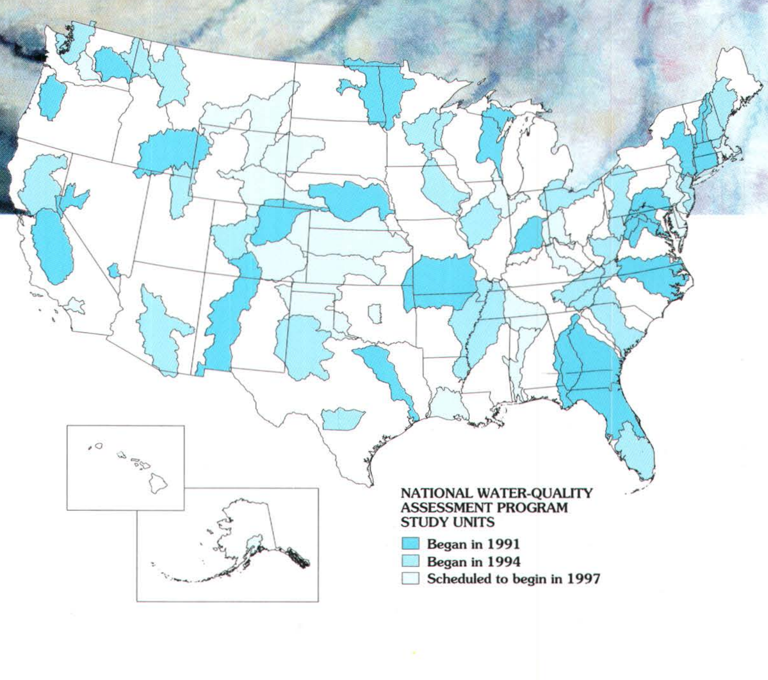
Design of the National Water-Quality Assessment Program:
Occurrence and Distribution of Water-Quality Conditions



U.S. Geological Survey Circular 1112

Cover: South Yuba River, Sacramento River Basin.

Pastel by Susan H. Cooley-Gilliom

Design of the National Water-Quality Assessment Program: Occurrence and Distribution of Water-Quality Conditions

By Robert J. Gilliom, William M. Alley, and Martin E. Gurtz

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Multiply	By	To obtain
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	0.3861	square mile (mi^2)

GLOSSARY OF STUDY COMPONENTS

Basic Fixed Sites—Sites on streams at which streamflow is measured and samples are collected to assess the broad-scale spatial and temporal character and transport of inorganic constituents of streamwater in relation to hydrologic conditions and environmental settings. Data from these sites are the primary source of information for meeting water-column assessment objectives for temperature, salinity, suspended sediment, major ions and metals, nutrients, and organic carbon. Three types of water-column sampling activities—continuous monitoring, fixed-interval sampling, and extreme-flow sampling—are conducted for 2 years during each cycle of investigation. Reach assessments of ecological conditions and bed-sediment and tissue sampling also are conducted at these sites. Study Units usually have 8–12 Basic Fixed Sites.

Bed-Sediment and Tissue Studies—Assessment of concentrations and distributions of trace elements and hydrophobic organic contaminants in streambed sediment and tissues of aquatic organisms to identify potential sources and to assess spatial distribution. Studies are divided into two phases—the Occurrence Survey and the Spatial Distribution Survey.

Case Studies—Detailed studies of selected contaminants in selected hydrologic systems to address specific questions that concern the characteristics, causes, and governing processes of water-quality degradation.

Ecological Studies—Studies of biological communities and habitat characteristics to evaluate the effects of physical and chemical characteristics of water and hydrologic conditions on aquatic biota and how biological and habitat characteristics differ among environmental settings in Study Units. Ecological Studies have three main components—Fixed-Site Reach Assessments, Intensive Ecological Assessments, and Ecological Synoptic Studies.

Ecological Synoptic Studies—Short-term investigations of specific ecological characteristics within all or part of a Study Unit to provide improved spatial resolution and representativeness compared with fixed-site sampling, and to evaluate the spatial distribution of selected ecological characteristics in relation to causative factors, such as land uses or contaminant sources and instream habitat conditions. These studies supplement information derived from the more comprehensive data collected at Basic and Intensive Fixed Sites by targeting specific and more narrowly defined seasonal and habitat conditions for ecological characterization at more locations. One to two Ecological Synoptic Studies are conducted in most Study Units.

Environmental Framework—Natural and human-related features of the land and hydrologic system, such as geology, land use, and habitat, that provide a unifying framework for making comparative assessments of the factors that govern water-quality conditions within and among Study Units.

Environmental Setting—Land areas characterized by a unique, homogeneous combination of natural and human-related factors, such as row-crop cultivation on glacial-till soils.

Fixed-Site Reach Assessments—One-time assessments of biological communities and habitat conditions of a stream reach at all Basic and Intensive Fixed Sites.

Flowpath Studies—Assessments of the spatial and temporal distribution of ground-water quality in relation to ground-water flow and land use in shallow aquifer systems for selected Environmental Settings. Flowpath Studies contribute to understanding the natural processes and human factors that control the evolution of ground-water quality along flowpaths through the saturated zone and to evaluate the degree and water-quality significance of interaction between ground water and streams. Typically, one to two Flowpath Studies are undertaken in each Study Unit during the first NAWQA cycle, with most in Land-Use Study areas.

Indicator Sites—Stream sampling sites located at outlets of drainage basins with homogeneous land use and physiographic conditions. Basins are chosen to be as large and representative as possible while still encompassing primarily one Environmental Setting (typically 50–500 km^2).

Integrator Site—Stream sampling sites located downstream of drainage basins that are large and complex and often contain multiple Environmental Settings. Most Integrator Sites are on major streams with drainage basins that include a substantial portion of the Study Unit area (typically 10–100 percent).

Intensive Ecological Assessments—Annually repeated Fixed-Site Reach Assessments for at least three reaches for 3 or more years at selected Basic and Intensive Fixed Sites.

Intensive Fixed Sites—Basic Fixed Sites with increased sampling frequency during selected seasonal periods and analysis of dissolved pesticides for 1 year. Most Study Units have one to two integrator Intensive Fixed Sites and one to four indicator Intensive Fixed Sites.

Land-Use Studies—Investigations of the concentrations and distribution of water-quality constituents in recently recharged ground water (generally less than 10 years old) associated with the most important regionally significant Environmental Settings of land use and hydrogeologic conditions in each Study Unit. For each study, usually a combination of 20–30 shallow existing and observation wells are sampled. Two to four studies typically are completed in each Study Unit during the first cycle of NAWQA.

National Synthesis—Synthesis of results from all Study Units with information from other programs, agencies, and researchers to produce regional and national assessments for priority water-quality issues.

Occurrence and Distribution Assessment—Assessment of the broad-scale geographic and seasonal distributions of water-quality conditions for surface and ground water of a Study Unit in relation to major contaminant sources and background conditions. This assessment is the largest and most important component of the first intensive study phase in each Study Unit.

Occurrence Survey—The first phase of study of trace elements and hydrophobic organic contaminants in streambed sediment and tissues of aquatic organisms to determine which target constituents are common and important to water-quality conditions in each Study Unit. Typically, all Basic and Intensive Fixed Sites and 5–10 additional sites are sampled.

Retrospective Analysis—The review and analysis of existing water-quality data to provide a historical perspective on the water quality in the Study Unit, to assess strengths and weaknesses of available information, and to evaluate initial implications for water-quality management and study design.

Spatial Distribution Survey—Extension of the Occurrence Survey for bed sediments and tissues to improve geographic coverage with particular emphasis on assessment of priority constituents identified in the Occurrence Survey. Occurrence Survey results, combined with existing data, govern the analytical strategy and the geographic distribution of sampling sites. The combined data from the two phases of sampling, typically collected from 20–30 sites, provide a basic description of spatial distribution of trace elements and hydrophobic organic contaminants for each Study Unit and support initial evaluation of sources and biological availability for selected constituents.

Study Unit—A major hydrologic system of the United States in which NAWQA studies are focused. Study Units are geographically defined by a combination of ground- and surface-water features and usually encompass more than 10,000 km^2 of land area. The NAWQA design is based on an assessment of 60 Study Units, which collectively cover a large part of the Nation, encompass the majority of population and water use, and include diverse hydrologic systems that differ widely in natural and human factors that affect water quality.

Study-Unit Investigation—The systematic study of a NAWQA Study Unit. These investigations consist of four main components: Retrospective Analysis, Occurrence and Distribution Assessment, Trend and Change Assessment, and Case Studies. Study Units are organized into three groups of 20 that are studied on a rotational schedule, with 3-year intensive study periods repeated once every 9 years.

Study-Unit Survey—Broad assessment of the water-quality conditions of the major aquifer systems of each Study Unit. The Study-Unit Survey relies primarily on sampling existing wells and, wherever possible, on existing data collected by other agencies and programs. Typically, 20–30 wells are sampled in each of three to five aquifer subunits.

Trend and Change Assessment—Decadal scale trends and changes in water-quality conditions will be assessed by using a combination of existing historical data, periodic intensive assessments, and selected long-term monitoring strategies.

Water-Column Studies—Investigations of physical and chemical characteristics of stream water, which include suspended sediment, dissolved solids, major ions and metals, nutrients, organic carbon, and dissolved pesticides, in relation to hydrologic conditions, sources, and transport. These studies also involve selected studies of other water-quality conditions and include selective investigations of hydrophobic organic contaminants or trace elements where their importance is indicated by results of Bed-Sediment and Tissue Studies. Water-Column Studies have three main components—Basic and Intensive Fixed-Site Assessments and Water-Column Synoptic Studies.

Water-Column Synoptic Studies—Short-term investigations of specific water-quality conditions during selected seasonal or hydrologic periods to provide improved spatial resolution for critical water-quality conditions compared to fixed-site sampling. For the period and conditions sampled, they assess the spatial distribution of selected water-quality conditions in relation to causative factors, such as land use and contaminant sources, through mass-balance analysis of sources and transport. During the first 3-year intensive study period, two to three Water-Column Synoptic Studies are included in most Study-Unit Investigations.

Design of the National Water-Quality Assessment Program: Occurrence and Distribution of Water-Quality Conditions

By Robert J. Gilliom, William M. Alley, *and* Martin E. Gurtz

Abstract

The National Water-Quality Assessment Program of the U.S. Geological Survey is designed to assess the status of and trends in the quality of the Nation's ground- and surface-water resources and to link the status and trends with an understanding of the natural and human factors that affect the quality of water. The study design balances the unique assessment requirements of individual hydrologic systems with a nationally consistent design structure that incorporates a multiscale, interdisciplinary approach. The building blocks of the program are Study-Unit Investigations in 60 major hydrologic basins (Study Units) of the Nation. The Occurrence and Distribution Assessment is the largest and most important component of the first intensive study phase in each Study Unit.

The goal of the Occurrence and Distribution Assessment is to characterize, in a nationally consistent manner, the broad-scale geographic and seasonal distributions of water-quality conditions in relation to major contaminant sources and background conditions. The national study design for surface water focuses on water-quality conditions in streams, using the following interrelated components:

- Water-Column Studies assess physical and chemical characteristics, which include suspended sediment, major ions and metals, nutrients, organic carbon, and dissolved pesticides, and their relation to hydrologic conditions, sources, and transport.
- Bed-Sediment and Tissue Studies assess trace elements and hydrophobic organic contaminants.
- Ecological Studies evaluate the relations among physical, chemical, and biological characteristics of streams.

Sampling designs for all three components rely on coordinated sampling of varying intensity and scope at Integrator Sites, which are chosen to represent water-quality conditions of streams with large basins that are often affected by complex combinations of land-use settings, and at Indicator Sites, which are chosen to represent water-quality conditions of streams associated with specific individual Environmental Settings. The national study design for ground water focuses on water-quality conditions in major aquifers, with emphasis on recently recharged ground water associated with present and recent human activities, by using the following components:

- Study-Unit Surveys assess the water quality of the major aquifer systems of each Study Unit by sampling primarily existing wells.
- Land-Use Studies use observation wells and selected existing wells to assess the quality of recently recharged shallow ground water associated with regionally extensive combinations of land use and hydrogeologic conditions.
- Flowpath Studies use transects and groups of clustered, multilevel observation wells to examine specific relations among land-use practices, ground-water flow, and contaminant occurrence and transport and interactions between ground and surface water.

In selected locations, ground-water studies are codesigned with streamwater-quality studies to investigate interactions between ground and

surface waters. Overall, the broad range of coordinated spatial and temporal strategies employed for surface-water and ground-water assessments is designed to describe the most important aspects of water quality in a consistent manner for the wide range of hydrologic environments of the Nation.

INTRODUCTION

Over the past two decades, repeated evaluations of available water-quality information have reached the conclusion that the United States needs long-term national water-quality assessment to support effective water policy and management (Wolman, 1971; James and others, 1983; Cohen and others, 1988; National Research Council, 1990). Agreement on how to assess water quality on a national scale, however, has been much more elusive. One view is that a national water-quality assessment should be done by a national statistical design with prescribed rules for the location and timing of sampling and uniform methods and analyses; for example, Van Belle and Hughes (1983). A contrasting view is that each hydrologic system requires a custom-designed assessment that is based on its unique hydrologic features and human influences (U.S. General Accounting Office, 1981). National statistical designs are best suited for producing consistent descriptions of and monitoring large-scale water-quality conditions that are persistent over time. They tend to be poorly suited for assessing conditions that are short lived or unevenly distributed and for explaining causes and effects. Studies that are custom designed for each system can better assess specific water-quality conditions that are variable and short lived and are suited for explaining causes and effects; however, results for different systems cannot be consistently compared, which makes regional- and national-level assessment of patterns and trends in water-quality conditions difficult or impossible.

The National Water-Quality Assessment (NAWQA) Program of the U.S. Geological Survey (USGS) is designed to describe the status of and trends in the quality of the Nation's ground-water and surface-water resources and to link assessment of status and trends with an understanding of the natural and human factors that affect the quality of water. The design is based on balancing the unique assessment requirements of individual hydrologic systems with a nationally consistent design structure that incorporates a multiscale, interdisciplinary approach for ground water and surface water. By linking assessment of status and trends with an understanding of processes and causes that operate at various spatial and temporal scales, NAWQA can contribute most meaningfully to policies and management actions that improve water quality. The program integrates information about water quality at a wide range of spatial scales, from local to national, and focuses on water-quality conditions that affect large areas of the Nation, such as nutrients and pesticides associated with large agricultural regions, or that occur in many small areas, such as nutrients and pesticides associated with urban areas. Hirsch and others (1988) and Alley and Cohen (1991) discussed the conceptual design of NAWQA and its relation to other programs and design alternatives.

The building blocks of the NAWQA Program are Study-Unit Investigations in 60 major hydrologic basins (Study Units) of the Nation (fig. 1) (Leahy and others, 1990). The glossary at the front of this report includes brief definitions of all study components and related key terms used to describe the design, which are indicated throughout the report with capital first letters. The 60 NAWQA Study Units cover about one-half of the conterminous United States, encompass 60–70 percent of national water use and of the population served by public water supplies, and include diverse hydrologic systems that differ widely in the natural and human factors that affect water quality. This selection of Study Units ensures that the most important national water-quality issues can be addressed by comparative studies. The Study Units are divided into three groups, which are intensively studied on a rotational schedule (fig. 2). The first cycle of assessment for each group of 20 Study Units consists of 2 years of initial planning and Retrospective Analysis of existing data, 3 years of intensive data collection and analysis, and 6 years of report preparation and low-level assessment activity before the second cycle of intensive data collection and analysis begins. One-third of the Study Units are in the intensive study phase at any given time, and the decadal cycle is repeated perennially. The first complete cycle of intensive investigations of all 60 Study Units is scheduled to be completed in 2002.

The national assessment goals of NAWQA will be accomplished in two main ways. First, the accumulation of consistent and comparable perennial water-quality assessments for 60 of the largest and most

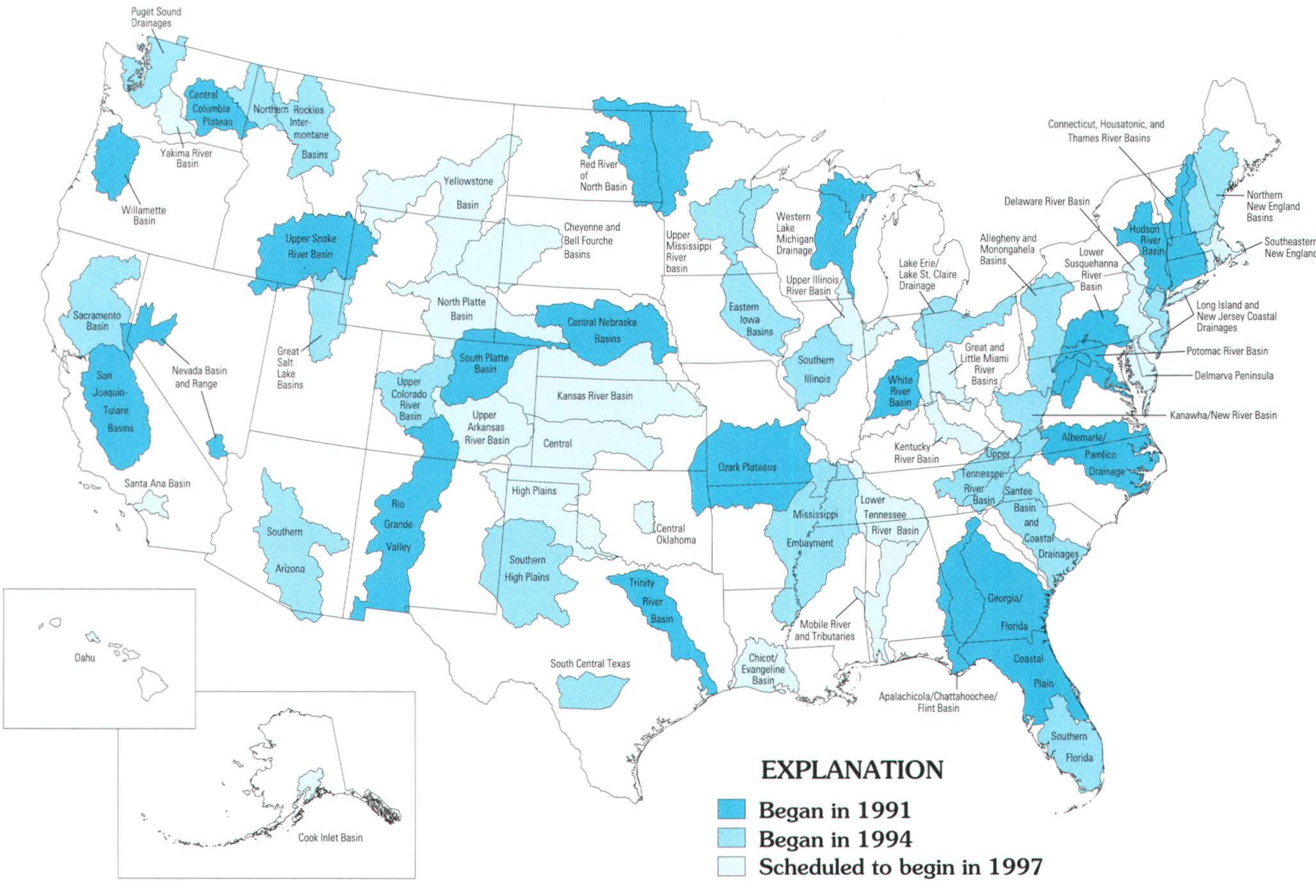

Figure 1. Study Units of the National Water-Quality Assessment.

significant hydrologic systems of the Nation will stand alone as a major contribution to our knowledge of regional and national water-quality conditions. Second, National Synthesis builds on and expands the findings from individual Study Units by interpreting results from multiple Study Units, as well as existing information from studies of USGS and other agencies and researchers, to produce regional and national assessments for priority water-quality issues. National Synthesis develops comprehensive assessments issue by issue at the national scale by comparative analysis of Study-Unit findings. Two to three major water-quality topics are simultaneously targeted for National Synthesis design and interpretation during 6- to 9-year periods in a rotational schedule with other topics. Pesticides and nutrients are the first two intensively studied National Synthesis topics, which began in 1991; the third topic, which will begin in 1994, is volatile organic contaminants; and plans are being developed for stream ecology.

External coordination at all levels is an integral component of the NAWQA Program. Information exchange and coordination through Study-Unit liaison committees help ensure that the water-quality information produced by the program is relevant to regional and local interests. The liaison committees are comprised of non-USGS members who represent a balance of technical and management interests. Represented organizations will include, as appropriate, Federal, State, interstate, and local agencies; Indian Nations; and universities. In addition, a national Federal/non-Federal advisory subcommittee specifically designated for the NAWQA Program ensures that Federal and non-Federal interests and needs at the regional and national levels are met.

Overview of Study-Unit Investigations

Study-Unit Investigations are designed to meet National Synthesis requirements for consistent and integrated information and Study-Unit requirements for assessing water quality with sufficient flexibility to adapt to local conditions. Each Study-Unit Investigation consists of four interrelated components:

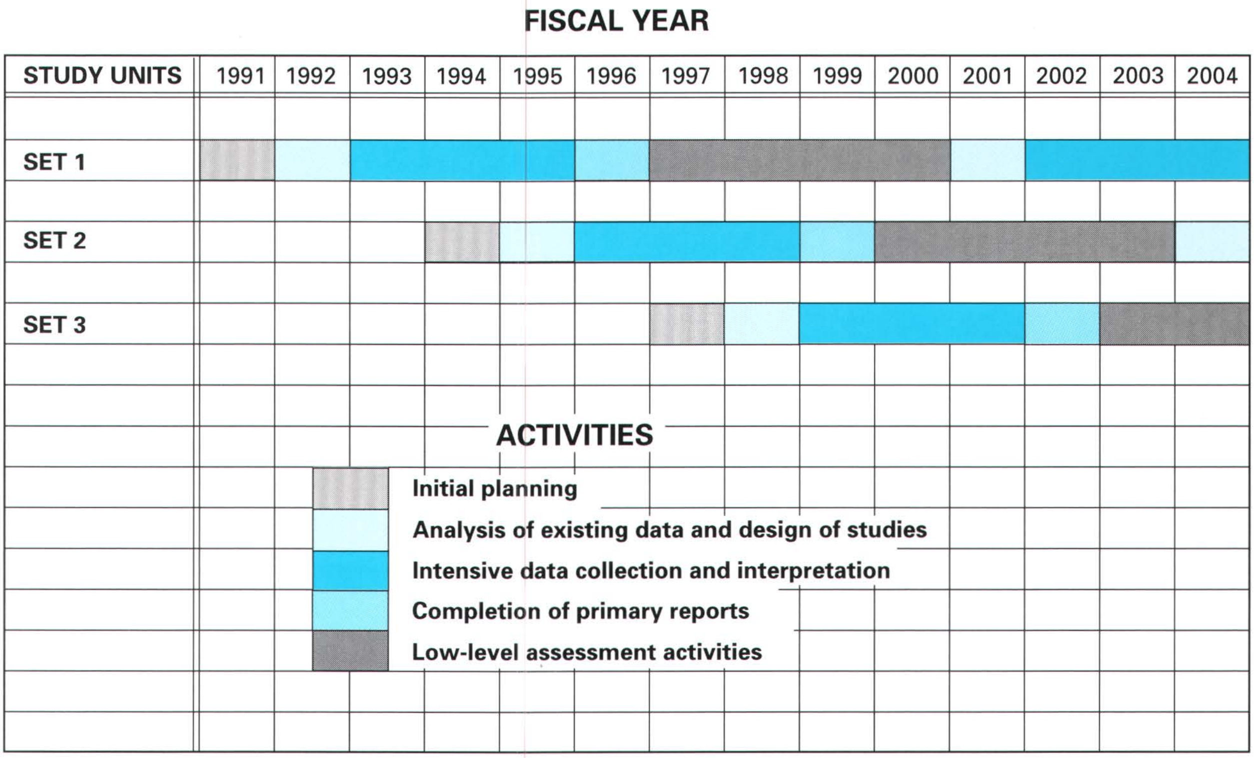

Figure 2. Phased implementation of Study-Unit Investigations.

- *Retrospective Analysis.* The review and analysis of existing water-quality data provide a historical perspective on water quality in the Study Unit and are used to assess strengths and weaknesses of available information and to evaluate initial priorities for water-quality management and study design.
- *Occurrence and Distribution Assessment.* This component characterizes the broad-scale geographic and seasonal distributions of water-quality conditions in relation to major point and nonpoint contaminant sources and natural or background conditions. A key objective is to fill gaps in existing data for each Study Unit. Design features, such as chemical constituents measured, media sampled, and spatial and temporal resolution, are consistent among the Study Units. The Occurrence and Distribution Assessment is the largest and most important component of the first 3-year intensive study phase in each Study Unit and serves as the basis for the design of assessments of long-term trends and changes and of more detailed case studies of specific water-quality issues.
- *Trend and Change Assessment.* Long-term trends and changes in water-quality conditions are assessed on a decadal scale in each Study Unit. Sampling strategies and coordinated efforts with other programs and agencies are designed from the combined results of Retrospective Analyses and Occurrence and Distribution Assessments, and the concurrent development of information on changes in land use, point sources, and other factors related to changes in contaminant sources. Historical trends and changes will be selectively assessed during the first cycle of each Study-Unit Investigation by using existing data. The Trend and Change Assessment will later be based on data collected between intensive study phases and on data from successive 3-year intensive phases.
- *Case Studies of sources, transport, fate, and effects.* Case Studies are detailed studies of

selected contaminants in selected surface- or ground-water systems to address specific high-priority questions that concern the characteristics, causes, and governing processes of water-quality degradation. Case Studies are done at a wide range of spatial and temporal scales during intensive study phases. During the first cycle of investigation, Case Studies are not emphasized because of the resource demands of the initial Occurrence and Distribution Assessment, but their emphasis will increase in future cycles.

Relations among the four components of Study-Unit Investigations are shown in figure 3. The Retrospective Analysis forms the basis for addressing what is already known and what needs to be further investigated with respect to current water-quality conditions, trends and change, and understanding causes and effects. The Occurrence and Distribution Assessment builds on findings of the Retrospective Analysis to complete a broad assessment of current water-quality conditions. Periodic repetition of selected parts of the Occurrence and Distribution Assessment during future intensive study phases is a key part of the Trend and Change Assessment. Results of the Occurrence and Distribution Assessment also are used to identify the most important questions about sources, transport, fate, and effects to be addressed by Case Studies. The Trend and Change Assessment focuses on documenting long-term trends and changes, results in new questions about causes and effects, and identifies changes that need to be made in the periodic intensive study phases. Case Studies are used to improve understanding of selected questions about sources, transport, fate, and effects that arise from all aspects of NAWQA investigations and often lead to changes in assessment approaches over time. The interaction among the study components centers on the Occurrence and Distribution Assessment, which provides the foundation of data on which other components build.

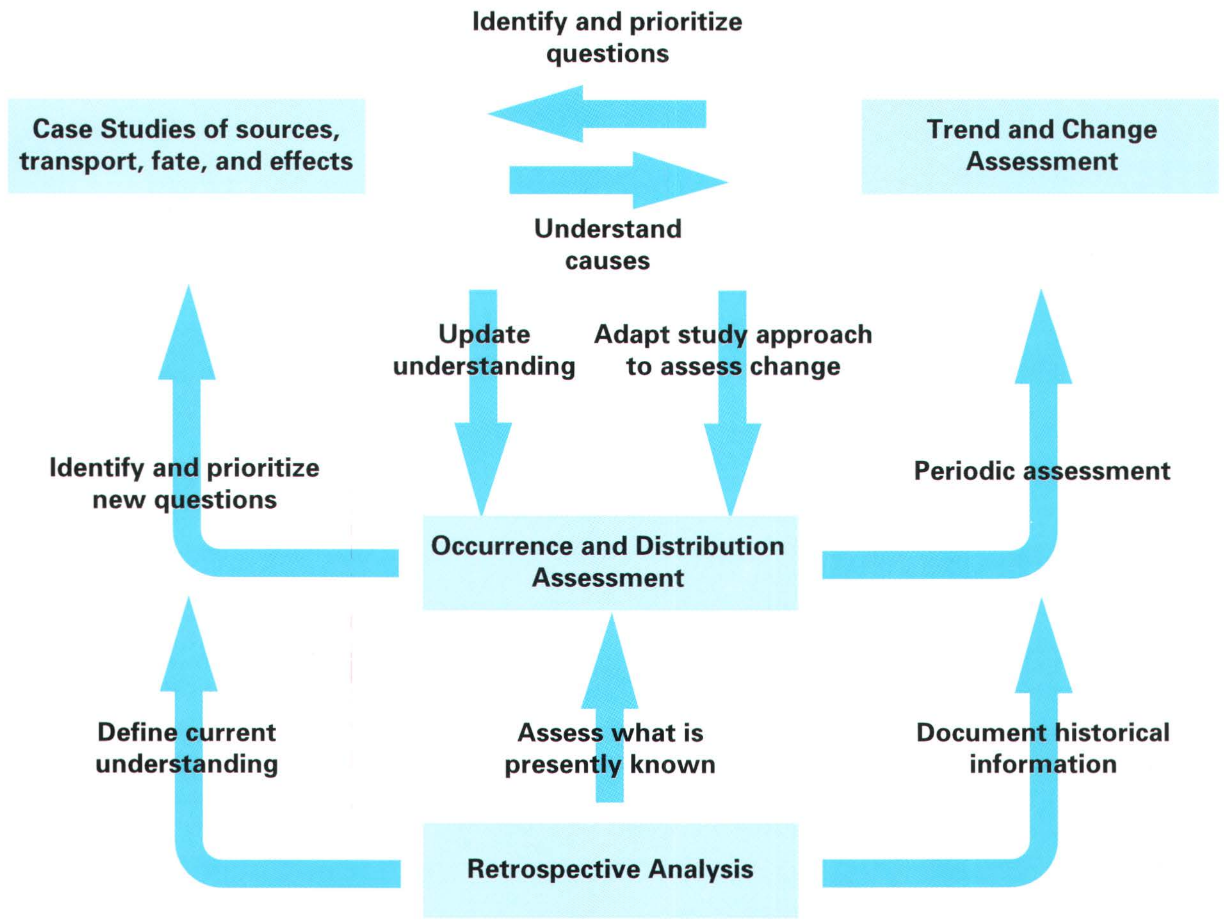

Figure 3. Components of Study-Unit Investigations and their interrelations.

Purpose and Scope

This report summarizes the design of the Occurrence and Distribution Assessment component of NAWQA Study-Unit Investigations, which is the primary focus during the first cycle in all 60 Study Units and thus spans the first decade of the program. The summary is presented in four main parts: goals and major design components, Environmental Framework for design, surface-water study design, and ground-water study design. The primary emphasis is on the nature and interrelations of the study components of the surface-water and ground-water designs. This report is one of a series that will describe selected aspects of the NAWQA design to encourage collaborative efforts with others in the water-resources community and to foster continued evaluation and critical review of approaches to national water-quality assessment.

GOALS AND MAJOR DESIGN COMPONENTS OF THE OCCURRENCE AND DISTRIBUTION ASSESSMENT

The Occurrence and Distribution Assessment is designed to meet goals at Study-Unit and national scales for surface- and ground-water issues (table 1). These goals are met to varying degrees in different Study Units and for different regional and national water-quality issues. The degree of success depends on such factors as availability of existing data, Study-Unit size and complexity, and the nature and complexity of the factors that govern particular water-quality conditions. In addressing the goals, NAWQA staff at all levels work closely with local, State, and Federal agencies, and the public through the liaison and advisory committees to assess potential implications of study results for management priorities and information requirements in the Study Units and nationally.

Figure 4 shows the study components of the Occurrence and Distribution Assessment. This report is organized by this design hierarchy and explains the role and design of each component.

ENVIRONMENTAL FRAMEWORK FOR DESIGN

Many factors that affect the sources, behavior, and effects of contaminants and water-quality conditions

Table 1. General goals of the Occurrence and Distribution Assessment

I. OCCURRENCE

A. *Study Unit*—Identify the occurrence of water-quality conditions that are significant issues.

B. *National Synthesis*—Identify the occurrence of water-quality conditions that are regionally and nationally significant water-quality issues.

II. SPATIAL AND TEMPORAL DISTRIBUTION

A. *Study Unit*—Characterize the broad-scale geographic and seasonal distribution of a wide range of water-quality conditions in relation to natural factors and human activities.

B. *National Synthesis*—Characterize and compare the geographic and seasonal distribution of selected water-quality conditions among the broad range of natural and land-use settings of the Nation.

III. DESIGN OF STUDIES FOR ASSESSING LONG-TERM TRENDS AND CHANGES

A. *Study Unit*—Evaluate Study-Unit priorities and required study approaches for effectively assessing long-term trends and changes.

B. *National Synthesis*—Work with Study Units to develop nationally consistent approaches to assess long-term trends and changes for priority issues.

IV. PRELIMINARY ASSESSMENT OF SOURCES, TRANSPORT, FATE, AND EFFECTS

A. *Study Unit*—For water-quality conditions of greatest importance, evaluate geographic and seasonal distributions in greater detail and in relation to the sources, transport, fate, and effects of contaminants. Determine the priorities and design for followup case studies.

B. *National Synthesis*—Characterize and compare the similarities and differences in relations to sources, transport, fate, and effects of selected contaminants prioritized for National Synthesis across the range of natural and anthropogenic settings of the Nation.

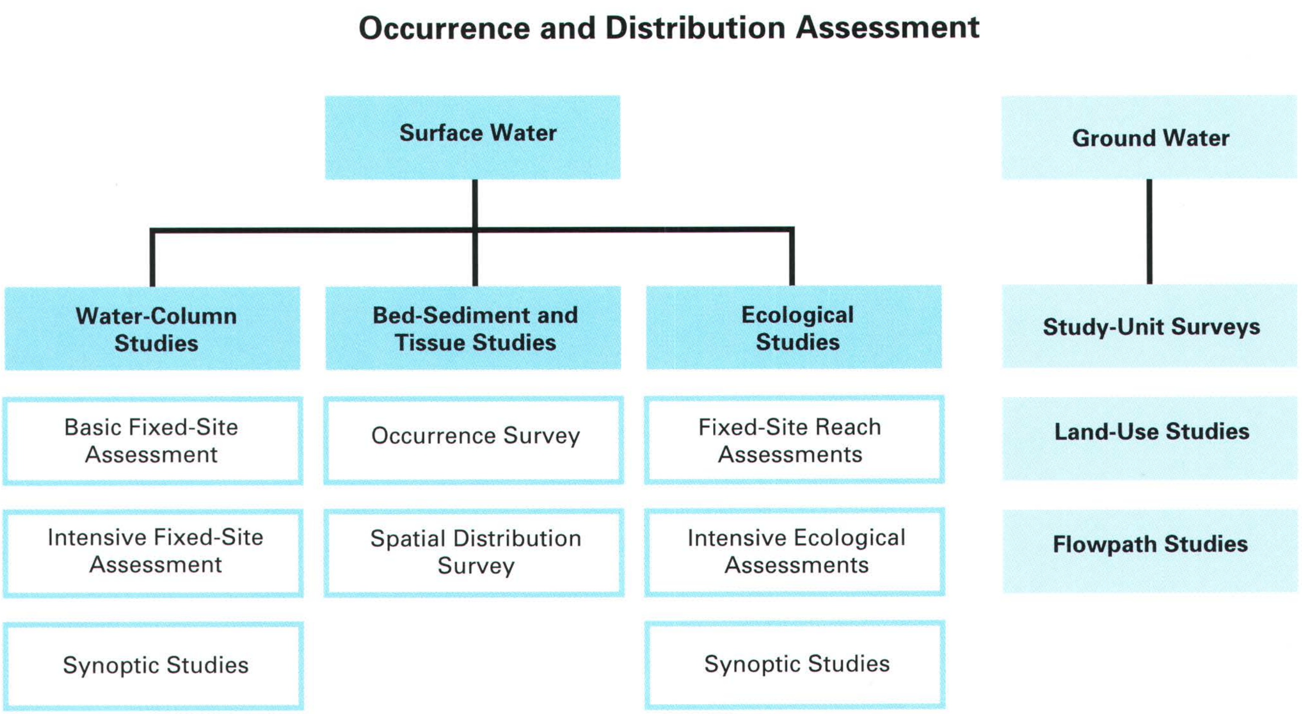

Figure 4. Components of the Occurrence and Distribution Assessment.

are common to most hydrologic systems, although in widely varying degrees of importance. These common natural and human-related factors, such as geology and land use, provide a unifying framework for making comparative assessments of water quality within and among hydrologic systems at a wide range of scales and characteristics in different parts of the Nation. Characterizing this Environmental Framework is an essential element of the Occurrence and Distribution Assessment that cuts across all individual water-quality issues and components of Study-Unit and National-Synthesis studies. The Environmental Framework is used to compare and contrast findings on water quality within and among Study Units in relation to causative factors and, ultimately, to develop inferences about water quality in areas that have not been sampled.

Although it is beyond the scope of this report to fully describe plans for developing the information base for the Environmental Framework for each Study Unit, an overview is helpful to understand the approach to sampling design and data analysis for the Occurrence and Distribution Assessment. The Environmental Framework is developed at three general scales for each Study Unit:

- *Study Unit.* The Environmental Settings of a Study Unit are initially characterized by dividing it into several major subareas (not necessarily contiguous) that have relatively homogeneous combinations of natural features and land-use conditions that generally are relevant to surface- and ground-water quality. The subareas are mapped and a conceptual stratification of the hydrologic system is developed. This general geographic characterization of the Environmental Settings of each Study Unit supports development of initial conceptual models for evaluating study priorities and approaches for Study Units and National Synthesis. An example of the Study-Unit scale of the Environmental Framework is shown diagrammatically in figure 5 and geographically in figure 6 for the White River Basin, Indiana.

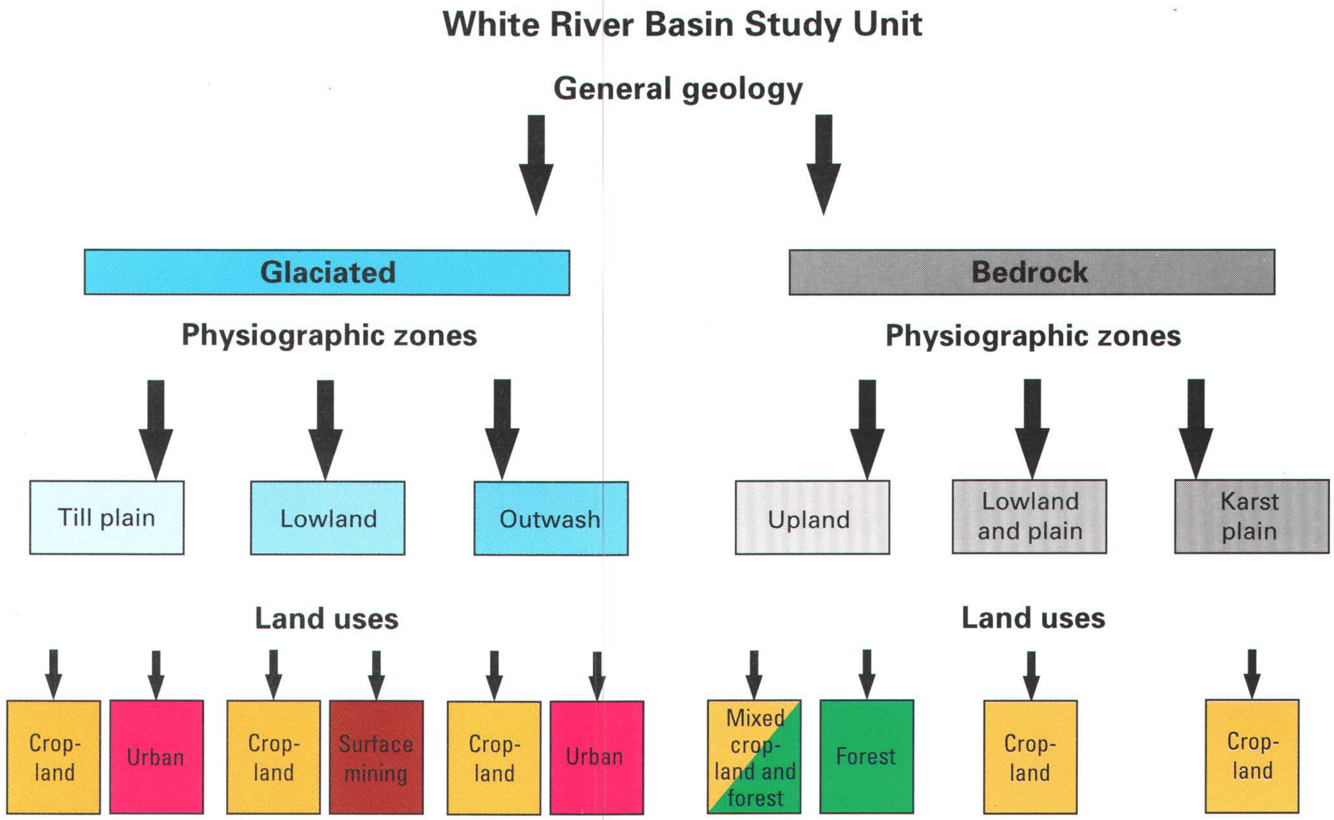

Figure 5. Conceptual stratification of Environmental Settings for the White River Basin Study Unit, Indiana.

In the White River Basin example, the Study Unit is divided into two major geologic categories, each with three physiographic zones. The distribution of major land uses among these physiographic zones results in 10 major subareas of the Study Unit characterized by the Environmental Settings that are the primary focus of water-quality investigations.

- *Aquifer subunits and stream drainage basins.* The ground- and surface-water resources of each Study Unit are spatially related to aquifer subunits and drainage basins, respectively, and these are the fundamental hydrologic units for sampling design. Aquifer subunits that are sampled and drainage basins that are associated with stream sampling sites are characterized in a consistent fashion for each Study Unit so that natural and human-related factors can be compared on an equal basis among Study Units. High-priority subunits and basins are characterized in much greater detail than is possible for the entire Study Unit. For example, agricultural land in a low-priority basin may be sufficiently characterized as "row crops," whereas in an intensively sampled high-priority basin, agricultural land will be further characterized in terms of the amount and location of specific crops cultivated, fertilizer and chemical use, seasonal timing of activities, and other relevant factors.

- *Well sites and stream sampling sites.* Natural characteristics and human activities in the vicinity of each well site and stream site at which samples are collected are recorded in a consistent format. This local characterization serves as a high-resolution complement to the aquifer subunit and drainage basin characterizations.

In the following description of the Occurrence and Distribution Assessment design, the implied development of extensive information on the Environmental Framework is a key aspect of the study design. Discussion of specific steps in the study-design process, such as choosing drainage basins with specific land-use features, gives the reader a general sense of the application of the Environmental Framework and the nature and scope of information requirements.

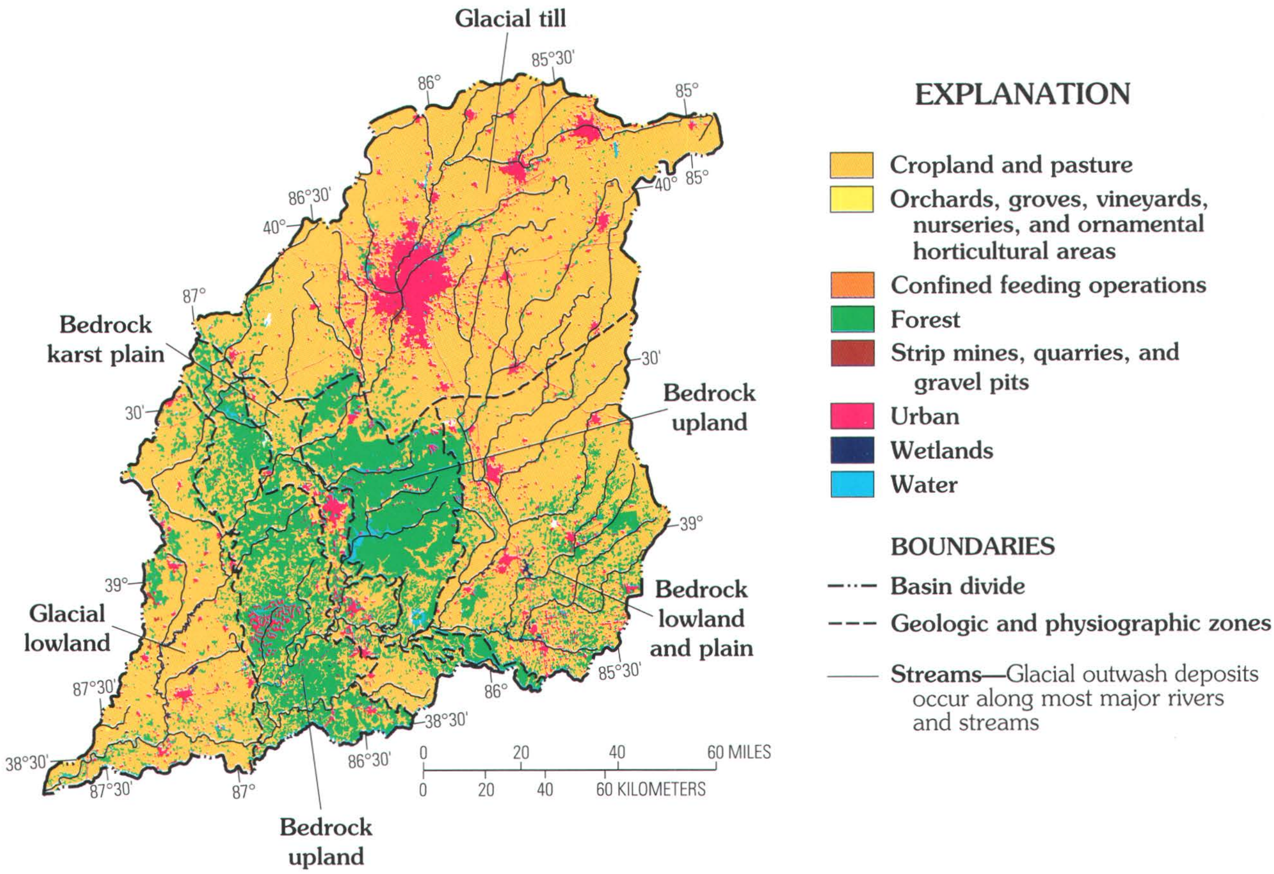

Figure 6. Environmental Settings of the White River Basin Study Unit, Indiana.

SURFACE-WATER STUDY DESIGN

The national study design for surface water addresses the goals of the Occurrence and Distribution Assessment (table 1) for water-quality conditions in streams and rivers of each Study Unit, hereafter referred to collectively as "streams." Lakes, reservoirs, wetlands, and other surface-water resources are not assessed as part of the national design, although they are selectively investigated in some Study Units. Assessment of most types of water-quality issues for streams, such as nutrient enrichment or pesticides, requires the measurement of many characteristics (table 2), frequently in multiple media, such as water, sediment, and tissues. In addition, each type of issue is related to water-quality conditions that tend to occur at particular places and times. For example, Hines and others (1976) described specific hydrologic settings and seasonal conditions associated with selected types of water-quality conditions in some streams. The differences in spatial and temporal patterns characteristic of different water-quality conditions require that the NAWQA design for assessing water quality balance many factors and make frequent compromises in the comprehensiveness of assessments for some issues, especially during the initial assessment of each Study Unit. As Study-Unit Investigations evolve, studies will focus more strongly on the most important water-quality conditions.

Overview of Approach

The approach taken by NAWQA to assess the water quality of streams is based on three interrelated components: Water-Column, Bed Sediment and Tissue, and Ecological Studies. Each component has unique strengths and weaknesses for assessing characteristics that are related to particular water-quality conditions, and each requires a unique, but closely related, sampling design. Table 3 shows the relation of each study component to measured characteristics.

Table 2. Relations among measurable water-quality characteristics and selected water-quality issues

[●, primary characteristics for each issue; O, secondary characteristics useful for evaluating each issue]

Water-quality characteristics	Water-quality issues										
	Pathogens	Nutrient enrichment	Trace elements	Pesticides	Industrial organics	Suspended sediment	Salinity	Temperature	Acidity	Dissolved oxygen	Ecological condition
Field:											
Streamflow	O	O	O	O	O	O	O	O	O	O	O
Dissolved oxygen		O	O	O	O			O		●	O
pH and alkalinity		O	O	O	O		O		●	O	O
Specific conductance		O	O	O	O		●				O
Temperature	O	O	O	O	O			●		O	O
Habitat characteristics		O	O	O	O	O	O	O	O	O	●
Biological communities		O	O	O	O	O	O	O	O	O	●
Laboratory:											
Suspended sediment	O	O	O	O	O	●					O
Major constituents											
Dissolved solids		O	O				●		O		O
Major ions and metals		O	O				O		O		O
Nutrients		●					O		O	O	O
Organic carbon		O	O	O	O				O	O	O
Trace elements			●			O			O		O
Organic contaminants											
Dissolved pesticides				●			O				O
Hydrophobic pesticides				●		O					O
Polychlorinated biphenyls					●	O					O
Other semivolatile organic contaminants					●						O
Volatile organic contaminants.				●	●						O
Biological											
Bacteria	●										O
Chlorophyll		O								O	O
Species identification											●

Water-Column Studies focus on assessing physical and chemical characteristics, which include suspended sediment, dissolved solids, major ions and metals, nutrients, organic carbon, and dissolved pesticides, and relating these characteristics to hydrologic conditions, sources, and transport. These studies also involve selected studies of other water-quality conditions, such as dissolved oxygen and pathogenic bacteria, where they are likely to be important, and include selective investigations of hydrophobic organic contaminants or trace elements if the results of Bed-Sediment and Tissue Studies indicate they are important.

Bed-Sediment and Tissue Studies are the primary means by which trace elements and hydrophobic organic contaminants are initially assessed in NAWQA. Concentrations and their areal distribution are assessed to identify sources and potential needs for more detailed study. Data for bed sediment and tissue levels at common sites are used for an initial assessment of biological availability.

Table 3. Water-quality characteristics measured in National Water-Quality Assessment surface-water components

[●, characteristics that are part of the national design for all Study Units; O, characteristics that are assessed in selected Study Units to variable degrees]

Water-quality characteristics	Study components: Water-Column Studies	Study components: Bed-Sediment and Tissue Studies	Study components: Ecological Studies
Field:			
Streamflow	●	●	●
Dissolved oxygen	●	●	●
pH and alkalinity	●	●	●
Specific conductance	●	●	●
Temperature	●	●	●
Habitat characteristics			●
Biological communities			●
Laboratory:			
Suspended sediment	●	●	
Major constituents			
Dissolved solids	●		
Major ions and metals	●		
Nutrients	●		
Organic carbon	●		
Trace elements	O	●	
Organic contaminants			
Dissolved pesticides	●		
Hydrophobic pesticides	O	●	
Polychlorinated biphenyls		●	
Other semivolatile organic contaminants		●	
Volatile organic contaminants	O		
Biological			
Bacteria	O		
Chlorophyll	O		
Species identification		●	●

Ecological Studies evaluate the effects of physical and chemical characteristics of water and hydrologic conditions on aquatic biota and how biological and habitat characteristics differ among Environmental Settings in Study Units. The aquatic ecological community of a stream is potentially affected by all the water-quality conditions assessed during the Water-Column and the Bed-Sediment and Tissue Studies and also by numerous factors that affect physical habitat, such as climate, stream size, riparian vegetation, and geology.

Sampling designs for the three study components rely on coordinated sampling of varying intensity and scope at two general types of sites—Integrator and Indicator. Integrator Sites are chosen to represent water-quality conditions of streams and rivers in heterogeneous large basins that are often affected by complex combinations of land-use settings, point sources, and natural influences. Indicator Sites, in contrast, are chosen to represent water-quality conditions of streams in relatively homogeneous and usually smaller basins associated with specific individual Environmental Settings; for example, a particular combination of land use and geologic setting.

Most Integrator Sites are on major streams with drainage basins that include a substantial portion of the Study Unit area (typically 10–100 percent). In Study Units where it is possible and appropriate to the hydrologic system, one of the Integrator Sites is located at the outlet of the entire Study Unit. A goal is to locate Integrator Sites at key nodes in the drainage network of the Study Unit so that the most significant contaminant sources in the unit are included within at least one Integrator-Site basin. Data from Integrator Sites provide a general check on the persistence of water-quality influences evident at Indicator Sites for specific Environmental Settings and are used for water-budget and contaminant-transport assessments.

Indicator Sites are located at the outlet of drainage basins with relatively homogeneous land-use and physiographic conditions. Generally, the drainage basin of an Indicator Site has more than 50 percent of its area in the targeted Environmental Setting, and the water quality is primarily influenced by the targeted setting. Sites are selected in an attempt to keep stream size, gradient, and geomorphic characteristics within a restricted range for each Study Unit or for major regions within the Study Unit. Most Indicator-Site basins range from 50–500 km^2 and are chosen to be as large and representative as possible while still mainly being comprised of the targeted setting.

Special types of Indicator Sites are reference and point-source sites. Reference Indicator Sites are located downstream of undisturbed drainages that represent the selected physiographic and ecological regions within the Study Unit and are chosen to represent background conditions. Point-source Indicator Sites are located downstream of specific major point sources of contaminants that may have regionally significant water-quality effects. Usually, they are paired with a site upstream of the point source. For example, a point-source Indicator Site may be located downstream from a major sewage-treatment plant for comparison to an Integrator Site upstream. Indicator Sites for point sources are not needed in all Study Units and generally are limited to situations where the point source is uniquely significant and not adequately represented by other sites.

The sampling strategy for Water-Column, Bed-Sediment and Tissue, and Ecological Studies is based on four general levels of sampling intensity at a combination of Integrator and Indicator Sites. The general concept is that a few selected sites have intensive sampling for all water-quality characteristics related to all three components, and progressively more sites are included for more-specialized and less-frequent sampling activity. Table 4 summarizes the integrated sampling strategy for the four levels of sampling intensity—Basic Fixed, Intensive Fixed, Bed-Sediment and Tissue, and Synoptic Sites. The core of the NAWQA sampling design is the Basic Fixed Sites, of which Intensive Fixed Sites are a specialized subset with the most extensive sampling, and to which Bed-Sediment and Tissue and Synoptic Sites are added to enhance spatial coverage. An example of the geographic structure of the fixed-site design for a Study Unit is shown in figure 7.

The number of sites listed in table 4 for the various design components and the level of sampling activities represent typical ranges for individual Study Units. Generally, the national average for each type of site is expected to fall within these ranges, even though conditions in some individual Study Units merit a higher or lower number of sites. Similarly, variation of other selected aspects of the strategy outlined in table 4, such as the degree of continuous monitoring, also depends on Study-Unit conditions.

Water-Column Studies

As shown in table 4, water-column conditions are assessed by three primary sampling strategies employed at selected Indicator and Integrator Sites:

- Basic Fixed-Site assessments characterize the spatial and temporal distribution of general water-quality and constituent transport in relation to hydrologic conditions and contaminant sources.
- Intensive Fixed-Site assessments characterize seasonal and short-term temporal variability of general water quality and constituent transport and determine the occurrence and seasonal patterns in concentrations and transport of dissolved pesticides.

Table 4. Sampling activities for characterizing streamwater-quality conditions for the Occurrence and Distribution Assessment

[Major constituents include dissolved solids, major ions and metals, nutrients, and organic carbon]

Design components	Sampling strategies	Targeted characteristics
Basic Fixed Sites: 3-5 Integrator Sites; 4-8 Indicator Sites (numbers include Intensive Fixed Sites)		
Water-Column Studies	Continuous monitoring	Streamflow Specific conductance Temperature
	Fixed-interval sampling for 2 years Extreme-flow sampling for 2 years	Field measurements Major constituents Suspended sediment
Bed-Sediment and Tissue Studies	Reach composites of depositional-zone bed sediments	Hydrophobic organic contaminants Trace elements Organic carbon and particle size
	Composite of tissues of target organisms	Hydrophobic organic contaminants Trace elements
Ecological Studies	Fixed-Site Reach Assessments Intensive Ecological Assessments at selected sites	Habitat, fish, invertebrates, and algae
Intensive Fixed Sites: 1-2 Integrator Sites and 1-4 Indicator Sites (subset of Basic Fixed Sites)		
Water-Column Studies	Basic Fixed-Site strategy plus seasonal high-frequency sampling for 1 year	Basic Fixed-Site strategy plus dissolved pesticides for 1 year
Bed-Sediment and Tissue Studies	Same as Basic Fixed Sites	Same as Basic Fixed Sites
Ecological Studies	Same as Basic Fixed Sites	Same as Basic Fixed Sites
Bed-Sediment and Tissue Sites: 5-10 Integrator Sites; 15-30 Indicator Sites (all fixed sites included)		
Bed-Sediment and Tissue Studies	Reach composites of depositional-zone bed sediments	Hydrophobic organic contaminants Trace elements Organic carbon and particle size
	Composite of tissues of target organisms	Hydrophobic organic contaminants Trace elements
	One-time water-column sampling	Streamflow Field measurements
Water-Column and Ecological Synoptic Sites: Variable in number and type (all fixed sites included)		
One or more study components and media (depends on topic)	Variable and issue specific	Variable, but usually few measurements in each study

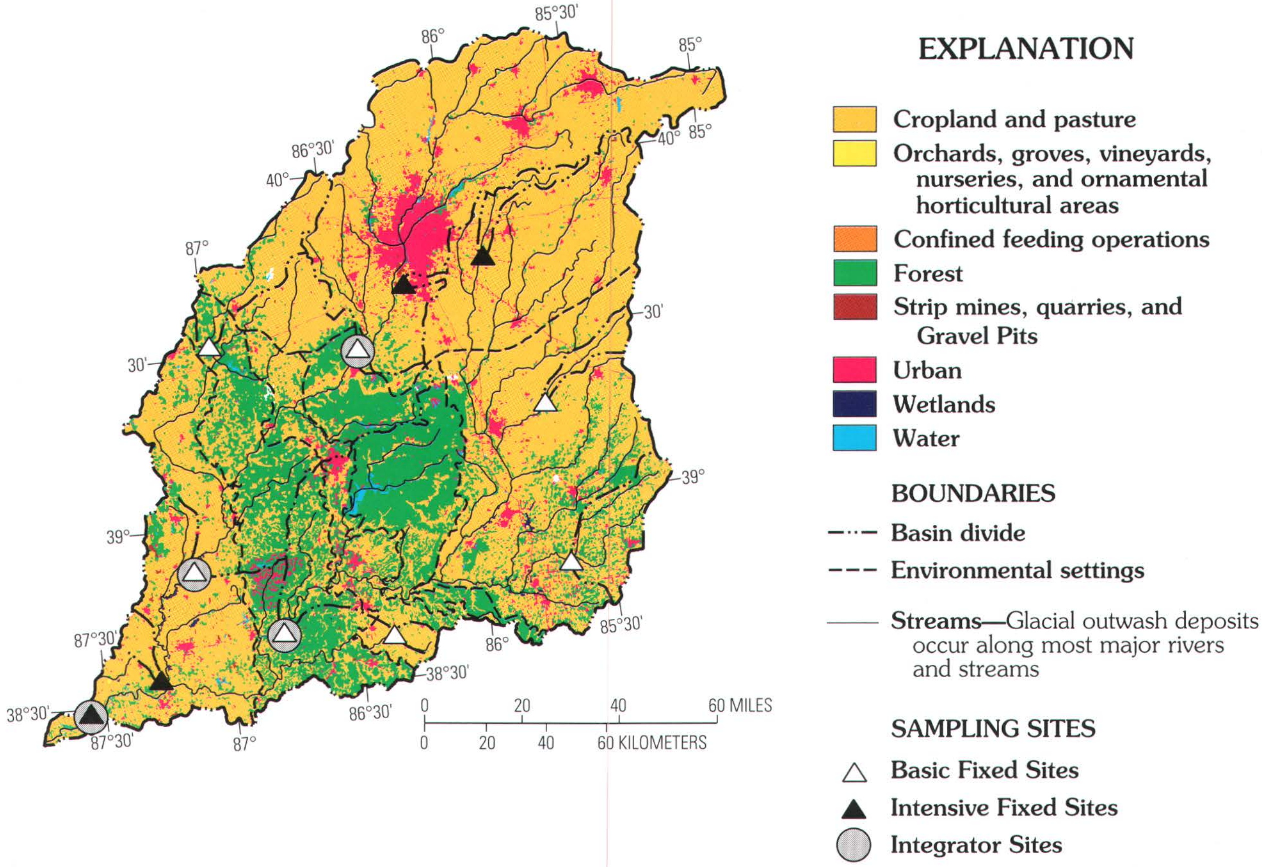

Figure 7. Example of distribution of Basic and Intensive Fixed Sites for the White River Basin Study Unit, Indiana.

- Water-Column Synoptic Studies investigate the geographic distribution of selected water-quality characteristics in greater detail during specific seasons and in relation to sources.

Site choices and sampling strategies for Intensive and Basic Fixed Sites are particularly important to the success of the surface-water design for National Synthesis because this is the part of the study design in which all study components are integrated by a nationally consistent strategy in all Study Units.

Basic Fixed-Site Assessment

The Basic Fixed-Site sampling is designed to provide an integrated assessment of the spatial and temporal distribution of general water-quality conditions and the transport of major inorganic constituents of streamwater in relation to hydrologic conditions and major sources. Data from Basic Fixed-Site sampling are the primary source of information for meeting water-column assessment objectives for temperature, salinity, suspended sediment, major ions and metals, nutrients, and organic carbon. Site selection and sampling strategy for Basic Fixed Sites are based on balancing needs and priorities for assessing water-column conditions, constituents in bed sediment and tissues, and ecological characteristics. Although each of these components has some unique requirements, Study Units also have common requirements to represent the ranges of spatial and temporal scales and Environmental Settings.

Site Selection

Each Study Unit typically has three to five Integrator and four to eight Indicator Basic Fixed Sites. The Integrator Basic Fixed Sites are chosen to represent the range of large streams in each Study Unit and include major nodes in the drainage system for large-scale transport analysis. Collectively, the basins of these Integrator Sites usually include all or most of the Study Unit. Ecological Studies require that Integrator Basic Fixed Sites represent as fully as possible the range of habitat and water-quality conditions in the large streams of each Study Unit. Sites thus are selected by balancing the needs for assessing large-scale water-column conditions and large-scale constituent transport with the need for characterizing stream ecology in a representative manner. These decisions are based on an analysis of existing data and field reconnaissance.

Indicator Basic Fixed Sites primarily are chosen to represent each of the Environmental Settings in the Study Unit that are most relevant to streamwater quality and, thus, also are most likely to represent Environmental Settings that most influence the water quality of the downstream Integrator Site. Commonly, the collective basin areas of Indicator Sites may represent only a small percentage of the total Study Unit area. Ecological Studies require that Indicator Basic Fixed Sites adequately represent physical habitat conditions found for streams of similar size in the selected Environmental Settings. Sites should be located so that chemical and hydrologic characteristics measured in the water column are similar throughout the sampling reach required for Ecological Studies.

Another factor that affects the selection of Indicator Sites is the correspondence of Indicator-Site basins with ground-water studies. Ground-water Land-Use and Flowpath Studies frequently overlap with indicator basins of Basic or Intensive Fixed Sites (see also "Ground-Water Study Design"). In particular, most flowpath transects that address surface- and ground-water interaction intersect streams that are associated with Basic or Intensive Fixed Sites.

The White River Basin Study Unit illustrates a typical application of the site-selection strategy for Basic Fixed Sites. The geographic distribution of sites is shown in figure 7. The characteristics of the seven Indicator Sites and four Integrator Sites are provided in table 5, which lists the Environmental Settings and basin sizes.

Sampling Strategy

The water-column sampling strategy at each Basic Fixed Site consists of three types of sampling activities designed to yield a core of consistent data on hydrologic and general water-quality conditions. The three types of sampling activities—continuous monitoring, fixed-interval sampling, and extreme-flow sampling—are conducted for at least 2 years. A third year may be added for some sites because of local situations, such as unusual hydrologic conditions during the first 2 years, high year-to-year variability, or

Table 5. Summary of fixed-site design for the White River Basin Study Unit, Indiana

[Site locations are shown in fig. 7. km^2, square kilometer]

Site	Sampling	Drainage basin area (km^2)	Site description
			Indicator Sites
1	Intensive	241	Row-crop agriculture on till plain.
2	Intensive	44	Urbanized area on till plain.
3	Basic	844	Row-crop agriculture on till plain.
4	Basic	236	Row-crop agriculture on bedrock lowland and plain.
5	Basic	759	Row-crop agriculture and woodland on bedrock lowland and plain.
6	Basic	91	Row-crop agriculture on karst plain.
7	Intensive	148	Row-crop agriculture on glacial lowland.
			Integrator Sites
8	Basic	6,327	Integrator for till plain urban and agricultural areas.
9	Basic	12,409	Integrator for main stem before confluence with East Fork.
10	Basic	12,755	Integrator for East Fork Basin.
11	Intensive	29,267	Integrator for entire Study Unit.

sparse existing data. The purpose for sampling Basic Fixed Sites for 2 years is, in combination with existing data, to assess year-to-year variability and any major differences or similarities between years in seasonal patterns.

Basic Fixed Sites and Intensive Fixed Sites are the only sites in the NAWQA study design where streamflow and selected additional characteristics are continuously measured. Continuous streamflow data are collected for the entire sampling period to support analyses of relations between water-quality and hydrologic conditions, to estimate transport over time, and for other interpretive analyses. Detailed characterization of hydrologic conditions also is essential to interpretation of Ecological Studies because of the relation of biological communities and processes to streamflow and its variability over time. Characterization of the thermal regime is a particularly important physical characteristic for interpretation of Ecological Studies, and 1 year of continuous temperature data will be collected at each Basic Fixed Site. Specific conductance will be continuously monitored at selected Basic Fixed Sites where local conditions merit.

Fixed-interval sampling is designed to provide a framework of consistent data on concentrations and typical fluxes at all Basic Fixed Sites for a broad range of water-quality characteristics that cannot be continuously monitored. Fixed-interval sampling is the collection of discrete samples at regular intervals of time for laboratory analysis of chemical and physical properties and for associated field measurements. All samples are flow weighted and cross-sectionally integrated by standard USGS methods (Ward and Harr, 1990). Complete descriptions of sample collection and processing methods are provided by Shelton (1994). The minimum and most common sampling frequency is monthly during the minimum 2-year period of operation.

Sampling at each Basic Fixed Site also includes samples at extreme flow conditions (typically four to eight additional samples per year) to supplement interval sampling. Although fixed-interval sampling provides data for the most common flows and concentrations, high and low flows and concentrations that occur less often during the 2-year sampling period have a small chance of being sampled even though they are particularly important. Occurrence of high and low flows and associated constituent transport and concentrations have significance for water quality far beyond the proportion of time during which they occur.

Sample Analyses

Each time a Basic Fixed Site is sampled, field measurements are made, and samples are submitted to the laboratory for analyses of a national target list of suspended sediment, dissolved solids, major ions and metals, nutrients, and dissolved and suspended organic carbon. Table 6 lists analytes in each category. These analytes are selectively augmented by some Study Units as required to meet specific local needs.

Table 6. Analytical strategy for Basic Fixed Sites

Field measurements
Dissolved oxygen
pH and alkalinity
Specific conductance (hourly or daily if local conditions require)
Temperature (hourly for 1 year)
Laboratory analyses
Suspended sediment
Major constituents:
Dissolved solids
Major ions and metals:
Calcium
Chloride
Fluoride
Iron
Magnesium
Manganese
Potassium
Silica
Sodium
Sulfate
Nutrients:
Nitrogen:
Total
Total dissolved
Ammonia
Nitrite
Nitrate
Phosphorus:
Total
Total dissolved
Ortho
Organic carbon:
Suspended
Dissolved

Intensive Fixed-Site Assessment

Intensive Fixed Sites are the part of the fixed-site design where all water-column sampling strategies are employed, as well as all levels of bed-sediment and tissue and ecological sampling. They are the same as Basic Fixed Sites except for the addition of enhanced sampling frequency and addition of dissolved-pesticide analyses for 1 year. As the program evolves, other types of priority contaminants, such as industrial organic contaminants or trace elements, may be added as a focus of sampling at existing or new Intensive Fixed Sites; as a result, design emphasis may change.

The site selection and sampling strategy for Intensive Fixed Sites during the first cycle of Study-Unit Investigations are governed primarily by requirements for assessing dissolved pesticides. Dissolved pesticides tend to occur erratically during seasonal periods when chemical use and hydrologic conditions favor transport. The premise of the Intensive Fixed Site sampling strategy is that relatively high-frequency sampling at a few carefully chosen sites during key seasonal periods initially yields superior information about occurrence and seasonal patterns compared with other design alternatives.

Site Selection

Each Study Unit typically has one to two Integrator and one to four Indicator Intensive Fixed Sites. Integrator Sites selected as Intensive Fixed Sites are downstream of the largest possible areas of the Study Unit that encompass the greatest intensity of pesticide sources. Major undeveloped basins are avoided. Thus, the chosen Integrator Site may be a major tributary that drains an agricultural valley in which a major city is located rather than, for example, the Study-Unit outlet. This strategy maximizes the value of the Integrator Sites for detecting significant contaminant issues not detected at Indicator Sites and enables comparisons of pesticide transport with upstream Indicator Sites. Whenever possible, the most important Indicator Sites are nested within the basin of an Integrator Site.

The Indicator Intensive Fixed Sites within each Study Unit are selected to represent land-use settings that are most critical for addressing pesticide contamination issues (reference sites generally are excluded). Where possible, these sites include the full range of settings for which pesticide issues are most significant. Known problems are not the only focus. For example, a key setting for an Intensive Fixed Site in many Study Units is urban land, even though most total use of pesticides in the Study Unit may be on agricultural land. The most prominent agricultural settings always are included. In some Study Units, only one or two primary agricultural settings are of significant importance, while other Study Units require four or five Indicator Sites even for a minimal design. National-Synthesis priorities for land-use settings and site suitability for Ecological Study requirements also are evaluated in making final choices. Once selected, the basin characteristics of Indicator Intensive Fixed Sites are assessed in greater detail than most other sites as part of describing the Environmental Framework.

Sampling Strategy

The sampling strategy at each Intensive Fixed Site is the Basic Fixed Site strategy with the addition of analyses of dissolved pesticides for all samples and a higher frequency of interval and extreme-flow sampling during selected seasonal periods. Intensive sampling and analyses usually are done for a 1-year period, after which sampling and analyses return to the same strategy as that of Basic Fixed Sites.

Seasonal periods selected for high-frequency sampling are the most critical periods for concentrations and transport of dissolved pesticides and nutrients. These periods are identified from information on chemical-use patterns, seasonal climatic conditions, irrigation practices, and existing water-quality data. Most Study Units have multiple, overlapping seasonal periods that are important for different chemicals or conditions. The periods of high-frequency sampling are chosen to bracket conservatively the hypothesized seasonal conditions for each Intensive Fixed Site. Typically, the high-frequency sampling periods at Intensive Fixed Sites range from 3 to 9 months.

During the high-frequency sampling, fixed-interval sampling typically is weekly or, if the basin is large, biweekly. Some sites are sampled more frequently if short-term fluctuations are an important concern, and some are sampled less frequently if fluctuations are expected to be less extreme, such as for some larger streams and rivers. The fixed-interval sampling is supplemented with extreme-flow samples of equal or greater number than those for standard operation of Basic Fixed Sites.

Sample Analyses

The analytical strategy for Intensive Fixed Site samples requires the analyses described for Basic Fixed Site samples in table 6 and the additional analyses of pesticides listed in table 7.

Water-Column Synoptic Studies

Water-Column Synoptic Studies are short-term investigations of water quality during selected seasonal periods or hydrologic conditions. Every Water-Column Synoptic Study is custom designed to provide improved spatial resolution, compared with fixed-site data, for critical water-quality conditions during selected seasonal periods or hydrologic conditions. They also evaluate the spatial distribution of selected water-quality conditions in relation to causative factors, such as land uses and other contaminant sources. Water-Column Synoptic Studies thus supplement information from the fixed sites by targeting specific water-quality conditions for more-detailed characterization.

Water-Column Synoptic Studies are designed to address the highest priority water-quality issues. Prioritization of topics within a Study Unit are based on such factors as potential ecological and human-health effects, areal extent, and duration and recurrence. These factors are determined from the results of the Retrospective Analysis, NAWQA data, land-use patterns, and local perspectives. Priorities for National Synthesis are based on the same general factors as for the Study-Unit scale, but for current synthesis topics and from a national point of view.

The process of choosing and designing Water-Column Synoptic Studies is coordinated among the Study Units. Most high-priority topics in one Study Unit also are priority topics in other Study Units and thus are likely to be regionally or nationally significant. For some issues, coordinated design involves only two or three Study Units; for other issues, it involves most of the 20 active Study Units.

Most Water-Column Synoptic Studies are done in the second and third years of the 3-year intensive data-collection phase after initial results from the first year of sampling can be combined with existing data to guide the study design. Selected Water-Column Synoptic Studies are done earlier, however, if well-defined, high-priority questions arise. Most Study Units will complete two to three Water-Column Synoptic Studies during the first intensive phase.

The strategies for site selection, sampling, and analysis for synoptic studies are issue specific and keyed to hydrologic conditions, times, and places of specific interest for the targeted water-quality issue. Design of Water-Column Synoptic Studies is coordinated with Bed-Sediment and Tissue Studies and Ecological Studies to enhance the interpretation of relations among physical, chemical, and biological water-quality characteristics. For some issues, a single sampling is done at numerous sites distributed throughout the entire Study Unit. Other Water-Column Synoptic Studies may require a short period of frequent sampling at a few sites in only one part of the Study Unit. The following general principles apply to design:

- Water-quality issues that are most relevant during low-flow conditions usually require many sites but only one or very few samples per site.
- Water-quality issues that are most relevant during runoff events or unsteady flow conditions commonly require frequent sampling at study sites during events or for a limited period of time. Intense sampling is usually feasible for only a few sites.
- Water-Column Synoptic Study designs commonly include all or most Basic and Intensive Fixed Sites so that the short-term findings from synoptic sampling can be related to longer time scales and a greater number of measured characteristics.
- Usually, Water-Column Synoptic Study sites are located to ensure balanced spatial coverage at the desired resolution in the target geographic area and near selected stream junctions to facilitate mass-balance analysis for the sampling period.
- Analytical requirements are sometimes narrowly defined by the specific objective for some synoptic studies. A broadened analytical approach, however, is often used to take advantage of the sampling visit to assess related issues.

Bed-Sediment and Tissue Studies

Bed-Sediment and Tissue Studies assess trace elements and hydrophobic organic contaminants in two phases. The Occurrence Survey is designed to provide an initial identification of important constituents in each Study Unit based on data from few sites.

Table 7. Analytical strategy for Intensive Fixed Sites in addition to the Basic Fixed Site analyses

[*, Degradation product; some of the analytes listed may be deleted or qualified depending on method performance for ambient samples]

Field measurements			
Specific conductance (hourly or daily for 1 year)			
Laboratory analyses—Dissolved pesticides			
Amids:			
Alachlor	Napropamide	Propachlor	
Metolachlor	Pronamide	Propanil	
Carbamates:			
Aldicarb	Carbofuran	Molinate	Thiobencarb
Aldicarb sulfone*	Carbofuran, 3-Hydroxy*	Oxamyl	Triallate
Aldicarb sulfoxide*	EPTC	Pebulate	
Butylate	Methiocarb	Propham	
Carbaryl	Methomyl	Propoxur	
Chlorophenoxy herbicides:			
2,4-D (acid)	2,4-DB	MCPB	2,4,5-T
Dichlorprop (2,4-DP)	MCPA	Silvex (2,4,5-TP)	Triclopyr
Dinitroanilines:			
Benfluralin	Oryzalin	Trifluralin	
Ethafluralin	Pendimethalin		
Organochlorines:			
Chlorothalonil	*p,p'*-DDE	Dieldrin	gamma-HCH
Dacthal (DCPA)	Dichlobenil	alpha-HCH*	
Organophosphates:			
Azinphos-methyl	Disulfoton	Malathion	Phorate
Chlorpyrifos	Ethoprop	Methyl parathion	Terbufos
Diazinon	Fonofos	Parathion	
Pyrethroids:			
cis-Permethrin			
Triazine herbicides:			
Atrazine	Cyanazine	Prometon	
Atrazine, desethyl*	Metribuzin	Simazine	
Uracils:			
Bromacil	Terbacil		
Ureas:			
Fenuron	Fluometuron	Neburon	
Diuron	Linuron	Tebuthiuron	
Miscellaneous:			
Acifluorfen	Clopyralid	DNOC	Propargite
Bentazon	Dicamba	1-Napthol*	
Bromoxynil	2,6-Diethylaniline*	Norflurazon	
Chloramben	Dinoseb	Picloram	

The Spatial Distribution Survey improves geographic coverage for priority constituents through broader areal sampling and improved resolution in priority areas. The design of the Spatial Distribution Survey is determined by results of the Occurrence Survey. Data from both phases are combined for assessing distribution.

Occurrence Survey

The primary objective of the Occurrence Survey is to determine which target constituents are important to water-quality conditions in each Study Unit. Importance is determined by the magnitude of constituent levels and the extent of their occurrence. The highest level of importance is assigned to constituents found at elevated levels over a wide geographic area or within many small areas, such that they are viewed as significant water-quality issues for a substantial part of the Study Unit. Site selection and sampling strategy are designed to maximize the probability of detecting important constituents in the Study Unit.

Site Selection

The site-selection strategy for the 15–20 sites sampled for the Occurrence Survey builds on the selection of Basic Fixed Sites (typically 7–13) for water-column sampling. The choice of additional Indicator Sites is a balance between locating sites where contamination is known to be probable and dispersing sites so that streams that drain each major Environmental Setting in the Study Unit are sampled. Integrator Sites are chosen to provide a coarse downstream network of sites where large-scale contaminant occurrences not detected at the Indicator Sites have a reasonable chance of being detected.

The sampling design in each Study Unit thus includes all Basic and Intensive Fixed Sites and additional sites selected specifically to meet objectives for bed sediments and tissues. Usually one or two Indicator Sites are selected to represent the broadest possible range of background trace-element levels expected in the Study Unit, if such sites are not already included as Intensive or Basic Fixed Sites. These reference Indicator Sites also serve to assess the background occurrence of hydrophobic organic contaminants.

Sampling Strategy

Sampling for bed sediment and tissues is done during summer or autumn low flows to minimize seasonal variability. The basic sampling strategy is the same at all sites. Each "site" refers to a reach of stream at that location. Sampling strategies for bed sediment and tissues ideally involve targeted sampling within a reach of stream near the location of water-column sampling or streamflow measurement. The general approach is to composite multiple samples in a manner that averages out anticipated spatial variability within the reach.

Bed Sediment

The strategy for sampling bed sediment is designed to exploit the sorptive properties of trace elements and hydrophobic organic chemicals by collecting fine-grained particles, which are natural accumulators of these chemicals, and to exploit the properties of stream environments by targeting low-flow depositional zones as natural integrators of fine-grained sediment. The general sampling strategy is to collect samples of fine-grained surficial sediments from natural depositional zones during low-flow conditions and to composite samples from several depositional zones in a stream reach, which yields a reach average of fine-grained surficial bed sediment.

The sampling procedures are described by Shelton and Capel (1994). The first step at a site is to identify the sampling reach. The standard sampling reach is the 100-m reach of stream upstream from the location for water-column sampling or streamflow measurement. However, the diverse nature of site locations, some of which are selected primarily for purposes other than bed-sediment sampling, make it necessary to go variable distances upstream or downstream from the water-column sampling or streamflow measurement location to find suitable depositional zones. Care is taken, however, to avoid including or excluding significant point sources or tributaries that may affect the suitability of the reach in representing the subbasin. The sampling reach is colocated with the reach where tissue samples are collected and within the sampling reach for Ecological Studies.

The ideal sample-collection procedure within each sampling reach is to identify 5–10 wadeable depositional zones that contain fine-grained particulate matter. The depositional zones within the sampling reach are broad areas at some sites and small pockets at other sites. Left- and right-bank and center-channel depositional zones with different depths of water are sampled to ensure that sediment that represents a range of histories and sources important for the reach is sampled. Samples from the surficial 2–3 cm of bed sediment in each depositional zone are collected at several locations, in approximate proportion to its size, and composited with samples from other depositional zones sampled at the site. The composited bed-sediment sample is sieved and processed into several subsamples for analyses of trace elements, hydrophobic organic chemicals, total organic carbon, and particle size.

Tissue

The sampling strategy for tissues in the Occurrence Survey is comparable with bed sediment in that it also is designed to minimize local scale spatial variability and to maximize comparability of data within and among Study Units. Generally, one taxon is collected at each site in the Occurrence Survey; the same taxon is collected at as many sites as possible within a Study Unit. National consistency is provided by a National Target Taxa (NATT) List and decision trees that will guide, with local flexibility, selection from that list (Crawford and Luoma, 1993). The NATT List includes mollusks, insect larvae, fish, and vascular plants (table 8). Selection of target taxa for each Study Unit is based on information from the Retrospective Analysis and water-quality reconnaissance.

Decision trees for selecting target taxa are different for hydrophobic organic contaminants and trace elements because organisms concentrate these contaminants differently (Crawford and Luoma, 1993). For hydrophobic organic compounds, the first-priority taxon for collection is the bivalve mollusk, *Corbicula fluminea* (the Asiatic clam). If this taxon is not present at a site, then whole fish from a single species of fish on the NATT List would be the second-priority taxon to collect. Of the fish species on the NATT List, bottom-feeders (carp, suckers, channel catfish) are higher priority than predators (largemouth bass, bluegill, brook and brown trout). If adequate numbers of these species cannot be collected, then no sample is submitted for organics analysis, except where a nontarget taxon may be of local importance.

Table 8. National Target Taxa List for tissue bioassessment in National Water-Quality Assessment
[Listed in order of priority within each group]

Group	Taxon
Mollusks	Asiatic clam (*Corbicula fluminea*)
Insect larvae	Trichoptera (caddisflies):
	Hydropsyche sp.
	Brachycentrus sp.
	Limnephilus sp.
	Chironomidae (midges)
	Chironomus sp.
	Plecoptera (stoneflies):
	Perlidae
	Perlodidae
	Pteronarcyidae
Fish	Carp (*Cyprinus carpio*)
	White sucker (*Catostomus commersoni*)
	Longnose sucker (*Catostomus catostomus*)
	Largescale sucker (*Catostomus macrocheilus*)
	Channel catfish (*Ictalurus punctatus*)
	Largemouth bass (*Micropterus salmoides*)
	Bluegill (*Lepomis macrochirus*)
	Brook trout (*Salvelinus fontinalis*)
	Brown trout (*Salmo trutta*)
Vascular plants	Pondweed (*Potamogeton* sp.)
	Hydrilla (*Hydrilla verticillata*)
	Waterweed (*Elodea* sp.)

For trace elements, *Corbicula fluminea* is again the first-priority taxon for collection. If a sufficient sample cannot be collected at a site, then the second-priority target organisms are aquatic insects from the NATT List. Stoneflies are lower priority than the caddisflies on the list. If a sufficient sample of any one of these target taxa cannot be found, then the third- and fourth-priority target organisms from the NATT List are fish livers and vascular plants.

Sample-collection procedures vary for different taxa and are described in detail in Crawford and Luoma (1993). Samples for each taxon are composited for a given site to average individual variability and to meet a minimum mass requirement for the intended analyses.

Sample Analyses

The analytical strategy is uniform for all Occurrence Survey sites except that chlorinated dioxins and furans are analyzed only at selected sites (for example, near potential sources, such as pulp and paper mills, for which existing data are not available) and that polynuclear aromatic hydrocarbons (PAH's) are analyzed only in bed sediment. The analytical strategy for bed sediments and tissues is listed in table 9. The list for tissues is a subset of the list for bed sediments because compounds known to be metabolized by target taxa have been eliminated from the target analyte list for tissues.

Spatial Distribution Survey

The Spatial Distribution Survey adds improved geographic coverage with particular emphasis on the assessment of priority constituents identified in the Occurrence Survey. Occurrence-Survey results affect the analytical strategy and the geographic distribution of sampling sites. The combined data from the two phases of sampling provide a basic description of spatial distribution for each Study Unit, with emphasis on priority constituents, and support initial evaluation of sources and biological availability for priority constituents.

Site Selection

Typically, 20–30 sites are sampled and include selected sites also sampled during the Occurrence Survey. The general goals in site selection for the Spatial Distribution Survey are to attain improved representation of the most important Environmental Settings in the Study Unit by appropriate addition of Indicator Sites and to attain adequate spatial resolution in priority main-stem channels and major tributaries by addition of Integrator Sites. Large areas with low contaminant levels and low variance require few sites. Compared to the Occurrence Survey, some parts of a Study Unit may require a significant increase in site density to assess priority contaminants.

Sampling Strategy

The sampling strategy for bed sediment in the Spatial Distribution Survey is the same as that for the Occurrence Survey. For tissue studies, samples of more than one species (preferably a fish and an invertebrate species) are collected at as many as 50 percent of the Spatial Distribution Survey sites. This collection ensures that some fish data are obtained for comparison with data from other programs and maximizes the comparability of data among sites within a Study Unit (where a single taxon may not be present at all sites).

Sample Analyses

Sample analyses are the same as those for the Occurrence Survey (table 9) except that the scope is reduced on the basis of results of the Occurrence Survey. To the extent that analytical methods allow, costly analyses are limited to contaminants that are most significant in the Study Unit or for National Synthesis.

Ecological Studies

Ecological Studies are an integral part of the approach used by NAWQA to assess water quality. Information on biological communities and habitat characteristics contributes to the conceptual model of factors that affect water quality and to improved understanding of the relations among physical, chemical, and biological characteristics of streams (Gurtz, 1994). The following primary strategies are used for Ecological Studies:

- Fixed-Site Reach Assessments provide nationally consistent ecological information at all Basic and Intensive Fixed Sites as part of an integrated physical, chemical, and biological assessment of water quality.
- Intensive Ecological Assessments assess spatial and temporal variability associated with biological communities and habitat characteristics.
- Ecological Synoptic Studies provide improved spatial resolution of selected ecological characteristics in relation to land uses, contaminant sources, and habitat conditions.

Fixed-Site Reach Assessments and Intensive Ecological Assessments provide an initial evaluation of the linkages among physical, chemical, and biological conditions across a wide range of Environmental Settings within and among Study Units. Ecological Synoptic Studies provide a much more complete geographic representation within a Study Unit but for a more limited set of physical, chemical, and biological characteristics.

Table 9. Analytical strategy for bed-sediment and tissue Occurrence Survey

[Bed sediments analyzed for all constituents; tissues analyzed only for those indicated by *; some of the analytes may be deleted or qualified depending on method performance for ambient samples]

Trace elements and major metals

Aluminum*	Cerium	Lead*	Potassium	Titanium
Antimony* (Stibium)	Chromium*	Lithium	Scandium	Uranium*
Arsenic*	Cobalt*	Magnesium	Selenium*	Vanadium*
Barium*	Copper*	Manganese*	Silver*	Yttrium
Beryllium*	Europium	Mercury*	Sodium	Ytterblum
Bismuth	Gallium	Molybdenum*	Strontium*	Zinc*
Boron (tissue only)	Gold	Neodymium	Sulfur	
Cadmium*	Iron*	Nickel*	Tantalum	
Calcium	Holmium	Niobium	Thorium*	
	Lanthanum	Phosphorus	Tin	

Organic contaminants

Organochlorine insecticides and polychlorinated biphenyls

Aldrin*	*o,p'*-DDT*	delta-HCH (in tissues only)	*trans*-Nonachlor*
cis-chlordane*	*p,p'*-DDT*	gamma-HCH (Lindane)*	Oxychlordane*
trans-chlordane*	Dieldrin*	Isodrin	Polychlorinated biphenyls (PCBs-total)*
Chloroneb	Endosulfan I	Methoxychlor, *o,p'**	*cis*-Permethrin
Dacthal*	Endrin*	Methoxychlor, *p,p'**	*trans*-Permethrin
o,p'-DDD*	Heptachlor*	Mirex*	Pentachloroanisole*
p,p'-DDD*	Heptachlor epoxide*	*cis*-Nonachlor*	Toxaphene*
o,p'-DDE*	alpha-HCH*		
p,p'-DDE*	beta-HCH*		

Other semivolatile organic contaminants

Acenaphthene	Dibenzo(a,h)anthracene	2-Methylanthracene
Acenaphthylene	Dibenzothiophene	2-Methyl-4,6-Dinitrophenol
Acridine	1,2-Dichlorobenzene	4,5-Methylenephenanthrene
C8-Alkylphenols	1,3-Dichlorobenzene	1-Methyl-9H-Fluorene
Anthracene	1,4-Dichlorobenzene	1-Methylphenanthrene
Anthraquinone	2,4-Dichlorophenol	1-Methylpyrene
Azobenzene	Diethyl Phthalate	Naphthalene
Benzo(a)anthracene	3,5-Dimethylphenol	Nitrobenzene
Benzo(b)fluoranthene	1,2-Dimethylnaphthalene	2-Nitrophenol
Benzo(k)fluoranthene	1,6-Dimethylnaphthalene	4-Nitrophenol
Benzo(g,h,i)perylene	2,6-Dimethylnaphthalene	N-Nitroso-Diphenylamine
Benzo(a)pyrene	Dimethyl Phthalate	N-Nitroso-Di-n-Propyl Amine
Benzo(c)quinoline	Di-n-butyl Phthalate	Phenanthrene
2,2'-Biquinoline	2,4-Dinitrophenol	Pyrene
4-Bromophenylphenylether	2,4-Dinitrotoluene	Pentachloronitrobenzene
Butylbenzyl Phthalate	2,6-Dinitrotoluene	Pentachlorophenol
9H-Carbazole	Di-n-octyl Phthalate	Phenanthridine
bis(2-Chloroethoxy) methane	*bis*(2-Ethylhexyl) Phthalate	Phenol
bis(2-Chloroethyl) ether	2-Ethylnaphthalene	Quinoline
bis(2-Chloroisopropyl) ether	Fluoranthene	2,3,5,6-Tetramethylphenol
4-Chloro-3-methylphenol	9H-Fluorene	1,2,4-Trichlorobenzene
2-Chlorophenol	Hexachlorobenzene*	2,4,6-Trichlorophenol
2-Chloronaphthalene	Hexachloroethane	2,4,6-Trimethylphenol
4-Chlorophenylphenylether	Indeno(1,2,3-cd) pyrene	2,3,6-Trimethylnaphthalene
p-Cresol	Isophorone	
Chrysene	Isoquinoline	

Carbon

Carbonate	Organic carbon	Total carbon

Fixed-Site Reach Assessment

Descriptions of biological communities and habitat conditions are essential for an overall assessment of the status of water resources. At all Basic and Intensive Fixed Sites, biological communities (fish, invertebrates, algae), and habitat conditions are described and recorded. These data are used to improve understanding of relations among aquatic biological communities and the physical, chemical, and hydrologic conditions associated with selected Environmental Settings. Basic and Intensive Fixed Sites provide the best opportunity to satisfy this objective because of the nationally consistent strategies for collecting data on water chemistry and hydrologic conditions at these sites.

Site Selection

Fixed-Site Reach Assessments are done at all Basic and Intensive Fixed Sites except those in which ecological conditions are not representative because of local geomorphology or other natural or human influences. Indicator Sites are selected with the goal of keeping stream size, gradient, and geomorphic characteristics in a relatively narrow range while meeting the other objectives of the Basic and Intensive Fixed Sites. Consistency in these attributes among sites is important for making comparisons of ecological characteristics and facilitates interpretation of other water-quality measurements, such as sediment concentration and transport of constituents associated with sediment.

Sampling Strategy

The unit of sampling for Ecological Studies is the sampling reach, which is a part of the stream where stream, bank, and flood-plain habitat features are representative of the local area, and near the fixed-site location where chemical data are collected. Collections of biological communities and characterizations of riparian and instream habitat conditions are made for at least one sampling reach at each Basic and Intensive Fixed Site. Reach length is defined at each site by a combination of factors, which include stream geomorphology and meander wavelength (Meador, Hupp, and others, 1993). For wadeable streams, the acceptable range for sampling reach length usually ranges from 150 to 500 m, but longer reaches may be necessary in nonwadeable streams. Criteria for minimum and maximum reach lengths are used to provide a sampling-reach length sufficient to ensure the collection of representative samples from, for example, the fish community.

Three taxonomic groups—fish, invertebrates, and algae—are sampled because they respond differently to various environmental stresses. Fish are valuable biological indicators of long-term water-resource conditions because they are long lived (years to decades) and have considerable economic value and public interest. Benthic invertebrates (aquatic insects, mollusks, crustaceans, worms) have life cycles (from months to a few years) that are intermediate between fish and algae, have close association with streambed sediments, and can be used for characterizing changes in water quality over small spatial areas. Algae respond quickly (within days to weeks) to changes in their environment and serve as valuable biological indicators of rapid changes in water-resource conditions.

Representative samples of the fish community are collected from the stream reach by using a combination of sampling methods to determine species presence and abundance (Meador, Cuffney, and Gurtz, 1993); the two primary sampling methods used are electrofishing and seining. Fish are identified as to species, length and weight are recorded, and the presence of external anomalies, which include skeletal deformities, eroded fins, lesions, tumors, diseases, and parasites, is noted.

Three types of benthic invertebrate samples are collected in each sampling reach (Cuffney and others, 1993b). Semiquantitative samples provide information on the abundance of taxa present in two targeted habitats—one that is expected to support the highest number of taxa within the reach (for example, riffles or woody snags) and a depositional habitat (for example, pool). In addition, a qualitative sample from all instream habitat types in the reach provides a more complete list of taxonomic groups present at the time of collection. All samples are composites collected throughout the entire reach.

The algal community is sampled from each of the habitats targeted for benthic invertebrates and a multihabitat composite sample is also prepared (Porter and others, 1993). All algal samples are collected in a semiquantitative manner.

Habitat characterizations of channel, bank, and flood-plain features follow a spatial hierarchy that incorporates basin, stream segment, stream reach, and sample descriptors (Meador, Hupp, and others, 1993). Basin descriptors are recorded as part of the Environmental Framework of each site and include such variables as ecoregion, physiographic province, geology, soils, climate, and land use. Stream-segment data are obtained from geographic information system databases and topographic maps and include information on stream meandering, gradient, elevation, and water-management features. Habitat characterizations at the reach scale include geomorphic channel units, such as riffle, run, and pool, as well as physical features of the channel, bank, and flood plain and observations of dominant species of woody vegetation and macrophytes. Habitat characteristics that are associated with individual biological samples include substrate particle size, water depth, and velocity.

Fixed-Site Reach Assessments are done at least once at each Basic and Intensive Fixed Site during the 3 years of the intensive data-collection phase. Sampling of biological communities is conducted during similar hydrologic and seasonal conditions for all fixed sites in the Study Unit. Scheduling of sample collection takes into consideration several factors, which include hydrology, life histories of aquatic species, accessibility of sites, and timing of major human activities.

Sample Analyses

Samples of fish, invertebrate, and algal communities are identified to the lowest practical taxon, preferably species, to obtain information on taxonomic composition and abundance. Procedures have been developed for processing and quality assurance of samples (Cuffney and others, 1993a). The Biological Quality-Assurance Unit at the U.S. Geological Survey National Water-Quality Laboratory monitors taxonomic data, which include coordinating verification of identifications, establishing taxonomic voucher collections, developing and maintaining computer databases, and collaborating with other agencies in sharing taxonomic data and coordinating databases.

Intensive Ecological Assessment

Intensive Ecological Assessments are done at a subset of Basic and Intensive Fixed Sites in each Study Unit to provide information on spatial and temporal variability of biological communities and habitat characteristics. An understanding of background variability is critical to interpreting the natural and human factors that influence ecological conditions.

Sites for Intensive Ecological Assessments (typically three to four sites) are chosen to represent a range of water-quality conditions, stream sizes, and habitat conditions within each Study Unit. Reach-to-reach variability is estimated at these sites by sampling multiple (minimum of three) reaches that are located so that each represents similar water-quality conditions to the fixed site. Year-to-year variability is described by sampling one of the three reaches during each year of the 3-year intensive data-collection phase. Sampling and sample-processing strategies for each reach are identical to those for the Fixed-Site Reach Assessments.

Ecological Synoptic Studies

Ecological Synoptic Studies are short-term investigations of specific ecological characteristics within all or part of a Study Unit. Their roles in the NAWQA study design are similar to those for Water-Column Synoptic Studies—to provide improved spatial resolution compared with fixed-site sampling and to evaluate the spatial distribution of selected ecological characteristics in relation to causative factors, such as land uses, contaminant sources, or instream habitat conditions. Ecological Synoptic Studies supplement information from the more comprehensive data collected at Basic and Intensive Fixed Sites by targeting specific and more narrowly defined conditions for ecological characterization at more locations.

Ecological Synoptic Studies usually focus on the relation of selected Environmental Setting characteristics to selected biological community characteristics. For example, the distribution of fish species may be assessed for small and moderate-sized streams within urban, agricultural, and undeveloped settings. The design is coordinated wherever possible with that of Water-Column Synoptic Studies in the same Study Unit and among Study Units to address questions of regional or national interest. Priorities for Ecological Synoptic Studies are evaluated based on the potential to address relations among physical, chemical, and biological characteristics; the areal extent of a water-quality problem or biological issue; and the degree to which the design contributes to regional understanding and current National Synthesis topics. Results of the Retrospective Analysis, information on land-use patterns and local priority issues, and ecological information obtained from field reconnaissance of sites are used to determine the design.

Most Study Units complete one to two Ecological Synoptic Studies during the second and third years of the 3-year intensive data-collection phase. Although, the strategy for site selection, sampling, and analysis is issue specific and usually includes a subset of the biological components sampled at the fixed sites, nationally consistent methods are used so results can be compared among Study Units.

GROUND-WATER STUDY DESIGN

The study design for ground water focuses on assessing the water-quality conditions of major aquifers in each Study Unit with emphasis on the quality of recently recharged ground water associated with present and recent human activities. Although stream-water quality is highly variable through time, ground-water quality is determined primarily by chemical characteristics that tend to vary more spatially than temporally. Thus, the general approach to the ground-water assessment focuses on spatial characterization. Furthermore, the initial emphasis is on the chemical characteristics of ground water. The need to understand microbial processes at regional scales, however, is increasingly evident (Chapelle and others, 1993), and this aspect of ground-water quality may receive greater emphasis as Study-Unit Investigations evolve.

Overview of Approach

Ground-water quality is assessed by three primary study components (table 10):

- Study-Unit Surveys assess the water quality of the major aquifer systems of the Study Unit by sampling primarily existing wells.
- Land-Use Studies use observation wells and selected existing wells to assess the quality of recently recharged shallow ground water associated with regionally extensive combinations of land use and hydrogeologic conditions.
- Flowpath Studies use transects and groups of clustered, multilevel observation wells to examine specific relations among land-use practices, ground-water flow, contaminant occurrence and transport, and surface- and ground-water interaction.

The sampling design is based on the need to examine ground-water quality at a range of spatial scales. Study-Unit Surveys are used, in conjunction with an analysis of available data, to broadly characterize ground-water quality across the Study Unit. Land-Use and Flowpath Studies are done at intermediate and more local scales, respectively, to build an understanding of causal relations and processes. The Land-Use and Flowpath Studies are directed, for the most part, toward the effects of human activities on ground-water quality. The three study components are phased in over different sequences and time frames in different Study Units; the sequence depends on the availability and quality of existing data and the size and complexity of the ground-water system. Generally, the first intensive study phase in each Study Unit includes two to four Land-Use Studies and one to two Flowpath Studies. The most important aquifer zones are sampled during the first phase of the Study-Unit Survey if existing data are inadequate.

The Study Units allocate different proportions of study resources to the three study components; the allocation depends on the types and extent of available water-quality data for the Study Unit, the complexity and extent of aquifer units and Environmental Settings, the types and locations of existing wells available to sample in the Study Unit, and whether new wells must be installed. In allocating resources among the different study components, each Study-Unit Investigation attempts to achieve a balance between broad-scale assessment and spatially focused studies aimed at understanding causal relations.

Study-Unit Survey

The primary objective of the Study-Unit Survey is to provide a broad assessment of the water-quality conditions of the most important present and future ground-water resources of each Study Unit. The large areal and depth dimensions of this resource require that the Study-Unit Survey rely primarily on sampling existing wells and, wherever possible, on existing data collected by other agencies and programs. In parts of some Study Units, existing data on presently used ground-water resources are more complete in many respects than NAWQA studies can produce.

Table 10. Components and attributes of the National Water-Quality Assessment ground-water sampling design

Feature	Study component		
	Study-Unit Survey	**Land-Use Studies**	**Flowpath Studies**
General objective	To supplement existing data in providing broad overview of ground-water quality within each Study Unit	To examine natural and human factors that affect the quality of shallow ground water that underlies key types of land use	To examine ground-water quality along inferred flowpaths and interactions of ground water with surface water
Spatial domain	Ground-water resource throughout Study Unit	Uppermost part of ground-water system in specified land-use settings	Shallow flow systems in specified settings
Selection of areas	Aquifer system divided typically into 3–5 subunits on the basis of physiographic and hydrogeologic features	Typically, 2–4 Land-Use Studies per Study Unit Each land-use setting represents a combination of a land-use type and a hydrogeologic subunit	Typically, 1–2 Flowpath Studies per Study Unit Generally, unconsolidated shallow aquifers Upper part of flowpath generally lies within one of land-use settings examined in Land-Use Studies Typically, located in an indicator basin for surface-water sampling design
Number of wells sampled	Typically, 20–30 wells in each subunit General goal for spatial density is one well per 100 km^2	Typically, 20–30 wells in each land-use setting	Typically, 10–12 wells along flowpath and 10 wells for areal sampling
Well-selection strategy	Spatially distributed "random" sampling Primarily existing wells	Spatially distributed "random" sampling New or existing wells	Wells distributed at multiple depths along flowpath and areally in vicinity of flowpath New wells to extent possible
Temporal sampling strategy	Each well typically sampled once	Each well typically sampled once	Variable; multiple samples from most wells

Subunit Definition and Prioritization

The first step in the design of a Study-Unit Survey is the division of the ground-water resource into aquifer subunits, generally 3–5 per Study Unit. The subunits serve as a first-order subdivision of the Study Unit into aquifer zones that are expected to be homogeneous in water-quality characteristics compared with the Study Unit as a whole (Alley, 1993a). This subdivision is based mainly on identification of major hydrogeologic settings. Shallow aquifer systems are further subdivided on the basis of physiographic characteristics, which include soil characteristics, landforms, discharge and recharge areas, and drainage characteristics; however, land use or other human influences are not the primary criteria. Some thick aquifers are subdivided into two or more subunits on the basis of depth; however, some grouping of aquifers with similar characteristics usually is necessary to achieve a manageable number of subunits.

A key challenge in defining aquifer subunits is to group a number of different factors that could affect ground-water quality to produce a small number of carefully chosen units. A detailed subdivision is done first, which is followed by grouping of the initial subdivisions to designate the three to five subunits for the Study-Unit Survey.

Because of the large spatial dimensions of ground-water resources, completion of the Study-Unit Survey in some Study Units will take place in phases over multiple NAWQA cycles. Although this approach means that some subunits might not be sampled for many years, careful prioritization ensures that the most important parts of the resource are assessed first. Prioritization of subunits is based on present water use, potential for future water use, likelihood of contamination, and potential for change.

Well Selection and Sampling Strategy

For each aquifer subunit, the well-selection process and sampling strategy are designed to achieve a preliminary assessment from a combination of new and existing data. As a general planning guideline, an areal sampling density of at least one well per 100 km^2 is desired, and at least 20 wells are selected in each subunit. The areal density sampling goal may not always be met in some larger Study Units, and some subunits with extensive existing data may not be sampled during the first cycle of NAWQA.

Perhaps the most significant factor that affects the utility of Study-Unit Surveys is that locations of existing wells are biased relative to the ground-water resource. Different types of wells (domestic, public water supply, and so forth) are likely to be biased in different ways. In general, each Study-Unit Survey uses as few different types of wells as needed to obtain adequate spatial (areally and with depth) distribution of ground-water samples from the aquifer system. A description of the type(s) of wells sampled is included as part of the description of the "target population" of the Study-Unit Survey.

Wells are selected for sampling in a subunit by using a grid-based random sampling approach (Scott, 1990; Alley, 1993b). Where feasible, candidate wells are identified by a systematic inventory of existing wells in each subunit. The inventory results in maps that display the lengths and three-dimensional distribution of the screened parts of available wells and well locations relative to the water table, land surface, and aquifer(s) of interest. The grid-based random sample is selected from suitable candidate wells. Where an initial well inventory is not feasible, potential sites are randomly selected on a grid system, and suitable wells are identified near each site to achieve a distribution of sampling wells through the subunit.

Sample Analyses

All samples collected for the Study-Unit Survey are analyzed for the same field characteristics and dissolved constituents that are analyzed for samples from Basic and Intensive Fixed Sites (tables 6 and 7). Depending on Study-Unit and National Synthesis priorities, all or part of the samples also are analyzed for other constituents. In particular, most Study-Unit Survey samples will be analyzed for volatile organic compounds.

Land-Use Studies

The primary objective of the Land-Use Studies is to assess the concentrations and distribution of water-quality constituents in recently recharged ground water (generally less than 10-years old) associated with the most significant settings of land use and hydrogeologic conditions in each Study Unit. A closely related second objective is to understand the human and natural factors in each setting that affect ground-water quality. This focus on recently recharged shallow ground water in priority settings enables direct assessment of relations between land-use activities and ground-water quality. The potential significance of shallow ground-water quality conditions to underlying and adjacent ground-water resources is assessed through the Study-Unit Survey and the Flowpath Studies.

Selection of Land-Use Studies

Two to four Land-Use Studies typically are completed in each Study Unit during the first cycle of NAWQA. The process of selecting Land-Use Studies in each Study Unit begins by mapping the distribution of major land uses in relation to the aquifer subunits designated for the Study-Unit Survey. The land uses are defined and mapped as part of developing the Environmental Framework for each Study Unit. The intersection of land-use areas with subunits defines an initial set of ground-water land-use settings, which are then further subdivided, if necessary, to reflect important differences in hydrogeologic settings within major subunits. This process results in a variable number, frequently from 5 to 20 potential land-use settings for study.

The priority of potential Land-Use Studies is based on a combination of Study-Unit and National Synthesis priorities. Factors considered in assigning priorities include importance of the land-use setting to used ground water in the Study Unit, contamination potential of the targeted land use, geographic correspondence to subunits concurrently sampled as part of the Study-Unit Survey, geographic correspondence to surface-water studies, and National Synthesis plans for comparisons among land-use settings of regional and national importance. The top two to four land-use settings are chosen for investigation. An example of the geographic relation of Land-Use Study areas to the Study-Unit Survey is shown by the study design in figure 8 for the San Joaquin/Tulare Basins Study Unit. The large vineyard area in the southern part of the Study Unit was not included in the Land-Use Study because of a much different hydrogeologic setting.

Well-Selection Strategy

Wells selected for a Land-Use Study are randomly distributed throughout the occurrences of the land-use setting (combination of land use and hydrogeologic conditions) of interest within the Study Unit. The grid-based selection method described by Scott (1990) is used in this process. A minimum of 20 wells are sampled in each land-use setting. A minimum of 30 wells are sampled in land-use settings where the ground-water quality is expected to vary the most.

Many, if not most, land-use settings defined for study are not single, homogeneous, contiguous areas but exist in multiple distinct "islands" or are intermingled with other land uses. In the study approach, the selection of sampling wells targets all occurrences of the defined setting rather than a representative subarea. A possible exception would be if a large (greater than 75-percent) majority of the targeted setting is in a single area or a few large contiguous areas, but with complex boundaries and small independent areas scattered around. Because of the increased uncertainty about land-use influences near boundaries, these small, independent areas with complex boundaries sometimes are excluded.

Usually in the mapped areas of the targeted land-use setting, land use is not truly homogenous, and more than one land use can be near a well. In evaluating the effects of land use on ground-water quality, the most reliable approach is to select wells located in recharge areas, screened near the water table, and directly downgradient from the specific targeted land-use setting. This approach helps avoid the influence of other land-use activities and complications from upward movement of water that originated in distant areas. Because land use can change with time, sampling locations are selected where it has been stable over the past decade.

These restrictions lead to very selective choices of wells to sample. The wells sampled for the Land-Use Studies have short (ideally less than 3 m in length) open intervals located near the top of unconfined aquifers. Only wells located in recharge areas underlying or immediately downgradient from the land use of interest are selected. Ideally, they are observation wells or low-capacity existing wells to avoid the complexities of determining contributing areas to heavily pumped wells. Many wells are installed by NAWQA to meet these criteria.

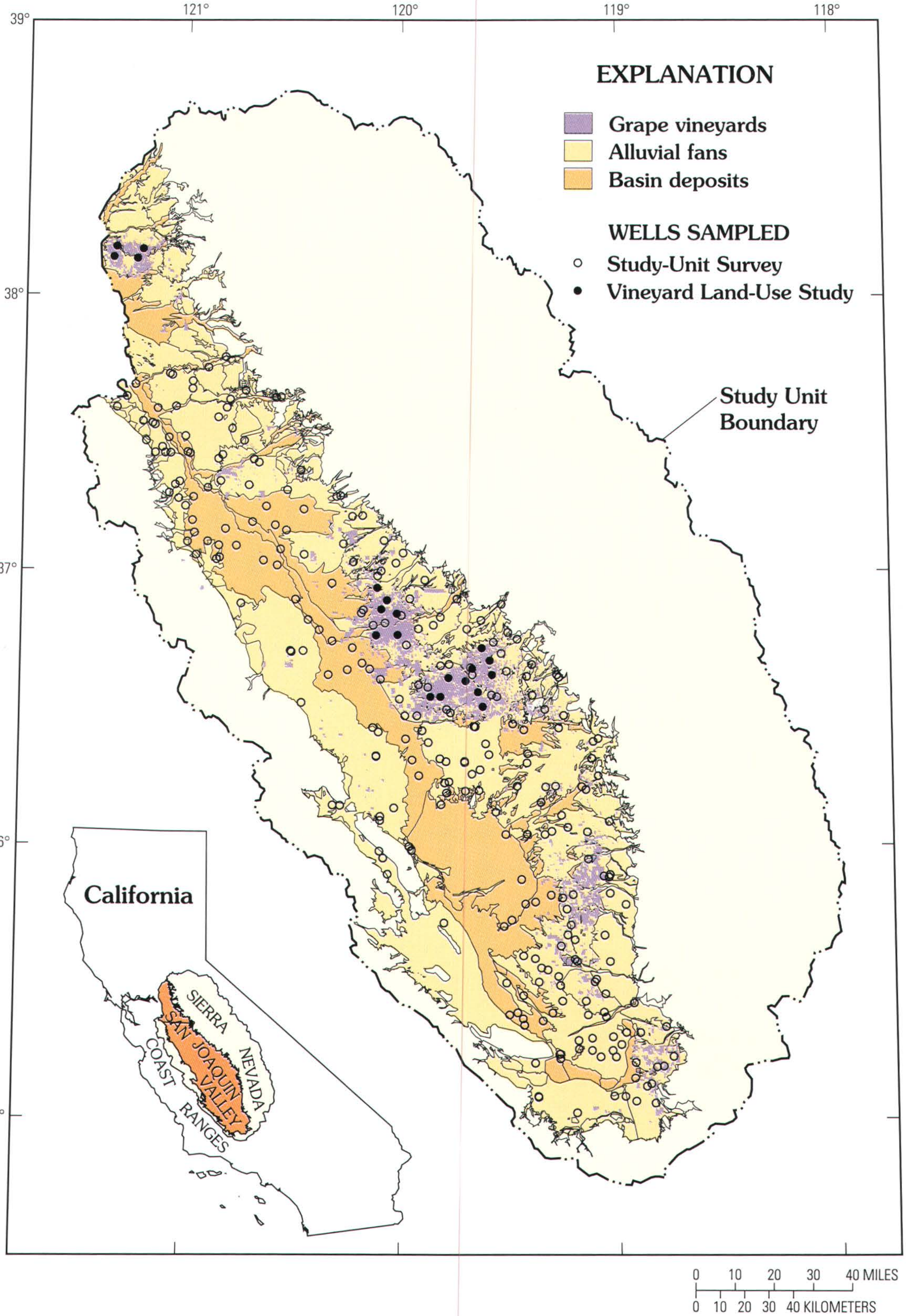

Figure 8. Example of study designs for a Study-Unit Survey and Land-Use Study, San Joaquin/Tulare Basins Study Unit.

Sample Analyses

In general, the same national target constituents are analyzed in samples from the Land-Use Studies as for the Study-Unit Survey. The addition of other constituents varies among Land-Use Studies as in the Study-Unit Survey. Volatile organic compounds will be analyzed in samples from many of the Land-Use Studies.

Flowpath Studies

The primary objectives of Flowpath Studies are to characterize the spatial and temporal distribution of water quality in relation to ground-water flow in shallow ground-water systems for particular settings, increase understanding of the natural processes and human influences in these settings that affect the evolution of ground-water quality along flowpaths through the saturated zone, and evaluate the degree and water-quality significance of interaction between ground water and streams for selected settings. Ideally, many of the Flowpath Studies provide a perspective on the potential significance of poor-quality shallow ground water to regional aquifers and streams.

Most Flowpath Studies are within Land-Use Study areas where the areal distribution of shallow ground-water quality is broadly characterized. Because of the low spatial density of sampling in many Land-Use Studies, Flowpath Studies frequently include additional areal sampling of shallow ground water in the vicinity of the transect.

Selection of Flowpath Study Sites

Typically, one to two Flowpath Studies are undertaken in each Study Unit during the first NAWQA cycle. Principal considerations for selecting and prioritizing Flowpath Study sites are as follows:

- A large part of the upgradient area of the well transect is located in a land-use setting examined during a Land-Use Study.
- When possible, the transect is located in an indicator basin selected for surface-water studies and passes through an area of the land use for which the indicator basin was chosen.
- The geologic framework and hydrology of the area are well defined and typical for the land-use setting. Ideally, the flow system should be simple and well understood.
- Ideally, the flow in the stream at the downgradient terminus of the transect is small enough so that comparisons between ground- and surface-water quality are feasible.
- When possible, Flowpath Studies are done at or near field research sites supported by other agencies to benefit from already existing data-collection activities.

Transect Design and Sampling Strategy

Ideally, well transects extend along a ground-water flowpath. Most flowpath transects either begin or terminate at a stream. As an example, a typical transect in terrain with a gaining stream is shown in figure 9. This "typical" transect illustrates some of the general concepts and level of detail envisioned for a Flowpath Study. Variations of the design are made to adjust to differences in scales and complexities of ground-water flow in different terrains. Four to six clusters of two to three wells are located along the transect in figure 9, for a total of 10 to 12 wells. Generally, in each cluster, one well is screened beginning 1 to 2 m below the lowest anticipated position of the water table, and the additional wells are screened between 5 to 75 m below the water table. Typically, well screens do not exceed 2 m in length to ensure that water samples are representative of a "point" in the ground-water flow system. To best define the hydrologic system, one well cluster is located at the ground-water divide and another at the bank or in the bed of the gaining surface-water body. Additional streambank wells include wells on the streambank opposite the well transect and wells screened directly below the streambed. The samples from these wells provide the best measure of the quality of ground water that interact with the stream. Where streambed wells cannot be maintained, an option is to collect a one-time series of ground-water samples below the streambed by driving a well point, or minipiezometer (Lee and Cherry, 1978), into the streambed and collect water samples and water-level information at several depths.

In general, well transects are located in unconsolidated earth materials, and the wells are constructed as part of the study. Occasionally, a well transect is located so that one or two existing wells can be used. The depth of the deepest screened interval in a transect well and the length of a transect vary considerably among different hydrogeologic settings. Ideally, the deepest transect wells are screened to the depth at which water samples show little or no human influence on water quality. Usually, the lengths of well transects, which range from one to several kilometers, depend on the scale of the flow system.

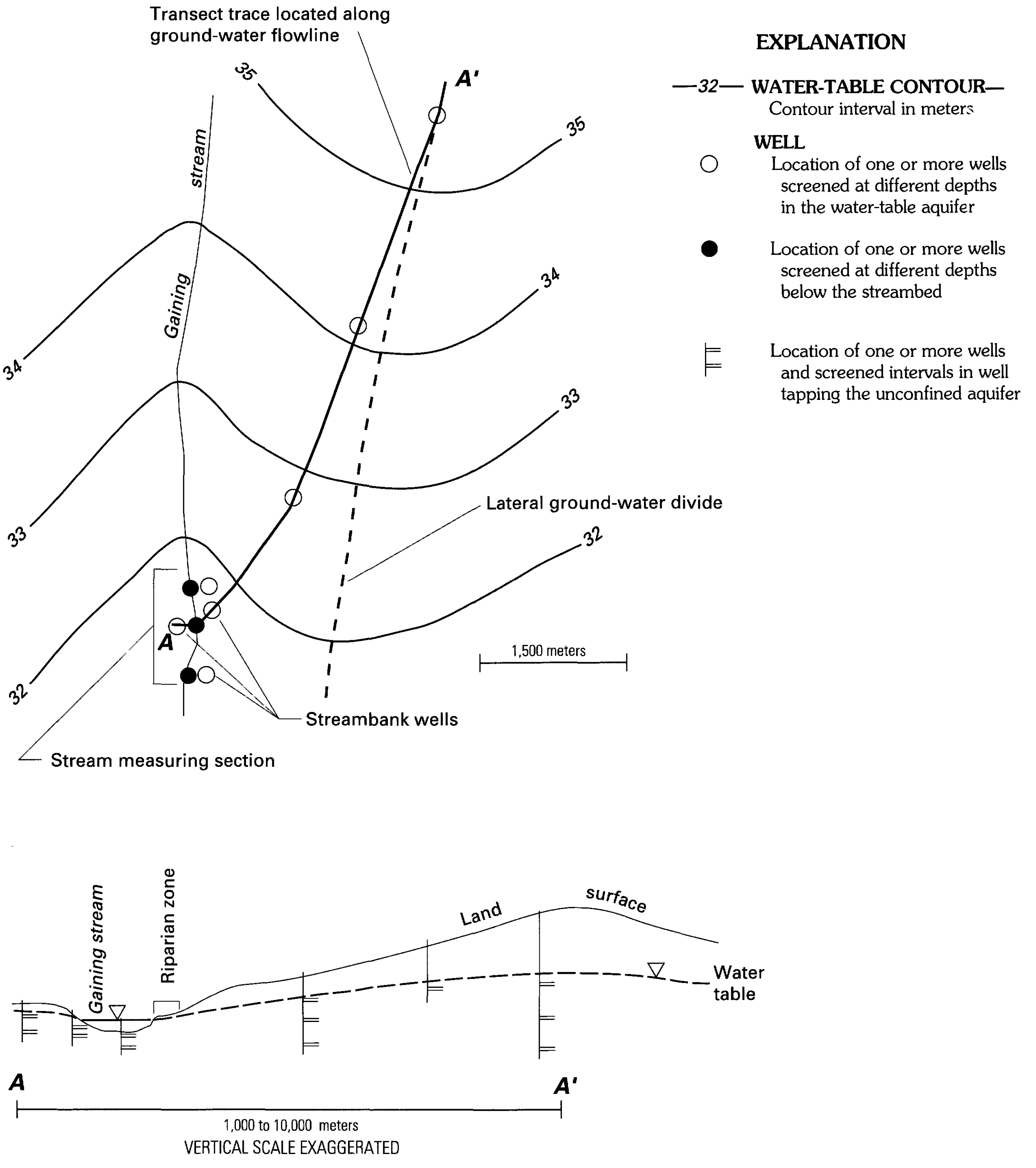

Figure 9. Typical idealized transect design for a Flowpath Study associated with a gaining stream.

Each Study-Unit team designs a specific sampling and analytical strategy for each transect site to meet study objectives. Typically, hydraulic measurements associated with a well-transect site include 2 years of monthly head measurements in all wells, three to four measurements of stream base flow at different seasons of the year (for transects with streams) and, if feasible, seepage investigations near the terminus of the transect during the annual low-flow period. Water-quality sampling associated with each Flowpath Study typically consists of at least one sample from all wells analyzed for the national target analytes (tables 5, 6) and isotopes (such as tritium) or chlorofluorocarbons that allow an estimate of water age; monthly or seasonal samples from some wells for selected analytes, particularly for wells screened near the water table; and samples of base flow in the stream associated with the well transect that are analyzed for selected analytes.

Flowpath Studies during the initial phase of NAWQA are viewed as the potential beginning of long-term studies that will lead to more intensive studies. Moreover, networks established as part of some Flowpath Studies may form an important element of a long-term trend network.

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