaying organic matter rather than through direct sunlight. As streams increase in size they become wider, more open to sunlight, and slower moving. In addition, suspended particles in the water column prevent sunlight from reaching the streambed. Slow currents enable free-living algae to thrive; these algae, together with imported organic materials from upstream, are the base of the food web.

Land and water use in watersheds are often superimposed on the natural changes in streams and rivers (see Altered River). Water temperatures and sunlight increase in headwater streams that are influenced by land management—such as logging—that removes trees and shrubs from the hillslopes and along stream channels. Agricultural or urban land uses can influence the hydrology, chemistry, and physical habitat of streams. Water-management strategies such as diversions and storage reservoirs, which often are used on mid-sized rivers, can dramatically alter the hydrologic characteristics and consequently the biological communities both upstream and downstream. Large-scale industrial activities that typically occur on large rivers can alter the water and sediment chemistry and physical habitat. In addition, the physical and chemical factors of large rivers can be influenced by the cumulative effects of human activities far upstream and throughout the watershed.

Streams Differ Across the Nation due to Natural Variation in Environmental Settings

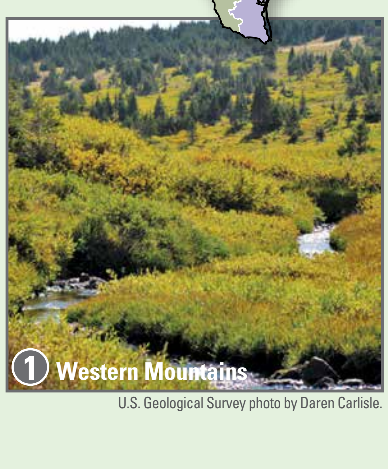
Differences in environmental settings (sometimes referred to as ecoregions; see map below), including geology, soils, topography, and climate, lead to natural geographic changes in the chemical and physical factors of streams. For example, headwater streams in mountainous areas are typically cold, fast flowing, and highly dilute—that is, have extremely low concentrations of chemical substances. In contrast, headwater streams in the Central Plains are typically warm, slow flowing, and contain high concentrations of natural substances such as nutrients or dissolved organic matter.

Natural variation in the chemical and physical characteristics of streams and rivers influences the abundance of aquatic species and must therefore be considered in all biological assessments, whether they are local, regional, or national in scale. It is impossible to attribute changes in biological communities to manmade factors without adjusting for the variation in biological communities caused by natural factors. A variety of design considerations and analysis tools are used in biological assessments to account for natural variability. For example, statistical models use the climatic, topographic, and geographic characteristics of a stream to predict the assemblage of species that are expected to occur if the stream were undisturbed by human activities (chapter 3). Understanding the natural variability in streams requires the sampling of physical, chemical, and biological characteristics of a relatively large number of least-disturbed or reference sites (chapter 3).



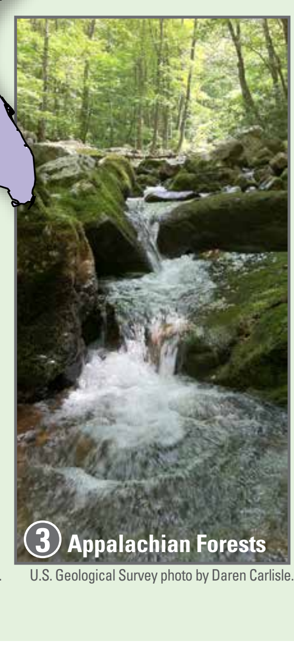
Generalized Ecoregions of the Conterminous United States

- Atlantic highlands
- Central plains and prairies
- Western mountains
- Mississippi alluvial and Southeast coastal plains
- Mixed wood plains
- Mixed wood shield
- Ozark-Appalachian forests
- South-central semiarid prairies
- Southeastern plains
- Mediterranean California and Western desert
- Temperate and west-central semiarid prairies

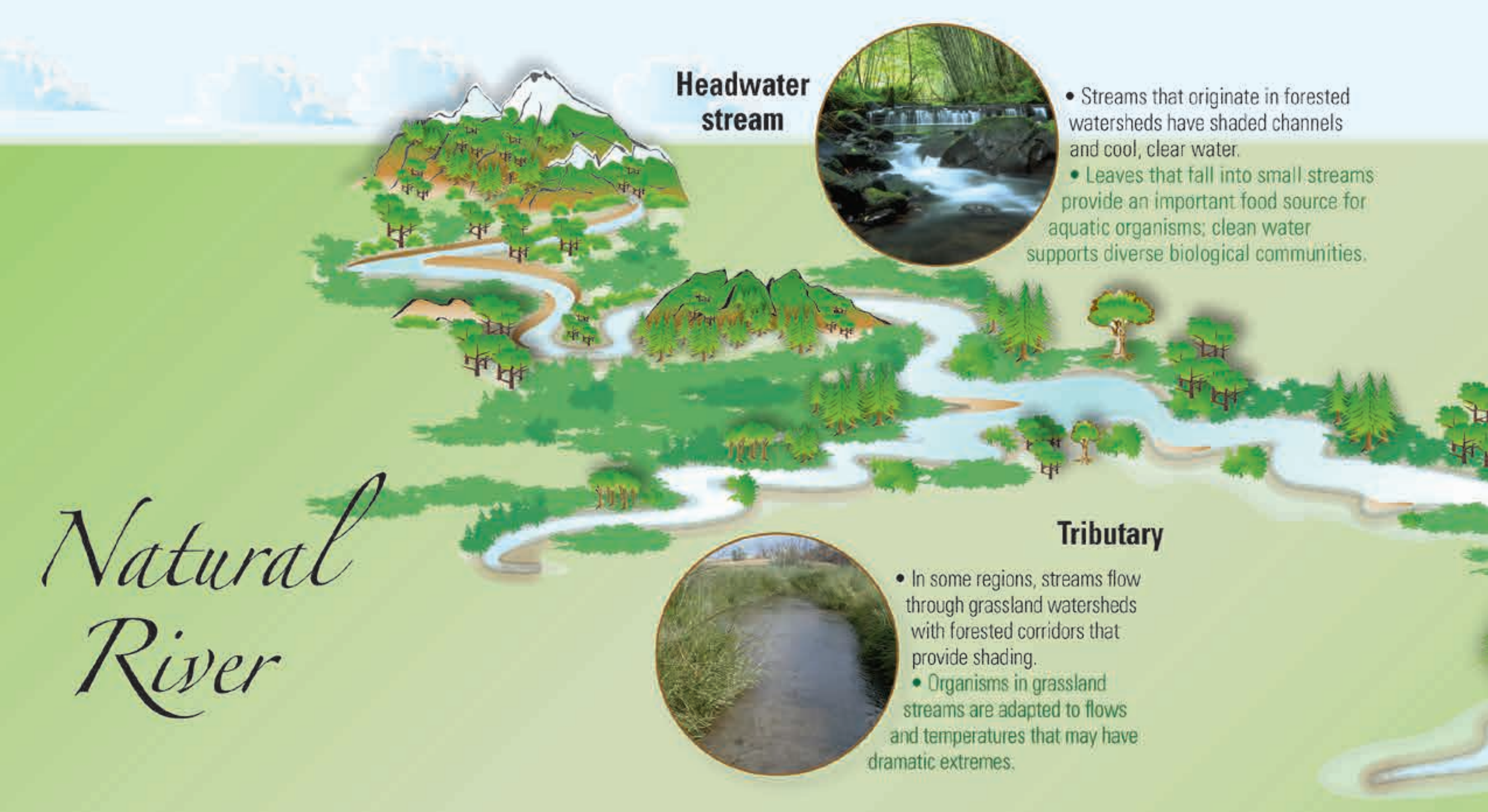


U.S. Geological Survey photo by Daren Carlisle.

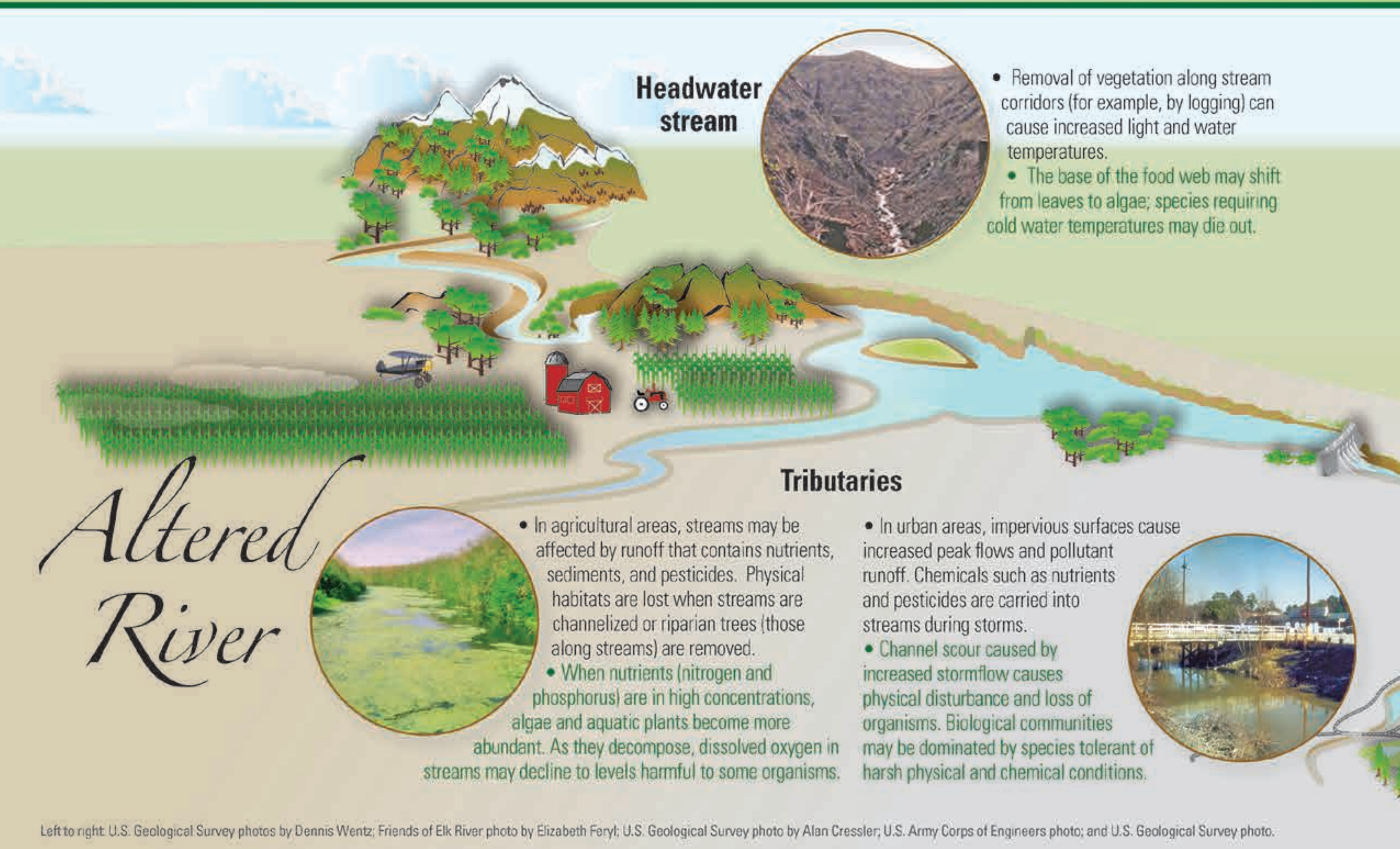
Central Plains Center for Bioassessment photo.



U.S. Geological Survey photo by Daren Carlisle.



Left to right: Central Plains Center for BioAssessment photo; U.S. Geological Survey photo by Dennis Wentz; photo reprinted from Stanford and others (2005), used with permission; and National Park Service photo.



Left to right: U.S. Geological Survey photos by Dennis Wentz; Friends of Elk River photo by Elizabeth Feryl; U.S. Geological Survey photo by Alan Cressler; U.S. Army Corps of Engineers photo; and U.S. Geological Survey photo.

Mid-sized river

- As streams get larger in size, the influence of riparian trees (those along streams) decreases, water velocities decline, and the stream bottom has larger amounts of fine sediments.
- Photosynthetic organisms, such as algae and aquatic plants, become more abundant in response to increased light reaching the stream bottom; aquatic animals that rely on these food sources also increase in abundance.

Large river

- Large rivers often support highly varied habitats such as sandbars, islands, and backwaters and have broad floodplains that are nourished by periodic flooding.
- Many species rely on floodplain habitats for reproduction; algae and organic particles from upstream form the base of the food web.

Mid-sized river

- Dams modify the timing, magnitude, and frequency of high and low flows. Flows can also be reduced by diversions or withdrawals for domestic or agricultural water use.
- Changes to natural flow patterns affect survival and reproductive success of aquatic species whose migration or reproduction are tied to specific streamflow cues. Reduced flooding "starves" the river and floodplain of sediment and woody debris.

Large river

- Water quality in large rivers is influenced by the cumulative effects of human activities nearby, such as channelization, as well as the impacts of land use and water management upstream throughout the watershed.
- Aquatic communities are often dominated by non-native species that thrive in artificial channels or modified environments, such as reservoirs.

Environmental Factors Influenced by Agriculture and Urban Land Use

In addition to natural variation, many hydrological, chemical, and physical factors in streams are influenced by land- and water-use activities in watersheds. The effects of land and water management on stream ecosystems are briefly described below and illustrated at left. More detail is given later in this chapter in three two-page sidebars—Dynamics of a Natural Stream Ecosystem, Dynamics of an Agricultural Stream Ecosystem, and Dynamics of an Urban Stream Ecosystem.

Natural Stream Ecosystem

Agricultural Stream Ecosystem

Urban Stream Ecosystem

Illustrations by Frank Ippolito/www.productionpost.com.

Hydrology

The natural timing, variability, and magnitudes of streamflow influence many of the key physical, chemical, and biological characteristics and processes of streams (Natural Stream). For example, recurring high flows from seasonal rainfall or snowmelt shape the basic structure of a river and its physical habitats, which in turn influences the types of aquatic organisms that can thrive. For many aquatic organisms, low flows impose basic constraints on the availability and suitability of habitat, such as the amount of the stream bottom that is actually submerged. The life cycles of many aquatic organisms are highly synchronized with the variation and timing of natural streamflows. For example, the reproductive period of some species is triggered by the onset of spring runoff.

Human activities that change the natural flow regime of streams and rivers include (1) withdrawals of water for public supply, industrial uses, and thermoelectric power and (2) dams and reservoirs for flood control, water storage (sometimes involving transfers between basins), hydropower, and navigation. In agricultural areas (Agricultural Stream), tile drains, used to drain subsurface water, route seepage directly to the stream channel rather than allowing gradual infiltration through soils. Water withdrawal for irrigation and channelization can also change the natural flow regime. In urban areas (Urban Stream) impervious surfaces, such as pavement, lead to increased storm runoff and higher and more variable peak streamflows, which scour the streambed and degrade the stream channel; reduced infiltration to groundwater may also lead to diminished streamflows during dry periods when groundwater is the main source of streamflow.

Water Chemistry

The unique water chemistry requirements and tolerances of aquatic species help to define their natural abundance in a given stream, as well as their geographic distribution. Many naturally occurring chemical substances in streams and rivers are necessary for normal growth, development, and reproduction of biological communities (Natural Stream). For example, sufficient dissolved oxygen in water is necessary for normal respiration. Dissolved oxygen concentrations in streams and rivers is determined, in part, by physical aeration processes that are influenced by the slope and depth of the stream, as well as the water temperature. Similarly, small amounts of nutrients (nitrogen, phosphorus, and silica) and trace elements dissolved from the weathering of soils and rocks and from the atmosphere are necessary for normal growth of aquatic plants.

Human activities often contribute additional amounts of these naturally occurring substances, as well as other synthetic (manmade) chemicals to streams from point and nonpoint sources. Runoff from agricultural lands (Agricultural Stream) may contain (1) sediment from soil erosion on tilled lands; (2) nutrients from the application of fertilizer and manure; (3) chloride and other salts from irrigation return flows; (4) pesticides used in the past and present to control insects, weeds, rodents, bacteria, or other unwanted organisms; and (5) other synthetic compounds used for varying purposes along with their degradates. Runoff from urban lands (Urban Stream) may contain (1) sediment from construction activities; (2) nutrients and pesticides applied to lawns and recreational areas; and (3) petroleum compounds, trace metals, and de-icing salts from roads and parking lots. Point sources include municipal and industrial wastewater effluent that, depending on the sources of wastewater and level of treatment, may contain different amounts of nutrients and other contaminants.

Physical Habitat

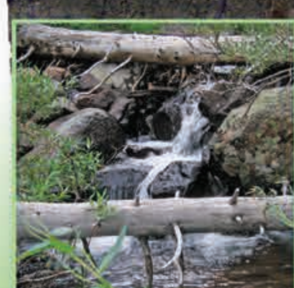
Physical habitat includes factors such as streambed substrates, water temperature, and large debris from streamside vegetation. Streambed substrates include the rocks, sediments, and submerged woody material in a stream (Natural Stream). Streambed sediments may range in size and composition from large rocks to sand and silt that reflect the local geology. These substrates are important because they provide living space for many stream organisms. Stable substrates, such as cobbles and boulders, protect organisms from being washed downstream during high flows and, thus, generally support greater biological diversity than do less stable substrates, such as sand and silt. Water temperature is crucial to aquatic organisms because it directly influences their metabolism, respiration, feeding rate, growth, and reproduction. Most aquatic species have an optimal temperature range for growth and reproduction. Thus, their natural spatial and temporal distributions are largely determined by regional differences in climate and elevation along with more local effects from riparian (stream corridor) shading and groundwater influence. Water temperature also influences many chemical processes, such as the solubility of oxygen in water. The riparian zone is the land adjacent to the stream inhabited by plant and animal communities that rely on periodic or continual nourishment from the stream. The size and character of riparian zones are important to biological communities because these have a major influence on the amount of shelter and food available to aquatic organisms and the amount of sunlight reaching the stream through the tree canopy, which influences water temperature and the amount of energy available for photosynthesis. Riparian zones also influence the amount and quality of runoff that reaches the stream.

Land uses that affect streamflow, sediment availability, or riparian vegetation can alter physical habitats in streams. Some agricultural practices (Agricultural Stream), such as conventional tillage near streambanks and drainage modifications, lead to increased sediment erosion, channelization, or removal of riparian vegetation. Increased sediment from erosion can fill crevices between rocks, which reduces living space for many stream organisms. As watersheds urbanize (Urban Stream), some segments of streams are cleared, ditched, and straightened to facilitate drainage and the movement of floodwaters. These modifications increase stream velocity during storms, which can transport large amounts of sediment, scour stream channels, and remove woody debris and other natural structures that provide habitats for stream organisms. In addition, culverts and ditches can be barriers to aquatic organisms that need to migrate throughout the stream network. Humans can alter natural stream temperature through changes in the amount and density of the canopy provided by riparian trees. In some extreme cases, streams through urban areas are routed through conduits and completely buried.

Dynamics of

Hydrology: Water connects the watershed to the stream. In an undisturbed ecosystem, precipitation (rain and snow) reaches a stream gradually by flowing over the vegetated land surface into the stream and by infiltrating the soil and flowing underground (as groundwater) toward the stream. Natural seasonal patterns of streamflow serve as life-cycle cues to aquatic organisms.

Water chemistry: Nutrients such as nitrogen, phosphorus, and carbon are required for all stream life. Nutrients are incorporated into algae that are then consumed by other organisms, introducing the nutrients into the stream's food web. Oxygen dissolved in water is essential for most aquatic organisms because they respire through their skin or gills.



Physical habitat: The physical living space of aquatic organisms includes the water in the stream—whether in pools or faster flowing riffles—as well as the rocks and sediment in the stream bottom and along the banks, submerged leaves and wood, and aquatic plants. A stream with more diverse physical habitats will generally have more diverse kinds of organisms.

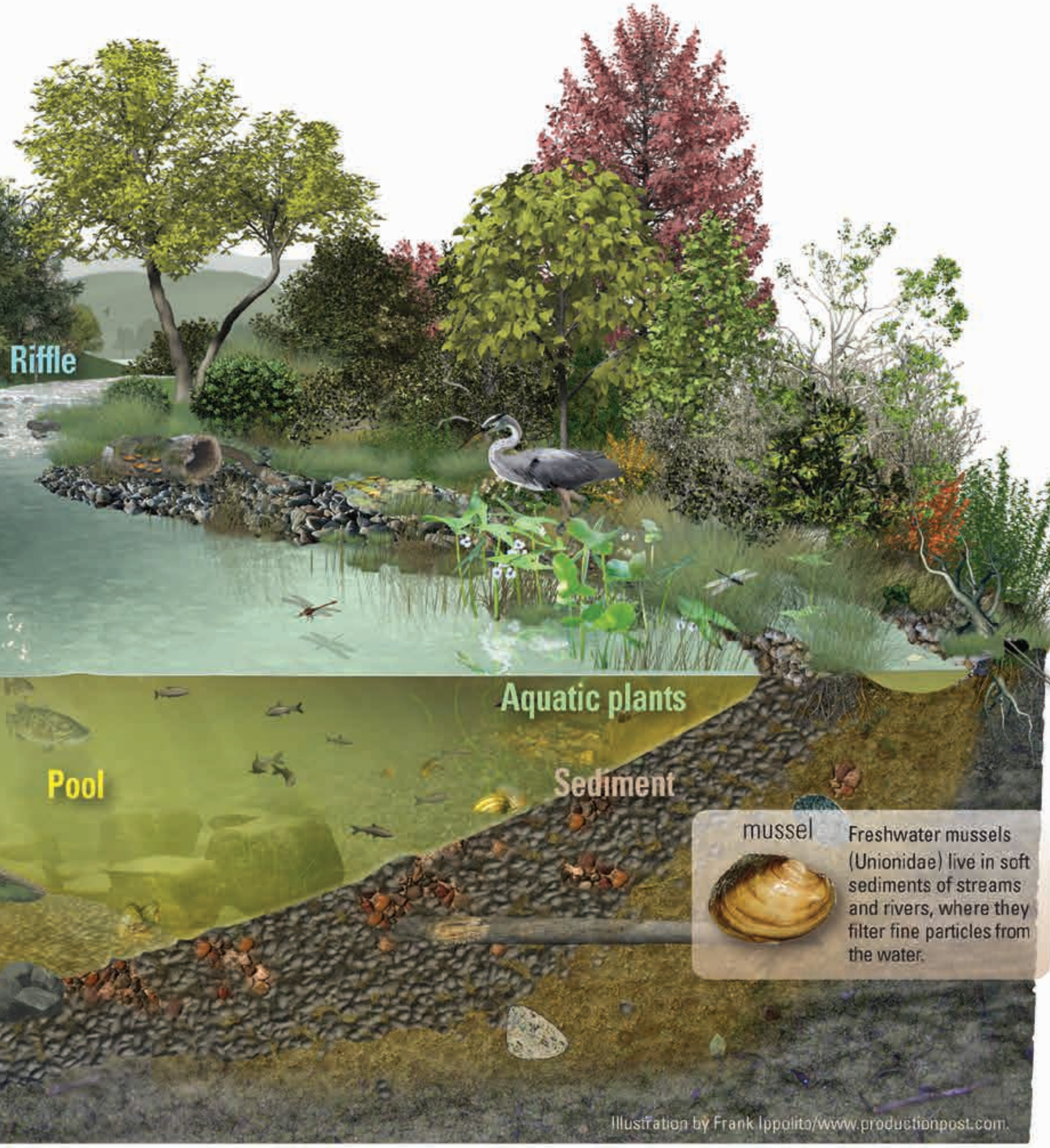
smallmouth bass

greenside darter

U.S. Geological Survey photos by Daren Carlisle.

a Natural Stream Ecosystem

Healthy stream ecosystems support diverse communities of aquatic organisms.



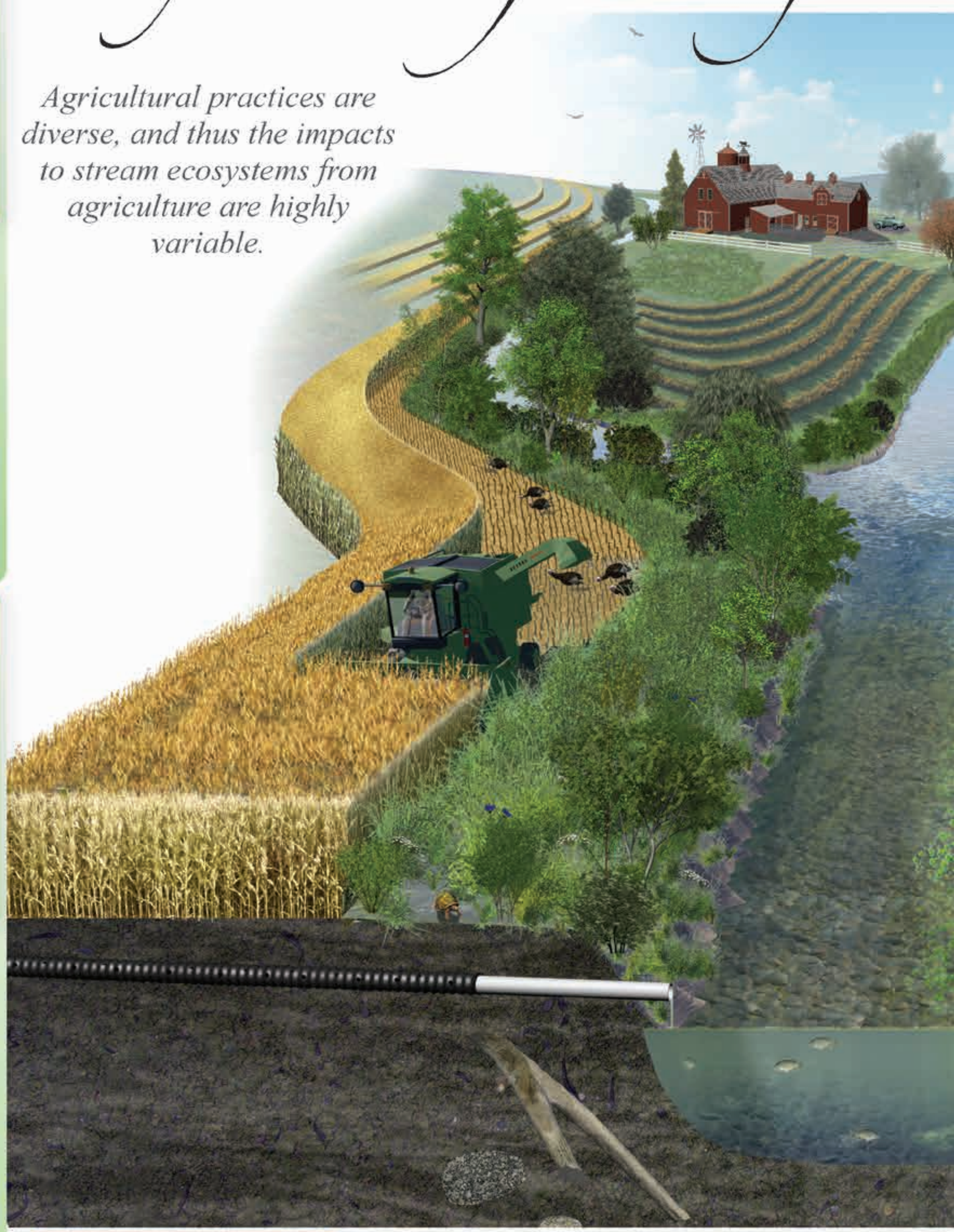
Fish have life cycles that span years. Because they are more mobile than algae or macroinvertebrates, they are affected by conditions that extend upstream and downstream within the river network. Smallmouth bass *(Micropterus dolomieu)* may hide under logs or undercut banks along stream edges or in pools, emerging to feed on invertebrates and small fish. Greenside darters *(Etheostoma blennioides)* live in riffle habitats of streams, where they feed on aquatic insects such as mayflies.

Algae have short life cycles of days to weeks and can respond relatively rapidly to changes in water chemistry. The most common algae found in natural streams of small to moderate size are diatoms, which attach to underwater surfaces such as rocks and aquatic plants. The diatom genus *Cymbella* can be found in riffles, either as solitary cells or at the ends of branched stalks on rocks and other surfaces. The diatom genus *Epithemia* is commonly found on the surfaces of submerged aquatic plants. Algae are the foundation of most aquatic food webs.

Macroinvertebrates, including these aquatic insects, have complex life cycles that occur over time spans of weeks to months. Most aquatic insects spend nearly all their life in the water as eggs and larvae and then leave the water and develop wings as adults. Many mayflies (Ephemeroptera) crawl on the surfaces of rocks in riffle areas and feed by gathering fine particles of organic matter or scraping algae. Some stoneflies (Plecoptera) feed by shredding submerged leaves that have been colonized by bacteria and fungi.

Dynamics of an Agricu

Agricultural practices are diverse, and thus the impacts to stream ecosystems from agriculture are highly variable.



Hydrology: Agricultural practices can alter the movement of water in a watershed through (1) subsurface drains, which lower the water table and quickly route water to nearby streams; (2) ditches and straightening of headwater streams; and (3) irrigation, which supplements available water for crops. These changes can result in more rapid runoff, reduced streamflows during dry periods, and increased transport of sediments and chemicals.

Water chemistry: Agricultural chemicals applied to fields can move to streams and groundwater; other sources of chemicals include irrigation water or waste from animal feeding operations. Nutrients—primarily nitrogen and phosphorus—in streams can exceed natural levels when fertilizer infiltrates through the soil or runs off the surface of the ground. Excess nutrients can cause nuisance growths of algae and aquatic plants, which when they die and decompose lead to low oxygen levels downstream. Pesticides are applied to control insect damage and growth of weeds or fungus but can also harm aquatic organisms.

Physical habitat: Some agricultural practices reduce the quality of stream habitats and have negative effects on organisms. Straightening and dredging headwater streams removes living spaces for aquatic organisms. Removal of riparian trees and shrubs results in more sunlight and warmer water temperatures. Soil disturbances from conventional tilling of the soil or overgrazing can cause erosion, resulting in buildup of sediment in the stream channel.

U.S. Fish and Wildlife Service photo by Scott Roth (top) , USDA Natural Resources Conservation Service photo by Jeff Vanuga (middle), and photo by Eric Caldwell, North Carolina State University (bottom).

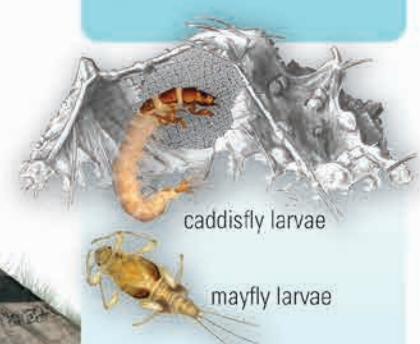
ltural Stream Ecosystem

green sunfish

central stoneroller

Fish communities in agricultural streams may be dominated by species—such as the central stoneroller *(Campostoma anomalum)*—that graze on algae attached to rocks and other submerged surfaces. Green sunfish *(Lepomis cyanellus)* are tolerant to high turbidity (water cloudiness), deposition of silt, and temperature.

Algae may proliferate in agricultural streams with high nutrient concentrations and available sunlight. *Cladophora* (a genus of green algae that grows in long filaments) and *Amphora* (a diatom genus) are examples of algae that can reach nuisance levels, occurring as large clumps or floating mats. As these mats are transported downstream and decompose, they can contribute to low levels of dissolved oxygen in the water that are harmful to other aquatic life.

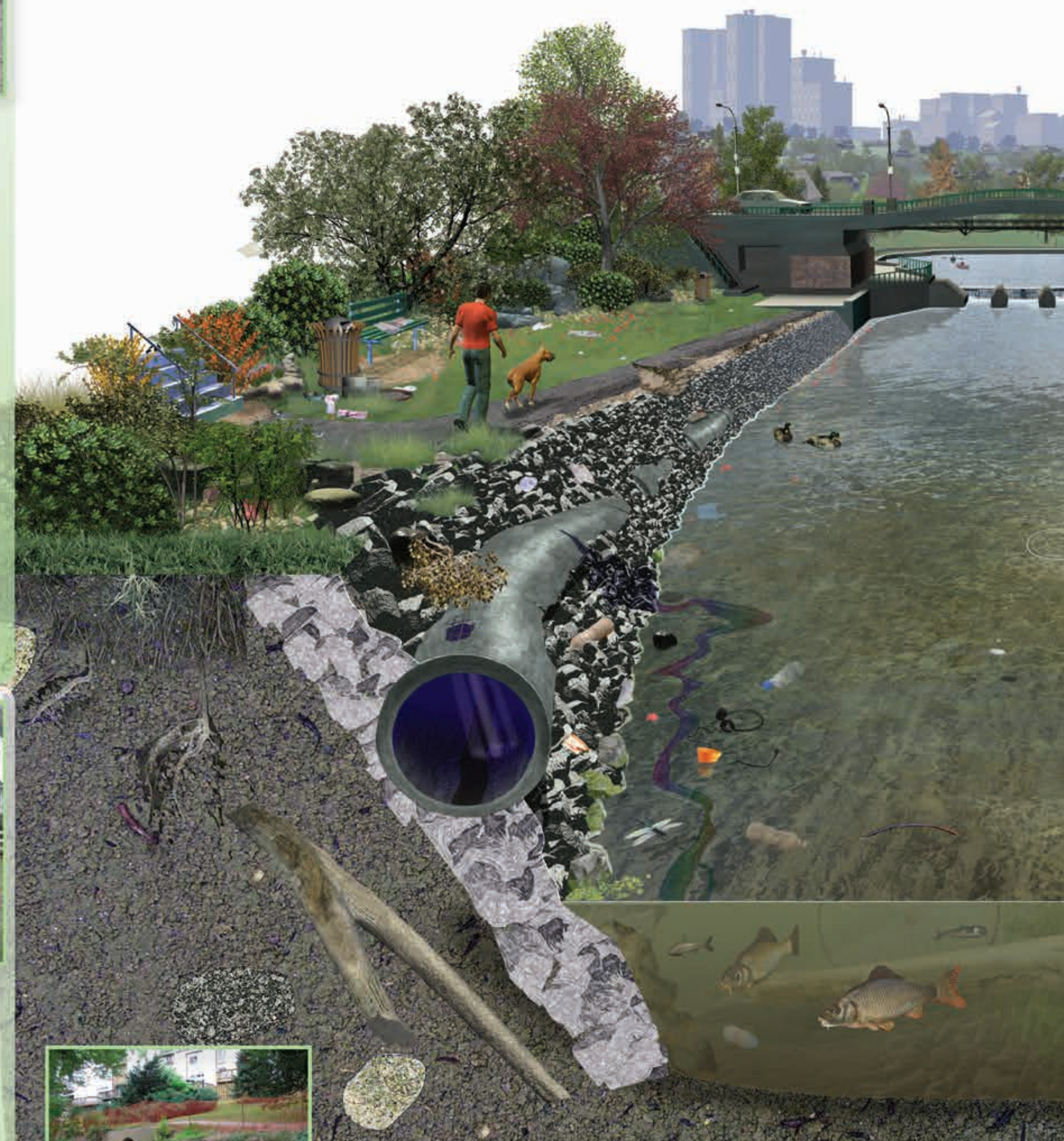


Macroinvertebrates that consume algae or organic-matter particles can thrive in some agricultural streams, whereas those that are sensitive to high silt inputs may decline. Net-spinning caddisflies of the family Hydropsychidae are filter feeders that collect and ingest organic particles that are suspended in the water; these particles may originate from crop residues, animal wastes, or algae as they gradually decompose. The triangular gill covers of this mayfly (*Tricorythodes* sp.) protect the sensitive oxygen-gathering gills from silt in sediment-laden streams.

Dynamics of an Urban Stream

Urban development may have significant impacts on stream ecosystems that are often obvious to the casual observer.

Hydrology: Urban development alters the movement of water through a watershed. Impervious surfaces (for example, roads, parking lots, and buildings) restrict the infiltration of precipitation into the groundwater system, and the construction of artificial drainage systems (for example, storm drains) quickly moves runoff to the stream. Rapid runoff and high streamflow increase the power or energy of the water flowing in the stream, which can deepen or widen stream channels and cause streambank erosion.

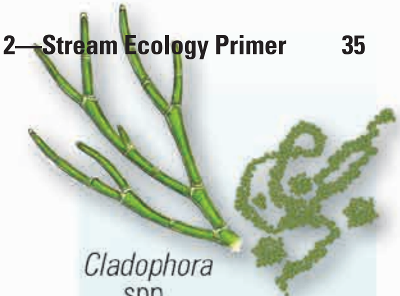


Water chemistry: Urban development may increase the inputs of complex chemical mixtures typically found in runoff from impervious surfaces in industrial and suburban areas. These mixtures may include pesticides, nutrients, and hydrocarbons that are known to have harmful biological effects.

Physical habitat: Urban development can lead to removal of vegetation near a stream, which increases the amount of light reaching the stream and increases the water temperature. Streamflow modification associated with urban development drives changes in stream habitat, including excessive flow velocities that erode the streambanks and scour the streambed.

U.S. Geological Survey photos by Martin Gurtz (top and middle) and Wetland Studies and Solutions, Inc., photo (bottom).

Ecosystem



Algae that are tolerant of pollution may increase in abundance with increased urban development. Diatom algae tend to decrease and nondiatom algae tend to increase with urbanization. Some algae-like bacteria and nondiatom algae, such as cyanobacteria or the green algae genus *Cladophora,* may increase in abundance to nuisance levels in the sunlight- and nutrient-rich conditions of many urban streams. These can be seen as long bands or strands of green slime on the surface of water and rocks.

Macroinvertebrates that are sensitive to pollution may be lost as a watershed becomes urbanized. More-tolerant organisms—such as leeches and isopods—may increase in abundance. Leeches, such as the North American freshwater leech *Macrobdella decora*, are most common in warm, protected shallows where there is little disturbance from currents. Isopods (Isopoda) are tolerant of relatively low dissolved oxygen levels.

Native fish communities generally become less diverse with increased urban development. Common carp *(Cyprinus carpio),* a non-native species, prefer large bodies of slow or standing water and soft sediment. The fathead minnow *(Pimephales promelas)* is tolerant of cloudy, low-oxygen water.

Chapter 3 Approach to Assessing Biological Condition

The NAWQA assessment of ecological health in the Nation's streams is based on an analysis of the condition of three biological communities—algae, macroinvertebrates, and fish. The biological condition assessment followed a study design using nationally consistent sampling and analytical methods in streams within 51 river basins across the Nation. Assessment methods accounted for variability in biological communities associated with natural differences among geographic regions. Chemical, hydrological, and other environmental data were integrated with biological condition to examine relations between land use and stream health. This chapter summarizes the primary features of the study design and provides the context for understanding findings about stream health across the Nation.

U.S. Geological Survey photo by Stephen Moulton.

The objectives of this assessment were to determine the health of streams in various land-use settings and investigate the factors related to reduced stream health.

Targeted Sampling Across the Nation's Diverse Land Uses and Natural Settings

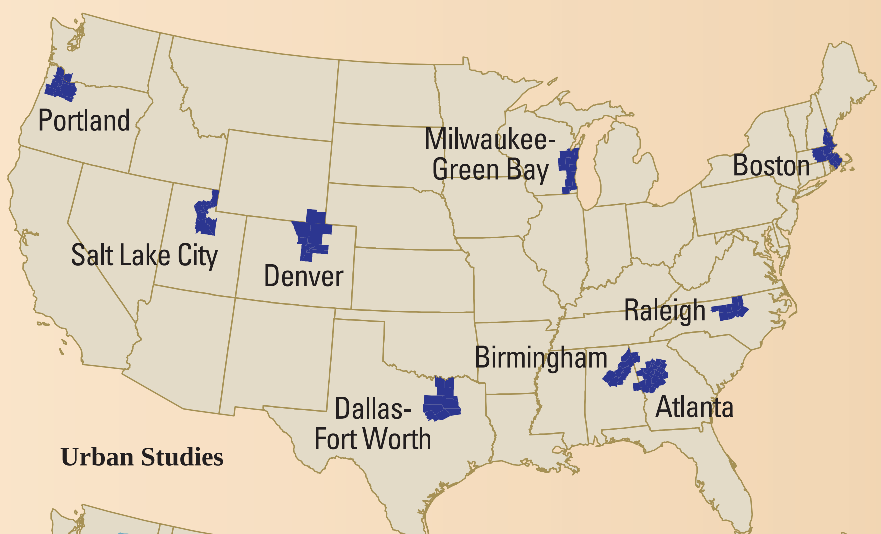
This report is based primarily on results of NAWQA assessments from 1993–2005 that were conducted in 51 major river basins across the United States (referred to as study units). Collectively, the 51 NAWQA study units cover a substantial part of the Nation's land area, accounting for more than 70 percent of total water use and spanning a wide range of hydrologic and environmental settings. Such an approach gives priority to understanding the chemical and physical factors—natural and manmade—affecting stream health in diverse environmental settings.

The primary objectives of this biological assessment were to (1) determine the health of streams—based on assessments of the condition of biological communities—in agricultural, urban, and mixed land-use watersheds and (2) investigate how land and water use influence the chemical and physical factors that reduce biological condition and ultimately stream health. Streams in this report are defined as being wadeable, regardless of named designation (for example, brook, creek, river). In addition to this report, two companion NAWQA studies also assessed stream biological condition (see sidebar, below).

Focused Biological-Condition Assessments in Urban and Agricultural Settings

NAWQA investigated the effects of urbanization on stream ecosystems in nine metropolitan areas in the conterminous United States (upper map). These studies were done to provide information and understanding to urban planners and those seeking ways to restore stream health in urban areas. A summary of these studies is provided in U.S. Geological Survey Circular 1373 (http://pubs.usgs.gov/circ/1373/), and further details are available at http://water.usgs.gov/nawqa/urban/.

NAWQA conducted an intensive study of nutrient enrichment—elevated concentrations of nitrogen and phosphorus—in streams in eight agricultural basins in the conterminous United States (lower map). These studies were done to improve understanding of how nutrients influence stream ecosystems, which will provide information for developing nutrient criteria to protect stream health in different geographic regions. Details on these studies and a link to reports is available at http://wa.water.usgs.gov/neet/.



The NAWQA approach targeted specific land-use settings among the diverse natural settings across the Nation. Assessed streams were primarily located in areas of agricultural and urban development because of (1) the possible physical and chemical effects of these land-use activities on biological condition (chapter 2) and (2) to meet the needs of local stakeholders. The agricultural areas are diverse in climate, geography, and crop types, including corn and soybeans in the Midwest; wheat and other grains in the Great Plains; rangeland in the Southwest; and grains, fruits, nuts, vegetables, and specialty crops in California and the Pacific Northwest. The urban areas also represent diverse environmental settings, including New England coastal basins, the southern Appalachians, the mid-Atlantic Piedmont, northern and southern Midwest plains, arid western basins, and the Pacific Northwest. Other assessments were made in Alaska and Hawai‘i. Most assessments in urban areas focused on residential land with low-to-medium population densities (300 to 5,600 people per square mile) (Hitt, 1994). Some commercial or industrial areas also were included, but point sources and extensive industrial and urban areas generally were not assessed (Gilliom and others, 2006).

Features of NAWQA's Biological-Condition Assessment

This biological-condition assessment provides a national perspective on understanding water-quality issues in relation to land use and water-resources management. Listed below are several characteristics and limitations of the NAWQA approach that are important to consider when interpreting the findings presented in this report.

- Assessments include measures of three biological communities (algae, macroinvertebrates, and fish), which is not common among monitoring programs in the United States. A survey of 65 State and other monitoring programs in 2001 showed that macroinvertebrates are the most widely used community (86 percent of programs), followed by fish communities (63 percent) and algal communities (31 percent). In addition, 69 percent of programs use two or more communities in biological assessments, whereas 25 percent use all three communities (U.S. Environmental Protection Agency, 2002).

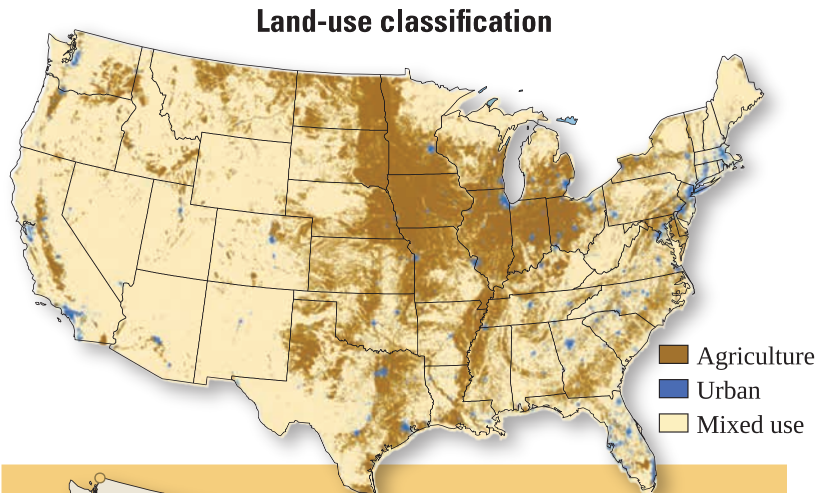
- Assessments include both geographically extensive and time-intensive sampling. Many sites are visited once and are generally distributed throughout a large geographic area or region. In addition, many repeated measurements of chemistry and biological communities are made at a smaller set of selected sites, because they are indicative of specific land-use features, such as urban development. Time-intensive sampling at a few fixed sites provides much needed understanding of the temporal dynamics and long-term trends of important chemical and physical factors, whereas geographically large study areas provide a broader regional context of water-quality conditions.

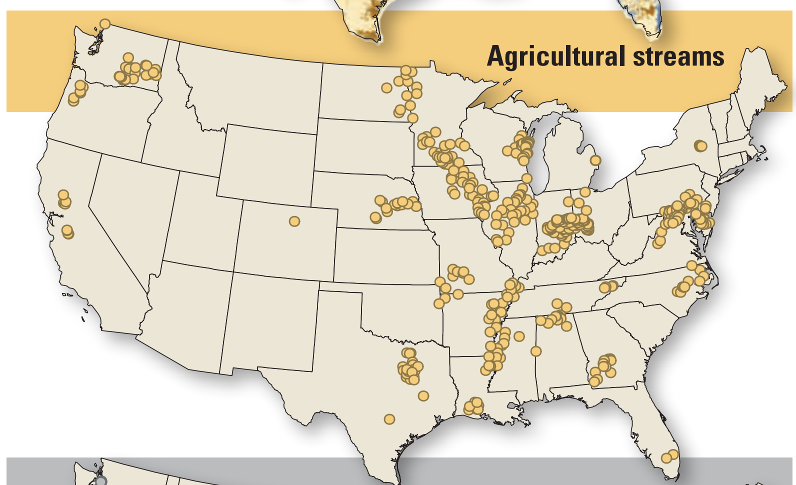
- Daily streamflow measurements are included in most fixed-site monitoring. Long-term streamflow monitoring provides crucial understanding of the hydrological context (that is, wet, dry, or average seasonal rainfall) of study sites and the streamflow conditions crucial to stream health.

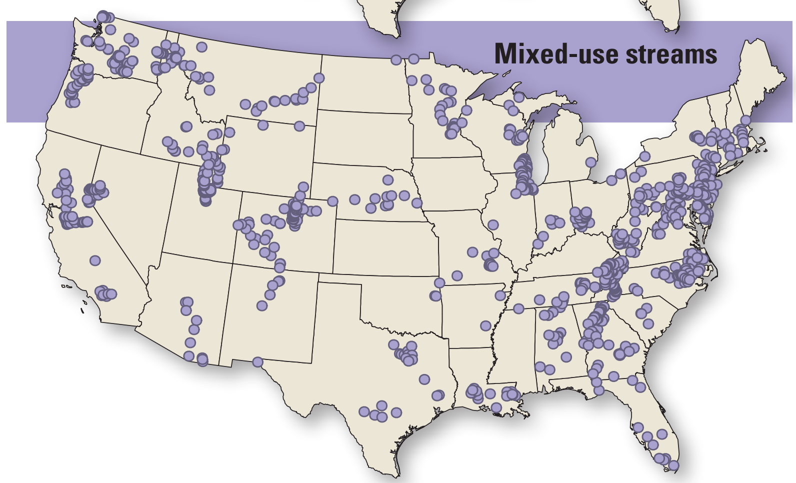
- Specific land-use settings in a wide range of hydrologic and environmental settings are targeted across the Nation. This approach gives priority to understanding crucial factors influencing water quality and biological condition in these land-use settings but does not provide a representative sample of all stream segments within a given region of the Nation (see next page).

Table showing criteria used by NAWQA to classify streams assessed for biological condition by the dominant land use in their watersheds (modified from Gilliom and others, 2006; Dubrovsky and others, 2010).

Land-use classification	**Watershed land-cover criteria**
Agricultural	50 to 100 percent agricultural land and 0 to 5 percent urban land
Urban	25 to 100 percent urban land and 0 to 24 percent agricultural land
Mixed use	All other combinations of urban and agricultural land





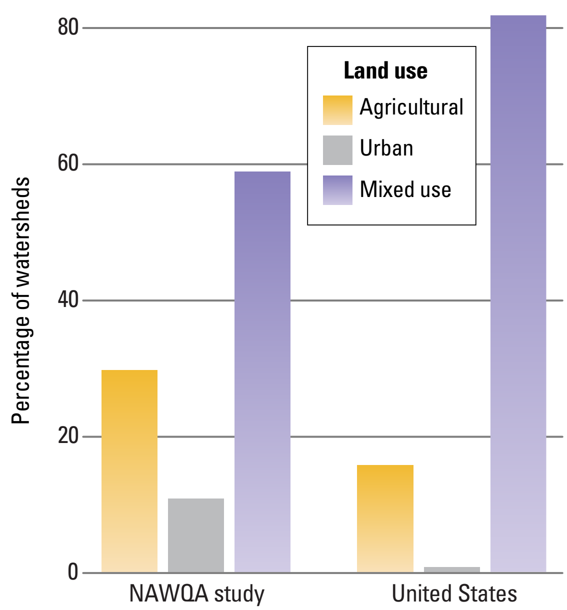


These maps of the conterminous United States show land-use classifications and stream-sampling sites classified as agricultural, urban, or mixed use by NAWQA. Stream sampling sites (dots) were distributed across the Nation's diverse environmental settings to assess biological condition within specific types of land uses.

NAWQA's Biological Assessment in a National Context

Consistent with the design of NAWQA's investigations, which targeted specific land-use settings, the biological condition findings in this report are presented by land-use category. Each stream assessed by NAWQA was classified into one of three land-use categories—agricultural, urban, or mixed use (see opposite page)—on the basis of the predominant land cover in its watershed (Gilliom and others, 2006). Most streams that were classified as agriculture or urban also commonly have small amounts of other land uses in their watersheds. Streams classified as "mixed use" represent a mix of two or more land uses and do not meet the criteria for individual agricultural or urban settings. Mixed-use streams range in their intensity of development, including some (about 5 percent) that are influenced by large amounts of agricultural and urban land (draining greater than 50 percent of agricultural land and 25 percent of urban land) and some with little agricultural or urban development.

By design, NAWQA's assessment over represented urban and agricultural streams and under represented those within all other land uses, relative to their occurrence throughout the conterminous United States. For example, urban streams represent about 1 percent of all streams in the conterminous United States but represent nearly 10 percent of the sites sampled by NAWQA. Agricultural streams represent less than 20 percent of all streams in the conterminous United States but represent about 30 percent of the sites sampled by NAWQA.



As shown by this bar graph, NAWQA's targeted sampling design for assessing the biological condition of the Nation's streams emphasized streams that drain agricultural and urban watersheds. Targeted watersheds are shown relative to the actual percentage of such watersheds in the United States. (Modified from Gilliom and others, 2006.)

Chemical and Physical Measurement and Assessment

USGS scientists with NAWQA made a wide variety of water-chemistry and physical measurements at sites where biological communities were sampled. Chemical sampling of water included analyses of nutrients (1,504 sites), major ions (1,309 sites), dissolved pesticides (593 sites), and contaminants associated with streambed sediments (414 sites). All chemical samples were analyzed at the USGS National Water-Quality Laboratory, Denver, Colorado, and all field and laboratory protocols are available at http://water.usgs.gov/nawqa/bib/. Measures of physical habitat were also made at 920 sites where biological condition was assessed. Habitat measurements included the characterization of channel morphology, substrate types, riparian canopy, and water depth and velocity. NAWQA protocols for characterizing stream physical habitats are available at http://water.usgs.gov/nawqa/bib/.

U.S. Geological Survey photo by Terry Short.

Photograph of a U.S. Geological Survey scientist making physical measurements of a stream.

U.S. Geological Survey photo.

U.S. Geological Survey gage measuring stream flow.

Sampling sites were considered to have elevated salinity if measured electrical conductivity of the stream water exceeded regional background levels established in a recent national assessment (Van Sickle and Paulsen, 2008). The occurrence of biological alteration was compared between streams with and without excess salinity at 1,808 sites where conductivity and biological communities had been sampled at the same times.

Sampling sites were classified into one of three broad categories of nutrient status using existing criteria (Dodds and others, 1998). This simple classification scheme was used to compare biological condition to nutrient status at 1,504 stream sites across the Nation where nutrients and biological communities had been sampled at the same times.

Streamflow modification was assessed at 2,888 sites with USGS gaging stations by comparing observed magnitudes of annual (1980–2007) high and low flows to those expected in the absence of manmade disturbances in the watershed. Expected flows were estimated for each assessed site with statistical models developed from a set of 1,059 hydrologic reference sites (Falcone and others, 2010; Carlisle and others, 2010). Daily streamflows were monitored for at least 5 years before making assessments of algal, macroinvertebrate, and fish condition at 283, 274, and 237 sites, respectively.

Water temperature modification was assessed at 2,149 stream sites where continuous monitoring had been conducted for at least one summer during 1999–2009. The observed summertime mean water temperature at each site was compared to an expected natural temperature, which was estimated from statistical models (Hill and others, 2013) similar to those used for assessing streamflow modification.

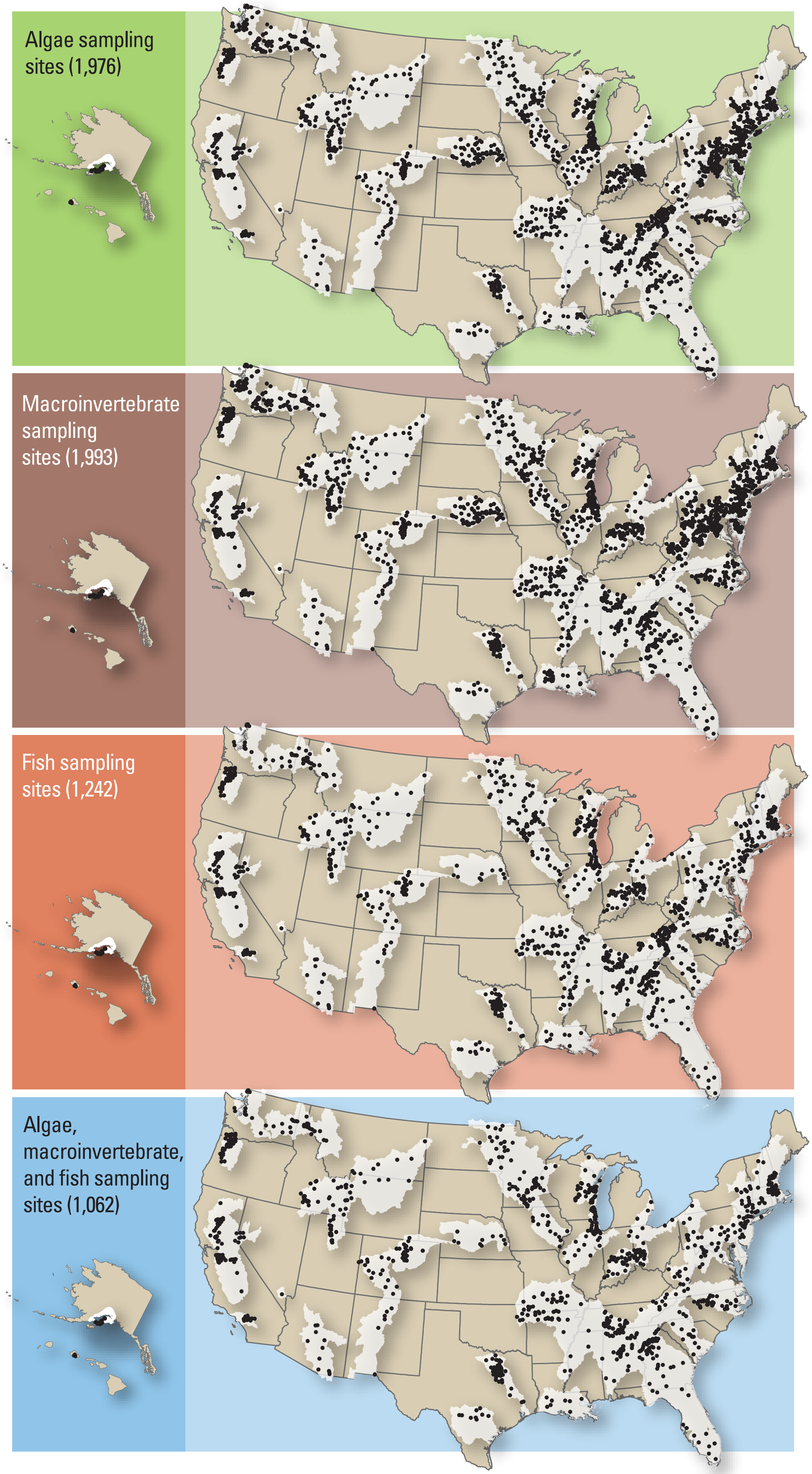
U.S. Geological Survey photos by Martin Gurtz, Douglas Harned, and Rodney Knight.

Photographs of biological samples being collected by U.S. Geological Survey scientists. Left, collecting algae from the surface of a rock; middle, sampling macroinvertebrates in a stream riffle; right, using electrofishing to stun fish for collection and examination.

As a measure of stream health, NAWQA sampled and assessed the condition of three unique biological communities—algae, macroinvertebrates, and fish.

Biological Sampling

Nationally consistent field sampling methods developed by NAWQA for algae, macroinvertebrates, and fish made it possible to compare results across a wide variety of stream types and geographic locations. NAWQA's assessments of algae, macroinvertebrates, and fish were derived from samples collected at 1,976, 1,993, and 1,242 stream sites, respectively, using published methods (http://water.usgs.gov/nawqa/bib/). Samples of all three communities were collected at 1,062 stream sites. Biological sampling was generally conducted during predetermined time periods, typically during low stream flows. The analysis of these samples was accomplished using consistent methods with continual quality assurance and data management (see Assessment Tools sidebars). Macroinvertebrate and algal samples were processed at the USGS National Water Quality Laboratory (Denver, Colorado) and Academy of Natural Sciences of Drexel University (http://ansp.org), respectively, using published methods (NAWQA field and laboratory protocols can be accessed at http://water.usgs.gov/nawqa/bib/). All biological data collected by NAWQA are publicly available (see Assessment Tools sidebars).



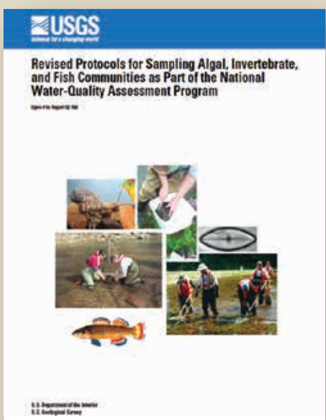
Maps showing sites in the United States (dots) where biological samples were collected during NAWQA studies. Algal, macroinvertebrate, and fish communities were sampled in streams within NAWQA study units (tan shading) across the Nation. All three communities were sampled at a subset of these sites (bottom panel). Alaska and Hawai‘i not shown to scale.

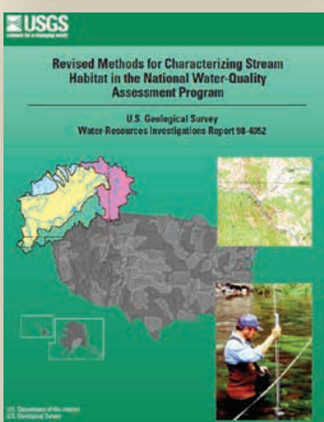
Assessment Tools

Field Sampling and Taxonomic Quality Assurance

Field Sampling

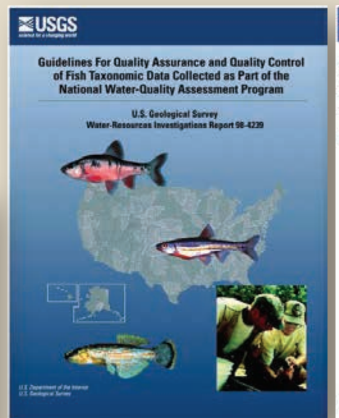
Nationally consistent field sampling methods developed for algae, macroinvertebrates, and fish, and their habitats made it possible for U.S. Geological Survey (USGS) scientists to compare results across a wide variety of stream types and geographic locations.

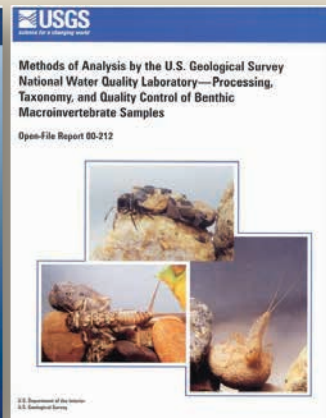


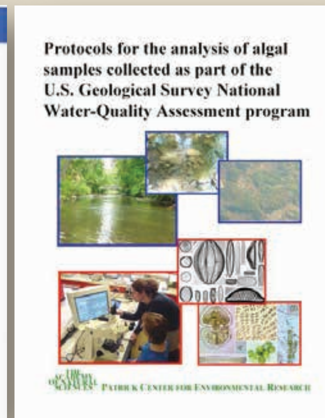


Taxonomic Quality Assurance and Sample Processing

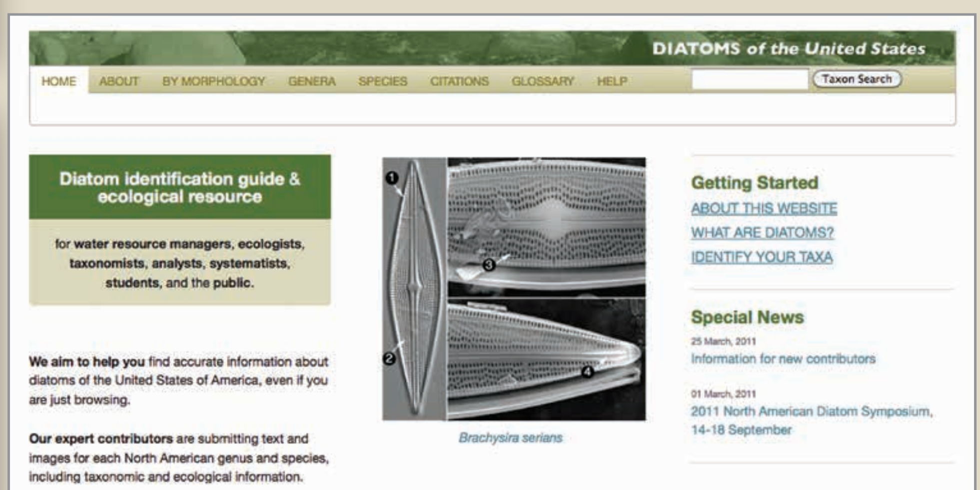
Data sharing depends on strict quality assurance of taxonomic identification, consistency, and resolution. Standard procedures for quality assurance and control are published for algal, macroinvertebrate, and fish community samples. Representative individuals of each taxon (taxonomic unit) collected are maintained in “voucher” collections that allow comparisons with other contemporary and future sampling programs and will potentially be useful for evaluating changes in species and genetic composition (see, for example, Walsh and Meador, 1998).





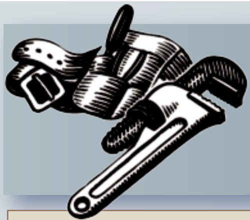


Links to these and other resources are available at http://water.usgs.gov/nawqa/bib/.



Tool for Taxonomic Consistency

USGS and the U.S. Environmental Protection Agency cooperated to develop a single comprehensive source of taxonomic and ecological information for diatoms of the United States. The guide can be accessed at http://westerndiatoms.colorado.edu/.



Assessment Tools

Nationally Consistent Ecological Data and Tools for Interpretation

A National Database of Aquatic Bioassessment Data

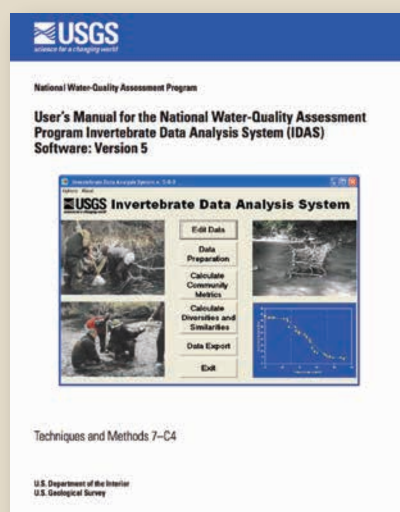
The U.S. Geological Survey (USGS) BioData Retrieval system provides access to aquatic bioassessment data (biological community and physical habitat data) collected by USGS scientists from stream ecosystems across the Nation. USGS scientists collect algal, macroinvertebrate, and fish community data, as well as stream physical habitat data, which is part of the USGS's fundamental mission to describe and understand the Earth. The publicly available BioData Retrieval system disseminates data from more than 15,000 fish, aquatic macroinvertebrate, and algal community samples. Additionally, the system serves data from more than 5,000 physical datasets (samples), such as for reach habitat, that were collected to support the community sample analyses. Scientists, resource managers, teachers, and the public can retrieve data using an online query. BioData can be accessed at http://aquatic.biodata.usgs.gov.

Nationally Consistent Biological Data Advance Environmental Assessment and Basic Science

Biological data collected by NAWQA have been successfully used by other monitoring organizations and scientists to address questions ranging from local issues to continental-scale phenomena. One of the greatest strengths of the data is the consistency with which they have been collected across a wide geographic area. For example, Passy (2008) used algal data collected across the Nation to describe continental-scale patterns in diatom distributions. Similarly, NAWQA macroinvertebrate data from reference-quality sites across the Nation were used to establish baseline conditions in the U.S. Environmental Protection Agency's Wadeable Streams Assessment (U.S. Environmental Protection Agency, 2006a). Fish-community data collected by NAWQA were used by Mitchell and Knouft (2009a) to examine nationwide patterns of invasive fish species.

Data Processing Tools Facilitate Analysis and Interpretation

Tools for analyzing biological data help in making comparisons of results among sites at local, regional, and national scales. For example, the Invertebrate Data Analysis System (IDAS) allows users to resolve taxonomic discrepancies, calculate a wide variety of macroinvertebrate metrics and indices, and export data to other analysis software. Similar software has been developed for analyzing algal community data based on algal attributes compiled by USGS biologists (http://pubs.usgs.gov/ds/ds329/).



Assessing Biological Condition—The Reference Concept

Biological reference sites are needed to establish a baseline or expectation in most biological-condition assessments. Implicit in the concept of reference sites used in this assessment is that such sites are in reality least-disturbed or potentially best attainable given the current degree of human influence on the Nation's landscapes (Stoddard and others, 2006). Few, if any, streams are totally unaffected by human activities, particularly considering historical disturbances (such as timber harvesting) or atmospheric inputs of pollutants from global sources. Also, the level of historical disturbance varies widely across the country. For example, biological reference sites closely approximate pristine conditions in areas that are within protected wilderness, parks, and nature preserves. In contrast, biological reference sites in the Midwest are in watersheds that historically experienced intensive transformations from prairie to farmland but are currently among the least-disturbed watersheds in that region—such as those with protected riparian buffers.

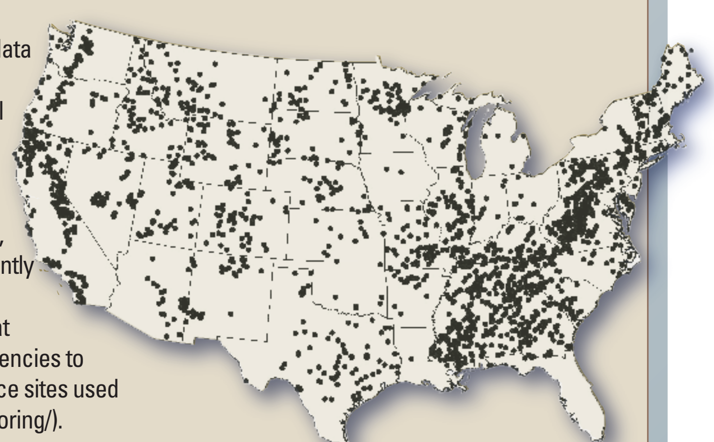
A consequence of variation in the quality of reference sites is that assessments in some areas of the country are based on a lower expectation than those in regions where more natural reference sites exist. Despite this difficulty, biological assessments are still meaningful because they express the degree to which biological communities in a stream differ from those in streams that are least-disturbed in a particular region.

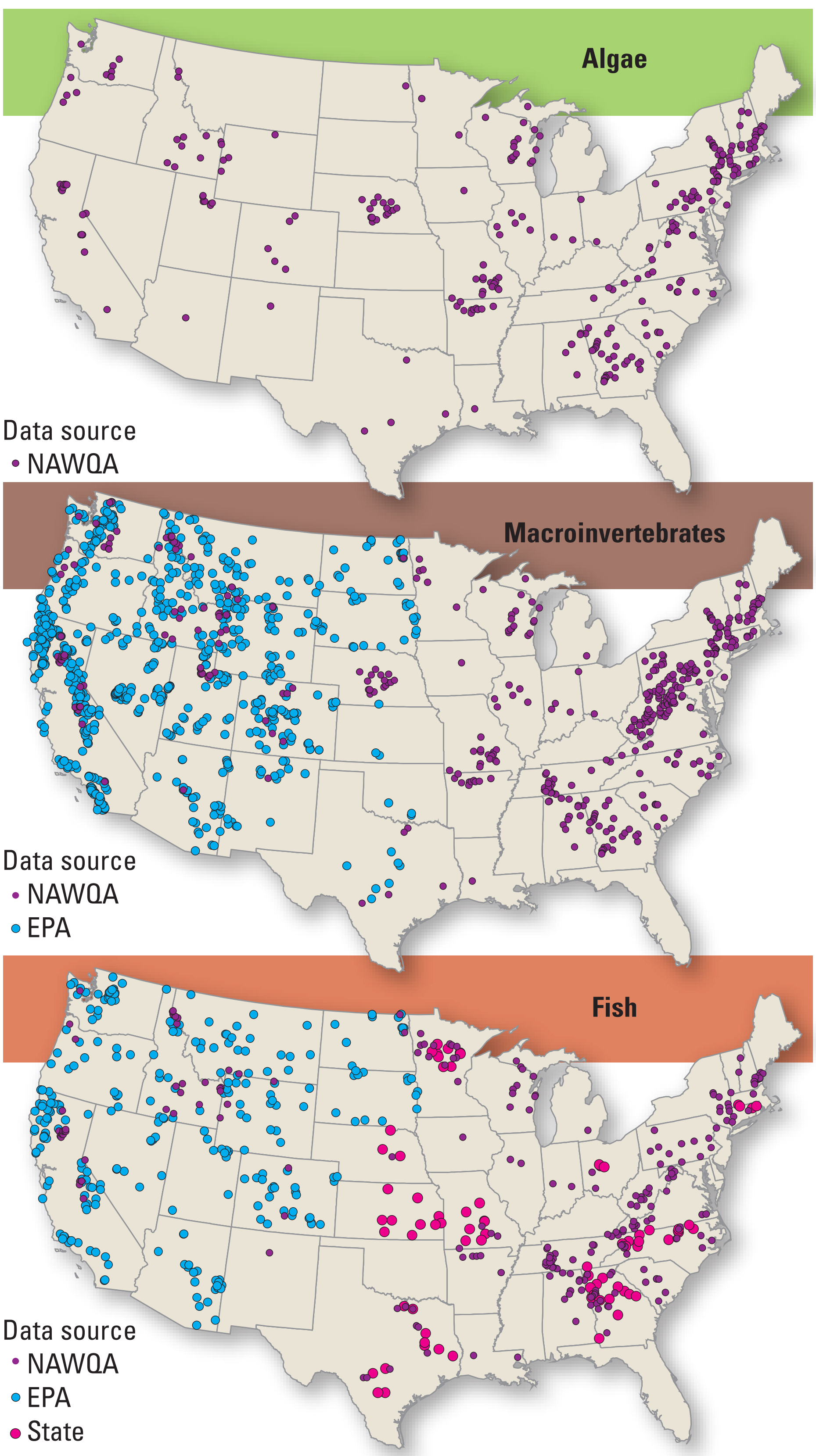
To characterize reference conditions, biological data from USGS, the U.S. Environmental Protection Agency, and select State agencies were combined. Reference sites were identified from this large set of sites by evaluating watershed and riparian land-cover disturbance, applying site-specific measures of habitat and chemical conditions, and using professional scientific judgment (Herlihy and others, 2008). Separate reference sites were identified and used for each biological community. Nationwide, algal and macroinvertebrate communities, as well as fish communities, were assessed using 276, 585, and 1,238 reference sites, respectively. Differences in numbers of reference sites among biological communities are largely due to data availability. Reference site biological data were archived for public use (see sidebar, below).

Assessment Tools

National Repository of Reference-Site Data for Rivers and Streams

In cooperation with the Western Center for Monitoring and Assessment of Freshwater Ecosystems, U.S. Geological Survey (USGS) scientists with NAWQA led an effort to compile biological data and map reference-quality sites from Federal assessment projects throughout the Nation (dots on map of the conterminous United States). This effort provides public access to the data collected at these sites, as well as other environmental information, so that future stream bioassessments can benefit from the work of Federal agencies and better characterize reference conditions across the Nation's diverse landscapes. Data for more than 2,000 reference-quality sites originated from sampling efforts of the U.S. Environmental Protection Agency, USGS, Bureau of Land Management, U.S. Forest Service, and university researchers. The types of data currently available include macroinvertebrate taxon counts, habitat features, chemistry data, and geospatial data. Access to these data is available at http://www.cnr.usu.edu/wmc/htm/data/. USGS is working with other agencies to further develop this database into a comprehensive network of reference sites used by Federal, State, and local monitoring programs (http://acwi.gov/monitoring/).





The baseline by which algal, macroinvertebrate, and fish communities were assessed for biological condition by NAWQA were derived from reference sites sampled by the U.S. Geological Survey, the U.S. Environmental Protection Agency (EPA), and select State agencies (see Measures of Biological Condition sidebar). These maps of the conterminous United States show the locations of these sites (dots).

U.S. Geological Survey photo by Daren Carlisle.

Reference sites range from those in near pristine watersheds in protected wilderness areas (photo above) to those in watersheds with substantial landscape alteration that have protected riparian buffers (photo below).

USDA Natural Resources Conservation Service photo by Lynn Betts.

A nationally consistent way to measure biological condition is to standardize by each site's biological potential.

Assessing Biological Condition—General Approach

Biological condition is used as an indicator of stream health and is defined as the degree to which biological communities differ from their expected natural potential. A major challenge in national assessments is the ability to make comparisons of biological condition in streams across diverse geographic settings. This requires standardized measures of biological condition that adjust for natural factors, such as stream size and climate, that control the types of species present in a given stream (chapter 2). In some geographic areas, including Alaska, Hawai'i, and Florida, such measures of biological condition could not be used because of small numbers of sampled reference sites. Results from these areas are included in this report, although not presented in a national context.

Biological condition at each stream site was assessed by comparing observed community characteristics (such as number of taxa) to those expected if the site was minimally disturbed by human influences. The observed characteristic (O) is obtained from a sample of the biological community at a site, whereas the expected characteristic (E) is predicted with a model developed using data from a collection of reference sites. Because deviation of O from E is expressed as a ratio, the measure is standardized by each site's biological potential and is therefore a comparable measure of biological condition across the Nation, despite large differences in naturally occurring biological communities. In addition, because natural variation in environmental settings is accounted for in estimates of E, departures of O from E are likely the result of human influences. Importantly, O does not always equal E at reference sites because of natural environmental variability (such as storm events), differences in the level of human-caused modification among reference sites, and inevitable error in models used to estimate E.

For clarity of presentation, O:E ratios were modified in two ways. For some analyses, O:E ratios were rescaled to a simple percentage, so that the measure of biological condition ranged from 0 (no similarity to natural potential) to 100 (identical to natural potential). For other analyses, the biological community at each site was classified as "altered" if its O:E score was lower than that of 90 percent of the reference sites within its region and was classified as "unaltered" if not. Importantly, this simple classification of biological condition is based on statistical properties unique to the data in this study and therefore not related to criteria used by States and other monitoring jurisdictions to assess beneficial-use attainment (that is, whether the designated use of a water body can be attained).

Because of differences in the natural distributions of algal, macroinvertebrate, and fish communities, the characteristics used to define O and E also differed. For example, the number of taxa was used as a measure for invertebrate communities, relative abundance of different taxonomic groups was used for algal communities, and a combination of both was used for fish communities (see sidebar at right). In addition, different procedures were used to determine expected conditions for the three different taxonomic groups.

Measures of Biological Condition Were Tailored to Each Community and Region

Biological condition is assessed by comparing observed (O) community attributes, such as number of native species, to those expected (E) if the community was minimally disturbed by human influences. The observed attribute (O) is derived from a sample collected at a stream site, whereas the expected (E) condition is modeled from data collected at reference sites with similar natural environmental characteristics, such as climate and stream size. The community attributes measured for O and E and the procedures for estimating E differ for the communities assessed, as described below.

For macroinvertebrate communities, the expected characteristic (E) was a site-specific list of taxa derived from statistical models that predict the probabilities of observing each taxon at a site, given its environmental setting (for example, stream size, climate, geographic location). The statistical models were developed for each of three regions of the conterminous United States—the area west of the Continental Divide (Carlisle and Hawkins, 2008), the south-central plains (Yuan and others, 2008), and the remaining part of the conterminous United States, including the Eastern United States and central and northern plains (Carlisle and Meador, 2007). The observed characteristic (O) for macroinvertebrate communities at a stream site was the list of taxa actually observed in the sample collected at that site and that were among those taxa expected to occur there (that is, on the “E” list of taxa for that site). Because O is constrained by the list of taxa in E, the O:E index is not simply a measure of taxa richness but is sensitive to the replacement of taxa that often occurs in disturbed environments. For example, if a pollution-sensitive taxon is replaced by a pollution-tolerant one, total taxa richness does not change. However, the O:E index would indicate a loss of one taxon.

Fish communities were divided into three regions. For fish communities in the Eastern and Central United States, O:E was developed and is interpreted identically to that for macroinvertebrates (Meador and Carlisle, 2009). Fish communities in the Western United States were not assessed with statistical models because natural communities contain very few species. Instead, fish communities were assessed using an index of biological integrity (IBI) developed from 210 reference sites, where the IBI represents measures of community composition other than species richness (for example, proportion of exotic species; Whittier and others, 2007). Thus, in the Western United States, E for each site was estimated as the average IBI value for all reference sites within the region, whereas O was the observed value of the IBI calculated from the sample collected at that site (Meador and others, 2008).

The relatively small number of sampled reference sites for algae precluded the use of statistical models for assessing algal communities. Instead, an IBI was developed in a way similar to that for western fish communities. The diatom IBI represents measures of the relative abundance of diatom taxa collected at a site. Thus, for algae throughout the United States, E for each site was estimated as the average IBI value for all reference sites within its region, whereas O was the observed value of the IBI calculated from the sample collected at that site. Separate IBIs were developed for each of five generalized regions spanning the conterminous United States (Potapova and Carlisle, 2011).

Chapter 4 National Assessments of Physical and Chemical Factors that Influence Stream Health

Reduced stream health is often associated with manmade changes to the physical and chemical properties of streams. The presence and abundance of species in a biological community are a function of the inherent requirements of each species for specific ranges of physical and chemical conditions. When changes in land and water use in a river basin cause physical or chemical properties of streams to exceed their natural ranges, vulnerable aquatic species are eliminated, ultimately reducing biological condition and stream health. This chapter reports on national assessments of how land and water management influence the physical and chemical properties of streams.

U.S. Geological Survey photo by Martin Gurtz.

Land and Water Management Across the Nation

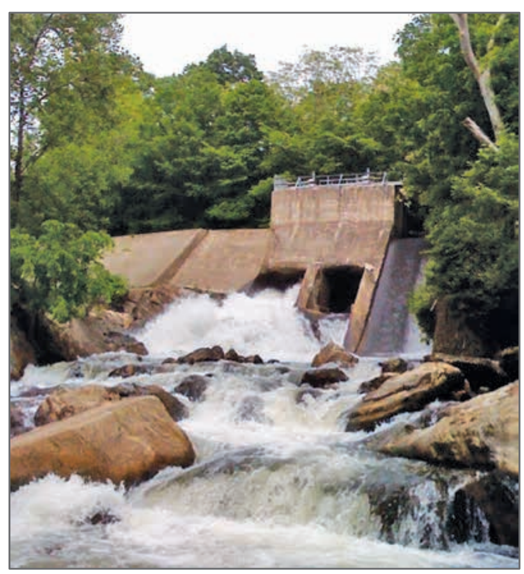
The United States has a great diversity of natural landscapes, which are the products of variation in climate, topography, soils, and geology. It is on this diverse backdrop that humans historically settled and currently manage land and water. Geographic differences in climate influence the kinds of crops grown on agricultural lands and the ways in which water is managed. As a result, the degree to which land and water management influences physical and chemical properties of streams—and ultimately stream health—varies widely across the Nation.

Urban land has expanded greatly over the past century. Urban development since 1900 was substantial along the eastern seaboard and within pockets of the Midwestern United States. The expansion of urban lands in the arid Southwest is even more striking and has major implications for water management given the scarcity of rainfall in this region. The current and possible future stresses of water scarcity for cities is a major issue in the Southwest.

The volume of stream flows stored in reservoirs has also expanded greatly over the past century. All parts of the United States experienced dramatic increases in reservoir storage since 1900. Reservoirs in arid regions of the West were primarily constructed for irrigation and municipal use, whereas reservoirs in wetter climates were constructed for flood control and municipal uses. The effect of reservoirs on stream health depends on the type of reservoir, how it is managed, and the types of biological communities that were naturally present (Collier and others, 1996).

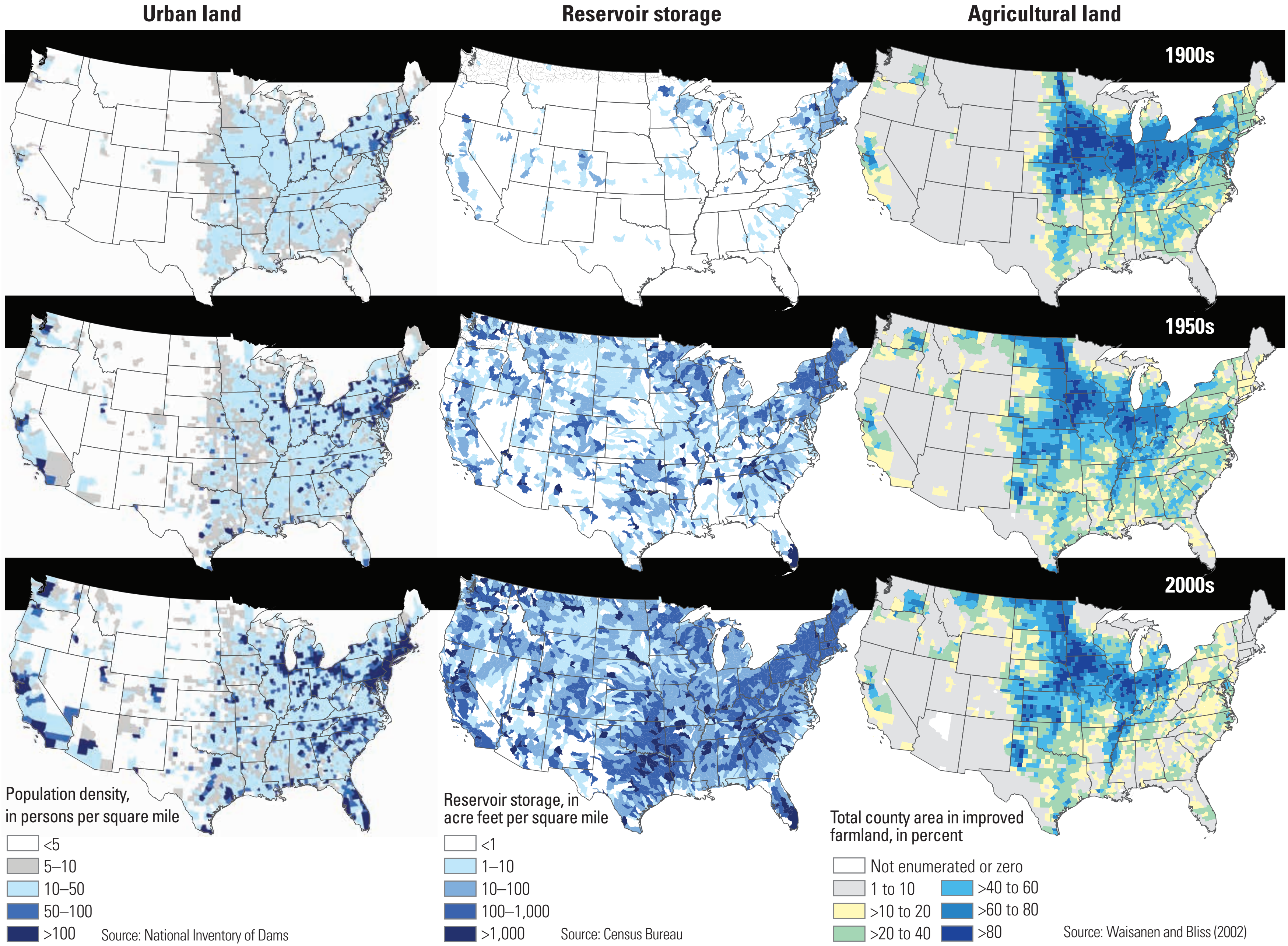
Relative to urban and reservoir development, the extent of agricultural lands has changed less since 1900. Expansion of agricultural lands occurred in the western plains and arid West due to the development of water for irrigation. In contrast to the arid West, agricultural land acreage in many States in the East declined since 1900, either due to fields being allowed to go fallow or because of conversion to urban lands.

Bureau of Reclamation photo.



U.S. Geological Survey photo by Daren Carlisle.

Water development in the arid Western United States typically aimed to divert and store streamflows for irrigation, as on the Carson River, Nevada (photo above). In contrast, water development in the East was typically intended for flood control or hydropower, as on the Housatonic River, Connecticut (right photo).



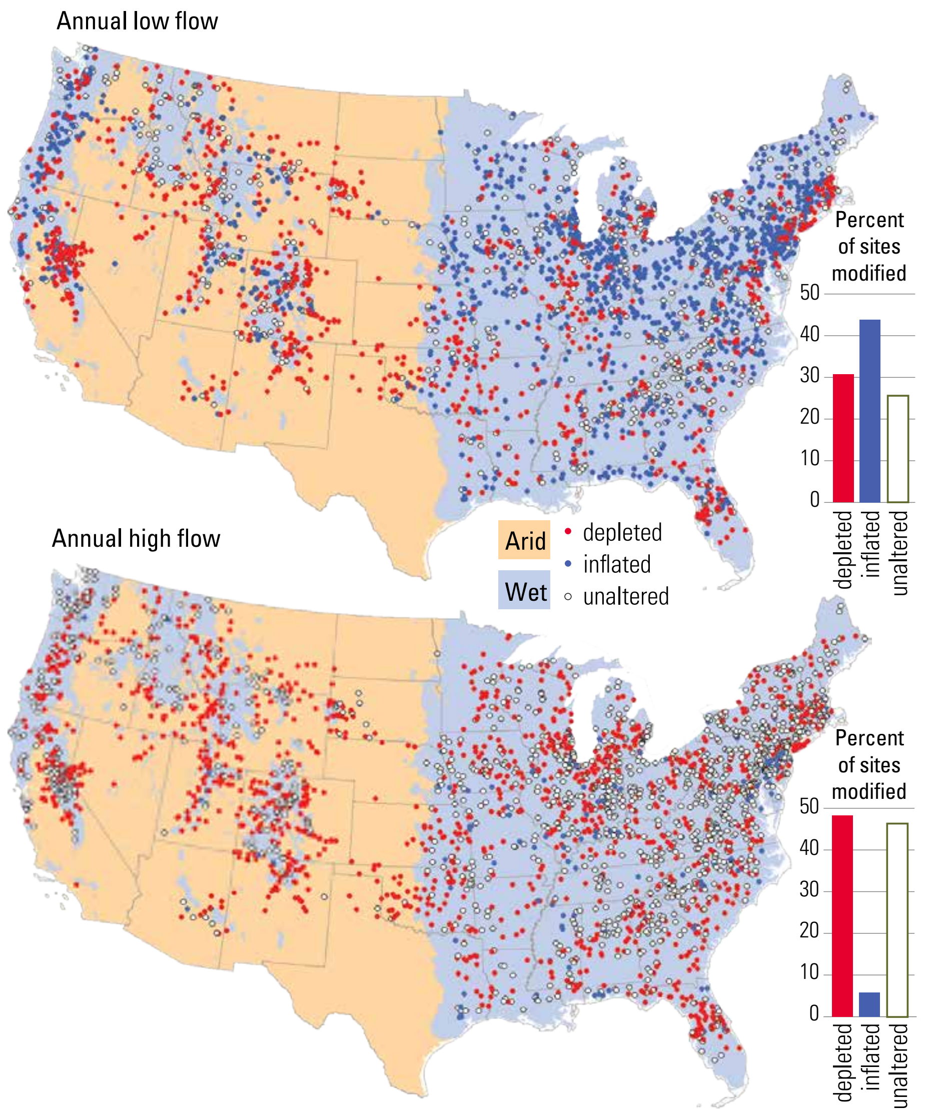
Maps of the conterminous United States showing the expansion of land and water management over the past century. This expansion has led to widespread modification of the properties of watersheds that influence stream health. Since 1900, expansion of urban lands and reservoir storage has been substantial across the Nation. In contrast, agricultural lands have expanded in irrigated areas of the West but declined in the Northeast and Southeast, often being replaced by urban development. (<, less than; >, greater than.)

Annual low or high flows were modified in 86 percent of the almost 3,000 assessed streams.

Streamflow Modification

Flowing water is the defining feature of streams. Natural fluctuations of flows are crucial to stream health because they build and maintain physical habitats, influence physical and chemical characteristics of water, and provide important life-stage (for example, migration) cues for aquatic organisms.

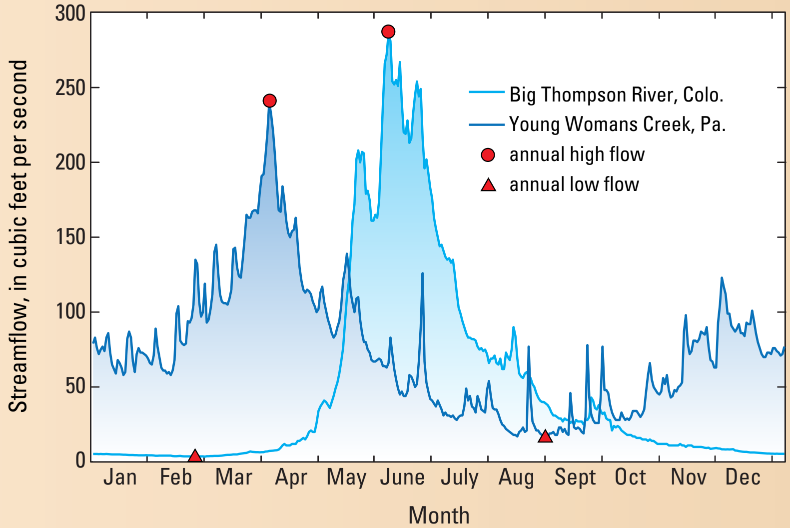
Land use and water management have dramatically changed natural streamflows across the United States. The magnitude of low streamflows was modified in 75 percent of assessed stream sites, and the magnitude of high streamflows was modified in 54 percent of assessed sites—resulting in a total of 86 percent of assessed streams having modified low flows or high flows or both. This national assessment builds on previous findings (National Research Council, 1992; Jackson and others, 2001; Baron and others, 2002; Postel and Richter, 2003) documenting widespread hydrological modification in watersheds across the Nation.



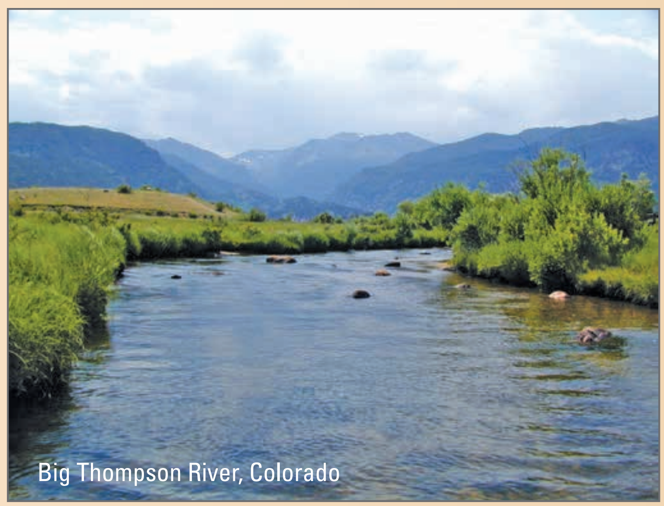
As shown on these maps of the conterminous United States, annual high or low streamflows were modified at 86 percent of stream sites assessed by NAWQA. Streamflow modification was depleted (less than), inflated (greater than), or unaltered relative to expected natural magnitudes. Although high flows were depleted throughout the Nation, low flows tended to be depleted in arid regions and inflated in wet regions. These results highlight the value of long-term streamflow data collected by the U.S. Geological Survey in cooperation with numerous local, State, and Federal partners.

Natural Patterns of Streamflow Vary Geographically

Seasonal patterns of natural streamflows are influenced by environmental factors such as climate, soils, and geology of the river basin. As shown in this graph of monthly streamflows averaged over several years, streamflows in the Northeastern United States (for example, Young Womans Creek, Pennsylvania) are typically highest in spring when accumulated snow melts, lowest in late summer, then increase again with rainfall events in fall and winter. In contrast, Rocky Mountain streams (for example, Big Thompson River, Colorado) experience their highest streamflows during summer when the accumulated snowpack melts but are lowest during the winter when all precipitation is snow.



U.S. Geological Survey photo by Lee Eicholtz.



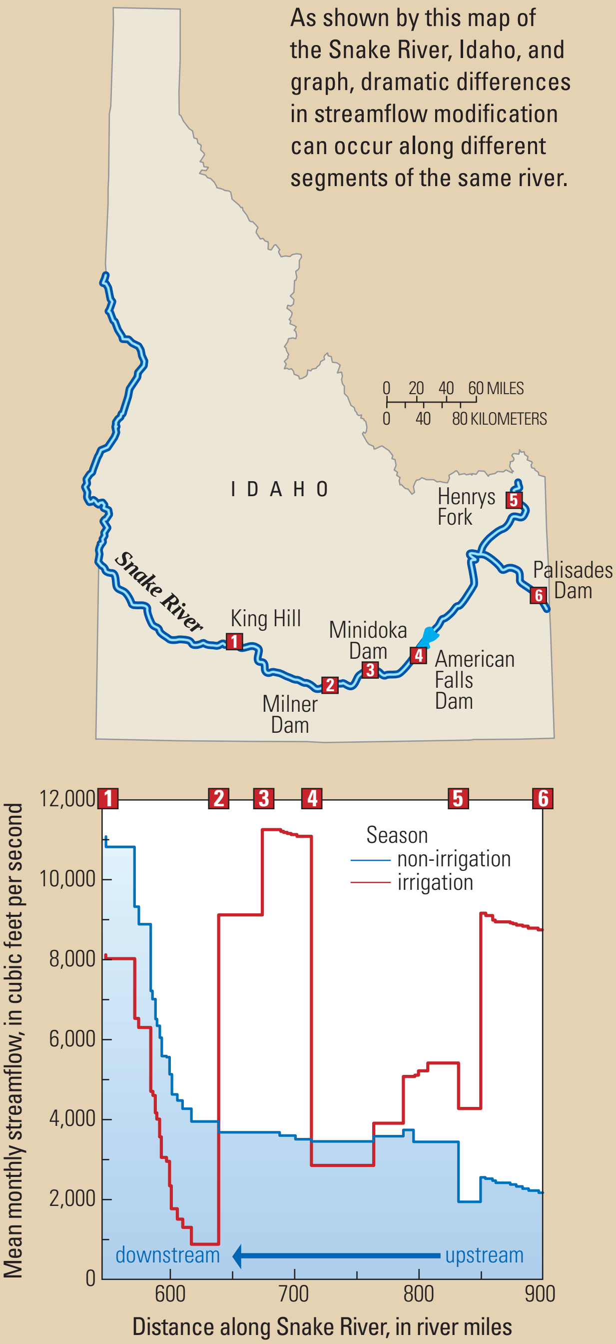
U.S. Geological Survey photo by Robert Zuellig.

Streamflow modification differed between arid and wet climates (Carlisle and others, 2011). Low-flow magnitudes in wet climates were often inflated, whereas low-flow magnitudes in arid climates were often depleted. The widespread depletion in streamflow magnitudes in arid regions is likely due to a variety of "consumptive" water uses—that is, water that evaporates or is transferred to other river basins and not returned to the stream channel. Water withdrawals for irrigation from streams and aquifers in arid areas have lowered groundwater and surface-water levels in many regions (Jackson and others, 2001). Reservoirs are also managed differently between arid and wet regions (Collier and others, 1996). Reservoirs in wet regions are typically used for flood control and therefore designed to eliminate high flows. Release of the stored water later during dry periods results in increased low flows relative to natural conditions. Reservoirs used for water storage and irrigation in arid regions also remove high flows and release water during dry periods but are also often filled during fall and winter. Thus, reduced low flows in arid areas are likely due to consumptive use of water (Poff and others, 2007) or the filling of water-storage systems. This relation among climate, water management, and streamflow modification suggests that the occurrence and severity of streamflow modification will continue to shift because water-management strategies will evolve and adapt to long-term climatic changes in temperature and the timing and quantity of precipitation.

Long-term shifts in climatic conditions and resulting changes in water-management strategies will influence the type and severity of streamflow modification.

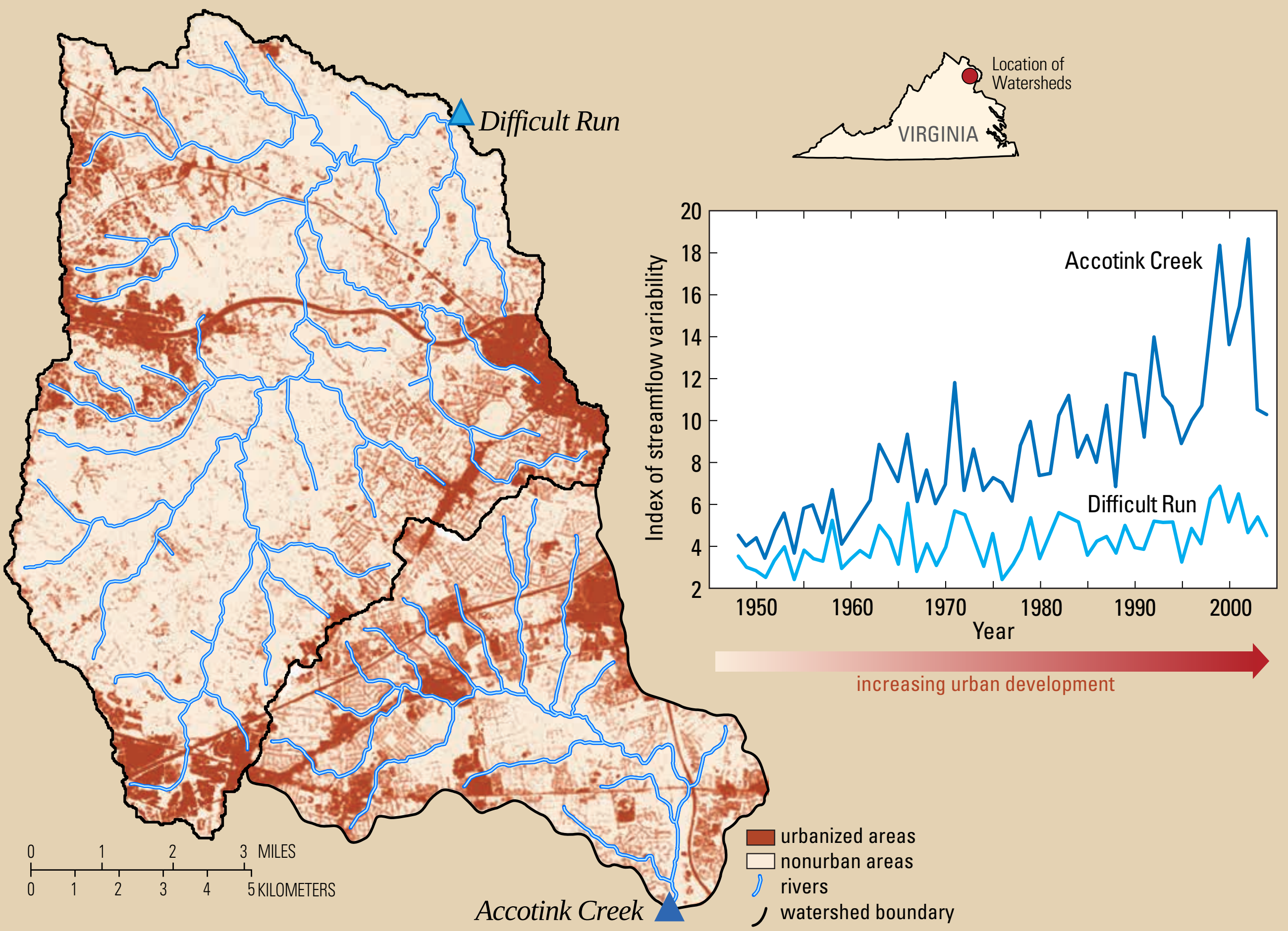
Streamflow Modification and Land Use

National-scale generalizations about streamflow modification and land use can be obscured by different land- and water-management practices within individual watersheds. In agricultural settings, drastically different types of streamflow modification can occur among adjacent segments of the same river because of the location and operations of specific water-management infrastructure. Flow during the non-irrigation season (for example, January) is typical of an unregulated stream—the flow magnitude increases with downstream distance. During the irrigation season (for example, August), streamflow in the Snake River fluctuates widely over its length in response to diversions, irrigation return flows, and groundwater discharge (Clark and others, 1998).



As shown by this map of the Snake River, Idaho, and graph, dramatic differences in streamflow modification can occur along different segments of the same river.

Local differences in land and water management within urban areas can also be dramatic. In general, urbanization reduces the amount of precipitation (rain and snow melt) that infiltrates into soils and groundwater, which causes increased variability in streamflows. However, there are intervening factors that can affect this pattern. For example, two adjacent watersheds in northern Virginia—Accotink Creek and Difficult Run—began to urbanize in 1950. Although streamflow variability was similar for the two streams in 1950, this similarity soon began to change. Over the next five decades, streamflow variability in Accotink Creek increased 100 to 500 percent. In contrast, streamflow variability in Difficult Run remained largely unchanged. The major differences between these watersheds is that the density of urban development is two times higher in Accotink Creek than in Difficult Run, which also has several small reservoirs in the headwaters that mitigate urban runoff. Also, the watershed of Accotink Creek is half the size of the Difficult Run watershed.



Local patterns of urbanization can lead to divergent effects on streamflow. This map shows urbanization that occurred in two adjacent watersheds in Virginia from 1950 to 2000. However, the expected increase in streamflow variability only occurred in Accotink Creek (see graph), which experienced much greater density of urban development within a smaller watershed than did Difficult Run.

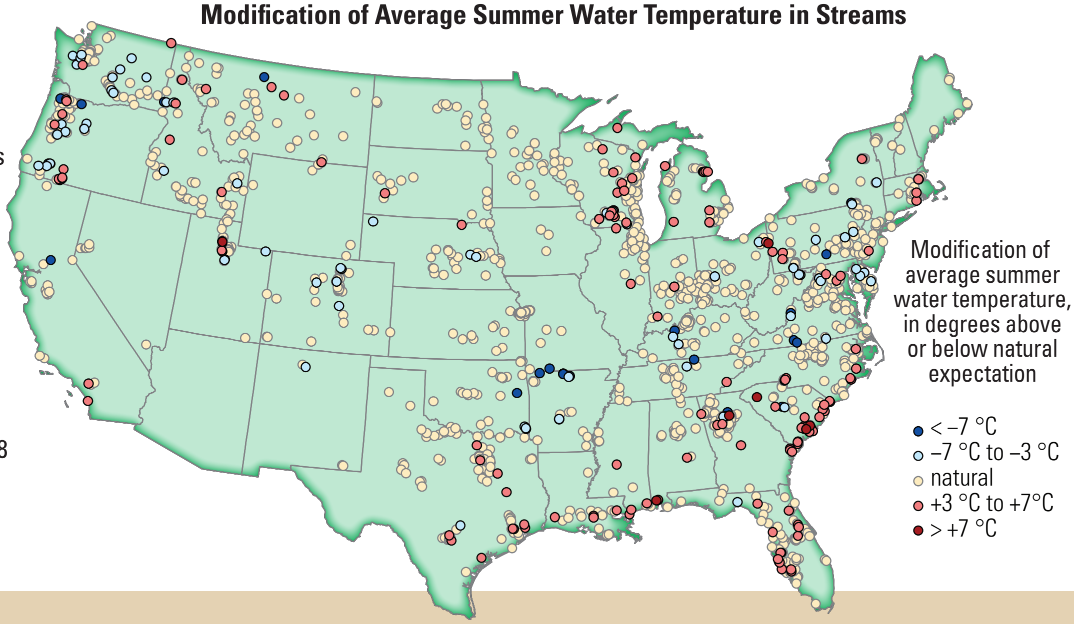
Summertime stream temperatures were modified throughout the Nation and in all types of land uses.

Stream Temperature

Most aquatic species have an optimal range of water temperature for growth and reproduction. Water temperature also influences water chemistry, such as the solubility of oxygen in water. As a result, water temperature has a major influence on water quality and stream health (chapter 2) (U.S. Environmental Protection Agency, 2002).

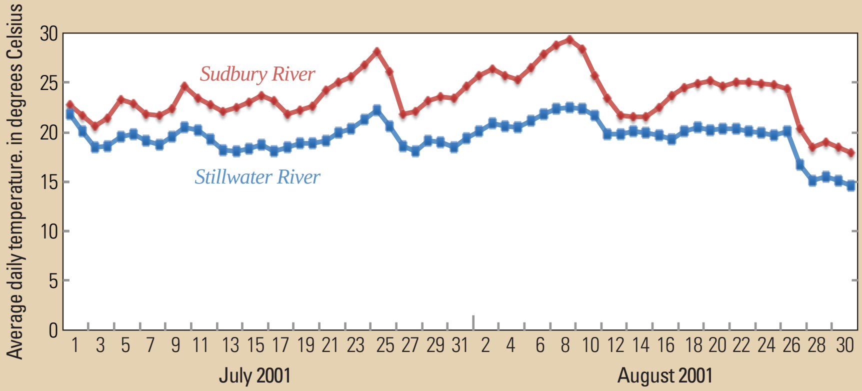
Average summertime water temperature was altered—either cooler or warmer than naturally expected—at 17 percent of assessed streams across the conterminous United States. A major cause of modified stream temperatures is the loss of shading from riparian trees, which occurs in all types of land-use settings. Because riparian tree canopies tend to insulate stream water from the surrounding air temperature, the loss of riparian trees can lead to warmer than natural temperatures in summer and cooler than natural temperatures in winter. Cooling of stream water can also result from artificial inputs of groundwater, water imported from other river basins, or the release of waters from the bottom of large reservoirs.

Modification of Average Summer Water Temperature in Streams



Map of the conterminous United States showing sites at which U.S. Geological Survey scientists measured summertime stream temperatures. Average summertime water temperature was either cooler or warmer than naturally expected in 17 percent of assessed streams. (A change of a degree Celsius (°C) is equivalent to a change of 1.8 degrees Fahrenheit (°F). <, less than; >, more than.)

Riparian-Tree Removal and Stream Temperature



U.S. Geological Survey photo by James Coles.

U.S. Geological Survey photo by Karen Beaulieu.

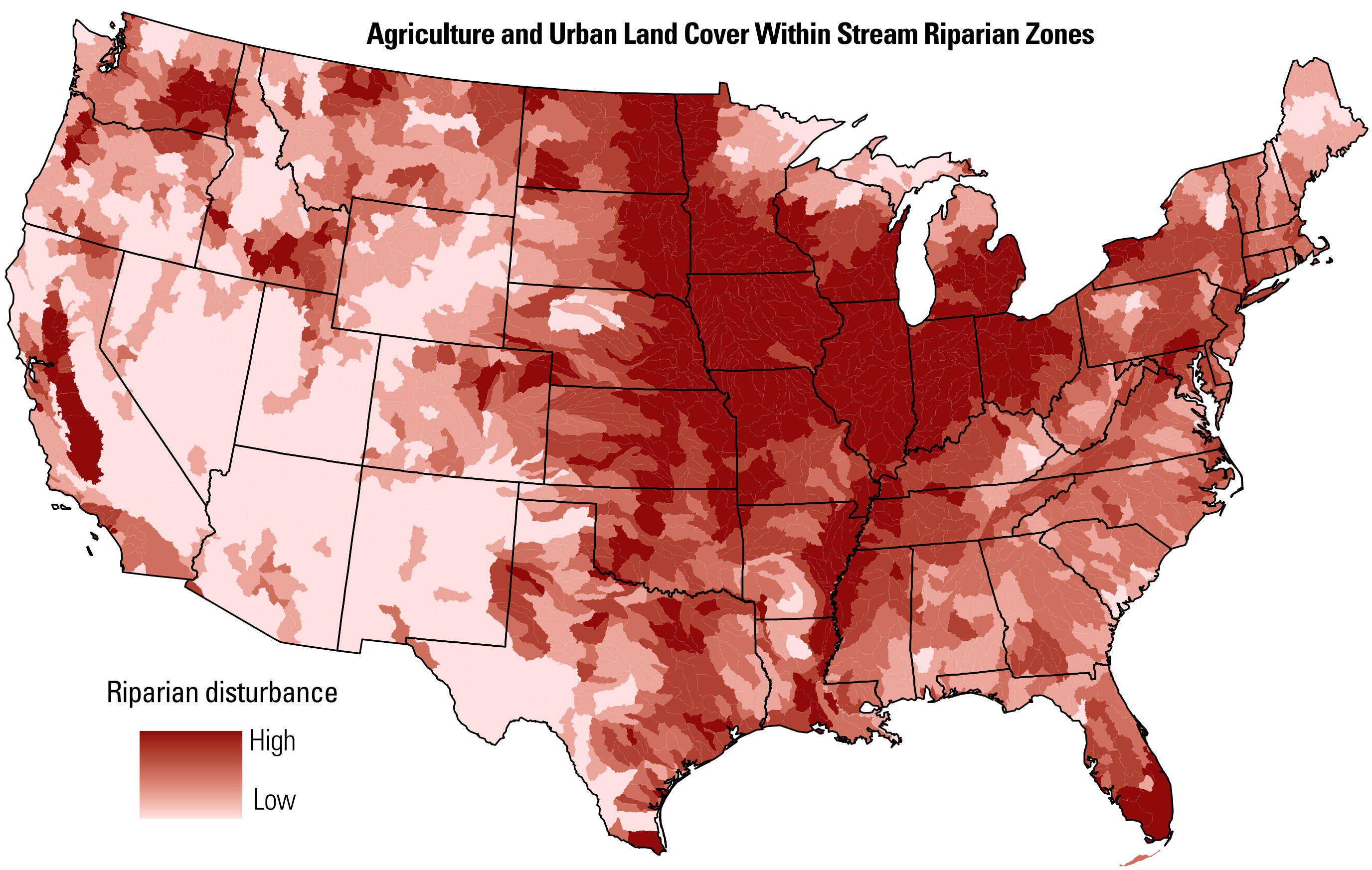
Streams in urban settings (top photo) often experience warmer than natural water temperatures due to the removal of riparian tree canopies. For example, the Sudbury River, Massachusetts, has lost 10 percent of its riparian zone to urban development and is also influenced by many small impoundments (such as in the foreground of top photo). As shown by this graph, daily water temperature in the Sudbury River averaged 3 degrees Celsius (°C) warmer than the nearby Stillwater River (bottom photo), which is within a forested watershed. (Temperature in degrees Fahrenheit = 1.8×°C+32.)

Stream Riparian Zones

Removal of stream-side trees and other natural vegetation by agriculture and urban development is widespread.

Stream-side trees and other vegetation, collectively known as riparian zones, are especially important to the health of stream ecosystems. This vegetation stabilizes stream banks and reduces soil erosion, provides food and habitat structure for stream organisms in the form of leaf litter and woody debris, and mitigates seasonal temperature extremes through shading of the stream channel (chapter 2). Manmade disturbance of riparian zones is identified as one of the major causes of reduced water quality and stream health nationwide (U.S. Environmental Protection Agency, 2006a).

Development of riparian zones and adjacent lands as a result of activities such as urbanization, agriculture, and mining often results in large-scale removal of stream-bank vegetation and other disturbances to riparian habitat. A national map of riparian land-cover development (see below) shows that disturbance to this important habitat is widespread but particularly severe in heavily agricultural areas such as the Midwest and western basins and in urban areas such as the Atlantic coast. Although other land-management activities, such as grazing and forestry, can also disturb riparian zones and are not represented on the map, this finding corroborates similar national assessments of stream habitats (Esselman and others, 2011) and supports the widespread concern that riparian-habitat loss is a potential cause of reduced stream health across the Nation (U.S. Environmental Protection Agency, 2006a).



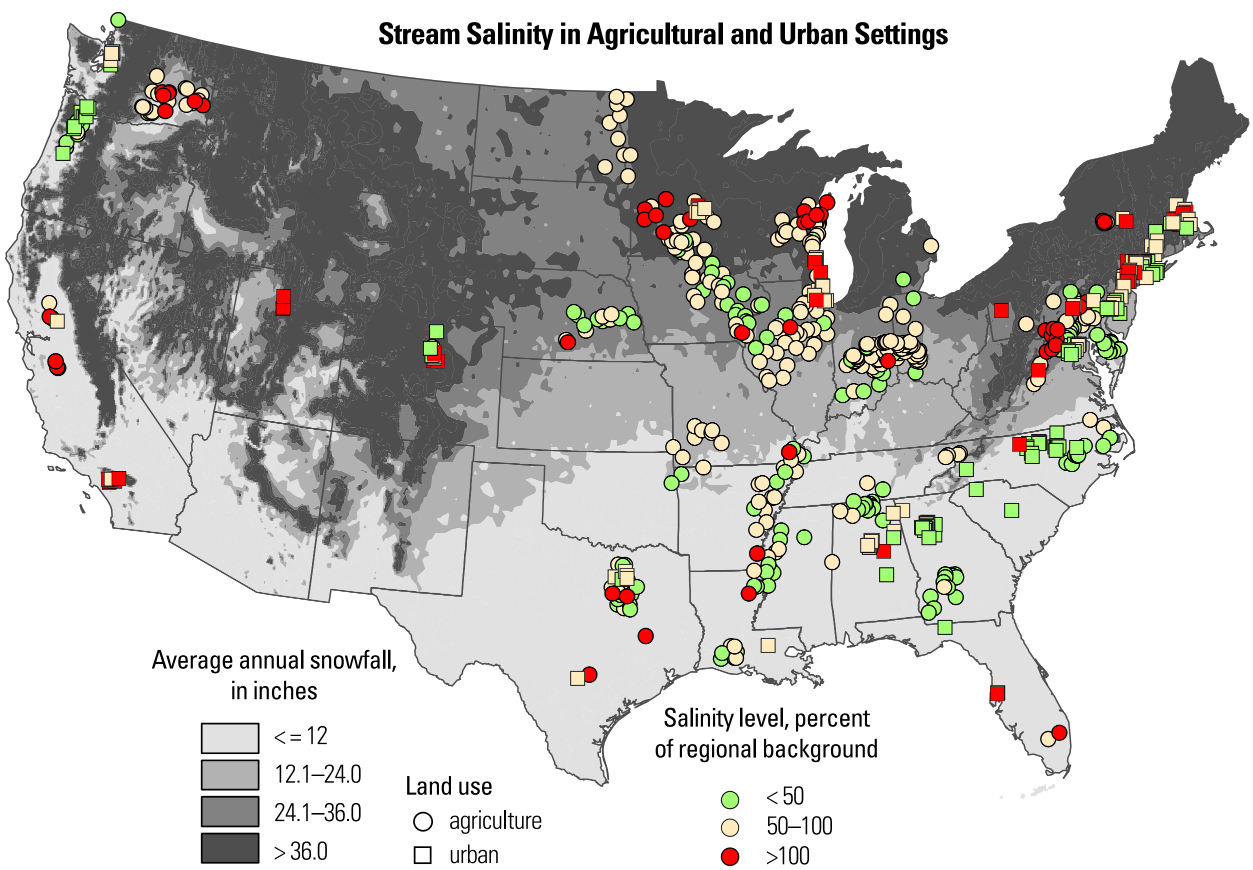
As this map of the conterminous United States shows, removal of streamside trees and other natural vegetation is widespread. Agricultural and urban land cover adjacent to streams and rivers occurs throughout the Nation but is more prevalent in regions like the Midwest and western agricultural areas. Riparian zones are defined as all lands within about 300 feet (100 meters) of streams. Importantly, this measure of riparian disturbance does not account for activities such as grazing and forestry, which can also disrupt riparian zones. (Source: National Land Cover Dataset 2006, http://landcover.usgs.gov/natlandcover.php.)

Elevated salinity levels in streams and rivers occur throughout the Nation in basins with substantial urban and agricultural land use.

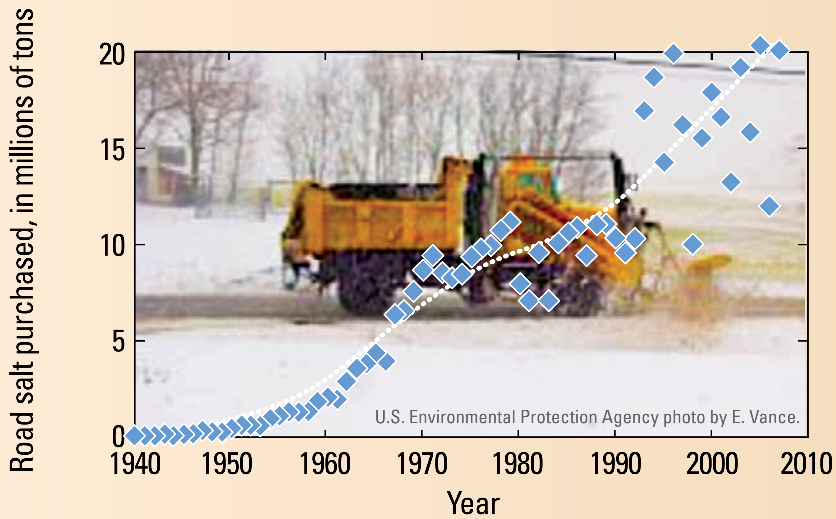
Stream-Water Salinity

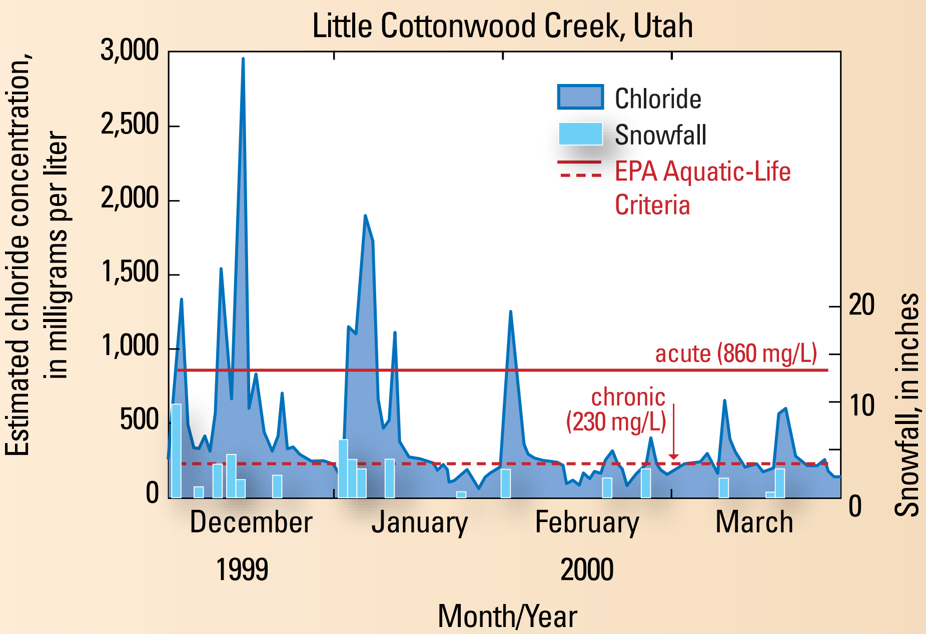
The salinity of stream water is influenced naturally by geologic and soil properties of the watershed, but there is growing concern that human activities are increasing stream salinity throughout the Nation (Kaushal and others, 2005). Excess salinity in streams is a growing issue because salt has many domestic, industrial, and municipal uses; salt use has increased dramatically over the past 50 years (Mullaney and others, 2009); and there is growing evidence that salts from human uses accumulate in soils and groundwater (Lindsey and Rupert, 2012), which poses long-term threats to streams.

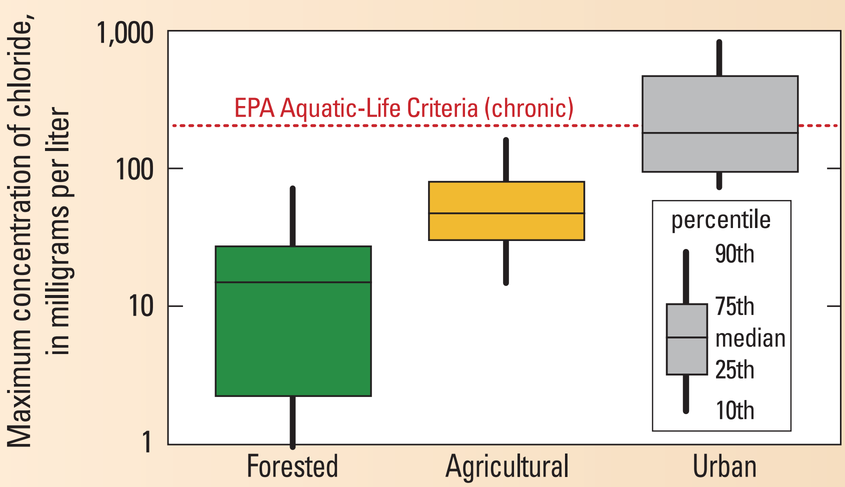
Streams with elevated salinity occur in urban and agricultural land-use settings throughout the Nation. Elevated salinity in urban settings is most prevalent in northern States that receive relatively high snowfall, which suggests that road de-icing is a major salt source (see facing page). Other sources of salinity in urban streams include waste-water effluent and aged septic systems. Elevated salinity in agricultural streams occurs throughout the Nation. The largest sources of excess salinity in agricultural streams include fertilizer applications and irrigation wastewater (Mullaney and others, 2009). Stream salinity in rural watersheds has also been linked to salt applications on roadways (Kelly and others, 2008).



This map shows stream salinity in the conterminous United States. Elevated salinity in urban streams is most prevalent in northern States that receive substantial amounts of snowfall. Elevated salinity in agricultural streams occurs throughout the Nation. Salinity was considered "elevated" for NAWQA stream sites where measured electrical conductivity, a measure of salinity, exceeded regional background levels. (<, less than; >, more than.)







Road De-icing and Stream Salinity

One source of elevated salinity in streams, particularly in urban and suburban areas, is the application of salt to roadways. The purchase of rock salt for highway use has increased dramatically over the past 70 years (Salt Institute, 2010). Although this application makes roadways safer for travel, once the salt dissolves it runs off roads and into soils and streams. Annually, nearly 9.5 million tons of salt is estimated to run off into streams in the United States (Stefan and others, 2008). Salt that percolates throughout soils can enter and remain in groundwater for months to years, leading to long-term increases in groundwater salinity.

NAWQA studies found evidence that road de-icing salts contributed to increased salinity in streams. For example, chloride concentrations (a measure of stream salinity) as high as 3,000 milligrams per liter (mg/L; 1 mg/L = 1 part per million) were recorded in an urban stream in Utah and often exceeded U.S. Environmental Protection Agency (EPA) guidelines for freshwater aquatic life. Peaks in salinity were associated with snowfall events (Waddell and others, 2004).

A regional analysis by NAWQA showed that elevated salinity in streams is widespread in urban areas of northern States (Mullaney and others, 2009). Chloride concentrations were higher in streams in urban areas than in those in agricultural areas and forests. In urban streams, the highest levels of chloride were measured during the winter months when salt and other chemicals are used for de-icing.

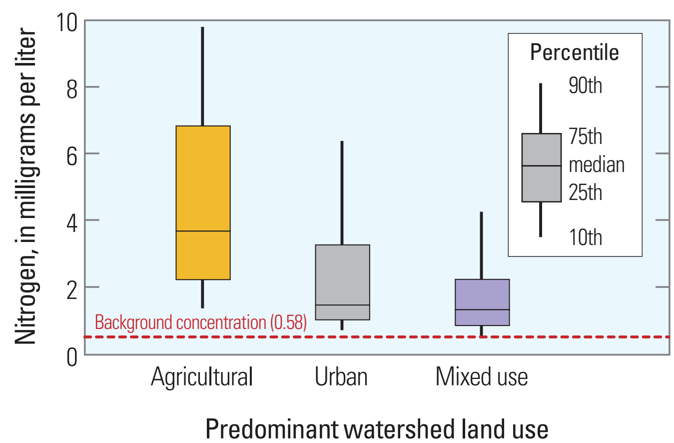
Nutrient concentrations in stream water are as much as six times greater than background levels in urban and agricultural lands across the Nation.

Nutrients in Stream Water

Although plant nutrients such as nitrogen and phosphorus are a basic need of aquatic ecosystems, excessive nutrients can have harmful effects on stream health (chapter 2). Nutrient concentrations in streams are directly related to water management, land use and associated fertilizer applications, and animal wastes in upstream watersheds.

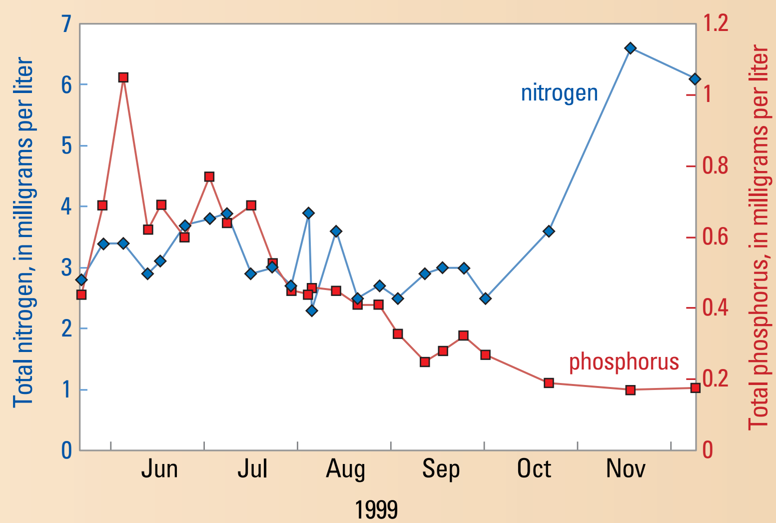
NAWQA conducted a national assessment of nutrient concentrations in streams and groundwater from 1992 through 2004 (Dubrovsky and others, 2010). Total nitrogen concentrations were higher in agricultural streams than in streams draining urban, mixed land-use, or undeveloped areas, with a median concentration of about 4 milligrams per liter (mg/L; 1 mg/L = 1 part per million)—about 6 times greater than background concentrations. Nitrogen concentrations in agricultural streams generally were highest in geographic areas such as the Northeast, Midwest, and the Northwest—which are areas with some of the most intense applications of fertilizer and manure in the Nation. Surveys by other Federal (U.S. Environmental Protection Agency, 2006a) and State agencies (http://iaspub.epa.gov/waters10/attains_nation_cy.control) have also reported that excess nutrients were among the leading factors associated with reduced stream health throughout the Nation.

This graph shows that across the Nation concentrations of total nitrogen measured by NAWQA were higher in agricultural streams than in urban or mixed land-use streams. (1 milligram per liter = 1 part per million.)

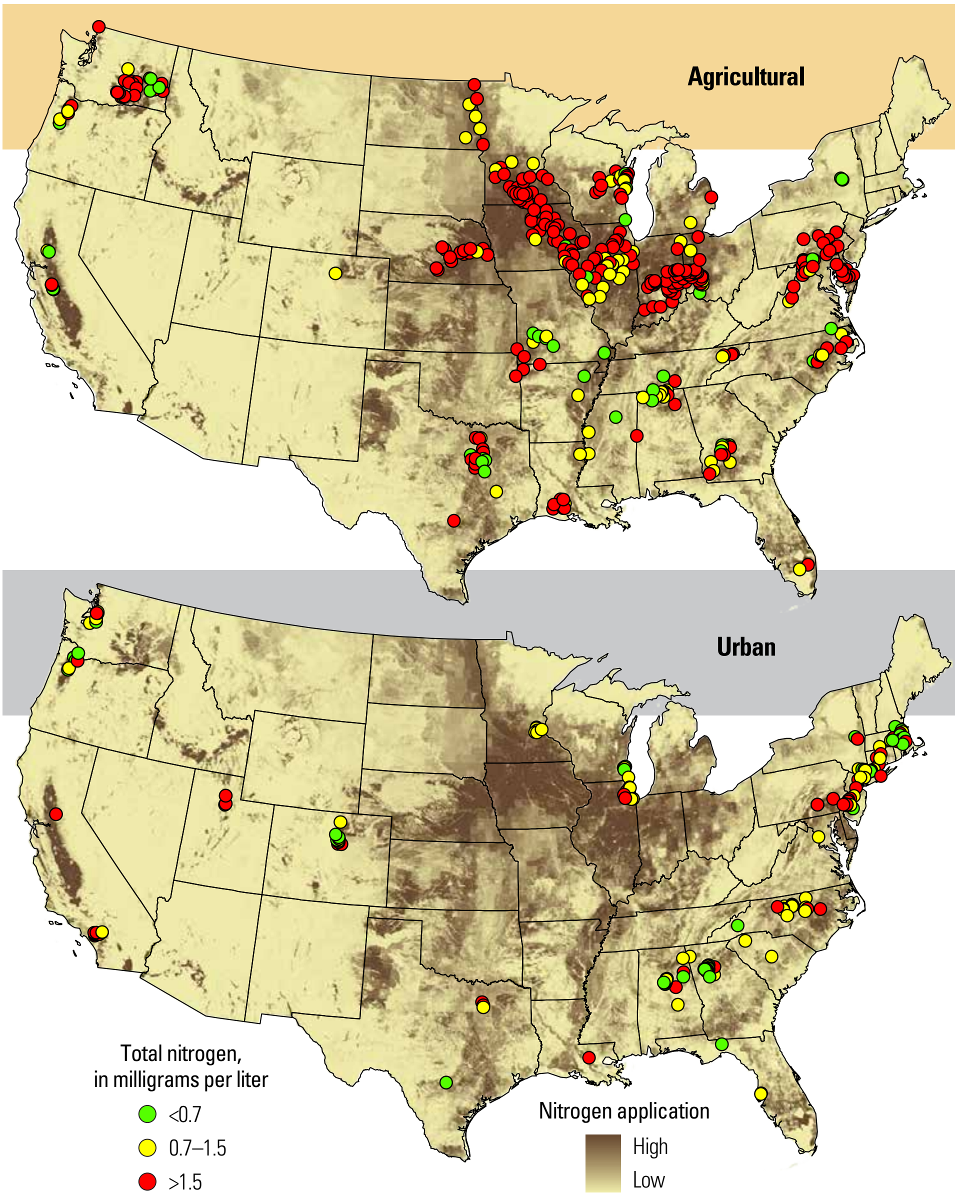


Nutrient Concentrations in Streams Vary Seasonally

Concentrations of nitrogen and phosphorus in streams vary in response to their major transport pathways. An example of this is Granger Drain, Washington. This graph shows that nitrogen concentrations are highest during the non-irrigation season (fall and winter months), when groundwater is the primary source of water to the stream, whereas phosphorus concentrations are highest during the irrigation season (spring and summer months), when surface runoff transports phosphorus-rich sediment to the stream (Fuhrer and others, 2004). (1 milligram per liter = 1 part per million.)



Nitrogen Concentrations in Streams



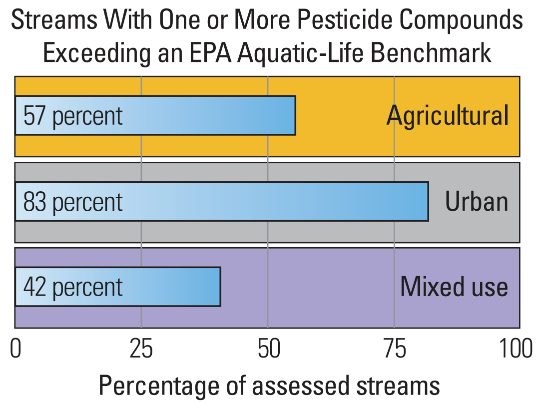
These maps of the conterminous United States show that total nitrogen concentrations measured by NAWQA were generally highest in streams within agricultural areas of the Midwest, Northwest, and Northeast, where the highest nitrogen fertilizer applications occur. Total nitrogen concentrations in urban areas were typically at intermediate levels. (<, less than; >, greater than.)

One or more pesticides exceeded Aquatic-Life Benchmarks in more than half of the streams assessed.

Dissolved Pesticides in Stream Water

Pesticides frequently occur in stream water in both agricultural and urban land-use settings and typically reflect patterns of land use in the watershed. NAWQA made a comprehensive national assessment of pesticide concentrations in streams from 1992 through 2001 and found that 56 percent of assessed streams had one or more pesticides in water that exceeded at least one U.S. Environmental Protection Agency Aquatic-Life Benchmark (Gilliom and others, 2006). Urban streams had pesticide concentrations that exceeded one or more benchmarks at 83 percent of sites—mostly for the insecticides diazinon, chlorpyrifos, and malathion. Agricultural streams had concentrations that exceeded one or more benchmarks at 57 percent of sites—most frequently for chlorpyrifos, azinphos-methyl, atrazine, dichlorodiphenyldichloroethylene (a breakdown product of DDT), and alachlor.

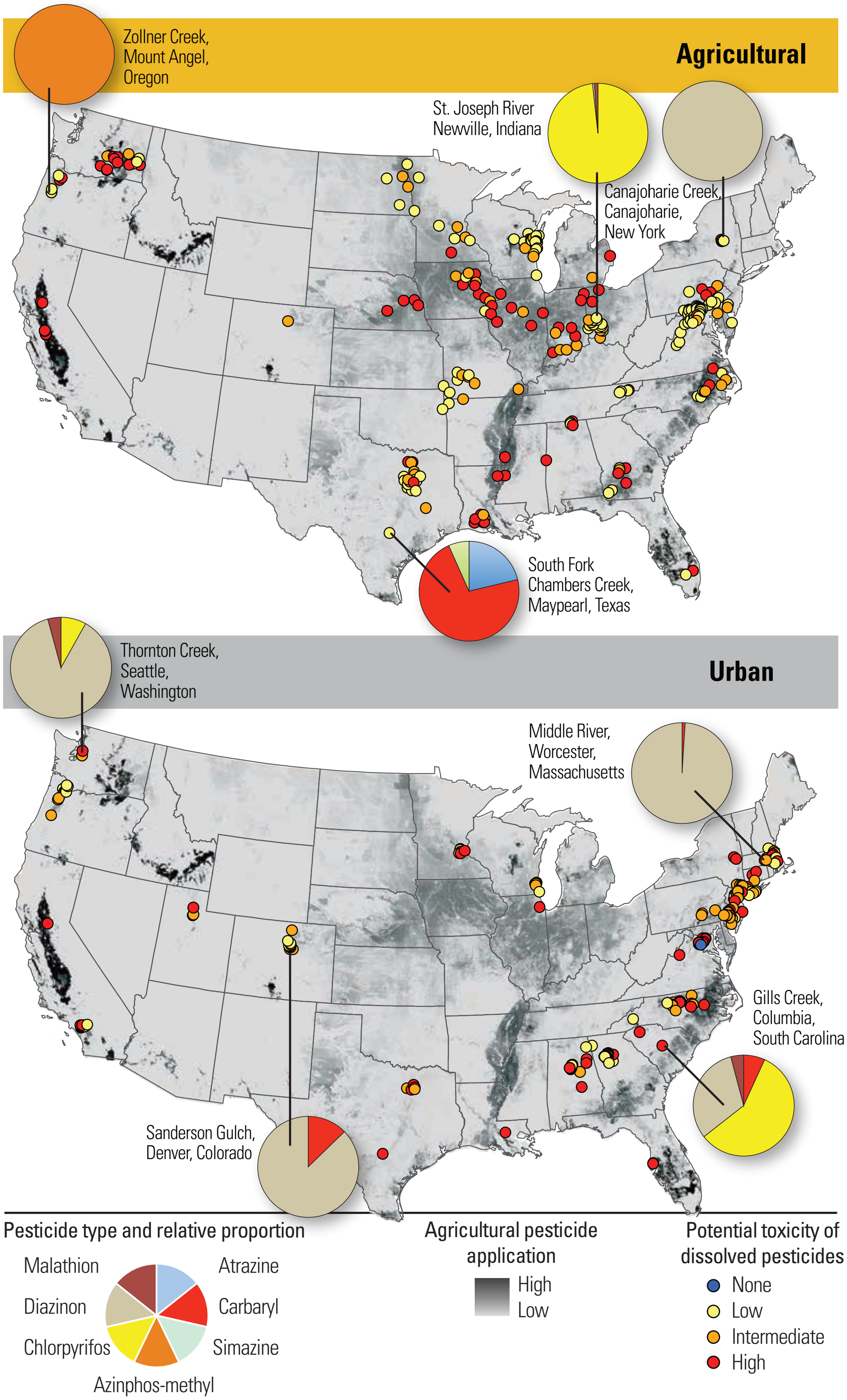
NAWQA found that across the Nation, pesticides have the ability to affect aquatic life, particularly in urban areas. This bar graph shows the relatively high proportion of urban streams with concentrations greater than U.S. Environmental Protection Agency (EPA) Aquatic-Life Benchmarks.



The specific pesticide compounds contributing to the potential toxicity of pesticide mixtures vary geographically according to their use across the Nation (see facing page). Insecticides are the dominant compounds contributing to potentially high toxicity, largely because these compounds have much lower toxic thresholds than other pesticides due to the fact that they were designed to kill insects. For example, the insecticide chlorpyrifos was used during the study period in both urban and agricultural areas, such as on corn in the central United States and suburban lands in South Carolina. Diazinon was also used extensively in urban areas across the Nation, as well as in some agricultural areas. Other heavily used insecticides include malathion, azinphosmethyl, and carbaryl, which were also used in agricultural and urban areas (Gilliom and others, 2006).

Estimating the Potential Toxicity of Pesticide Mixtures

The toxicity of dissolved pesticide mixtures was estimated by NAWQA using a pesticide toxicity index (PTI) (Munn and others, 2006; Gilliom and others, 2006). The PTI accounts for the concentration of each compound measured in a water sample, the toxicity of each compound measured, and the possibility that multiple compounds have additive effects on aquatic organisms. Importantly, the PTI does not measure actual toxicity but is a relative index of potential toxicity—the higher the PTI value, the greater the potential toxicity of dissolved pesticides. The PTI is based on available toxicity data for major groups of aquatic organisms (Munn and others, 2006). In this Circular, the PTI for cladocerans (small crustaceans found in most freshwater habitats) was used because toxicity data for this common invertebrate are available for a large number of compounds. Relations among PTI and biological communities were therefore only examined for macroinvertebrates. For each stream site, PTI values were computed for each water sample collected within 90 days before macroinvertebrates were collected. The maximum of these separate PTIs was used to indicate the potential for toxicity of dissolved pesticides at each site.



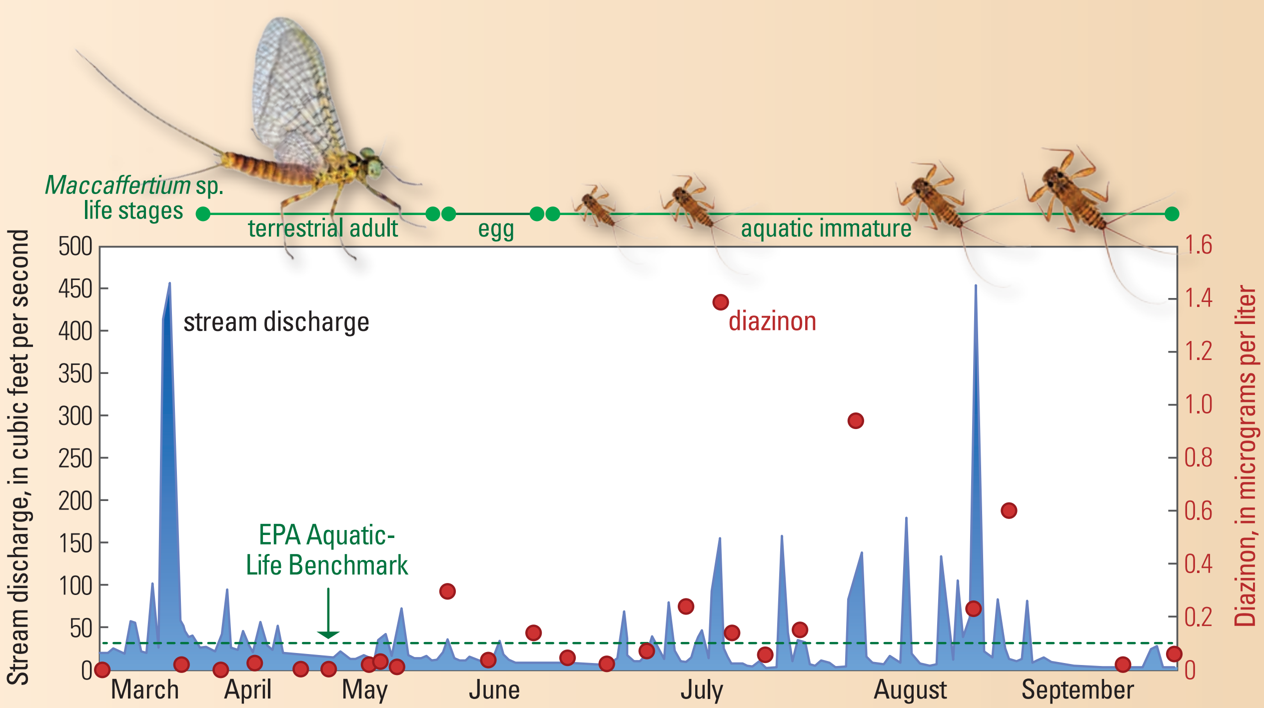
These maps of the conterminous United States show the potential toxicity of pesticide mixtures in agricultural and urban areas during a 1992–2001 NAWQA study (Gilliom and others, 2006). Patterns in the relative contribution of different pesticides to the potential toxicity of mixtures reflect the geographic distribution of crop types among agricultural settings. Insecticides were the dominant pesticides contributing to potential toxicity. In urban settings, diazinon was the dominant insecticide contributing to potential toxicity, but sales for residential use were phased out by the U.S. Environmental Protection Agency at the end of 2004.

The pesticides contributing to the potential toxicity of mixtures vary geographically according to their use across the Nation.

Pesticide Concentrations in Stream Water Vary Seasonally

Pesticide concentrations in stream water vary by season, with lengthy periods of low concentrations punctuated by seasonal pulses of much higher concentrations. This variation occurs because transport to streams is controlled, in large part, by the timing of precipitation and associated runoff relative to pesticide applications (Leonard, 1990). For example, before sales for residential use were phased out in 2004, diazinon was commonly used during the growing season to control insects on lawns and gardens. During 1994, concentrations of diazinon during summer frequently exceeded levels known to be harmful to aquatic life in Accotink Creek, Virginia (see map earlier in this chapter).

Seasonal variation in pesticide concentrations in stream water has important biological implications because of the timing of the life cycles of aquatic organisms. For example, aquatic insects are especially vulnerable to dissolved contaminants early in life because of their relatively small body sizes (Liess and others, 2005). A mayfly, *Maccaffertium* sp., that was common in a nearby reference stream was absent from Accotink Creek (see graph below). This aquatic insect species emerges from the stream as a terrestrial adult during the spring, then deposits fertilized eggs back into the water soon thereafter. By early summer, the eggs hatch and the small immature insects begin their aquatic life. This species would have been extremely vulnerable to diazinon and likely was eliminated from Accotink Creek because its early life stages coincided with the highest concentrations of dissolved insecticides. (EPA, U.S. Environmental Protection Agency; 1 microgram = 1 part per billion.)



Streamflow and diazinon concentrations in Accotink Creek, Virginia, 1994

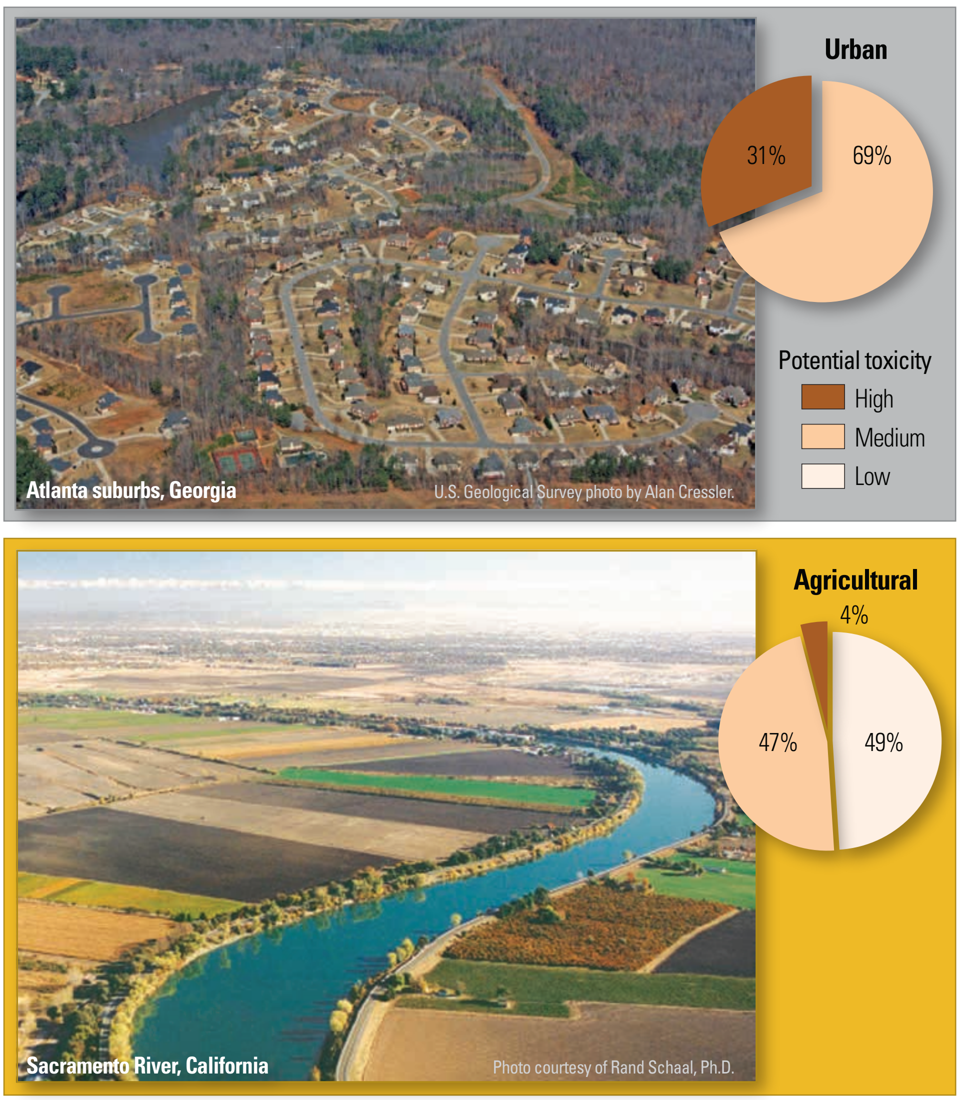
Pesticides and Other Organic Contaminants in Stream Sediments

NAWQA found that contaminants associated with streambed sediments were frequently present at concentrations that may adversely affect stream health. A national assessment of the occurrence and distribution of contaminants in streambed sediments reported that U.S. Environmental Protection Agency Aquatic-Life Benchmarks for pesticide compounds were exceeded at 70 percent of assessed streams in urban settings and 30 percent of streams in agricultural settings (Gilliom and others, 2006). As with dissolved pesticides, sediment contaminants generally occurred in complex mixtures of multiple compounds.

Potentially toxic sediment-contaminant mixtures occurred in 31 percent of urban streams, compared to 4 and 6 percent in agriculture and mixed-use settings, respectively. This finding suggests that relative to other land-use settings, human activities in urban areas lead to higher amounts of contaminants in stream sediments, which is consistent

The potential toxicity of contaminant mixtures in stream sediments was higher in urban than in agricultural streams.

Land Use and the Potential Toxicity of Sediment Contaminants



NAWQA found that the potential toxicity of sediment contaminants in streams in the United States was highest in urban areas. Mixtures most likely to be toxic occurred in 31 percent of urban streams (top photo), compared to just 4 percent of agricultural streams (bottom photo). (%, percent.)

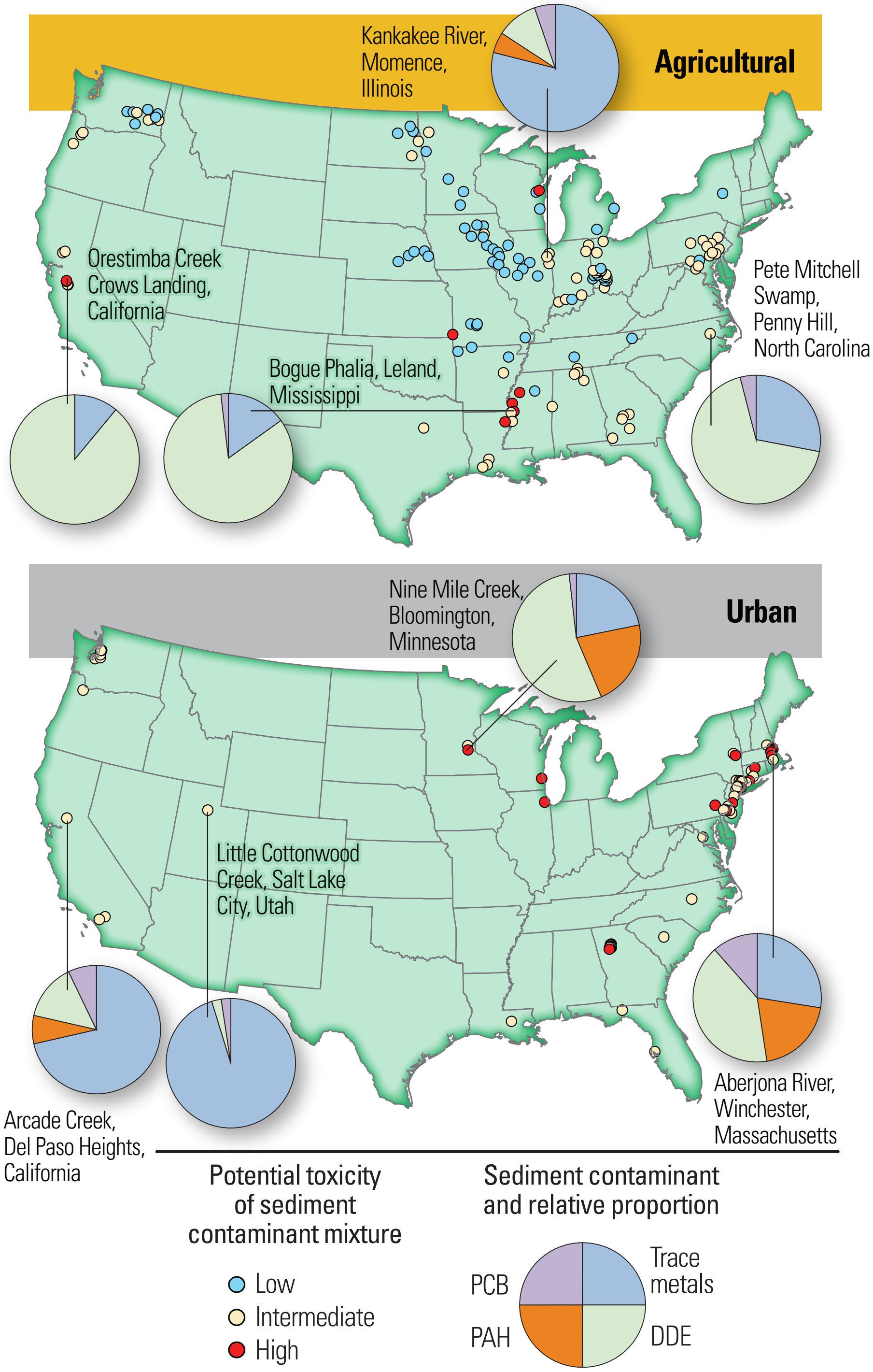
Estimating the Potential Toxicity of Streambed-Sediment Contaminants

An index of relative potential toxicity derived from scientific consensus-based freshwater sediment-quality guidelines was used to assess the potential effects of sediment contaminant mixtures on biological condition (MacDonald and others, 2000). Each contaminant in a sample is divided by its respective sediment-quality guideline (SQG), which is the concentration above which toxic effects are expected based on laboratory toxicity tests. The mean SQG provides a basis for screening whether sediment samples are toxic to aquatic life (Long and others, 2006).

NAWQA sediment samples were categorized into one of three ranges of mean SQGs identified by Long and others (2006) that represent classes of increasing likelihood of toxicity to sediment-dwelling aquatic organisms. Importantly, mean SQGs include only those compounds for which sediment-quality guidelines have been developed and include organochlorine insecticides, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and trace metals such as mercury and zinc. Other important limitations of this approach are presented in Long and others (2006).

with other NAWQA studies that found high concentrations of pesticides and other organic contaminants (Bryant and others, 2007) and trace elements (Coles and others, 2012) in urban streams.

The types of compounds contributing to potential sediment toxicity are related to land use (see facing page). In agricultural areas, high potential toxicity was largely the result of elevated concentrations of legacy organochlorine compounds, such as DDT. In urban areas, high potential toxicity was mostly the result of elevated concentrations of polycyclic aromatic hydrocarbons (PAHs), many of which are known to be highly toxic to aquatic life (Albers, 2003). Recent USGS studies (Mahler and Van Metre, 2011) have identified coal-tar-based sealcoat—the black, viscous liquid sprayed or painted on asphalt pavement such as parking lots—as a major source of PAH contamination in urban areas for large parts of the Nation. Macroinvertebrates are particularly susceptible to PAH contamination, especially those that live in the fine stream-bed sediments where PAHs tend to accumulate.



NAWQA studies found that patterns in the relative contribution of different compounds to potential toxicity of sediment-contaminant mixtures reflect dominant land uses in a watershed. As shown on these maps of the conterminous United States, sediment-contaminant mixtures in agricultural sites often include legacy organochlorine insecticides such as dichlorodiphenyldichloroethylene (DDE), which is a breakdown product of dichlorodiphenyltricloroethane (DDT). More generally, sediment-contaminant mixtures in urban streams are often dominated by polycyclic aromatic hydrocarbons (PAHs). Polychlorinated biphenols (PCBs) are another major contaminant.

Chapter 5 Biological-Condition Assessment

Algae, macroinvertebrates, and fish are the biological communities most often evaluated in water-quality assessments by local, State, and Federal authorities. Each of these communities represents a different functional role in the ecosystem, responds in different ways to manmade environmental change, and thus provides different and complementary perspectives on water quality and stream health.

U.S. Geological Survey photo of mayfly (Ephemeroptera) by Daren Carlisle.

U.S. Geological Survey photo of longear sunfish *(Lepomis megalotis)* by Billy Justus.

Alteration of biological communities was evident in more than 80 percent of streams assessed by NAWQA, regardless of land use.

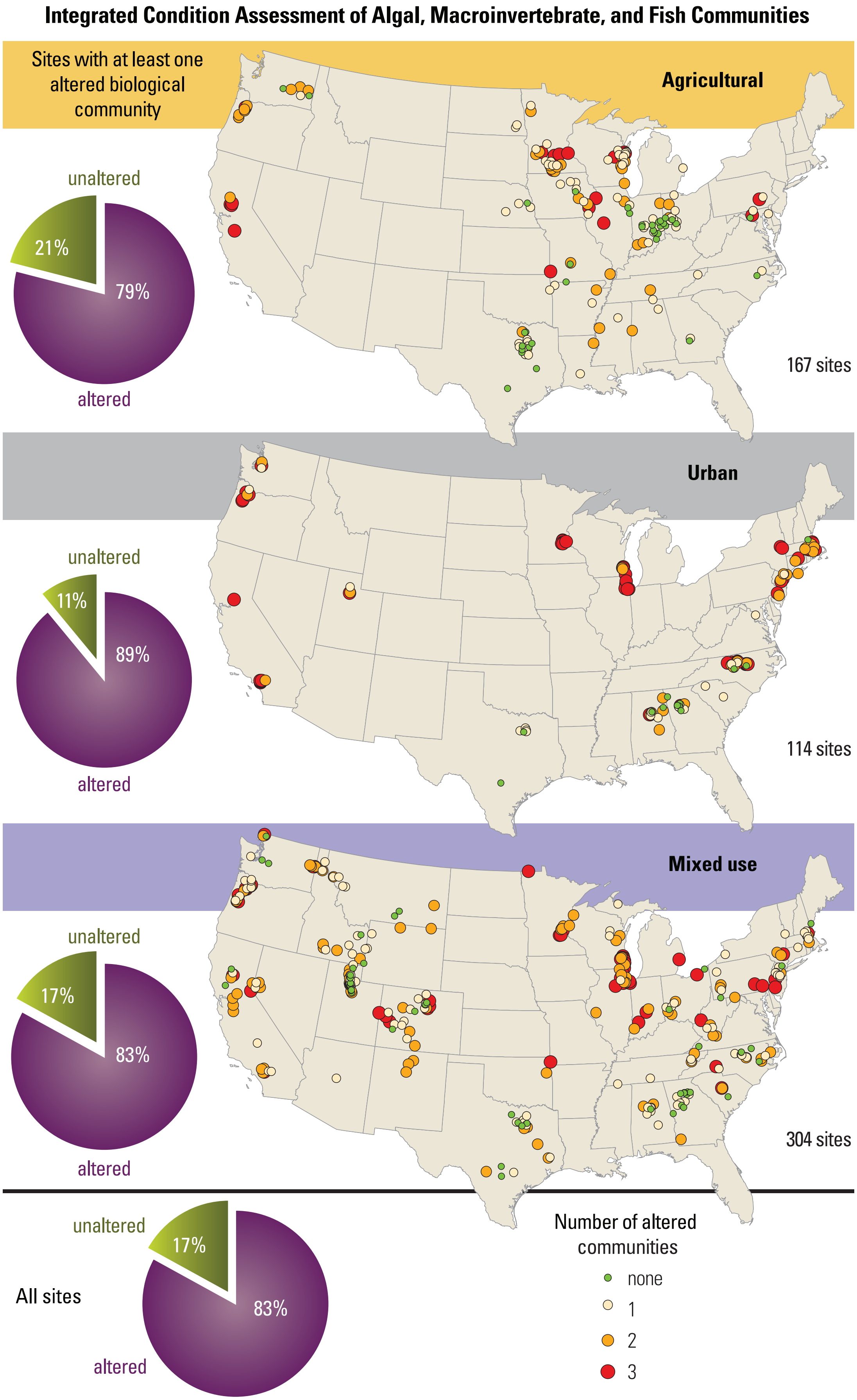
Integrated Assessments of Algal, Macroinvertebrate, and Fish Communities

Across all land-use settings (see facing page) at least one biological community was altered in 83 percent of assessed streams. In urban settings, 89 percent of assessed sites had at least one altered biological community, compared with 79 percent of sites in agricultural settings and 83 percent of sites in mixed-use lands. All three biological communities were altered in 22 percent of assessed streams. A biological community was classified as altered if the numbers and types of organisms in it were substantially different from its natural potential, as estimated from regional reference sites (chapter 3). The high incidence of altered biological communities in all land-use settings suggests that stream health is threatened by a wide variety of land and water-use activities across the Nation (chapter 2). These findings are also corroborated by a recent national survey confined to macroinvertebrate communities (U.S. Environmental Protection Agency, 2006a) that found substantial biological alteration in two-thirds of the Nation's streams. In summary, these findings show that biological communities—and by inference, stream health—have been widely disrupted by land and water management in the Nation's watersheds.

Streams with unaltered biological communities were present in 11 to 21 percent of assessed streams in all land-use settings. Further, a wide range in biological condition scores was found among streams within each land-use setting (page 77 of this chapter), which indicates that the influences of land and water management on stream health differ widely across the Nation. This variation occurs, in part, because of local and regional differences in land and water-use activities. For example, agricultural settings across the Nation range from pasture lands with little or no chemical applications and soil disturbance to intensively managed row crops where soil disturbance, chemical use, and water management are comparatively intense.

Understanding NAWQA's Assessment of Biological Communities

NAWQA used a consistent approach for assessing the biological condition of algae, macroinvertebrate, and fish communities across the diverse landscapes of the Nation. Biological condition was assessed by comparing observed (O) community attributes (such as number of native species) to those expected (E) if the community was minimally disturbed by human activities. The observed attribute (O) is derived from a sample collected at the stream site being assessed, whereas the expected (E) condition is estimated from data collected at a set of environmentally similar reference sites. Because variation in environmental settings is accounted for in this approach, departures of O from E are likely the result of human-caused changes to the stream environment. Further, because O:E is standardized to each stream's natural potential (that is, expressed as a percentage of the expected condition), data can be aggregated and interpreted across diverse geographic regions. Each biological community was classified as "altered" if its O:E value was less than that of 90 percent of the reference sites within its respective region; otherwise, sites were classified as "unaltered" (chapter 3). For the integrated assessment, a stream was considered biologically altered if any one community was altered. This approach assumes that each of the three communities has equal ecological importance, which is reasonable given the major roles of algal, macroinvertebrate, and fish communities in stream ecosystems (chapter 2).



These maps of the conterminous United States show the locations of 585 streams where NAWQA performed integrated assessments of multiple biological communities. Regardless of land-use setting—agricultural, urban, or mixed use—at least one biological community—algae, macroinvertebrates, or fish—was altered, relative to regional reference conditions, at 83 percent of the streams. (%, percent.)

Stream assessments based on a single biological community may underestimate the scope of biological alteration due to human activities.

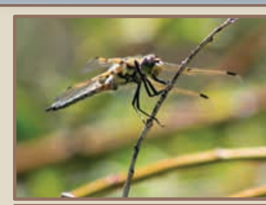
When integrated assessments of all three biological communities are compared to assessments limited to a single community, it is evident that single-community assessments underestimate the scope of biological alteration—especially in agricultural and mixed-use areas. Specifically, 79 percent of agricultural streams contained at least one altered community if all three communities are assessed, versus 37 to 52 percent if assessments are limited to algal, macroinvertebrate, or fish communities alone. Similarly, multicommunity assessments in mixed-use areas show at least one altered community in 83 percent of streams, versus 40 to 61 percent if only a single community is assessed. In contrast, the percentage of altered streams in urban streams increases less dramatically with the inclusion of all three communities (89 percent versus 69 to 70 percent). In all land-use settings, assessments based on any two biological communities reveal a similar number of altered communities as do assessments of all three communities. These findings suggest that, as a general rule, biological assessments should include at least two communities to detect changes to stream health resulting from land and water management—although the identity of the communities to be assessed will likely vary among regions and the types of manmade disturbances that prevail.

The consistency of single-community assessments in urban areas may be related to the severity of urban-related effects on streams relative to other land-use settings. In predominantly urban basins, human modifications to the physical and chemical characteristics of streams are often pervasive and severe (Coles and others, 2012), and therefore all biological communities are strongly affected and yield similar assessment results. In contrast, human modifications to streams in agricultural and mixed-use areas are often more variable than those in urban basins. For example, agricultural basins include a wide range of agricultural practices and intensity of landscape disturbance (chapter 2, page 78 of this chapter, and chapter 6).

Assessments limited to a single biological community may not detect the effects of land and water management on stream health because individual biological communities have different sensitivities to manmade changes to the physical and chemical conditions of streams. Organisms differ in their traits and, therefore, their preference for and tolerance to different types of physical and chemical conditions. Indeed, the traits of species that persist in communities that have been altered by human influences often provide clues about which physical or chemical changes may have caused stream health to decline (page 76 of this chapter). Relative to natural communities, the dominant species in altered algal communities often require high levels of nutrients or are tolerant of elevated salinity, which indicates the presence of excessive nutrients and salinity in stream water. Altered macroinvertebrate communities are often dominated by species that burrow into streambed sediments, indicating that excessive loading of fine sediments has buried coarse rocks on the streambed. Similarly, native fish species that nest in gravel are often replaced by non-native species that scatter their eggs throughout the stream, indicating that human influences have led to highly fluctuating and unpredictable habitat conditions—which often occur when streamflows are depleted or artificially variable.

Assessment Tools

Building Databases for Future National Assessments

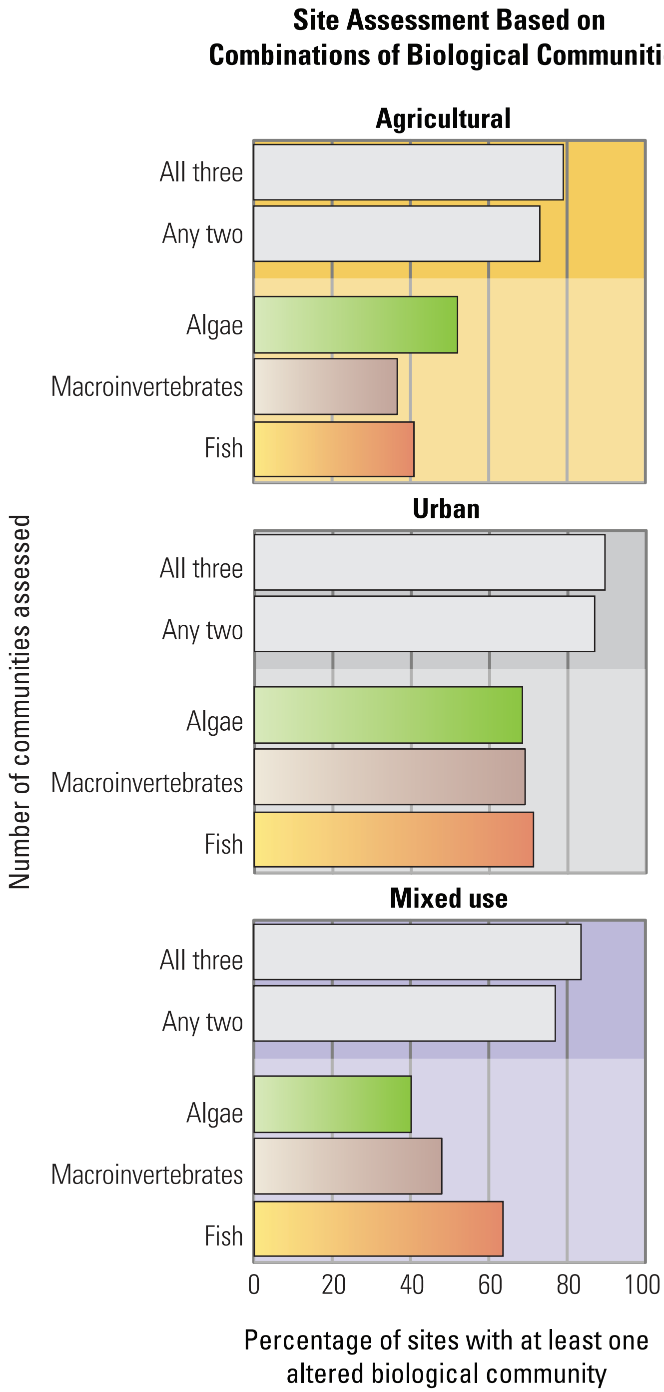


Species traits are important to assessments of biological condition and the interpretation of those assessments (chapter 2). For example, knowing something about the habitat requirements of the native species eliminated from a stream that has been influenced by a reservoir would provide important clues about what factors may have caused the changed biological condition. If, for example, the eliminated species required a specific range of water temperatures, this would be a clue that alteration of the temperature regime is likely to have caused changes to biological communities.

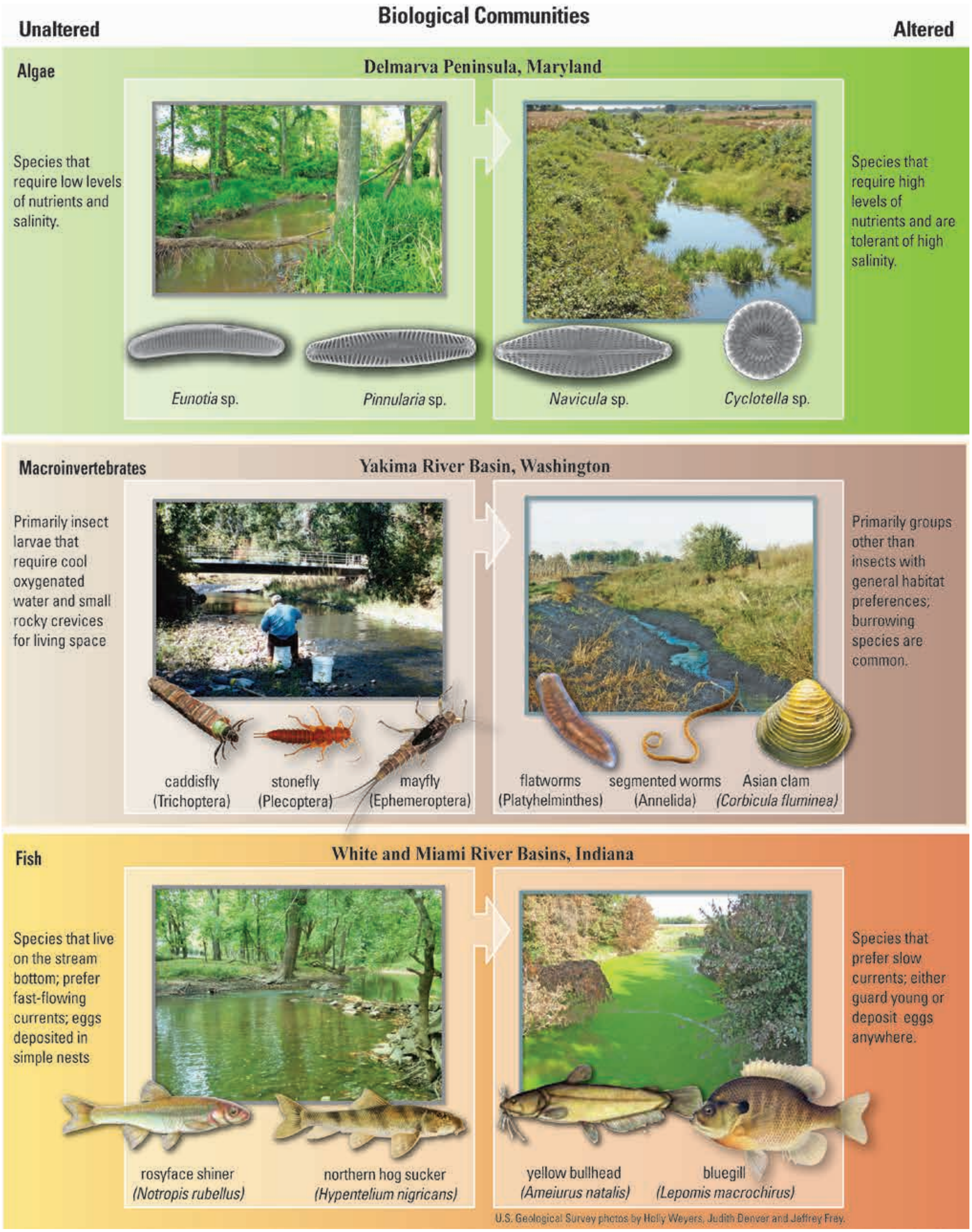
Species traits include information about body shape, feeding preferences, habitat requirements, reproductive strategies, and tolerance to specific pollutants.

Unfortunately, information on species traits is often hard to find because it is scattered throughout published and unpublished literature. NAWQA led efforts to compile species trait information for algae, macroinvertebrates, and fish of the United States. This information is now available at http://water.usgs.gov/nawqa/ecology/.

Utah Department of Environmental Quality photo of mottled sculpin by Ben Holcomb, photo of dragonfly courtesy of Jason Carlisle, U.S. Geological Survey photo of algae (diatoms) by Sarah Spaulding.



These graphs show that NAWQA assessments of any individual biological community—algae, macroinvertebrates, or fish—always indicated fewer streams to be in poor health than did assessments of two or more communities. This difference was larger in agricultural and mixed land-use settings than in urban settings. Assessments of any combination of two biological communities resulted in twice the number of streams being identified as having poor health, compared to single-community assessments. A stream was considered to be in poor health if at least one biological community in it was altered.



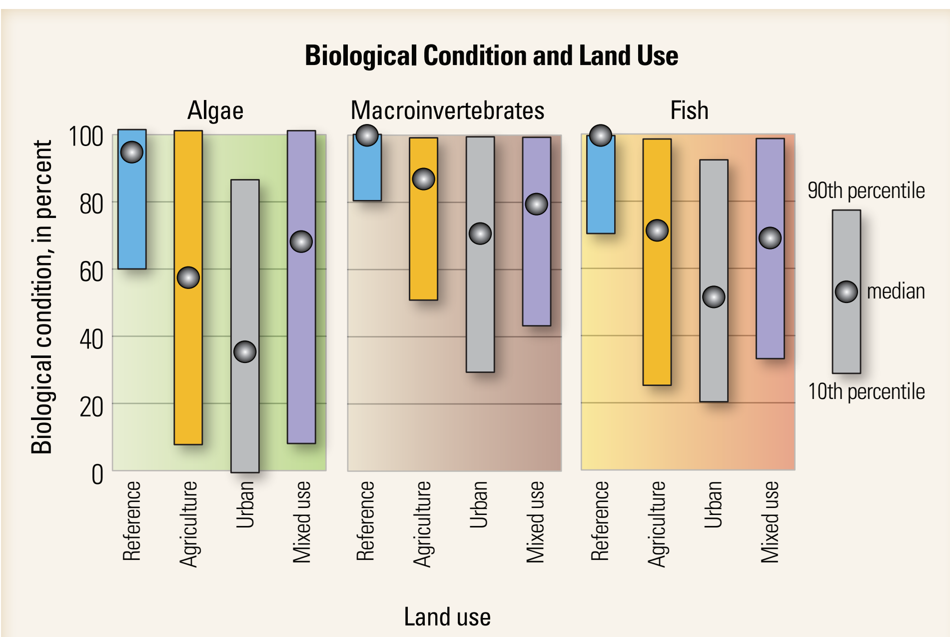
The traits of algal, macroinvertebrate, and fish species typically found in altered biological communities differ from those found in unaltered communities and are indicative of different physical and chemical changes to streams caused by human activities. These diagrams show examples of unaltered and altered algae (Delmarva Peninsula, Maryland), macroinvertebrates (Yakima River, Washington), and fish (White and Miami River Basins, Indiana).

Assessments of Algal, Macroinvertebrate, and Fish Communities

Streams with relatively intact biological communities can be found in watersheds with substantial amounts of agricultural, urban, and mixed land use.

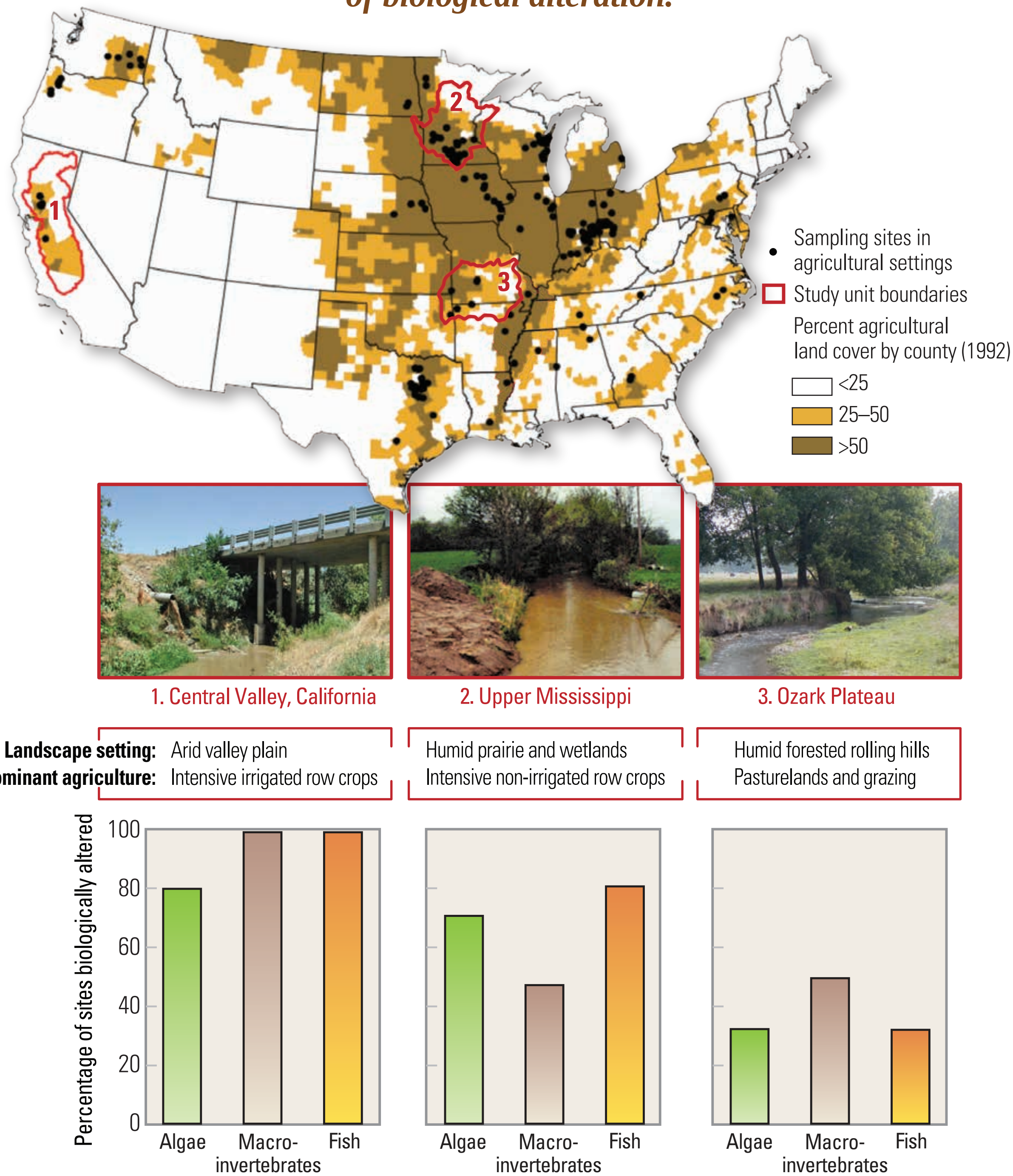
Biological condition scores for each community (algae, macroinvertebrates, and fish) varied considerably within each land-use setting (agricultural, urban, or mixed use). In all land-use settings, at least one community had biological condition scores near 100 percent, indicating that streams with intact biological communities can occur in watersheds with substantial amounts of land use. Large ranges in biological condition scores can occur for several reasons. First, there are likely large differences in the intensity of human influence within each land-use category. For example, streams classified as urban in this assessment had from 25 to 100 percent urban land cover in the watershed; the severity of disturbance to streams likely increases with the extent of urban land cover (Coles and others, 2012). In a similar way, agricultural settings include a wide range of farming practices—from row crops to orchards to pastures—which result in widely different intensities of soil disturbance and chemical use. Within a land-use setting, many local factors may also influence the intensity of human influence on streams. For example, some basins classified as urban have extensive forested riparian zones, whereas others have concrete-lined stream channels.

A second cause of variation in biological condition within land-use settings is the inherent natural variability of the biological community. Natural variability is best examined at reference sites where variability due to human influences is minimal. Algal communities had the widest range of biological condition scores among reference sites, indicating that this community is inherently more variable as a result of natural factors, such as storm events, or inherent traits, such as shorter lifespans (chapter 2) (Carlisle and others, 2008). However, another cause of variation among reference sites is differences in the severity of human influence, which is inevitable because few truly pristine ecosystems remain (chapter 3). Last, variation in biological condition can be caused by error in modeled estimates of the natural expectations of each site, which were determined to be relatively minor in this assessment (Carlisle and Meador, 2007; Carlisle and Hawkins, 2008).



As shown in these graphs, NAWQA studies found that a wide range of biological condition exists in streams within each land-use setting—agricultural, urban, or mixed use. Streams with relatively intact biological communities occur in watersheds with substantial amounts of land use. Algal communities had the widest range of biological condition scores among reference sites (sites where variability due to human influence is minimal). Biological condition is expressed as a percentage of expected natural potential.

Different combinations of agricultural practices, land features, and climate can lead to varying levels of biological alteration.

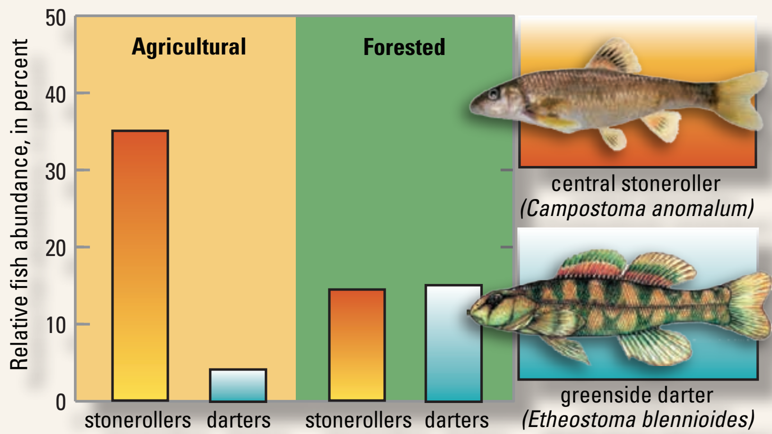


This map of the conterminous United States shows agricultural land cover by county, and the photographs and bar graphs below highlight examples of biological modification in three agricultural landscape settings. NAWQA studies found that biological alteration was most severe in agricultural streams in intensively irrigated basins, such as the Central Valley, California, where chemical use and streamflow modification can be pervasive. Biological communities in heavily cultivated basins in the Corn Belt, such as the Upper Mississippi, were relatively less severely altered but are often influenced by near-stream cultivation practices and runoff laden with sediment and agricultural chemicals. Biological communities in agricultural areas dominated by pasture, as in the Ozark Plateau, were altered less frequently than streams in other agricultural areas. (<, less than; >, greater than.)

Fish Communities are Related to Land Use in Ozark Streams

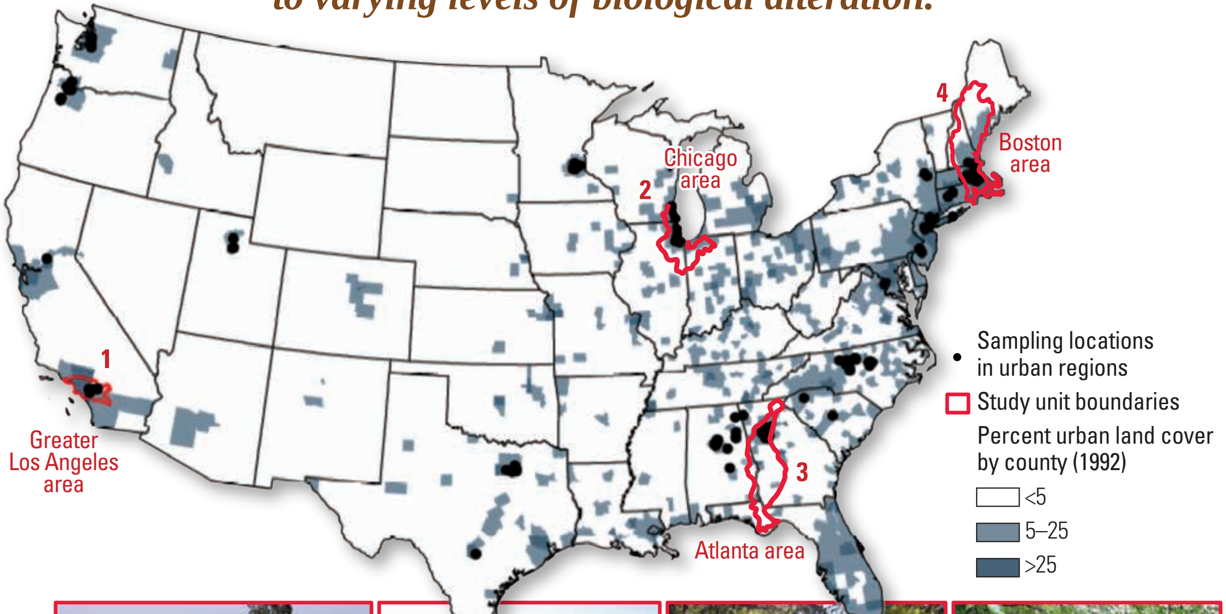
NAWQA found that streams in agricultural areas of the Ozark Plateau (Arkansas, Kansas, Missouri, and Oklahoma) generally have less shading, higher nutrient concentrations, and increased sediment deposition on the stream bottom compared to nearby forested streams. Fish communities in agricultural streams contained more stonerollers (which graze algae from the stream bottom) and fewer darters (which require sediment-free gravels for nesting) than in nearby forested streams. These findings suggest that removal of riparian forests and fertilizer applications may lead to increased light and nutrients within the stream, which may result in increased production of algae and in turn increased abundance of grazing fish species. In addition, reductions in abundance of fish species that are sensitive to sedimentation suggest that soil erosion in agricultural watersheds may also play a role in changes to fish communities (Petersen and others, 1998).

Shoal Creek, Missouri (bottom left), illustrates the influence of agricultural practices that reduce riparian forests and increase light, nutrients, and sediment entering a stream. Compared to forested streams, the relative abundance of stonerollers increased and that of darters decreased in agricultural streams (graph modified from Petersen and others 1998). North Sylamore Creek, Arkansas (bottom right), is typical of an Ozark stream in a relatively undeveloped, forested basin.



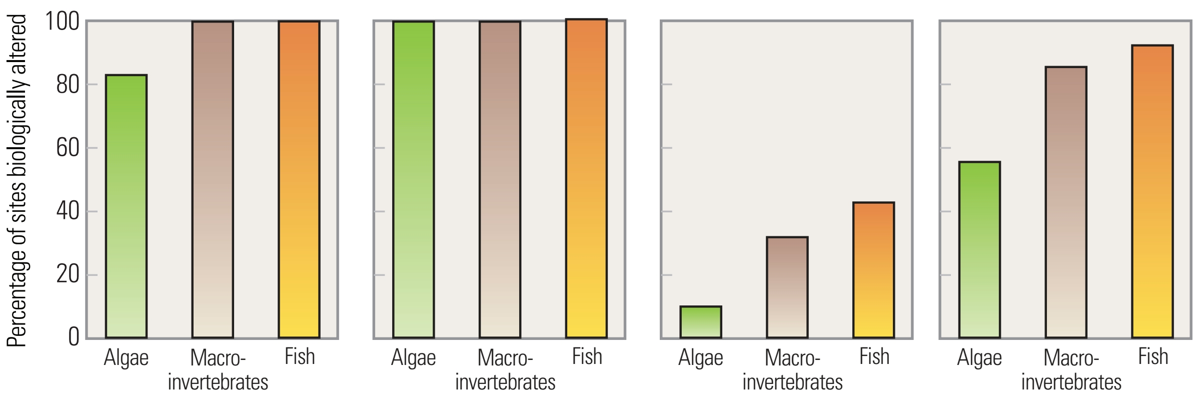
U.S. Geological Survey photos by James Petersen.

Different combinations of urban land-use practices, land features, and climate can lead to varying levels of biological alteration.



1. Greater Los Angeles, California | 2. Chicago, Illinois, area | 3. Atlanta, Georgia, area | 4. Boston, Massachusetts, area

	1. Greater Los Angeles, California	2. Chicago, Illinois, area	3. Atlanta, Georgia, area	4. Boston, Massachusetts, area
Landscape setting:	Arid valley plain	Humid prairies	Humid forested hills	Humid forested hills
Key stream features:	Artificial channels, treated wastewater	Legacy agricultural influence	Forested riparian zones	Small mill dams



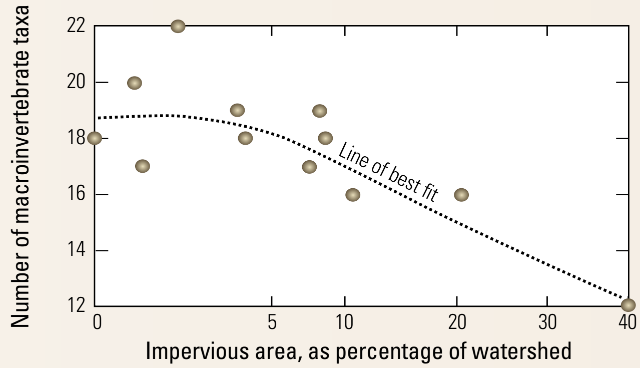
This map of the conterminous United States shows urban land cover by county, and the photographs and bar graphs below highlight examples of biological alteration in four urban landscape settings. Alteration of algal, macroinvertebrate, and fish communities was generally severe in most urban areas across the Nation, but local factors that influenced biological condition varied considerably among metropolitan areas. For example, some of the most frequently altered streams were in the arid greater Los Angeles area, where treated wastewater effluent is often the dominant source of stream water, and many streams are channelized or concrete lined. The frequency of altered biological communities was also high in streams of the Chicago suburbs, where dense urbanization occurred on lands already altered by intensive historical agricultural cultivation. Biological communities in streams of the Boston suburbs were associated with development of riparian zones and streamflow alteration caused by mill dams. Comparatively better biological condition was observed in streams of the Atlanta suburbs, where stream channels were often within forested riparian zones and natural instream habitats were relatively intact. (<, less than; >, greater than.)

Effects on Macroinvertebrate Communities Observed at Low Levels of Urban Development

U.S. Geological Survey scientists with NAWQA found that a decline in the numbers and kinds of macroinvertebrate taxa was associated with increasing amounts of urban development, as measured by the extent of impermeable surfaces, such as roads, parking lots, and houses, in a watershed. In the Anchorage, Alaska, metropolitan area, streams with increasing amounts of impervious area in the watershed generally had fewer macroinvertebrate taxa than streams with lesser amounts of impervious area, confirming that relatively small amounts of urban development may have measurable effects on stream health (Coles and others, 2012). NAWQA studies indicate that chemical contamination and physical habitat disturbance may be factors contributing to a decline in biological condition in some urban Alaskan streams (Ourso and Frenzel, 2003).

Understanding relations among biological communities and urban development can be helpful in developing water-quality management actions that will most effectively improve stream health. Such information is crucial for water-resource managers in prioritizing management strategies for a particular system (for example, restoring physical habitat in the stream channel versus tracking and reducing chemical use in the watershed) and in knowing which factors influence stream ecosystems in the early stages of landscape change.

U.S. Geological Survey photos by Robert Ourso.



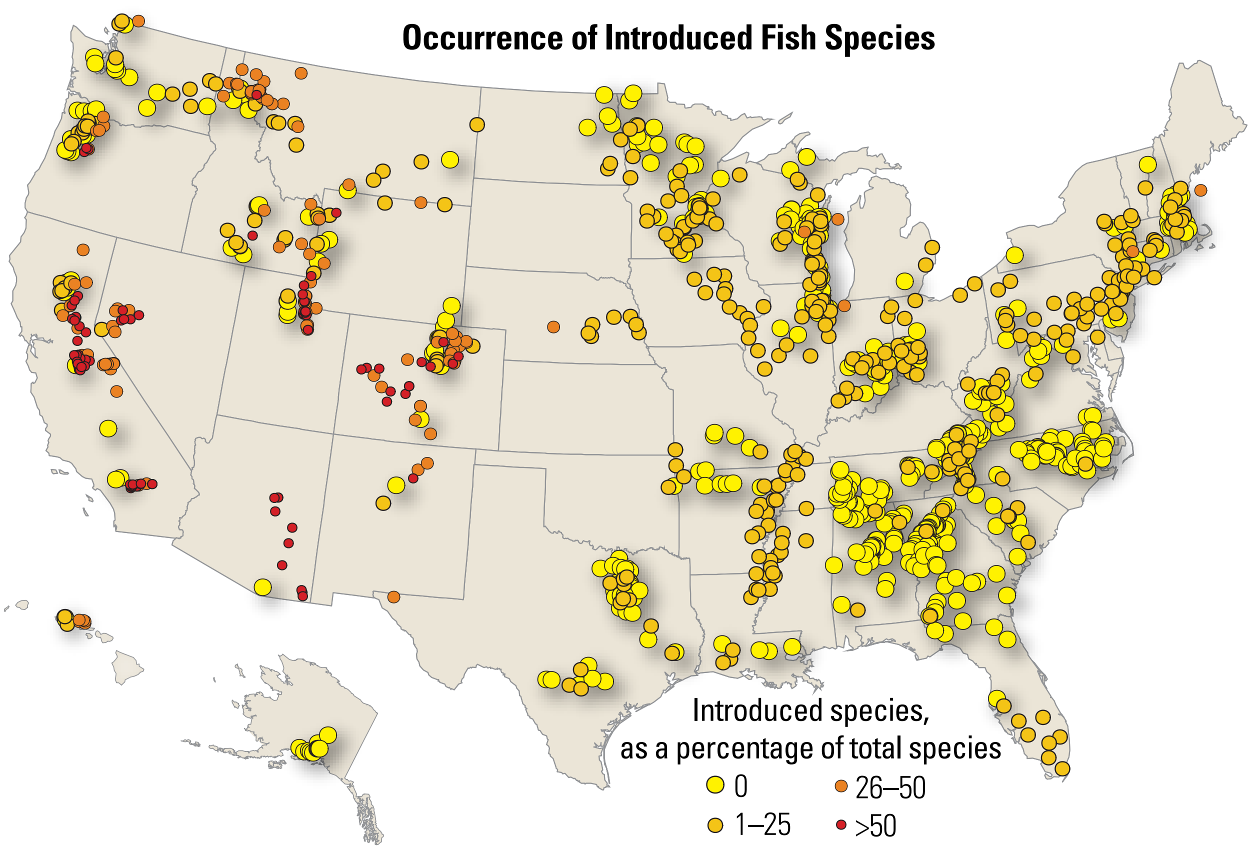
Rabbit and Chester Creeks are in the Anchorage metropolitan area, Alaska. Rabbit Creek (top photo) is an example of a relatively undeveloped watershed. Chester Creek (bottom photo) is an example of a watershed influenced by urban development, including channelization and loss of riparian forests (Glass and others, 2004). The richness of macroinvertebrate taxa in streams in the Anchorage metropolitan area declined with increasing urban development (measured as a percentage of impervious area in watersheds; graph modified from Glass and others, 2004).

Introduced fish species were common, but most frequently encountered in the Western United States.

Introduced Fish Species—Occurrence and Relations to Biological Condition

At least one species of introduced fish was collected at 50 percent of sites studied by NAWQA. Introduced fish species as a percentage of total species richness was highest in streams in the Western United States, where native fish species richness is relatively low (Meador and others, 2003). The strong regional pattern in introduced species reflects to some degree the colonization of the United States by European settlers and the fact that western waters have few native fish species and most lacked what were considered desirable game fish, such as walleye, bass, sunfish, and catfish species (Rahel, 2000). Further accelerating the east-to-west introductions of species was the creation of large impoundments that provided habitats for many eastern species that required warm- or cool-water lake environments that were naturally uncommon in the West (Rahel, 2000).

The prevalence of introduced species is often indicative of human-caused changes to the chemical and physical conditions in streams. Furthermore, introduced species can have a major influence on native biological communities, stream health, and the economic benefits of aquatic resources (Pimentel and others, 2000). The problems associated with introduced species in Hawai‘i are described on the facing page.



This map of the conterminous United States shows the occurrence of introduced fish species at sites studied by NAWQA. Scientists found introduced fish species at 50 percent of sampled stream sites. The majority of fish species collected at sites in the Western United States were introduced species. Alaska and Hawai‘i not shown to scale. (<, less than; >, greater than.)

The Presence of Introduced Macroinvertebrate and Fish Species is a Major Threat to Native Species in Hawaiian Streams

Introduced macroinvertebrate species such as the Tahitian prawn *(Macrobrachium lar)* and the Asian clam *(Corbicula fluminea)* were intentionally introduced into the streams of Hawaiʻi as sources of food for local peoples (Devick, 1991). Other macroinvertebrates such as the crayfish *(Procambarus clarkii)* became established in Hawaiian streams through intentional introductions for aquaculture. One or more of these introduced species were present in all streams sampled on the island of Oʻahu, Hawaiʻi (Brasher and others, 2004).

The presence of introduced fish in Hawaiian streams has been linked to a decline in numbers of native fish, such as gobies, and a decline in native macroinvertebrates, such as damselflies. U.S. Geological Survey studies found that the highest abundance of introduced fish species, such as the guppy *(Poecilia reticulata)* and the mosquitofish *(Gambusia affinis)*, generally occurred in urban streams where they have been introduced for mosquito control or released from home aquariums (Anthony and others, 2004). In contrast, relatively few of the five native fish species were found in urban streams (Brasher and others, 2004).

native damselfly (Odonata)

native fish oʻopu nākea *(Awaous guamensis)*

U.S. Geological Survey photos by Reuben Wolff.

Intentionally Introduced Fish Species

Introduced fish species have been perceived as both detrimental and beneficial. Introduced species often displace (through predation or competition) native fish species, particularly in streams where chemical and physical factors have been modified by land or water management. As a result, high numbers of introduced—relative to native—species are often indicative of reduced stream health. However, some introduced species have been intentionally stocked and contribute substantial economic value for recreational sport fishing, especially in intensively managed streams that are no longer able to support native fish communities. For example, the rainbow trout *(Oncorhynchus mykiss)* has been widely introduced outside of its native range along the west coast of the United States. Although rainbow trout have been implicated in reducing native fish populations, the species' value in recreational fishing is important in some streams—such as those below large dams.

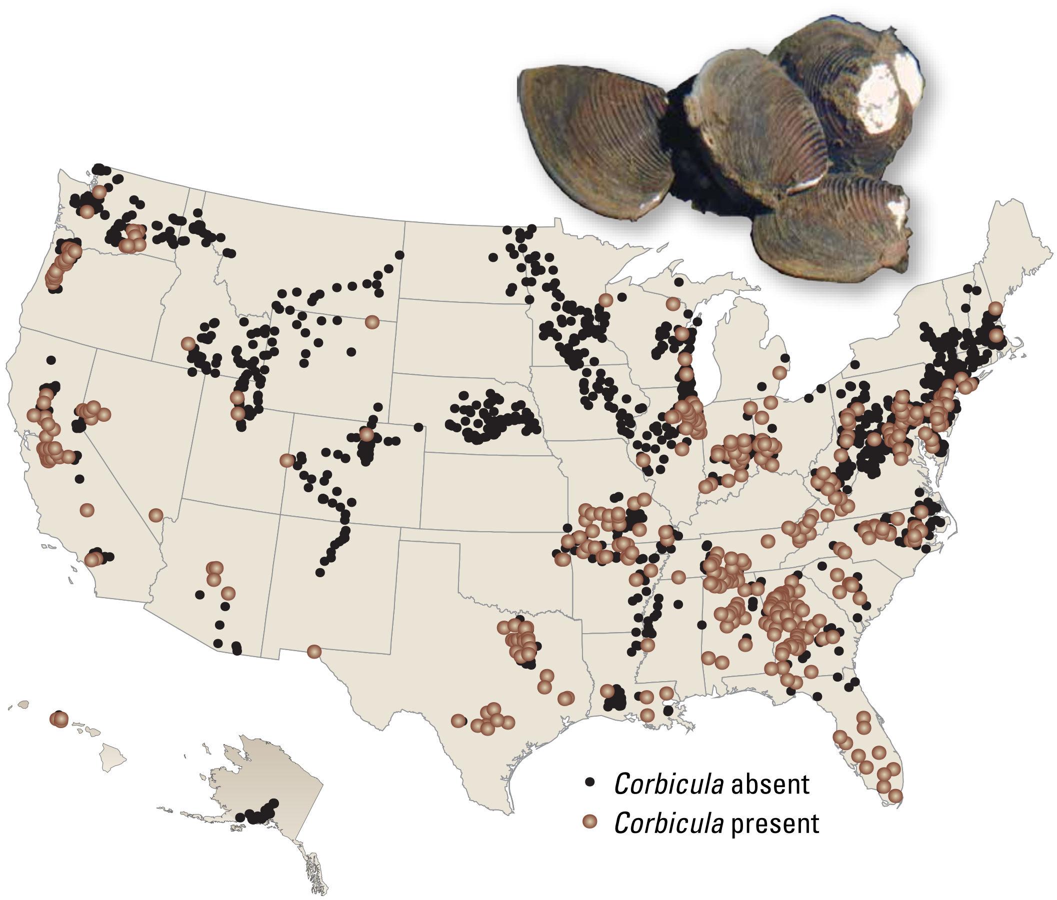
U.S. Geological Survey photo of rainbow trout by Daren Carlisle.

The Asian clam* (Corbicula fluminea) *was the most frequently observed introduced macroinvertebrate species.

Introduced Macroinvertebrate Species—Occurrence and Relations to Biological Condition

The Asian clam *(Corbicula fluminea)*, encountered at 25 percent of NAWQA sampling sites, was the most frequently observed introduced macroinvertebrate species. The Asian clam was likely intentionally introduced in the Columbia River, Washington, in about 1938 as a source of food, but subsequently spread throughout most of the United States (Fuller and others, 1999). When present in large numbers, the Asian clam can foul powerplant water-intake pipes, industrial and municipal water systems, and irrigation canals.

Another rapidly spreading introduced macroinvertebrate species is the New Zealand mud snail *(Potamopyrgus antipodarum)*. Native to New Zealand, the mud snail has spread widely in Australia, Europe, and North America through inadvertent introductions (Benson, 2006). At high population densities, colonies of the tiny mud snail disrupt the base of the food chain by consuming algae in the stream and competing with native bottom-dwelling macroinvertebrate species. The rapid reproduction rate of this snail has led to it accumulating quickly in new environments, where it can reach densities above a half million per square yard (Benson, 2006). A case study illustrating the ecological effects of mud snails is presented on the facing page.

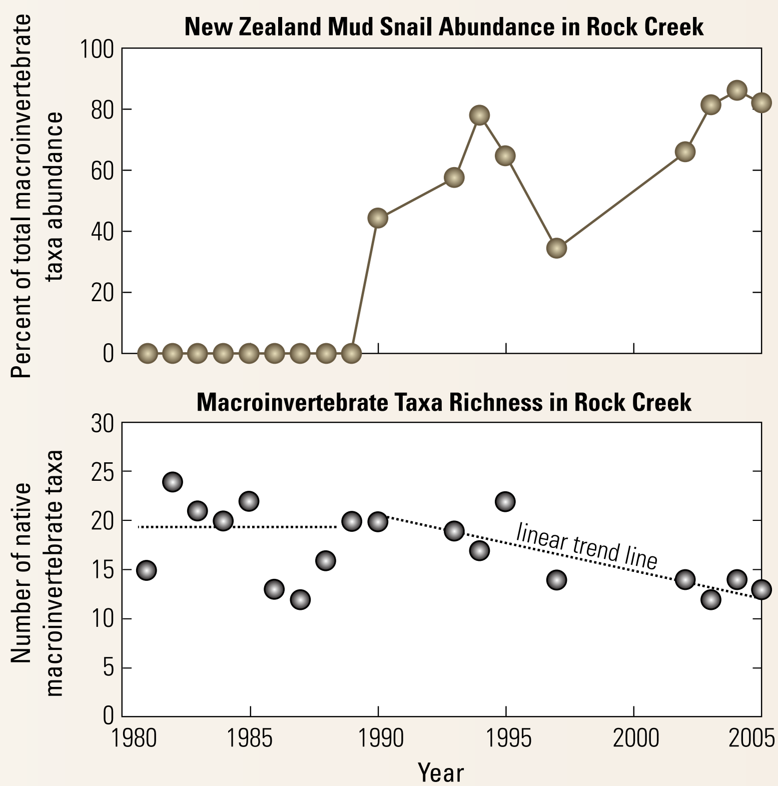


Map of the United States showing the distribution of the Asian clam *(Corbicula fluminea)*. Asian clams were found by U.S. Geological Survey scientists at 25 percent of sampling sites and were the most frequently observed introduced macroinvertebrate species. (Alaska and Hawai‘i not shown to scale.)

Introduced Species Often Thrive in Streams Already Modified by Land Use

Streams where physical or chemical conditions have been modified by land and water management are often subject to the proliferation of introduced species that have living requirements better suited to disturbed environments than do native species. For example, water quality in Rock Creek, Idaho, has been diminished by agricultural runoff laden with sediment and nutrients (Maret and others, 2008). Beginning in the early 1980s, best management practices aimed at reducing nutrient and sediment runoff were implemented throughout the watershed and appeared to promote a modest ecological recovery (Maret and others, 2008). Unfortunately, the appearance of an introduced species— the New Zealand mud snail *(Potamopyrgus antipodarum)*—may have disrupted Rock Creek's recovery.

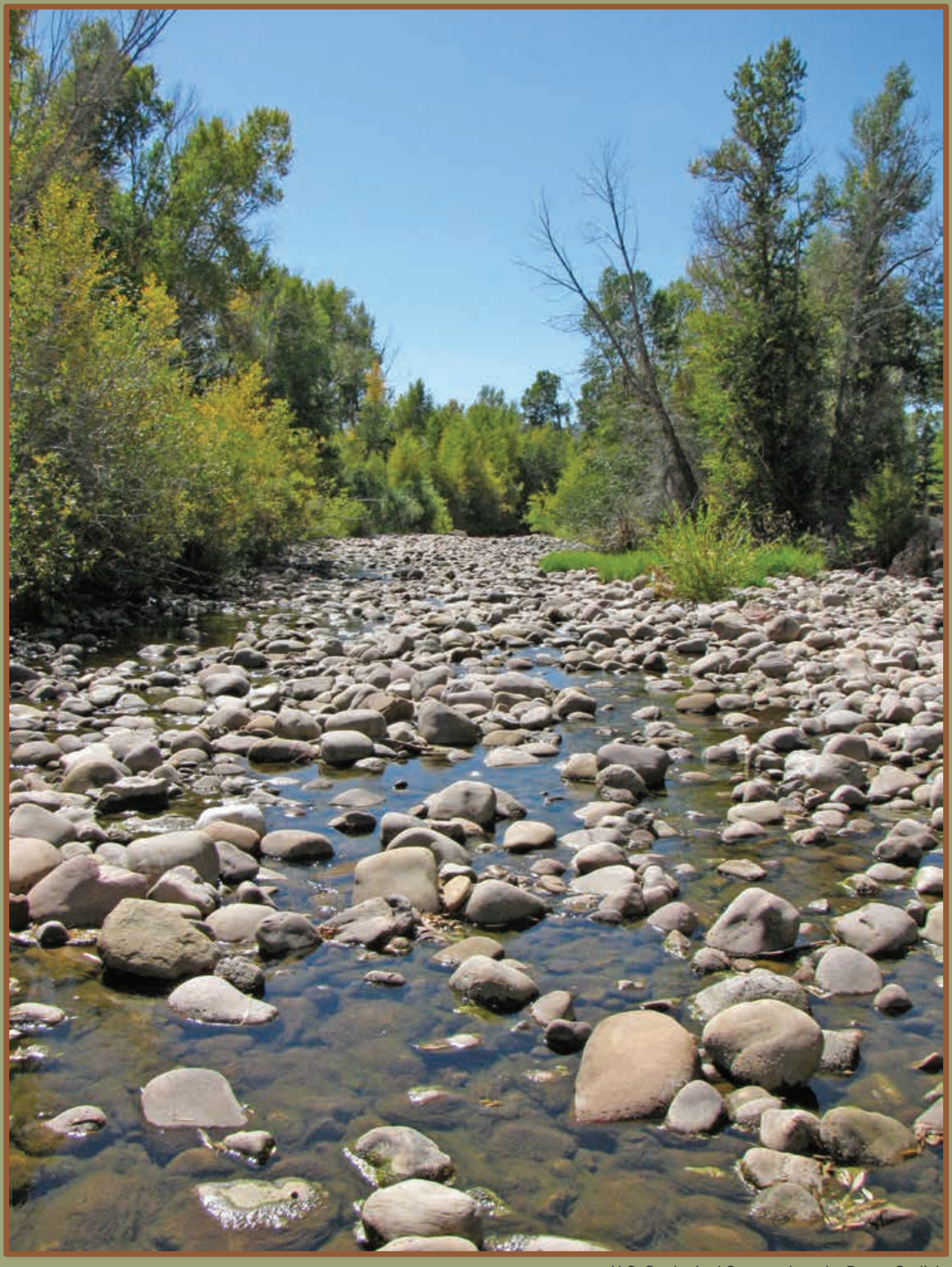
Long-term monitoring in Rock Creek (Maret and others, 2008) found that within a short period of time, densities of the tiny New Zealand mud snail (photo below with penny for scale) rapidly increased after being introduced in 1989. Although its abundance varied considerably from year to year, the New Zealand mud snail quickly became the dominant species, on average accounting for more than two-thirds of the entire streambed invertebrate community (top graph). The mud snail invasion corresponds to a decline in the diversity of native macroinvertebrate taxa in Rock Creek (bottom graph). The case of Rock Creek illustrates how invasions by introduced species can negate the positive ecological benefits of remediation strategies and thereby complicate management decisions aimed at restoring stream health.



Ecoanalysts, Inc., photo used with permission.

Chapter 6 Factors Associated with Diminished Biological Condition

Scientists and resource managers often become environmental detectives when assessments indicate that stream health is diminished. A major challenge to understanding why stream health is diminished is the ability to unravel the effects of many interacting natural and human-caused factors. Interdisciplinary scientific data on the physical, chemical, and biological conditions of streams can be used to improve our understanding of the relative importance of these factors in affecting biological communities—and ultimately, stream health.



U.S. Geological Survey photo by Daren Carlisle.

No single physical or chemical factor was universally associated with reduced stream health across the Nation.

Factors Associated with Diminished Biological Condition—Summary

When assessments reveal that stream health is diminished, scientists and resource managers must determine which physical or chemical factors have been modified by human activities sufficiently to alter biological communities. This information is necessary so that remedial management strategies can be identified and implemented. A major challenge to understanding why biological communities are altered is unraveling the effects of many interacting natural and human-caused factors.

The findings and case studies presented in this chapter enhance our understanding of factors that influence stream health. Two general principles about these factors are briefly summarized here using findings from a national study of urban streams (Bryant and Carlisle, 2012; Coles and others, 2012). The remainder of the chapter describes more in-depth analyses of how, in a variety of land-use settings, different factors are related to biological alteration.

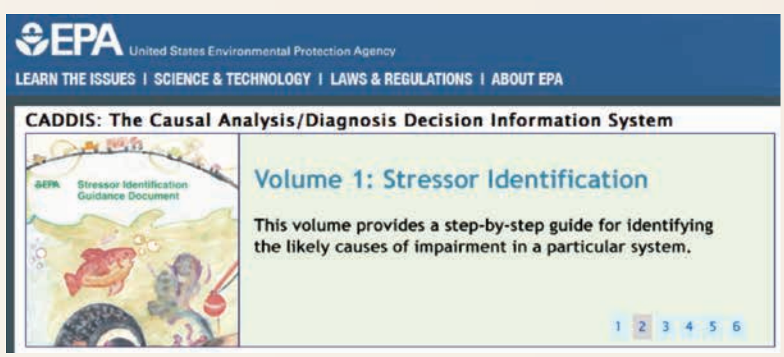
Biological alteration is often related to manmade modifications of multiple physical and chemical factors. For each biological community—algae, macroinvertebrates, and fish—in most geographic regions, biological alteration was generally associated with two or more physical or chemical factors. These findings reflect the fact that many physical and chemical factors are related or co-occur in watersheds influenced by human activities. These findings suggest that assessments and restoration efforts should take a multifactor approach, wherein a number of factors—and their possible interactions—are investigated and managed.

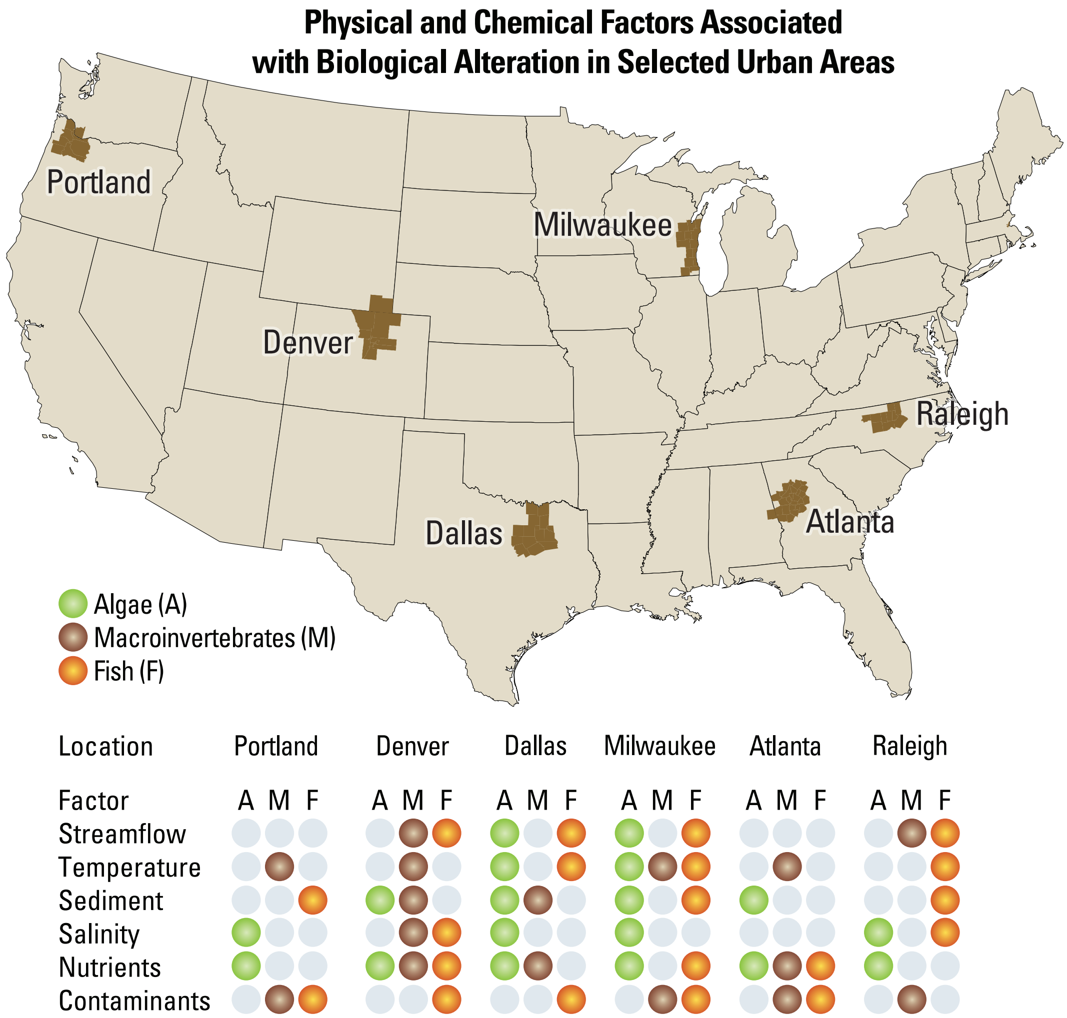
Factors associated with biological condition differ among environmental settings—there is no single physical or chemical factor that is universally associated with reduced stream health. None of the factors examined were associated with biological alteration in every geographic area. These findings suggest that management strategies aimed at restoring stream health are best developed and applied at the local scale, such as the watershed, where there is an understanding of how land- and water-management activities modify the physical, chemical, and biological attributes of streams. Nevertheless, the widespread importance of factors such as nutrients and streamflow suggest that regional and national priorities aimed at managing these factors can help restore and maintain stream health across the Nation.

Tool for Diagnosing the Causes of Diminished Stream Health

Special tools are required to help identify the causes of diminished stream health. Experimentation is an important tool for understanding causality because it allows scientists to manipulate and measure the effect of one factor, while simultaneously controlling other factors. However, experimental manipulation of streams and their watersheds is rarely feasible or recommended, so a variety of other tools must be employed. In general, these tools integrate information from independent monitoring and other observational studies and examine whether this information provides evidence that alternative factors are responsible for declines in biological condition.

CADDIS (Causal Analysis/Diagnosis Decision Information System) is an online application developed by the U.S. Environmental Protection Agency that helps users organize and use information for identifying the causes of impaired stream health. It is designed for scientists involved in assessing causality, but resource managers, watershed groups, teachers, and others who are interested in factors reducing stream health may also find CADDIS useful. CADDIS features (1) advice on how to use specific data analysis methods and manage data for evaluating causality, (2) downloadable data analysis tools, and (3)other information sources such as databases of quantitative relations among specific environmental factors and biological communities. CADDIS can be accessed at http://www.epa.gov/caddis.





NAWQA studies found that diminished biological condition in urban streams was associated with multiple physical and chemical factors. For example, in watersheds in six U.S. metropolitan areas (Portland, Oregon; Denver, Colorado; Dallas, Texas; Milwaukee, Wisconsin; Atlanta, Georgia; and Raleigh, North Carolina), associations of physical and chemical factors and biological condition were evaluated across 25 to 30 study sites in each of the areas (Bryant and Carlisle, 2012; Coles and others, 2012). This diagram shows these associations for algae, macroinvertebrate, and fish communities for each metropolitan area. Note that increases in all listed factors were associated with diminished biological condition. For example, increasing concentrations of contaminants were associated with reduced biological condition.

Cause-and-Effect Relations and the Role of Monitoring Data

Demonstrating that a specific physical or chemical factor is the cause of biological alteration is difficult when evidence is limited to monitoring data. This is largely because natural factors, such as stream size, and human-caused factors, such as streamflow alteration, may also vary with the factor of interest. For example, streams with elevated levels of insecticides may also have excess nutrients, which can also affect biological condition. As a result, attributing changes in biological condition to a single factor of interest can be misleading if other factors are not taken into account.

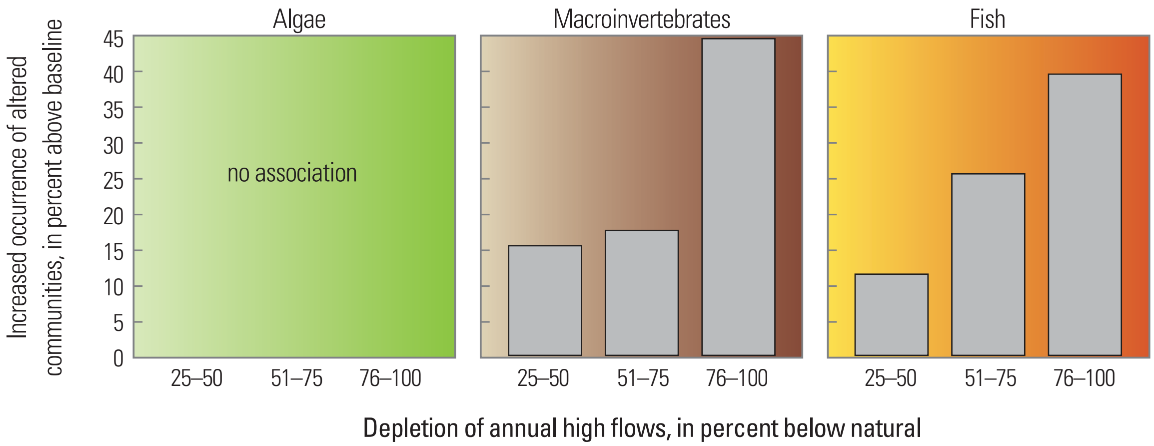
Ultimately, cause-and-effect relations must be established with the accumulation of evidence from rigorously designed observational studies and supporting laboratory experimentation (Clements and others, 2002). NAWQA is by design observational, relying on monitoring of current conditions rather than field or laboratory experimentation. Associations among biological condition and chemical and physical factors are presented in this report, but these do not alone prove causality. Rather, these findings provide evidence that these factors must be considered as likely contributors to biological alteration in more detailed studies.

Macroinvertebrate and fish communities were more frequently altered as streamflow modification increased.

Streamflow Modification

The natural timing, variability, and magnitudes of streamflow influence many key physical, chemical, and biological characteristics and processes of streams and are therefore crucial to maintaining stream health. Human-caused modification of natural streamflows occurs throughout the Nation and in all types of land uses (chapter 4).

NAWQA found that biological communities were more frequently altered in streams with increasingly modified flows. For example, with increasing manmade depletion of annual high flows, the incidence of altered communities increased from 16 to 45 percent for invertebrates and from 12 to 40 percent for fish. Similar patterns were observed for depletion of annual low flows. These associations between biological alteration and streamflow modification were evident even after controlling for the influence of other factors that influence biological communities, such as nutrients, salinity, and land cover



NAWQA studies found that macroinvertebrate and fish communities in the Nation's streams were more frequently altered in streams with increasingly severe flow depletion (bar graphs above). Algae were not affected by flow depletion. Reservoirs, diversions, and other manmade changes to streams and their watersheds modify natural streamflows that are crucial to the life cycles of aquatic organisms. Baseline is the occurrence of altered communities in approximately 60 streams with annual highflow depletion less than 25 percent.

Understanding Biological Alteration

The biological condition of a community is expressed as the ratio of observed (O) community attributes (such as number of native species) to those expected (E) if the community was minimally disturbed by human activities. The resulting O:E ratio is multiplied by 100 and expressed as a "percentage of natural potential" (chapter 3). Increasing biological condition values indicate that a biological community is closer to its expected natural potential and, by inference, the stream is in better health. This continuous measure is used to describe the biological condition of individual sites.

A community was classified as "altered" by NAWQA if its biological condition was less than that of 90 percent of the reference sites within its region. Otherwise, a community was considered to be "unaltered." This classification is used to summarize biological condition across the diverse regions of the Nation. Increased occurrence of altered biological communities indicates that more stream sites have diminished biological condition and, by inference, diminished stream health.

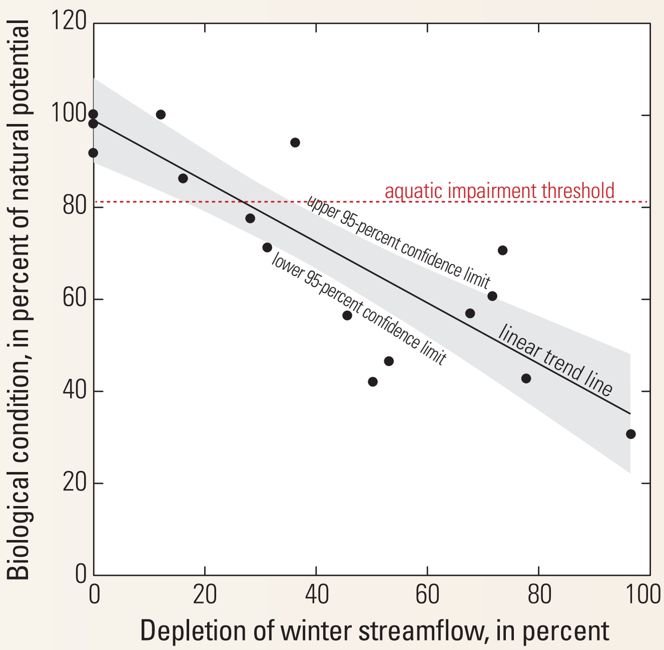
(Carlisle and others, 2011). Algal community condition, in contrast, was unrelated to streamflow modification.

These national findings are similar to a large body of case studies that have documented negative ecological consequences of streamflow modifications (review by Bunn and Arthington, 2002), especially for macroinvertebrate and fish communities (review by Poff and Zimmerman, 2010). The life cycles of many aquatic species are highly synchronized with the variation and timing of natural streamflows. For example, the reproductive period of some fish species is triggered by the onset of spring runoff. Algal community responses to modified streamflows are less understood than other communities (Poff and Zimmerman, 2010). Although the incidence of altered algal communities was unrelated to streamflow modification, other attributes of these communities, such as total biomass, may be indicative of modified streamflows.

Understanding the relations between streamflow modification and stream health is essential if society is to make informed decisions about tradeoffs between water use and the maintenance of ecosystems (Postel and Richter, 2003; Poff and others, 2010). NAWQA findings provide a national-scale assessment of the importance of natural streamflow to the maintenance of biological communities and stream health and provide policy makers and water managers a much-needed perspective on the pervasiveness and severity of streamflow modification.

Diminished Biological Condition Related to Winter Flow Depletion in Utah Streams

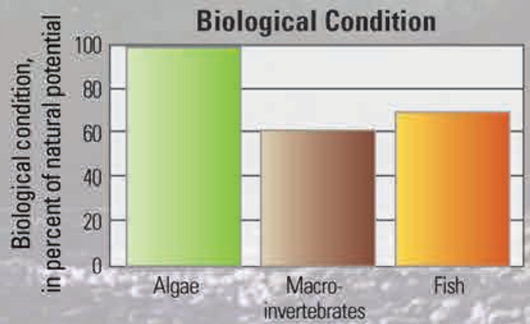
A collaborative regional study done by the U.S. Geological Survey, Bureau of Reclamation, and Utah Division of Environmental Quality in 2010 found that the biological condition of macroinvertebrate communities declined in streams with increasing depletion of winter flows. In streams with more than 40 percent depletion of winter flows, macroinvertebrate community condition was below the threshold considered by the State to be protective of aquatic life (see graph). Results from this study provide a potentially important guideline for water-management strategies aimed at improving biological conditions in streams below dams and diversions (Carlisle and others, 2012).



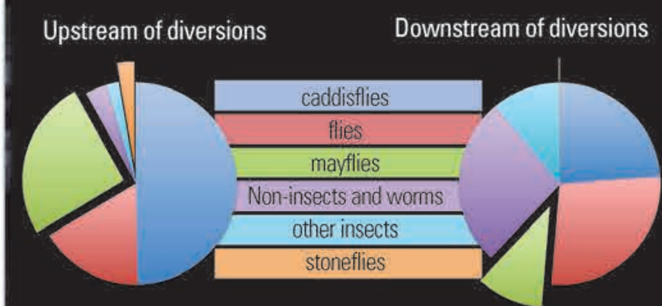
Streamflows are diverted from the South Fork of Rock Creek, Utah, for use in other river basins.

Biological Communities are Influenced by Depleted Streamflows—The Example of Cache la Poudre River, Colorado

The Cache la Poudre River, Colorado, originates on the Continental Divide in the Rocky Mountains and flows through a rugged canyon popular with recreationists. Water is diverted at several locations for irrigation and other uses, which leaves some parts of the river with depleted flows during summer, fall, and winter.



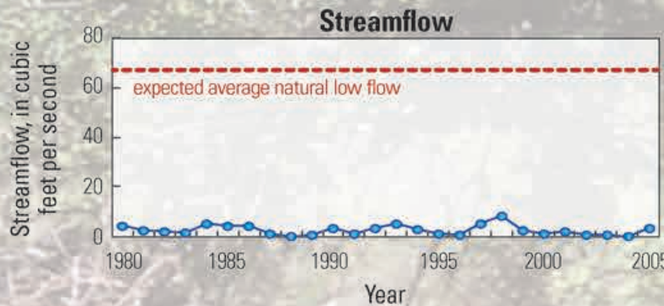
As shown in this graph, macroinvertebrate and fish communities in the Cache la Poudre River were more than 30 percent below their expected natural potential. In contrast, algal community condition was unrelated to streamflow depletion.



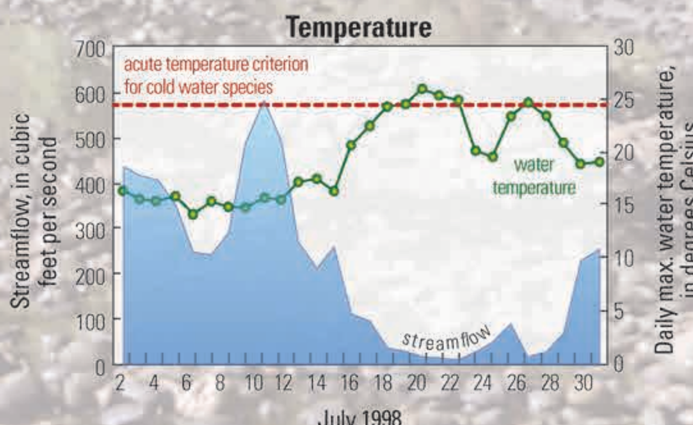
Mayflies and stoneflies, which require cold and well-oxygenated water, are typically major components of macroinvertebrate communities in Rocky Mountain streams, as shown for the Cache la Poudre River upstream of diversions (left pie chart). However, the macroinvertebrate community in the Cache la Poudre River downstream of diversions (right pie chart) was dominated by flies, worms, and other organisms that are indicative of warm and stagnant water.

Fish Communities

Fish communities in naturally flowing Rocky Mountain streams typically include trout, suckers, and other species that require fast-flowing water. In the Cache la Poudre River, however, species adapted to intermittent or slow-flowing streams, such as green sunfish and fathead minnow, were most common.



As shown in this graph, annual low flows in some segments of the Cache la Poudre River are typically less than 10 percent of expected natural low flows.



This graph shows that depleted flows in the Cache la Poudre River in summer are associated with extremes in water temperature that threaten cold-water species.

Background photo courtesy of Save the Poudre/Poudre Waterkeeper.

The incidence of altered biological communities increased with greater agricultural or urban land development within stream riparian zones.

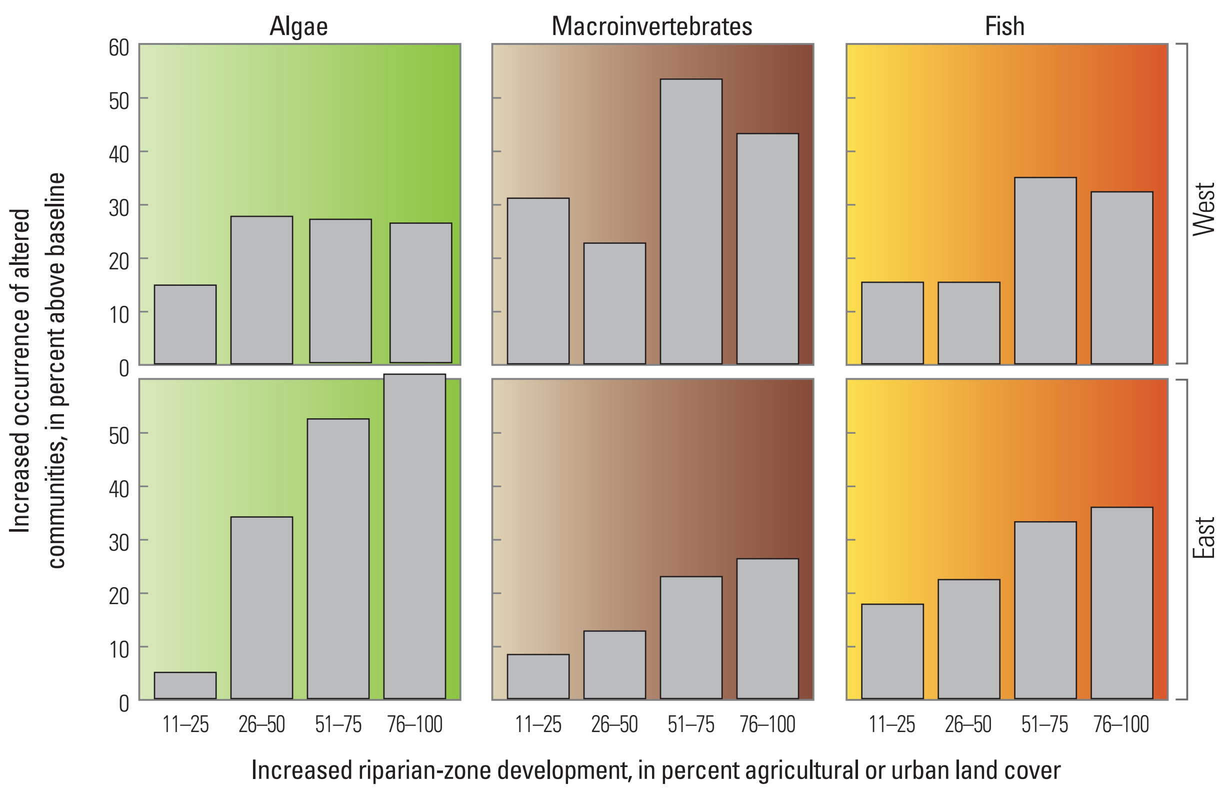
Land Development within Stream Riparian Zones

Streamside trees and other vegetation, collectively known as riparian zones, are important to stream health because they influence the amount of shelter and food available to aquatic organisms, the amount of sunlight reaching the stream through the tree canopy, and the amount and quality of runoff that reaches the stream from surrounding uplands. However, agricultural and urban land development within riparian zones is pervasive, particularly in the eastern half of the Nation. The extent and severity of riparian-zone development in the Nation's watersheds suggests it may contribute to reduced stream health (U.S. Environmental Protection Agency, 2006a).

Biological communities were more frequently altered in streams with greater agricultural and urban development within the riparian zone. As the extent of development within the riparian zone increased, the incidence of altered biological communities increased from 5 to 61 percent for algae, 8 to 55 percent for macroinvertebrates, and 15 to 36 percent for fish communities.

Disturbance or removal of riparian vegetation, in any type of land-use setting, can have profound effects on stream biological communities. Increased exposure of the stream to sunlight can increase water temperature—for which many aquatic organisms have narrow requirements—and stimulate growth of nuisance algal species if nutrient levels are also excessive. Reduced inputs of leaves and woody debris from the riparian zone to the stream result in less food and living space for many invertebrate and fish species. Finally, disturbed riparian zones lose their ability to filter potentially harmful

Biological Alteration and Land Development in Stream Riparian Zones by Region



NAWQA studies found that algae, macroinvertebrate, and fish communities were more frequently altered in streams with increasing amounts of streamside development (defined as agricultural or urban land cover). These bar graphs show this relation for both the Eastern and Western United States. Disturbance or removal of streamside vegetation often leads to increased water temperature and inputs of sediment and other contaminants to a stream. Baseline is the occurrence of altered communities in approximately 250 streams with less than 10 percent agricultural or urban land cover in riparian zones.

contaminants in runoff from developed upland areas, thereby increasing the risk that sediments, nutrients, and harmful chemicals will enter the stream.

Findings were generally similar for streams in the Eastern and Western United States, which suggests the biological consequences of riparian-zone development are similar even though biological communities and the nature of riparian disturbance may differ from east to west. For example, many riparian zones of western streams with little agricultural or urban development may nevertheless be disturbed by rangeland livestock grazing and some forestry practices.

NAWQA's findings on a national scale corroborate many local and regional-scale studies showing that stream biological communities benefit from naturally vegetated riparian zones (for example, Moore and Palmer, 2005), even in intensively managed agricultural or urban watersheds. There is a great deal of evidence that the maintenance and restoration of vegetated stream riparian zones can improve stream health.


Before restoration

Photo courtesy of Wetland Studies and Solutions, Inc.


After restoration

U.S. Geological Survey photo by Martin Gurtz.

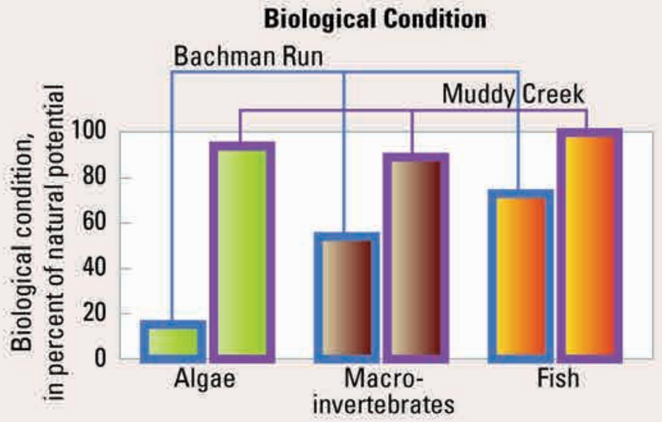
Reestablishment of streamside vegetation is an important part of efforts to restore health to urban streams. These photographs show part of Snakeden Branch, Virginia, before restoration (top) and after restoration (bottom).

Photo courtesy of Kenneth Cole, Western Watersheds Project.

Even in areas with little agricultural or urban development, livestock management practices that allow animals to disturb streamside vegetation can lead to severe erosion and reduced stream health. This photograph shows such erosion along Basin Creek, Idaho.

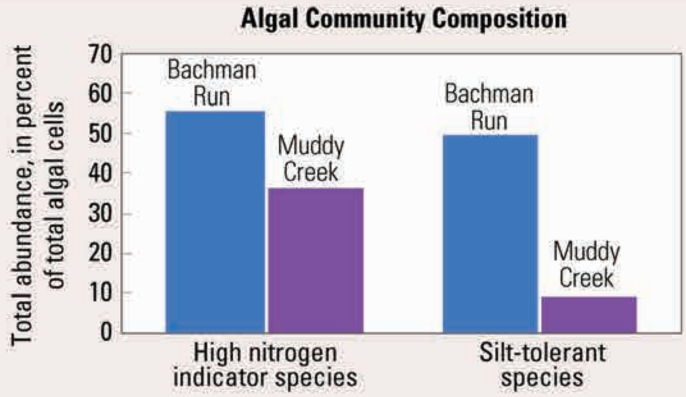
Vegetated Riparian Zones Influence Stream Health in Agricultural Settings—The Example of Bachman Run and Muddy Creek, Pennsylvania

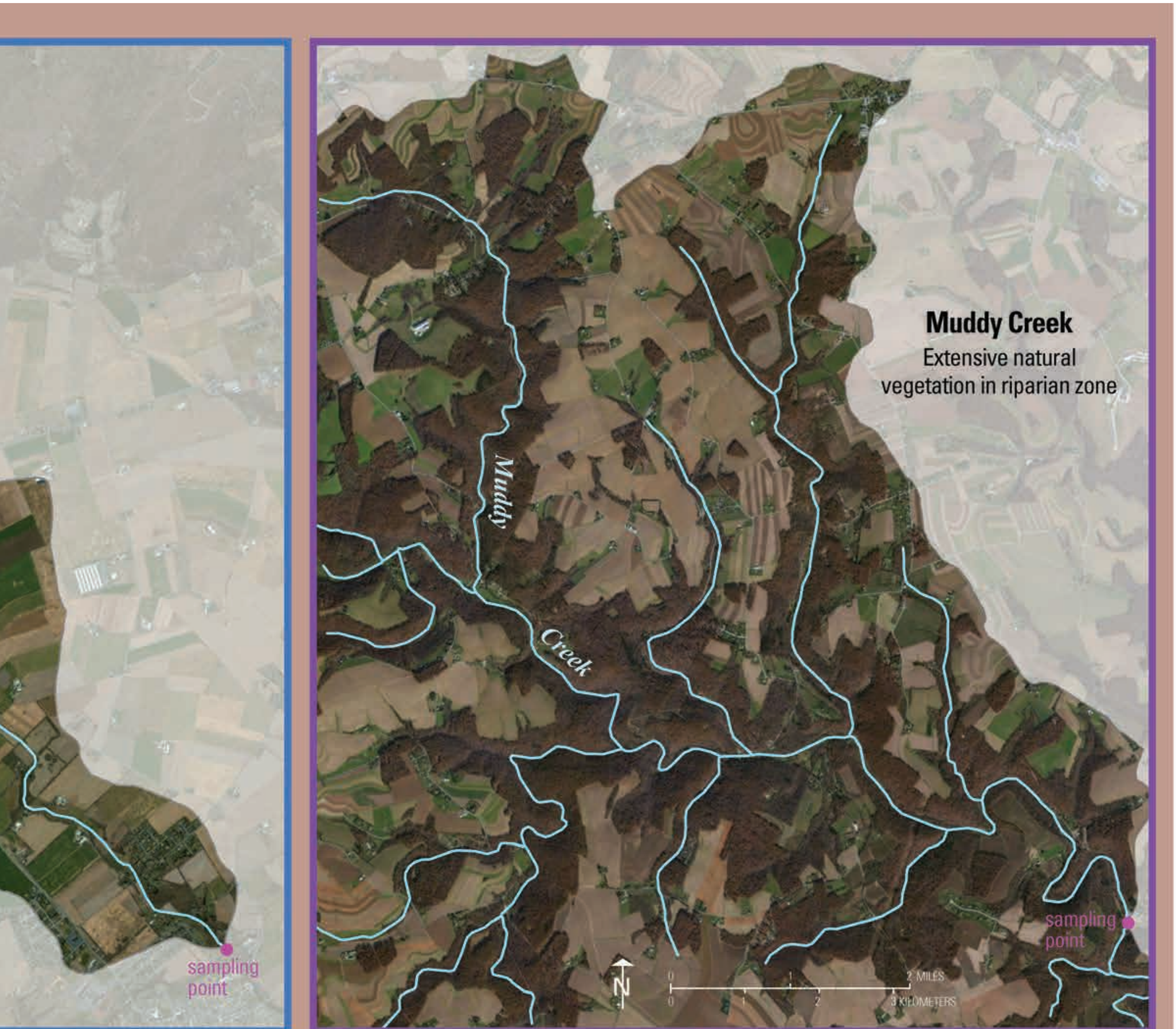
Croplands are 75 percent of the land cover in the watersheds of Bachman Run and Muddy Creek, Pennsylvania. Land cover in the riparian zone, however, is dominated by cropland in Bachman Run (left) and trees and shrubs in Muddy Creek (right). Greater amounts of natural vegetation in the riparian zone correspond to less altered biological condition and lower nutrient concentrations in Muddy Creek than in Bachman Run. The ability of riparian vegetation to buffer the effects of land use are well known.

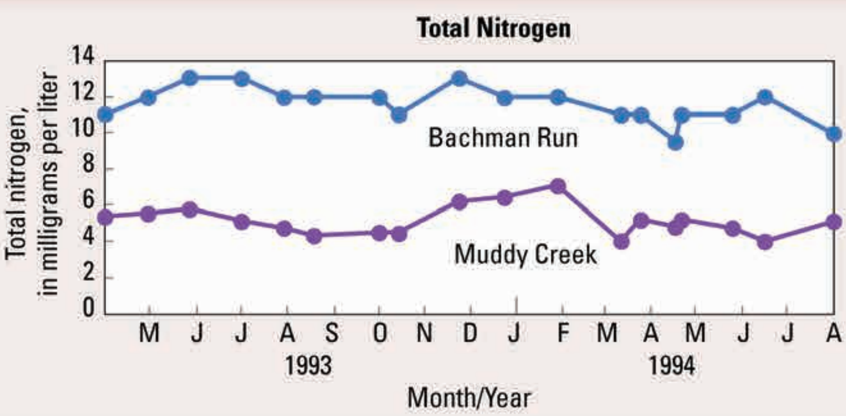


As shown on this bar graph, NAWQA studies found that algal, macroinvertebrate, and fish communities were 25 to 85 percent below their expected natural potential in Bachman Run and close to their expected natural potential in Muddy Creek.

The types and amounts of diatoms within the algal communities suggest that Bachman Run is affected by excess nutrients and sediments from the watershed. As this bar graph shows, species that require high nitrogen levels or that are adapted to silty conditions are 20 to 40 percent more common in Bachman Run than Muddy Creek.







This graph compares total nitrogen concentration in Bachman Run and Muddy Creek. NAWQA found that total nitrogen concentration in Bachman Run was consistently two times higher than that in Muddy Creek. (1 milligram per liter = 1 part per million.)

Images from U.S. Geological Survey National Land Cover Dataset 2006.

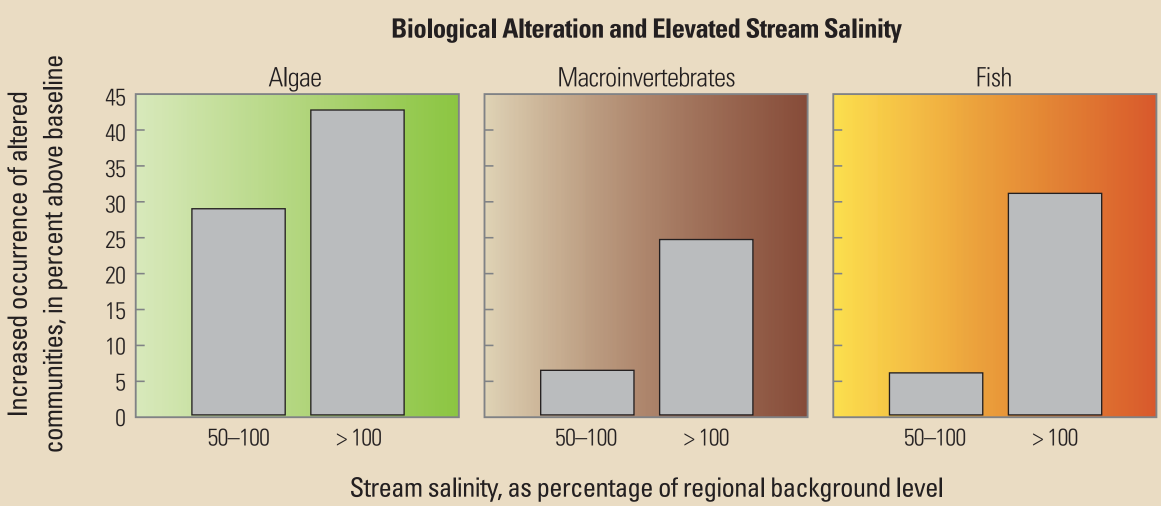
Biological communities were more frequently altered in streams with increasingly elevated salinity relative to background levels.

Elevated Salinity

Although geographic variation in natural salinity levels is high due to factors such as geology and soils, elevated salinity levels occur throughout the Nation, particularly in watersheds with substantial urban and agricultural land use. Recent studies have also documented increasing trends in salinity levels in streams and groundwater due to human activities (Kaushal and others, 2005; Mullaney and others, 2009).

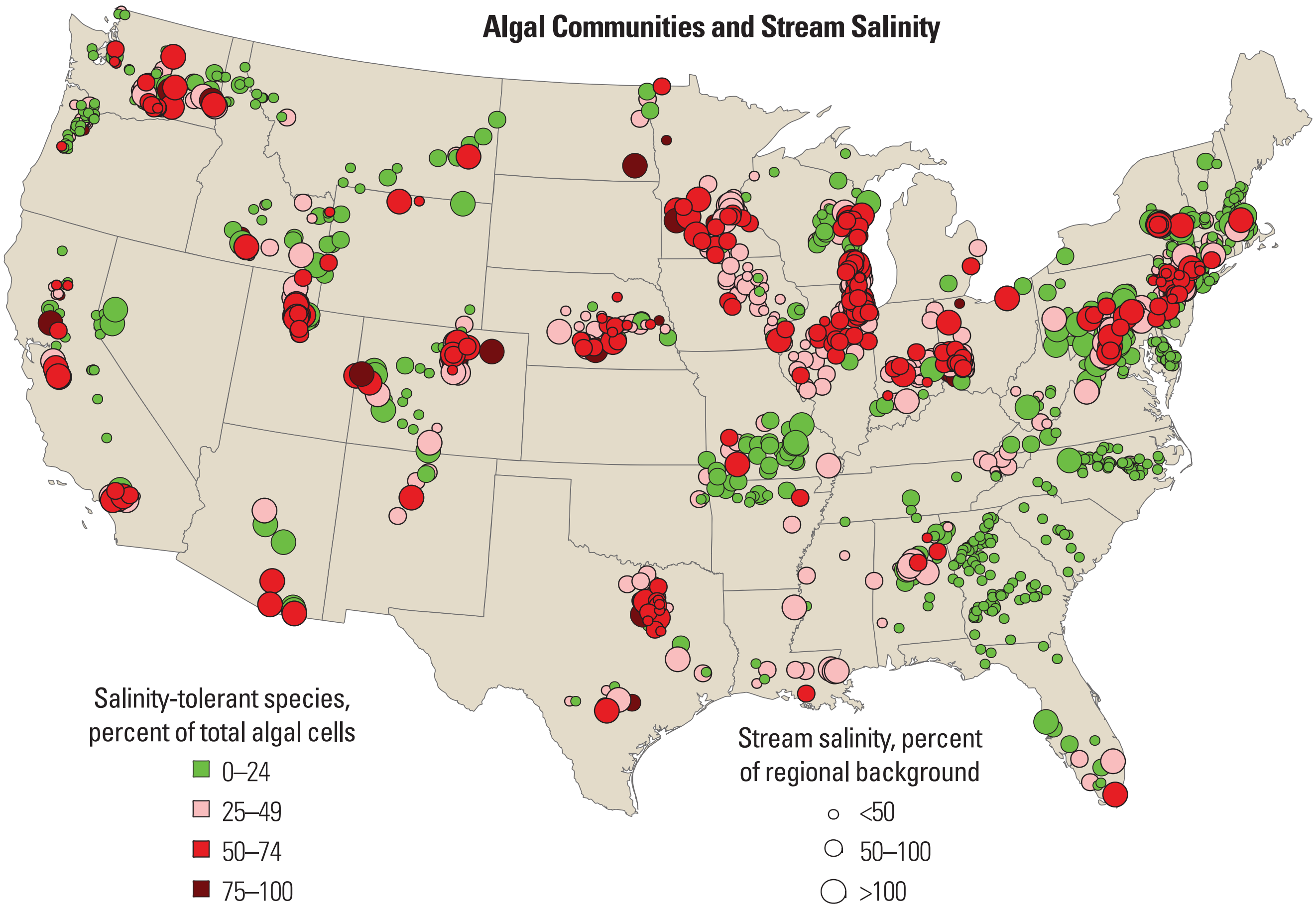
Biological communities were more frequently altered in streams with increasingly elevated salinity levels. In streams with increasingly elevated salinity relative to regional background levels (Van Sickle and Paulsen, 2008), the incidence of altered communities increased from 29 to 43 percent for algae, 7 to 25 percent for macroinvertebrates, and 6 to 31 percent for fish.

Excess salinity in stream water disrupts the balance of salts and fluids between the tissues of aquatic organisms and the surrounding water, which often leads to death and, ultimately, the loss of vulnerable species. Many experimental studies have demonstrated that elevated salinity reduces growth, reproduction, and survival of aquatic organisms; young life stages appear to be particularly vulnerable (Findlay and Kelly, 2011). Toxic effects of salinity have been documented in fish, invertebrates, and amphibians. Algae, particularly diatoms, are also known to be highly sensitive to changes in salinity (for example, Bloom and others, 2003).



NAWQA studies found that algal, macroinvertebrate, and fish communities in the Nation's streams were more frequently altered in streams with increased salinity over natural background levels (bar graphs above). Land-use practices such as irrigation and road-salt application can lead to excess salinity in stream water, which disrupts the balance of salts and fluids in aquatic organisms, often leading to death. Baseline is the occurrence of altered communities in approximately 500 streams with salinity levels less than 50 percent of regional background levels.(>, greater than.)

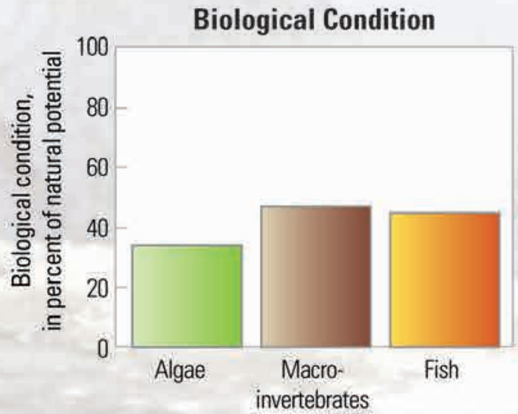
Diatom species that tolerate saline conditions were often the most common inhabitants of algal communities in streams with elevated salinity. Salinity-tolerant diatoms often accounted for more than two-thirds of all individuals in algal communities. This pattern occurs throughout the Nation and in all types of land-use settings and suggests that when salinity is excessive it is a likely cause of altered algal communities. These findings provide evidence that salinity is elevated—and a potential factor influencing biological condition—in streams throughout the Nation.



Map of the conterminous United States showing salinity levels and the abundance of salinity-tolerant diatom species in streams. NAWQA found streams with elevated salinity levels throughout the Nation. Salinity-tolerant diatoms were often the most abundant species in streams with elevated salinity, which suggests that excess salinity has altered algal communities. (<, less than; >, greater than.)

Salinity is One of Several Factors That Contribute to Diminished Stream Health—The Example of Shingle Creek, Minnesota

Diminished stream health in Shingle Creek, an urban watershed in Minnesota, was originally thought to be caused by a single factor—elevated salinity. However, follow-up studies found evidence that streamflow alteration and consequent habitat modification and low dissolved oxygen levels were also likely contributing to biological alteration. As a result of NAWQA assessing multiple factors, resource managers now know that improving the health of Shingle Creek requires remediation of several important chemical and physical factors.



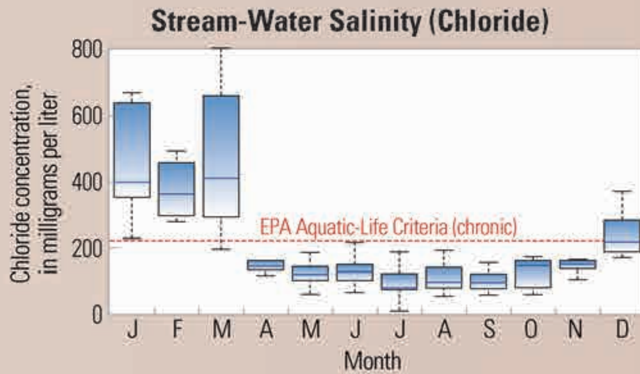
As shown in this bar graph, algal, macroinvertebrate, and fish communities were 40 to 70 percent below their expected natural potential in Shingle Creek.

Species Traits Provide Clues About the Causes of Biological Alteration

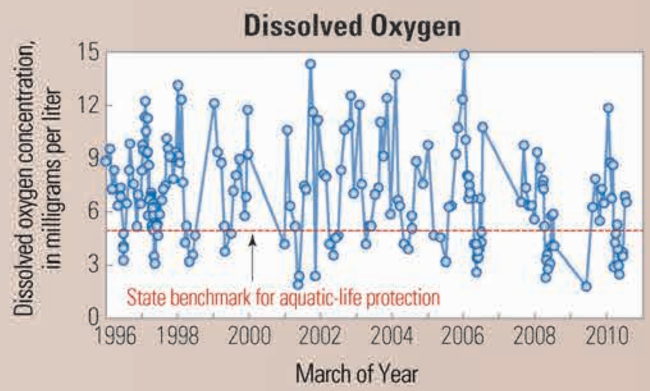
Human-caused changes to the physical and chemical properties of streams generally lead to the replacement of species whose traits are poorly suited to change with species whose traits are more suited to the change. If the sensitivities of species to chemical and physical factors are known, changes in the occurrence and abundance of species can provide clues about which factors contribute to alteration of biological communities.

The composition of biological communities in Shingle Creek suggests that several physical and chemical factors are responsible for diminished stream health. The number of species tolerant of elevated salinity and nutrients (algae), low dissolved oxygen (macroinvertebrates), and habitat alteration (fish) was nearly twice that of natural expectations. These clues from biological

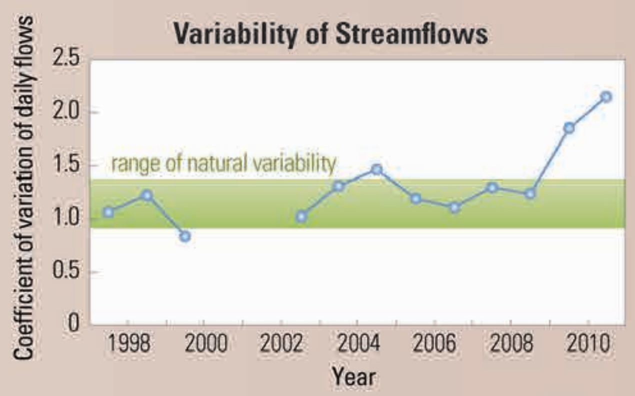
Background photo courtesy of Chris Meehan, Wenck Associates.



This graph shows that chloride concentrations (a measure of salinity) often exceed U.S. Environmental Protection Agency (EPA) Aquatic-Life Criteria during winter, when salt is applied to roadways in the Shingle Creek watershed. (1 milligram per liter = 1 part per million.)



Dissolved oxygen concentrations in Shingle Creek often fall below State guidelines, particularly in summer months when algal and other plant growth is highest. (1 milligram per liter = 1 part per million.)



Streamflow in recent years in Shingle Creek (blue dots on graph) is more variable than would naturally occur, indicating the potential for degradation of habitat for many aquatic species.

communities, when combined with information from actual measurements of chemical and physical factors in Shingle Creek, suggest that low dissolved oxygen and streamflow modification—in addition to elevated salinity—were key factors in reducing stream health.

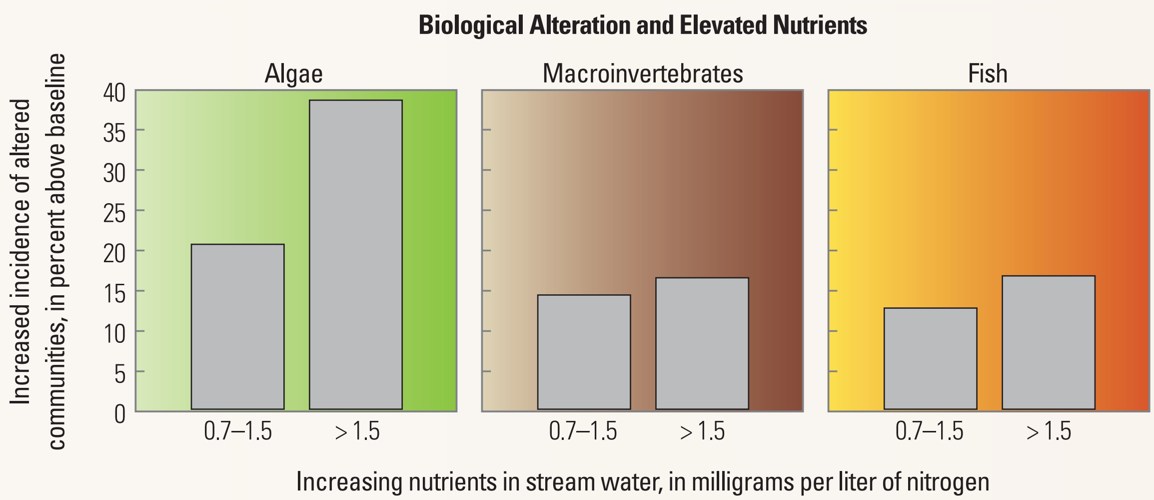
Biological communities, particularly algae, were more frequently altered in streams with elevated nutrients such as total nitrogen.

Elevated Nutrients

Although plant nutrients such as nitrogen and phosphorus are a basic need of aquatic ecosystems, excessive nutrients can have harmful effects on stream health (chapter 2). Nutrient levels in stream water are as much as six times greater than background levels in urban and agricultural lands across the Nation and are widely cited as a cause of diminished stream health (U.S. Environmental Protection Agency, 2006b; see http://ofmpub.epa.gov/tmdl_waters10/attains_nation_cy.control).

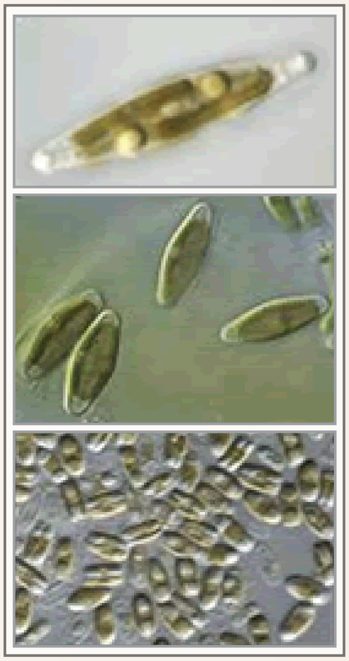
Biological communities, particularly algae, were more frequently altered in streams with elevated nutrients. With increasing nutrient concentrations in stream water, the incidence of altered biological communities increased from 21 to 39 percent for algae, from 15 to 17 percent for macroinvertebrates, and 13 to 17 percent for fish. Changes in biological alteration associated with nutrient levels were most pronounced for algal communities, likely because of the direct link between nutrient availability and algal growth and reproduction. Alteration of algal communities was largely due to changes in the types of algae found in streams with elevated nutrients relative to streams with low nutrients. For example, one set of diatom species thrive in streams with elevated nutrients and are referred to as "eutrophic diatoms." These species were the largest part of algal communities in streams with elevated nutrients throughout the Nation (see sidebar, opposite page).

Relative to algal communities, associations between excess nutrients and macroinvertebrate and fish communities are less direct and often mitigated by other factors. Harmful effects to aquatic animals occur when elevated nutrients cause excessive growths of algae and aquatic plants, which consume oxygen in the water as they grow and decompose. However, these effects can vary from one stream to another as a result of differences in patterns of streamflow, amount of riparian shading, water temperature, water clarity, and the extent of groundwater and surface water exchange (Dubrovsky and others, 2010; Riseng and others, 2011). These results also serve as a reminder that many factors can adversely affect biological communities in urban and agricultural streams. Attributing causality to linkages between nutrient concentrations (or any other single factor) and biological alteration can be misleading because a single factor may not be responsible for all adverse biological effects. Instead, biological alteration is most often the result of multiple factors, each of which can have different effects and at different times of the year.



NAWQA studies found that biological communities, particularly algae, in the Nation's streams were more frequently altered in streams with elevated levels of the nutrient nitrogen (bar graphs above). Algae that flourish in streams with excess nutrients can become prolific and consume oxygen in the water, often leading to the death of aquatic animals. Baseline is the occurrence of altered communities in approximately 400 streams with total nitrogen concentrations less than 0.7 milligram per liter. (>, greater than; 1 milligram per liter = 1 part per million.)

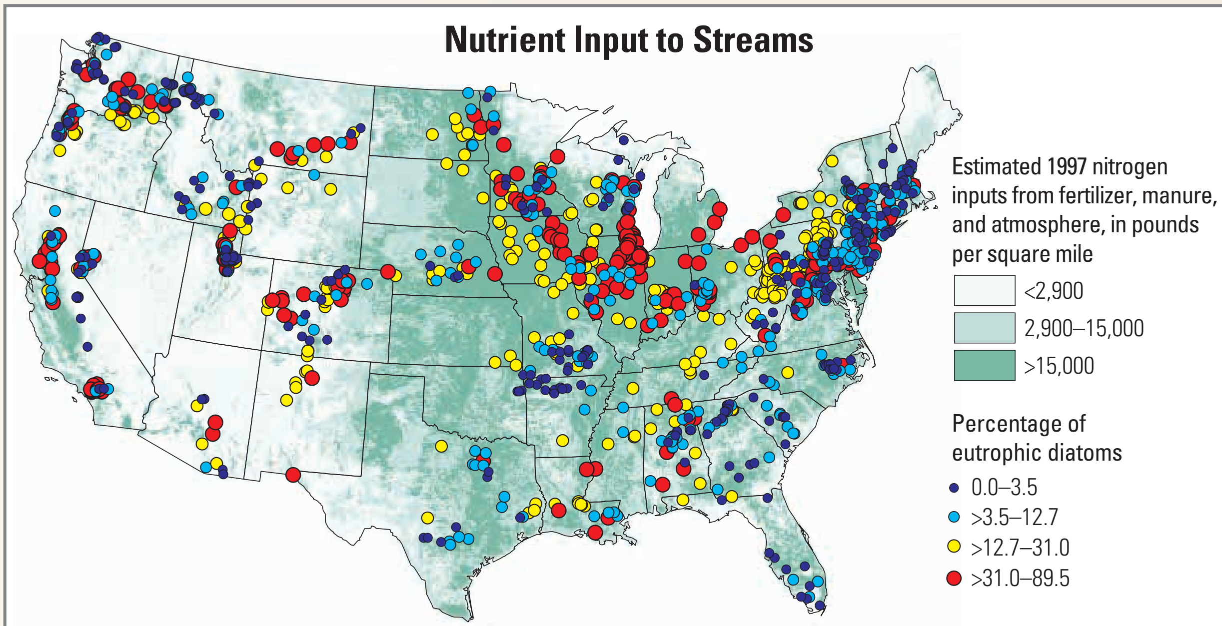
Algae as Indicators of Nutrient Enrichment



Photos of eutrophic diatoms from the Academy of Natural Sciences of Drexel University, Patrick Center for Environmental Research, used with permission.

The biological condition of algal communities is an especially effective indicator of human-influenced changes in water and habitat quality because many algal species have specific environmental requirements for growth and development. These requirements—such as food and habitat preferences, reproductive behavior, and lifespan are all part of each species' life-history-strategy for survival. Because all algal species have unique combinations of life history strategies and environmental preferences, their presence in a stream indicates a specific—and sometimes narrow—range of environmental conditions. Species occurring in streams in which water and habitat quality are degraded generally are limited to those organisms that are tolerant of existing physical and chemical properties of the stream environment.

As an example, the relative abundance of eutrophic diatoms in algal communities increased as concentrations of nitrogen and phosphorus increased (Porter and others, 2008). Eutrophic diatoms, which are algal species that prefer streams with elevated levels of nutrients, had a higher relative abundance in areas of the Nation with intensive agriculture, such as the upper Midwest, and in heavily urbanized areas. The relative abundance of other algal species may reflect other important environmental conditions, such as the concentration of dissolved oxygen or salinity. Algal indices are increasingly being considered in State and tribal bioassessment programs (U.S. Environmental Protection Agency, 2002), as well as in development of nutrient criteria at the State level (Ponader and others, 2005; Belton and others, 2006).



Eutrophic diatoms—those that prefer streams with elevated levels of nutrients—have a high relative abundance in areas of the Nation with intensive agriculture, such as the upper Midwest, and in intensively urbanized areas (map of the conterminous United States modified from Dubrovsky and others, 2010). (>, greater than.)

Macroinvertebrate communities were more frequently altered in streams with elevated concentrations—and potential toxicity—of pesticides.

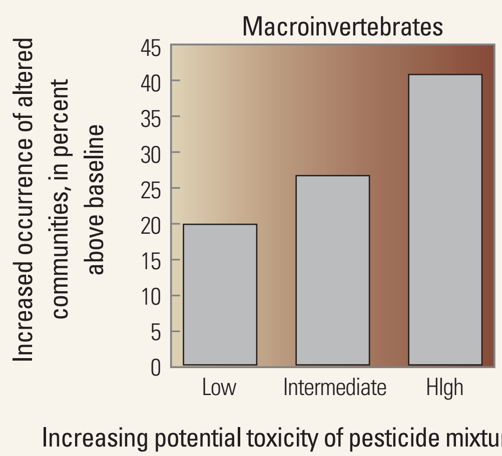
Pesticides in Stream Water

Pesticides frequently occur in stream water in all land-use settings and typically reflect patterns of use in the watershed (Gilliom and others, 2006). Although pesticide concentrations are highly variable seasonally and from year to year, they often reach levels that threaten aquatic organisms, particularly in agricultural and urban streams.

NAWQA studies found that macroinvertebrate communities were more frequently altered in streams with elevated concentrations—and potential toxicity—of pesticides. Specifically, the incidence of altered macroinvertebrate communities increased from 20 to 42 percent as the potential toxicity of pesticide mixtures increased. This association is predictable given that stream macroinvertebrate communities are mainly composed of insects and that the most frequently detected—and potentially toxic—pesticides were insecticides (chlorpyrifos, carbaryl, and diazinon). Substantially altered macroinvertebrate communities were associated with potentially toxic pesticides in urban settings throughout the Nation and in agricultural settings in the upper Midwest; Mississippi drainage basin south of Cairo, Illinois; and west coast States.

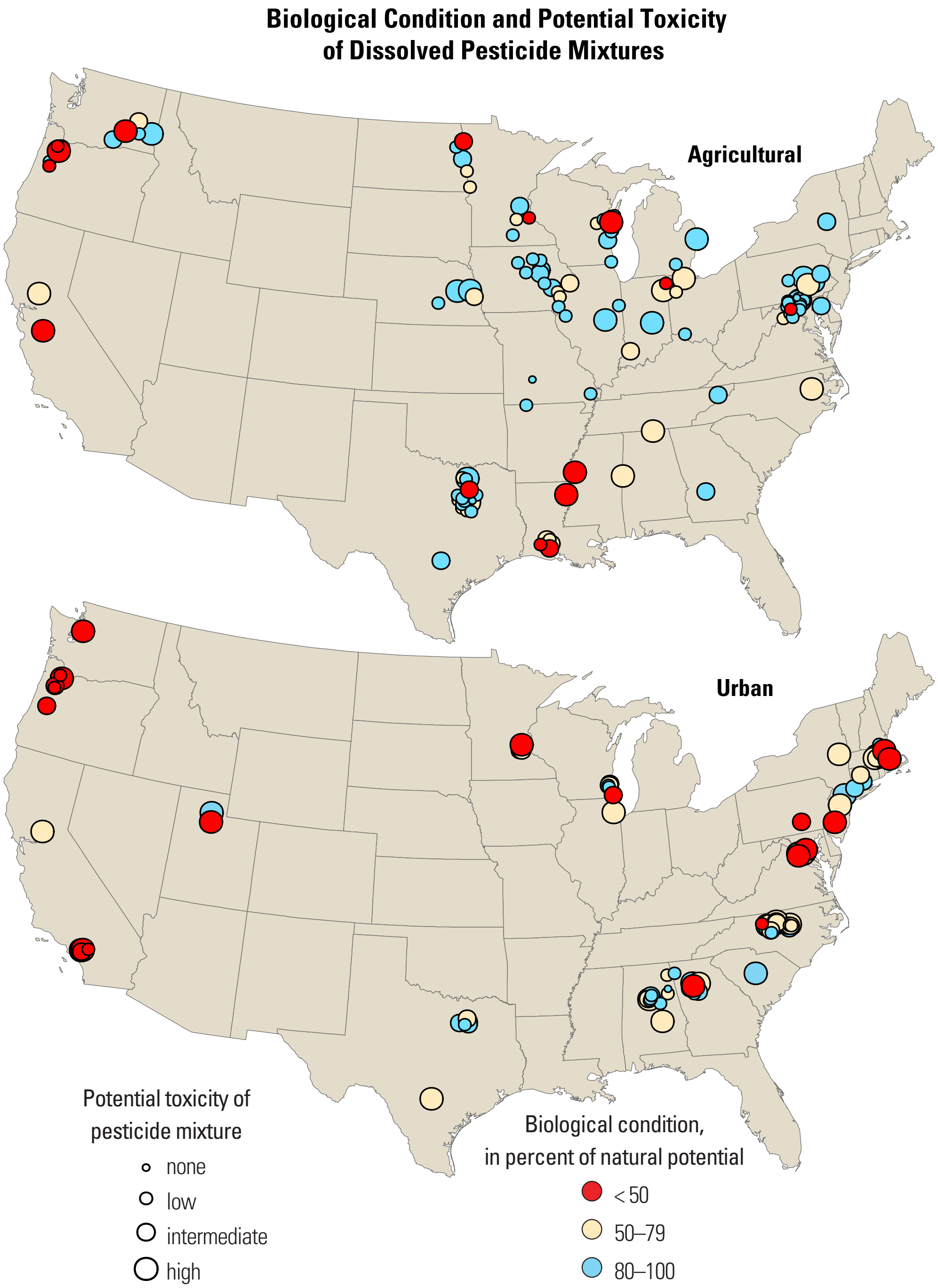
The effects of insecticides on macroinvertebrate communities were evident even after controlling for the influence of other factors. After controlling for nutrients, salinity, habitat, and land use, streams with insecticide levels that exceeded U.S. Environmental Protection Agency Aquatic-Life Benchmarks had 12 percent fewer macroinvertebrate taxa than streams without benchmark exceedances. These findings suggest that insecticides contribute to reduced stream health in agricultural and urban streams and support a growing body of scientific research documenting the ecological effects of pesticides on stream biological communities (Relyea, 2005; Macneale and others, 2010; review by Schulz and Liess, 1999).

Macroinvertebrate Community Alteration and Potential Toxicity of Pesticides



NAWQA studies found that macroinvertebrate communities in the Nation's streams were more frequently altered in streams with increasing levels of pesticides, as measured by the potential toxicity of pesticide mixtures (bar graph above). Insecticides, which are designed to kill insects, were the most frequently detected and potentially toxic pesticides and were found in stream water in agricultural and urban settings. Baseline is the occurrence of altered communities in 132 streams with no pesticide detections.

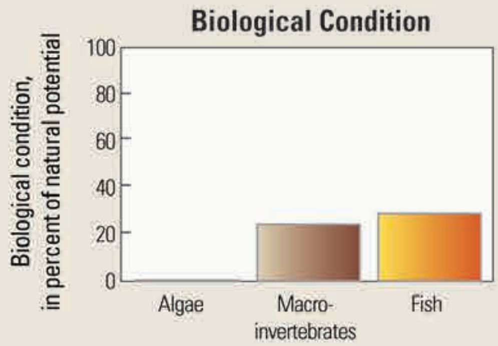
Finally, it is important to note that two insecticides (diazinon and chlorpyrifos) found during the NAWQA study period have subsequently been discontinued, and concentrations in streams have declined (Gilliom and others, 2006). Indeed, pesticide use fluctuates over time, and these discontinued insecticides have been replaced with others (Spurlock and Lee, 2008) that may or may not pose a risk to stream health.



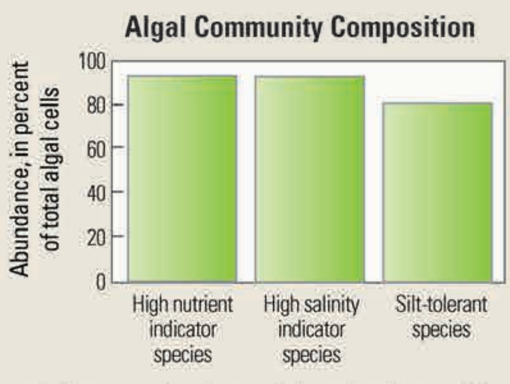
NAWQA studies found that substantially altered macroinvertebrate communities were associated with potentially toxic pesticide mixtures in urban settings throughout the Nation and in agricultural settings in the upper Midwest; Mississippi drainage basin south of Cairo, Illinois; and west coast States. These maps show agricultural and urban sites in the conterminous United States at which pesticides were measured in water samples and macroinvertebrate communities were assessed. (<, less than.)

Elevated Pesticides and Nutrients Threaten Biological Communities—The Example of Zollner Creek, Oregon

Biological communities were highly altered in Zollner Creek, a predominantly agricultural watershed in Oregon. Forty-three pesticides were detected (1991–1995), some of which occurred at concentrations potentially harmful to aquatic life. Nutrient levels were also elevated—usually more than 10 times higher than expected background concentrations. Habitat conditions within the stream were also degraded.



As this bar graph shows, macroinvertebrate and fish communities in Zollner Creek were 70 to 80 percent below their expected natural potential. Algal communities were almost 100 percent below their expected natural potential.

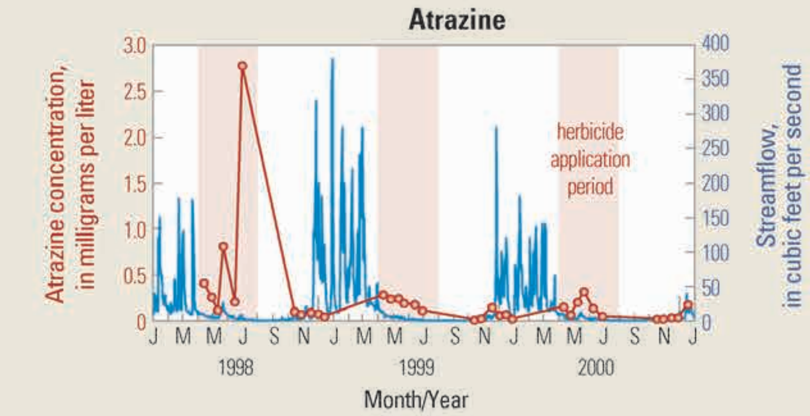


As this bar graph shows, species tolerant of elevated nutrients, salinity, and silt were 83 to 96 percent of the total algal community in Zollner Creek, which suggests that diminished biological condition was at least partially due to these factors.

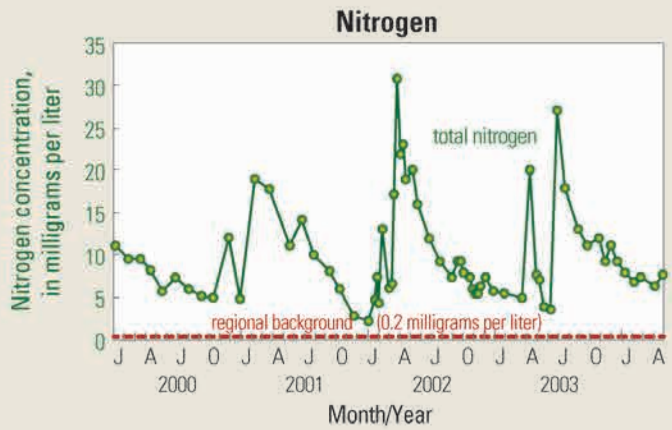
Fish Communities

Native fish communities historically found in Zollner Creek and nearby rivers include more than 30 species, such as the torrent sculpin and cutthroat trout, as well as several minnow and salmon species. The present-day fish community in Zollner Creek is composed primarily of bullhead catfish (an introduced species) and largescale sucker—both species are tolerant of turbid (clouded with silt), sluggish streams.

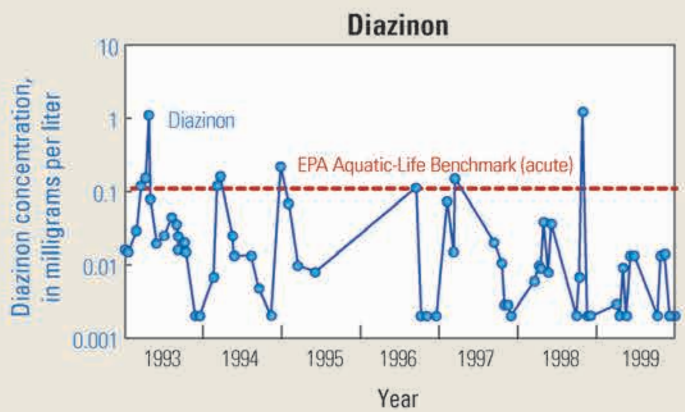
Image from U.S. Geological Survey National Landcover Dataset.



Concentrations of the herbicide atrazine in Zollner Creek (red dots on graph) were elevated during spring, which coincided with rainfall events during the pesticide application season. Elevated concentrations in the fall were associated with rainfall washing residual atrazine from croplands. (1 milligram per liter = 1 part per million.)



Nitrogen concentrations in Zollner Creek (green dots on graphs) varied widely but were usually 10 to 100 times higher than regional background levels.



Concentrations of the pesticide diazinon in Zollner Creek (blue dots on graph) often exceeded the U.S. Environmental Protection Agency (EPA) Aquatic-Life Benchmark, although the frequency of exceedances declined through time.

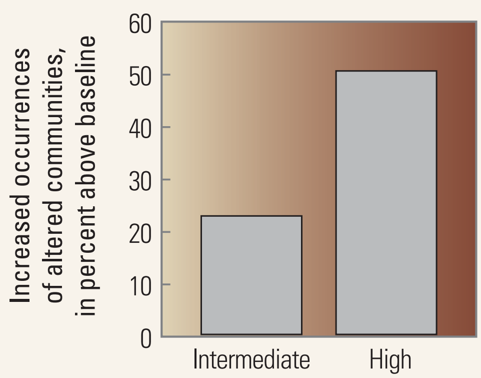
Macroinvertebrate communities were more frequently altered in streams with greater potential toxicity of sediment contaminant mixtures.

Contaminants in Stream Sediments

NAWQA found contaminants in stream sediments throughout the Nation and at concentrations that may be toxic to aquatic species. Although present in all land-use settings, sediment contaminants had the greatest potential for toxicity in urban streams and were often various hydrocarbon chemicals known to be toxic to aquatic life. Because most macroinvertebrates live on the stream bottom, they are likely to be exposed to contaminants in sediments and therefore provide useful information about potential ecological effects (chapter 2).

Macroinvertebrate communities were more frequently altered in streams with greater potential toxicity of sediment contaminant mixtures. Specifically, the incidence of altered macroinvertebrates communities increased from 23 to 51 percent as the potential toxicity (based on Long and others, 2006) of sediment contaminants increased. Invertebrate species can be exposed to sediment compounds directly through their skin (through which many species respire), gills, or by consuming plants or animals that have already absorbed contaminants. These findings are corroborated by a wealth of field and laboratory studies documenting the toxic effects of sediment contaminants, such as metals and hydrocarbons, in aquatic invertebrates (for example, Scoggins and others, 2007) and suggest that sediment contaminants should be considered a potential cause of reduced stream health, especially in urban areas.

Macroinvertebrate Community Alteration and Potential Toxicity of Sediment Contaminants



NAWQA studies found that macroinvertebrate communities in the Nation's streams were more frequently altered in streams with increasing concentrations and potential toxicity of contaminants in streambed sediments (bar graph above). Sediment-bound contaminants in streams typically include polycyclic aromatic hydrocarbons in urban settings and persistent pesticides in agricultural settings. Baseline is the occurrence of altered communities in 132 streams within the lowest category of potential toxicity.

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Glossary

agricultural stream A stream draining a watershed covered by more than 25 percent agricultural land.

algae Chlorophyll-bearing, primarily aquatic plants that have no true roots, stems, or leaves; most algae are microscopic, but some species can be as large as vascular plants (*see* vascular plants).

algal bloom A surge of algal growth typically caused by excessive nutrients in water. Dissolved oxygen in the water is consumed when algae grows and decomposes, which can lead to death of aquatic animals if the oxygen deficit is severe.

aquatic Pertaining to water. Plant and animal life living in water.

Aquatic-Life Benchmark A threshold value established by the U.S. Environmental Protection Agency above which the concentrations of a chemical in water or sediment may have adverse effects on aquatic organisms. Benchmarks for water are established to address either acute (short-term) or long-term (*see* chronic effect) exposures.

Aquatic-Life Criteria Water-quality guidelines established by the U.S. Environmental Protection Agency (EPA) for protection of aquatic life. Often refers to EPA water-quality criteria for protection of aquatic organisms.

atrazine A herbicide that is used to control weeds in major crops. It is widely used around the world.

baseline A standard by which things are measured or compared. In water-quality assessments, generally defined as the conditions before human intervention. For example, among a set of streams in an assessment, those with minimal manmade modifications to hydrology, chemistry, and biology would be considered representative of baseline conditions.

basin *See* drainage basin.

bed sediment Sediment particles, including eroded soil and organic matter, deposited at the bottom of a stream, lake, or ocean.

beneficial-use attainment The status of a water body relative to its ability to meet its designated beneficial use, as defined by the Clean Water Act. Typical beneficial uses include the protection of aquatic life and recreation.

benthic Refers to organisms that live on the bottoms of lakes, streams, or oceans.

benthic invertebrates Insects, mollusks, crustaceans, worms, and other organisms without a backbone that live in, on, or near the bottom of lakes, streams, or oceans.

bioaccumulation The biological sequestering of a substance at a higher concentration than that at which it occurs in the surrounding environment or medium. Also, the process whereby a toxic substance enters organisms through the gills and tissues or from dietary or other sources at a rate greater than that at which the substance is lost.

biodiversity *See* species diversity.

biological alteration The condition of a biological community that has been changed, relative to communities at regional reference sites, primarily due to human influences. These changes are typified by a loss of native species or changes in the relative abundance of species.

biological assessment An assessment of environmental quality by means of sampling and analyzing the characteristics of biological communities.

biological community A collection of species that inhabit a particular ecosystem or place. Distinctions among communities are typically arbitrary and reflect convenient categories of general types of organisms, such as algal, macroinvertebrate, and fish communities that inhabit a particular stream.

biological condition A measure of the degree to which biological communities differ from a natural (undisturbed or reference) state; generally, biological indicators at a site are compared with those at relatively natural sites to assess status of, or change in, condition.

biomass The total weight or volume of living material or type of organism within a given area and at a particular time.

carbon dioxide A naturally occurring chemical compound that is composed of two atoms of oxygen and one atom of carbon. It most often occurs in nature as a gas. Carbon dioxide is an important ingredient of photosynthesis by plants and is a product of respiration in animals.

channelization Modification of a stream, typically by straightening the channel, to provide more uniform flow; often done for flood control or for improved agricultural drainage or irrigation.

chloride A chemical ion most familiar as a component of common salt (sodium chloride). Chloride can enter streams from leaking sewage lines and septic tanks, road salt application, fertilizer use, and the use of water softeners, bleach, and swimming pool chemicals. Chloride may be transported to streams through groundwater and wastewater-treatment plant discharges.

chlorophyll A green, photosynthetic pigment common to plants.

chlorpyrifos An insecticide introduced in 1965 and widely used for pest control on corn, cotton, and fruit trees.

chronic effect Physiological response (such as death or impaired reproduction) resulting from long-term exposure to elevated concentrations of one or more chemicals or other changes in the physical or chemical characteristics of the environment.

community In ecology, the species that interact in a common area.

concentration The amount or mass of a substance present in a given volume or mass of sample. Usually expressed as micrograms per liter (water sample) or micrograms per kilogram (sediment or tissue sample).

confidence limit The upper or lower value of the range in the estimate of a specific quantity. Used to express the reliability of the estimate, where a larger range indicates less reliability and smaller ranges indicate greater reliability.

consumptive water use Water removed from a particular water supply or water body that is not returned to it.

crustacean Any of a large group (Crustacea) of arthropods (invertebrate animals, including insects, with an external skeleton, segmented body, and jointed appendages). Familiar species such as crabs, lobsters, crayfish, and shrimp are crustaceans. (*See also* invertebrate.)

cubic foot per second Rate of water discharge within a stream channel representing a volume of 1 cubic foot passing a given point during 1 second, equivalent to approximately 7.48 gallons per second or 0.02832 cubic meter per second.

cyanobacteria A group of microorganisms that are related to bacteria but are capable of photosynthesis.

daily streamflow The average of stream discharge measurements recorded over a 24-hour period.

DDT (dichlorodiphenyltrichloroethane) A synthetic organic chemical whose insecticidal properties were not discovered until 1939. DDT was widely used as an antimalarial insecticide and in agriculture before being banned in the United States and other countries due to its tendency to persist in the environment and cause harm to wildlife, particularly birds.

diatom Single-celled, colonial, or filamentous algae with cell walls constructed of silica and having two overlapping parts.

diazinon An insecticide developed in 1952 and heavily used for general purpose indoor and outdoor pest control in lawns, gardens, and agricultural crops. Since the early 2000s, diazinon use has been phased out in the United States.

discharge Rate of fluid flow passing a given point at a given moment of time (*see* cubic foot per second), expressed as a volume per unit time.

diversion A turning aside or alteration of the natural course of a flow of water, normally considered physically to leave the natural channel. In some U.S. States, this can be a consumptive use direct from another stream, such as by livestock watering. In other States, a diversion may consist of such actions as taking water through a canal, pipe, or conduit.

drainage area The drainage area of a stream at a specified location is that area, measured in a horizontal plane, which is enclosed by a drainage divide.

drainage basin The part of the surface of the Earth that contributes water to a stream through overland runoff, including tributaries and impoundments.

drainage divide The line or ridge of high ground that separates neighboring drainage basins (*see* also watershed).

ecoregion A geographic area of similar climate, landform, soil, potential natural vegetation, and hydrology.

ecosystem The interacting populations of plants, animals, and microorganisms occupying an area, plus their physical environment.

electrofishing A common method to survey fish populations. This method uses electricity to temporarily stun fish. After the fish are caught, identified, and measured, they are typically returned to the stream unharmed.

eutrophic Aquatic ecosystems that are highly enriched with plant nutrients, most commonly phosphorus and nitrogen. Also said of organisms that thrive in such conditions.

floodplain The low-lying area adjacent to streams and rivers that periodically (or historically) is inundated during extreme high flows.

food web An interconnected network of feeding linkages among organisms in an ecosystem.

gaging station A particular site on a stream, canal, lake, or reservoir where systematic observations of discharge are obtained.

groundwater Water beneath the ground surface in pore spaces, fractures, and other voids in geologic formations.

habitat The living space and environmental setting of a particular organism.

headwater The source or most upstream parts of a river basin.

high flow Streamflow that is created by runoff from precipitation or melting snow and is typically much higher than the long-term average flows.

hydrocarbon A compound composed solely of hydrogen and carbon. Most naturally occurring hydrocarbons on Earth are in the form of crude oil and natural gas. Most hydrocarbon contamination in the environment is from petroleum products refined from such oil and gas.

hydrologic system The assemblage of pathways by which water travels as it circulates beneath, at, and above the Earth's surface through various processes such as precipitation (rain and snow), runoff, evaporation, infiltration, transpiration (loss of water vapor from parts of plants, especially in leaves), and groundwater discharge.

impermeable surface Hard surfaces that block the infiltration of rain and snowmelt into the ground, including rooftops and paved surfaces, such as roads, parking lots, and driveways.

impoundment A body of water, such as a pond or reservoir, created by a dam or other natural or manmade obstruction to water flow (*see also* reservoir).

index of biological integrity (IBI) An aggregated number, or index, based on several attributes or metrics (such as species diversity and relative abundance) of a biological community that provides an assessment of the community's health and therefore helps identify issues with that community's surrounding environment.

insecticides Pesticides that are used to kill unwanted insects.

invertebrate An animal having no backbone or spinal column (*see also* benthic invertebrate).

kelp Kelps are a group of brown algae (Phaeophyceae) that typically can grow to more than 100 feet tall and are found in underwater "forests" in shallow oceans.

low flow Streamflow that is derived entirely by groundwater discharge and is typically much lower than the long-term average flows.

macroinvertebrate Animals that do not have backbones, such as worms, clams, crustaceans, and insects; "macro" refers to those animals that can be easily seen without magnification.

maximum annual streamflow The highest recorded daily streamflow value over a period of 1 year.

mean The average of a set of observations.

median The middle or central value in a distribution of data ranked in order of magnitude. The median is also known as the 50th percentile.

micrograms per liter (µg/L) A unit expressing the concentration of constituents in solution as weight (micrograms, µg) of solute per unit volume (liter, L) of water; equivalent to one part per billion in most stream water and groundwater. One thousand micrograms per liter equals 1 milligram per liter (1 mg/L).

minimum annual streamflow The lowest recorded daily streamflow value over a period of 1 year. In this report, minimum flow was calculated on a 7-day moving average rather than using daily values.

mixed-use streams Streams draining watersheds with a mixture of agriculture and urban land cover or relatively natural watersheds with substantial amounts of mining or water-management activities, such as dams and diversions. This is an operational definition used by NAWQA.

natural streamflow The natural patterns of flowing water in streams and rivers, including daily, seasonal, and annual variability and magnitudes.

NAWQA National Water-Quality Assessment Program of the U.S. Geological Survey. NAWQA was started in 1991 to develop long-term consistent and comparable information on streams, rivers, groundwater, and aquatic systems in support of national, regional, State, and local information needs and decisions related to water-quality management and policy.

nitrogen A naturally occurring chemical element and an important ingredient in many organic chemicals and proteins. It is also an important nutrient for plants.

non-native species Any organism found to be living outside its natural range (*see also* range).

nonpoint source A pollution source that cannot be defined as originating from discrete points such as pipe discharges. Areas of fertilizer and pesticide applications, atmospheric deposition of pollutants, and manure generation are types of nonpoint source pollution.

nutrient An element or compound essential for animal and plant growth. Common nutrients in fertilizer include nitrogen, phosphorus, and potassium.

oxygen A naturally occurring element, most frequently present as a gas. Dissolved oxygen in water is an important component of water quality because many aquatic animals respire by passing water over gill structures, which allows the transport of oxygen into the organism.

peak flow The largest magnitude stream discharge measured over a period of time, typically a year.

pesticide A chemical applied to crops, rights of way, lawns, or residences to control weeds, insects, fungi, nematodes, rodents or other pests.

pesticide toxicity index (PTI) A numeric score or index that accounts for the concentration of each pesticide compound measured in a water sample, the toxicity of each compound measured, and the possibility that multiple compounds have additive effects on aquatic organisms. The PTI does not measure actual toxicity of a water sample but assesses potential for toxicity relative to other samples. The PTI is computed separately for different taxonomic groups, such as fish or invertebrates (Munn and others, 2006).

pH The logarithm of the reciprocal of the hydrogen-ion concentration (activity) of a solution; a measure of the acidity (pH less than 7) or alkalinity (pH greater than 7) of a solution; a pH of 7 is neutral.

photosynthesis Synthesis of chemical compounds by organisms with the aid of light. Carbon dioxide is used as raw material for photosynthesis, and oxygen is a product.

point source A source of something, such as pollution, at a discrete, identifiable location such as a discharge pipe, drainage ditch, tunnel, well, concentrated livestock operation, or fixed watercraft.

polychlorinated biphenyls (PCBs) Widely used as dielectric and coolant fluids, for example in transformers, capacitors, and electric motors before being banned by the United States Congress in 1979. PCBs have been shown to cause cancer in animals, and there is also evidence that they can cause cancer in humans.

polycyclic aromatic hydrocarbons (PAHs) Also known as poly-aromatic hydrocarbons or polynuclear hydrocarbons, PAHs are complex organic molecules that occur in the environment as by-products of natural (for example, forest fires or volcanic activity) and human-caused (for example, fossil fuels) combustion. PAHs are a concern as a pollutant because some have been identified as damaging to DNA (deoxyribonucleic acid) and causing cancer. In aquatic systems, PAHs typically aggregate and are usually associated with sediments, but they can also occur in the dissolved phase in water at low concentrations.

potential toxicity Relative potential for toxicity of a water sample, as based on the pesticide toxicity index (*see also* pesticide toxicity index).

primary producer Organisms—typically plants—that produce their own energy through photosynthesis.

range (species range) A geographic boundary that encompasses the area in which a species is found.

reach A short, usually about 500 foot (~150 meter) section of a stream or river where organisms are sampled as part of a biological assessment (*see also* biological assessment).

reference The least-disturbed condition available in an ecoregion; determined based on specific criteria and used as a benchmark for comparison with other sampled sites in the region (*see also* baseline).

relative abundance The number of organisms of a particular kind present in a sample relative to the total number of organisms in the sample.

reservoir A body of water created by a dam and used to store water for various uses.

riffle A section of stream that is typically relatively shallow and fast moving.

riparian zone The land area adjacent to rivers and streams populated by plants and animals that rely on water from the stream for survival.

river mile The distance between any given point on a river and the river's mouth.

runoff [spring or seasonal] A period of time when water flows into streams as a result of rainfall or the melting of a snowpack.

runoff [surface] Water, generally from rain fall, that travels over the ground surface to the nearest surface stream.

salinity An indication of the amount of dissolved salt in water.

sediment Particles—derived from rocks or biological materials that have been transported by a fluid or other natural process—suspended or settled in water.

sediment quality guideline (SQG) A threshold value above which the concentrations of a chemical in sediment may have adverse effects on aquatic organisms, similar in concept to U.S. Environmental Protection Agency Aquatic-Life Benchmark.

sessile An organism that is fixed in one place or is generally immobile.

species diversity An ecological concept that incorporates both the number of species (taxa) in a particular sampling area and the evenness with which individuals are distributed among the various species.

species richness The number of species (taxa) present in a defined area or sampling unit.

species traits Descriptive features of a species that define its way of life, body shape, role in the ecosystem, and vulnerability to manmade environmental change.

statistical model A formalization, in the form of mathematical equations, of relations among a variable of interest and other variables that are related to it.

stormflow Flow in a stream that is largely derived from a storm event.

streamflow A type of channel flow, applied to that part of surface runoff in a stream whether or not it is affected by diversion or regulation (*see also* minimum and maximum annual streamflow).

streamflow modification Human-caused changes to natural variation and magnitudes of natural streamflows.

suspended sediment Particles of rock, sand, soil, and organic detritus carried in suspension in the water column in a stream, in contrast to sediment that moves on or near the streambed (*see also* turbidity).

suspended-sediment concentration The concentration of suspended sediment in water expressed as milligrams of dry sediment per liter of water-sediment mixture (mg/L).

taxa richness *See* species richness.

taxon [plural taxa] A grouping of organisms given a formal name such as species, genus, or family.

taxonomic A system of grouping organisms based on their characteristics and theorized evolutionary origin.

temperate climate The climate that is present in the middle latitudes between the tropics and the polar regions. Temperate climates typically have a wider range of temperature and precipitation than other regions.

terrestrial Pertaining to land. Organisms that live or grow on land.

tile drain Perforated pipes that are buried to shallow depths in the ground to reduce the water content of poorly drained soils and divert shallow groundwater to nearby streams.

tolerant [for example, tolerant taxa] Organisms that have characteristics that make them able to thrive in polluted environments.

total nitrogen The sum of inorganic (nitrate, nitrite, ammonia) and organic forms of nitrogen.

total phosphorus The sum of inorganic and organic forms of phosphorus.

toxicity The degree to which the presence of a chemical substance at a particular concentration may be harmful to the health of humans and other organisms.

trace metal Elements that are metals and typically occur in the environment in small amounts.

turbidity Reduced clarity of surface water because of suspended particles, usually sediment (*see also* suspended sediment and suspended-sediment concentration).

urban stream A stream draining a watershed with at least 5 percent coverage of residential, commercial, industrial, or other urban lands and less than 25 percent agricultural land.

vascular plants A large group of plants that are defined as those land plants that have tissues for conducting water and minerals throughout the plant. They also have tissue to conduct products of photosynthesis. Most visible terrestrial plants are vascular.

vertebrate Any animal with a backbone.

water-quality criteria Specific levels of water quality which, if reached, are expected to render a body of water unsuitable for its designated use. Commonly refers to water-quality criteria established by the U.S. Environmental Protection Agency. Water-quality criteria are based on specific levels of pollutants that would make the water harmful if used for drinking, swimming, farming, fish production, or industrial processes.

water-quality guidelines Specific levels of water quality which, if reached, may adversely affect human health or aquatic life. These are nonenforceable guidelines issued by a governmental agency or other institution.

water-quality standards State-adopted and U.S. Environmental Protection Agency-approved ambient standards for water bodies. Standards include the use of the water body and the water-quality criteria that must be met to protect the designated use or uses.

watershed A region bounded by a drainage divide that is drained by, or contributes water to, a stream, lake, or other body of water.

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