# Review of Phosphorus Control Measures in the United States and Their Effects on Water Quality

By David W. Litke

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 99–4007

NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

Denver, Colorado
1999

U.S. DEPARTMENT OF THE INTERIOR
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# FOREWORD

The mission of the U.S. Geological Survey (USGS) is to assess the quantity and quality of the earth resources of the Nation and to provide information that will assist resource managers and policymakers at Federal, State, and local levels in making sound decisions. Assessment of water-quality conditions and trends is an important part of this overall mission.

One of the greatest challenges faced by water-resources scientists is acquiring reliable information that will guide the use and protection of the Nation's water resources. That challenge is being addressed by Federal, State, interstate, and local water-resource agencies and by many academic institutions. These organizations are collecting water-quality data for a host of purposes that include: compliance with permits and water-supply standards; development of remediation plans for a specific contamination problem; operational decisions on industrial, wastewater, or water-supply facilities; and research on factors that affect water quality. An additional need for water-quality information is to provide a basis on which regional and national policy decisions can be based. Wise decisions must be based on sound information. As a society we need to know whether certain types of water-quality problems are isolated or ubiquitous, whether there are significant differences in conditions among regions, whether the conditions are changing over time, and why these conditions change from place to place and over time. The information can be used to help determine the efficacy of existing water-quality policies and to help analysts determine the need for, and likely consequences of, new policies.

To address these needs, the Congress appropriated funds in 1986 for the USGS to begin a pilot program in seven project areas to develop and refine the National Water-Quality Assessment (NAWQA) Program. In 1991, the USGS began full implementation of the program. The NAWQA Program builds upon an existing base of water-quality studies of the USGS, as well as those of other Federal, State, and local agencies. The objectives of the NAWQA Program are to:

- Describe current water-quality conditions for a large part of the Nation's freshwater streams, rivers, and aquifers.
- Describe how water quality is changing over time.
- Improve understanding of the primary natural and human factors that affect water-quality conditions.

This information will help support the development and evaluation of management, regulatory, and monitoring decisions by other Federal, State, and local agencies to protect, use, and enhance water resources.

The goals of the NAWQA Program are being achieved through ongoing and proposed investigations of 59 of the Nation's most important river basins and aquifer systems, which are referred to as study units. These study units are distributed throughout the Nation and cover a diversity of hydrogeologic settings. More than two-thirds of the Nation's freshwater use occurs within the 59 study units and more than two-thirds of the people served by public water-supply systems live within their boundaries.

National synthesis of data analysis, based on aggregation of comparable information obtained from the study units, is a major component of the program. This effort focuses on selected water-quality topics using nationally consistent information. Comparative studies will explain differences and similarities in observed water-quality conditions among study areas and will identify changes and trends and their causes. The first topics addressed by the national synthesis are pesticides, nutrients, volatile organic compounds, and aquatic biology. Discussions on these and other water-quality topics will be published in periodic summaries of the quality of the Nation's ground and surface water as the information becomes available.

This report is an element of the comprehensive body of information developed as part of the NAWQA Program. The program depends heavily on the advice, cooperation, and information from many Federal, State, interstate, Tribal, and local agencies and the public. The assistance and suggestions of all are greatly appreciated.

Robert M. Hirsch
Chief Hydrologist

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## CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

| Multiply | By | To obtain |
|---|---|---|
| | **Length** | |
| inch per year (in/yr) | 2.54 | centimeter per year |
| | **Flow** | |
| mile | 1.609 | kilometer |
| million gallons per day (Mgal/d) | 0.04381 | cubic meter per second |
| | **Mass** | |
| ton | 0.9072 | megagram |
| metric ton | 1.1023 | ton |
| | **Area** | |
| acre | 0.004047 | square kilometer |

### ADDITIONAL ABBREVIATIONS

| | |
|---|---|
| mg/kg | milligram per kilogram |
| mg/L | milligram per liter |
| (lb/capita)/yr | pound per capita per year |
| (kg/capita)/yr | kilogram per capita per year |

# Review of Phosphorus Control Measures in the United States and Their Effects on Water Quality

*By* David W. Litke


## ABSTRACT

Historical information on phosphorus loadings to the environment and the effect on water quality are summarized in this report, which was produced as part of the U.S. Geological Survey's National Water-Quality Assessment (NAWQA) Program. Phosphorus is a water-quality constituent of concern because it is often the limiting nutrient responsible for accelerated eutrophication in water bodies.

Phosphorus inputs to the environment have increased since 1950 as the use of phosphate fertilizer, manure, and phosphate laundry detergent increased; however, the manufacture of phosphate detergent for household laundry was ended voluntarily by the industry in about 1994 after many States had established phosphate detergent bans. Total phosphorus concentrations in raw wastewater effluent contained about 3 milligrams per liter of total phosphorus during the 1940's, increased to about 11 milligrams per liter at the height of phosphate detergent use (1970), and have currently declined to about 5 milligrams per liter. However, in some cases, tertiary wastewater treatment still is needed to effectively improve water quality of streams.

Downward trends in phosphorus concentrations since 1970 have been identified in many streams, but median total phosphorus concentrations still exceed the recommended limit of 0.1 milligram per liter across much of the Nation. Data from the NAWQA Program are representative of a variety of phosphorus-control measures and, therefore, may be used to evaluate the effects of various control strategies. Current areas of concern include: evaluation of the effects of increased manure loadings of phosphorus on soil phosphorus and, subsequently, on ground water and subsurface runoff; determination of point-source and nonpoint-source components of phosphorus loads by geographic modeling and hydrologic separation techniques; and development of methods or indices to evaluate nutrient impairment in streams and rivers to serve as a basis for developing phosphorus criteria or standards.


## INTRODUCTION

Eutrophication was recognized as a primary water-quality concern in the United States during the late 1960's, as typified by the emerging water-quality problems in the Great Lakes that captured the Nation's attention. Lake Erie was characterized as being a "dead lake," and there were estimates that 10,000 lakes were affected by eutrophication (ReVelle and ReVelle, 1988). Spurred on by public outcry, scientists and legislators worked to identify causes and remedies. By the early 1970's, it was generally accepted that phosphorus was the limiting nutrient responsible for the accelerated eutrophication in the majority of lakes and reservoirs (Likens, 1972; Schindler, 1975), and remedies focused on methods to control inputs of phosphorus to the environment. Phosphorus inputs to the environment had increased substantially in prior years because of increasing use of phosphate fertilizers and phosphate detergents. In order to quickly reduce phosphorus in the environment, phosphate detergent bans were enacted by some States and local municipalities, although the efficacy of this remedy continued to be debated throughout the 1970's and early 1980's. Meanwhile, the Federal Water Pollution Control Act of 1972 (known as the Clean Water Act) was enacted, and billions of dollars were spent on the task of upgrading wastewater-treatment plants to remove pollutants, including phosphorus in some cases, from effluent. In the 1990's, as pollutants from wastewater-treatment plants were reduced, efforts turned toward reducing nonpoint sources of pollution, including phosphorus inputs to the environment from sources such as agricultural runoff. Currently (1998) there is limited information at a national scale concerning the status and success of phosphorus controls. It would be useful for water-quality managers to know how fully these remedies have been implemented and what the effects have been on water quality.

## Purpose and Scope

The purpose of this report is to review the history of phosphorus controls in the United States, to review what is known about the effect of these controls on water quality, and to describe how data collected by the U.S. Geological Survey's (USGS) National Water-Quality Assessment (NAWQA) Program might be used to evaluate the effect of phosphorus controls on water quality. The history of phosphorus controls is reviewed by summarizing the timing and geographic extent of phosphate detergent legislation and detergent use in the United States and by a summary of point-source phosphorus limit data from the U.S. Environmental Protection Agency (USEPA) Permit Compliance System data base (PCS). Current knowledge about the effect of these controls is reviewed by discussion of three issues: what is the magnitude of the eutrophication problem; have phosphorus control strategies substantially reduced concentrations and loads of phosphorus in streams; and has the magnitude of any resulting decrease been sufficient to affect eutrophic conditions? The relevance of NAWQA data on phosphorus controls and water quality will be evaluated by comparing the geographic extent of the NAWQA data base to the geographic extent of implemented phosphorus controls and by summarizing current (1998) NAWQA findings.

## Acknowledgments

The author thanks Steven Rubin of the USEPA for providing a retrieval from the PCS data base. Project staff among the NAWQA study units throughout the Nation are gratefully acknowledged for providing information about NAWQA sites, data, and relevant findings.

# PHOSPHORUS IN THE ENVIRONMENT

Although phosphorus is a nutrient essential to the growth of plants, too much of a good thing can be harmful to the environment (Mueller and Helsel, 1996). Enriched phosphorus levels can accelerate the growth of algae and other plants that impair the suitability of the water for municipal, recreational, and fishery use. To control eutrophication, the USEPA has established a recommended limit of 0.05 mg/L for total phosphates in streams that enter lakes and 0.1 mg/L for total phosphorus in flowing waters (U.S. Environmental Protection Agency, 1986). Twenty-two States have adopted numerical criteria for phosphorus and 12 States have narrative criteria, but 21 States have no water-quality standard for phosphorus (Parry, 1998). Nutrient standards are currently under review as part of the Clean Water Action Plan (U.S. Environmental Protection Agency, 1998a), and new regional numerical criteria based on ecoregion and type of receiving water are being developed (U.S. Environmental Protection Agency, 1998b).

Phosphorus concentrations in streams in pristine (unaffected by human activities) areas generally are small. Stream sampling in 63 relatively unaffected basins as part of the USGS Benchmark Program (Alexander and others, 1996) indicated a median total phosphorus concentration of 0.016 mg/L. A USEPA study (Omernik, 1977) of 928 basins around the Nation found that basins that were more than 90 percent forested had streamwater with a median total phosphorus concentration of 0.018 mg/L. This same study identified no relation between rock type and phosphorus concentration. However, in a few areas of the Nation (Florida, Idaho, Kentucky, Oregon, South Carolina), elevated concentrations of phosphorus in stream water are associated with phosphate rock deposits or large natural soil phosphorus levels (Abrams and Jarrell, 1995).

Dissolved phosphate occurs in small concentrations in water because it has low solubility, is readily taken up by biota, and adsorbs to metal oxides in soils (Hem, 1992). Large total phosphorus concentrations generally are associated with runoff events, which carry a substantial proportion of suspended sediment to which phosphorus is attached. Yields of phosphorus can, therefore, vary considerably from year to year in both natural (Lewis and others, 1984) and developed environments (Svendsen and others, 1995), depending on water yield.

## Phosphorus Sources and Sinks

The most recent nationwide loading estimates (Gianessi and Peskin, 1984) indicated that, in the 1980's, the largest anthropogenic sources of phosphorus to the environment were fertilizer application (1.8 million metric tons), manure application (1.8 million metric tons), other nonpoint sources (1.1 million metric tons), and wastewater-treatment-plant discharges (260,000 metric tons). Phosphorus use in fertilizer (fig. 1) more than doubled from 1950 to 1980 when it peaked at about 2.5 million metric tons per year. Use then declined somewhat but appears to be holding steady since 1985 at about 2 million metric tons per year. Estimates of manure use based on livestock populations also have increased over the past 50 years (fig. 1). Measurements of the phosphorus content of soils were relatively static from 1940 to 1980 (Midwest Research Institute, 1979) but have shown increases in recent years. For example, the average level of soil-test phosphorus in Wisconsin soils has increased from 34 mg/kg in 1967 to 48 mg/kg in 1990; and in 17 States, more than one-half the soils tested were rated by State soil-test laboratories as high or above for phosphorus in 1989 (Sharpley and others, 1994). Soil phosphorus also is increasing in areas of high manure application rates (Beauchemin and others, 1996). Large soil phosphorus concentrations are a water-quality concern because large phosphorus concentrations in streams (Haag and Porter, 1995; Van der Molen and others, 1998) and in soil-drainage water (Beauchemin and others, 1998) have been associated with areas with high soil phosphorus content. Manure application in particular is a water-quality concern because phosphorus from manure is more mobile through the soil profile than is phosphorus from chemical fertilizer (Eghball and others, 1996).

It is difficult to estimate what portion of the nonpoint-source inputs reaches rivers and streams. A nationwide study of the sources of phosphorus to streams (Midwest Research Institute, 1979) estimated that 2.5 million metric tons of phosphorus was contributed by runoff from agricultural lands (cropland, pasture, and rangeland), or almost one-half of the annual amount of fertilizer applied at that time. This quantity was determined by using soil erosion rates (using the Universal Soil Loss Equation method), estimates of phosphorus content of soils, transport enrichment factors, and sediment delivery ratios. However, this method does not adequately take into account storage of material in small watersheds (Wischmeier, 1976). Alternatively, stream loads also have been calculated directly by measurement at stream-monitoring stations; these estimates generally indicate that less than 5 percent of the applied fertilizer load of phosphorus reaches the streams (see, for example, Vollenweider, 1970; Smith and others, 1997). Field-based yield estimates tend to show that suspended phosphorus comprises at least 75 percent of the load (see, for example, Sharpley and others, 1994), whereas stream-based yield estimates indicate that as much as 50 percent of the phosphorus is dissolved (see, for example, Omernik, 1977). These differences could indicate that much of the particulate phosphorus eroded from fields is stored throughout the surface-water hydrologic system but has the potential to become available for uptake by biota under favorable conditions. Resuspended phosphorus can constitute more than one-half of the phosphorus load in a stream (Svendsen and others, 1995). Much of the suspended phosphorus load may ultimately be deposited in lakes and reservoirs, which can act as long-term sinks. Substantial conversion to the dissolved form can occur at the sediment/water interface, however, under both anoxic (Horne and Goldman, 1983) and aerobic conditions (Lung and Larson, 1995).

Phosphorus concentrations in precipitation generally are low (less than 0.03 mg/L as P) in nonpopulated areas (Wetzel, 1983). Ninety-five

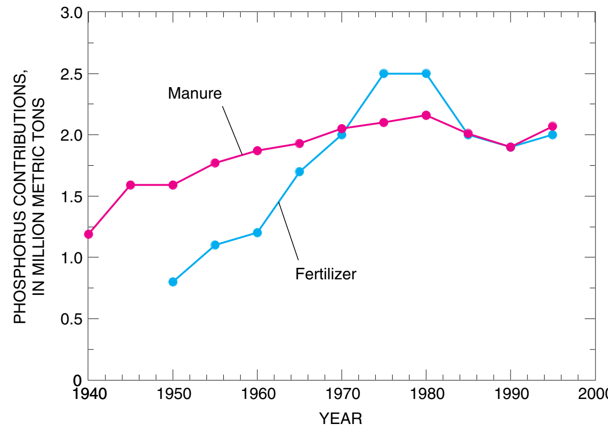


**Figure 1.** Contributions to the environment of phosphorus from fertilizer and manure, 1940-95 [source of data: fertilizer use from Puckett (1995); manure use estimated using method of Alexander and Smith (1990), and animal counts from U.S. Bureau of the Census (1976, 1995)].

percent of orthophosphate measurements at National Atmospheric Deposition Program/National Trend Network precipitation sites are less than the detection limit (0.02 mg/L), and orthophosphate detections are generally used to indicate sample contamination (Mark Nilles, U.S. Geological Survey, oral commun., 1998). However, rainfall can scavenge phosphate dust in agricultural areas, and phosphorus in urban rainfall has been measured at concentrations as large as 0.5 mg/L (Gibbs and Doerfer, 1982). The median total phosphorus concentration in urban storm runoff from 30 metropolitan areas in the United States was 0.25 mg/L (Driver, 1988). Relatively small concentrations of phosphorus in rainfall can result in substantial loads. For example, in a North Carolina basin where rainfall averages 43 in/yr, an average phosphate concentration of 0.06 mg/L in rainfall corresponds to a loading rate of 0.19 ton of phosphorus per square mile per year. This loading rate accounts for 22 percent of the total phosphorus loading to the basin (McMahon and Woodside, 1997).

## Phosphorus and Eutrophication

Eutrophication is a process whereby the condition of a water body changes from one of low biologic productivity and clear water to one of high productivity and water made turbid by the accelerated growth of algae. Natural eutrophication has been observed to take place in lakes: increased loadings of nutrients lead to accelerated biologic productivity and eventually, through sedimentation of biologic debris, the lake becomes a bog. Anthropogenic nutrient sources have amplified the accelerated growth of aquatic plants and algae; this effect has been termed cultural eutrophication and has been applied in reference to lakes and reservoirs (Hutchinson, 1969), streams, and estuaries (Ketchum, 1969).

Eutrophication cannot be related directly to the dissolved phosphorus concentration of lake water because phosphorus is cycled very quickly in a reservoir (within the water, biota, and sediment), at times on the order of 1 minute (Rigler, 1964). A more useful way to evaluate trophic state is to examine the state of the system (a lake and its drainage basin) in relation to nutrient loading rates. Nutrient loadings must be sustained to support increased productivity. Empirical relations have been developed (Vollenweider, 1975) between lake characteristics (lake depth and retention time), the total phosphorus loading rate to a lake, and the trophic status of a lake. These relations can be used to predict the trophic status of a lake under varying phosphorus loading scenarios (Gakstatter and Maloney, 1975; Lee and Jones, 1986). A further outcome of the Vollenweider relation is the ability to index the trophic status of a lake by using the total phosphorus concentration of lake water (Smith and others, 1993).

The term “eutrophic” does not properly apply to flowing waters (Hynes, 1969) because terminal trophic succession does not occur. However, nutrient-enriched streams have the potential for accelerated plant growth. Studies of pristine streams indicate that a phosphorus enrichment of as little as 0.01 mg/L can stimulate abundant algal growth. Aquatic plants and benthic algae require suitable attachment sites for enhanced growth, and phytoplankton require warm, clear water open to the sun. Where these conditions are met, nuisance growths can occur, but the turbidity of rivers and the frequency of scouring high streamflows generally are limiting factors.

Eutrophication can occur in estuaries, although the dynamics are different than in lakes due to the processes of tidal ebb and flow, mixing of freshwater with seawater, and resultant differences in concentrations of nutrients. Estuarine and coastal studies indicate that nitrogen is likely to be the limiting nutrient in those environments (Ketchum and others, 1958).

Phosphorus generally is the limiting nutrient in eutrophication (Correll, 1998) because the ratio of phosphorus in plant content to its availability in water is larger than for any other nutrient (Wetzel, 1983). Therefore, under typical freshwater conditions where physical factors are conducive to the growth of algae, additions of phosphorus to the system are more likely to lead to accelerated growth than are additions of other nutrients. This view was held strongly enough in 1974 that an International Congress of Limnologists ratified a resolution emphasizing the critical role of phosphorus in eutrophication (Wetzel, 1975). However, more recent studies indicate that increased nitrogen and phosphorus together stimulate growth the most (Goldman and others, 1990).

# PHOSPHORUS CONTROL MEASURES

Regardless of the resolution of the debate on limiting nutrients in eutrophication, control of phosphorus sources to the environment will continue to be important because almost all elevated levels of phosphorus in water bodies are due to anthropogenic sources. The history and current status of phosphorus controls are discussed in the sections that follow.

## Phosphate Detergent Bans

Traditional bar soap, which contains little phosphate, was the primary cleaning agent used in the United States until the end of World War II. At that time, cleaning agents began to be reformulated, partly in response to shortages of raw materials due to the war and partly in an effort to produce more sophisticated formulations that met the needs of evolving household uses such as the washing machine. The new powdered formulations of clothes-washing detergent included as much as 60 percent by weight of sodium tripolyphosphate (STPP) (about 15 percent by weight as phosphorus) as a builder, whose function was to remove hardness from water so that surfactants could perform properly. Builders are needed even for soft water because hardness is dissolved off clothes in the washing machine (Gosselin, 1992). Phosphorus consumption for the manufacturing of detergents was negligible in 1940 when synthetic detergents were newly introduced, but use grew rapidly to about 220,000 metric tons in 1967 as synthetic detergents became prevalent (fig. 2). At the peak use of phosphate detergents, consumption of phosphorus was about one-tenth of the amount used for fertilizer.

In 1967, the U.S. Congress established the Joint Industry-Government Task Force on Eutrophication with the goal of accelerating research into the development of suitable substitutes for phosphates in detergent. In 1970, a Congressional committee determined that the Task Force was not moving quickly enough and recommended that the manufacture of phosphate detergents be ended by 1972 (U.S. Congress, 1970). However, there were concerns of possible health hazards of the leading substitutes for phosphate in detergents; sodium carbonates and sodium silicates (zeolites) are more caustic than sodium phosphates. There also were concerns over the teratogenic effects of sodium nitrilotriacetate (NTA) and the carcinogenicity of NTA degradation by-products. In 1970, the detergent industry voluntarily agreed to limit phosphate in detergents to 8.7 percent by weight as phosphorus; this is a level at which phosphate builders can be effective without introducing additional builders. While no Federal legislation was passed in the United States, phosphate levels were regulated in Canada (8.7-percent phosphorus limit in August 1970 followed by a 2.2-percent phosphorus limit in December 1972). In February 1971, five cities in Illinois became the first to limit phosphate detergents in the United States (table 1). Legislative limits generally apply only to domestic laundry detergents; phosphate is still permitted in dishwashing detergent and in commercial cleaning agents.

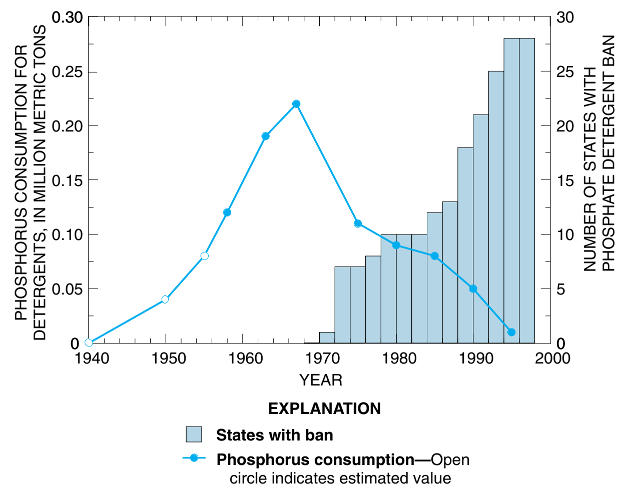


**Figure 2.** Consumption of phosphorus in detergent manufacturing and number of States with phosphate detergent bans, 1940-98 [source of data: phosphorus consumption for 1958-94; U.S. Congress (1970) and Peter Truitt (U.S. Environmental Protection Agency, written commun., 1997); States with phosphate detergent ban: compiled from numerous sources].

The number of States with phosphate detergent bans has increased steadily (fig. 2); the most recent detergent ban was passed in New Hampshire in 1995, and 27 States and the District of Columbia now have complete or partial bans. States with bans (fig. 3) are located primarily around the Great Lakes and along the eastern coast of the United States. As more States passed detergent-ban legislation, the industry was faced with maintaining duplicate inventories of detergent products around the Nation and ultimately decided it was cost effective to phase out the use of phosphorus in domestic laundry detergent, which was accomplished by about 1994 (fig. 2). Currently (1998),

**Table 1.** States with phosphate detergent bans

[--, information not available]

| State | Date of ban[1] | Geographic extent of ban | Phosphorus limit, in percentage of phosphorus by weight |
|---|---|---|---|
| Arkansas | January 1, 1994 | Statewide | 0.5 |
| Connecticut | February 1, 1972 | Statewide | 8.7 |
| District of Columbia | September 1986 | Districtwide | 0.5 |
| Florida | December 31, 1972 | Statewide | 8.7 |
| | -- | Monroe County | 0.5 |
| Georgia | May 1989 | Statewide (voluntary) | 0.5 |
| | November 1990 | Statewide (mandatory) | 0.5 |
| Idaho | March 1989 | Bonner County, 10 cities | 0.5 |
| Indiana | February 22, 1972 | Statewide | 8.7 |
| | January 1, 1973 | Statewide | 0.5 |
| Illinois | February 1971 | Five cities | 8.7 |
| | -- | Nine cities | 0.5 |
| Maine | June 1, 1972 | Statewide | 8.7 |
| | | | 0.5 |
| Maryland | December 1, 1985 | Statewide | 0.5 |
| Massachusetts | July 1994 | Statewide | 0.5 |
| Michigan | July 1, 1972 | Statewide | 8.7 |
| | October 1, 1977 | Statewide | 0.5 |
| Minnesota | January 1, 1977 | Statewide | 0.5 |
| Missouri | -- | Two cities | 0.5 |
| Montana | May 1989 | Missoula | 0.5 |
| | April 1984 | Flathead and Lake Counties | |
| New Hampshire | January 1995 | Statewide | 0.5 |
| New York | January 1, 1972 | Statewide (household products) | 8.7 |
| | June 1, 1973 | Statewide (household products) | 0.5 |
| | January 1, 1976 | Statewide (commercial products) | 0.5 |
| North Carolina | January 1988 | Statewide | 0.5 |
| Ohio | [2]March 26, 1988 | Partial (32 counties) | 0.5 |
| | | Three cities | 8.7 |
| Oregon | July 1992 | Statewide | 0.5 |
| Pennsylvania | March 1, 1990 | Statewide | 0.5 |
| Rhode Island | 1995 | Partial | -- |
| South Carolina | January 1, 1992 | Statewide | 0.5 |
| Texas | June 2, 1991 | Austin | 0.5 |
| | | Three other cities | 0.5 |
| Vermont | April 1, 1978 | Statewide | 0.5 |
| Virginia | January 1988 | Statewide | 0.5 |
| Washington | July 1990 | Spokane | 0.5 |
| | -- | Statewide | 0.5 |
| Wisconsin | July 1, 1979 | Statewide | 0.5 |
| | June 30, 1982 | Ban lifted | -- |
| | January 1, 1984 | Statewide | 0.5 |

[1]Detergent bans typically restrict phosphate only for household laundry detergents, with use of phosphate still allowed in dishwashing detergents and in commercial cleaning products.
[2]Bill signed in 1988; limits to be met by 1990.

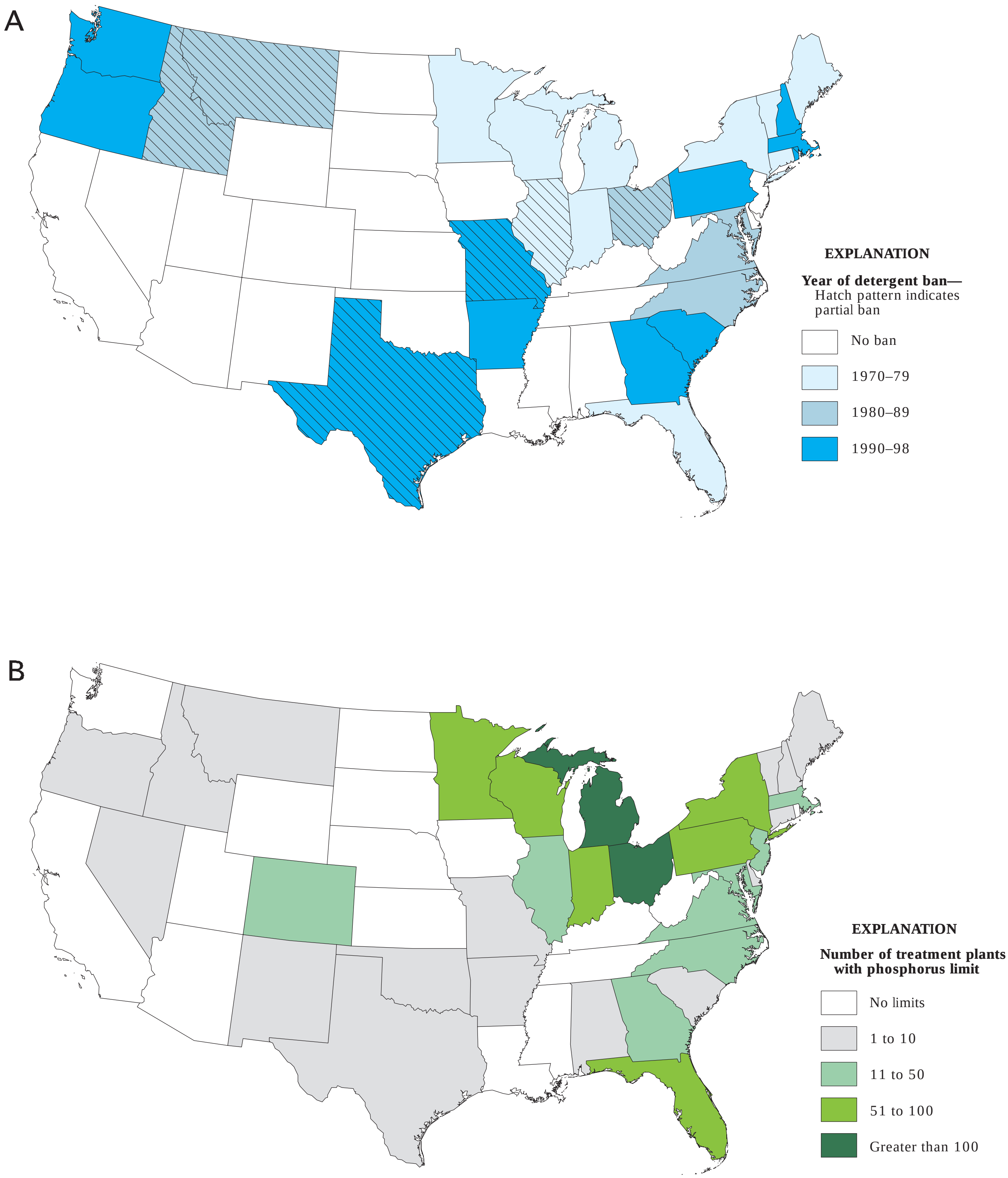


**Figure 3.** (A) States with phosphate detergent bans, and (B) number of wastewater-treatment plants with phosphorus limits. Alaska and Hawaii have neither bans nor phosphorus limits.

the trend in laundry detergent is toward liquid concentrates (compacts), which use alternative builders, or nonionic surfactants that are not affected by water hardness. However, there are proponents in the phosphate industry who advocate the reintroduction of phosphate into detergents, arguing that the hazardous effects of phosphate on human health and the environment are less than the effects of phosphate substitutes [Scientific Committee on Phosphates in Europe (SCOPE) online newsletter at http://www.ceep-phosphates.org/scope.htm].

## Effluent Phosphorus Limits

As the consumption of phosphate for detergent manufacturing rose and fell from 1940 to the present, so did the concentrations and loads of phosphorus in wastewater-treatment-plant effluent. A study of historical phosphorus concentrations in effluent (Hetling and Carcich, 1972) indicated that raw effluent contained about 3 mg/L of total phosphorus [equivalent to about 1 (lb/capita)/yr or 0.4 (kg/capita)/yr] during the 1940's and that concentrations increased to about 11 mg/L total phosphorus [3.3 (lb/capita)/yr, or 1.5 (kg/capita)/yr] by 1970; the study also determined that, at that time, about 6 mg/L of the phosphorus (54 percent) was due to detergent use, but that there was an additional increase in phosphorus in raw effluent (about 2 mg/L) that might be due to the increased use of phosphate in prepared foods. These data were collected during 1970-71 when phosphorus consumption for detergent manufacture was near its peak. The extrapolation of these data to current times indicates that, with the discontinuance of use of phosphate laundry detergents, raw effluent can be expected to contain about 5 mg/L of total phosphorus.

A major focus of the Federal Water Pollution Control Act and its amendments has been to improve water quality through control of point-source discharges. From 1972 to 1991, about $200 billion was spent on construction of wastewater-treatment plants and about $154 billion was spent on operation and maintenance expenses at treatment plants (Harcum and others, 1997). Figure 4 shows that the number of wastewater-treatment plants in the United States has not increased significantly since 1968; however, the type of treatment at the plants has changed considerably. The proportion of plants with primary or less treatment has decreased from about 50 percent in 1962 to almost none in 1996, while the number of plants with tertiary treatment has increased from none to about 25 percent. Wastewater-treatment plants with primary treatment remove 5 to 10 percent of phosphorus, plants with secondary treatment remove 10 to 20 percent of phosphorus, and plants with tertiary treatment for phosphorus remove as much as 99 percent of phosphorus (U.S. Environmental Protection Agency, 1974a, 1976a). Therefore,

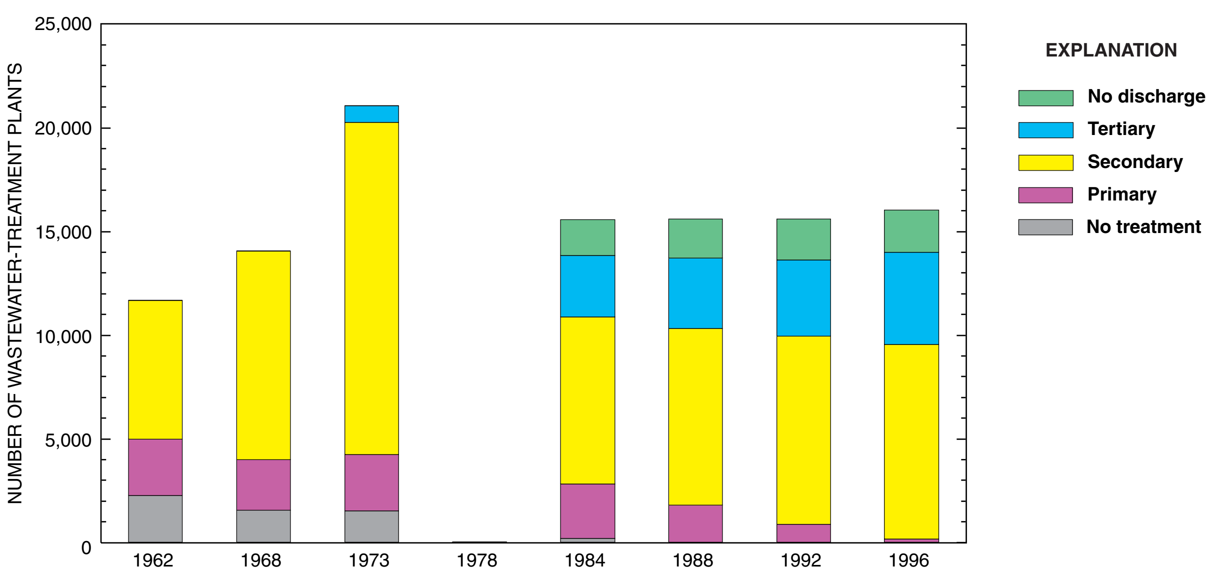


**Figure 4.** Number of wastewater-treatment plants in the United States, by treatment type [no available data 1974-83; source of data, U.S. Environmental Protection Agency (1974b, 1990, 1997c)].

a combination of cessation of phosphate detergent use and secondary treatment of the resulting effluent can reduce total phosphorus concentrations in treated effluent to within the range of 3 to 5 mg/L. In some areas of the country it has been found that further reductions in effluent phosphorus concentrations are necessary to have a beneficial effect on water quality in streams. These further reductions can be realized by implementation of effluent phosphorus limits that require tertiary treatment of effluent for phosphorus.

A retrieval from the USEPA's Permit Compliance System (PCS) was compiled to evaluate the status of phosphorus controls at treatment plants in the United States. At the time of the retrieval (August 1997), there were about 73,000 facilities listed in the PCS data base, which discharged a total of 2,380 billion gallons per day of effluent (table 2). However, much of this discharge was from power plants and other industries that discharge cooling water. About 4.7 percent of industrial facilities are required to monitor for phosphorus, and about 1.7 percent of industrial facilities have phosphorus limits for their discharge. There were about 16,000 municipal wastewater-treatment plants in the PCS data base, which discharged 42.2 billion gallons per day of effluent, serving about 190 million people (about 70 percent of the total population). About 15.3 percent of the municipal wastewater-treatment plants in the United States, which account for about 39 percent of the total municipal wastewater-treatment-plant discharge, were required to monitor for phosphorus. However, only about one-half of these plants have phosphorus concentration limits.

Phosphorus limits are assigned a start date in the PCS data base, and the historical implementation of phosphorus controls is shown in figure 5. Prior to 1973, there were few municipal facilities with phosphorus concentration limits; but from 1975 to 1985, limits were actively implemented, with a maximum of 104 limits implemented during 1986. Since that year, the implementation rate has dropped but still averages about 50 per year. The magnitude of phosphorus limits does not vary much; most plants have a phosphorus limit in the range of 0.5 to 1.5 mg/L. Currently, with the management focus shifting toward allotment of total maximum daily loads (TMDLs) within river basins, there is an increasing emphasis on restricting phosphorus loads from dischargers rather than phosphorus concentrations; however, data on phosphorus load limitations were not compiled for this study.

The location of wastewater-treatment plants with phosphorus limits (fig. 3B) is distinctly regional, with limits concentrated in the Great Lakes and East Coast States. Few limits on plants were implemented in States west of the Mississippi River. Limits in Colorado are unique because they apply primarily to ground-water discharges from land application or from evaporation ponds.

## Nonpoint-Source Controls on Phosphorus

The large amount of money spent on wastewater-treatment-plant improvements since the enactment of the Clean Water Act has led to substantial reductions of loadings for many pollutants. As a result, attention is shifting toward nonpoint sources of pollut-

**Table 2.** Summary of facilities in Permit Compliance System data base with phosphorus requirements

[Source of data: U.S. Environmental Protection Agency Permit Compliance System, 1997 retrieval; na, not available; Mgal/d, million gallons per day]

| Facility type | Total number of facilities | Total discharge (billion gallons per day) | Facilities required to monitor phosphorus | | | Facilities with phosphorus concentration limits | | |
|---|---|---|---|---|---|---|---|---|
| | | | Number of facilities | Percentage of facilities | Sum of design flow (Mgal/d) | Number of facilities | Percentage of facilities | Sum of design flow (Mgal/d) |
| Municipal | 15,939 | 42.2 | 2,437 | 15.3 | 16,447 | 1,163 | 7.3 | 7,145 |
| Industrial | 50,599 | na | 2,379 | 4.7 | 16,950 | 877 | 1.7 | 9,336 |
| Federal | 1,119 | na | 110 | 9.8 | 113 | 50 | 4.5 | 51 |
| Other | 5,087 | na | 142 | 2.8 | 28 | 26 | 0.5 | 5 |
| Total | 72,744 | 2,380 | 5,068 | 7.0 | 33,538 | 2,116 | 2.9 | 16,537 |

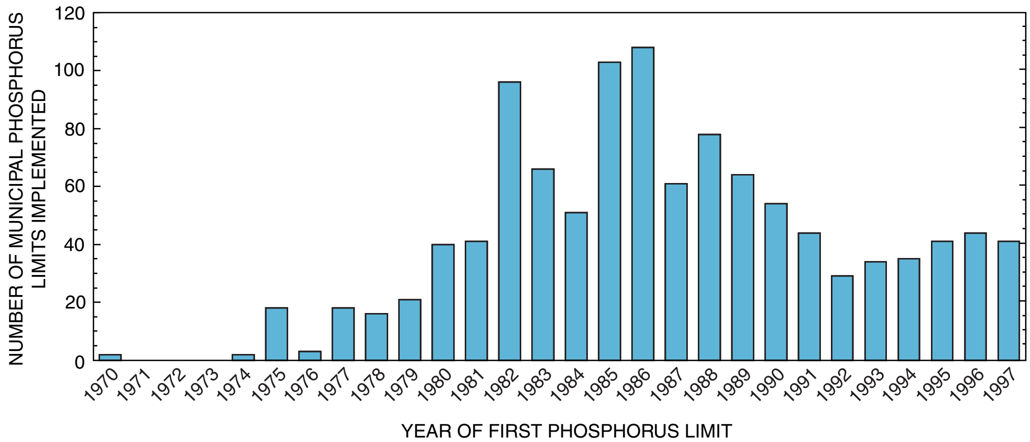


**Figure 5.** Implementation of phosphorus effluent limits by year, 1970-1997 [source of data: U.S. Environmental Protection Agency Permit Compliance System data-base retrieval, 1997].

ants. The USEPA Clean Water Action Plan for 1998 states that polluted runoff, particularly from agricultural nonpoint sources, is now the most important source of water pollution (U.S. Environmental Protection Agency, 1998a). However, only about 7 percent of municipal wastewater-treatment plants have tertiary treatment for removal of phosphorus; thus, additional reduction in point-source phosphorus loads from treatment plants could be possible.

The primary agricultural nonpoint sources of phosphorus are runoff from fields and from manure disposal sites related to concentrated animal-feeding operations (CAFOs). CAFOs are beginning to be regulated by the USEPA as point sources, although as of 1995, only 760 of approximately 6,600 CAFOs had National Pollutant Discharge Elimination System (NPDES) permits (Parry, 1998). Land-application requirements for CAFOs can be specified as part of NPDES permits. However, land application requirements cannot be specified for CAFOs that do not have permits or for land application of manure when the manure is moved off the CAFO.

Management of agricultural runoff historically has been encouraged by the USEPA by development of local best management practices (BMPs) funded through Section 319 of the Clean Water Act. Development of effective agricultural BMPs is complex because of the many hydrologic and environmental factors that affect nonpoint-source pollution. Transport pathways for agricultural runoff include overland runoff, subsurface flow (Sims and others, 1998), and ground-water flow (Gburek and Sharpley, 1998). Because field runoff and delivery to streams depend on many site-specific factors, a strategy of ranking sites for potential runoff risk has been suggested (Sharpley and others, 1994). Where agricultural BMPs focus on minimizing runoff while not reducing phosphorus applications to the land surface, nutrient transport may simply be transferred from surface water to ground water. Studies have found that ground-water transport can be a substantial source of phosphorus pollution; for example, it has been estimated that 10 to 20 percent of the phosphorus entering the Chesapeake Bay travels through ground water (Rebecca Phipps, U.S. Geological Survey, written commun., 1997). Therefore, it is recognized that source management, which necessitates improved methods for measuring soil phosphorus, is an important part of agricultural BMPs (Daniel and others, 1998). Source management also must consider the nitrogen-to-phosphorus ratios in animal manure because application based on nitrogen content alone can lead to gross overapplication of phosphorus (Liu and others, 1997).

Although BMPs are generally voluntary, there are mechanisms that States can use to enforce reduction of nonpoint-source pollution (Environmental Law Institute, 1997). The required development of watershed TMDLs will encourage a balanced approach for managing both point and nonpoint sources of phosphorus. Other Federal programs, such as the conservation provisions of the 1996 Farm Bill and nonpoint-source management provisions of the Coastal Zone Act of 1990, also will encourage the reduction of nonpoint sources of phosphorus (Parry, 1998).

# EFFECTS OF PHOSPHORUS CONTROL STRATEGIES ON WATER QUALITY

Debates in the U.S. Congress over phosphate detergent bans (U.S. Congress, 1970, 1972) raised several issues that are still relevant today and which are discussed in this report. First, what is the magnitude and extent of the eutrophication problem? Second, would the proposed phosphorus control strategies substantially reduce concentrations and loads of phosphorus in lakes and streams? Finally, would the magnitude of any resulting decrease be sufficient to affect eutrophic conditions?

## Extent of Eutrophication

The extent of eutrophication could not easily be defined in 1970 because there was no national inventory of water bodies. The magnitude of the potential for eutrophication could not easily be defined because there was scarce information about nutrient loadings to the environment or about trends in concentrations of phosphorus in receiving streams. Although the problems of Lake Erie were well publicized, one scientist testified that only 15 percent of the Nation's population contributed waste to waters vulnerable to eutrophication (U.S. Congress, 1972) because most phosphorus was discharged to ground water, to the oceans, or to turbid rivers. Only anecdotal and localized information was available on the extent of eutrophic conditions.

In response to the lack of information, the USEPA began the National Eutrophication Survey in 1972. This survey included nationwide data collection and analysis of nutrient concentrations in wastewater (U.S. Environmental Protection Agency, 1974a), streams (Omernik, 1977), and lakes (Lorenzen, 1979). A compilation of the results (Gakstatter and Maloney, 1975) stated that 10 to 20 percent of all lakes and reservoirs in the United States were eutrophic; that phosphorus was the limiting nutrient in 67 percent of the lakes studied; and that, while a phosphate detergent ban would improve the trophic status of about 21 percent of the lakes studied, additional phosphorus control strategies would be needed to improve the trophic status of many lakes and streams.

With the passage of the Federal Water Pollution Control Act of 1972, States were required to report biennially to the USEPA an assessment of the quality of their surface waters. Using the State assessments, the USEPA was required to issue a biennial National Water Quality Inventory report to the Congress. The first National Water Quality Inventory (U.S. Environmental Protection Agency, 1974b), published in 1974, examined only stream-water quality, summarizing available data from 22 of the Nation's largest rivers, and found that, from the mid-1960's to the early 1970's, total phosphorus concentrations had increased in 82 percent of the reaches studied and that 57 percent of the reaches exceeded the recommended total phosphorus limit of 0.1 mg/L. Among eight rivers that were studied more intensively, seven had no nuisance algal growths despite large nutrient concentrations. The lack of algal growth was attributed to turbid conditions where growth was light limited. The eighth river, the Snake River, had low turbidity, large nutrient concentrations, and nuisance algal growths. However, algal growths in the Snake River had occurred historically, in part due to naturally large levels of phosphorus derived from phosphate rock deposits. The 1976 National Water Quality Inventory (U.S. Environmental Protection Agency, 1976b) reported that 16 States had compiled data on lake trophic status in their State reports, but these data were not summarized in the national inventory. The most recent National Water Quality Inventory for 1996 (U.S. Environmental Protection Agency, 1997a) reported that 36 percent of lakes inventoried by States were classified as eutrophic.

Since 1988, the national inventories have expanded the definition of nutrient pollution by reporting on nutrient impairment in streams, lakes, and estuaries. Impairment is evaluated on the basis of whether a water body can fully support its historical beneficial uses. Excess nutrients can cause accelerated growth of algae and aquatic plants that can impair uses by clogging navigable waters, interfering with swimming and boating, and outcompeting native submerged aquatic vegetation and, with excessive decomposition, can lead to oxygen depletion in the water, which is harmful to fish. Data from the 1996 national inventory (table 3) indicated that 14 percent of stream miles, 20 percent of lake acres, and 22 percent of estuary acres were nutrient impaired. Nutrient impairment was the most prevalent type of pollution for lakes and estuaries and ranked second for streams. Agricultural sources were the leading sources of impairment for streams and lakes, but municipal wastewater-treatment-plant discharges were the leading source of impairment for estuaries.

**Table 3.** Summary of 1996 National Water Quality Inventory of nutrient status of streams, lakes, and estuaries

[Source of data: U.S. Environmental Protection Agency (1997a); WWTP, wastewater-treatment plant; na, not applicable].

| Water-body type | Percentage assessed | Percentage nutrient impaired | Percentage impaired by agricultural sources | Percentage impaired by municipal WWTP discharge | Percentage of eutrophic lakes |
|---|---|---|---|---|---|
| Streams | 19 | 14 | 25 | 5 | na |
| Lakes | 20 | 20 | 19 | 7 | 36 |
| Estuaries | 72 | 22 | 10 | 17 | na |

## Reductions in Phosphorus Concentrations and Loads

As States implemented phosphate detergent bans and treatment-plant limits, regulators and detergent-industry scientists sought to analyze the results as quickly as possible, and numerous studies were published (table 4). Most early studies investigated changes in phosphorus concentrations and loads from wastewater-treatment plants. By the 1980's enough site-specific data had been collected (U.S. Environmental Protection Agency, 1992) to show that reductions in phosphorus concentrations and loads in effluent as large as 50 percent could be accomplished as a result of detergent bans. A combination of detergent bans and phosphorus limits reduced annual municipal phosphorus loads to Lake Erie from 14,000 metric tons in 1972 to 2,000 metric tons in 1990 (Dolan, 1993) and annual point-source phosphorus loads to the Chesapeake Bay from 5,100 metric tons in 1985 to 2,500 metric tons in 1996 (U.S. Environmental Protection Agency, 1997b). However, there is no nationwide historical data base of phosphorus loadings from wastewater-treatment plants with which to document nationwide changes. Estimates of treatment-plant phosphorus loadings were made for years prior to 1979 by multiplying an estimated nationwide average phosphorus concentration for effluent times the estimated nationwide effluent discharge rate. Estimates were made at a county scale in 1979 (Midwest Research Institute, 1979) by using per capita loading estimates multiplied by county populations. With the advent of the PCS data base, it has been possible to make more accurate estimates; a method was established to make estimates of coastal nutrient loadings (National Oceanic and Atmospheric Administration, 1993), and these estimates are being updated for current (1998) conditions and are to be made available on the World Wide Web (Percy Pacheco, National Oceanic and Atmospheric Administration, oral commun., 1997). The NOAA methods were adapted to make nationwide nutrient-loading estimates for 1991 (Richard Alexander, U.S. Geological Survey, oral commun., 1998), but limitations of the PCS data base make these estimates unsuitable for local use. The USEPA has made nutrient-loading estimates for only the major dischargers, and these data are available as part of the BASINS software and data base (U.S. Environmental Protection Agency, 1996b) and through the ENVIROFACTS online data base (http://www.epa.gov/enviro/index.html).

While the effects of phosphorus controls on wastewater-treatment-plant loads were simple to measure, the effects of phosphorus controls on stream concentrations and loads were more difficult to immediately document. The magnitude of the effect on streams depended on the dilution factor where effluent was discharged into streams and on the relative contributions of other phosphorus sources to the stream load. Reported decreases in stream concentrations of phosphorus ranged from undetectable (Smith, 1972) to a reduction by one-half (Hoffman and Bishop, 1994). The statistical significance of reported stream concentration and load trends was questioned due to the inadequacy of short-term data sets (generally just 2 or 3 years of data) to account for seasonality and to meet the requirements of time-series analysis (Etzel and Bell, 1975c; Pallesen and others, 1985; Booman and Sedlak, 1986; Walker, 1987). It also has been reported that hourly fluctuations in phosphorus concentrations at point-source dominated sites can complicate data analysis (Hoffman, 1990). Long-term data sets also

**Table 4.** Summary of previous studies assessing the effectiveness of phosphorus controls

[P-ban, phosphate detergent ban; P-limit, wastewater-treatment-plant phosphorus effluent limit; both, both types of controls; WWTP, wastewater-treatment plant]

| Area | Type of control | Reference | WWTP changes (influent/effluent) | | Water-body concentrations and loads | Water use | Biologic measures | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Concentration/ load | Costs | | | Trophic status | Chlorophyll | Algal biomass |
| | | | **NATIONAL** | | | | | | |
| States with bans | P-bans | U.S. Environmental Protection Agency, 1992 | X | X | | | | | |
| Nationwide | P-bans | Gakstatter and Maloney, 1975 | | | | | X | | |
| Nationwide | both | Lorenzen, 1979 | | | X | | X | X | |
| States with bans | P-bans | Maki and others, 1984 | | | X | X | X | X | X |
| | | | **REGIONAL** | | | | | | |
| Eastern United States | P-limit | Gakstatter and Allum, 1978 | X | | | | | | |
| The Chesapeake Bay | both | Lung, 1986a,b | X | | X | | | X | |
| | both | U.S. Environmental Protection Agency, 1997b | X | X | X | X | X | X | X |
| | P-ban | U.S. Environmental Protection Agency, 1992 | X | X | | | | | |
| Great Lakes Region | both | Richards and Baker, 1993 | X | | X | | | | |
| | both | Dolan, 1993 | X | | X | | | | |
| | both | Neilson and others, 1995 | X | | | | X | X | X |
| | | | **STATE** | | | | | | |
| District of Columbia | both | Booman and Sedlak, 1986 | X | | | | | | |
| | both | U.S. Environmental Protection Agency, 1992 | X | X | | | | | |
| Georgia | P-limit | Nungesser and Franz, 1997 | | | X | | | | |
| | P-ban | U.S. Environmental Protection Agency, 1992 | X | | | | | | |
| | P-limit | Frick and others, 1993 | | | X | | | | |
| | both | Wangsness and others, 1994 | X | | X | | | | |
| | P-ban | U.S. Environmental Protection Agency, 1977 | X | | | | | | |
| Illinois | P-ban | U.S. Environmental Protection Agency, 1992 | X | X | | | | | |
| | P-limit | Terrio, 1995a | X | | X | | | | |
| Indiana | P-ban | Etzel and others, 1975a, b, c | | | X | | X | | |
| | P-ban | Eberly, 1974 | | | | | X | | |

**Table 4.** Summary of previous studies assessing the effectiveness of phosphorus controls—Continued

[P-ban, phosphate detergent ban; P-limit, wastewater-treatment-plant phosphorus effluent limit; both, both types of controls; WWTP, wastewater-treatment plant]

| Area | Type of control | Reference | WWTP changes (influent/effluent) | | Water-body concentrations and loads | Water use | Biologic measures | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Concentration/ load | Costs | | | Trophic status | Chlorophyll | Algal biomass |
| | | | **STATE-continued** | | | | | | |
| Indiana | P-limit | Crawford and Wangsness, 1993 | X | | X | | | | |
| Maryland | P-ban | Jones and Hubbard, 1986 | X | X | | | | | |
| | P-ban | U.S. Environmental Protection Agency, 1992 | X | X | | | | | |
| Michigan | P-ban | Hartig, and Horvath, 1982; Hartig and others, 1982 | X | X | X | | | X | |
| | P-ban | Wendt, 1982 | X | | X | | | | |
| Minnesota | P-limit | Lung and Larson, 1995 | | | X | | X | | |
| | P-ban | Runke, 1982 | X | | X | | | X | |
| Montana | P-ban | U.S. Environmental Protection Agency, 1992 | X | | | | | | |
| New Jersey | both | Rosensteel and Strom, 1991 | | | X | | X | | |
| New York | P-ban | Hetling and Carcich, 1972 | X | | | | | | |
| | P-ban | Sharfstein and others, 1977 | X | | X | | | | |
| North Carolina | P-ban | U.S. Environmental Protection Agency, 1992 | X | | | | | | |
| Ohio | P-ban | Hartig and others, 1990 | X | | | | | | |
| Pennsylvania | P-ban | U.S. Environmental Protection Agency, 1992 | X | X | | | | | |
| Vermont | P-ban | U.S. Environmental Protection Agency, 1992 | X | | | | | | |
| Virginia | P-ban | Hoffman and Bishop, 1994 | | | X | | | | |
| | P-ban | Lee and Jones-Lee, 1995 | | | X | | | | X |
| | both | Lung, 1986b | | | X | | X | | |
| | P-ban | U.S. Environmental Protection Agency, 1992 | X | | | | | | |
| Wisconsin | P-ban | Pallesen and others, 1985 | X | | | | | | |
| | P-ban | U.S. Environmental Protection Agency, 1992 | X | X | | | | | |

are needed for national-scale analysis because phosphorus controls have been instituted over a 28-year period from 1970 to the present.

Limited long-term data are available that indicate that phosphorus concentrations in surface water have increased substantially over the last 50 years as population and the agricultural use of phosphorus has increased (Heathwaite and others, 1996; Thomas, 1973; Hutchinson, 1969; Edmondson, 1969; Kemp and others, 1972). Data became more abundant beginning in the mid-1970's as a result of the establishment of national water-quality-monitoring networks. Data primarily from the USGS National Stream Quality Accounting Network (NASQAN) (Alexander and others, 1996) have been analyzed for phosphorus concentration trends using robust statistical techniques (seasonal Kendall test on raw and flow-adjusted data). For 1974-81, downward trends in total phosphorus were detected at 50 stations located mostly in the Great Lakes and Upper Mississippi regions (Smith and others, 1987); these trends generally occurred at stations that were point-source dominated. Upward trends were detected at 43 stations, most of which were associated with agricultural land use; no trends were detected at 288 stations. For 1982-89, downward trends in total phosphorus concentrations were detected at 92 stations, upward trends at 19 stations, and no trends at 299 stations (Smith and others, 1993); thus, the proportion of stations with downward trends had increased from 13 percent to 22 percent. The geographic extent of stations with downward trends had expanded to include stations scattered across the entire conterminous United States, except for the southeastern part of the Nation. An analysis of NASQAN data in the Mississippi River Basin for 1974-94 (Lurry and Dunn, 1997) reported downward trends for total phosphorus concentrations at 25 of 40 stations and upward trends at only 2 stations. An analysis of NASQAN data for streams flowing into the Gulf of Mexico for 1972-93 (Dunn, 1996) reported downward trends for total phosphorus concentrations at 11 of 37 stations and upward trends at 7 stations. These trend studies suggest that the decline in production of phosphate detergents is having a detectable effect across the United States, except in the Southeast, especially when analyzing longer time periods, but also that only a small proportion of steam sites have a large enough point-source component for the effect to be detectable.

Despite the declines in phosphorus concentrations, the USEPA-recommended limit of 0.1 mg/L for total phosphorus is exceeded in many rivers. Among 410 USGS stations tested, the percentage of stations with average annual total phosphorus concentrations greater than the recommended limit only decreased from 54 percent to 42 percent from 1982 to 1989 (Smith and others, 1993). Data for 1990-95 from the USEPA STORET data base indicated that 32 percent of the hydrologic units examined had more than one-half of the observed total phosphorus concentrations exceeding the recommended limit (fig. 6). The majority of exceedances occurred in hydrologic units located in the central United States, but exceedances also occurred in hydrologic units throughout the Nation. An additional 44 percent of hydrologic units had from 10 to 50 percent of phosphorus concentrations greater than the recommended limit. These data indicate that the potential for nutrient impairment in surface water remains substantial in the United States.

## Improvements in Eutrophic Conditions

In a paper summarizing the reported effects on water quality of phosphate detergent bans in six States, Maki and others (1984) pointed out that water-quality improvements could not be assessed by using only concentration-reduction data, but that the effects of concentration reductions on the trophic state of lakes needed to be considered. Further, Maki and others (1984) suggested that water-quality improvements ultimately must be measured in reference to the designated use of water.

For individual water bodies or watersheds where acknowledged nutrient problems are being addressed, the USEPA is advocating watershed-level data bases that are developed to address local issues and needs, and it is suggested that these watershed data bases include biologic and nutrient impairment information (U.S. Environmental Protection Agency, 1998b). Two examples of the watershed-based approach for evaluating biologic responses are the environmental programs and data sets established for the Great Lakes (http://www.epa.gov/grtlakes/) and the Chesapeake Bay (http://www.chesapeakebay.net/bayprogram/). As part of these programs, phosphorus inputs have been monitored or estimated, strategies have been implemented for reduction of inputs, and water-quality and numerous biologic response variables have been

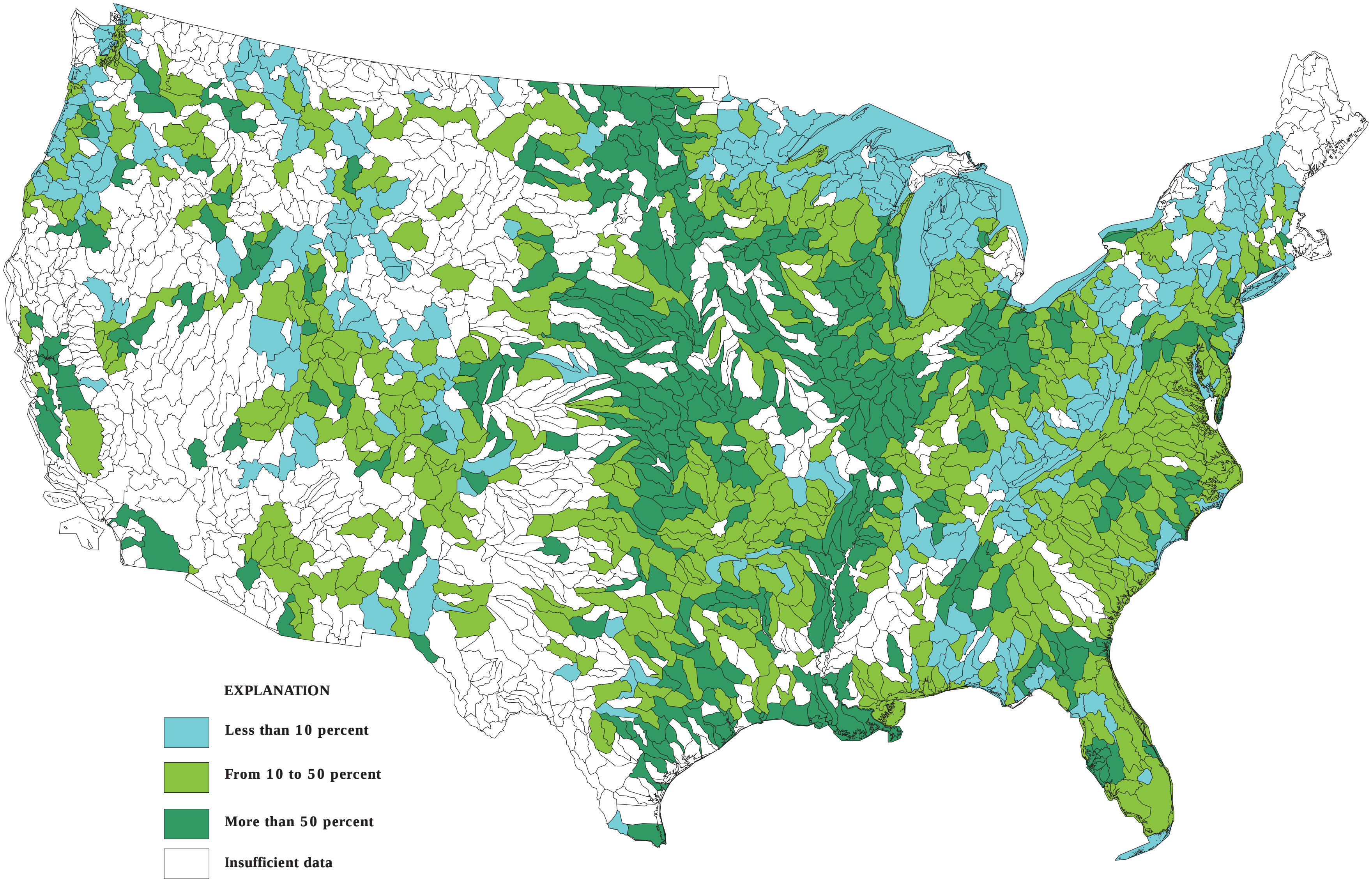


**Figure 6.** Percentage of total phosphorus concentrations that exceeded recommended limit of 0.1 milligram per liter, by hydrologic unit, 1990-95 [source of data: U.S. Environmental Protection Agency STORET data base].

measured. The Great Lakes data for Lake Erie show that spring phosphorus concentrations in the lake's central basin decreased from 0.17 mg/L in 1968 to 0.10 mg/L (the restoration target level) in 1992 and that, as a result, the excessive growth of algae declined and the algal composition shifted toward more desirable and historically prevalent species. However, the problem of hypolimnetic oxygen depletion had not been eliminated or reduced as much as was expected (Bertram, 1993). In the Chesapeake Bay, the goal of a 40-percent reduction in phosphorus loadings by the year 2000 is on schedule, but the results of the reduction are mixed (U.S. Environmental Protection Agency, 1997b). There has been no clear trend in oxygen levels in the bay or in the health of bottom-dwelling organisms, but there are signs of improvements in the health and diversity of plankton communities, and the acreage of bay grass has increased.

At a national level, simple measures of water quality are needed to assess improvements in trophic conditions. One simple method often used to classify the trophic status of lakes is the Vollenweider model, which only requires data on lake depth, hydrologic retention time, and total phosphorus loading (Vollenwader, 1975). A USGS analysis of 85 reservoirs (Smith and others, 1993) used a eutrophication index based on the Vollenweider model and found little change during 1982-89 in the proportion of reservoirs classified as eutrophic. Similarly, the proportion of eutrophic lakes as reported in the National Water Quality Inventories for 1986-96 varied little, with a median value of 36 percent of sampled reservoirs classified as eutrophic.

The USEPA has attempted to evaluate designated-use impairment due to nutrient pollution in its National Water Quality Inventories but has recognized that the State data have limited utility as a historical record of water-quality improvement (Mayio and Grubbs, 1993). For example, the proportion of water bodies that were reported to be nutrient impaired decreased by 50 percent between 1994 and 1996, but this difference may largely be due to States' modifying their evaluation criteria or surveying different water bodies.

The trophic status of estuaries is being evaluated at a national level as part of the USEPA's Environmental Indicators program (U.S. Environmental Protection Agency, 1996a). Indicator 14 is Estuarine Eutrophication Conditions, which are eventually to be evaluated for 129 estuaries by using 16 eutrophication-related water-quality parameters. However, as of 1996, data were incomplete and inconsistent so that trends could only be reported on four water-quality parameters for 12 estuaries. Improving trends were reported at three estuaries for chlorophyll *a*, at four estuaries for nitrogen, at no estuaries for anoxia, and at two estuaries for submerged aquatic vegetation (U.S. Environmental Protection Agency, 1996a).

## USE OF NATIONAL WATER-QUALITY ASSESSMENT PROGRAM DATA TO EVALUATE EFFECTS OF PHOSPHORUS CONTROLS

The NAWQA Program is a systematic assessment of the quality of the Nation's stream and ground-water resources (Leahy and others, 1990). The USGS implemented the NAWQA Program in 1991 to describe the status and trends in the quality of a large, representative part of the Nation's water resources and to identify the natural and human factors affecting water quality. The NAWQA data can be used to evaluate the status of National water-quality issues as well as to investigate site-specific water-quality problems.

### Description of NAWQA Water-Quality Data

The basic elements of the NAWQA Program are study units (fig. 7) that include parts of most of the Nation's major river basins and aquifers; investigations were started in groups of 20, 16, and 13 study units in 1991, 1994, and 1997, respectively. Data collection for the NAWQA Program includes biologic, ground-water, and surface-water components.

Selection of NAWQA study units focused on urban and agricultural land and water use; together, the study units encompass about 46 percent of the land area of the United States but include 63 percent of the population and 76 percent of the total surface-water use in the Nation during 1995 (data from U.S. Geological Survey's Water-Use Information Program data base). The NAWQA study units also include 66 percent of the total wastewater-treatment-plant discharge during 1995 (table 5) and about 55 percent of the total number of wastewater-treatment plants. With regard to phosphorus controls, the NAWQA study units include about one-half of the area of the Nation that is subject to a phosphate detergent ban and

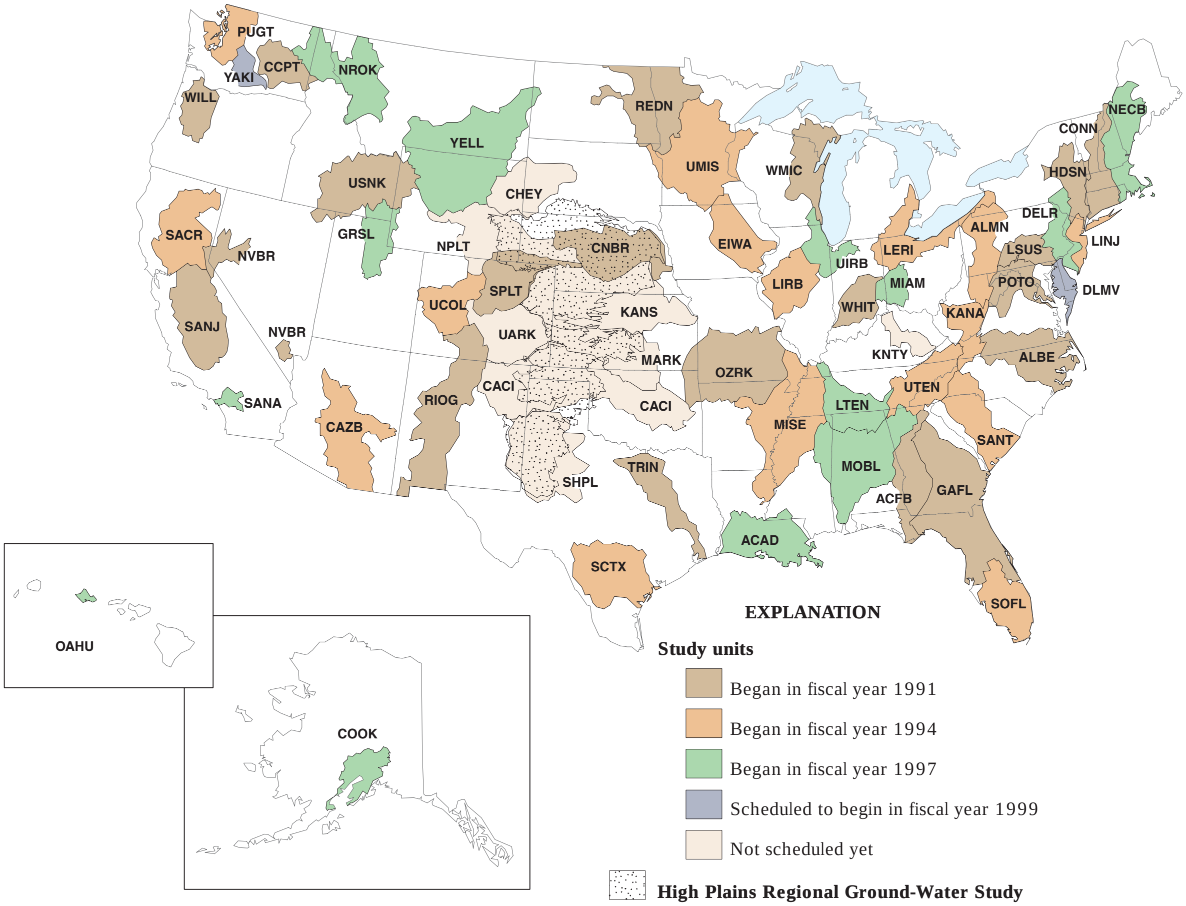


**Figure 7.** Location of National Water-Quality Assessment Program study units.

more than one-half (52 percent) of the municipal wastewater-treatment plants that have phosphorus limits (fig. 8).

Study units vary substantially in the magnitude of point-source discharges and in the degree of implementation of phosphorus controls (table 5). Within NAWQA study units, municipal wastewater-treatment-plant discharges for 1995 ranged from 20 Mgal/d in the North Platte Basin and Cheyenne and Belle Fourche Basin study units to 3,590 Mgal/d in the Upper Illinois River Basin study unit. However, in some study units (for example, Cook Inlet Basin and Puget Sound Basin), the bulk of the treatment-plant discharge is to coastal saltwater bodies. Five study units have phosphorus concentration limits on most of the wastewater-treatment-plant discharges within their boundaries, 31 have some plant discharges with limits, and 23 have no plants with limits. There is a similar variability among study units with regard to phosphate detergent bans. Twenty-one study units are located almost entirely within States that have phosphate detergent bans, and 27 study units are located in States having no phosphate detergent bans. Several study units (Western Lake Michigan Drainage, Lake Erie-Lake St. Clair Drainage, Hudson River Basin, Southern Florida) are located in States that passed phosphate detergent bans in the 1970's, while several study units (Puget Sound Basin, Willamette Basin, Lower Susquehanna River Basin) are located in States that did not pass phosphate detergent bans until the 1990's. These differences in phosphorus-control characteristics would allow for nationwide relations to be tested using phosphorus-control characteristics as independent variables and phosphorus concentrations and loads as dependent variables.

Data from NAWQA studies also might be used to evaluate the effects of phosphorus controls at specific stream locations. The emphasis of the NAWQA surface-water design (Gilliom and others, 1995) is to monitor stream quality at indicator sites, which represent relatively homogeneous land-use areas, and at integrator sites, which represent combi-

**Table 5.** Summary of municipal wastewater-treatment-plant discharges and controls on phosphorus within National Water-Quality Assessment Program study units

[Mgal/d, million gallons per day; na, not applicable]

| NAWQA Study Unit name | Study unit abbreviation (fig. 7) | Wastewater-treatment plants[1] | | | | | Percentage of study unit within phosphate detergent ban area |
|---|---|---|---|---|---|---|---|
| | | [2]Discharge during 1995 (Mgal/d) | Percentage of entire U.S. discharge | [2]Number of plants | [3]Number of plants with phosphorus limits | [3]Total design flow at plants with phosphorus limits (Mgal/d) | |
| Acadian-Pontchartrain | ACAD | 1,370 | 3.3 | 111 | 0 | 0 | 0 |
| Apalachicola-Chattahoochee-Flint River Basin | ACFB | 380 | 0.9 | 173 | 16 | 146 | 85 |
| Albemarle-Pamlico Drainage | ALBE | 490 | 1.2 | 106 | 6 | 126 | 98 |
| Allegheny and Monongahela Basins | ALMN | 200 | 0.5 | 235 | 2 | 5 | 78 |
| Canadian-Cimarron River Basins | CACI | 190 | 0.5 | 175 | 3 | 19 | 0 |
| Central Arizona Basins | CAZB | 320 | 0.8 | 87 | 1 | 2 | 0 |
| Central Columbia Plateau | CCPT | 50 | 0.1 | 56 | 0 | 0 | 96 |
| Cheyenne and Belle Fourche Basins | CHEY | 20 | 0.0 | 23 | 0 | 0 | 0 |
| Central Nebraska Basins | CNBR | 60 | 0.1 | 123 | 0 | 0 | 0 |
| Connecticut, Housatonic, Thames River Basins | CONN | 560 | 1.4 | 214 | 10 | 56 | 98 |
| Cook Inlet Basin | COOK | 30 | 0.1 | 12 | 0 | 0 | 0 |
| Delaware River Basin | DELR | 860 | 2.1 | 172 | 34 | 56 | 75 |
| Delmarva Peninsula | DLMV | 80 | 0.2 | 74 | 14 | 6 | 60 |
| Eastern Iowa Basins | EIWA | 200 | 0.5 | 295 | 0 | 0 | 6 |
| Georgia-Florida Coastal Plain | GAFL | 850 | 2.1 | 475 | 45 | 340 | 100 |
| Great Salt Lake Basins | GRSL | 220 | 0.5 | 39 | 0 | 0 | 0 |
| Hudson River Basin | HDSN | 810 | 2.0 | 197 | 13 | 2 | 100 |
| Kanawha-New River Basin | KANA | 100 | 0.2 | 191 | 1 | 1 | 32 |
| Kansas River Basin | KANS | 100 | 0.2 | 270 | 0 | 0 | 0 |
| Kentucky River Basin | KNTY | 60 | 0.1 | 39 | 0 | 0 | 0 |
| Lake Erie-Lake St. Clair Drainage | LERI | 3,010 | 7.3 | 536 | 141 | 1,700 | 100 |
| Long Island and New Jersey Coastal Drainages | LINJ | 1,240 | 3.0 | 164 | 34 | 6 | 24 |
| Lower Illinois River Basin | LIRB | 310 | 0.8 | 137 | 11 | 6 | 100 |
| Lower Susquehanna River Basin | LSUS | 160 | 0.4 | 64 | 47 | 192 | 100 |
| Lower Tennessee River Basin | LTEN | 230 | 0.6 | 100 | 0 | 0 | 1 |
| Middle Arkansas River Basin | MARK | 80 | 0.2 | 118 | 0 | 0 | 0 |

**Table 5.** Summary of municipal wastewater-treatment-plant discharges and controls on phosphorus within National Water-Quality Assessment Program study units—Continued

[Mgal/d, million gallons per day; na, not applicable]

| NAWQA Study Unit name | Study unit abbreviation (fig. 7) | Wastewater-treatment plants[1] | | | | | Percentage of study unit within phosphate detergent ban area |
|---|---|---|---|---|---|---|---|
| | | [2]Discharge during 1995 (Mgal/d) | Percentage of entire U.S. discharge | [2]Number of plants | [3]Number of plants with phosphorus limits | [3]Total design flow at plants with phosphorus limits (Mgal/d) | |
| Great and Little Miami River Basins | MIAM | 1,760 | 4.3 | 251 | 4 | 23 | 20 |
| Mississippi Embayment | MISE | 370 | 0.9 | 382 | 0 | 0 | 32 |
| Mobile River and Tributaries | MOBL | 450 | 1.1 | 240 | 4 | 17 | 12 |
| New England Coastal Basins | NECB | 1,080 | 2.6 | 238 | 29 | 174 | 95 |
| North Platte Basin | NPLT | 20 | 0.0 | 28 | 0 | 0 | 0 |
| Northern Rockies Intermontane Basins | NROK | 190 | 0.5 | 75 | 6 | 75 | 15 |
| Nevada Basin and Range | NVBR | 150 | 0.4 | 28 | 3 | 188 | 0 |
| Oahu | OAHU | 120 | 0.3 | 15 | 0 | 0 | 0 |
| Ozark Plateaus | OZRK | 260 | 0.6 | 590 | 4 | 23 | 21 |
| Potomac River Basin | POTO | 520 | 1.3 | 139 | 22 | 169 | 76 |
| Puget Sound Basin | PUGT | 400 | 1.0 | 127 | 0 | 0 | 100 |
| Red River of the North Basin | REDN | 70 | 0.2 | 209 | 3 | 4 | 45 |
| Rio Grande Valley | RIOG | 90 | 0.2 | 47 | 2 | 3 | 0 |
| Sacramento Basin | SACR | 270 | 0.7 | 158 | 0 | 0 | 0 |
| Santa Ana Basin | SANA | 420 | 1.0 | 43 | 0 | 0 | 0 |
| San Joaquin-Tulare Basins | SANJ | 310 | 0.8 | 283 | 0 | 0 | 0 |
| Santee Basin and Coastal Drainages | SANT | 540 | 1.3 | 236 | 2 | 35 | 100 |
| South Central Texas | SCTX | 490 | 1.2 | 102 | 2 | 10 | 0 |
| Southern High Plains | SHPL | 30 | 0.1 | 81 | 0 | 0 | 0 |
| Southern Florida | SOFL | 810 | 2.0 | 108 | 9 | 44 | 100 |
| South Platte Basin | SPLT | 300 | 0.7 | 151 | 3 | 3 | 0 |
| Trinity River Basin | TRIN | 620 | 1.5 | 174 | 1 | 24 | 10 |
| Upper Arkansas River Basin | UARK | 90 | 0.2 | 62 | 0 | 0 | 0 |
| Upper Colorado River Basin | UCOL | 30 | 0.1 | 96 | 5 | 8 | 0 |
| Upper Illinois River Basin | UIRB | 3,590 | 8.8 | 168 | 22 | 73 | 60 |
| Upper Mississippi River Basin | UMIS | 400 | 1.0 | 292 | 29 | 270 | 96 |

**Table 5.** Summary of municipal wastewater-treatment-plant discharges and controls on phosphorus within National Water-Quality Assessment Program study units—Continued

[Mgal/d, million gallons per day; na, not applicable]

| NAWQA Study Unit name | Study unit abbreviation (fig. 7) | Wastewater-treatment plants[1] | | | | | Percentage of study unit within phosphate detergent ban area |
|---|---|---|---|---|---|---|---|
| | | [2]Discharge during 1995 (Mgal/d) | Percentage of entire U.S. discharge | [2]Number of plants | [3]Number of plants with phosphorus limits | [3]Total design flow at plants with phosphorus limits (Mgal/d) | |
| Upper Snake River Basin | USNK | 40 | 0.1 | 27 | 1 | 2 | 0 |
| Upper Tennessee River Basin | UTEN | 420 | 1.0 | 124 | 0 | 0 | 46 |
| White River Basin | WHIT | 290 | 0.7 | 133 | 18 | 52 | 100 |
| Willamette Basin | WILL | 370 | 0.9 | 71 | 2 | 30 | 100 |
| Western Lake Michigan Drainage | WMIC | 390 | 1.0 | 135 | 52 | 592 | 100 |
| Yakima River Basin | YAKI | 90 | 0.2 | 28 | 0 | 0 | 100 |
| Yellowstone Basin | YELL | 100 | 0.2 | 82 | 0 | 0 | 0 |
| Sum of all NAWQA study units | | 27,100 | 66.0 | 9,109 | 601 | 4,500 | na |
| Remainder of the United States | | 13,900 | 34.0 | 7,319 | 562 | 2,700 | na |
| Total for United States | | 41,000 | 100.0 | 16,428 | 1,163 | 7,200 | na |

[1]Does not include industrial wastewater-treatment plants.
[2]Data from U.S. Geological Survey Water-Use Information System data base.
[3]Data from retrieval from U.S. Environmental Protection Agency Permit Compliance System (PCS) data base, 1997.

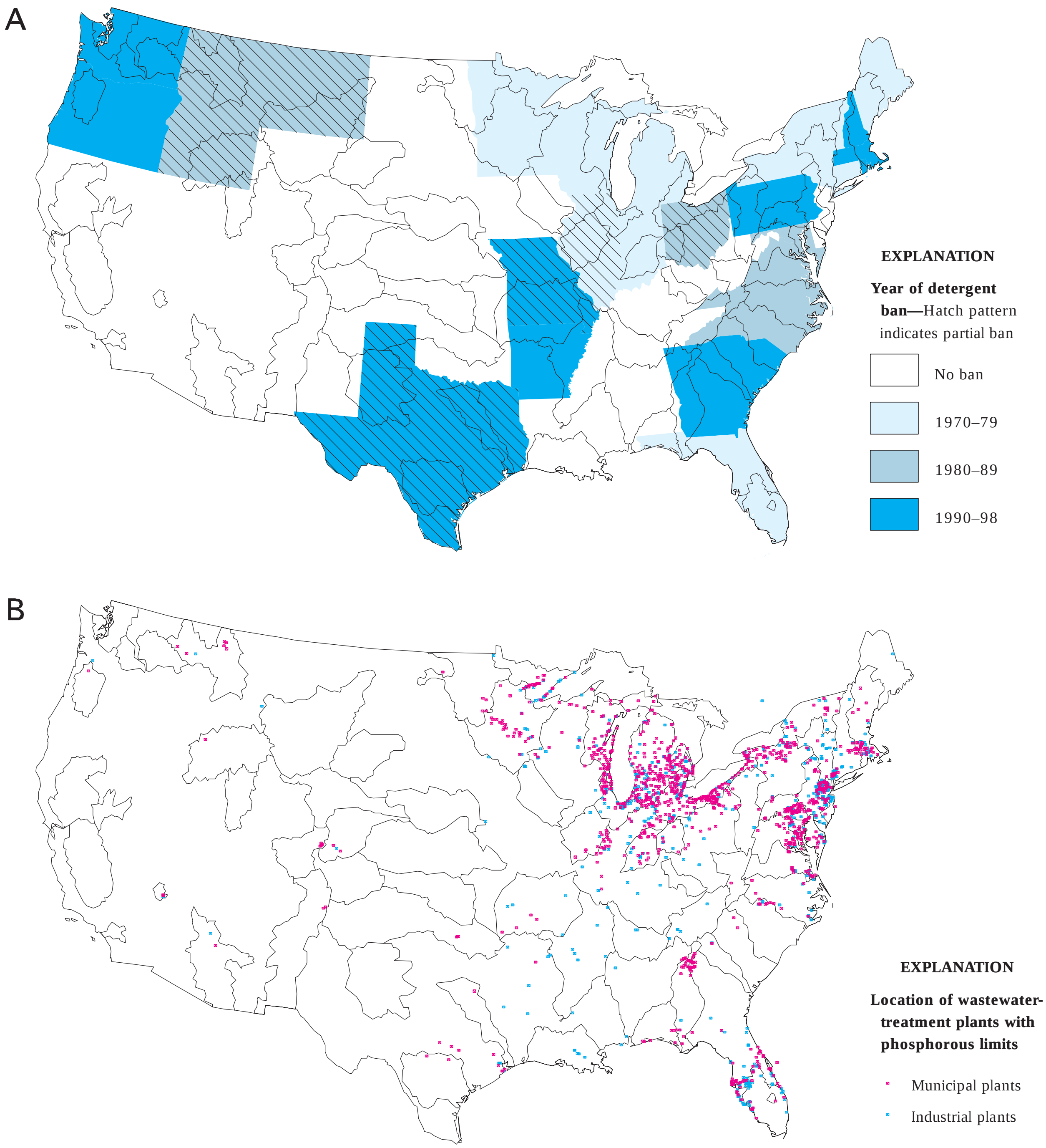


**Figure 8.** Location of National Water-Quality Assessment Program study units, (A) States with phosphate detergent bans, and (B) locations of industrial and municipal wastewater-treatment plants having phosphorus limits.

nations of land-use settings, point sources, and natural influences. Reservoir, lake, and estuary sampling is not part of the NAWQA study design, although these types of water bodies have been sampled in some study units as part of synoptic studies or case studies. As a result, NAWQA data can be used primarily to evaluate stream conditions; the status of other water bodies might be evaluated by analysis of stream loads where streams enter reservoirs, lakes, and estuaries. Each NAWQA study unit includes about 12 fixed monitoring sites where data are collected monthly and during extreme streamflow conditions for at least 2 years. Every 10 years, selected sites are to be revisited and sampled again for 2 years. Some sites within each study unit also are selected for monthly monitoring during the intervening years. Data collected at these sites include all principal nitrogen and phosphorus species as well as ecological data (algae, macroinvertebrates, fish, and habitat data), which provide information on response variables that may be related to eutrophication. Streamflow is measured continuously at all fixed sites.

Fixed monitoring sites have currently (summer of 1998) not been established for the study-unit investigations that started in 1997, but among study units started in 1991 and 1994, 394 fixed monitoring sites were established (fig. 9), which include 241 indicator sites and 153 integrator sites. Among indicator sites, 40 represent urban land use, 123 represent agricultural land use, 19 represent forest land use, and 59 represent other land uses. There are 34 sites (fig. 9 and table 6) that are reference sites suitable for defining natural background concentrations and loads for phosphorus. There are 20 fixed sites that are point-source dominated (fig. 9 and table 6) where, during the most frequently occurring streamflow conditions, the majority of the phosphorus loads to the stream are derived from point sources. These point-source-dominated sites may be suitable for examining trends in phosphorus concentrations and loads resulting from the implementation of phosphorus detergent bans and wastewater-treatment-plant limits.

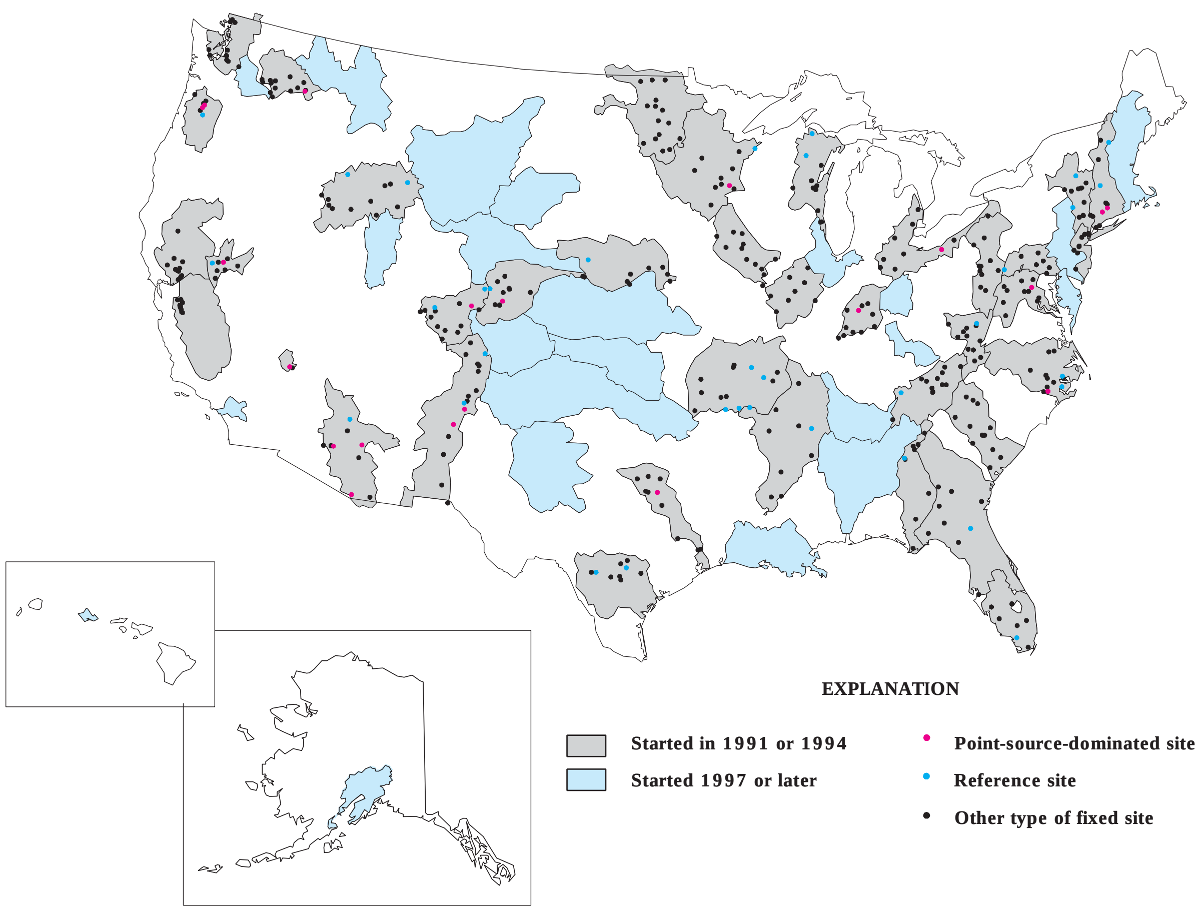


**Figure 9.** Location of National Water-Quality Assessment Program fixed monitoring sites.

**Table 6.** Summary of reference sites and point-source-dominated sites at National Water-Quality Assessment Program study units

[NAWQA, National Water-Quality Assessment Program; USGS, U.S. Geological Survey; WWTP, wastewater-treatment plant; NASQAN, National Stream Quality Accounting Network]

| NAWQA study unit name (studies begun in 1991 or 1994) | Reference site | | Point-source-dominated site | |
|---|---|---|---|---|
| | Station identification number | Comment | Station identification number | Comment |
| Albemarle-Pamlico Drainage | 02084557<br>02084540 | Some natural phosphorus from geologic sources. | 02089500 | -- |
| Apalachicola-Chattahoochee-Flint River Basin | 02337500 | -- | -- | State monitoring sites show effects of phosphorus controls. |
| Allegheny and Monongahela Basins | 03015795 | Site is in wilderness area. | -- | -- |
| Central Arizona Basins | 09505800 | Drainage basin is within Coconino National Forest. | 09481740<br>09486500<br>09512407 | USGS is studying water quality associated with Phoenix WWTP. |
| Central Columbia Plateau | -- | -- | 13349200 | -- |
| Central Nebraska Basins | 06775900 | Peat bogs may elevate natural levels of phosphorus in Nebraska. | -- | -- |
| Connecticut, Housatonic, Thames River Basins | 01170100<br>01137500 | -- | 01189000<br>01192500 | -- |
| Eastern Iowa Basins | -- | -- | -- | -- |
| Georgia-Florida Coastal Plain | 02229000 | Concentrations may be affected by wetlands upstream. | -- | -- |
| Hudson River Basin | 01362200<br>01325010 | WWTP may have some effect.<br>Some development, but largely forest. | -- | -- |
| Kanawha-New River Basin | 03186500 | -- | -- | -- |
| Lake Erie-Lake St. Clair Drainage | -- | -- | 04208504 | Long-term data at nearby NASQAN station. |
| Long Island and New Jersey Coastal Drainages | -- | -- | -- | Proportions of point-source loadings are being evaluated (Price and Schaefer, 1995). |
| Lower Illinois River Basin | -- | -- | -- | Illinois River sites have large agricultural sources in addition to effluent inputs from Chicago. |
| Lower Susquehanna River Basin | 01559795 | Minor agricultural land use in basin. | -- | -- |
| Mississippi Embayment | 07030392 | Minor agricultural land use in basin; some marshland. | -- | -- |
| Nevada Basin and Range | 10346000 | Rangeland site. | 09419753<br>10350500 | Data sets show effects of tertiary phosphorus removal at both sites. |

**Table 6.** Summary of reference sites and point-source-dominated sites at National Water-Quality Assessment Program study units—Continued

[NAWQA, National Water-Quality Assessment Program; USGS, U.S. Geological Survey; WWTP, wastewater-treatment plant; NASQAN, National Stream Quality Accounting Network]

| NAWQA study unit name (studies begun in 1991 or 1994) | Reference site | | Point-source-dominated site | |
|---|---|---|---|---|
| | Station identification number | Comment | Station identification number | Comment |
| Ozark Plateaus | 06929315<br>07060710 | -- | -- | -- |
| Potomac River Basin | -- | -- | 01643020 | -- |
| Puget Sound Basin | 12056500 | -- | -- | -- |
| Red River of the North Basin | -- | -- | -- | -- |
| Rio Grande Valley | 374752105300801<br>08313350 | -- | 08317200<br>08331000 | -- |
| Sacramento Basin | -- | -- | -- | -- |
| San Joaquin-Tulare Basins | -- | -- | -- | -- |
| Santee Basin and Coastal Drainages | 02143040 | -- | -- | -- |
| South Central Texas | 08169000<br>08198000 | -- | -- | -- |
| Southern Florida | 02288798 | -- | -- | -- |
| South Platte Basin | 402114105350101 | Site in Rocky Mountain National Park. | 06720500 | About 60 percent of flow is from treatment plant. |
| Trinity River Basin | -- | -- | 08057410 | -- |
| Upper Colorado River Basin | 09010500 | -- | 09066510 | -- |
| Upper Mississippi River Basin | 05331833 | -- | 05331580 | Point-source dominated during low streamflow conditions. |
| Upper Snake River Basin | 13010065<br>13120500 | May be some effects due to Yellowstone fires. | -- | -- |
| Upper Tennessee River Basin | 03539778 | -- | -- | -- |
| White River Basin | -- | -- | 03354000 | No long-term data at this site. State has some long-term data sets at other sites. |
| Willamette Basin | 14203750<br>14200400 | Phosphorus concentrations low despite high soil concentrations. | 14207500<br>14202000 | Pudding River point-source dominated only at low flow. |
| Western Lake Michigan Drainage | 04062085<br>04063700 | -- | -- | -- |

NAWQA water-quality data might be used in a variety of ways to address questions associated with the effects of point-source controls of phosphorus on stream water quality. For example:

- Phosphorus concentration and load data at sites across the Nation could be analyzed relative to the timing and extent of phosphorus point-source controls to evaluate the effects of these controls.
- Reference site data could be analyzed to determine background concentrations and yields of phosphorus from a variety of natural environments that include some areas where concentrations may be naturally large.
- Point-source-dominated site data could be analyzed to evaluate site-specific phosphorus concentration and load trends under a variety of different phosphorus controls.
- Nutrient, algal, and benthic-community data could be analyzed to evaluate biologic responses to differing nutrient loadings, to evaluate limiting nutrient species, and to develop metrics for nutrient impairment of streams.
- Phosphorus budgets could be constructed at sites to evaluate phosphorus loadings, yields, and retention rates as related to land-use type within the basins.
- Data from aquifer and land-use studies could be analyzed to evaluate typical ground-water concentrations of phosphorus in different environments and to assess the potential for phosphorus contributions from ground water to receiving streams relative to other sources of phosphorus.

Work on several of these activities is underway by NAWQA personnel. Summaries of current NAWQA activities can be found using the NAWQA home page on the World Wide Web (http://wwwrvares.er.usgs.gov/nawqa/nawqa_home.html).

## NAWQA Findings

As part of the NAWQA study design, information is collected about the priority of water-quality concerns; historical data are reviewed in a retrospective report, and water-quality data collected as part of the NAWQA Program are discussed in topical reports and in a final report for each study unit. Information from these activities that is relevant to the phosphorus issue is summarized in table 7. Nutrient-caused surface-water impairment was a principal issue in 22 of the 49 currently active study units. Phosphorus was identified as a primary concern in such geographically diverse areas as the Upper Snake River Basin, the Great Salt Lake Basins, Southern Florida, the Lake Erie-Lake St. Clair Drainage, and the Albemarle-Pamlico Drainage. Nutrient impairment was not considered an issue in some study units despite elevated levels of nutrients because of naturally eutrophic conditions (primarily in the South), because of turbidity of streams that prevented nuisance algal growth, or because the designated use of the streams was not affected. In study units draining to the Gulf of Mexico, nitrogen was more of a concern than phosphorus because the increase in hypoxic conditions in the Gulf has been related to increases in nitrogen loading (Rabalais and others, 1996). In some areas of the West where surface-water resources are scarce and treatment-plant effluent is a primary source of streamflow, identifying what stream standards for phosphorus are necessary and reasonable is an issue. In many study units, the overriding nutrient concern is not phosphorus but rather the presence of large concentrations of nitrate in ground-water drinking supplies.

Phosphorus concentrations are reported to be decreasing in many NAWQA study units owing to reductions in the use of phosphate detergents and phosphorus limits at treatment plants. In some study units (Lake Erie-Lake St. Clair Drainage, Albemarle-Pamlico Drainage, Potomac River Basin, and Southern Florida), point-source controls probably have reached their limit of effectiveness, and attention is being turned toward nonpoint-source controls such as agricultural BMPs, nutrient TMDL allotment and trading, or nutrient retention in wetlands. In some study units (Eastern Iowa Basins, Red River of the North Basin, and Sacramento Basin), agricultural sources of phosphorus predominate to such a degree that agricultural BMPs are the focus rather than point-source controls.

Determining why declines in phosphorus concentrations have not been observed in parts of the Nation despite the cessation of production of phosphorus detergents is of interest. Declines have not occurred in some areas because agricultural nonpoint sources are the primary sources of phosphorus or because agricultural nonpoint sources of phosphorus have increased. In other areas, declines in detergent

**Table 7.** Summary of phosphorus issues and findings in National Water-Quality Assessment Program study units

[NAWQA, National Water-Quality Assessment Program; TMDL, total maximum daily load; USEPA, U.S. Environmental Protection Agency; BMP, best management practice; --, no information to date]

| NAWQA study unit name | Phosphorus issues | Phosphorus findings |
|---|---|---|
| Acadian-Pontchartrain | Phosphorus is not a principal issue. | Standard definitions of eutrophication do not apply for this part of the Nation (Charles Demas, U.S. Geological Survey, oral commun., 1998). |
| Apalachicola-Chattahoochee-Flint River Basin | Eutrophication in water-supply reservoirs have led to TMDL controls on phosphorus. | Phosphorus concentrations and loads have decreased due to controls (Wangsness and others, 1994; DeVivo and others, 1995; Peters and others, 1997). |
| Albemarle-Pamlico Drainage | Nutrient impairment in the Tar and Neuse Rivers and in Albemarle-Pamlico Sounds is an important issue. Pfiesteria is a problem in the Sounds. | Point-source reductions have led to decreasing phosphorus concentrations in streams in North Carolina (Harned and others, 1995). Phosphate minerals in deep aquifer sediments are an important source of phosphorus to the environment (Spruill and others, 1998). |
| Allegheny and Monongahela Basins | Phosphorus is not a principal issue. | -- |
| Central Arizona Basins | Phosphorus is not a principal issue. | Nitrogen is thought to be the limiting nutrient in desert systems (David Anning, U.S. Geological Survey, oral commun., 1998). |
| Central Columbia Plateau | Some nutrient impairment on the South Fork Palouse River, but phosphorus is not a principal issue in the study unit. | Nitrogen was the limiting nutrient on the Palouse River (Greene and others, 1997). |
| Central Nebraska Basins | Some eutrophic conditions in irrigation reservoirs and algal blooms in Platte River, but these do not interfere with use of water for irrigation. | Phosphorus concentrations are moderately large in ground water in the Sand Hills area and in streams in urban areas (Helgesen and others, 1994). Large phosphorus concentrations in a small stream (Prairie Creek) may be due to localized livestock inputs (Boyd, 1996). |
| Connecticut, Housatonic, Thames River Basins | Point sources are dominant sources in many streams. | Total phosphorus concentrations have decreased (1974-92) at 13 of 16 stations (Zimmerman, 1997). |
| Cook Inlet Basin | Phosphorus is not a principal issue. | Nutrient concentrations are very small; there is some interest in adding nutrients to streams to increase biologic productivity (Steven Frenzel, U.S. Geological Survey, oral commun., 1998). |
| Delaware River Basin | Phosphorus is not a principal issue. | Even after substantial decreases in phosphorus loadings to the Delaware Estuary, phosphorus levels are high, but nutrient impairment has not been an issue (Jeffrey Fischer, U.S. Geological Survey, oral commun., 1998). |
| Eastern Iowa Basins | Eutrophication is a concern in reservoirs and lakes. | Primary source of phosphorus is suspended phosphorus from agricultural sources (Stephen Kalkhoff, U.S. Geological Survey, oral commun., 1998). |
| Georgia-Florida Coastal Plain | Nitrate is more of a concern than phosphorus. | Total phosphorus concentrations have increased (1970-91) at 11 of 17 stations (Ham and Hatzell, 1996). Phosphate rock is a source of phosphorus in some areas (Berndt and others, 1998). |

**Table 7.** Summary of phosphorus issues and findings in National Water-Quality Assessment Program study units—Continued

[NAWQA, National Water-Quality Assessment Program; TMDL, total maximum daily load; USEPA, U.S. Environmental Protection Agency; BMP, best management practice; --, no information to date]

| NAWQA study unit name | Phosphorus issues | Phosphorus findings |
|---|---|---|
| Great Salt Lake Basins | Nutrients are a primary issue in all three principal rivers in the study unit. | Phosphate rock and associated mining have led to elevated phosphorus in some areas (Kidd Waddell, U.S. Geological Survey, oral commun., 1998). |
| Hudson River Basin | Phosphorus is not a principal issue. | Phosphorus concentrations are small. There is generally insufficient data for analysis of phosphorus trends (Pat Phillips, U.S. Geological Survey, oral commun., 1998). |
| Kanawha-New River Basin | Phosphorus is not a principal issue. | Primarily dispersed development in study unit; nutrient concentrations are small (Lisa Ham, U.S. Geological Survey, oral commun., 1998). |
| Lake Erie-Lake St. Clair Drainage | Phosphorus loadings to Lake Erie are a principal issue. | Phosphorus loadings to Lake Erie have substantially decreased, but additional nonpoint-source controls may be needed to reduce the anoxic zone in Lake Erie (Donna Myers, U.S. Geological Survey, written commun., 1998). |
| Long Island and New Jersey Coastal Drainages | Phosphorus is not a principal issue. | Total phosphorus concentrations have decreased (1986-95) at 24 of 52 stations (Tom Barringer, U.S. Geological Survey, written commun., 1998). |
| Lower Illinois River Basin | Phosphorus is not a principal issue. Nitrate is a more important issue. | Total phosphorus concentrations have decreased (1974-94) at two sites on the Illinois River (Lurry and Dunn, 1997). |
| Lower Susquehanna River Basin | Phosphorus loads to the Chesapeake Bay are an issue. | Total phosphorus concentrations have decreased (1985-96) at five of six stations due primarily to detergent bans and treatment-plant controls (Lindsey and others, 1998). |
| Lower Tennessee River Basin | Algal blooms in water-supply reservoirs are causing taste and odor problems. | Phosphate rock and associated mining have led to elevated phosphorus in some areas (Michael Woodside, U.S. Geological Survey, oral commun., 1998). |
| Great and Little Miami River Basins | Excessive algal growths have made phosphorus an issue in both major rivers in the study unit. | In the Little Miami River, nonpoint sources contribute the majority of total phosphorus, but municipal point sources contribute the majority of orthophosphorus and virtually all phosphorus during low-flow periods (Gary Rowe, U.S. Geological Survey, oral commun., 1998). |
| Mississippi Embayment | Phosphorus is not a principal issue. | Turbidity in rivers prevents algal blooms; water is warm and slow moving; anaerobic conditions remove nutrients from streams (Barbara Kleiss, U.S. Geological Survey, oral commun., 1998). |
| Mobile River and Tributaries | Nutrient impairment is a primary issue; reservoirs, the Coosa River system, and Mobile Bay are affected. | It has not yet been determined whether nitrogen or phosphorus is the limiting nutrient (Brian Atkins, U.S. Geological Survey, oral commun., 1998). |
| New England Coastal Basins | Phosphorus is not a principal issue. | -- |
| Northern Rockies Intermontane Basins | Phosphorus is a concern in reservoirs due to degradation of aesthetic quality of the water. | Phosphorus concentrations have decreased at some sites, probably due to detergent bans and phosphorus limits (Lan Tornes, U.S. Geological Survey, written commun., 1997). |

**Table 7.** Summary of phosphorus issues and findings in National Water-Quality Assessment Program study units—Continued

[NAWQA, National Water-Quality Assessment Program; TMDL, total maximum daily load; USEPA, U.S. Environmental Protection Agency; BMP, best management practice; --, no information to date]

| NAWQA study unit name | Phosphorus issues | Phosphorus findings |
|---|---|---|
| Nevada Basin and Range | High levels of nutrients are a concern in the Las Vegas area where treatment plants discharge into ephemeral channels. Control of nonpoint nutrient sources is a concern in the Lake Tahoe drainage. | Phosphorus concentrations in Las Vegas Wash decreased substantially after 1981 when tertiary phosphorus removal began (Kilroy and others, 1997). |
| Oahu | Phosphorus not a principal issue. | Urban streams exhibit consistantly larger dissolved phosphorus concentrations than rural and forested streams. Despite a history of intense phosphorus fertilization, dissolved phosphorus concentrations in agricultural areas are small, probably due to adsorption to soil particles. (Stephen Anthony, U.S. Geological Survey, oral commun., 1998). |
| Ozark Plateaus | Phosphorus enrichment in streams and lake eutrophication are issues in some areas. | Phosphorus concentrations are increasing probably due to increases in human population and number of poultry and cattle operations (Dave Freiwald, U.S. Geological Survey, oral commun., 1998). |
| Potomac River Basin | Phosphorus loadings to the Chesapeake Bay are a concern. | Phosphorus concentrations in the Potomac River have decreased since 1979, probably due to detergent bans and treatment-plant limits (Ator and others, 1998). |
| Puget Sound Basin | Phosphorus impairment is a concern in some urban streams and lakes. In Puget Sound, nitrogen is the nutrient of concern. | Total phosphorus concentrations in streams are generally less than the USEPA recommended limit (Embrey and Inkpen, 1998). |
| Red River of the North Basin | Noxious algal blooms have occurred frequently in Lake Winnipeg. | Phosphorus yields are correlated with agricultural phosphorus application rates. No phosphorus trends have been detected; natural variability in concentrations is large due variability in hydrologic conditions (Tornes and others, 1997). |
| Rio Grande Valley | Phosphorus is not a principal issue. | Total phosphorus concentrations exceeded the USEPA recommended limit in 250 of 526 samples (Levings and others, 1998). |
| Sacramento Basin | Phosphorus is not a principal issue. | Nutrient sources are primarily agricultural nonpoint sources (Joseph Domogalski, U.S. Geological Survey, oral commun., 1998). |
| Santa Ana Basin | Phosphorus is not a principal issue. Big Bear Lake is moderately eutrophic. | A flood control dam appears to affect nutrient concentrations on the Santa Ana River (Scott Hamlin, U.S. Geological Survey, oral commun., 1998). |
| San Joaquin-Tulare Basins | Phosphorus is not a principal issue. | Nutrient sources are primarily agricultural; total concentration trends vary among sites (Kratzer and Shelton, 1998). |
| Santee Basin and Coastal Drainages | Eutrophication in reservoirs is a principal issue, but reservoirs are a sink for nutrient loads, so loads to estuaries are not an issue. | Some downward trends detected for total phosphorus (Maluk and others, 1997). |
| South Central Texas | Phosphorus is not a principal issue. | -- |
| Southern Florida | Phosphorus is a principal issue due to nutrient impairment in Lake Okeechobee, the Everglades, and Florida Bay. | Phosphorus concentrations are large in some basins due to phosphate deposits; atmospheric loadings are an important source in some basins; constructed wetlands are being used to remove phosphorus from agricultural runoff (Haag and others, 1996). |
| South Platte Basin | Despite large concentrations, phosphorus is not a principal issue. Some algal blooms occur in urban flood-control reservoirs and in offstream irrigation water-supply reservoirs. | USEPA-recommended limit for total phosphorus is generally exceeded in a 150-mile reach of the South Platte River from Denver to Balzac, Colorado (Dennehy and others, 1998). |

**Table 7.** Summary of phosphorus issues and findings in National Water-Quality Assessment Program study units—Continued

[NAWQA, National Water-Quality Assessment Program; TMDL, total maximum daily load; USEPA, U.S. Environmental Protection Agency; BMP, best management practice; --, no information to date]

| NAWQA study unit name | Phosphorus issues | Phosphorus findings |
|---|---|---|
| Trinity River Basin | Eutrophication is an issue in a water-supply reservoir (Lake Livingston). | Phosphorus concentrations have decreased at sites downstream from Dallas, possibly due to reductions in use of phosphate detergents (Van Metre and Reutter, 1995). |
| Upper Colorado River Basin | Phosphorus is not a principal issue. | Downward trend in total phosphorus (1982-94) detected at one of five sites (Spahr and Wynn, 1997). |
| Upper Illinois River Basin | Phosphorus is not a principal issue; nitrate is more of an issue. | Phosphorus concentrations have decreased (1978-90) at three of eight sites; phosphorus concentrations are not large in the Iroquois River despite the extensive use of tile drains (Terrio, 1995b). |
| Upper Mississippi River Basin | Eutrophication is a problem in Lake Pepin; a major project is underway to reduce phosphorus loadings from treatment plants to the Mississippi and Minnesota Rivers. | Most stream sites had no long-term trends (1984-93) for total phosphorus or dissolved orthophosphorus (Kroening and Andrews, 1997) |
| Upper Snake River Basin | Algal blooms are a problem on the middle Snake River; TMDLs for phosphorus are currently being implemented. | Phosphorus concentrations are large in some areas due to phosphate deposits; phosphate has decreased in one basin probably due to implementation of agricultural BMPs (Clark, 1994). Sources of phosphorus to the middle Snake River include aquaculture, springs, and treatment-plant effluent (Clark, 1997). |
| Upper Tennessee River Basin | Phosphorus is not a principal issue. | Most streams had no trends in phosphorus despite phosphate-detergent bans (M.W. Treece, U.S. Geological Survey, oral commun., 1998). |
| White River Basin | Eutrophication is an issue in lakes; although blooms occur in the White River, they are not a principal water-quality concern. | Phosphorus concentrations are not large in runoff from tile drains (Jeffrey Martin, U.S. Geological Survey, oral commun., 1998). Upward trends in phosphorus concentrations (1981-90) at sites upstream from Indianapolis were probably due to changes in the quantity or quality of treated municipal effluent (Martin and others, 1996). |
| Willamette Basin | Eutrophication is an issue in the Tulatin Basin; TMDLs are currently being set for phosphorus. | No strong temporal trends (1979-89) were evident for phosphorus at six sites (Bonn and others, 1995); however, when 1990's data are included in the data set, decreasing trends are evident, which may be attributed to point-source reductions (Dennis Wentz, U.S. Geological Survey, written commun., 1998). |
| Western Lake Michigan Drainage | Eutrophication is a principal issue in the Fox and Wolf River Basins and in Lake Winnebago. | Few trends were detected in total phosphorus for 1980-90, but for 1971-90, downward trends were detected at several sites (Robertson and Saad, 1996). Point sources currently contribute approximately 28 percent of the phosphorus load to Green Bay (Robertson, 1996). |
| Yellowstone Basin | Phosphorus is not a principal issue. | -- |

use may have been offset by population increases. In still other areas, there has simply been a lack of long-term data sets from which to evaluate phosphorus trends.

Current areas of concern or research include the evaluation of the effects of increased manure loadings of phosphorus on soil phosphorus and, subsequently, on ground water and subsurface runoff; the determination of point-source and nonpoint-source components of loads, either by geographic modeling and by hydrologic separation techniques; and the development of methods or indices to evaluate nutrient impairment of streams and to provide understanding for establishing phosphorus standards for streams.

## SUMMARY

Eutrophication became an issue in the United States during the late 1960's when increasing inputs of phosphorus to the environment from phosphate detergent use and the agricultural application of fertilizer and manure caused an increasing incidence of cultural eutrophication among water bodies in the United States. A combination of phosphate detergent bans and controls on phosphorus in wastewater-treatment-plant effluent was used to combat this problem.

Data from the 1996 National Water Quality Inventory indicated that 14 percent of stream miles, 20 percent of lake acres, and 22 percent of estuary acres were nutrient impaired. To control excessive algal growth, the USEPA has established a recommended limit of 0.05 mg/L for total phosphates in streams that enter lakes and 0.1 mg/L for total phosphorus for flowing waters. Total phosphorus concentrations in streams in pristine areas generally are less than 0.02 mg/L, but in some areas of the Nation, elevated concentrations of phosphorus in stream water are associated with phosphate rock deposits or large natural soil phosphorus levels. The largest anthropogenic sources of phosphorus to the environment, as estimated for the 1980's, were fertilizer application (1.8 million metric tons), manure application (1.8 million metric tons), other nonpoint sources (1.1 million metric tons), and wastewater-treatment-plant discharges (260,000 metric tons). Use of phosphorus in fertilizers more than doubled from 1950 to 1998, and phosphorus inputs from manure also increased.

The use of phosphorus for the manufacturing of detergents was negligible in 1940, grew rapidly to about 220,000 metric tons in 1967, but decreased to small amounts in 1998 owing to enactment of phosphate detergent bans and the manufacturers' voluntary cessation of phosphate use in household laundry detergent. Phosphorus concentrations in raw wastewater-treatment-plant effluent contained about 3 mg/L of total phosphorus during the 1940's, increased to about 11 mg/L total phosphorus at the height of phosphate detergent use in 1970, and are currently estimated to be about 5 mg/L. Wastewater-treatment plants with secondary treatment remove 10 to 20 percent of phosphorus and can, therefore, reduce phosphorus concentrations in effluent to 3 to 5 mg/L; however, in some cases, tertiary treatment is needed to have a beneficial effect on ambient water quality in streams. Phosphorus limits on wastewater-treatment-plant effluent (typically set between 0.5 and 1.5 mg/L) have been implemented to reduce phosphorus loads to streams. Prior to 1973, there were few municipal facilities with phosphorus concentration limits, but from 1975 to 1985, limits were actively implemented. Currently (1998), about 1,200 plants have limits.

As a result of progress in the implementation of point-source controls, attention is shifting toward nonpoint sources of pollutants, and the USEPA Clean Water Action Plan for 1998 states that polluted runoff is now the most important source of water pollution. The primary agricultural sources of phosphorus are runoff from fields and from manure-disposal sites related to concentrated animal-feeding operations. Concentrated animal-feeding operations are beginning to be regulated by the USEPA as point sources, although as of 1995, only 760 of approximately 6,600 concentrated animal-feeding operations had NPDES permits. Development of effective agricultural BMPs is complex because of the many hydrologic and environmental factors that affect nonpoint-source pollution. Transport pathways for agricultural runoff include overland runoff, subsurface flow, and ground-water flow. Source management is important to agricultural BMPs because without decreases in phosphorus use, nutrient loads may simply be transferred from surface water to ground water.

Point-source controls have been effective in reducing phosphorus loads to the environment. A combination of detergent bans and treatment-plant phosphorus limits reduced annual municipal-wastewater phosphorus loads to Lake Erie from

14,000 metric tons in 1972 to 2,000 metric tons in 1990, and annual point-source phosphorus loads to the Chesapeake Bay were reduced from 5,100 metric tons in 1985 to 2,500 metric tons in 1996. However, there is a lack of a nationwide historical data base of phosphorus loadings from wastewater-treatment plants to document nationwide changes. Trend analyses of phosphorus concentrations in streams has detected decreasing concentrations since 1970 at many sites across the Nation; however, at most sites no trends were detected. These results indicate that the decline in production of phosphate detergents is having a detectable effect across the United States, but also that only a small proportion of stream sites have a large enough point-source component for the effect to be detectable. Despite the declines in phosphorus concentrations, the USEPA-recommended limit of 0.1 mg/L for total phosphorus is exceeded in many rivers. Data for 1990-95 from the USEPA STORET data base indicate that median total phosphorus concentrations exceeded the recommended limit in 32 percent of the hydrologic units analyzed. These data indicate that the potential for nutrient impairment in surface water is still substantial in the United States.

The USEPA has attempted to evaluate designated-use impairment due to nutrient pollution in its National Water Quality Inventories but has recognized that the State data have limited utility as a historical record of water-quality improvement. For example, the proportion of water bodies that were reported to be nutrient impaired decreased by 50 percent between 1994 and 1996, but this difference may largely be due to States' modifying their evaluation criteria or surveying different water bodies.

The USGS NAWQA Program, a systematic assessment of the quality of the Nation's stream and ground-water resources, includes about one-half of the area of the Nation that is subject to a phosphate detergent ban and 52 percent of the municipal wastewater-treatment plants that have phosphorus limits. There is a large variation among study units in the magnitude of point-source discharges and in the degree of implementation of phosphorus controls. This variety in phosphorus control characteristics would allow for nationwide relations to be tested using control characteristics as independent variables and phosphorus concentrations and loads as dependent variables; six areas of research are suggested in which NAWQA data might be used to address questions associated with the effects of point-source controls of phosphorus on water quality. Data from NAWQA fixed sites also might be used to evaluate site-specific effects of point-source phosphorus controls; there are 20 fixed sites that are point-source dominated.

Nutrient impairment has been identified as a principal concern in 22 of the 49 currently active NAWQA study units. Nutrient impairment was not an issue in some study units despite elevated levels of nutrients because of naturally eutrophic conditions, because of turbidity of streams that prevented algal growths, or because the designated use of the streams was not affected. Phosphorus concentrations are reported to be decreasing in many NAWQA study units. In some study units, point-source controls probably have reached their limit of effectiveness and attention is being turned toward nonpoint-source controls such as agricultural BMPs, nutrient TMDL allotment and trading, or nutrient retention in wetlands. In some study units, agricultural sources predominate to such a degree that agricultural BMPs are the focus rather than point-source controls. Determining why declines in phosphorus concentrations have not been observed in parts of the Nation despite the cessation of production of phosphorus detergents is of interest. Declines have occurred in some areas because agricultural nonpoint sources are the primary sources of phosphorus or because agricultural nonpoint sources of phosphorus have increased. In other areas, declines in detergent use may have been offset by population increases. In still other areas, there has simply been a lack of long-term data sets from which to evaluate phosphorus trends.

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