CONCEPTS FOR A NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

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Concepts For A National Water-Quality Assessment Program

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FOREWORD

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

The history of the earth sciences demonstrates that the ''scale'' at which scientists examine the Earth has a major effect on the kinds of insights gained from their studies. In geology, for example, roles exist for investigations at the quadrangle map scale (1:24,000) and for continental or global scale studies focused on plate tectonics. Furthermore, geologic studies at one scale often enhance the understanding of the phenomena examined at the other scales. Similarly, in meteorology, there is a role for microscale climatic studies over distances of less than a mile, mesoscale studies of regional weather systems, and global circulation studies. Again, the overall science would be weakened by the lack of any one of these scales of study.

Investigations at different temporal scales also are needed. Some studies of earthquake phenomena, for example, measure processes that last for seconds or even milliseconds, and others chart the buildup of the stresses responsible for earthquakes over periods of decades to centuries.

This document defines an approach for examining the quality aspects of water resources at a unique combination of spatial and temporal scales. The spatial scale is primarily regional (several thousands of square miles), and the temporal scale is primarily multiyear and decadal. The study design stems from the view that insights about water quality, which would be of great value to resource managers and policy makers, can be best achieved by examining water quality at these scales and by aggregating the findings of the studies with time and across the Nation. These assessments would rely on many of the data already being collected as part of smaller scale studies focused on local problems, although the questions under investigation would be quite different. The primary questions would concern the natural and human factors that give rise to different types of widespread water-quality conditions and the long-term fate of contaminants stored in aquifers, sediments, or biota.

Throughout its history, the Nation has made major investments in assessing natural resources, such as soils, minerals, and hydrocarbons, and human resources in terms of the health, the education, the employment, and the economic status of the population. The reason for these investments in information is that decisions our society makes about using or conserving these resources, investing in their improvement, or regulating their use will be better if they are based on sound information. The maintenance and the improvement of water quality is now one of the major areas of public investment and government regulation. Therefore, it is appropriate that serious attempts be made to document the need for, and the effects of, such governmental actions.

The best method of conducting such an assessment is not easily determined. The difficulty is due to a number of considerations: the multiplicity of water-quality constituents, natural water-quality variations in time and among locations, and the high cost of collecting and analyzing samples. This report represents the present thoughts of the Geological Survey on a new direction for water-quality assessment in the United States. It is proposed, not as a replacement for the smaller scale studies presently conducted by many agencies, but as a complement, resulting in more complete information on the Nation's water quality that can be used for making decisions.

The proposed National Water-Quality Assessment Program is currently in a pilot phase. As part of this pilot program, this report is intended as a forum for sharing and soliciting ideas on our concepts and approaches to water-quality assessment.

Philip Cohen
Chief Hydrologist

CONTENTS

FIGURES

TABLES

METRIC CONVERSION TABLE

For the use of readers who prefer to use metric units (International System), conversion factors for inch-pound units used in this report are listed below.

Multiply inch-pound unit	*By*	*To obtain metric unit*
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.59	square kilometer (km^2)

Concepts For A National Water-Quality Assessment Program

By Robert M. Hirsch, William M. Alley, and William G. Wilber

EXECUTIVE SUMMARY

Beginning in 1986, the Congress appropriated funds for the U.S. Geological Survey to test and refine concepts for a National Water-Quality Assessment (NAWQA) Program. The goals of the program would be to:

1. Provide a nationally consistent description of current water-quality conditions for a large part of the Nation's water resources,
2. Define long-term trends (or lack of trends) in water quality, and
3. Identify, describe, and explain, as possible, the major factors that affect observed water-quality conditions and trends.

This information, which will be obtained on a continuing basis, would be made available to water managers, policy makers, and the public to provide an improved scientific basis for evaluating the effectiveness of water-quality management programs and for predicting the likely effects of contemplated changes in land- and water-management practices.

At present, the program is in a pilot phase that is to last about 4 years. Seven pilot projects, which represent a diversity of hydrologic environments and water-quality conditions, were selected to test and further develop the assessment concepts; four projects focus primarily on surface water, and three projects focus primarily on ground water. The surface-water pilot project areas are the Yakima River basin in Washington, the lower Kansas River basin in Kansas and Nebraska, the Kentucky River basin in Kentucky, and the Upper Illinois River basin in Illinois, Indiana, and Wisconsin. The ground-water pilot project areas are the Carson basin in Nevada and California, the Central Oklahoma aquifer in Oklahoma, and the Delmarva Peninsula in Delaware, Maryland, and Virginia.

Each pilot project has a liaison committee, which consists of representatives from other Federal, State, and local agencies, to help ensure that the scientific information produced by the project is relevant to local and regional interests. In addition, a National Coordinating Work Group, which consists of nine Federal members, seven non-Federal members, and a representative from each pilot project liaison committee, has been established to advise the Geological Survey on the pilot program.

In 1990, a committee of the National Academy of Sciences will complete an evaluation of the design and potential utility of the program. A decision about proceeding to full-scale implementation of the program will be made upon completion of this evaluation.

General Concepts

A full-scale program would be accomplished through investigations of about 120 study areas that are distributed throughout the Nation and that incorporate about 80 percent of the Nation's water use.

The areas studied, which are referred to as study units, include river basins in which the focus of attention is on surface-water quality and aquifer systems in which the focus of attention is on ground-water quality. The areas of the study units range from a few thousand to several tens of thousands of square miles. By conducting the national program as an aggregation of individual studies of key river basins and aquifer systems, the assessment will provide results that are useful in understanding and managing these important water resources, as well as in answering national questions about water quality.

Each study-unit investigation will be conducted by a small team of individuals familiar with the river basin or aquifer system.

Thus, the assessment can take full advantage of the region-specific knowledge of individuals in the areas under study. The development of interpretations and communication of findings is done largely by those who collect the data.

The study units will be linked together to form a national program in several ways.

- A prescribed set of study approaches and protocols for sample collection, sample handling, laboratory analysis, and quality assurance will be followed.
- Data will be collected and interpreted on a nationally consistent set of water-quality constituents.
- Consistent records of ancillary information will be recorded on streamflow and basin characteristics, well and aquifer characteristics, and land use and other measures of human activity.
- Written reports will contain similar information for each study unit.
- Data will be stored in national data files.

The assessment program will be perennial.

Because of the emphasis on trends in water quality, the program needs to be perennial. The program will evolve with time as a result of changes in knowledge of hydrogeology, improved methods of measurement, and changes in the types of contaminants of concern. However, the program will place a high emphasis on repetition of measurements with time and on documentation both of the methods of data collection and analysis and of the locations and the characteristics of data-collection sites.

Assessment activities in each of the study units will be done on a rotational rather than continuous basis.

Only a subset of the study units will be studied in detail at a given time. For each study unit, 3- to 5-year periods of intensive data collection and analysis will be alternated with longer periods during which the assessment activities will be less intensive.

The program will focus on water-quality conditions that are prevalent or large in scale and persistent in time.

The program will emphasize regional water-quality degradation, such as occurs from nonpoint sources of pollution or from many point sources. The program will not diminish the need for smaller scale studies and monitoring presently designed and conducted by State, Federal, and local agencies to meet their individual needs. The program, however, will provide a larger scale framework for conducting many of these activities and a knowledge about regional and national water-quality conditions that cannot be acquired from individual, smaller scale programs and studies.

Chemical measurements will focus on a set of target variables.

A national list of target variables will consist of a common set of physical measurements, inorganic constituents, and organic compounds that are included in sample analyses for all study units. These will enable the assessment to provide interpretations of water quality at the national scale. Additional target variables to supplement the national list will be selected for each study unit by the project team.

Biological measurements will be used for several purposes in the assessment.

Biological measurements will be used in the assessment to assist in (1) determining the occurrence and distribution of waters contaminated by fecal material, (2) determining the occurrence and distribution of potentially toxic substances, (3) assessing the relations between the physical and the chemical characteristics of streams and the functional or structural aspects of the biological community, and (4) defining and quantifying biological processes that affect the physical and the chemical aspects of water quality.

The program will make use of available water-quality data to supplement the field studies.

Considerable water-quality data have been collected by various agencies for various purposes. One of the first activities of each project will be to compile, screen, and interpret available data to (1) provide an initial description of water-quality conditions, (2) develop hypotheses about major factors that influence water quality, and (3) define data needs.

Design of the Surface-Water Investigations

Three major types of sampling activities will be undertaken in a surface-water study unit.

- Fixed-station sampling,
- Synoptic sampling, and
- Studies of selected stream reaches.

A network of fixed stations will be sampled for a wide array of water-quality constituents each month and during high streamflows.

The purposes of fixed-station sampling will be to (1) describe the temporal variation and the frequency of occurrence of selected water-quality constituents, (2) estimate loads past stations and attempt mass balances of selected target constituents between stations, and (3) define long-term trends in water quality. Sites selected for fixed-station sampling will include locations (1) near the mouths of major tributaries and selected points on the main stem that account for a large portion of the total basin runoff, (2) upstream and downstream from reservoirs, urban areas, and other areas that significantly affect water quality, (3) on streams draining large areas that have relatively uniform land use, and (4) near major public water-supply intakes or other important water uses.

Synoptic sampling will be used primarily to provide a finer degree of spatial resolution to the descriptions of certain kinds of water-quality conditions than will be attainable from the fixed-station sampling network.

Synoptic surveys are generally accomplished by making single water-quality measurements representing a specific hydrologic condition at many sites in a study area during a brief period of time. The number, the timing, and the design of the surveys will depend on the specific objectives of the survey and the factors affecting the water-quality constituents of interest. These surveys will typically be done in stages in a study unit, building on the descriptions of water-quality conditions in a hierarchical manner.

Studies of selected reaches will be done to address certain more narrowly focused water-quality issues that are identified during the course of the surface-water study-unit investigations.

The primary concern of these studies will be to provide an improved understanding of the sources, distribution, and fate of particular constituents in the selected stream reaches. Results from mathematical models applied during some of these studies will be used to test understanding of cause-and-effect relations and to evaluate the outcome of alternative management strategies. Model results could be tested in later study cycles to determine if conditions have changed and if these changes correspond to prior understanding.

Design of the Ground-Water Investigations

Three major types of sampling activities will be undertaken in a ground-water study unit.

- Regional sampling,
- Targeted sampling, and
- Long-term sampling.

Regional sampling will be conducted for a wide array of water-quality constituents.

The purposes of the regional sampling will be to provide descriptive statistics on the occurrence and concentrations of the target variables for major hydrogeologic settings and to form an initial basis for describing the geographic distribution of water-quality conditions within the study unit. Sampling locations for regional sampling will be selected so as to be spatially distributed, areally and with depth, throughout each major hydrogeologic setting and to be unbiased with respect to known or suspected local problem areas.

Targeted sampling of known or suspected water-quality problem areas will be used to examine the spatial distribution of selected water-quality constituents.

The targeted sampling designs will focus on broadly defined groups of water-quality constituents, such as agricultural chemicals, contaminants associated with urban and suburban areas, and naturally occurring trace elements. The approaches that will be used include search-oriented sampling within particular areas of concern, sampling to test particular statistical hypotheses about the regional distribution of contaminants, and sampling along local scale transects of wells. The approaches will be tailored to the major hydrogeologic and land-use factors that affect ground-water quality in different situations. Similar targeted sampling designs will be applied to selected study units to allow multistudy-unit comparisons.

Long-term trends in ground-water quality will be examined by use of data from a network of wells that are selected in each study unit at the conclusion of the first high-activity period.

Selection criteria will be established to assure a distribution of wells for long-term sampling that represent ground water of different ages and hydrogeologic settings. Wells screened in the upper part of water-table aquifers may be particularly useful for early detection of contamination from surface sources and for relation of observed trends to changes in land-use practices.

Information Provided by the Assessment Program

The program will provide unique regional and national scale information concerning the Nation's water quality.

The intent is for the Geological Survey to provide information through the NAWQA Program to those who set policy, write regulations, establish priorities, or manage water resources. Information on the status, the trends, and the causes of water-quality conditions across the country should be particularly useful to other agencies who are involved in (1) identifying key substances for possible regulation and for which research is needed on toxicity, human exposure, and drinking-water treatability, (2) allocating budgetary resources among competing types of water-quality problems, (3) determining whether desired goals for water-quality improvement are being met, (4) designing monitoring programs in different parts of the country (in terms of the constituents analyzed, sampling locations, sampling frequency, and timing of sampling), (5) targeting regulations for selected water-quality constituents to particular geographic regions or hydrologic settings, (6) determining the relative effects on water quality of various types of point and nonpoint sources, (7) identifying aquifers requiring different types and degrees of water-quality protection, and (8) evaluating management practices in terms of their large-scale effects on the water quality of river basins and aquifer systems.

Statistical descriptions of water-quality conditions and their changes with time will be provided for many different types of constituents.

These constituents include pesticides and other synthetic organic compounds, nutrients, certain metals and trace elements, and sediment. The statistical descriptions will consist of the following types of information:

- Frequencies of occurrence, frequencies of exceedance of established water-quality standards, and concentrations of water-quality constituents at key streamflow stations and in the ground water of major hydrogeologic settings,
- Transport of selected constituents past key streamflow stations, and
- Long-term trends in water-quality constituents at key streamflow stations and in the ground water of major hydrogeologic settings.

Information on the geographic distribution of various contaminants will be provided for major river basins and aquifer systems of the United States.

The information will be used to identify areas that have water-quality problems, as well as areas that have generally high-quality water. This information will be useful to Federal, State, and local managers in the allocation of resources for water-quality management and protection. Depending on the spatial distribution of the constituents of interest, the geographic descriptions will take the following forms:

- Maps that show locations of sampling sites and results of water-quality analyses,
- Descriptions and maps that distinguish reaches or zones that differ in their average values or in their frequencies of exceedance of given concentrations of water-quality constituents,
- Descriptions and maps of the locations of water-quality anomalies that cover large areas (tens of river-miles or tens of square miles in an aquifer system), and
- Descriptions of ground-water-quality changes that occur with depth in different hydrogeologic settings.

Information on key factors that affect water quality will be provided to relate the occurrence and the concentrations of the target constituents to different hydrologic environments, land uses, and human activities.

An understanding of these relations will provide a basis for predicting where and when certain types of contamination problems are likely to occur and for determining the large-scale effects of alternative water-quality management strategies. This information will include the following:

- Statistical models of expected levels of contamination or probabilities of exceeding certain levels that are based on readily measured variables related to soils, hydrogeology, land use, population, streamflow, and climate,
- Explanations of the causes of observed geographic and temporal variations in water quality,
- Information on the portions of surface-water constituent loads that are derived from various point and non-point sources, and
- Descriptions of factors that affect the vulnerability of aquifer systems to contamination.

INTRODUCTION

Background

The protection and the enhancement of the quality of the Nation's ground- and surface-water resources are high-priority concerns of the public and of government at its various levels. Over the past two decades, several large water-quality spending and regulatory programs have been enacted into law. In addition, many major decisions that will determine the directions of water-quality management for future decades have yet to be made. Many of these decisions will be made in areas of great scientific uncertainty; for example, many will relate to controlling nonpoint sources of contamination, which commonly are much more complex to control than the point sources of contamination addressed by past regulations.

Nationally consistent information on the status and the trends of the Nation's water quality is needed to help determine the degree to which past investments in water-quality management are working and to provide a base of knowledge for evaluating future decisions. To meet this need, the Congress appropriated funds in 1986 for the U.S. Geological Survey to test and refine concepts for a National Water-Quality Assessment (NAWQA) Program. The long-term goals of the program would be to:

1. Provide a nationally consistent description of current water-quality conditions for a large part of the Nation's water resources,
2. Define long-term trends (or lack of trends) in water quality, and
3. Identify, describe, and explain, as possible, the major factors that affect observed water-quality conditions and trends.

This information, which will be obtained on a continuing basis, would be made available to water managers, policy makers, and the public to provide an improved scientific basis for evaluating the effectiveness of water-quality management programs and for predicting the likely effects of contemplated changes in land- and water-management practices.

At present, the program is in a pilot phase that is to last about 4 years. In 1990, a committee of the National Academy of Sciences is scheduled to complete an evaluation of the design and potential utility of the program. A decision about proceeding to full-scale implementation will be made upon completion of this evaluation.

Purpose and Scope

The purpose of this report is to describe the conceptual design of the NAWQA Program. The design concepts represent a set of views which were originally developed by a committee of Geological Survey scientists (Rubin, 1987) that subsequently were refined and revised in response to comments by other Geological Survey scientists, officials of a large number of Federal and State water agencies, the Department of the Interior Water Policy Working Group, and the Water Science and Technology Board of the National Research Council (National Research Council, 1985, 1987).

The emphasis in this report is on the principles that should govern the long-term national acquisition and analysis of water-quality data for assessment purposes. Some current activities of the pilot NAWQA Program are described to illustrate these concepts.

The approaches of the program will continue to evolve as experience is gained, measurement and analysis techniques advance, and water-quality issues change. In this regard, although considerable use of the word "will" is used in this report, it should be interpreted within the context of the pilot nature of the present effort and the requirement for an independent evaluation before proceeding to a full-scale program.

Acknowledgments

The authors of this report have drawn heavily on the assistance, suggestions, and contributions of a large group of people within and outside of the U.S. Geological Survey.

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Members of other Federal, State, and local agencies participating on the National Coordinating Work Group for the pilot NAWQA Program have provided numerous suggestions to help ensure that the information produced by

the program will have maximum utility to the public and water-management agencies. Current (1988) members of the National Coordinating Work Group are Lee Barclay, U.S. Fish and Wildlife Service; Carroll Curtis, Council on Environmental Quality; Norbert Dee, U.S. Environmental Protection Agency; Lewis Dodgion, Nevada Department of Conservation and Natural Resources; Judith A. Duncan, Oklahoma State Department of Health; Earl E. Eiker, U.S. Army Corps of Engineers; Ival V. Goslin, engineering consultant; Donald C. Haney, Kentucky Geological Survey; Dirk C. Hofman, Interstate Conference on Water Policy; U. Gale Hutton, Association of State and Interstate Water Pollution Control Administrators; Leon Hyatt, U.S. Bureau of Reclamation; Carol Jolly, Washington Department of Ecology; Gyula Kovach, Kansas Department of Health and Environment; James N. Krider, Soil Conservation Service; Richard Lanyon, Metropolitan Sanitary District of Greater Chicago; Frederick D. Leutner, U.S. Environmental Protection Agency; Robert E. Raschke, National Association of Conservation Districts; Gray F. Reynolds, U.S. Forest Service; Andrew Robertson, National Oceanic and Atmospheric Administration; Kenneth D. Schmidt, American Water Resources Association; Russell H. Susag, Chemical Manufacturers Association; Peter S. Tinsley, Maryland Office of Environmental Programs; and Hugo F. Thomas, Association of American State Geologists.

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Finally, the seven project teams and regional coordinators for the pilot NAWQA Program have contributed immeasurably to the concepts in this report through exchange of ideas on the feasibility of various aspects of the design and through their implementation of concepts in the pilot projects. These contributors include Stephen F. Blanchard, Robert C. Bubeck, Scott C. Christenson, Donald A. Goolsby, John S. McLean, Stuart W. McKenzie, W. David Nichols, Gary L. Pederson, Robert J. Shedlock, James L. Smoot, John K. Stamer, Lindsay A. Swain, Wayne E. Webb, and Alan H. Welch.

GENERAL TYPES OF INFORMATION PROVIDED BY AN ASSESSMENT PROGRAM

The NAWQA Program is designed to provide statistical descriptions of water-quality conditions and their changes with time, descriptions of the geographic distribution of water quality across the Nation and within particular regions, and explanations of the observed water-quality conditions and trends (see fig. 1).

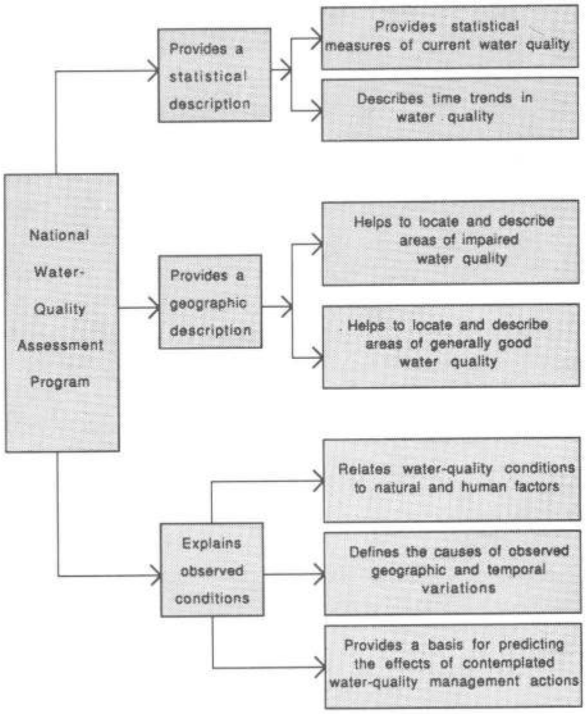

Figure 1. General types of information provided by the National Water-Quality Assessment Program.

Statistical descriptions will be provided on a continuing basis for many different types of contaminants, including pesticides and other synthetic organic compounds, nutrients, certain metals and trace elements, and sediment. The statistical descriptions are needed to obtain a perspective on the frequency of occurrence and concentrations of these water-quality constituents in the Nation's surface and ground water. Statistical data to describe current conditions are particularly sparse for many synthetic organic compounds of concern, while consistent long-term water-quality data are lacking both for inorganic and organic constituents.

Information on the geographic distribution of various contaminants will be used to help identify locations of impaired water quality and the nature and the severity of the problems, as well as to help identify and describe those parts of the water resource that are generally problem free. For ground water, the results will include descriptions of areal variations in water quality and of water-quality changes that occur with depth in different hydrogeologic environments. The consistently derived information on the geographic distribution of water quality across the Nation and within particular regions will be helpful to various agencies in allocating resources for water-quality management and protection; for example, knowledge about regional differences in the occurrence of particular chemicals could lead to reductions in the list of substances that require monitoring in specific regions or in the frequency of their analysis at monitoring sites.

Finally, statistical relations and knowledge of water-quality processes will be used to relate the occurrence and the concentrations of various chemicals to different hydrologic environments, land uses, and human activities. An understanding of these relations is important for several reasons. First, they provide a basis for predicting where and when certain types of contamination problems are likely to occur; for example, statistical models would be used to calculate expected levels of contamination or the probabilities of exceeding certain concentrations, based on readily measured variables related to soils, hydrogeology, land use, population, streamflow, and climate. Second, understanding of causal relations will help Federal, State, and local water-management officials predict the consequences of various policy and regulatory options; for example, an understanding of major factors affecting water quality would provide a basis for estimating the different effects of an activity in different geographic settings and, therefore, a starting point for targeted regulation.

WATER-QUALITY ACTIVITIES OF THE U.S. GEOLOGICAL SURVEY AND THEIR RELATION TO WATER-QUALITY ASSESSMENT

The U.S. Geological Survey has collected and interpreted data on water quality for more than 100 years. A brief review of some of these activities is useful as background for discussion of the plans for the NAWQA Program. Two points should be considered in this review. First, virtually every aspect of the NAWQA Program plan has some precedent in other Geological Survey programs. The NAWQA Program is an evolutionary step in organizational concepts, goals, and level of effort rather than the start of a totally new set of activities. Second, the NAWQA Program is not intended to be the total water-quality program of the agency. Many existing Geological Survey water-quality projects serve other purposes and provide information at different levels of detail than would the NAWQA Program; moreover, many of these activities provide a base on which the NAWQA Program would build.

Geological Survey involvement in water-quality investigations dates back to the latter part of the 19th century. Initial water-quality investigations were directed toward the suitability of water for domestic consumption, irrigation, and industrial use (Durum, 1978). The first major Geological Survey report addressing water quality was on the use of sewage for irrigation of crops (Rafter, 1897). Results of the first regional assessment of water-quality conditions were published in 1909 for the Eastern United States (Dole, 1909).

Since these early investigations, the Geological Survey has conducted studies directed at a wide array of water-quality issues. Detailed process-oriented and larger scale studies of prominant water-quality issues have been conducted. These studies cover a range of disciplines from hydrology to interdisciplinary biogeochemical studies. Examples of issues addressed include nutrient enrichment (Mattraw and Elder, 1984), dissolved oxygen depletion in rivers (Rickert and Hines, 1978), contamination of streambed sediments by trace elements (Rickert and others, 1977), acid rain (Turk, 1983; Smith and Alexander, 1983), the transport of radionuclides in rivers (Hubbell and Glenn, 1973; Pickering, 1969), and the contamination of aquifers and rivers by potentially toxic, anthropogenic organic compounds (Schroeder and Barnes, 1983a, b; LeBlanc, 1984; Mattraw and Franks, 1986).

Presently, the Geological Survey's water-quality programs are supported by three sources of funds—the Federal-State Cooperative Program, other Federal agencies, and the Geological Survey Federal programs. These programs are described below.

The Federal-State Cooperative Program has existed since 1895 and involves agreements wherein State and local agencies provide at least one-half of the funding for investigations by the Geological Survey on regional and local water-resources issues. The Geological Survey presently has such agreements with about 950 agencies (Gilbert and Mann, 1988). Many of the resulting investigations involve assessing water-quality conditions in a particular river reach or part of an aquifer. These studies include extensive data acquisition (forming the core of some State's ambient monitoring programs), analysis and interpretation of existing data, and modeling of hydrologic systems to understand the probable consequences of various management actions. In a number of States, the Cooperative Program has provided extensive long-term data bases that are extremely valuable to regional and national assessment efforts, such as the NAWQA Program. The Cooperative Program has been instrumental in keeping the Geological Survey abreast of the emerging water problems and the needs and interests of water-management officials. Close involvement with State and local governments has helped identify needs that have guided many of the research efforts in the Geological Survey water programs.

The Geological Survey does a significant amount of water-quality data acquisition, interpretation, and research at the request of other Federal agencies; for example, the Geological Survey is assessing the long-term changes in the salinity of the Colorado River and its tributaries as part of the U.S. Bureau of Reclamation's salinity-control program (Liebermann and others, in press). Additional activities on behalf of other Federal agencies include assessing the effects of irrigation drainage on selected National Wildlife Refuges in cooperation with the U.S. Bureau of Reclamation and the U.S. Fish and Wildlife Service, evaluation of ground-water quality near toxic waste-disposal sites for the Department of Defense and the U.S. Environmental Protection Agency (EPA); and studies of the local and regional water resources in conjunction with present or planned nuclear waste repositories for the Department of Energy.

As part of its Federal program (activities funded entirely by direct appropriations from the Congress), the Geological Survey operates two national networks to measure surface-water quality. The first of these is the Hydrologic Benchmark Network, which consists of 53 stations in relatively small, pristine watersheds. The Hydrologic Benchmark Network provides a baseline of "near natural" water quality and an understanding of the inherent variability of water quality where humans have little influence on the water resources. This network proved useful, for example, in detecting the effects of atmospheric deposition on water quality, including long-term trends in sulfate concentrations in streams in relation to regional changes in sulfur dioxide emissions (Smith and Alexander, 1983).

The second network is the National Stream Quality Accounting Network (NASQAN), which presently consists of 423 stations that collectively measure outflows from most of the surface-water hydrologic accounting units (Seaber and others, 1986) in the country. NASQAN data have been used to detect trends and to estimate transport rates of more than 30 different constituents and have been compared to data on climate, geology, population, agriculture, industrial activities, and point-source effluents. These comparisons (Peters, 1984; Smith and others, 1987) have shown a number of significant relations between water quality and human activities. Examples include relations between lead in streams and the use of leaded gasoline, nitrate in streams and atmospheric emissions of nitrous and nitric oxides, and dissolved solids in streams and climate, geology, and human population. NASQAN data also provide extensive information on the fluxes of nutrients and metals into the Nation's estuaries and reservoirs.

In addition to the two national networks, the Federal Program of the Geological Survey supports studies of acid rain and toxic substances hydrology. The acid rain work includes deposition monitoring that enables the detection of long-term trends in acid rain (Peters and others, 1982; Schertz and Hirsch, 1986) and evaluation of the effects of acid deposition on aquatic systems (Kramer and others, 1986, p. 231–299). The Geological Survey coordinates and operates part of the Federal National Trends Network, which collects and analyzes samples of wet deposition on a weekly basis nationwide (Robertson and Wilson, 1985).

The Toxic Substances Hydrology Program (Franks, 1987; Ragone, 1987; Mallard, 1988), which was started in 1982, provides increased understanding of the occurrence, movement, and fate of hazardous substances in the Nation's ground and surface waters and sediments. The program focus is on the development of new methods for sampling and analysis of trace elements and organic compounds; research on the chemical, physical, and biological processes that govern the behavior of these substances in surface and ground water; and development of methods to define the relation of water quality to land use and hydrogeology. Much of the work occurs through interdisciplinary field investigations of highly contaminated aquifers or streams; thus, the results are directly useful for developing restoration plans for existing contaminated sites and for designing improved waste-disposal practices.

The Regional Aquifer-Systems Analysis (RASA) Program (Sun, 1986) provides an understanding of regional aquifer and flow characteristics of fundamental importance to large-scale water-quality studies, such as the NAWQA Program. Many of the studies also provide regional descriptions of the distribution of major ionic species.

The National Research Program of the Water Resources Division is engaged in studies of fundamental hydrogeologic processes and has developed many of the methodologies that the NAWQA Program will use. Some of the various water-quality-related research activities for which the National Research Program are recognized internationally include those related to the chemistry and geochemistry of natural waters (Hem, 1985; Thurman, 1985; Back and Hanshaw, 1970), the development of widely used geochemical computer models (Truesdall and Jones, 1974; Plummer and others, 1983), the development of simulation models for solute transport in ground water (Konikow and Bredehoeft, 1978; Voss, 1984) and in surface water (Jobson, 1985), hydrology and chemistry of the unsaturated zone (Weeks and others, 1982; Winograd, 1981), the study of metal bioavailability and partitioning in sediments (Luoma, 1983), the hydrogeochemistry at ground-water contamination sites (Baedecker and Apgar, 1984), and the transport and role of sediment (Meade, 1982).

Finally, in addition to the water-quality programs described above, the Geologic and the National Mapping Divisions of the Geological Survey will contribute geologic, geochemical, and mapping expertise. These Divisions are involved in the pilot program in studies of the distribution of naturally occurring trace elements and in helping to meet the mapping needs.

The NAWQA Program will differ from past and present programs in the emphasis placed on various approaches and in its overall structure. When fully implemented, it will not replace existing programs because there will continue to be significant need for programs focused on different temporal and spatial scales. However, the NAWQA Program will lead to modifications of

Geological Survey water-quality programs; for example, data collected at NASQAN sites in NAWQA study units will be coordinated with other data collected as part of the NAWQA projects. In addition, the NAWQA Program will identify local problem areas that would be candidates for investigation under other programs of the Geological Survey, such as the Federal-State Cooperative Program and the National Research Program.

GENERAL CONCEPTS OF THE NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

Strategic Selections

The challenge of organizing an effort to acquire and interpret data, and to assess the Nation's water quality is formidable. Difficulties result from the large area involved, the high degree of spatial and temporal variability of water quality, the large number of water-quality constituents of interest, and the high cost of field work and laboratory analyses (especially for trace organic chemicals).

Several strategic selections have been made in designing the proposed program to make the assessment tractable. The first is the spatial and temporal scales at which the program will focus. The second is the selection of that part of the total national resource to be examined and the manner in which this examination will be organized, geographically and with time. The third choice is selection of the chemical measurements, and the fourth is selection of biological measurements.

Selection of Scales

Water-quality data are collected to address problems at a wide range of scales. It is useful to consider three spatial scales and three temporal scales and then to identify which of them are the focus of the assessment program.

Spatial Scales

Water-quality programs provide information at different spatial scales. For Geological Survey water-quality programs, three of these scales are shown in table 1.

A local scale program attempts to describe the pattern of water-quality characteristics within small areas. Often, these areas are associated with known point sources of contamination. In surface water, an example is the study of a

Table 1. *Primary spatial and temporal scales of U.S. Geological Survey water-quality programs*

Temporal scale	Spatial scale		
	Local	Regional	National
Short term	Federal-State Cooperative Program. Urban hydrology. Some research on rivers.		
Multiyear	Federal-State Cooperative Program. Toxic Substances Hydrology Program. Acid-rain studies.	Federal-State Cooperative Program. Toxic Substances Hydrology Program (regional studies). Acid-rain studies. Regional Aquifer-Systems Analysis (geochemical studies).	
Decade(s)	Acid-rain studies. Nuclear hydrology.	Federal-State Cooperative Program (water-quality networks).	National Stream Quality Accounting Network (NASQAN). Hydrologic Benchmark Network. National Trends Network (acid rain).

dissolved oxygen sag (occurring over a stream reach of perhaps several miles). In ground water, an example is the study of a contaminant plume from a hazardous-waste-disposal site (perhaps several acres in area). Some local scale studies also may be conducted in conjunction with a regional scale study to examine representative river reaches or parts of aquifers in more detail.

A regional scale program attempts to characterize water-quality conditions within areas of hundreds to tens of thousands of square miles. Depending on the spatial distribution of the variable of interest, the descriptions resulting from a regional scale study might take several forms—areawide average levels of water-quality constituents, maps of the locations of water-quality anomalies that cover large areas (tens of river miles, or tens of square miles in an aquifer system), maps that distinguish reaches or zones that differ in their average values (or frequencies of exceedance of given levels) of one or more water-quality constituents, or statements that relate geologic, soils, land-use, and other information to water-quality characteristics. A regional scale program will identify local scale anomalies that are prevalent or that occur with high frequency; however, it should not be expected to find or characterize all or even many of these local scale features.

A national scale study is concerned with characterizing water-quality conditions over much of the Nation; for example, the fluxes in nutrients, metals, and other inorganic and organic constituents transported to estuaries, oceans, and large lakes or from one region to another and the trends in the fluxes are of great concern. There are also national scale concerns that involve developing clearer inferences about the primary effects of human activities, climate, geology, and soils on the status and the trends of water quality by analyzing consistent data from a wide variety of locations.

Many agencies at various levels of government collect water-quality data to address questions relevant to the local scale. The data are collected for a host of purposes that include research on specific water-quality issues and many regulatory, monitoring, and remediation purposes. Less attention is given to collection of data at the regional scale, and many of these efforts tend to focus at the level of counties or small drainage basins. At the national scale, water-quality data generally have been collected through national networks of fixed-location monitoring stations for surface water and through selected one-time sampling surveys for ground water. At present in the United States, no program exists to integrate information from the regional scale to the national scale to provide a consistent description of water quality across the Nation and insight on the major factors that control water quality in different regions. This integrated information is the focus of the NAWQA Program.

Temporal Scales

Water-quality programs also provide information at different temporal scales. Three scales are included in table 1; the shortest of these, referred to as the short-term scale, relates to phenomena that occur at time scales of minutes to a few days, primarily in surface water. The purposes of short-term scale data collection include the prediction or documentation of naturally influenced events, such as a fish kill caused by natural low-flow conditions in a river with a high oxygen demand, and of human-caused events resulting from toxic-waste spills, sudden industrial accidents, and treatment plant upsets or shutdowns.

The second temporal scale is the multiyear scale. It involves collecting sufficient data to make inferences about probability distributions of concentrations and surface-water transport rates and probabilities of exceedance of given levels of water-quality constituents. Multiyear scale assessments require enough consistent data so that one can separate out seasonal variation, annual climatic variation, and human influences. If the repeated occurrence of transient phenomena is significant to the usefulness of the resource, then a description of the magnitude and frequency of these conditions is an important part of these multiyear descriptions.

The third temporal scale for water-quality studies is the decadal scale. Such studies focus on long-term trends in water quality that arise due to changes in population, land use, technology, waste-disposal practices, water-resource development, or climate. These longer term studies also focus on the fate of hazardous materials that are intentionally or inadvertently stored in bed sediments, flood plains, and aquifers. Such studies may be required to ascertain the rates at which substances migrate and transform in these types of systems.

As with spatial scales, the lower end of the range of temporal scales—the short-term scale—is addressed by a large number of water-quality programs, many of them at the State and the local government level. Fewer programs focus at the longer time scales, particularly at the scale of a decade or longer.

Scales of Focus for Water-Quality Assessment

The scales of focus for the NAWQA Program are the regional and national spatial scales and the multiyear and decadal temporal scales. Although the local and the short-term scales are not the focus of the assessment, the program will alert others of the discovery of previously unknown local scale problems or identification of short-term threats to human health or ecosystems.

The multidecade or perennial nature of the NAWQA Program is required to discover unexpected changes in water quality and to reveal the presence of important, slowly evolving trends. A perennial study also will allow a progressive understanding of water quality in specific study areas.

The goal of documenting long-term trends in water quality creates some fairly stringent demands on the way that data are collected; the NAWQA design is influenced heavily by these demands. First, field-sampling techniques and laboratory procedures and their associated analytical precision and bias will be documented throughout the program. Thus, knowledge about changes in procedures can be incorporated into the analysis of water-quality changes. Second, the criteria for selection of sampling sites will be documented and consistent among locations. Third, long-term sampling networks will be designed so that each sampling location can be placed in its hydrologic and land-use context to achieve an appropriate mixture of sampling locations.

The scales of focus in the assessment program affect the issues that will be addressed and vice versa. Examples of issues addressed by the surface-water part of the program include effects of large urban, agricultural, or mining areas on surface-water quality. The program will allow these areal sources to be contrasted in magnitude with the estimated point sources of contamination. The surface-water program also will provide information about the long-term delivery of contaminants from geologic sources or from past discharges of pollutants.

Examples of issues addressed by the ground-water part of the program include those due to widespread application of materials at the surface (for example, pesticides and fertilizers) and from aggregations of a large number of small sources at or near the land surface (for example, household chemicals and wastes resulting from a large number of septic tanks or leaky sewers). Additional issues include the regional effects of irrigation on the movement of naturally occurring trace elements, problems related to surface- and ground-water interaction, prevalent problems resulting from cross contamination (movement of water between aquifers), and natural geologically related water-quality problems.

Selection of Study Areas

The program is not intended to consider all parts of the Nation's water resources. The target will be freshwater rivers and aquifers; waters so saline as to have little potential for consumptive use will not be examined. To achieve a manageable size, the program will not assess saline estuaries or the Great Lakes, although it will measure the quantity and the quality of the water flowing into many of these water bodies.

Study-Unit Design

One design considered to accomplish the assessment goals was a national statistical design. This approach would lead to random sampling, stratified random sampling, or clustered stratified random sampling. The selection of sampling sites would be directed from a central office. The role of local personnel would be to establish the sampling sites and to collect the samples. The data analysis would occur at the national level. This design has not been selected for reasons that will be discussed.

An alternative design, and the one selected, will be to investigate a large set of hydrologic systems by using nationally consistent methods; the results will be aggregated to provide large regional and national overviews. These *study units* will include river basins where the focus is on surface-water quality and aquifer systems where the focus is on ground-water quality. The relative emphasis on surface- and ground-water quality in each study unit will depend on the degree of interconnection between the two resources. The areas of the study units will range from a few thousand to several tens of thousands of square miles.

The results will be linked together to form a national assessment in the following ways:

1. A prescribed set of study approaches and protocols for sample collection, sample handling, laboratory analysis, and quality assurance will be followed,
2. The data will be collected and interpreted on a nationally consistent set of water-quality constituents,
3. Consistent records of ancillary information will be recorded on streamflow and basin characteristics, well and aquifer characteristics, and land use and other measures of human activity,
4. Written reports will contain similar information for each study unit, and
5. The data will be stored in national data files.

Because the program is an assessment program (as opposed to a monitoring program) and because a feasible design needed to be achieved, the major activities in these study units will be periodic rather than continuous. For surface water, the data-collection activities will occur in 3-year segments, followed by 1 year for completing data interpretation and report preparation. Between the 3-year high-activity periods, there will be a 6-year period during which only a relatively small amount of data collection and analysis will occur. The 9-year cycle will be repeated, and a new 3-year data set will become available to compare with past 3-year data sets. Under this scheme, one-third of the surface-water study units will be in an active data-collection mode at any one time.

Because ground-water quality changes more slowly, the program cycle will be longer than the 9 years used in surface water and will be of different lengths in different study units. The high-activity periods will consist of 3 to 5 years of data collection and interpretation followed by a year for final interpretation and report writing. Between these active phases, there will be an ongoing lower level data-collection and analysis effort.

The study-unit design has several key advantages over a national statistical design. These include the following:

1. *Major river basins and aquifer systems have unique characteristics and are a natural focus for individual regional scale investigations that are the building blocks for a national assessment.* Important regional differences in climate, geology, land use, and other major factors can lead to large regional differences in water quality among the major river basins and aquifer systems of the country. Information on the Nation's water quality will be more meaningful if interpreted and presented in the context of these regional variations. In addition, comprehensive studies of the water quality of individual river basins and aquifer systems can contribute valuable information that assists in understanding and managing these water resources. A key feature is the ability to conduct studies across State boundaries. Much of the water, sediment, and chemicals in a river basin, for example, can originate in adjacent States; thus, it can be very difficult for an individual State to develop a comprehensive understanding of water-quality problems in the basin and their solutions. Likewise, it is often more efficient to conduct large regional ground-water investigations based on natural hydrogeologic boundaries rather than State boundaries.
2. *The benefits to having persons familiar with individual study areas do most of the data interpretation are considerable.* The objectives for the NAWQA Program include providing general statistical measures of water quality and information on the location, nature, and causes of principal water-quality problem areas. The second type of information is most effectively developed from region-specific knowledge of hydrologists familiar with a particular river basin or aquifer system. The overall area to be described is too large and diverse, and the problems are too complex to be adequately addressed from a central office. A major advantage of the structure of the Geological Survey is that the bulk of the work in water resources is conducted by hydrologists in offices located in the 50 States. Most of the work within the NAWQA Program will be done by these personnel who are assigned the task of describing water quality in the selected study unit.
3. *The study-unit design facilitates an approach that can adapt to, and build effectively on, increasing knowledge.* A characteristic of virtually all sampling programs is that considerable knowledge is attained about a more efficient design after the sampling is completed and the results are analyzed. In recognition of this characteristic, the study-unit design relies heavily on the need for an iterative approach that adapts to improved knowledge over time. Effective feedback between sampling design and data interpretation is made possible by having close interactions among those who select sampling sites, those who collect the data, and those who interpret the data.
4. *Conducting the investigations at the regional scale provides an opportunity for more effective use of existing data as part of the assessment.* It is very difficult to effectively use existing water-quality data within the framework of a national statistical design. There are two reasons for this. First, a national statistical design would place rigid requirements on the selection of sampling sites. Second, before any use, existing data should be screened for their suitability to address the issues under study. It is difficult to perform this function at a national scale. The problem is much more tractable at the scale of river basins and aquifer systems, through direct communication with the State and local agencies and the local offices of the Federal agencies that collected many of the data. At this scale, there is also the opportunity to coordinate activities to mutual benefit between a national assessment program and ongoing State and local monitoring. The Geological Survey streamflow-gaging program is an example. The Geological Survey mission requires long-term collection and analysis of these data, whereas other agencies have short-term uses related to flood warning and real-time management. The Geological Survey and other agencies cooperate on the stream-gaging program to achieve both purposes.

Study Units Selected for the Pilot Program

Seven project areas, which represent a diversity of hydrologic environments and water-quality conditions, were selected for the pilot program to test and refine the assessment concepts. The seven pilot project areas, shown in figure 2, include four that focus primarily on surface water and three that focus primarily on ground water. The surface-water pilot project areas are the Yakima River basin in Washington (McKenzie and Rinella, 1987), the lower Kansas River basin in Kansas and Nebraska (Stamer and others, 1987), the Upper Illinois River basin in Illinois, Indiana, and Wisconsin (Mades, 1987), and the Kentucky River basin in Kentucky (White and others, 1987). The ground-water pilot project areas are the Carson basin in Nevada and California (Welch and Plume, 1987), the Central Oklahoma aquifer in Oklahoma (Christenson and Parkhurst, 1987), and the Delmarva Peninsula in Delaware, Maryland, and Virginia (Bachman and others, 1987). Table 2 describes the important water-quality issues, the major categories of climate and land use, and other characteristics for each project area.

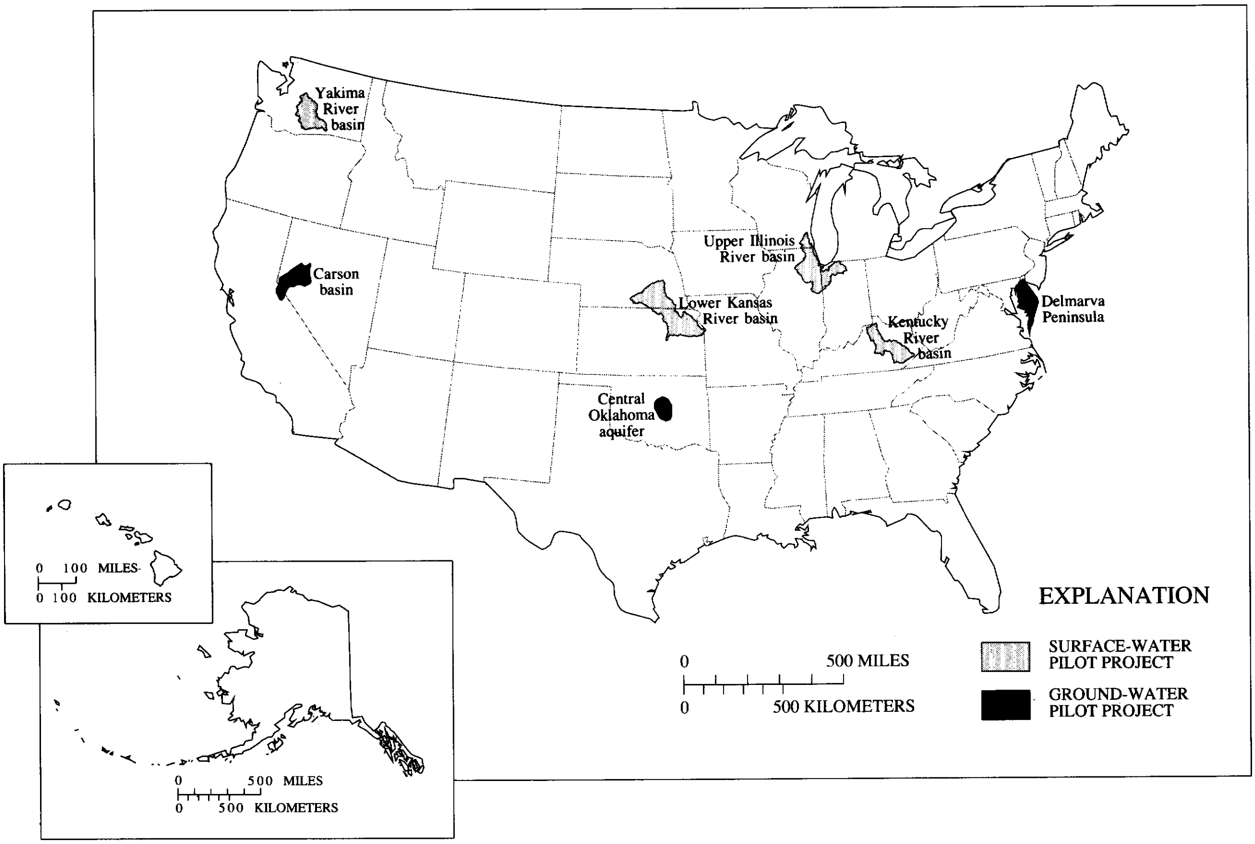

Figure 2. Locations of the pilot projects of the National Water-Quality Assessment Program.

Preliminary Selection of Study Units for a Full-Scale Program

A set of 123 study units have been selected as a preliminary set that could constitute a full-scale NAWQA Program. These study units were selected so that they would be well dispersed around the Nation and would represent a large percentage of the Nation's freshwater use. The surface-water study units account, in aggregate, for about 80 percent of the fresh surface-water withdrawals (excluding thermal and hydropower uses) in the Nation and about 80 percent of the population served by public surface-water supplies. The ground-water study units account, in aggregate, for about 80 percent of the fresh ground-water withdrawals in the Nation and about 80 percent of the population served by public ground-water supplies.

The first step in the selection process was to select *candidate* study units (CSU's). A set of 200 surface-water CSU's was selected primarily on the basis of hydrologic subregions (Seaber and others, 1986). In some cases; where a given subregion is too large, individual accounting units or groups of accounting units were aggregated to form a set of smaller CSU's. In other cases, subregions were joined together or an accounting unit from one subregion was added to an adjoining subregion. Several factors were considered in selecting the surface-water CSU's. An attempt was made to select CSU's that had similar area (although study units in arid regions typically are larger than those in humid regions). In some cases, modifications were made so that all sources of water to a major lake or estuary were included in the same study unit. Finally, where possible, an attempt was made to select CSU's that had environmental and land-use characteristics that are relatively homogeneous throughout the study unit.

A set of 116 ground-water CSU's also were identified. The boundaries of these units are hydrogeologic boundaries, some of which coincide with those of a surface-water CSU. In many cases, the boundaries of the ground-water study units are less obvious than those for surface water, particularly where several overlying aquifers are involved. Thus, many of these boundaries will be further defined as part of the planning for a full-scale program.

A modified linear programming model (Fox and Scudder, 1986), which is a mathematical optimization technique, was used as a screening tool in the selection process (T. A. Cohn and K. J. Lanfear, U.S. Geological Survey, written commun., 1988). The objective function of the linear program was to minimize the number of study units that were selected subject to a set of constraints. The constraints included the above-mentioned 80-percent requirements on

Table 2. *Characteristics of the pilot projects of the National Water-Quality Assessment Program*

Study unit name, location, and size	Climate and land use	Water-quality concerns and other characteristics
Upper Illinois River basin of Illinois, Indiana, and Wisconsin (10,950 mi²).	Humid climate; very large city (Chicago), suburbs, heavy industry and intensive agriculture.	The project area has a broad array of water-quality issues including sedimentation, nutrient enrichment, and toxic contamination and potential sources of contamination, including agricultural and urban runoff and municipal and industrial effluent.
Kentucky River basin of Kentucky (6,970 mi²).	Humid climate; coal mining, timber harvesting, grazing, some urban and industrial areas (Lexington).	The project area has a broad array of water-quality concerns associated with varied land uses, including coal mining, oil and gas production, and timber harvesting in the upper basin and row crops, grazing, urban land, and industry in the lower basin.
Lower Kansas River basin of Kansas and Nebraska (15,000 mi²).	Subhumid climate; intensive irrigated and nonirrigated agriculture, urban area (Topeka).	The project area is typical of the midwestern agricultural region. There are concerns about sediment, pesticides, other nonpoint-source contaminants, and reservoir eutrophication.
Yakima River basin of Washington (6,200 mi²).	Arid to semiarid climate; forest, irrigated agriculture, grazing, and food processing industry, Indian fishing grounds.	The project area is typical of many agricultural areas in the western part of the Nation. Water quality is affected by forestry, grazing, and large reservoirs in the mountainous upper basin, and by about 420,000 acres of irrigated agriculture and small urban areas in the lower basin. Fish habitat is a key concern.
Delmarva Peninsula of Delaware, Maryland, and Virginia (6,050 mi²).	Humid climate; irrigated and nonirrigated agriculture; chemical industry in north near Wilmington, Del.; many small urban areas that have food processing and light industry; poultry farming common; forested lands interspersed among agricultural lands.	The project area is part of the Atlantic Coastal Plain that extends from Long Island to Florida. Ground water is the source of supply for about 90 percent of water use and occurs in a surficial aquifer of large areal extent and in deeper aquifers. The high recharge rates to the surficial aquifer make it vulnerable to contamination. Nitrate contamination is known to occur in the shallow aquifer system.
Central Oklahoma aquifer (3,000 mi²).	Subhumid climate; large urban area (Oklahoma City) surrounded by farmland and rangeland; oil and gas industry very intensive.	The Central Oklahoma aquifer supplies the greatest volume of water for public supplies of any aquifer in Oklahoma. The aquifer supplies water for all the municipalities in the Oklahoma City area, except for Oklahoma City, which is supplied by surface water. Water-quality concerns include high levels of naturally occurring trace elements and radionuclides and the effects of urban and suburban development on ground-water quality.
Carson basin of Nevada (3,980 mi²).	Semiarid climate; irrigated agriculture and growing urban areas; significant wildlife.	The project area includes several basin-fill ground-water reservoirs that are traversed by, and interact with, the Carson River. Concerns include naturally occurring trace elements, such as arsenic, as well as the effects of irrigation practices and increased urban development. There is considerable competition for limited water resources that are affected by and affect water quality.

water withdrawals and population served and a requirement that all States be represented by at least one study unit having at least 30 percent of its area within the State. The results were found to be relatively insensitive to the 30-percent State requirement—only two additional study units were needed to meet this constraint. Overall, the linear program process led to the selection of a total of 119 study units in the conterminous United States—67 surface-water and 52 ground-water study units.

Once available, the results of the linear program were reviewed by Geological Survey District and Regional Offices to assure good coverage of key areas, and a few modifications were made to the screening model selections. In addition, ground-water study units were selected for Alaska and Hawaii. To date, the results of this selection process are the 69 surface-water and 54 ground-water study units shown in figures 3 and 4, respectively.

Additional planning for the full-scale program will be undertaken during the pilot program to further evaluate the preliminary set of study units, to inventory their properties, and to refine the boundaries of the ground-water study units. The surface- and ground-water study units will be grouped into major categories based on climate, hydrogeology, and land-use characteristics. Investigations of the study units will be staged so that, at any given time, the units are spatially distributed throughout the country and represent a mix of the major factors that influence water-quality conditions. For those areas having surface- and ground-water study units, the surface- and ground-water quality generally will be studied simultaneously or during closely spaced time periods.

As the NAWQA Program evolves, a greater understanding of the association of water-quality problems with climate, geography, land use, geology, and other factors will develop. This information will provide insight on the need for alternate or additional study units to incorporate conditions not sufficiently covered or to account for major shifts in environmental concerns, in water use, or in land-use practices.

Selection of Chemical Measurements

Surface- and ground-water quality may be characterized by literally thousands of properties, elements, and compounds. One of the key elements of the NAWQA design is the selection of a set of chemical constituents to comprise the suite of target variables on which the program will focus. Selection of these target variables will be based on their relevance to important water-quality issues and on the existence of appropriate analytical methodologies.

Figure 3. Locations of the preliminary set of surface-water study units for a full-scale National Water-Quality Assessment Program.

Figure 4. Locations of the preliminary set of ground-water study units for a full-scale National Water-Quality Assessment Program.

For some water-quality issues, the choice of target variables is a relatively simple task; for example, the substances relevant to the issues of nutrient enrichment, acidification, salinity, and sedimentation are of limited number, and their chemical analysis is relatively inexpensive. In contrast, for the issue of chemical contamination, the selection of target variables is much more difficult because of the large number of substances to consider and their relatively high cost of measurement.

Several levels of target variables will be selected. A set of national target variables will be established to enable the assessment to provide interpretations of water quality at the national scale. The national target variables will consist of a common set of physical measurements, inorganic constituents, and organic compounds that are included in sample analyses for all study units. Specified laboratory analytical methods will be used for each constituent.

Study-unit target variables will be selected for each study unit by the project team to supplement the national list. Under a full-scale NAWQA Program, the selection of study-unit target variables will be coordinated within a geographical region of the country; as a result, regional target variables will be established.

All sets of target variables--the national, regional, and study unit—will evolve with time. Changes are expected as analytical capabilities improve and become less costly and as knowledge increases about production of chemicals, geographical usage patterns, and other factors affecting the likelihood of water-quality problems associated with particular constituents. As used in this report, the term "target variable," unless specified otherwise, refers to the combined set of national, study unit, and regional target variables.

All samples collected within a study unit will not be automatically analyzed for the complete set of target variables. Many samples will be analyzed for a subset of the complete list. Often, a hierarchical approach will be used in which initial samples are analyzed for all or many target variables and, based on periodic reviews of the data, some target variables are excluded from further measurement or analyzed less frequently. Some of the strategies that will be used in determining the target variables for individual samples are described in the sections "Design of the Surface-Water Investigations" and "Design of the Ground-Water Investigations."

In some cases, the analytical methods chosen for the target variables will provide information on other constituents of less concern; for example, the emission spectrophotometric method used for simultaneous analysis of many of the target trace elements in the pilot program also will provide results on other trace elements. These additional constituents will be included in the NAWQA data base as a contribution to the description of water quality, but less emphasis will be placed on their interpretation. When these nontarget constituents are detected more frequently or at higher levels than expected, they may be designated as target variables.

Inorganic Constituents and Physical Measurements

Table 3 provides information on the inorganic constituents and physical measurements that were selected as national target variables for the pilot program. These were selected primarily on the basis of their effects on human health, ecosystems, and agriculture and on their relevance to the listed water-quality issues. Guidance in selecting these constituents was provided by a group of scientists from the Geological Survey and other agencies. Many of the constituents listed in table 3 are presently targeted on lists for regulatory purposes, such as those lists developed under the 1986 Amendments to the Safe Drinking Water Act. Some constituents, such as many of the major ions in ground water, were selected to provide information on the geochemical environment associated with each sample.

Organic Compounds

The selection of organic target compounds is more difficult. It has been estimated that more than 60,000 synthetic organic compounds are used in manufacturing processes today (Shackelford and Cline, 1986); moreover, the number of byproducts and degradation products from these compounds is unknown. Only a small fraction of the total number can be measured by using existing analytical techniques, particularly on a routine basis. Because health concerns are primarily associated with synthetic rather than naturally occurring organic compounds, analyses for the former will be emphasized. In some situations, naturally occurring organic compounds may be measured to improve understanding of the transport and the fate of other constituents of concern.

It is difficult to select a few, or even a few dozen, organic compounds as the set of national target variables. Thus, an exploratory component to the selection of organic target compounds will be needed. Otherwise, much effort might be expended looking for substances of infrequent occurrence, while others, possibly more important, go unnoticed. As an example, industrial wastewaters have been under continuous scrutiny for a set of specific priority pollutants since 1977. Yet, examination of some broad-spectrum analytical results (Shackelford and Cline, 1986) shows that many other potentially toxic organic compounds may be occurring more frequently than many of the organic priority pollutants. This also may be true of ambient waters.

Part of the problem is that, based purely on their physical and chemical properties, misleading predictions of the potential for compounds to move into surface and ground waters may be made. In addition, some chemicals may undergo transformations to other potentially toxic compounds that are not detected by standard analytical procedures; for example, premarket evidence concerning the pesticide aldicarb led to the conclusion that it would not move through soils into ground water. Yet, data collected on Long Island (Soren and Stelz, 1985; Suffolk County Department of Health Services, 1984; Zaki and others, 1982), in Wisconsin (Harkin and others, 1986), and in other States (Cohen and others, 1986) have demonstrated that this pesticide (primarily as metabolites) has reached ground water. Unexpected frequencies of detection of other pesticides have been found in water from a number of wells—notably dibromochloropropane in California and Hawaii and ethylene dibromide in Florida.

Almost all samples for organic analyses will be routinely analyzed by several broad-spectrum methods, each capable of detecting a number of target compounds. In addition, certain selected samples will be analyzed for a wider array of additional, less expected, compounds by using such techniques as high-resolution mass spectrometry combined with computerized searches of comprehensive "libraries" of mass spectra. These exploratory analyses will yield tentative identifications of additional compounds for which internal records will be kept. For those compounds that are repeatedly noted as tentative identifications, efforts will be made to obtain standards and to include the compounds within the laboratory's analytical capabilities, possibly as national or regional target variables. Selection of the samples for exploratory analyses will be based on various indicators of possible organic contamination. These will include the hydrologic and the land-use setting associated with the sampling location, the presence of indicator constituents, and the number and the nature of peaks associated with either the broad-spectrum analyses for target variables or screening techniques. Undoubtedly, knowledge and technology in trace organic analysis will improve rapidly with time; as it does, the list of organic target variables will be modified.

In general, the suites of synthetic organic compounds analyzed for surface water will be different than those for ground water. In surface water, organochlorine compounds [for example, polychlorinated biphenyls (PCB's) and chlorinated insecticides], and selected herbicides, phenols, and polycyclic aromatic hydrocarbons will be emphasized in the pilot projects. Organic compounds of primary concern in ground water include volatile organic compounds (Westrick and others, 1984; Barbash and Roberts, 1986) and various pesticides (Cohen and others, 1986; Holden, 1986).

Table 3. *Inorganic constituents and physical measurements selected as target variables in the pilot National Water-Quality Assessment Program*

Constituent	Principal effects			Water-quality issues					Target variables	
	Human health	Eco-systems	Agri-culture	Toxic contami-nation	Nutrient enrich-ment	Acidi-fica-tion	Salinity	General suit-ability	Surface water[1]	Ground water
Major metals and trace elements										
Aluminum		+	+	+		+			+	
Antimony	+	+		+					+	+
Arsenic	+	+	+	+			+		+	+
Barium	+			+					+	+
Beryllium	+			+					+	
Boron			+				+		+	+
Cadmium	+	+		+		+			+	+
Chromium	+	+		+		+			+	+
Copper		+	+	+		+			+	+
Fluoride	+			+					+	+
Iron								+	+	+
Lead	+	+		+		+			+	+
Manganese								+	+	+
Mercury	+	+	+	+		+			+	+
Molybdenum	+		+	+			+		+	+
Nickel	+			+		+			+	+
Selenium	+	+	+	+			+		+	+
Silver		+		+					+	
Vanadium	+			+					+	+
Zinc		+		+		+			+	
Nutrients										
Ammonium		+		+	+				+	+
Nitrate	+	+	+	+	+	+			+	+
Nitrite	+	+	+	+	+				+	+
Total nitrogen		+			+				+	+
Orthophosphate		+			+				+	
Total phosphorus		+			+				+	
Major constituents and dissolved solids										
Calcium		+	+			+	+	+	+	+
Magnesium		+	+			+	+	+	+	+
Potassium									+	+
Sodium	+	+	+			+	+	+	+	+
Chloride		+	+			+	+	+	+	+
Sulfate	+	+				+	+	+	+	+
Total dissolved solids		+	+				+	+	+	+
Field measurements										
Acidity		+				+			+	
Alkalinity		+				+	+	+	+	+
Dissolved oxygen		+						+	+	+
pH		+				+			+	+
Specific conductance							+		+	+
Temperature		+						+	+	+
Radionuclides										
Gross alpha	+			+					+	+
Gross beta	+			+					+	+
Radon-222	+			+						+

[1]Includes national target variables and candidate study-unit target variables measured initially in all surface-water study units.

Accordingly, these groups will be emphasized in the ground-water pilot projects.

In addition to providing information on specific contaminants, the NAWQA study-unit results will be used to evaluate the utility of various screening techniques and certain constituents that have the potential to be inexpensive indicators of contamination; for example, screening techniques that scan a sample for the presence or absence of selected groups of organic compounds will be tested on samples for which detailed analyses are being made. If the screening techniques prove successful, then considerable efficiencies in sampling for organic compounds could be obtained. Likewise, potential indicator constituents will be evaluated in various study units. These will include nitrate as an indicator of the occurrence of selected pesticides in ground water or a particular organic compound (or a suite of organic compounds) as an indicator of the presence of other synthetic organic compounds.

Selection of Biological Measurements

Another challenging aspect of designing an assessment program is deciding upon the role(s) of and the emphasis to place on biological measurements. Much of the concern about water quality is biologically motivated, particularly the protection of public health and fish and wildlife resources. In addition, the fate and the transport of many inorganic and organic contaminants in water are affected by biological processes.

As presently envisioned, biological measurements will be used in the assessment to assist in (1) determining the occurrence and distribution of waters contaminated by fecal material, (2) determining the occurrence of potentially toxic substances, including trace elements and organic compounds, through the use of tissue analyses and ambient toxicity tests, (3) assessing the relations between the physical and the chemical characteristics of streams and the functional or structural aspects of the biological community through ecological surveys, and (4) defining and quantifying biological processes that affect the physical and the chemical aspects of water quality. Development and testing of specific approaches is being undertaken in the pilot program. Progress in each is summarized below.

Fecal Contamination

Water contaminated by fecal matter has served as a medium for the spread of a large number of diseases, including cholera, typhoid fever, and bacillary and amoebic dysentery. Thus, knowledge of the sanitary quality of water can be very important in assessing its suitability for public supply and recreational uses. Relatively elaborate procedures are required for the detection of most pathogens in natural waters. The most widely accepted procedures to indicate the presence of fecal matter in water rely on the detection of non-pathogenic bacteria, which are native to the intestines of humans and other warm-blooded animals.

In the scientific community, a lack of consensus exists as to what bacterium or group of bacteria should be used to indicate the presence of fecal contamination. In some European countries, *Escherichia coli* (*E. coli*) is preferred as an indicator because of its specific association with the source of pathogens—fecal waste from humans and other warm-blooded animals. Until recently, professionals from other countries, including the United States and Canada, preferred to use fecal coliform bacteria (Dufour, 1977, p. 57).

Based on the results of studies by Cabelli (1977, p. 222–238), the EPA has revised the bacteriological, ambient water-quality criteria for marine and freshwaters (U.S. Environmental Protection Agency, 1986) and recommended that criteria for E. coli and the enterococci organisms replace criteria for fecal coliform and total coliform bacteria in State water-quality standards for the protection of primary contact recreation.

The approach for assessing the occurrence and the distribution of fecal indicator bacteria in a surface-water study unit generally will consist of a review and an analysis of available information and several synoptic surveys during which concentrations of *E. coli* will be determined at many sites within a basin.

Untreated ground water is a major source of water-borne disease in the United States. Contamination generally occurs in local areas by seepage of sewage into aquifers and improperly developed wells or the entry of sewage-contaminated surface water into poorly protected wells (Craun, 1984). Unlike surface water, however, it is not clear which organisms are appropriate indicators of fecal contamination in ground water. Discussions are being held with scientists outside the Geological Survey to consider appropriate measures of fecal contamination that could be tested for ground water before implementation in a full-scale program.

Occurrence of Potentially Toxic Substances

In combination with physical and chemical measurements, analyses of plant and animal tissues and ambient toxicity tests (using local waters and sediments) are being evaluated to determine their utility for providing information about the occurrence of potentially toxic contaminants in surface waters.

Plant and animal tissues will be analyzed in the surface-water study-unit investigations to help determine the occurrence of certain trace elements and organic compounds, to provide a measure of the availability of these contaminants in water and sediment to biota, and to help understand their fate. The utility of tissues as indicators of the distribution and bioavailability of trace elements is widely recognized (Huggett and others, 1973; Phillips, 1980). However, their use in determining the distribution and availability of synthetic organic compounds is less well established. One reason is that current analytical procedures for organic compounds in tissues are not as well suited to the task of scanning for a broad list of compounds as are the procedures for water. Considerably more effort is required to prepare tissue samples than water samples for organic analysis. Moreover, specific ''cleanup'' procedures are needed to distinguish the compounds of interest, which are often present in small concentrations, from the background organic matrix. These procedures become more important and more difficult as attempts are made to lower the detection levels for specific compounds of interest.

As part of the pilot program, a study is underway (in consultation with scientists from other agencies and universities) to develop, test, and evaluate a protocol for the collection of organisms, analysis of tissues, and interpretation of data to assess trace contaminants in rivers. Questions that are being addressed include (1) which organisms or suites of organisms are best suited for use in different types of rivers, (2) what are the appropriate procedures for collection of organisms, preparation and analysis of tissues, and interpretation of data, and (3) who should do the field sampling and laboratory analyses?

Toxicity tests involve measuring a physiological or behavioral response of organisms to certain environmental conditions. One of the potential benefits of using toxicity tests is that they may provide an indication of the occurrence of contaminants that would not be detected by current laboratory analytical methods. In samples for which other analyses did not indicate the occurrence of potentially toxic substances, positive results of toxicity tests would result in more detailed chemical analyses of waters and sediments at the locations in question.

Toxicity tests also have been used in water-quality assessments to assess or predict the environmental effects of contaminants, but it is unlikely that they would be used routinely for this purpose in the NAWQA Program. It is extremely difficult, if not impossible, for toxicity tests to truly mimic natural systems. Responses of selected test organisms to contaminants in a controlled environment are unlikely to be representative of the responses of a complex natural community to the same contaminants. Further, even though a test may indicate a biological response, other studies are needed to identify the substance(s) or the concentration(s) causing the response.

Several questions will be considered in the evaluation of toxicity tests as part of the pilot program. What are the characteristics of different toxicity tests and their applications? How well can the results be related to physical and chemical measurements and (or) the ''health'' of an ecosystem? Will different toxicity tests result in different conclusions about the ''health'' of an ecosystem? How reproducible are the results? and When should toxicity tests be conducted on water and when should they be conducted on sediment?

Ecological Surveys

Developing an improved understanding of how the aquatic biological community is affected by (and, in turn, affects) the physical and the chemical environment is an important component of an integrated assessment of surface-water resources. During the pilot program, methods and approaches for conducting an ecological survey will be reviewed and tested. Goals of the survey will be to (1) document the current status of the biological community, (2) describe and explain, as possible, the relations of the biological communities to the physical and the chemical characteristics of the environment, and (3) provide background information that would serve as a framework for the design and the interpretation of other assessment activities.

Aquatic ecosystems are influenced by many environmental factors, including (1) the amount, character, and temporal distribution of energy entering the system, (2) the physical and chemical quality of the stream, (3) habitat quality, (4) the flow regime, and (5) biotic interactions. Thus, distinguishing changes induced by human activities from natural variation is a very difficult task. An ecological survey must assess the structure (number of species and individuals within a community) and the function (means by which organisms interact to utilize food and other resources) of biological communities, as well as the factors (for example, habitat, riparian vegetation, and hydrologic regime) that are expected to influence their spatial and temporal variability.

During early phases of the NAWQA Program, comprehensive characterizations of communities will not be possible. Thus, an important aspect of the survey design will be the development of manageable components that will contribute to a knowledge base and from which more comprehensive assessments can be developed (either in later phases of the NAWQA Program or supported by other agencies). Ecological surveys in all study units will be guided by a similar set of focused objectives relating different aspects of community ecology to physical and chemical characteristics of the watershed.

Biogeochemical Processes

Explanations of water-quality observations often rely on understanding biogeochemical processes. Where deemed important in the early phases of study, relatively simple biological measures may be used to help describe and explain certain observations; for example, measurements of plant biomass or productivity could be used with other physical and chemical data to assess the characteristics and the causes of dissolved-oxygen depletion in a designated stream reach. As knowledge of water-quality conditions in a study unit grows, more complex biogeochemical investigations may be conducted. Examples include determining the role of biological processes affecting the sources, transport, and fate of nutrients in a stream reach; the fate of nitrogen compounds in soil and the unsaturated zone; and the fate of pesticides applied in a study area. Definition of relevant biogeochemical processes may not occur until the later stages or after the initial round of investigation in a study unit. Past and ongoing activities in universities and in the National Research and the Federal-State Cooperative Programs of the Geological Survey will provide a base of experience for development of studies and protocols.

Uses of Available Water-Quality Data

Over the years, a large amount of water-quality data has been collected by many organizations for a wide range of purposes. Many of these data are useful for water-quality assessment provided that care is taken to ascertain the manner in which they were collected and analyzed and the individual settings they represent. Because of the varied methods and sampling approaches, existing data cannot be aggregated in an automatic fashion to form a meaningful national assessment. The limitations of some of these data sets are discussed in a variety of reports, including those by Blodgett (1983), van Belle and Hughes (1983), U.S. Congress (1983, 1984), Judy and others (1984), U.S. Environmental Protection Agency (1985), Association of State and Interstate Water Pollution Control Administrators (1985), U.S. General Accounting Office (1986), Hren and others (1987), Resources for the Future (1987), and Smith and others (1987). Some of the constraints on the direct use of existing data for water-quality assessment are (1) the data often represent treated wastewater or water supplies rather than ambient water in a stream or an aquifer, (2) the data often are not publicly available or else not adequately indexed and, thus, cannot be readily located or accessed for use in assessments, (3) analytical procedures vary among laboratories and with time, (4) sampling locations may be difficult or impossible to determine, (5) historically, few samples have been analyzed for trace elements and organic compounds, (6) water-quality sampling sites are often clustered around known or suspected areas of contamination; thus, assessments based only on these data have a potential for substantial bias, (7) few sites have been sampled sufficiently to assess changes in water-quality conditions, and (8) few stream sites have been sampled frequently enough to estimate the transport of constituents.

Within these limitations, considerable amounts of existing water-quality data will be utilized in the assessment program. One of the first activities in each project is to compile, screen, and interpret available water-quality data to provide an initial description of water-quality conditions and to assist in formulating plans for project field activities. These data will be used to help identify areas and reaches that have significant water-quality problems, to select appropriate sampling locations, to establish the list of study-unit target variables, and to develop hypotheses about the causative factors that influence water-quality conditions.

Many of the water-quality data will be obtained from Geological Survey and EPA computerized data bases. Additional water-quality data (some of which may not be in computer files) will be obtained through literature reviews and contacts with other organizations. Information about field and laboratory procedures will be obtained to ensure that the data are compatible with their use in the assessment.

Development of National Data Bases

The NAWQA study teams will need to store, retrieve, and manipulate large amounts of water-quality data, site characteristics, and geographic information. To avoid duplicating existing data bases, the pertinent files of the National Water Information System will be used as the primary repository of the water-quality data, streamflow data, and site information (Edwards and others, 1986). Other systems such as the EPA BIOS system (U.S. Environmental Protection Agency, 1987) for biological data will be used when needed.

A computerized geographic information system (GIS) will be used to analyze and display spatially referenced information (Rennick, 1986). Once data are associated with a geographic location, digitized, and stored within a GIS, they can be combined with other natural and human factors and the results readily displayed; for example, water-quality data originally referenced to hydrologic units can be cross referenced and linked with socioeconomic data on population and economic activity.

The assessment will use various types of ancillary data to examine relations between water-quality conditions and natural and human factors. Consistent ancillary data on site characteristics, such as streamflow rates, ground-water levels, and well screen intervals, will be collected for all sampled sites and will be included in the national data bases. Records of site characteristics are particularly important for ground water because local scale factors are likely to be very important determinants of ground-water quality. Table 4 lists site characteristics that will be recorded to the extent possible at all wells. In addition, available spatial data bases on various aspects of soils, geology, population, land and resource uses, and waste discharges will be obtained. Several of these data bases are described in table 5. Smith and others (1987) used many of these data to develop hypotheses about possible causes of trends detected in water-quality variables.

Table 4. *Site characteristics for sampled wells in the National Water-Quality Assessment Program*

Unique site identification number
Type of site (well, drain, and others)
Data reliability
Project identification number
District, State, and county codes
Latitude and longitude of site
Altitude of land surface
Topographic setting
Use of site (observation well, withdrawal well, and so forth)
Primary use of water
Aquifer name code
Aquifer type code (unconfined, confined, mixed)
Depth of well
Water level
Depth to top and bottom of each open interval
Depth to top and bottom of each geohydrologic unit
Rated pump capacity
Type of lift
Date of well construction
Method of construction
Type of finish
Type of surface seal
Casing material
Sampling method
Primary reason for well selection (with or without regard to known or suspected local problem areas)
Occurrence of various land uses and local features such as gas stations and septic tanks within a 100-ft and ¼-mi radius of the sampling well
Predominant land use within 100-ft radius of the sampling well
Predominant land use within ¼-mi radius of the sampling well
Percent of total area within a ¼-mi radius of the well that consists of predominant land use
Known occurrences of major changes in land use near the well within the last decade
Local agricultural practices

Quality Assurance

As part of the pilot NAWQA Program, a quality assurance (QA) program has been established to assure that technically sound procedures are used to test the assessment concepts and that data collection, analysis, and interpretation procedures are documented and capable of being verified. The QA program includes a plan that sets forth programwide requirements and defines program managers' responsibilities for the pilot project studies. The QA program also includes protocols for surface- and ground-water field procedures.

Communication and Program Coordination

Communication and coordination are critical components of the NAWQA Program. The results from the program will be communicated through publications and meetings. Interpretive reports, which will be published as part of each study-unit investigation and as national and multistudy-unit summaries, will be the principal method of disseminating results from the program. Initial reports that summarize the analysis of available information for a study unit and final reports that summarize the results from each high-activity period will have a high degree of consistency among study units. Press notices announcing release of reports will contain summaries of significant findings for the general public.

Each pilot project has a liaison committee to help ensure that the scientific information produced by the program is relevant to local and regional interests. The committees are comprised of non-Geological Survey members who represent a balance of technical and management interests. Represented organizations include Federal, State, interstate, and local agencies, Indian Nations, and universities. Specific activities of each liaison committee include (1) exchanging information about water-quality issues of local and regional interest, (2) helping to identify sources of relevant data and information, (3) discussing potential adjustments in the project design, (4) assisting in the design of information products from the projects, and (5) reviewing and commenting on planning documents and project reports.

In addition to the liaison committees, a National Coordinating Work Group has been established to advise the Geological Survey on national aspects of the NAWQA Program. The work group functions under the general auspices of the Interagency Advisory Committee on Water Data and the Advisory Committee on Water Data for Public Use. The work group advises the Geological Survey on water-quality information needs of non-Federal and Federal communities of water information users and on procedures for making the data and the information from the assessment appropriate to planning needs and available in a timely manner.

The work group is chaired by the Chief Hydrologist of the Geological Survey and currently consists of nine Federal members, seven non-Federal members, and representatives from each of the pilot-project liaison committees. Organizations represented include the American Water Resources Association, the Association of American State Geologists, the Association of State and Interstate Water Pollution Control Administrators, the Chemical Manufacturers Association, the Interstate Conference on Water Policy, the National Association of Conservation Districts, the U.S. Army Corps of Engineers, the U.S. Bureau of Reclamation, the U.S. Environmental Protection Agency, the U.S. Fish and Wildlife Service, the U.S. Forest Service, the National Oceanic and Atmospheric Administration, the U.S. Soil Conservation Service, and the Council on Environmental Quality.

Table 5. *Data bases containing ancillary data to be used in the National Water-Quality Assessment Program*

Data base	Description	Reference
Acid Deposition System	Information on the chemistry of wet atmospheric deposition collected at about 400 sites in North America.	Olsen and Slavich, 1986.
National Uranium Resource Evaluation.	Information on the concentrations of a broad array of trace elements for nearly one million samples in water and sediments from the 48 conterminous States and Alaska, identified by 1° × 2° quadrangle.	Averett, 1984.
Natural Resources Inventory	Estimates of sheet and rill erosion for about 800,000 sample plots, aggregated by county and identified according to land use, including cropland, pasture land, rangeland, and forest land.	U.S. Department of Commerce, 1984a.
Resources for the Future, Environmental Data Inventory.	Estimates of biochemical-oxygen demand, nutrient, and metal loads discharged to U.S. streams and lakes from about 32,000 industrial and municipal waste treatment facilities and from runoff from major land types, including urban, cropland, pastureland, rangeland, and forest land.	Gianessi and Peskin, 1984. Gianessi and others, 1986.
Resources for the Future, Pesticide Usage Inventory.	Inventory of 184 pesticides used in the United States, identified by crop type and by county.	Gianessi and Puffer, 1986.
U.S. Census of Agriculture	Census of farm operators, including county-based estimates of crop, forest, pasture, and range acreage, agricultural chemical and fertilizer use, and inventories and sales of livestock and poultry.	U.S. Department of Commerce, 1984b.
U.S. Census of Population	Population in the United States summarized for about 400,000 block groups and enumeration districts; identified by latitude and longitude.	U.S. Census Bureau, 1983.
U.S. Coal Production	Surface and underground coal production by county.	Mining Informational Services, 1983.
U.S. Environmental Protection Agency Industrial Facility Discharge File.	Estimated discharge from about 54,000 industrial and municipal facilities having U.S. Environmental Protection Agency permits; identified by permit number in the National Pollution Discharge Elimination System (NPDES) and by river-reach number.	Philip Taylor, U.S. Environmental Protection Agency, verbal commun., 1988.
U.S. Environmental Protection Agency Needs Survey.	Estimates of flow and concentrations of biochemical-oxygen demand in the effluent discharged from about 30,000 publicly owned sewage treatment plants identified by NPDES permit number and river-reach number.	U.S. Environmental Protection Agency, 1982b.
U.S. Environmental Protection Agency River-Reach File.	Numeric listing of about 67,000 stream reaches arranged systematically to provide hydrologic linkages among major U.S. rivers.	Dewald and others, 1987.
U.S. Environmental Protection Agency STOrage and RETrieval System (STORET).	A computerized data base containing geographic and other descriptive data for water-quality data-collection sites; data related to the physical characteristics and chemical constituents of water, fish tissue, and sediment; information on municipal waste sources and disposal systems; data on pollution-caused fish kills; and daily streamflow data.	U.S. Environmental Protection Agency, 1982a.
U.S. Fish and Wildlife Service National Contaminant Biomonitoring Program.	Formerly referred to as the National Pesticide Monitoring Program, the program was established to monitor temporal and geographic trends in organochlorine chemical and elemental contaminants in the Nation's freshwater fish.	May and McKinney, 1981, and Lowe and others, 1985.

Table 5. *Data bases containing ancillary data to be used in the National Water-Quality Assessment Program*—Continued

Data base	Description	Reference
U.S. Geological Survey National Digital Cartographic Data Base.	Base categories of cartographic data at standard scales, accuracies, and formats suitable for computer-based analysis. The categories include the Public Land Survey System, boundary, hydrography, transportation, and altitude data at 1:24,000 scale; hydrography and transportation data at 1:100,000 scale; boundary, Census tract, hydrologic unit, Federal land ownership, land use and land cover, and altitude data at 1:250,000 scale; and boundary, transportation, and hydrography data at 1:300,000 scale.	McEwen and others, 1983.
U.S. Geological Survey Rock Analysis Storage System.	Chemical analyses for more than 500,000 samples of sediments, surficial materials, plants, and rocks from the United States; identified by State, county, and latitude and longitude.	U.S. Geological Survey, 1983.
U.S. Geological Survey National Water Information System.	A computerized system to provide for the processing, storage, and retrieval of water data pertaining to surface water, ground water, and water quality.	Edwards and others, 1986.
U.S. Geological Survey National Water-Use Information Program.	Information compiled for 12 categories of water use for 47 States. Each State has an automated data system that contains site-specific information about the water use in each category. The National Water-Use Data System contains information for the 12 categories summarized by counties and river basins within each State.	Mann and others, 1982.

DESIGN OF THE SURFACE-WATER INVESTIGATIONS

Earlier sections of this report have focused on general design concepts and on the goals and the scope of the assessment. This section describes the specific objectives, sampling activities, and anticipated products of the surface-water part of the assessment program.

Objectives

The surface-water investigations have the following major objectives, which are to:

1. Describe the occurrence and the spatial distribution of a broad array of water-quality constituents,
2. Estimate loads of selected water-quality constituents at key locations,
3. Provide information on the seasonal variation and the frequency of occurrence of selected water-quality constituents at key locations,
4. Define long-term trends in the concentrations and (or) loads of selected constituents, and
5. Identify, describe, and explain, as possible, the major factors that affect observed conditions and trends in surface-water quality.

In addition to an analysis of available data, described earlier, three major types of sampling activities will be undertaken in a study unit to achieve these objectives. These activities, described in the section ''Sampling Activities,'' are fixed-station sampling, synoptic sampling, and studies of selected reaches.

Timing and Duration of Investigations

The surface-water part of the assessment will be done on a rotational basis in a 9-year cycle; about one-third of the designated study units will undergo intensive study at any one time. For any given study unit, a 3-year period of concentrated data acquisition, interpretation, and publication of results will be followed by publication of a final summary report. Following the 3-year period, data acquisition in the study unit will be reduced for 6 years to a level sufficient only to document major changes in water quality. In any given year, if the total number of study units in the program is 69, then most of the effort will be focused on 23 study units that are widely dispersed about the Nation, while the activities in the remaining 46 study units will be conducted at a low level of intensity. In this manner, the national level of effort will remain constant and reasonably uniform.

The choice of a 3-year period is a compromise between achieving a quick ''snapshot'' of conditions and observing a wide range of flow conditions over each of the seasons within each cycle. Sufficient time is also needed to carry out exploratory sampling, to develop and test hypotheses, and to document and begin to publish findings. Conceptually, the approach is similar to the U.S. Census of Population and Housing, wherein a set of variables is measured over a period of a few weeks every 10 years. In this case, the period of measurement must be longer, but the interval between measurements is approximately decadal (9 years), and the data collection is rotational rather than simultaneous.

Figure 5 shows the major interrelations among activities and objectives and the general timing of activities. The first high-activity period is preceded by 1 to 2 years for project planning, preliminary analysis of available information, and, as appropriate, reconnaissance-level sampling.

Sampling Activities

Fixed-Station Sampling

The network of fixed-location river-sampling stations, which will be operated in each study unit, will have the following objectives:

1. Describe the seasonal variations and the frequency of occurrence of selected water-quality constituents,
2. Estimate loads past stations and attempt mass balances of selected target constituents between stations, and
3. Define long-term trends in water quality.

The locations of sampling stations will be determined by the objectives of the assessment, knowledge of the factors that affect water-quality conditions in each basin, and the suitability and the accessibility of sites for sampling. Although several techniques have been proposed for locating sampling sites for assessment purposes (Sharp, 1970, 1971; Lettenmaier, 1978), the task does not lend itself easily to the formulation of a mathematical objective function. At present, a less formal approach for locating sites is appropriate. Sites that are suitable for addressing the objectives of fixed-station sampling in the NAWQA Program include locations (1) at the mouths of major tributaries and at selected points on the main stem that account for a large portion of the total basin runoff, (2) upstream and downstream from reservoirs, urban areas, agricultural drains, and other areas that significantly affect water quality, (3) on streams draining large areas that have relatively homogenous land use, and (4) near major public water-supply intakes or other important water uses. Where appropriate, existing stations operated as part of State monitoring efforts and other Federal programs, such as NASQAN, the Hydrologic Benchmark Network, and the Federal-State Cooperative Program will be used to take advantage of available data and minimize duplication of effort.

Operation of the fixed stations in the pilot projects began in April 1987. Initially, 7 fixed stations were selected for the Kentucky River and Yakima River basins, 8 for the Upper Illinois River basin, and 13 for the lower Kansas River basin. The selection of fixed stations in each project area represents initial efforts to balance the fixed-station sampling activities against other planned project activities, given available resources. As data become available, the fixed-station networks will be evaluated as to the benefits and the costs of adding, moving, and deleting stations.

Fixed stations will be sampled for selected target variables at least once a month during the 3-year, high-activity period. In addition to regularly scheduled sampling, three to six additional high-flow samples will be collected annually at each station. The need for repetitive sampling arises from the considerable temporal variability of surface-water quality that can result from variations in river discharge, temperature, municipal and industrial discharges, and seasonal variations in agricultural practices. In each 3-year, high-activity period, the newly collected data will be compared with data collected before the program began and with data collected from earlier cycles to detect and describe water-quality trends. The approaches that will be used to detect and describe these water-quality trends are designed to remove variation in water quality associated with variation in discharge and season (Hirsch and others, 1982).

Table 6 shows the lists of national and candidate study-unit target variables to be determined at fixed stations. During the first year, the candidate study-unit target variables will be measured seasonally at all fixed stations—four to five times—over a range of hydrologic conditions to determine their occurrence and relative importance in the basin. After the first year of sampling, data collected seasonally for the candidate study-unit target variables will be reviewed and decisions made about which of these constituents to continue measuring at fixed stations in the study units. These decisions will be made by the study-unit teams in consultation with the liaison committees and regional and national coordinators. They will be based largely on the occurrence of the constituents relative to appropriate analytical detection limits, regional and national norms, and existing water-quality criteria and standards.

Initial division of target variables between the two groups assumes no prior knowledge of the occurrence and of the relative magnitude of concentrations of certain water-quality constituents in a study unit. Where knowledge exists that one or more of the candidate study-unit target variables occur at significant concentrations or are highly relevant to important water-quality issues, the specific constituents will be determined at the same frequency as the national target variables.

Gross-alpha and gross-beta radioactivity will be determined seasonally during the first year of sampling at fixed stations to screen for the occurrence of radiochemicals. Should either of these measures indicate significant levels in all or parts of a basin, more specific radiochemical analyses will be made during subsequent years.

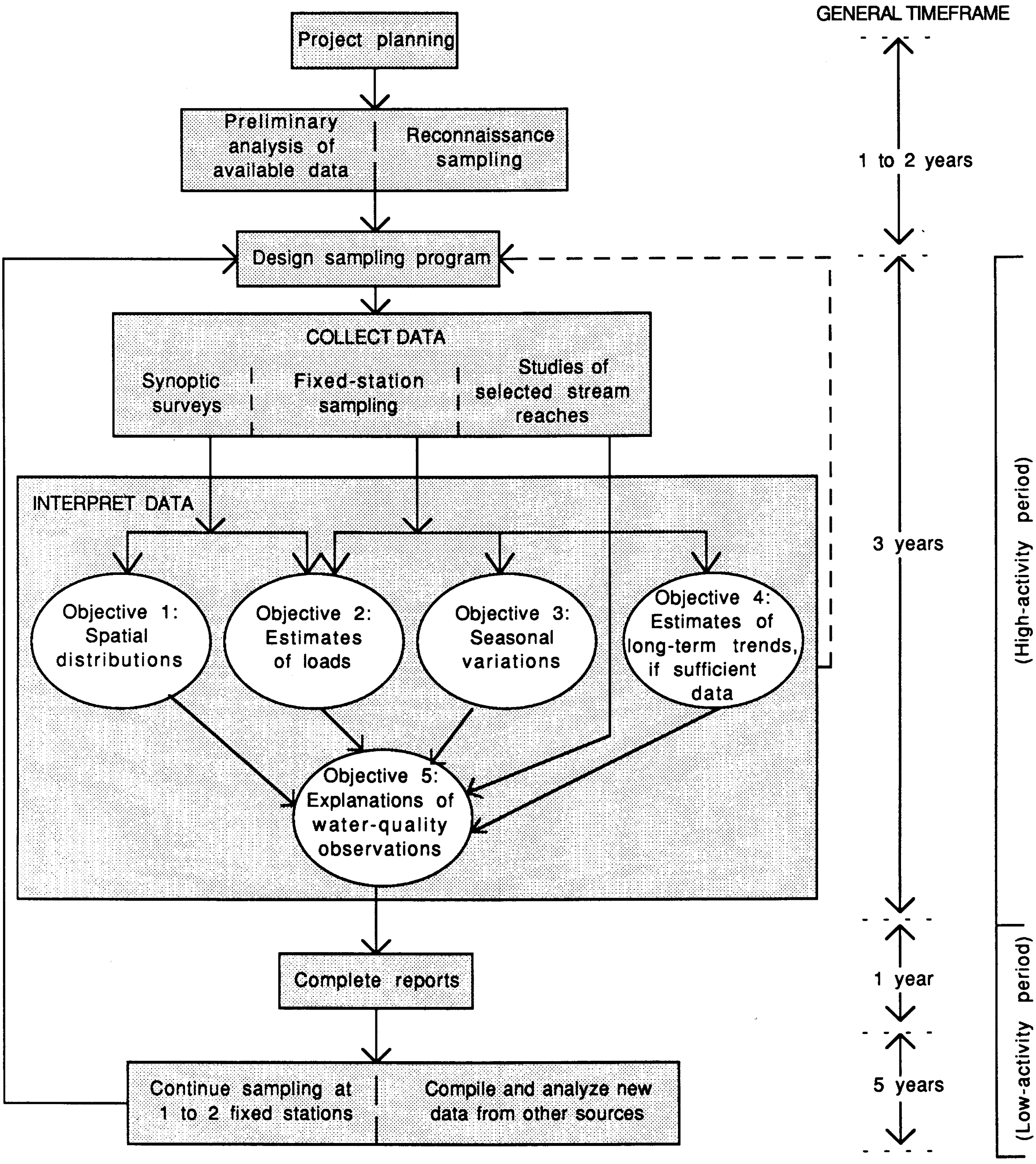

Figure 5. Interrelations among tasks and objectives for surface-water study-unit investigations for the National Water-Quality Assessment Program.

Table 6. *National and candidate study-unit target variables for fixed stations in the surface-water part of the pilot National Water-Quality Assessment Program*

National target variables[1]	Candidate study-unit target variables[2]	
Field measurements		
Alkalinity	Acidity	
pH		
Specific conductance		
Temperature		
Major constituents (dissolved)		
Chloride	Calcium	Potassium
Dissolved solids	Magnesium	Fluoride
Sulfate	Sodium	
Nutrients		
Nitrogen:		
Ammonia plus organic (total)		
Ammonia (dissolved)		
Nitrite (dissolved)		
Nitrite plus nitrate (dissolved)		
Phosphorus:		
Ortho (dissolved)		
Total		
Major metals and trace elements (dissolved and suspended)		
Arsenic	Aluminum	Molybdenum
Cadmium	Antimony	Nickel
Chromium	Barium	Selenium
Copper	Beryllium	Silver
Lead	Boron	Vanadium
Mercury	Iron	Zinc
	Manganese	
Other		
Suspended sediment	Cyanide (dissolved)	
Organic carbon (dissolved and suspended)	Gross-alpha radioactivity (dissolved and suspended)	
	Gross-beta radioactivity (dissolved and suspended)	

[1]Field measurements and constituents to be determined in all water samples collected from fixed stations.

[2]Field measurements and constituents to be determined in water samples collected seasonally (four to five times) from fixed stations during at least the first 12 months of operation.

Because of resource constraints, initial analyses for organic substances in samples from fixed stations will be restricted to gross measures—dissolved and suspended organic carbon. In most cases, these measures will be used to help interpret other water-quality constituents. Analyses for specific organic compounds at fixed stations will be considered for those study units where a widely used pesticide or particular industrial compound is of such concern that information is warranted about its frequency of occurrence and transport. Likewise, no biological measurements are listed in table 6. Trace organic substances and biological measurements will be emphasized in synoptic surveys and, possibly, in some studies of selected stream reaches.

Synoptic Sampling

Synoptic sampling surveys are generally accomplished by taking single or multiple water-quality measurements at many sites in a study area during a brief period of time, usually 1-2 weeks, representing a specific hydrologic condition.

The synoptic surveys in the assessment will have the following primary uses, which are to:

1. Provide a finer degree of spatial resolution to the descriptions of certain kinds of water-quality conditions than will be attainable from the fixed-station sampling network, and
2. Document the spatial distribution of concentrations and loads of selected target variables in relation to land and water uses and to land- and waste-management practices.

In addition to their primary uses, synoptic surveys will serve several other purposes. Early in each project, results from reconnaissance-level synoptic surveys of streambed materials and water will be used to help decide which trace elements and synthetic organic compounds should be included as study-unit target variables. Results from synoptic surveys also will be used in the initial selection of locations for the fixed-station network and in future modifications to the network. These modifications will occur where the results from synoptic surveys indicate major changes in water quality that are not apparent from the results of fixed-station sampling.

Synoptic surveys will generally be done in stages in a study unit and will build on the descriptions of water-quality conditions in a hierarchical manner. By conducting the surveys in stages, project teams will be able to use the knowledge gained from early reconnaissance-level efforts to make appropriate modifications to the design of larger surveys. A phased approach also will allow project teams to balance the need for nationally consistent approaches against the need for flexibility so that the assessments can appropriately address local and regional issues.

The number, the timing, and the design of the synoptic surveys will depend on the specific objectives of the surveys and the factors affecting the water-quality constituents of interest. Groups of target variables to be determined in water and bed-material samples collected during synoptic surveys are presented in table 7. Surveys used to describe the geographic distribution of concentrations of major dissolved constituents, nutrients, and suspended sediment in water usually will be repeated several times during a 3-year intensive phase of investigation. The timing of these surveys will

Table 7. *Groups of target variables to be determined in samples collected during surface-water synoptic surveys for the National Water-Quality Assessment Program*

[Groups of target variables to be included in each synoptic survey will depend upon the specific objectives of the survey and the factors affecting the water-quality constituents of interest]

Target variables	Stable flows				Unstable flows
	Water	Bottom materials	Tissue	Other biota	Water
Field measurements...	+				+
Major dissolved constituents..........	+				+
Nutrients................	+				+
Suspended sediment...	+				+
Dissolved oxygen......	+				
Escherichia coli........	+				+
Major metals and trace elements.......		+	+		
Hydrophilic trace organic compounds...........	+				+
Hydrophobic trace organic compounds...........		+	+		
Other biological measurements (for example, ecosystem surveys)..............				+	

generally represent different seasons or hydrologic conditions within a study unit.

The design of the surveys will depend on whether the streamflow conditions of interest will be relatively stable or unstable. For stable conditions where streamflows are not expected to change significantly over the duration of the survey, sites to be sampled will include all fixed stations, other sites on the main stem and major tributaries to ensure a resolution of at least 50 river miles, and a group of randomly selected sites on small-order streams stratified by land use. The group of randomly selected sites will represent a balance between the goal of providing information that is reasonably uniform in geographic coverage and the goal of relating the information to causative factors. In the absence of any knowledge about the statistical variances in concentrations for the target variables of interest, uniform geographic coverage could be accomplished by making the allocation of sites for each land-use strata proportional to the area it represents within the study unit; however, if information is available for the target variables, such that estimates of the variances for individual strata can be made and compared, then this information will be incorporated into the sampling design. Use of existing information may result in a less uniform density of sampling sites for small-order streams across a study unit but will result in more information in areas where the concentrations are expected to be the most variable.

The design of synoptic surveys for unstable flows (runoff events) is much more difficult because the timing, the duration, and the areal extent of runoff events is difficult to predict. Further, the effect of changing streamflow on concentrations of target variables must be determined to make interstation comparisons or to discern differences caused by other factors, such as land use. Sampling strategies to address these considerations at the study-unit scale are infeasible. Thus, the scope of synoptic surveys for runoff events will be focused on parts of a study unit (major tributaries or parts of the main stem) that can be sampled at enough sites and at a high enough frequency to allow comparisons among sites and identification of reaches that have major point- and nonpoint-source loadings of selected target variables. Over time (several 3-year active periods of investigation), project teams will attempt to sample runoff events of different magnitudes for different seasons for different parts of a study unit.

It is envisioned that about 5 to 10 sites will be sampled during a single storm event. The objectives of sampling at a site will be to estimate the flow-weighted average concentrations, peak concentrations, and storm loads of selected target variables. Sampling sites will include sites at the upstream and downstream ends of the reach, at major tributaries, and downstream from areas of fairly homogeneous land use. Preference will be given to any fixed-station sampling sites and sites where streamflow is monitored within the area.

Planning for runoff-event sampling will include a review of existing discharge records for sites to be sampled or other sites that have similar drainage area, physiography, climate, and land use to determine the range of conditions (duration, magnitude, and rate of change in discharge) for storms that might be expected to be sampled during the season. Knowledge of the range of conditions will be useful for scheduling of field crews and for estimating the frequency of sampling that will be needed at the different sites.

In addition to streamflow, other environmental factors need to be considered in the timing and the design of the synoptic surveys for certain target variables; for example, concentrations of dissolved oxygen in streams can vary widely in space and time in response to physical, chemical, and biological processes interacting in the water column, bed materials, and biota. These processes need to be considered in determining the appropriate season(s) for conducting a survey and times of day for sample collection. In much of the continental United States, the lowest concentrations of dissolved oxygen generally occur in late summer or early fall. This seasonal pattern is due to low streamflows that provide less dilution of oxygen-demanding wastes and high water temperatures that reduce the solubility of oxygen in water and result in higher rates of microbial oxidation of oxygen-demanding material. Consequently, the timing of synoptic surveys to describe dissolved-oxygen conditions in a study unit will be restricted to these conditions, which will increase the probability of detecting stream reaches that have significant dissolved-oxygen deficits. Another characteristic of dissolved-oxygen concentrations in streams that must be considered is the significant diurnal variations that can occur due to plant photosynthesis and respiration. To make intersite comparisons and to detect stream reaches that have significant dissolved-oxygen deficits, measurements will be made during a specified time window (2–3 hours) during the day when concentrations are lowest. Typically, these conditions occur in early morning before net photosynthesis begins. In some cases, the restricted time period for which a large number of sites must be sampled may preclude the possibility of sampling for other target variables at the same time.

The timing and the design of synoptic surveys for determining the occurrence and the distribution of trace elements and organic compounds also will be influenced by certain environmental factors; for example, surveys to determine the occurrence of water-soluble pesticides will be done during those seasons when the compounds are applied and are most likely to be detected. Bed-material synoptic surveys to determine the occurrence of trace elements and hydrophobic organic compounds will be done during periods of sustained low flow to increase the chances of sampling recently deposited material. Sampling locations will be carefully chosen to maximize the probability of detecting the target variables of interest; for example, sampling sites for water-soluble pesticides will include locations on small-order streams and irrigation drains near where the compounds are applied. Sampling sites for trace elements and hydrophobic organic contaminants will include depositional areas rich in organic matter, because these constituents and compounds are frequently found in association with fine-grained sediment that has a high organic carbon content. Water samples will be analyzed during the reconnaissance phase for the more persistent hydrophilic organic compounds including the chlorophenoxy-acid and triazine herbicides and acid-extractable compounds. Bed-material samples will be analyzed for the same lists of trace elements determined in water samples from fixed stations as well as organochlorine insecticides, gross PCB's, and other selected hydrophobic organic compounds.

Products from synoptic surveys will include information about the occurrence of potentially toxic trace elements and synthetic organic compounds in a study unit, maps showing sampling locations and concentrations of these and other target variables, and summary statistics for the study unit and for areas within the study unit that represent different land uses and geochemical terranes.

Studies of Selected Stream Reaches

During the course of the study-unit investigations, certain water-quality topics and questions will be identified from the analysis of available information and from the fixed-station and synoptic-sampling data that warrant more detailed study. Thus, some studies will be conducted to better understand the sources, the distribution, and the fate of particular constituents in selected stream reaches. Mathematical models may be useful in these types of studies to test understanding of cause-and-effect relations and to evaluate the outcome of alternative management strategies. Model results could be tested in later study cycles to determine if conditions have changed and if these changes correspond to prior understanding of the relevant biogeochemical processes at work. Some of these studies will be likely candidates for other programs of the Geological Survey, such as the Federal-State Cooperative Program and the National Research Program. Examples of studies that have been proposed as part of the pilot projects include the following:

- A detailed assessment of the lower reaches of the Des Plaines River in the Upper Illinois River Basin before and after implementation of the Tunnel and Reservoir Plan. The purpose would be to measure the changes in water quality caused by the temporary storage and the subsequent treatment of combined sewer overflows.
- An evaluation of the effects of changes in agricultural practices and management alternatives on the distribution, the transport, the fate, and the effects of triazine herbicides in selected reaches of the lower Kansas River basin.
- An investigation of the factors affecting the formation of trihalomethane compounds during chlorination of Kentucky River water. These compounds are carcinogenic and difficult to remove by using conventional water-treatment practices. Of particular interest is the effect of bromine and other constituents and compounds in brines produced during oil and gas production on the type and the rate of trihalomethane compounds produced.
- An assessment of the occurrence and the distribution of pesticides and selected inorganic constituents in shallow ground water in an agricultural subbasin of the Yakima watershed and their relation to concentrations in surface water.

Presentation of Results

Anticipated products of the surface-water investigations are listed by objective in table 8 along with an indication of the principal sampling activity that will be used to prepare each product and the relative degree of difficulty of preparation. Products will include (1) tables listing summary statistics of concentrations and estimates of loads and trends for target variables at individual sites and groups of sites that represent a particular area, land use, or other factor,

Table 8. *Anticipated products of the surface-water investigations for the National Water-Quality Assessment Program*

Objective	Principal design component	Examples of products	Relative degree of difficulty
1. Describe the occurrence and spatial distribution of a broad array of water-quality constituents.	Synoptic surveys	1. Maps showing locations of sampling sites and concentrations of water-quality constituents.	Low.
		2. Descriptive statistics of constituent concentrations within a drainage basin.	Do.
		3. Maps showing stream reaches that have persistent water-quality problems and reaches that have generally high-quality water.	Medium-high.
2. Estimate loads of selected water-quality constituents at key locations.	Fixed-station sampling.	1. Estimates of loads for selected constituents delivered from parts of the watershed.	Medium-high.
		2. Information on the portions of constituent loads derived from point, as compared to nonpoint, sources.	High.
3. Provide information on the seasonal variation and the frequency of occurrence of selected water-quality constituents at key locations.	Fixed-station sampling.	1. Descriptive statistics of constituent concentrations at sampling sites within a drainage basin.	Low.
		2. Frequencies of detection or exceedance of water-quality standards by site.	Do.
		3. Tests for significant differences in constituent concentrations among sampling sites or for different seasons.	Low-medium
4. Define long-term trends in the concentrations and (or) loads of selected constituents.	Fixed-station sampling.	1. Comparisons of descriptive statistics for a drainage basin with historic data and among high-activity periods.	Low.
		2. Maps showing general direction of trends (increasing, decreasing, no trend) and rate of change for sampling sites within a drainage basin.	Medium.
5. Identify, describe, and explain, as possible, the major factors that affect observed conditions and trends in surface-water quality.	All sampling activities.	1. Descriptive statistics of constituent concentrations, frequencies of occurrence, and loads grouped by various factors and tests for significant differences among groups.	Low-medium.
		2. Regression relations between water-quality characteristics and natural and human factors.	Medium.
		3. Explanations of observed conditions within a basin, such as the sources of constituents, factors influencing the losses of constituents, and the characteristics and factors influencing the stream ecosystem.	Medium-high.
		4. Explanations of similarities and differences in surface-water quality among drainage basins.	Do.
		5. Explanations of water-quality trends and their relation to causal factors, such as changes in land-management practices.	Do.

(2) graphs depicting relations of different factors to concentrations, loads, and trends for selected target variables, (3) maps showing the geographic distribution of median concentrations, frequencies of exceedance of criteria or standards, loads, and trends of selected target variables, and (4) explanations describing observed conditions and trends within a study unit and their relation to causal factors.

Similar products will be prepared for regional and national assessments. Multistudy-unit descriptions of current conditions and trends in surface-water quality will be prepared by aggregating comparable summary statistics and estimates for individual study units or for subbasins within study units. Insights into the major factors affecting surface-water quality will be gained by developing statistical relations that use comparable summary statistics and ancillary data from the study units.

DESIGN OF THE GROUND-WATER INVESTIGATIONS

Ground water flows in a heterogeneous, three-dimensional framework of geologic materials, and the patterns of flow can be complex. Whereas surface water generally is confined to a small percentage of an area, ground water can be found almost anywhere if drilling is done to sufficient depth. The resource can be sampled, however, only where a well is present, a test hole is drilled, or a spring or seep occurs. Moreover, only wells that meet certain criteria should be sampled (Barcelona and others, 1985; Gillham and others, 1983). Information on well construction and the local hydrogeology is needed for each well to properly interpret the sampling results and to assure that the well is suitable for sampling the constituents of concern. Logistical complications can occur—wells need to be inventoried over large areas and permission obtained for sampling from a large number of owners.

The chemical quality of ground water is a function of the quality of recharge water and the reactions that occur along the flow path, particularly between the moving fluids and the geologic materials. The spatial variability of ground-water quality tends to be very large, areally and with depth. Relative to surface water, however, two simplifying characteristics exist for ground water. First, ground-water velocities are generally low; thus, contaminants move slowly, and the quality of ground water tends to change slowly with time. Second, in the absence of movement of near-surface water down wells or their annuli and outside of karst or fractured-rock terraines, contamination from surface sources tends to diminish with depth. Most manmade contaminating substances have been heavily used only in the past half century. In many cases, these contaminants have not reached great depths because of the slow rate of ground-water flow; moreover, sorptive processes and the chemical and the biological transformations that occur in the subsurface retard the movement of many contaminants and attenuate their concentrations.

Objectives

Ground-water investigations conducted as part of the assessment program have the following major objectives, which are to:

1. Describe general ground-water quality conditions for major hydrogeologic settings,
2. Describe the geographic distribution within the study units of selected water-quality constituents and problem areas;
3. Define long-term trends in ground-water quality; and
4. Identify, describe, and explain, as possible, the major factors that affect observed current conditions and trends in ground-water quality.

Several major types of sampling activities will be undertaken in a study unit to achieve these objectives. These activities are (1) regional sampling for a wide array of water-quality constituents, (2) targeted sampling in selected locations of the study unit for specific groups of water-quality constituents, and (3) long-term sampling of selected wells.

Before describing these sampling activities, three key aspects of the ground-water investigations are discussed. These are the approach to rotating periods of intensive sampling with periods of low-intensity sampling, the importance of conducting the investigations within a hydrogeologic context, and the scope of the investigations, particularly in light of the large spatial variability of ground-water quality.

Timing and Duration of Investigations

Each high-activity period within a study unit will consist of 3 to 5 years of intensive sampling and data interpretation, followed by a year to complete reports. Because ground-water quality tends to change more slowly than surface-water quality, the duration of low-activity periods will likely exceed the 6 years planned for the surface-water activities and will vary among study units, depending upon the expected rates of change in ground-water quality and the nature of the water-quality problems. The purposes of the returns to the high-activity periods will be to improve the resolution of the spatial descriptions of ground-water quality, to apply techniques that have been developed since the last high-activity period, to adapt to changing water-quality concerns, and to document changes in water quality that have occurred since the previous intensive sampling period.

The low-activity periods will include lower intensity sampling and recordkeeping for important ancillary information, such as on pesticide and fertilizer usages and land-use changes. Long-term trends will be examined through continued sampling at a subset of those wells sampled during the high-activity periods. In addition, some investigative studies may be conducted to enhance the comparability of results among study units. Specific studies may be designed to verify findings of recent investigations in other similar study units or to explain significant similarities or differences discovered between study units.

A general flowchart of the study-unit investigations (fig. 6) illustrates the major interrelations among activities and objectives. The arrows indicate the general sequence of events. The first high-activity period is preceded by 1 to 2 years for project planning and for preliminary analysis of available data. Some initial reconnaissance sampling, such as a geochemical study to further define the movement of ground water in parts of the study unit, also might be done during this period.

Utility of Hydrogeologic Information

A conceptual hydrogeologic framework for each study unit is important to lay the foundation for judicious selection of sampling sites and proper interpretation of the water-quality measurements at each site; for example, hydrogeologic and geochemical data will be used to provide estimates of the age of ground water (time since recharge) and knowledge about the locations of recharge and (or) discharge areas, flow paths, hydraulic connections between aquifers, and how the flow paths are affected by pumping. This information is important to help identify those parts of the ground-water system that are most likely to be affected by human activities. In addition, a major unifying concept in providing national overviews of ground-water quality will be to place the observed water-quality results in the context of major hydrogeologic settings across the country.

Each project team will rely heavily on existing regional knowledge of hydrogeology and geochemistry. For most, if not all, projects, the hydrogeologic framework will have been described for the study unit through the RASA Program (Sun, 1986) or through other regional hydrogeologic investigations. However, additional hydrogeologic investigations will be necessary in some cases; for example, in some study units, further definition of shallow-flow systems may be necessary to understand the sources and the movement of contaminants to deeper aquifers.

Various types of data on the geochemical environment of the aquifer system will be valuable to the assessments. Often, geochemical data can be used to corroborate hydrogeologic results and vice versa. Knowledge of the geochemistry of major elements can help to explain the chemical reactions that affect the distribution of naturally occurring contaminants and, in general, how substances will react. In addition, sampling activities will sometimes include geochemical surveys of solid-phase materials, such as soils, cores, and drill cuttings. Attempts will be made to determine relations between the occurrence and concentrations of the constituents in ground water and both the distribution of constituents among the solid-phase materials and known geologic features.

Some samples will be analyzed for selected isotopic measurements (including hydrogen and oxygen isotopes) to provide information on flow paths and ages of water (International Atomic Energy Agency, 1983); for example, measurements of tritium (a hydrogen isotope associated with atmospheric testing of nuclear weapons) often can be used to estimate whether ground water withdrawn from a well is older or younger than about 1952. Many synthetic organic compounds were not manufactured before that time. Hence, ground waters that are estimated to be younger than 1952 may be more likely to contain synthetic organic chemicals than older water.

Scope of Investigations

Spatial Characterization

Ideally, the assessment program would provide a detailed three-dimensional characterization of water quality throughout all the aquifers of a study unit. Because this is infeasible, tradeoffs must be made in the proportion of sampling effort allocated to different parts of the ground-water system.

In general, each of the major aquifers of a study unit will be sampled to provide a statistical description of the water-quality conditions. More detailed sampling to further characterize the geographic distribution of water quality will be directed only toward selected parts of each ground-water system. Often, the initial sampling for this purpose will be focused on water-quality problems that occur either in the shallow parts of the more intensively used aquifers or in aquifers that are important sources of recharge to the principal water-use aquifers. Information on the distribution of water-quality problems at shallow depths will be combined with information on ground-water flow paths to provide guidance for sampling deeper ground water.

The quality of shallow ground water should be more likely than that of deeper ground water to exhibit correlations with the overlying land use and other measures of human activities. Thus, sampling of shallow ground water may be critical to the development of explanations of observed water-quality conditions.

Typically, for a given study unit, a few major hydrogeologic settings naturally arise from an analysis of general hydrogeologic information. Water-quality conditions often will be referenced to these settings. Some will correspond to aquifers, and others may be combinations of aquifers. Some thick aquifers may be subdivided into two or more hydrogeologic settings based on depth. To illustrate

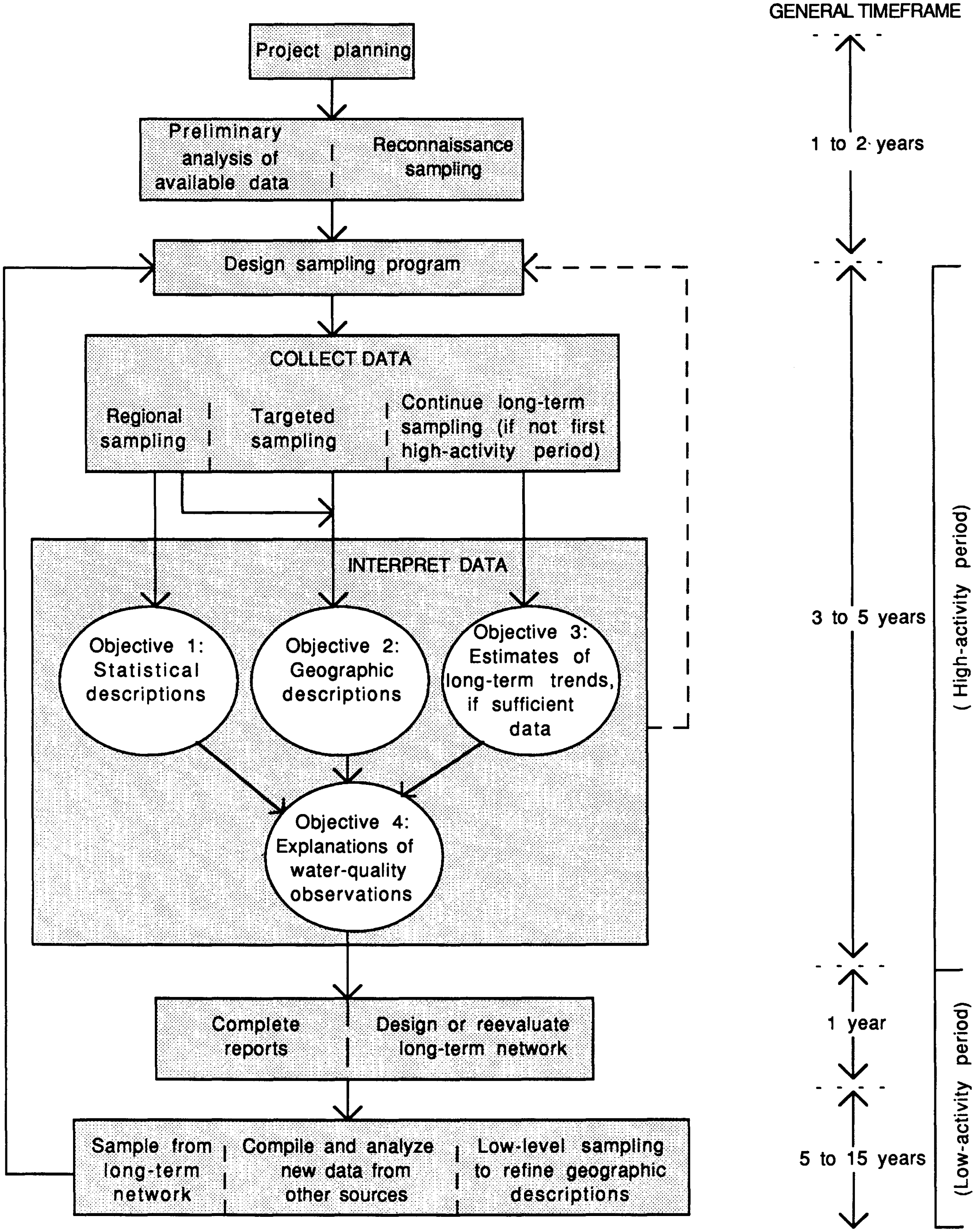

Figure 6. Interrelations among tasks and objectives for ground-water study-unit investigations for the National Water-Quality Assessment Program.

some of the concepts, the major hydrogeologic settings defined for the three ground-water pilot areas and an indication of the general allocation of sampling effort among these settings are discussed below.

The aquifer system of the Delmarva Peninsula consists of a relatively horizontal surficial aquifer and a sequence of nine underlying confined aquifers that dip generally eastward. The surficial aquifer is the main source of recharge to the underlying confined aquifers, supplies about one-half of the current ground-water use, and is more susceptible to contamination than the underlying aquifers. Furthermore, the majority of future development likely will come from the surficial aquifer because of limitations on well construction and water-level drawdowns in the confined aquifers (Cushing and others, 1973). For these reasons, sampling in the pilot program will focus on the surficial aquifer. Information obtained on the underlying aquifers will consist primarily of a statistical description of general water-quality conditions, as well as information on the potential for contaminants to move into the different deeper aquifers.

There are two major hydrogeologic settings for the Central Oklahoma pilot study area—alluvial and terrace deposits along major streams and a dipping bedrock aquifer. More detailed sampling in the Oklahoma City metropolitan area will focus on both the alluvial and terrace deposits and the shallow unconfined part of the bedrock aquifer. There are also concerns about elevated levels of naturally occurring trace elements and radionuclides. The distribution and principal causes of these high levels will be investigated in the bedrock aquifer in selected areas.

The third ground-water study unit, the Carson basin, is underlain by a variety of rocks that can be grouped broadly into (1) a series of interconnected basin-fill deposits in different alluvial valleys and (2) consolidated rocks that form both the mountainous uplands of the project area and the bedrock that underlies each alluvial valley. Virtually all the ground-water use is derived from the basin-fill aquifers; hence, the sampling will focus on this setting. Many of the ground-water quality concerns in the Carson basin are associated with naturally occurring trace elements, such as arsenic. The concentrations of these trace elements, as well as the extent of ground-water development, differ markedly among the different alluvial basins; thus, the sampling effort will be allocated differently among these basins. The effects of increased urban development on ground-water quality are of concern; therefore, as a case study, more detailed sampling will be done from shallow ground water in the vicinity of Carson City.

Temporal Characterization

Seasonal and other short-term variations in water quality generally are less important to the assessment of ground water than of surface water. Nevertheless, in some circumstances short-term variations in ground-water quality may be important (Pettyjohn, 1976; Schmidt, 1977); for example, pesticides are applied seasonally and may degrade considerably within weeks or months. In general, shallow ground water should exhibit the most pronounced short-term variability in water quality.

Initial sampling during a study-unit investigation will consist primarily of a single sample from each sampling well. As the investigations of each study unit evolve, specific hypotheses regarding monthly and seasonal variations in ground-water quality will be tested, as needed, through multiple sampling of selected wells, particularly those screened in shallow ground water. Seasonal sampling also will be conducted on wells that are being considered for inclusion in the long-term sampling network.

Sampling Activities

Regional Sampling

Regional sampling for a wide array of water-quality constituents will be conducted throughout each major hydrogeologic setting. These constituents will include most of, if not all, the target variables. The purposes of the regional sampling will be to provide descriptive statistics on the occurrence and the concentrations of the target variables for each major hydrogeologic setting and to form an initial basis for describing the geographic distribution of water-quality conditions within the study unit.

Regional sampling locations will be selected so as to be spatially distributed, areally and with depth, throughout each major hydrogeologic setting and to be unbiased with respect to known or suspected local problem areas. For the pilot program, 150 to 200 samples will be collected for each study unit as part of the first 2 years of regional sampling. These data will be used to provide the initial statistical summary information. The needs for subsequent regional sampling will be determined based on the results from this initial sampling.

Results from the regional sampling will be useful to provide a perspective on the extent of ground-water contamination in each hydrogeologic setting. Cartwright and Shafer (1987) noted "the majority of ground-water monitoring in the United States seems to be special purpose and provides a very biased sample of national ground-water quality and trends." At the national scale, the regional sampling results will be used to compare general water-quality conditions in various hydrogeologic settings across the Nation. Within study units, broad spatial relations determined from the regional sampling and from existing data will be used as a frame of reference to interpret results from targeted samplings of particular areas. The regional sampling results also could be used to supplement background information for site-specific studies conducted by others; for example, some constituents of interest are ubiquitous in certain areas. Without knowing these "background" levels, it is sometimes difficult to delineate contaminated areas.

Targeted Sampling

The problem of characterizing the geographic distribution of water-quality problem areas is one of the most challenging objectives of the assessment program. The problem is complicated by the high spatial variability of ground-water quality in general and of contaminated ground-water quality in particular. Simple use of very intensive areal sampling will not produce meaningful results within the funding and the personnel constraints of the assessment. Instead, it is important to have a major aspect of the investigations in which wells are selected for sampling based on knowledge of factors likely to control the distribution of particular types of contaminants in ground water.

Thus, targeted sampling of known or suspected water-quality problem areas will be used to examine the spatial distribution of selected, broadly defined groups of water-quality constituents (selected target variables), such as agricultural chemicals, contaminants associated with urban and suburban areas, or naturally occurring trace elements. The targeted sampling approaches will be tailored to the major hydrogeologic and land-use factors that affect ground-water quality in different situations. Similar designs for targeted sampling will be applied, however, to selected study units to permit multistudy-unit comparisons within and across particular regions of the country. As successful techniques are developed in one study unit, they will be applied to similar situations in other study units.

Three general approaches will be used, either individually or in combination. These are search-oriented sampling within particular areas of concern, sampling to test particular statistical hypotheses about the regional distribution of contaminants, and sampling along local scale transects of wells. The targeted sampling activities for the three pilot projects are listed in table 9.

Search-oriented sampling will involve sampling for selected constituents within the particular settings in which they are most expected; these efforts usually will be iterative, and will involve multiple-sampling sequences. In some cases, indicator variables that are relatively inexpensive to measure will be used at the outset to help identify potential problem areas. Initially, the searches will be based on general knowledge about sources of the constituents and the controlling hydrogeologic and soil characteristics. As knowledge increases, it may be possible to design statistical search procedures.

The second targeted sampling approach will involve testing particular hypotheses about the regional distribution of contaminants in a statistical hypothesis-testing framework. Examples of these types of studies are reported by Cain and others (in press); for example, a sampling program could be designed to examine ground-water quality underlying areas that have different land-use practices or within different depth zones. Sometimes this approach to sampling will be used to test hypotheses based on statistical relations found in the initial phases of sampling.

The above two approaches will be conducted at scales that vary widely in size, from several hundred square miles to areas that approach the size of the study unit. The third approach, which will often supplement such regional scale investigations, is to sample a higher density of wells (generally, one or more wells per square mile) along local scale transects. The purpose of these studies will be to characterize representative settings that are commonly occurring throughout a large part of the study unit. These studies often will involve locating wells along shallow ground-water flow paths (hundreds of feet to several miles

Table 9. *Targeted sampling activities for the ground-water pilot projects of the National Water-Quality Assessment Program*

Pilot project	Sampling activity	Principal approach
Carson basin	More detailed sampling of shallow ground water underlying the Carson City area.	Statistical hypothesis testing and (or) search-oriented sampling.[1]
	Higher density sampling along shallow ground-water transects in major alluvial valleys.	Local scale transects.
Central Oklahoma aquifer	More detailed sampling to define the distribution and the causes of elevated levels of naturally occurring trace elements and radionuclides.	Search-oriented sampling.
	More detailed sampling in shallow ground water underlying the Oklahoma City area.	Statistical hypothesis testing and (or) search-oriented sampling.[1]
Delmarva Peninsula	Higher density sampling along shallow ground-water transects in six distinct regions of the surficial aquifer.	Local scale transects.

[1]Design currently under development (1988).

in length). Results from the local scale studies will help to place observed regional water-quality variations in the context of smaller scale variability and to identify local scale features that may have a major effect on regional water quality. It will be possible, for example, to develop more detailed ancillary data bases for the local scale study areas than is feasible for the entire study unit. This information can lead to identification of key factors that were not originally considered in the regional scale interpretations. Factors identified in these local scale studies then will be tested for correlations with water quality at the regional scale. Local scale studies also may be very useful for examining the effects of surface-water quality on ground-water quality and vice versa.

As an example of the use of local scale studies, the surficial aquifer of the Delmarva Peninsula has been subdivided by the project team into six regions that are based on a combination of factors that include geologic and geomorphic characteristics, soils, degree of drainage, and land use. These regions will be tested for differences in water quality by using regional scale data. In addition, local scale networks are being installed in selected areas within each of these regions to examine differences in local scale ground-water-quality patterns. Hydrogeologic and geochemical data also will be collected from these local scale networks to examine differences among the regions in recharge patterns and in the size and the vertical penetration of shallow ground-water flow systems. This information will be useful to evaluate the potential for shallow contamination to move into the underlying aquifers. Dependent on the outcome of these studies, additional focus may be placed on individual confined aquifers during future high-activity periods.

Long-Term Sampling

Temporal trends in ground-water quality will be examined by using data from a long-term sampling network that is established in each study unit at the conclusion of the first high-activity period. In addition, some sampling activities within selected study units will be repeated over several high-activity periods to supplement the long-term network.

Selection criteria for the long-term sampling wells will be established to assure a distribution of wells that represent ground water of different ages and hydrogeologic settings. As a basis for selection, candidate wells will be assigned to different age groups based on the estimated age of the ground water; for example, less than 1 year, 1 to 30 years, 30 to 100 years, and greater than 100 years. A set of wells then will be selected from each age group; a greater percentage of the wells will be from the younger groups. Wells screened in the upper part of water-table aquifers may be particularly useful for early detection of contamination from surface sources and for relating observed trends to changes in land-use practices. In addition to long-term sampling from a regionally distributed set of wells, sampling also will continue from wells in some of the local scale networks.

The frequency of long-term sampling will vary among wells. Initially, wells under consideration will be sampled seasonally or monthly for selected constituents to examine seasonal and other short-term variations in water quality that might confound identification of long-term trends. Some wells that are initially selected to sample very young water and that have considerable short-term variability in water quality might be dropped from the long-term network. For wells in the eventual network, those that contain younger water will be sampled more frequently than wells that contain older water, because conditions in the former are likely to change more rapidly. After the initial sampling periods, the interval between sampling may be extended to as long as several years for many wells.

Analyses of samples to determine long-term trends will emphasize the current set of target variables. At individual wells, target variables that occur below environmentally significant concentrations or that are not detected will be analyzed much less frequently than those occurring at greater concentrations.

Finally, because long-term sampling will continue during the low-activity periods, the approach will continually provide data that are useful for making concurrent statistical comparisons of water quality among study units.

Presentation of Results

Interpretive reports will be published as part of each study-unit investigation, and periodic reports will be published that present interpretations at multistudy-unit and national scales. As appropriate, these reports will integrate information from surface- and ground-water studies.

Examples of products associated with each of the objectives of the ground-water-quality investigations are listed in table 10. The relative degree of difficulty in developing each of these products is also indicated in this table.

For each objective, different approaches will be used to aggregate the results to the multistudy-unit and the national scales. Information about general conditions and trends in ground-water quality (objectives 1 and 3, table 10) will be aggregated by providing comparable statistical descriptions for each major hydrogeologic setting. Information used to describe the geographic distribution of water quality within study units (objective 2, table 10) will be aggregated primarily by comparing results from targeted sampling designs that have been applied to selected study units. Finally, information on major factors that affect ground-water quality (objective 4, table 10) will be aggregated through development of statistical relations that use consistent ancillary data. In addition, key explanatory results that may have significant implications at broader scales will be summarized for each study unit.

National reports will include, for each key water-quality constituent, a U.S. map that shows the major

Table 10. *Anticipated products of the ground-water investigations for the National Water-Quality Assessment Program*

Objective	Principal sampling activity	Examples of products	Relative degree of difficulty
1. Describe general ground-water quality conditions for major hydrogeologic settings.	Regional sampling	1. Descriptive statistics of constituent concentrations by hydrogeologic setting.	Low.
		2. Frequencies of detection or exceedance of water-quality standards by major hydrogeologic setting.	Do.
		3. Tests for significant differences in constituent concentrations among major hydrogeologic settings.	Do.
2. Describe the geographic distribution within the study units of selected water-quality constituents and problem areas.	Targeted sampling that builds on regional sampling.	1. Maps showing locations of sampling wells and results of water-quality analyses.	Low.
		2. Descriptive statistics for different areal and depth zones and tests for significant differences.	Medium.
		3. Illustrations showing water-quality variations with depth.	Do.
		4. Cross sections showing variations in water quality along transects.	Do.
		5. Maps showing general delineation of areas with a particular type of water-quality problem.	Medium-high.
		6. Maps showing areal and depth zones of different water quality.	High.
3. Define long-term trends in ground-water quality.	Long-term sampling	1. Comparisons of descriptive statistics among high-activity periods.	Low.
		2. Figures showing changes over time in the relation between water quality and depth.	Medium.
		3. Maps showing general direction of trends (increasing, decreasing, no trend) and rate of change by major hydrogeologic setting.	Do.
4. Identify, describe, and explain, as possible, the major factors that affect observed current conditions and trends in ground-water quality.	All sampling activities.	1. Descriptive statistics of constituent concentrations and frequencies of occurrence grouped by various factors and tests for significant differences among groups.	Low-medium.
		2. Regression relations between water-quality characteristics and natural and human factors.	Medium.
		3. Maps, cross sections, or both showing hydrogeologic factors that can affect the vulnerability of ground water to contamination.	Do.
		4. Maps, cross sections, or both showing different age zones of ground water.	Do.
		5. Explanations of observed conditions within major hydrogeologic settings.	Medium-high.
		6. Explanations of similarities and differences in ground-water quality among major hydrogeologic settings.	Do.
		7. Explanations of water-quality trends and their relation to causal factors, such as changes in land-management practices.	High.

hydrogeologic settings sampled by the program and indicates the relative concentrations of the constituent in each of the hydrogeologic settings. As the program evolves, similar maps will be included to summarize and display the results of trend analyses for particular constituents within each hydrogeologic setting. Certain hydrogeologic settings will be identified by these national scale maps as having relatively high concentrations or trends in particular constituent(s). These identified settings often will be the focus of more detailed descriptions and presentations of explanatory results in the national reports. For some other hydrogeologic settings, however, the maps of descriptive statistics may indicate relatively low constituent concentrations in general, but there are particular areas of high concentrations. Key results from these areas also will be presented in the national summaries. The end result will be a broad overview of general conditions and trends in the constituent concentrations across the Nation and more detail provided for particular areas of concern.

SUMMARY

During recent decades, the Nation has made major investments in water-quality management and protection, and the potential is there for much larger investments in the future. During the same period, considerable sums of money also have been spent on water-quality data acquisition for various purposes. However, to date, no cohesive program exists that can provide consistent information on the status, the trends, and the causes of surface- and ground-water-quality conditions across the country. This information is needed to determine the effects of past investments in water-quality improvement and to provide a sound basis for future decisions. The NAWQA Program described in this report is designed to provide the needed information.

The NAWQA Program will be conducted at a combination of spatial and temporal scales that are unique for water-quality assessment. The large spatial scales (river basins and aquifer systems) and long temporal scales (multiyear and decadal) are critical to allow the program to address the factors that give rise to different types of widespread water-quality problems and to address long-term trends in water quality. The program will not diminish the need for smaller scale studies and monitoring presently designed and conducted by State, Federal, and local agencies to meet their individual needs. The program, however, will provide a larger scale framework for conducting many of these activities and a knowledge about regional and national water-quality conditions that cannot be acquired from individual smaller scale programs and studies.

The design of the NAWQA Program differs significantly from any other assessment activities. By conducting the national program as an aggregation of individual studies of key river basins and aquifer systems, the assessment will provide results that are useful in understanding and managing these important water resources, as well as in answering national questions about water quality. The program will build on knowledge gained from an analysis of existing data but will also collect new data, as necessary, to achieve the program's goals. The results of the NAWQA Program will be based primarily on physical, chemical, and biological measurements of waters in streams and aquifers. Professional judgements, mathematical model output, and effluent data will be used, but will not be the sole basis for conclusions. Perhaps most importantly, many assessments have involved interpretation and reporting of results by persons other than those who collect the data. In this assessment, the development of interpretations and the communication of findings is done largely by those who collect the data. The design is based on the philosophy that integration of data collection and data interpretation is the key to assuring that the data are of high quality and that they are continually evaluated, thus leading to relevant and meaningful interpretations.

Information to be provided by the NAWQA Program will help to answer some of the major questions concerning the Nation's water quality. The intent is for the Geological Survey to provide information through the NAWQA Program that those who set policy, write regulations, establish priorities, or manage water resources can use. Information on the status, the trends, and the causes of water-quality conditions across the country should be particularly useful to other agencies who are involved in (1) identifying key substances for possible regulation and for which research is needed on toxicity, human exposure, and drinking-water treatability, (2) allocating budgetary resources among competing types of water-quality problems, (3) determining whether the desired goals for water-quality improvement are being met, (4) designing monitoring programs in different parts of the country (in terms of the constituents analyzed, sampling locations, sampling frequency, and timing of sampling), (5) targeting regulations for selected water-quality constituents to particular geographic regions or hydrologic settings, (6) determining the relative effects on water quality of various types of point and nonpoint sources, (7) identifying aquifers requiring different types and degrees of water-quality protection, and (8) evaluating management practices in terms of their large-scale effects on the water quality of river basins and aquifer systems.

At present (1988), the assessment program, which is in a pilot phase, has investigations under way in seven project areas. In 1990, a committee of the National Academy of Sciences will complete an evaluation of the design and the potential utility of the program. A decision about proceeding to full-scale implementation will be made upon completion of this evaluation.

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