Analysis of Phosphorus Trends and Evaluation of Sampling Designs in the Quinebaug River Basin, Connecticut

By Elaine C. Todd Trench

In cooperation with the Connecticut Department of Environmental Protection

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Conversion Factors and Datums

Multiply	By	To obtain
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F = (1.8 x °C) + 32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C = (°F - 32) / 1.8

Vertical coordinate information is referenced to the *North American Vertical Datum of 1988 (NAVD 88).*

Horizontal coordinate information is referenced to the *North American Datum of 1983 (NAVD 83).*

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

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Abstract

A time-series analysis approach developed by the U.S. Geological Survey was used to analyze trends in total phosphorus and evaluate optimal sampling designs for future trend detection, using long-term data for two water-quality monitoring stations on the Quinebaug River in eastern Connecticut. Trend-analysis results for selected periods of record during 1971–2001 indicate that concentrations of total phosphorus in the Quinebaug River have varied over time, but have decreased significantly since the 1970s and 1980s. Total phosphorus concentrations at both stations increased in the late 1990s and early 2000s, but were still substantially lower than historical levels. Drainage areas for both stations are primarily forested, but water quality at both stations is affected by point discharges from municipal wastewater-treatment facilities.

Various designs with sampling frequencies ranging from 4 to 11 samples per year were compared to the trend-detection power of the monthly (12-sample) design to determine the most efficient configuration of months to sample for a given annual sampling frequency. Results from this evaluation indicate that the current (2004) 8-sample schedule for the two Quinebaug stations, with monthly sampling from May to September and bimonthly sampling for the remainder of the year, is not the most efficient 8-sample design for future detection of trends in total phosphorus. Optimal sampling schedules for the two stations differ, but in both cases, trend-detection power generally is greater among 8-sample designs that include monthly sampling in fall and winter. Sampling designs with fewer than 8 samples per year generally provide a low level of probability for detection of trends in total phosphorus.

Managers may determine an acceptable level of probability for trend detection within the context of the multiple objectives of the state's water-quality management program and the scientific understanding of the watersheds in question. Managers may identify a threshold of probability for trend detection that is high enough to justify the agency's investment in the water-quality sampling program. Results from an analysis of optimal sampling designs can provide an important component of information for the decision-making process in which sampling schedules are periodically reviewed and revised.

Results from the study described in this report and previous studies indicate that optimal sampling schedules for trend detection may differ substantially for different stations and constituents. A more comprehensive statewide evaluation of sampling schedules for key stations and constituents could provide useful information for any redesign of the schedule for water-quality monitoring in the Quinebaug River Basin and elsewhere in the state.

Introduction

The U.S. Geological Survey (USGS) and the State of Connecticut have worked together since 1955 to monitor and interpret the water quality of Connecticut's rivers and streams. Management decisions of increasing complexity require a monitoring program that provides data for multiple purposes, including periodic assessment of trends to detect improvement or deterioration in water quality over time. Multi-station trend analyses provide opportunities to describe and interpret water-quality conditions by identifying basinwide differences or similarities. Evaluation of optimal monitoring designs for future trend analysis provides an important additional interpretive step. Managers and scientists can use information on the best monitoring designs to ensure that monitoring programs continue to accomplish their purpose and can do so efficiently.

Water quality in the Quinebaug River in eastern Connecticut (fig. 1) has been monitored through the cooperative monitoring program of the USGS and the Connecticut Department of Environmental Protection (CTDEP) since the late 1960s. Significant long-term downward trends in phosphorus concentrations have taken place during the 1970s and 1980s (Trench, 1996; 2000; Colombo and Trench, 2002). These downward trends probably have resulted from reductions in the use of phosphate in detergent and from major improvements in wastewater treatment. Despite these water-quality improvements, current (2004) concentrations of total phosphorus in the Quinebaug River and some of its tributaries are substantially higher than those that would be found under natural or near-natural conditions in Connecticut. Total phosphorus concentrations sometimes exceed concentrations that are likely to cause eutrophication in still water, a common condition along many impounded reaches of the Quinebaug River and its major tributaries, particularly during the summer months. Warm weather algal blooms occur annually in several river reaches and impoundments (fig. 2). Trend analyses will be necessary in the future to continue to monitor progress in water-quality improvements that result from the implementation of management programs to control nutrients.

As part of the continuing effort to understand and improve water quality in Connecticut, the USGS and the CTDEP began a cooperative project in 2002 to analyze long-term trends in total phosphorus in the Quinebaug River Basin and evaluate optimal sampling designs for monitoring future trends.

Purpose and Scope

This report presents the results of an analysis of phosphorus trends and an evaluation of sampling designs based on data from two water-quality-monitoring stations on the Quinebaug River in Connecticut. These stations are part of a network of 34 monitoring stations throughout Connecticut. The two stations each have more than 20 years of water-quality record, and their drainage areas represent a variety of land uses and hydrogeologic conditions. A thorough interpretation of how the detected trends relate to hydrogeology, land use, population distribution, hydrologic modifications, and pollution sources is beyond the scope of this report. Some supporting information is presented to provide perspective on the detected trends and to point toward possibilities for further analysis.

Acknowledgments

Aldo V. Vecchia of the USGS developed the time-series analysis model used for trend detection and sampling design evaluation in this study, and made this work possible by providing extensive consultation on applying the time-series techniques and interpreting the results. Eric Thomas, Ernest Pizzuto, and Lee Dunbar of the CTDEP reviewed the report. Lee Dunbar and Michael Beauchene of the CTDEP and Therese Beaudoin of the Massachusetts Department of Environmental Protection (MADEP) provided information on state water-quality monitoring, assessment, and management programs. Aldo V. Vecchia and Laura Medalie of the USGS provided colleague reviews for the report. Barbara Korzendorfer of the USGS provided editorial review and prepared the report for publication. Claudia Tamayo of the USGS prepared the maps that appear in this report. All of the reviewers provided numerous suggestions and insights that have contributed to the improvement of the report.

Description of the Study Area

The Quinebaug River in eastern Connecticut is a major tributary of the Shetucket River, which flows into the Thames estuary at the eastern end of Long Island Sound (fig. 1). Together, the Quinebaug and Shetucket Rivers and their tributaries drain most of eastern Connecticut. The main stem of the Quinebaug River originates in south-central Massachusetts, and numerous tributaries to the Quinebaug originate in Massachusetts and western Rhode Island. Historically, the Quinebaug River and its tributaries played an important role in the industrial development of Connecticut and Massachusetts, with mills, dams, and associated structures located throughout the watershed (fig. 3). Although industrial use of the Quinebaug has waned in recent decades, many of these structures remain. Additional dams have been constructed for flood-control purposes, following the severe damage caused by hurricanes in 1938 and 1955. Consequently, numerous impoundments are located along the main stem of the Quinebaug and its major tributaries, and streamflow regulation is part of the hydrologic setting for the watershed.

The Quinebaug River Basin, with a drainage area of 739 square miles (mi^2), includes undeveloped forested areas, agricultural areas, villages, new suburban developments, and small urban areas (fig. 4, table 1). Municipal wastewater is discharged in both the Massachusetts and Connecticut parts of the watershed; consequently, interstate concerns relate to the quality of water flowing into Connecticut. Water-quality issues in the drainage basin include streamflow regulation, accumulation and storage of nutrients and other pollutants in sediments, and prolonged warm weather algal blooms in several impoundments and river reaches.

Phosphorus and Water Quality in the Quinebaug River Basin

Phosphorus and nitrogen are essential nutrients for plant growth. Nitrogen availability rarely limits aquatic plant growth in freshwater, whereas phosphorus concentrations in natural or near-natural streams are generally low enough to limit plant growth. Excessive phosphorus concentrations in freshwater promote growth of aquatic algae and eutrophic conditions (Hem, 1985, p. 128). When the algae die, they decompose, consuming oxygen in the water and contributing to a condition called hypoxia, or low dissolved oxygen. Excessive growth of algae, often called an algal bloom, also can affect water quality and aquatic habitat by increasing turbidity, limiting light penetration, and altering the composition of the food chain. During the day, the photosynthetic activity of aquatic plants, including algae, removes carbon dioxide and releases oxygen to the water, whereas during the night, as photosynthesis ceases, aquatic plants and animals continue to respire, consuming oxygen and producing carbon dioxide. Consequently, waterbodies with

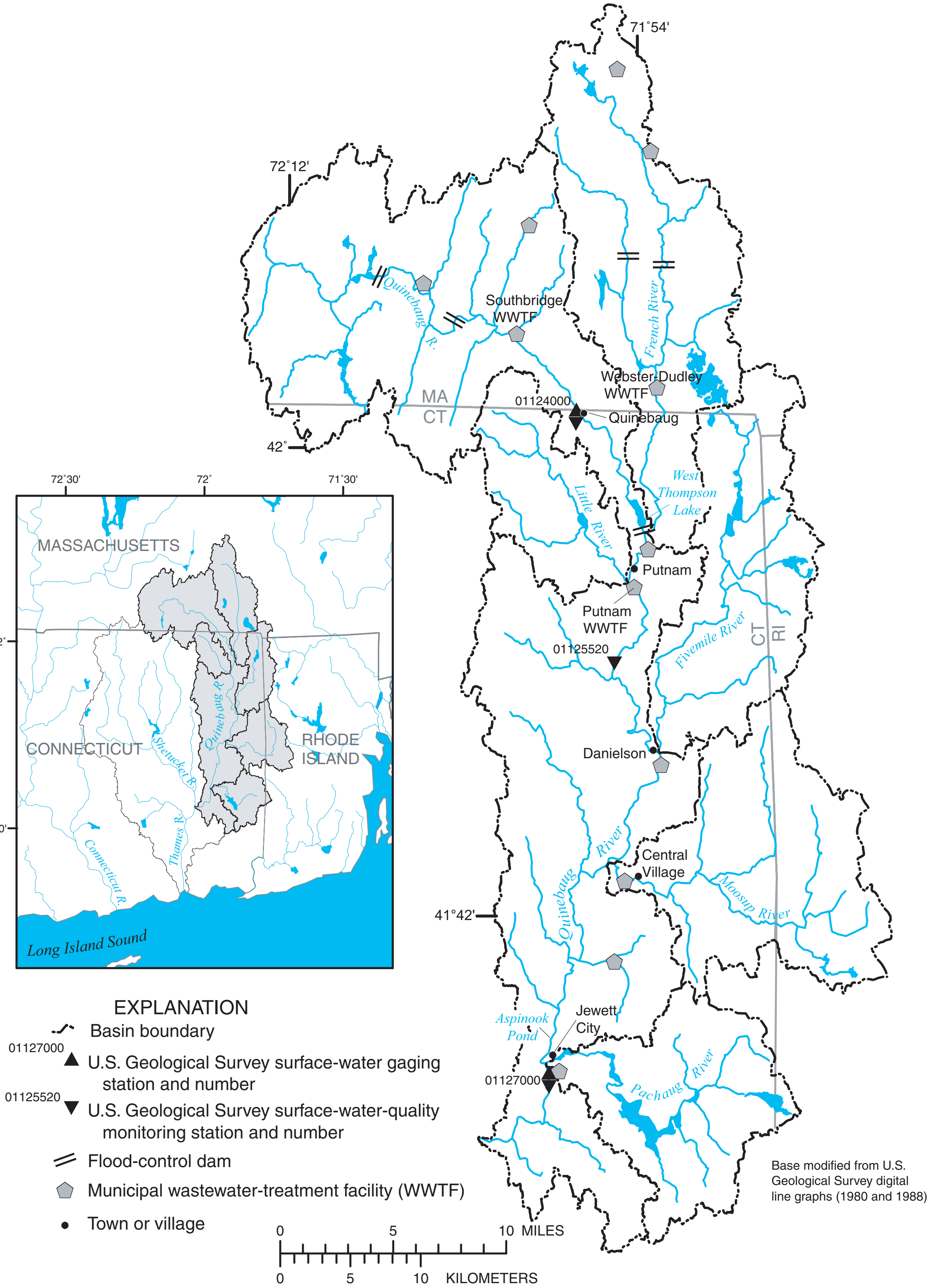


Figure 1. Hydrologic features of the Quinebaug River Basin, including major streams, drainage basin boundaries, and monitoring stations.

Table 1. Summary of major land uses in the Quinebaug River Basin.

[Source: National Land Cover Dataset, Vogelmann and others, 2001. Numbers may not total to 100 percent because miscellaneous land-use categories that total less than 1 percent of basin area have not been included in the table and because of rounding]

Basin name	Drainage area (in square miles)	Land use (in percent)				
		Water	Wetland	Forest	Agriculture	Urban
Quinebaug River at Quinebaug, Conn. (USGS station 01124000)	155	3.8	9.3	70.4	7.0	8.8
French River (at mouth downstream from West Thompson Lake)	112	5.9	10.0	60.3	8.7	14.3
Little River (at mouth near Putnam, Conn.)	39.1	1.3	8.1	60.8	23.8	5.3
Quinebaug River at Putnam, Conn. (USGS station 01125500)	328	4.2	9.5	64.8	10.4	10.4
Five Mile River (at mouth near Danielson, Conn.)	76.4	3.1	8.8	74.2	7.3	5.9
Moosup River (at mouth near Central Village, Conn.)	89.1	1.0	6.8	78.6	9.0	4.2
Pachaug River (at mouth in Jewett City, Conn.)	63.0	4.2	8.0	73.2	9.6	4.4
Quinebaug River at Jewett City, Conn. (USGS station 01127000)	713	3.1	8.9	68.0	11.2	8.1
Entire basin to mouth (confluence with Shetucket River)	739	2.9	9.0	67.8	11.6	7.9

large algal populations may experience large daily fluctuations in dissolved oxygen concentrations and pH, affecting habitat conditions for other aquatic organisms.

Sources of Phosphorus

Phosphorus constituents in streams are derived from natural sources and from many human uses of land and water resources. Major sources of phosphorus in Connecticut include decaying plants, animal wastes (from farm animals, pets, and wild animals), fertilizers, detergents, and municipal and industrial wastewater. Atmospheric deposition contributes minor amounts of phosphorus to the land surface. Some forms of phosphorus are chemically reactive, adhering to particulate materials in water and accumulating in stream sediment. Phosphorus-bearing minerals in rocks and soil are not major sources of phosphorus in Connecticut.

Phosphorus concentrations in the Quinebaug River and other streams in Connecticut were historically very high during the mid-20th century as a result of untreated or minimally treated wastewater discharges and phosphorus in detergents. Sediments in streambeds and impoundments continue to constitute a reservoir of nutrients that may be recycled into the water column under some conditions. An investigation of water quality, mass of phosphorus in sediment, and seasonal phosphorus cycling in West Thompson Lake (fig. 1) is currently (2003–04) in progress (John R. Mullaney, U.S. Geological Survey, written commun., 2003).

Trends in Phosphorus Concentrations

Total phosphorus concentrations in many streams in Connecticut, including the Quinebaug River, declined substantially between the 1970’s and the 1990’s (Trench, 1996, figs. 30a–b; Trench, 2000, table 12; Colombo and Trench, 2002, fig. 18). Improvements in wastewater treatment under state water-quality management programs in Massachusetts and Connecticut, and the decline in the manufacture and use of detergents containing phosphorus, have probably contributed significantly to the detected decreases in phosphorus concentrations in streams.

Current Challenges Related to Phosphorus

To control eutrophication, the U.S. Environmental Protection Agency (USEPA) has recommended that total phosphorus concentrations should not exceed 0.1 milligram per liter (mg/L) in flowing waters that do not discharge directly into lakes or impoundments, and that concentrations of total phosphates should not exceed 0.05 mg/L (as phosphorus) in a stream at a point where it enters a lake or reservoir (U.S. Environmental Protection Agency, 1986; Mueller and others, 1995, p. 4). Despite significant improvements in wastewater treatment and significant long-term downward trends in phosphorus concentrations in the Quinebaug River, current (2004) concentrations of total phosphorus are substantially higher than those that would be found under natural or near-natural conditions in Connecticut. More importantly, total phosphorus concentrations along some reaches of the Quinebaug River and its tributaries

Figure 2. Summer algal bloom on the French River in Connecticut, August 20, 2002. (Photograph by S. Lyle Phipps, USGS)

sometimes exceed 0.1 mg/L, and concentrations exceeding 0.05 mg/L are common in several reaches (Ranzau and others, 2001).

Numerous impoundments along the Quinebaug River and its tributaries cause low stream velocities and extensive backwater areas, creating conditions that are favorable for nutrient and particulate retention and algal growth. Still water is common along many reaches of the Quinebaug River, particularly during the summer months. Consequently, the stream system is highly sensitive to phosphorus. Additionally, impoundments may store and release nutrients and algae and may function as point sources for downstream reaches under some conditions. Nuisance algal blooms have been observed by the USGS and the CTDEP during late spring, summer, and early fall in various locations (M.J. Colombo, U.S. Geological Survey, written commun., 2003) (fig. 2). Continuous water-quality-monitoring data for the Quinebaug River Basin show large daily fluctuations in pH and dissolved oxygen concentrations during the growing season (fig. 5), indicating the importance of algal populations in determining water-quality conditions (Davies and others, 1999, p. 73–74; Ranzau and others, 2000, p. 82–83).

Assessing and Managing Water Quality

Provisions of the Federal Clean Water Act (CWA) require states to (1) adopt water-quality standards, (2) assess surface waters to evaluate compliance with these standards, (3) identify waters not currently meeting the standards, and (4) develop Total Maximum Daily Load (TMDL) analyses and other management plans to bring waterbodies into compliance with the standards (Connecticut Department of Environmental Protection, 2002a, p. 1). The USEPA has developed guidance to assist states in assessing nutrient impairment of waterbodies and in developing regionally based numeric criteria for river and stream systems (U.S. Environmental Protection Agency, 2000). The criteria development process is currently (2004) in progress. Connecticut currently has narrative criteria for nutrients that describe goals for various water-quality classifications; ranges of nutrient concentrations are established for four lake trophic categories (table 2). The state standards require that "an assessment of the natural trophic category of the lake, absent significant cultural impacts, must be performed to determine which criteria apply" (Connecticut Department of Environmental Protection, 2002b, p. 18).

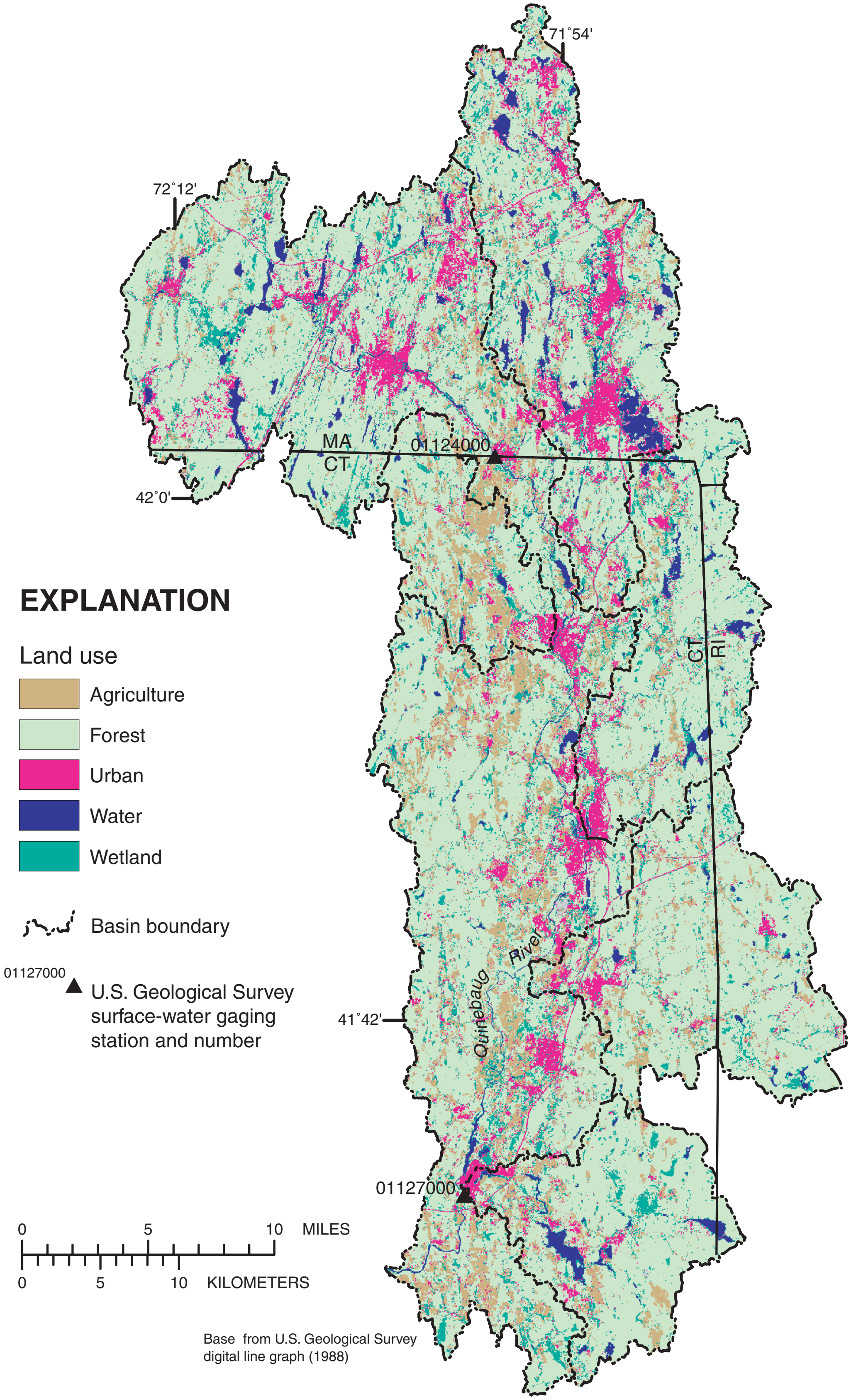
Table 2. State of Connecticut criteria for total phosphorus concentrations for lakes.

[Source: Connecticut Department of Environmental Protection, 2002b, p. 18–19]

Lake trophic category	Range for total phosphorus concentrations (micrograms per liter, μg/L)
Oligotrophic	0–10
Mesotrophic	10–30
Eutrophic	30–50
Highly eutrophic	50 +

Surface-water assessments are reported bi-annually by each state as required under Section 305 (b) of the CWA. In Connecticut, this document is called the Water-Quality Report to Congress. Waterbodies that have been identified as not meeting designated uses also are reported bi-annually in a document called the List of Connecticut Water Bodies Not Meeting Water Quality Standards, as required under Section 303 (d) of the CWA. Several waterbodies or stream reaches in the Quinebaug River Basin are on the 303 (d) Lists for Massachusetts and Connecticut because of nutrient-related water-quality impairments (table 3) (Connecticut Department of Environmental Protection, 2002a; Kennedy and others, 2002).

Figure 3. Quinebaug River at the Metals Selling Dam, next to the Belden Mill, Putnam, Connecticut, March 25, 2003. (Photograph by Elaine C. Todd Trench, USGS)



Base from U.S. Geological Survey digital line graph (1988)

Figure 4. Major land uses in the Quinebaug River Basin. (Data from Vogelmann and others, 2001.)

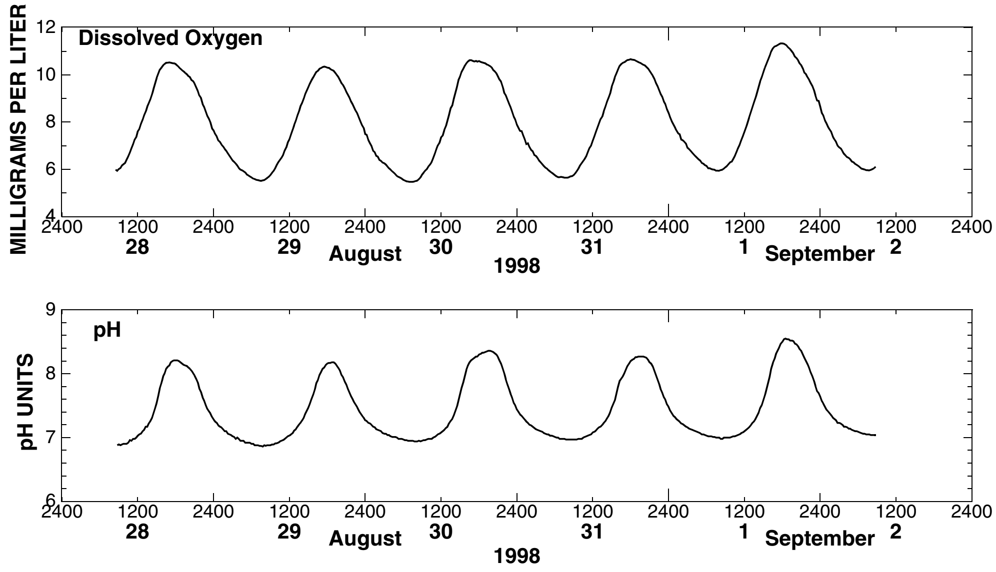


Figure 5. Daily fluctuations in dissolved-oxygen concentrations and pH associated with algal metabolism, Quinebaug River at Cotton Road Bridge near Pomfret Landing, Connecticut (USGS station 01125520), August 28 to September 2, 1998. (From Davies and others, 1999, p. 74.)

Table 3. List of waterbodies in the Quinebaug River Basin not meeting water-quality standards because of nutrient-related problems.

[Sources: Connecticut Department of Environmental Protection, 2002a, Appendix A; Kennedy and others, 2002, p. 16–18); Format differs for state documents for Connecticut and Massachusetts. Other impairments not specifically related to nutrients may be present but are not listed here. Locations for Connecticut waterbodies are shown in figure 1. DO, dissolved oxygen; WWTF, wastewater treatment facility]

Waterbody segment		Impaired designated use	Cause (or potential cause) of impairment
Name	Location		
	French River Basin		
Dutton Pond	Leicester, Mass.		Nutrients
Peter Pond	Dudley, Mass.		Nutrients, organic enrichment/low DO
Rochdale Pond	Leicester, Mass.		Nutrients, organic enrichment/low DO
Thayers Pond	Oxford, Mass.		Nutrients
French River	Webster-Dudley, Mass. WWTF to Connecticut state line		Nutrients, organic enrichment/low DO
	Quinebaug River Basin		
Alum Pond	Sturbridge, Mass.		Organic enrichment/low DO
Glen Echo Lake	Charlton, Mass.		Organic enrichment/low DO
Quinebaug River	Southbridge WWTF, Southbridge, Mass. to West Dudley Impoundment, Dudley, Mass.		Nutrients
West Thompson Lake	Impoundment of Quinebaug River in Thompson, Conn.	Aquatic life support; primary contact recreation	Organic enrichment, low DO, algal growth, chlorophyll-a, nutrients
Quinebaug River	From confluence with Moosup River upstream to Putnam, Conn. WWTF	Aquatic life support	Cause unknown (algal growth, chlorophyll-a, flow alteration, organic enrichment, low DO)
Aspinook Pond	Impoundment of Quinebaug River in Canterbury, Griswold, and Lisbon, Conn.	Primary contact recreation	Algal growth, chlorophyll-a, nutrients
Quinebaug River	From mouth at Shetucket River upstream to outlet of Aspinook Pond, Conn.	Aquatic life support	Cause unknown (algal growth, chlorophyll-a, nutrients)

The TMDL process results in a watershed plan that provides a framework to restore impaired waters by establishing the maximum amount of a pollutant that a waterbody can assimilate without adverse impact to aquatic life, recreation, or other public uses (Connecticut Department of Environmental Protection, 2002a, p. 2). Phosphorus trend analyses for the Quinebaug River provide information that can be used to evaluate the effectiveness of various phosphorus control measures. Management programs can use information on optimal sampling designs to improve the effectiveness, efficiency, and value of future water-quality monitoring efforts.

Methods for Time-Series Analysis of Trends and Evaluation of Sampling Designs

A set of observations of a monitored variable, arranged chronologically, is called a time series. Time-series analysis is a process of fitting a time-series model to a time series of observations, such as water-quality data. Trends were analyzed and sampling designs were evaluated in this study using a statistical time-series model developed by Vecchia (2000). The methods and theoretical background for the time-series model have been described in detail by Vecchia (2000) and summarized by Trench and Vecchia (2002a). The time-series model can be used to evaluate data for linear trends that have one or more changes in slope during the period being evaluated, to detect cyclic trends, and to evaluate data for combinations of linear trends and step trends. This method can be applied to datasets with variable sampling frequencies. When carefully applied and interpreted, time-series analysis can be used to detect complex trends in concentration, and also can be used to evaluate the efficiency of various sampling designs for monitoring future trends in water quality. Trends analyzed in this report are annual trends; that is, the trends may have taken place in any season of the year, or in more than one season.

Selection of Data for Trend Analysis

Data for two water-quality stations on the Quinebaug River in eastern Connecticut were analyzed for trends in total phosphorus using time-series analysis. Records for monitoring stations on the Quinebaug River at Quinebaug and the Quinebaug River at Jewett City (table 4; fig. 1) were retrieved from the USGS National Water Information System (NWIS) and were analyzed for trends in total phosphorus for selected periods of record from January 1, 1971 to September 30, 2001. Total phosphorus analyses began in 1971 for the Quinebaug River at Jewett City and in 1980 for the Quinebaug River at Quinebaug.

Effects of Method Changes on Historical Data

Possible effects of changes in field or laboratory methods need to be taken into account in analyzing trends and evaluating results of trend analysis. Information on dates of important laboratory method changes was used to select dates for linear-trend periods or step-trend periods and to evaluate results. A negative bias in total phosphorus data has been reported for analyses at the USGS National Water Quality Laboratory (NWQL) prior to 1992 (D.A. Rickert, U.S. Geological Survey, written commun., 1992). That is, reported total phosphorus concentrations may have been less than actual environmental concentrations under certain conditions prior to 1992. Possible implications of this bias for the analysis and interpretation of phosphorus data for Connecticut streams have been discussed by Zimmerman and others (1996, p. 29–30) and Trench and Vecchia (2002a, p. 8, 28).

Discharge-Related Variability in Concentration

Concentrations of many chemical constituents are related to streamflow conditions. Much of the variability in concentration is caused by variability in streamflow. Identifying and removing the streamflow-related variability in concentration increases the ability to detect trends (Vecchia, 2003, p. 6).

Constituent concentrations typically vary seasonally because of seasonal variability in discharge. Many Connecticut streams that receive wastewater discharges commonly have high total phosphorus concentrations during low-flow conditions, because of the phosphorus in wastewater, and low concentrations during medium- and high-flow conditions, because of dilution from rainfall and runoff. In streams where wastewater discharges constitute a substantial percentage of the lower streamflows, this relation between concentration and discharge persists, despite improvements in wastewater treatment. Phosphorus concentrations may increase, however, during storm events that are large enough to transport substantial amounts of phosphorus-bearing particulates and sediment to streams. In general, the relation between total phosphorus concentration and streamflow is more complex than the relation between many major ions and streamflow (A.V. Vecchia, U.S. Geological Survey, written commun., 2004).

Streamflow varies from year to year (fig. 6) as well as seasonally, and constituent concentrations vary accordingly. The solid lines in figure 6 are 1-year moving averages that represent annual variability in discharge at the two Quinebaug stations.

The time-series analysis program is designed to adjust for both seasonal and annual variations in streamflow, and all trend results in this report are for flow-adjusted total phosphorus concentrations. The process used by the time-series model to relate concentration to streamflow is more complex than that of many commonly used flow-adjustment techniques, and consequently is able to remove more streamflow-related variability from concentration (Vecchia, 2003, p. 19).

Table 4. Information for water-quality monitoring stations selected for trend analysis in the Quinebaug River Basin.

[Station locations are shown in fig. 1]

U.S. Geological Survey water-quality station		Drainage area (square miles)	Period of water-quality record used in this study	Part of current (2004) monitoring network
Name	Number			
Quinebaug River at Quinebaug, Conn.	01124000	155	1980–2001	yes
Quinebaug River at Jewett City, Conn.	01127000	713	1971–2001	yes

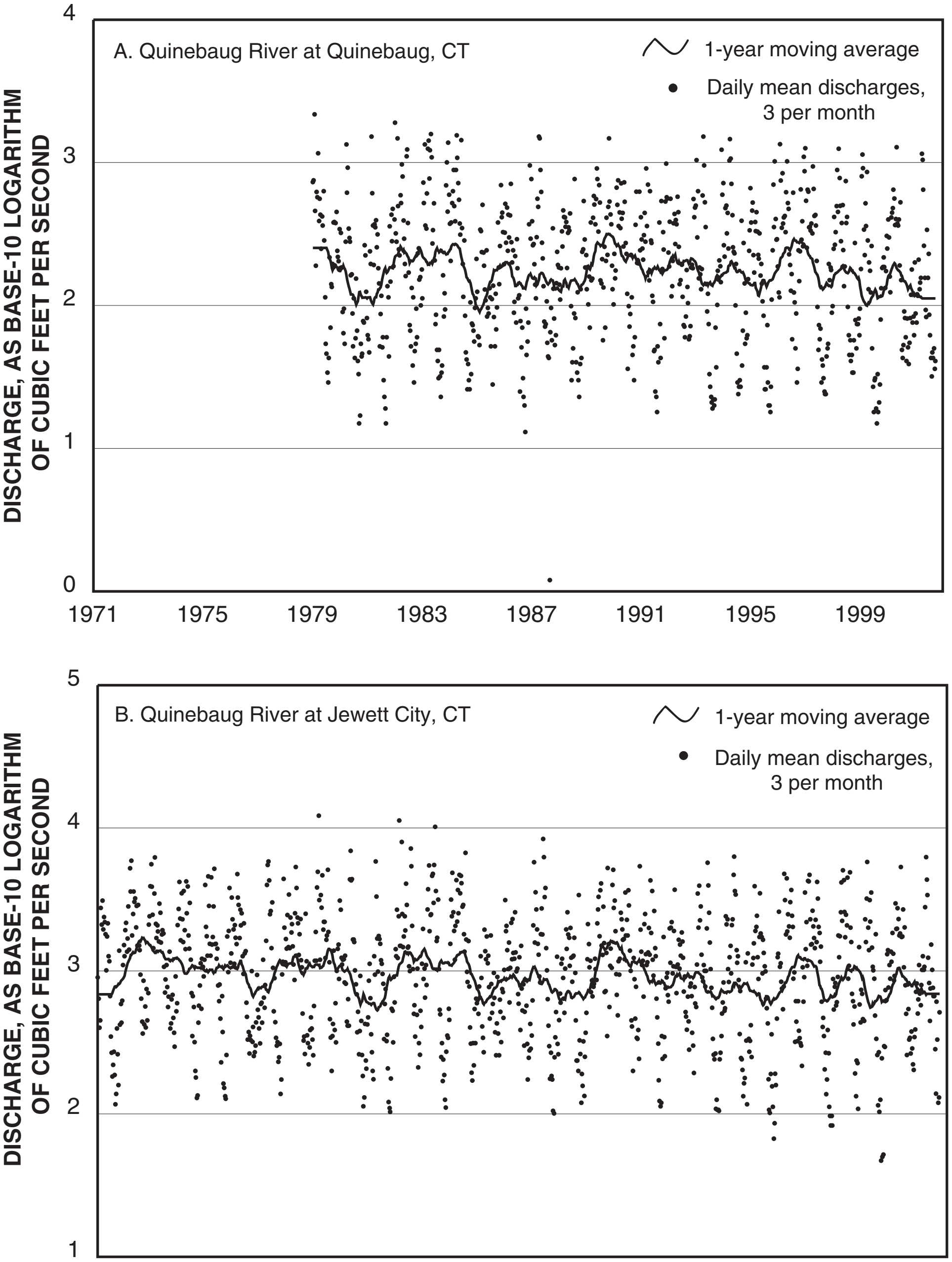


Figure 6. Annual variability in discharge for (A) Quinebaug River at Quinebaug, Connecticut (1980–2001) and (B) Quinebaug River at Jewett City, Connecticut (1971–2001). Points indicate daily mean discharges (3 per month). Line indicates 1-year moving average.

A joint time-series model for daily mean discharge and concentration is fitted to historical data for each water-quality station and constituent. The time-series model is applied to log-transformed discharge and concentration data. The model is used to filter out as much natural, discharge-related variability in concentration as possible before analyzing for trends. The time-series model separates the concentration data into components of annual variability, seasonal variability, trend, and deviations from the basic conditions. These deviations from basic conditions are sometimes referred to as "noise." Deviations from basic conditions also are referred to as the "daily concentration anomaly" (Vecchia, 2003, p. 11, 14), to distinguish this short-term variability from the longer-term seasonal and annual variability in concentration that constitutes the basic conditions.

Differentiating Trends from Other Sources of Concentration Variability

In the flow-adjustment process, most of the flow-related annual and seasonal variability is removed from measured concentration values, as described by Vecchia (2000, p. 41). The flow-adjusted concentrations are composed of a constant, plus any trend present, plus the daily concentration anomaly (or noise). In some statistical-modeling procedures, noise is considered an error term and is not evaluated further. The daily concentration anomaly, however, may have a complex time-series structure that is not immediately apparent from simple inspection of the data. The daily concentration anomaly may be serially correlated, or may be cross-correlated with the daily anomaly in discharge data, and the magnitude or direction of the daily concentration anomaly and of these correlations may vary seasonally. The statistical significance of the detected trends depends on the statistical properties of the daily concentration anomaly. A special type of time-series model, called a periodic autoregressive moving average (PARMA) model (Vecchia, 2000, appendix A), is used to detect and filter out the complex statistical properties of the daily concentration anomaly. After the PARMA model is applied to the daily concentration anomaly, the residuals from the PARMA model represent the unexplained remnant of concentration variability, plus any trends that may be present but have not yet been removed by including a trend term in the model. The PARMA model provides a convenient way to identify and filter out structure in the daily concentration anomaly and correct for any bias in estimated trends and significance levels. The PARMA model also uses information on the statistical properties of the daily concentration anomaly to identify months during which constituent sampling yields the most information for trend analysis, enabling sampling schedules to be identified that maximize the sensitivity for detecting trends.

Application of the Time-Series Model

The time-series model was initially applied to total phosphorus data at each station with no trend periods specified. Because trends are likely in any long-term water-quality dataset, it is expected that the residuals from the no-trend model will not be randomly distributed. A smooth line was added to the plot of PARMA model residuals to aid in identifying central patterns in the data. The smooth line indicates trend directions and major changes in slope during the period of record. The plot of PARMA model residuals from the no-trend model was used to select appropriate trend periods for the time-series model. Information on dates of laboratory method changes, where available, also was used to select dates for linear-trend periods or step-trend periods and to evaluate trend results. Several trend models were tested for each station using linear-trend periods and step-trend periods of varying lengths. Numerical evaluations of the model fit, as well as p-values for the various trend periods, were examined and compared to select the model that best represented changes in the constituent during the period of record. Residual plots for the selected model were examined to ensure that residuals met assumptions of random distribution with constant variance and no apparent trends. Trend results in this report were considered significant if the p-value (attained significance level) for the test statistic was less than or equal to 0.05. A more detailed discussion and illustration of the modeling procedure is provided in Trench and Vecchia (2002a, p. 15–16.

Evaluation of Sampling Designs

The time-series model can be used to evaluate the efficiency and sensitivity of various sampling designs (that is, sampling schedules) for monitoring trends in water quality. Sampling designs can be evaluated for purposes of maintaining a sampling frequency that is sufficient for future trend analysis, reducing sampling costs by eliminating samples that provide redundant information, or shifting the most frequent sampling to seasons that provide the greatest gain in information. The theory and mathematical basis for applying the time-series model to the analysis of sampling designs have been described in detail by Vecchia (2000, appendix A). A brief description of the application of the sampling-design program and related terminology is included here. A more detailed discussion and explanation of the procedure for identifying and evaluating optimal sampling designs is provided in Trench and Vecchia (2002a, p. 17–18).

Sampling schedules cannot be designed to detect trends with absolute certainty or to prove with absolute certainty that no trends exist. The size of the trend that can be detected depends on the acceptable level of tolerance specified for failing to detect a true trend or incorrectly identifying a trend. In the analysis described in this report, the acceptable level of tolerance is controlled by specifying two variables: the probability that a true trend is detected when a true trend exists, and the probability that a trend is incorrectly detected when no true trend exists. The selection of an efficient sampling design is not highly dependent on the values specified for these two probabilities (Vecchia, 2003, p. 39). In this analysis, the probability of detecting a trend when a true trend exists has been set at 0.8 (or 80 percent). The probability of incorrectly detecting a trend when none exists (also termed the significance level) has been set at 0.05 (or 5 percent).

In this analysis, monthly sampling is the maximum allowable sampling frequency based on cost considerations, with one sample per month collected at approximately the same time of month in the 12-sample design. Various designs with sampling frequencies ranging from 4 to 11 samples per year are evaluated by omitting selected months from the 12-sample design. Lower-cost (lower-frequency) designs are compared to the efficiency and trend-detection power of the monthly design to determine the best configuration of months to sample for a given cost.

The entire set of mathematically possible sampling designs has been reduced to a set of 150 designs (identified by design number in this report) that represent the range of reasonable possibilities for designs with 4 to 12 samples per year. The designs developed in this report assume that trends during all times of year are equally important, and samples are allocated throughout the year, with at least one sample in each of four seasons, to maximize the capability to detect trends whenever they take place. Trends that take place during specific seasons have not been investigated in this report.

Sensitivity and Efficiency of Sampling Designs

Sensitivity and efficiency, two related concepts, are used to evaluate sampling designs. Sensitivity measures the ability of a design to detect a trend – the smaller the trend that can be detected, the more sensitive the design. An efficient design for a given water-quality constituent maximizes the sensitivity to detect a trend for a fixed sampling cost, which is usually measured in terms of the number of samples per year. The only way to increase the sensitivity of an efficient design is to increase the cost – that is, to collect samples more frequently. As the number of samples is increased, the sensitivity for detecting a given trend increases, but the cost also increases. The timing of sample collection during the year is an important consideration. A design with fewer well-timed samples may be more efficient for trend detection than a more costly design with more frequent samples at times that provide redundant information.

The sensitivity of a sampling design can be evaluated in two equivalent ways: (1) in terms of the size of trend that can be detected for a given power, or (2) in terms of the power for detecting a trend of a given size. In this report, power is defined as the probability of detecting a log-linear trend that takes place over a specified design period. This probability has been set at 0.8, as described above, and the design period is 5 years. The characteristic trend (or detectable trend) for a design is defined as the percentage change in concentration (increase or decrease) that can be detected over the 5-year design period with power of 0.8 (80 percent probability). If the characteristic trend is fixed as the size of trend that can be detected with monthly sampling, then sampling designs with less than a monthly sampling frequency have less than an 80-percent probability of detecting the characteristic trend. The most efficient design for a given sampling frequency is the design with the highest power, because it provides the most trend information for a given cost.

The efficiency of a sampling design is not dependent on the number of years selected for the design period. If a particular 6-sample design is the most efficient design for detecting a trend that persists for 5 years, that same design generally also will be the most efficient 6-sample design for detecting a trend that persists for 3 years or 10 years.

Although the efficiency of a sampling design does not depend on the length of the design period, the sensitivity of a sampling design does depend on the duration of the trend. As the length of the sampling period increases, the sensitivity of a given design increases; that is, trends of smaller magnitude can be detected as the number of years of sampling increases.

Acceptable Levels of Probability for Trend Detection

In the process of using the time-series program to evaluate sampling designs, other choices could be made for the probability of trend detection, the significance level, or the length of the design period. Determining the acceptable level of probability for trend detection is a management consideration that can incorporate numerous factors, including the goals of the water-management program and the scientific understanding of the watersheds in question. In general terms, the probability of trend detection should be high enough to justify the agency's investment in the water-quality sampling program. In a previous study that used time-series analysis to evaluate trends in Connecticut, the acceptable level of trend-detection probability was set at 75 percent (power of 0.75) for the purpose of evaluating sampling designs (Trench and Vecchia, 2002a).

When considering an acceptable threshold of probability for trend detection, and comparing the relative efficiency of designs with the same sampling frequency, it may be useful to consider these probabilities in simpler terms. The time-series program is designed so that, with 12 monthly samples, the characteristic trend is detected in four of five cases (80-percent probability). If a 75-percent probability is selected as an acceptable threshold of trend-detection sensitivity for the lower sampling frequencies necessitated by budget constraints, then an acceptable design detects the characteristic trend in three out of four cases. Designs with a 67-percent probability detect the characteristic trend in two of three cases, and designs with a 50-percent probability have similar value to a coin toss in detecting the presence of a true trend.

Differences in design sensitivity need to be considered within a management framework that has established reasonable goals or targets for trend-detection probability, so that a distinction can be made between a reasonable design and a marginal design for trend detection. However, numerous other factors involved in water-quality management may influence the choice of sampling design.

Variability and Correlation in the Daily Concentration Anomaly

The time-series program, in its identification of optimal sampling designs, quantifies two aspects of the daily concentration anomaly. These two characteristics, termed variability and correlation, provide a means of identifying the seasons in which more frequent sampling improves the likelihood of trend detection, and the seasons in which more frequent sampling does not contribute to improved trend detection.

Trend detection is more difficult during seasons in which there is high variability in the daily concentration anomaly, and trends can be detected more easily when variability is low. Conversely, the degree of serial correlation in the daily concentration anomaly indicates the extent to which more frequent sampling may provide redundant information. An increased sampling frequency provides better information for trend detection when the serial correlation is low, and provides redundant information when the serial correlation is high. Ideally, sampling takes place when the variability in the daily concentration anomaly is low, and sampling times are spaced sufficiently far apart to avoid high serial correlation. Graphs of variability and correlation are not presented in this report; additional discussion of these measures can be found in Vecchia (2000, p. 8–10), Trench and Vecchia (2002a, p. 12–14), and Vecchia (2003, p. 14).

Long-Term Phosphorus Trends in the Quinebaug River

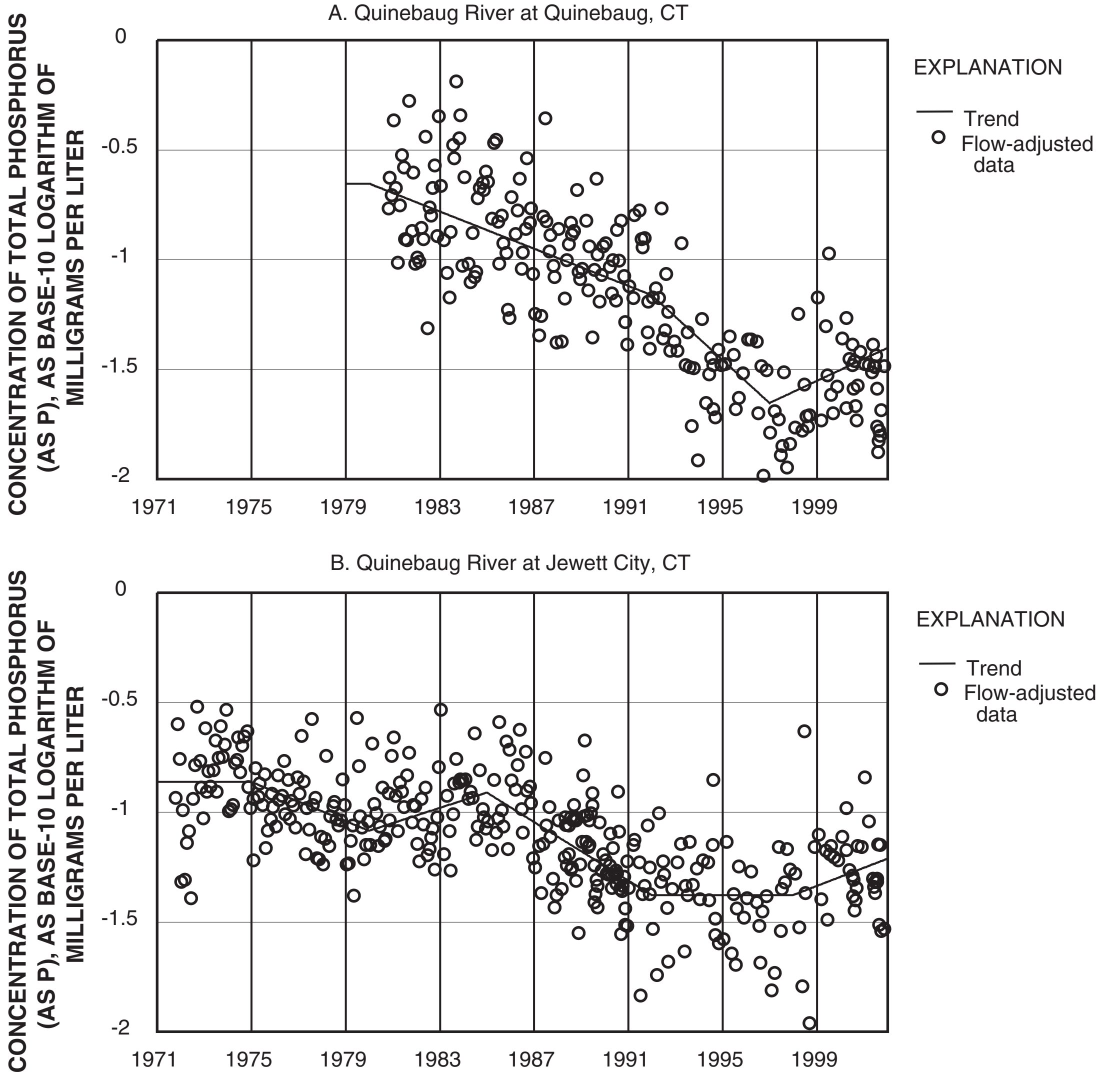
Concentrations of total phosphorus in the Quinebaug River have varied over time, but generally were substantially lower in the 1990s and early 2000s than in the 1970s and 1980s (table 5, fig. 7). At the Quinebaug River station at Quinebaug, flow-adjusted concentrations of total phosphorus decreased steadily from 1980 to 1996, with the steepest decrease from 1992 to 1996 (fig. 7A). At the Jewett City station, flow-adjusted concentrations decreased from 1975 to 1979, increased from 1980 to 1984, and then decreased steadily from 1985 to 1991 (fig. 7B). No significant trend was detected at the Jewett City station from 1992 to 1997. Flow-adjusted concentrations of total phosphorus at both stations increased during the late 1990s and early 2000s (fig. 7).

Long-term downward trends in total phosphorus concentrations in the Quinebaug River probably result from reductions in the use of phosphorus in detergents and from improvements in wastewater treatment at municipal treatment plants in Massachusetts and Connecticut. The use of phosphorus in detergents decreased substantially between the late 1960s and the late 1990s, as a result of phosphate detergent bans and voluntary manufacturing reductions (Litke, 1999, p. 31). Likewise, improvements in wastewater treatment have reduced phosphorus concentrations in effluent, although specific treatment-plant histories have not been compiled for this report. Reasons for increases in phosphorus concentrations in the late 1990s are not immediately apparent. Similar increases during the mid- to late-1990s have been detected in concentrations of total phosphorus in the Quinnipiac and Naugatuck Rivers in central and western Connecticut (Trench and Vecchia, 2002a, fig. 12d–e).

Table 5. Summary statistics for concentrations of total phosphorus for stations on the Quinebaug River at Quinebaug and Jewett City, Connecticut, 1974–2001.

[Sources: for 1974–85, Healy and others, 1994, table 35, p. 107; table 41, p. 118; for 2000–01, M.J. Colombo, U.S. Geological Survey, written commun., 2003; concentrations are not flow-adjusted; mg/L, milligrams per liter; P, phosphorus]

Period of record	Number of samples	Standard deviation	Total phosphorus concentrations (mg/L as P)		
			Minimum	Median	Maximum
Quinebaug River at Quinebaug, Conn. (USGS station 01124000)					
1981–85	57	0.159	0.03	0.210	0.81
2000–01	34	.014	.009	.040	.071
Quinebaug River at Jewett City, Conn. (USGS station 01127000)					
1974–85	140	.070	<.01	.100	.36
2000–01	32	.029	.035	.060	.183


A. Quinebaug River at Quinebaug, CT

B. Quinebaug River at Jewett City, CT

Figure 7. Trends in flow-adjusted concentrations of total phosphorus for (A) Quinebaug River at Quinebaug, Connecticut (1980–2001) and (B) Quinebaug River at Jewett City, Connecticut (1971–2001).

When water-quality data are analyzed for time periods that cross the 1991–92 time boundary, the potential exists for detecting artificial upward linear trends because of the negative bias in some total phosphorus data from the USGS NWQL prior to 1992. The time-series analysis program can evaluate linear trends and step trends simultaneously, making it possible to examine the potential effects of laboratory bias within the context of long-term environmental changes. Several combinations of step trends and linear trends were examined for both stations to evaluate the possible importance of this bias for trend results. In the case of the Quinebaug station, the downward linear trend during the early- to mid-1990s was highly significant, and there was no evidence that the pre-1992 bias had any effect on trend results. In the case of the Jewett City station, an upward step trend after 1991 was present in some of the trend models tested, but was not statistically significant, and the inclusion of the step trend in the model did not alter the direction or approximate level of significance of the linear trends present. Consequently, step trends were not included in the final models selected for either station.

Evaluation of Sampling Designs for Detecting Trends in Total Phosphorus

The statistical time-series model was used to evaluate the efficiency of various sampling designs for monitoring trends in flow-adjusted total phosphorus concentrations. Optimal sampling designs for the two stations on the Quinebaug River were identified for each of eight sampling frequencies ranging from 4 through 11 samples per year, based on a design period of 5 years, and compared to the trend-detection power of the monthly (12-sample) design.

Size of the Characteristic Trend

In the following discussion, the efficiency of a sampling design is evaluated in terms of its power to detect the characteristic trend (defined earlier in the Methods section). In a previous study of trends and sampling designs in Connecticut, characteristic trends for total phosphorus were generally much higher than the characteristic trends for the major ions chloride and sulfate (Trench and Vecchia, 2002a). Flow-adjusted concentrations of total phosphorus usually have a much higher variance than flow-adjusted concentrations for major ions (A.V. Vecchia, U.S. Geological Survey, written commun., 2004). Sources of phosphorus may be more spatially variable than for the major ions, and the influence of point and nonpoint sources on phosphorus concentrations often varies seasonally. Consequently, the relation between phosphorus concentration and streamflow often is weaker than the relation between concentrations of major ions and streamflow. This high variability in flow-adjusted phosphorus concentrations means that a trend must be large to be detected.

With monthly sampling, the characteristic trend for the Quinebaug River at Quinebaug is 78 percent. That is, there is an 80-percent probability of detecting a 78-percent change in the concentration of total phosphorus over a design period of 5 years. The characteristic trend for the Quinebaug River at Jewett City is 69 percent. That is, with monthly sampling, there is an 80 percent probability of detecting a 69-percent change in total phosphorus concentration over 5 years of sampling. If the power for all sampling designs is held constant at 0.8 (80-percent probability), then sampling designs with fewer than 12 monthly samples per year have characteristic trends that are larger than the characteristic trends for monthly sampling. As the sampling frequency decreases, the size of the trend must increase to maintain an 80-percent probability of detection. Likewise, if the size of the characteristic trend is held constant at 78 percent for the station at Quinebaug and 69 percent for the station at Jewett City, then designs with fewer than 12 monthly samples have less than an 80-percent probability of detecting the characteristic trend over the design period of 5 years. In the following discussion, the size of the characteristic trend for each station is held constant at the percentage change detectable with 12 monthly samples, and the probability of trend detection is less than 80 percent for designs with fewer than 12 samples per year. (This discussion is complicated to some extent by the circumstance that the numerical ranges happen to be similar for the probability of trend detection, the size of the characteristic trend, and the identifying numbers for some of the sampling designs.)

Low-Frequency Sampling Designs

Sampling designs with a frequency of 4 to 7 samples per year (not shown in this report) generally have low power for trend detection at both stations. All of the 4- and 5-sample designs have less than a 60-percent probability of detecting the characteristic trend, and many have less than a 50-percent probability. This is in part because sampling designs for all frequencies are constrained to represent each 3-month season with at least one sample. Consequently, with 4- and 5-sample designs, insufficient samples are available to represent all seasons and also conduct monthly sampling during a season that provides the best information for trend analysis. As the number of annual samples increases, the potential for a seasonal emphasis of monthly sampling becomes more feasible. Trend-detection power for 7-sample designs ranges from 0.58 to 0.71 for the Quinebaug River at Quinebaug, and from 0.60 to 0.69 for the Quinebaug River at Jewett City.

Eight-Sample Designs

Currently (2004), water-quality stations on the Quinebaug River at Quinebaug and the Quinebaug River at Jewett City are each sampled eight times per year. Consequently, the efficiency of 8-sample designs is discussed here in detail. Selected 8-sample designs for both stations are shown in figure 8. The designs with the highest power and designs with lowest power for detecting trends in total phosphorus are shown for each station, to compare the seasons in which monthly sampling provides the most information for trend detection with seasons that provide less information. For both stations, the most efficient designs provide at least a 70-percent probability of detecting the characteristic trend (fig. 8). Trend-detection power for the best 8-sample designs is somewhat higher for the Quinebaug station than for the Jewett City station, and the size of the characteristic trend also is larger for the Quinebaug station (78-percent) compared to that for the Jewett City station (69-percent).

For the station on the Quinebaug River at Quinebaug, the most efficient 8-sample designs include monthly sampling from fall or early winter through late winter or spring, and bimonthly sampling from spring or early summer through fall (fig. 8A). The most efficient designs (numbers 66, 75–77, and 87–89 in fig. 8A) have a 72- to 74-percent probability of detecting the characteristic trend (a 78-percent change in concentration). Designs 87 and 88, with power of 0.74, are the best 8-sample designs. The least efficient 8-sample designs (numbers 71–73 and 82–84 in fig. 8A) have a 63- to 66-percent probability of detecting the characteristic trend, and include monthly sampling from late spring or summer through fall or early winter. The current (2004) sampling schedule corresponds to design number 70, which has a 68-percent probability of detecting the characteristic trend. This sampling schedule, or a schedule similar to design number 70, has been in effect at both Quinebaug stations since 1993.

For the station at Jewett City, the most efficient 8-sample designs include monthly sampling from mid-summer or fall through winter, and bimonthly sampling from winter or spring to mid-summer or early fall. The most efficient designs (numbers 73–75 and 84–87 in fig. 8B) have a 70- to 73-percent probability of detecting the characteristic trend (a 69-percent change in concentration). Designs 74 and 86, with power of 0.73, are the best 8-sample designs. The least efficient 8-sample designs (numbers 70, 71, 78, 82, and 89 in fig. 8B) have a 65- to 66-percent probability of detecting the characteristic trend, and include monthly sampling from winter to late spring or from spring or early summer to fall. The current (2004) sampling schedule corresponds to design 70, which is among the least efficient of the 8-sample designs.

In a previous study of long-term stream-quality trends and optimal sampling designs in Connecticut (Trench and Vecchia, 2002a), a 75-percent probability of trend detection was selected as a reasonable threshold for evaluating the sensitivity of sampling designs. In that study, which did not include any stations in the Quinebaug River Basin, some of the 8-sample designs provided at least a 75-percent probability of trend detection for the stations and constituents evaluated. The sampling design analysis in the present study indicates that none of the 8-sample designs meet that threshold.

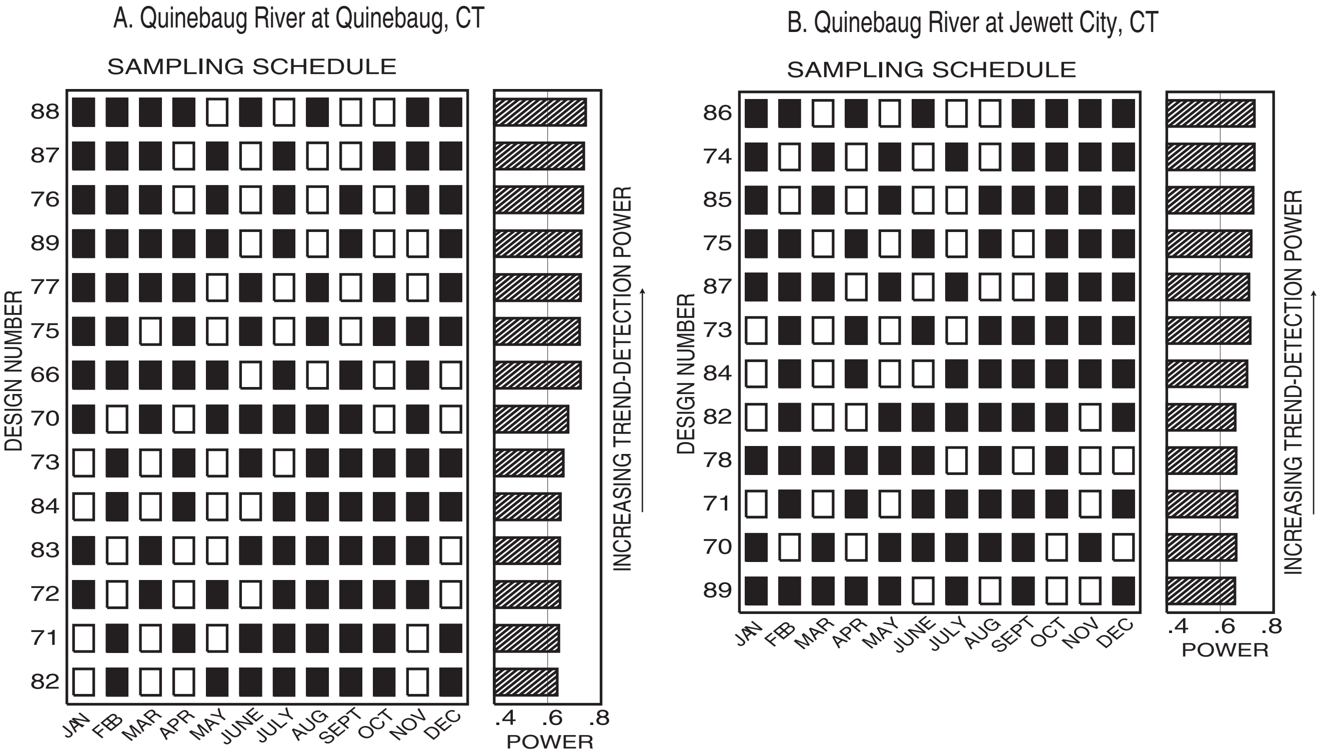


Figure 8. Comparisons of sampling schedules and power for detecting trends in total phosphorus for selected monitoring designs with 8 samples per year for (A) Quinebaug River at Quinebaug, Connecticut, and (B) Quinebaug River at Jewett City, Connecticut. [Power is defined as the probability of detecting the characteristic trend after 5 years of sampling; the characteristic trend is 78 percent for (A) and 69 percent for (B).]

Nine-Sample Designs

The majority of the 9-sample designs for both Quinebaug stations provide at least a 72-percent probability for detecting the characteristic trend. Many of the 10- and 11-sample designs (not shown in this report) provide trend-detection power close to that of the monthly (12-sample) design.

For the station on the Quinebaug River at Quinebaug, eight of the twenty-four 9-sample designs have a 75-percent or higher probability of detecting the characteristic trend (fig. 9A). The two most efficient designs (numbers 111 and 112 in fig. 9A) have a 77-percent probability of detecting the characteristic trend. The best monthly sampling season for these two designs begins in October or November and continues through May or June.

For the station at Jewett City, none of the 9-sample designs have a 75-percent or higher probability of detecting the characteristic trend. Six of the designs have a 74-percent probability of detecting the characteristic trend (fig. 9B). The addition of the ninth sample, however, does not substantially improve trend-detection power beyond that provided by the two most efficient 8-sample designs (73-percent probability) (fig. 8B).

Variability in Optimal Designs Among Stations and Constituents

Optimal sampling designs for trend detection may differ for different stations and constituents, as indicated by results from previous studies of long-term trends and sampling designs in Connecticut (Trench and Vecchia, 2002a, 2002b). For two of the stations evaluated in previous studies, some of the most efficient 8-sample designs for detecting trends in total phosphorus included monthly sampling during the period from April to October, which corresponds roughly with the sampling schedule followed under the current (2004) cooperative monitoring program between the USGS and the CTDEP. Monthly sampling during the low-flow period from summer to fall has been considered necessary for compliance-monitoring purposes on streams that receive wastewater discharges. This schedule, however, is not optimal for trend detection for the two Quinebaug River stations, according to the design results from this study.

Effects of Seasonal Changes in the Daily Concentration Anomaly

Analyses of seasonal variability and correlation in the daily concentration anomaly (described in the Methods section of this report) help to identify the seasons in which more frequent sampling improves the likelihood of trend detection, and the seasons in which more frequent sampling does not contribute to improved trend detection. Plots of variability and correlation (not shown in this report) indicate that, although there are seasonal changes in the magnitude of these two measures at

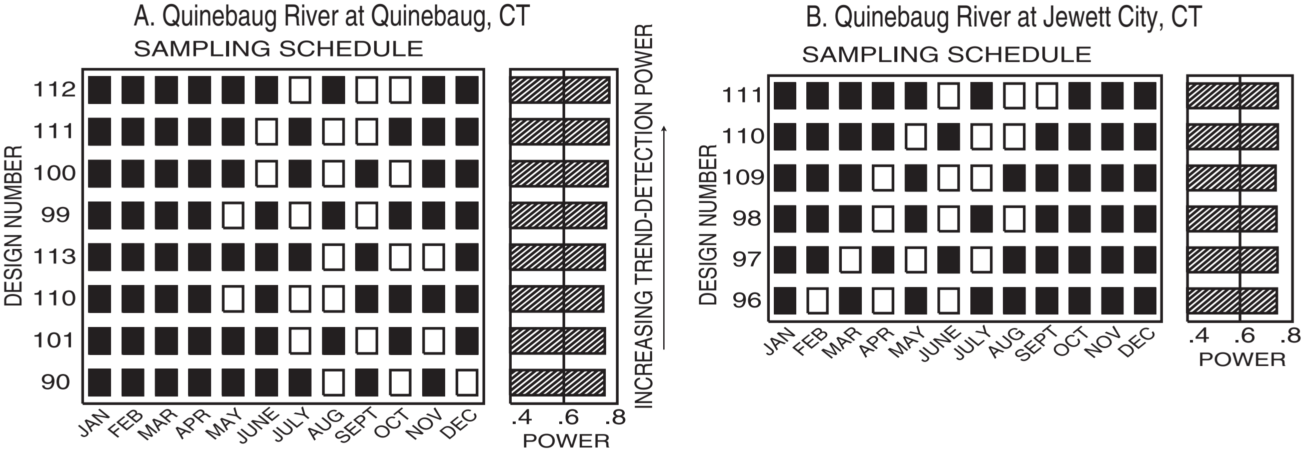


Figure 9. Comparisons of sampling schedules and power for detecting trends in total phosphorus for selected monitoring designs with 9 samples per year for (A) Quinebaug River at Quinebaug, Connecticut, and (B) Quinebaug River at Jewett City, Connecticut. [Power is defined as the probability of detecting the characteristic trend after 5 years of sampling; the characteristic trend is 78 percent for (A) and 69 percent for (B).]

both Quinebaug stations, the seasonal differences are not large. Consequently, the differences in trend-detection power between the most efficient and least efficient 8-sample designs also are not large.

Correlation results for the Quinebaug River at Quinebaug show that serial correlation in the daily concentration anomaly, although not strong in any season, is highest from July to October, indicating the potential for redundant information from frequent sampling during these months. Consequently, designs with monthly sampling during this period have less trend-detection power (fig. 8A). The magnitude of variability in the daily concentration anomaly does not change markedly from season to season, and may not be as important a factor as correlation in identifying optimal sampling designs for this station.

For the Quinebaug River at Jewett City, the magnitude of seasonal changes in variability and serial correlation is not large, and peak periods of variability and correlation in the daily concentration anomaly are distributed among several months. Consequently, both the most efficient and the least efficient 8-sample designs for the Quinebaug River at Jewett City have monthly sampling periods that collectively cover a large part of the year (fig. 8B).

Summary and Conclusions

A time-series analysis approach developed by the U.S. Geological Survey (USGS) was used to analyze trends in total phosphorus and evaluate optimal sampling designs for future trend detection using long-term data for two stations on the Quinebaug River in eastern Connecticut. Trend-analysis results from the two stations indicate that total phosphorus concentrations in the Quinebaug River have decreased significantly since the 1970s and 1980s. Downward trends in total phosphorus concentrations are more pronounced and persistent at the upstream station, the Quinebaug River at Quinebaug, whereas results for the downstream station, the Quinebaug River at Jewett City, include an upward trend during 1980–84 and a period of no trend during 1992–97. Data for both stations show small upward trends in the late 1990s and early 2000s; additional investigation would be necessary to determine possible causes for these increases.

Optimal sampling designs are based on water-quality data that reflect the unique combination of processes affecting a specific location on a river. Design results are based on an analysis of annual, seasonal, and short-term variability in discharge and concentration, and may provide clues to understanding constituent sources and watershed processes. A complex analysis of the characteristics of short-term variability in concentration (termed the daily concentration anomaly), assists in identifying the months or seasons that contain the best information for future trend analysis. The analysis identifies the months or seasons in which the trend signal is most readily differentiated from other sources of variability, and also identifies the months or seasons where more frequent sampling provides redundant information.

Various designs with sampling frequencies ranging from 4 to 11 samples per year were compared to the trend-detection power of the monthly (12-sample) design to determine the most efficient configuration of months to sample for a given annual sampling frequency. Results of this evaluation indicate that the current (2004) 8-sample schedule for the two Quinebaug stations, with monthly sampling from May to September and bimonthly sampling for the remainder of the year, does not provide the optimal information for future trend detection among the 8-sample designs. For the Quinebaug River at Quinebaug, the 8-sample designs with the highest power for detecting trends in total phosphorus have monthly sampling within the period from October to May. The 8-sample designs with the lowest trend detection power have monthly sampling within the period from May to December. For the Jewett City station, the 8-sample designs with the highest power for detecting trends in total phosphorus have monthly sampling starting within the period from July to October and ending within the period from December to March. The 8-sample designs with the lowest trend-detection power have monthly sampling from winter to late spring or from spring or early summer to fall. The current (2004) sampling schedule is among the least efficient of the 8-sample designs for the Jewett City station. Trend-detection probability for 8-sample designs ranges from 63 to 74 percent for the Quinebaug station and from 65 to 73 percent for the Jewett City station. Sampling designs with fewer than 8 samples per year generally provide a low level of probability for detection of trends in total phosphorus.

Determining the acceptable level of probability for trend detection is a management consideration that can incorporate numerous factors related to the goals of the water-management program and the scientific understanding of the watersheds in question. Managers may identify a threshold of probability for trend detection that is high enough to justify the agency’s investment in the water-quality sampling program. Numerous water-quality management considerations in addition to trend detection are likely to be involved in determining an appropriate sampling schedule. Monthly sampling during the low-flow period from summer to fall has been considered necessary for compliance-monitoring purposes on streams that receive wastewater discharges, and this factor has influenced the redesign of sampling schedules over a period of years in which financial constraints have necessitated less frequent sampling. Results from the analysis of optimal sampling designs can provide an important component of information for the decision-making process in which sampling schedules are periodically reviewed and revised.

The time-series analysis program used in this study is designed to evaluate long-term annual trends; that is, trends may originate in any season of the year. Trends that have taken place primarily during specific seasons have not been evaluated in this study. Seasonally variable sources of nutrients, such as agricultural areas or wastewater-treatment facilities with seasonal phosphorus removal, and the seasonal processes related to algal blooms and decay, are important aspects of phosphorus dynamics in the Quinebaug River Basin. Consequently, an analysis of seasonal trends in total phosphorus may improve understanding of seasonally variable phosphorus sources and processes in the watershed.

Modifications to the schedule for water-quality sampling, in the Quinebaug River Basin and elsewhere in the state, may be considered in the context of the multiple objectives of the state's water-quality management program. Results from the current study and previous studies indicate that optimal sampling schedules for trend detection may differ substantially for different stations and constituents. This suggests that a more comprehensive statewide evaluation of sampling schedules for key stations and constituents could provide useful information and insights for any redesign of the schedule for water-quality monitoring.

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