United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

Part 600
National Water
Quality Handbook

# National Handbook of Water Quality Monitoring

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# National Handbook of Water Quality Monitoring

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Water Quality Monitoring

# Chapter 1 Introduction

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# Chapter 1 Introduction

## 600.0100 General

Recognition of agriculture's contribution to nonpoint source (NPS) pollutant loadings to streams, lakes, estuaries, and ground water has led to increased emphasis on water quality monitoring in rural watersheds. Conservation Districts and the Natural Resources Conservation Service (NRCS) are often sponsors and cooperators, respectively, of studies and projects to reduce agricultural NPS loadings. The primary purpose of this handbook is to provide these entities and their partners with guidance for gathering and using water quality information to support planning and implementation activities.

Although opinions vary about the value of water quality monitoring, there is consensus that monitoring is relatively expensive. Therefore, it is imperative that monitoring be well designed. As stated by Ward, et al. (1986), appropriate designs of monitoring systems are needed to prevent a "data rich, but information poor" monitoring system. Part 1 of this handbook primarily addresses the design of intensive monitoring programs. Part 2 addresses the analysis of monitoring data.to enable us to refine our understanding of water quality.

For most projects that involve water quality concerns, the NRCS planning process requires information obtained by monitoring to perform the planning steps. Current and historical data are needed to perform Phase I, which includes identifying problem areas, determining objectives and setting goals, inventorying resources, and analyzing resource data. The results of Phase I work are used in Phase II to formulate and evaluate alternatives and decide on a plan. Phase III, implementation and evaluation, requires water quality information collected through time to evaluate the effectiveness of the implemented alternative.

The collection of water quality information is extremely important as we learn how to address water quality resource concerns. Adaptive management requires that we observe the effects of natural resources management decisions so we can maximize learning and increase the knowledge base for future natural resources management decisions. Even during studies, data could be used to calibrate and refine planning tools, such as computer models. The success of such efforts should eventually reduce the need for costly water quality monitoring in the future.

State water quality agencies are generally most active in assisting local water quality monitoring. At the Federal level, the Office of Management and Budget has directed agencies to coordinate their data acquisition efforts with the U.S. Geological Survey (USGS)(OMB Circular M-92-01). The local USGS office should be involved in the design of project monitoring.

## 600.0101 Definitions

The term water quality is used throughout this guide, so a definition is appropriate. Although many definitions for this term exist (APHA, et al. 1969; Rechard and McQuisten 1968; Veatch and Humphreys 1966), water quality can be broadly defined as the physical, chemical, and biological composition of water as related to its intended use for such purposes as drinking, recreation, irrigation, and fisheries.

The term water quality has different meanings to different users of the water, which can result in confusion among water quality managers. The term may be applied to a single characteristic of the water or to a group of characteristics combined into a water quality index.

A few other terms related to water quality are important to define.

***Water quality management*** can be defined as the management of the physical, chemical, and biological characteristics of water (Sanders, et al. 1983).

***Water quality monitoring,*** one function of water quality management, is the collection of information on the physical, chemical, and biological characteristics of water (Sanders, et al. 1983).

***Pollution*** refers to a condition of water within a water body caused by the presence of undesirable materials (APHA, et al. 1969).

***Contamination*** is the introduction of substances into water at a sufficient concentration to make the water unfit for its intended use (APHA, et al. 1969).

***Pollution control*** generally is associated with the regulation of pollutants.

## 600.0102 Monitoring purposes

Monitoring of water quality can serve many purposes. Each purpose is described using relevant examples.

### (a) Analyze trends

Monitoring on a regular basis has been used to determine how water quality is changing over time. A widely publicized example of trend analysis was that published by Smith and Alexander (1983) on stream chemistry trends at the USGS benchmark stations. Trend analysis was also used in several of the Rural Clean Water Program (RCWP) projects in the United States, including those in Vermont, Idaho, and Florida.

Monitoring of so called "baseline" conditions also has been used and is often recommended. Baseline generally is thought of as a pre-condition; that is, what the water quality conditions are that currently exist. Caution is recommended in using baseline monitoring. Unless such data are used for reconnaissance purposes or actually are the beginning of trend analysis, then baseline monitoring is not recommended except where the effects caused by climate are controlled in the design of the project. If, for example, the baseline data were collected during an abnormal year, the data could be biased.

### (b) Determine fate and transport of pollutants

Monitoring also is conducted to determine whether a pollutant may move and where it may go. For such projects, monitoring over a long period may not be needed. For example, if the objective is to determine whether a pesticide is leaving the root zone, a short-term (<5 years) study of intensive sampling would be sufficient.

Fate and transport studies typically require frequent sampling of all possible transport pathways in a relatively small area. These studies also are subject to climate influences and may require sophisticated sampling equipment.

### (c) Define critical areas

Water quality monitoring has been used to locate areas within watersheds exhibiting greater pollution potential than other areas. The results of such monitoring can then be used to target Resource Management Systems (RMSs). This type of monitoring has often been termed *reconnaissance* monitoring.

Targeting critical areas also could occur following interpretation of water quality data collected early in a project. For example, monitoring in a particular watershed could indicate that one of the subwatersheds may have the highest phosphorus concentrations and export as compared to the other monitored sub-watersheds. Supplemental investigation may reveal the source of the phosphorus, either natural or related to management. Based on these early findings from monitoring data, priority could be given to that subwatershed for implementation of RMSs.

Reconnaissance monitoring however, is generally conducted over a short time frame, and caution should be exercised to assure that decisions regarding targeting are not biased by unusual climate conditions during the period of monitoring.

### (d) Assess compliance

Water quality monitoring frequently has been used to determine compliance with water quality plans and standards. For example, bacteria monitoring has been used to determine the percentage of the time bacteria levels exceed a standard, such as 200 organisms per 100 milliliter. Compliance monitoring should consider climate conditions as well as the ability to link instream levels with actual sources before taking action.

### (e) Measure effectiveness of conservation practices

Monitoring to determine the effectiveness of individual conservation practices is typically conducted on a plot or field scale, or as close as possible to the practice. Water quality studies of individual practices can be conducted in a relatively short time frame (<5 years). However, some practices may take many years to show results.

An example of monitoring to assess the effectiveness of a conservation practice would be sampling above and below a filter strip being used to treat feedlot runoff. Another example of a practice suitable for monitoring would be field nutrient management, in which case, sampling of both the field soils and the field runoff would be conducted.

### (f) Evaluate program effectiveness

Water quality monitoring used to evaluate the effectiveness of a program in a watershed (e.g., Hydrologic Unit Areas, HUAs) is generally conducted on a watershed scale. Several land uses would probably be within the watershed. RMSs, implemented as a result of a water quality program, would most likely be staggered over time and managed with varying vigor. Monitoring for program effectiveness would be conducted over the long-term (>5 years).

Monitoring the effectiveness of a program is difficult because of the lack of control over exactly what happens and when it happens. Also, the staggering of events will most likely compensate each other. Finally, water quality responses to changes in practices may be gradual and take many years because of the buildup of the pollutant of concern in the watershed.

### (g) Make wasteload allocations

Monitoring of receiving water bodies would be needed to perform wasteload allocations. Though typically thought of for point sources, wasteload allocations are used in some parts of the United States for both point and nonpoint sources (e.g., Oregon). Monitoring could be used to determine how much additional (or less) agriculture or what conservation practice could be allowed in a watershed without exceeding a certain level or tropic state in a water body.

Monitoring to allocate loads from different sources requires a good knowledge of the actual contributions from the sources. For nonpoint sources, extensive monitoring may be needed to determine the actual source.

### (h) Model validation and calibration

Water quality monitoring may be needed to validate or calibrate models to local conditions. Also, it is used to verify a model's adequacy. In such tests, the values predicted by the model are compared to values observed by monitoring.

A major difficulty in model validation is that many models are developed to simulate long-term average conditions; whereas, most monitoring data are collected on a relatively short-term basis. In addition, many of the input variables used in a model, such as the hydraulic conductivity or wind speed, typically are not monitored.

### (i) Conduct research

Water quality monitoring is necessary for addressing specific research questions. An example would be a comparison of nitrate concentrations obtained from samples using various types of lysimeters including suction plate, porous cup, and zero-tension types. Such monitoring would normally be conducted by a research agency or university. The difference between research monitoring and other purposes of monitoring often is not great. However, research monitoring is not the purpose of this handbook.

### (j) Define water quality problem

Although discussed elsewhere in this guide, water quality monitoring may be required to give adequate definition to the water quality problem. For example, if a fishery is impaired in a water body, water quality monitoring will be needed to determine the cause of the impairment. Possible causes might include sediment, toxins, reduced dissolved oxygen, or temperature problems, to name a few.

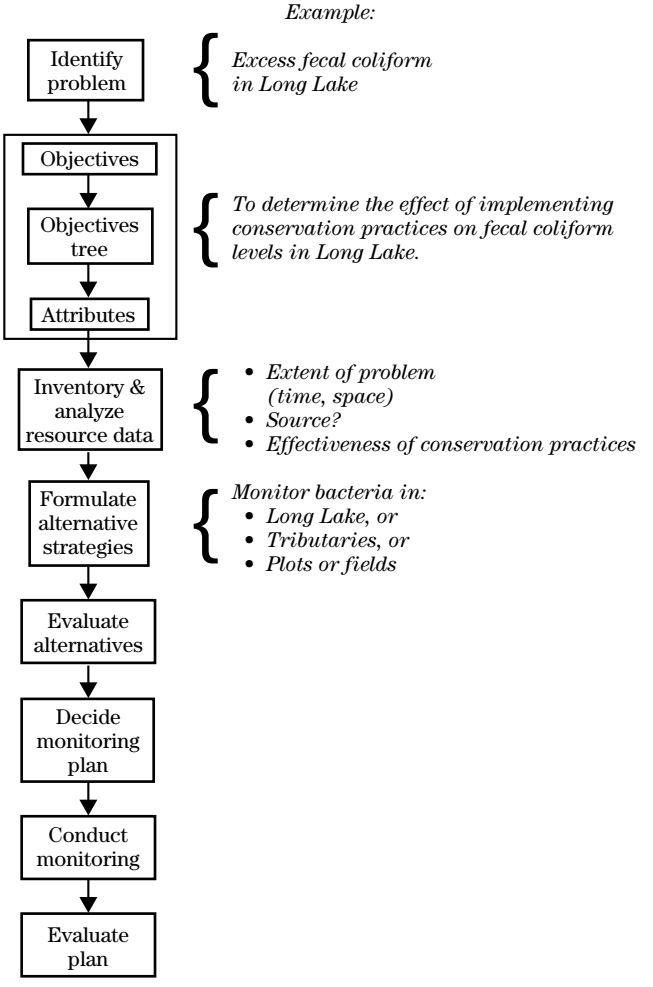
If monitoring to better define the water quality problem, the appropriate water quality characteristics must be monitored.

## 600.0103 Monitoring study design

Many outlines for developing a monitoring study have been made (Canter 1985; Ponce 1980; Sanders, et al. 1983; Solomon and Avers 12987; Tinlin and Everett 1978; Ward, et al. 1990; Whitfield 1988).

Water quality monitoring, like other tasks, can be viewed in a decisionmaking or planning context that begins with a definition of the problem and ends with an evaluation of the effectiveness of the plan (fig. 1–1).

**Figure 1–1** Steps in decisionmaking for a water quality monitoring system



This framework is similar to the 9-Step Planning Process (USDA-SCS 1993), although that process is primarily aimed at developing and implementing conservation practices. In some cases it may be desirable to develop the water quality monitoring plan within the context of the 9-Step Planning Process. The steps are:

| | |
|---|---|
| Step 1 | Identify problems |
| Step 2 | Determine objectives |
| Step 3 | Inventory resources |
| Step 4 | Analyze resource data |
| Step 5 | Formulate alternatives |
| Step 6 | Evaluate alternatives |
| Step 7 | Make decisions |
| Step 8 | Implement plan |
| Step 9 | Evaluate plan |

This handbook uses 12 steps for developing a monitoring study (fig. 1–2). Chapters 2 through 13 describe these steps in detail. The complexity of each step varies with the type of system being designed; however, each step should be addressed for all monitoring projects.

The first step, defining the water quality problem, is necessary to assure that monitoring actually matches the problem. Setting objectives for monitoring clarifies the purposes of the project and keeps it on track. Knowledge of the overall project objectives assures that monitoring is consistent with the implementation goals. The statistical design is needed as an overall framework to ensure that the samples are being collected from the appropriate locations. The monitoring design must also include the scale of the project (plot, field, or watershed); the type of sample; the variables and locations to sample; and the frequency and duration of sampling. The type of monitoring station and its construction should be defined. The methods for collecting land use and management data need to be described, including how the water quality data and land use data will be linked. Finally, a system for managing the data should be described.

The 12 steps for developing a water quality monitoring design are similar in some ways to the 9-Step Planning Process. Water quality monitoring can be used to identify resource problems. (Step 1), and formulate alternatives (Step 5), and evaluate the effectiveness of the plan (Step 9). In a side-by-side comparison, the first two steps of each method are analogous. Step 1 identifies problems, and step 2 determines objectives. The remaining steps in water quality monitoring design are included in step 3 of the 9-step process, which is to inventory resources. In actual practice, both frameworks would most likely be considered by the water quality specialist.

Example 1–1 is a case study for developing a water quality monitoring plan using the 12 water quality monitoring design steps. This case study is of the St. Albans Bay Rural Clean Water Program project in Northwestern Vermont (fig. 1–3). This project was one of 21 in the nation and one of 5 comprehensive monitoring and evaluation projects active from 1980 to 1990 (Cassell, et al. 1983). It contains physical, chemical, and biological monitoring.

**Figure 1–2** Steps in water quality monitoring system design

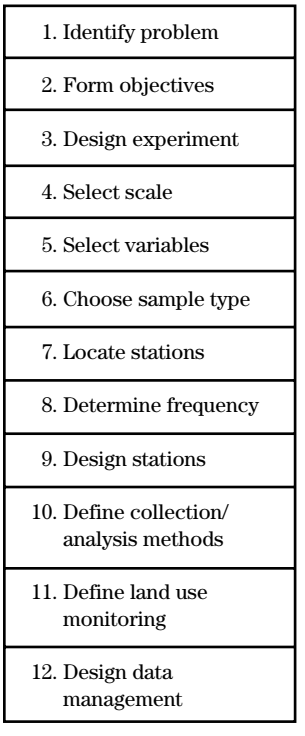
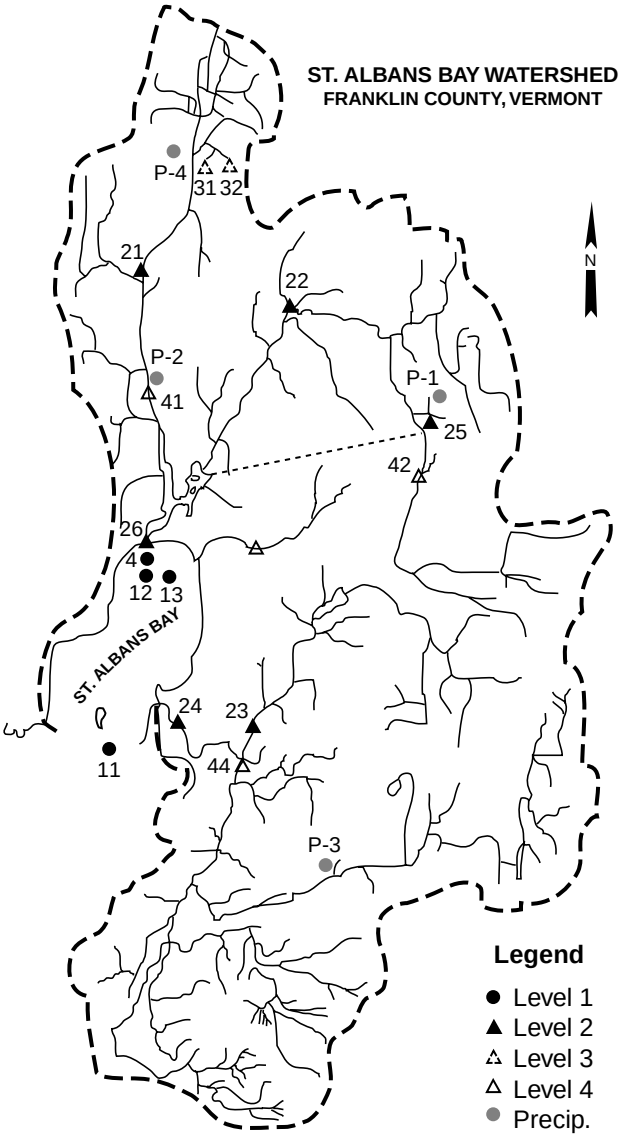


**Figure 1–3** St. Albans Bay watershed



**Example 1–1** Case study—St. Albans Bay RCWP

**Step 1 Water quality problem**

Recreation within St. Albans Bay was impaired because of excessive eutrophication. Also, a state park had closed because of reduced attendance associated with frequent beach closings resulting from coliform bacteria standard violations. A 1-year reconnaissance monitoring project by the state natural resource agency determined that both bacteria and phosphorus were coming from both point (wastewater treatment plant) and nonpoint (agricultural) sources.

**Step 2 Objectives**

Several monitoring objectives were defined:

- To document changes in the water quality of specific tributaries within the watershed resulting from implementation of manure management practices.
- To measure the changes in the amount of suspended sediment and nutrients entering St. Albans Bay resulting from implementation of water quality management programs within the watershed.
- To evaluate trends in the water quality of St. Albans Bay and the surface water within the St. Albans Bay watershed during the period of the RCWP Watershed Project.

Additional objectives were developed to address special projects in the study area. They included:

- To determine the role of an existing wetland, located between the point and nonpoint sources and the Bay, on the quality of water entering St. Albans Bay.
- To determine the role of Bay and wetland sediment on the quality of St. Albans Bay.
- To determine the effect of Bay circulation on the quality of St. Albans Bay.
- To determine the effect of individual BMPs, especially manure management, on exports to the Bay.
- To determine the effect of implementation of BMPs on aquatic organisms in the Bay and tributaries.

**Step 3 Statistical design**

Many statistical designs were used to meet the objectives. These designs were associated with four levels of study:

Level 1: Bay monitoring
Level 2: Tributary monitoring
Level 3: BMP monitoring
Level 4: Supplemental tributary monitoring

The primary statistical approach for the level 1 and 2 monitoring was trend analysis of data collected at each Bay (4) and tributary (4) station. In addition, since BMPs were not implemented at the same rate or intensity throughout the project area, paired regressions between tributary and bay stations were also used. An above-and-below paired water-

**Example 1–1** Case study—St. Albans Bay RCWP—Continued

shed study was used for the level 3 monitoring. These types of statistical approaches are described in chapter 4 of this handbook. The level 4 monitoring had no statistical basis and was later dropped. There was no control watershed in the study area to serve as a hydrologic comparison for the treated watersheds. This lack of a control was found to be an important deficiency.

**Step 4 Scale of study**

The scale varied with the level of monitoring. Level 1 Bay stations were points along a nutrient gradient in the Bay. Level 2 and 4 tributary stations were of watershed scale ranging from 3,900 to 8,800 acres in area. The level 3 BMP monitoring used a field scale. The wetland study used point scale for samples within the wetland and a watershed scale for the wetland outlet. Sediment and circulation monitoring used point scales.

**Step 5 Variables selection**

The variable selected for study also varied with the level of study (table 1–1).

**Table 1–1** Variables monitored for the St. Albans Bay project

| Variable | Levels |
|---|---|
| Turbidity | 1, 2, 4 |
| Total suspended solids | 1 – 4 |
| Volatile suspended solids | 1 – 4 |
| Total phosphorus | 1 – 4 |
| Ortho-phosphorus | 1 – 4 |
| Ammonia-nitrogen | 1 – 4 |
| Total Kjeldahl nitrogen | 1 – 4 |
| Nitrate-nitrogen | 1 – 4 |
| Chlorophyll a | 1 |
| Fecal coliform | 1, 2, 4 |
| Fecal streptococcus | 1, 2, 4 |
| Temperature | 1, 2, 4 |
| Dissolved oxygen | 1, 2, 4 |
| pH | 1, 2, 4 |
| Conductivity | 1, 2, 4 |
| Secchi disc | 1 |
| Flow | 2, 3, 4 |
| Chloride | Wetland |
| Fish populations | 2 |
| Invertebrates | 2 |
| Periphyton | 2 |
| Precipitation | |

**Example 1–1** Case study—St. Albans Bay RCWP—Continued

**Step 6 Sample type**

The type of sample varied with the level of monitoring (table 1–2)

**Table 1–2** Sample types for the St. Albany Bay Project

| Level | Sample type |
|---|---|
| 1 | Grab -2 depths<br>plankton - depth integrated |
| 2, 3 | time composite at point<br>grab - bacteria |
| 4 | grab |
| Wetland | grab<br>time composite at outlet |

**Step 7 Sampling location**

Sampling locations for all levels are shown in figure 1–3. Originally, three stations were located in St. Albans Bay. One station was associated with the closed beach; the other two represented an inner and outer bay component. A fourth station was added in the fourth year of the project to better characterize the nutrient gradient in the bay following the procedures described by Potash and Henson (1978). At each bay station, samples were taken at two points: one at the surface and one near the bottom. In addition, the extent and type of macrophyte growth were determined annually using aerial photography and a field survey.

Level 2 tributary stations were located along the four major tributaries to the bay at the lowest possible accessible site that passed a site selection criteria test. Samples were automatically collected in a tube at a single point at each cross section. Level 2 biological monitoring was conducted at the level 2 stations.

Two level 3 BMP stations were located with a ditch that drained two adjacent fields (fig. 1–4). The stations were located one up stream of the other, with the upper station serving as the control. At each station, samples were automatically collected in a tube at a point in the cross-section.

Level 4 stations were located at four tributaries as close to the bay as possible, and 15 wetland samples were located along stream channels at equal spacing. Additional wetland samples were located in the bay to better define a gradient (fig. 1–5).

**Example 1–1** Case study—St. Albans Bay RCWP—Continued

**Figure 1–4** Level 3 paired watershed

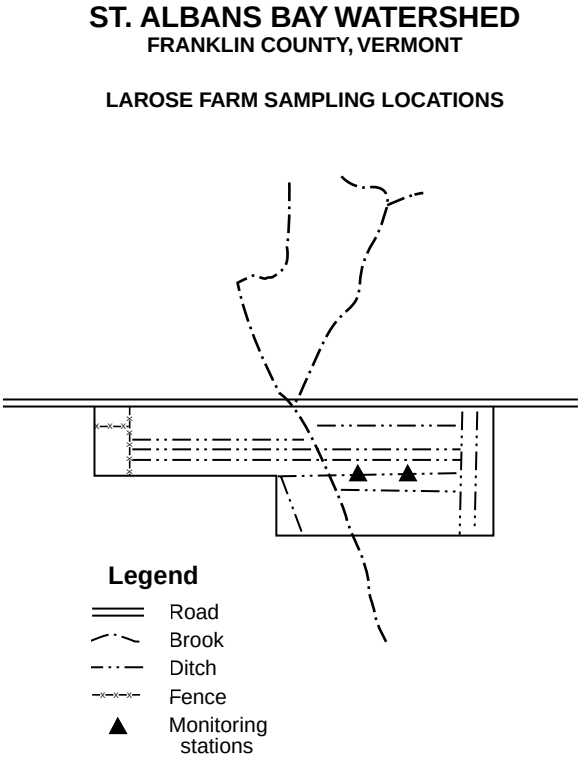
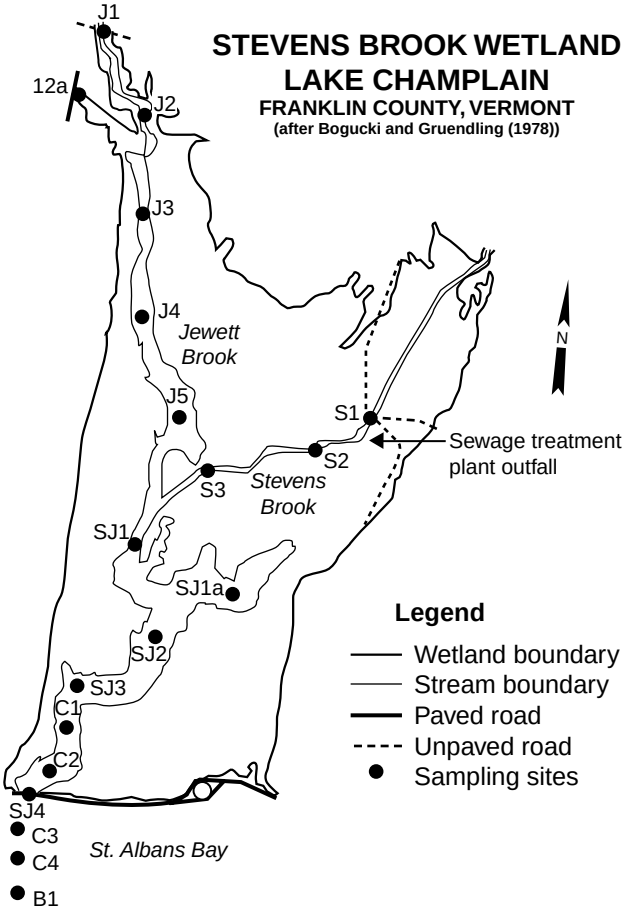



**Figure 1–5** Wetland sampling locations



**Example 1–1** Case study—St. Albans Bay RCWP—Continued

**Step 8 Sampling frequency and duration**

The number of samples collected also varied with the level of monitoring (table 1–3). The project was designed for a 10-year time frame.

**Table 1–3** St. Albans Bay monitoring frequency

| Level | Frequency |
|---|---|
| 1 | monthly (Oct – Apr)<br>biweekly (May – Jul)<br>weekly (Aug – Sep) |
| 2 | 2 - 48 hr and 1 - 72 hr composite/week from 8 hr samples |
| bacteria | weekly |
| 3 | 4 hr composites |
| 4 | every 20 days |
| biological | every 5 years |
| periphyton | 3 times per week |
| benthos | 2 times per year |
| fish | 2 times per year |

**Step 9 Station type**

The type of station used varied with the level of sampling. Level 1 sampling was conducted at reference points in the Bay. A Kemmerer sampler was used to collect water samples. A Wisconsin sampling net was used to obtain plankton samples.

The level 2 stations were permanent structures located adjacent to the streams. Each station was heated, had 110 VAC power, but ran on batteries. Bubbler-type stage-height recorders and automatic samplers were used. Stilling wells were added to most stations.

The level 3 stations were temporary installations in field ditches that included a sharp-crested 120 degree v-notch weir, bubbler gage, and automatic sampler. The stations were heated with propane gas.

The level 4 sampling stations were grab sites as were the biological monitoring sites. Periphyton was collected on plastic slides. A Surber sampler was used to collect benthos in riffles. Hester-Dendy samplers were also used. Block nets and a back-pack electrofisher were used to collect fish samples.

**Example 1–1** Case study—St. Albans Bay RCWP—Continued

**Step 10 Sample collection and analysis**

Sample collection, preservation, and analysis followed EPA guidelines (USEPA 1983). Automatic samples were collected in tubing with a peristaltic pump and stored in acid-washed, distilled water rinsed bottles in refrigerated samplers. Bacteria samples were collected in sterilized bottles. Samples were preserved with acid and analyzed within EPA recommended holding times (USEPA 1983). A quality assurance and quality control plan was developed, and the success of quality control was reported quarterly. Field test kits were generally not used; however, in situ analysis was made of dissolved oxygen and conductivity. Daily field sheets were used, and each technician used individual field books.

**Step 11 Land use and management monitoring**

An elaborate program of land use and management monitoring was used in this study. A daily field log developed for each farm was left with the landowners. Twice each year the farm was visited, the logs were picked up, and any missing data were reconstructed. Data were collected on a field-by-field basis and included the date, amount, and type of applications of manure, fertilizer, and pesticide. In addition, baseline information was collected on soils, topography, stream courses, roads, and farm and field boundaries. Livestock numbers were also tracked for each farm. Annually, 35mm slides obtained from the Agricultural Stabilization and Conservation Service (ASCS) were consulted for land use changes in areas where land use data were missing. These flyovers include only cropland as part of program compliance by ASCS.

The entire system was managed in a Geographic Information System (GIS). Maps and tables were used to track land use and management activities, such as where manure was applied and whether it was incorporated.

**Step 12 Data management**

A computer-based data management system, Bayqual, was developed specifically for the project. Water quality and precipitation data were manually entered into the computer. Stage charts were digitized. All data were stored on a VAX computer with backup on a mainframe computer. Currently data are archived in both paper and computer disk format. Statistical analysis was conducted first on mainframe and then on PC computers. The PC revolution occurred in the middle of the project, and a general transfer of many data management activities to PC's occurred.

Data entry included a validation process that involved double-entry with an error checking program. Tests of reason were also programmed, such as the impossibility of orthophosphorus exceeding total phosphorus. Summaries of the data were presented quarterly and annually at project meetings. Written reports were also provided. This frequent reporting was found to be highly useful.

## 600.0104 References

American Public Health Association, American Society of Civil Engineers, American Water Works Association, and Water Pollution Control Federation. 1969. Glossary of water and wastewater control engineering.

Canter, L.W. 1985. River water quality monitoring. Lewis Publ., Inc., Chelsea, MI.

Cassell, E.A., J.C. Clausen, R.C. Furbush, M. Long, and D.W. Meals, Jr. 1983. St Albans Bay Watershed comprehensive monitoring and evaluation and socioeconomic monitoring and evaluation. Report No. 1, Background information. Vermont Water Resources Research Center, Burlington, VT.

Office of Management and Budget. 1992. Coordination of water data information. OMB Cir. M-92-01, Washington, DC.

Ponce, S.L. 1980. Water quality monitoring programs. USDA Forest Serv., Watershed Sys. Dev. Group Tech. Pap WDG-TP-00002, Fort Collins, CO.

Potash, M., and E.B. Henson. 1978. Significance of geographic positioning for water quality monitoring in Lake Champlain. Proc. Establishing water quality monitoring programs. Amer. Water Resourc. Assoc., pp. 58-73.

Rechard, P.A., and R. McQuisten. 1968. Glossary of selected hydrologic terms. Water Resourc. Res. Inst., Water Resourc. Serv. No. 1, Univ. WY, Laramie.

Sanders, T.G., R.C. Ward, J.C. Loftis, T.D. Steele, D.D. Adrian, and V. Yevjevich. 1983. Design of networks for monitoring water quality. Water Resourc. Pub., Littleton, CO.

Smith R.A., and R.B. Alexander. 1983. Evidence for acid-precipitation-induced trends n stream chemistry at hydrologic benchmark station. U.S. Geol. Surv. Circ. No. 910, Alexandria, VA.

Solomon R.M., and P.E. Avers. 1987. A water quality monitoring framework to satisfy legal requirements. Proc. Symp. on monitoring, modeling, and mediating water quality, Amer. Water Resourc. Assoc., Bethesda, MD, pp. 231-242.

Tinlin, R.M., and L.G. Everett. 1978. Establishment of ground water quality monitoring programs. In Establishment of water quality monitoring programs. Proc. Amer. Water Resourc. Assoc., Minneapolis, MN.

United States Department of Agriculture, Soil Conservation Service. 1993. National Planning Procedures Handbook, part 600.2. Washington, DC.

United States Environment Protection Agency. 1983. Methods for chemical analysis of water and wastes. EPA 600/4-79-020, Off. Res. and Dev., Cincinnati, OH.

Veatch, J.O., and C.R. Humphrys. 1966. Water and water use terminology. Thomas Print & Publ. Co., Kau Kauna, Wi.

Ward, R.C., J.C. Loftis, and G.B. McBride. 1986. The "data-rich but information poor" syndrome in water quality monitoring. Environ. Manag. 10(3):291-297.

Ward, R.C., J.C. Loftis, and G.B. McBride. 1990. Design of water quality monitoring systems. Van Nostrand Reinhold, New York, NY.

Whitfield, P.H. 1988. Goals and data collection designs for water quality monitoring. Water Resourc. Bul. 24(4):775-780.

## Steps In Planning A Water Quality Monitoring System

Project Title _____

**1. Water Quality Problem**

_____

_____

**2. Objectives**

Project: _____

_____

_____

Monitoring: _____

_____

_____

_____

_____

**3. Statistical Design**

Plot _____ Above and below _____ Paired _____

Multiple _____ Trend _____

**4. Study Scale**

Stream: Plot _____ Field _____ Watershed _____

Ground water: Plot _____ Field _____ Watershed _____

Lake: Limnocorral _____ Bay _____ Lake-wide _____ Outlet _____

**5. Variables**

_____ _____

_____ _____

_____ _____

**6. Sample Type**

Grab _____ Composite _____ Integrated _____

Continuous _____ Time _____ Flow _____

## Steps In Planning A Water Quality Monitoring System (continued)

**7. Sampling Location**

Water body: _____ Location: _____ _____

Water body: _____ Location: _____ _____

Water body: _____ Location: _____ _____

**8. Sampling Frequency and Duration**

n = _____ per _____ Duration _____

**9. Station Type**

Discharge _____ Concentration _____

Precipitation _____ Other _____

**10. Sample Collection and Analysis**

Preservation _____ Lab methods _____

Field methods _____

**11. Land Use And Management**

Monitoring method _____

_____

Data management _____

_____

Relating land treatment to water quality _____

_____

**12. Data Management**

Storage system _____

Validation _____

_____

Reporting frequency _____

By: _____ Date: _____

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# Chapter 2 Water Quality Problem

# Chapter 2 Water Quality Problem

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# Chapter 2 Water Quality Problem

## 600.0200 Introduction

The first step in developing a water quality monitoring study is to define the water quality problem. The definition of the water quality problem is normally conducted before the design of the monitoring project. However, a redefinition or clarification of the water quality problem may often result as a monitoring design is developed or during actual monitoring.

In some cases a definite water quality problem may not exist, but rather a trend toward an emerging water quality problem is being monitored. For example, in Nebraska, monitoring of ground water nitrate concentrations has been used to identify trends toward exceeding a standard (Ehrman, et al. 1990). Chapter 2 describes defining the water quality problem. The *Water Quality Indicators Guide* by Terrell and Perfetti (1989) may be usefull in using biological and habitat approaches to identify surface water quality problems.

## 600.0201 Characteristics

In formulating a water quality problem statement, the difference between a problem and a symptom needs to be distinguished. A water quality *problem* is a water quality issue requiring a solution, often stated in the form of a question. A *symptom* is a characteristic or condition of a water body indicating a problem or cause of the problem. For example, a poor fishery might be symptomatic of a sediment or dissolved oxygen problem. Excessive algal blooms might be symptomatic of excessive nutrient loadings. Every water quality problem typically has several symptoms.

The problem statement should be written in terms of a *use impairment.* Uses may include contact recreation, aesthetics, irrigation, fishing, or drinking. Ecological integrity is increasingly thought of as a use by some.

An indication of the impaired water body also helps to clarify the water quality problem statement. The type of water body could be described generically (e.g., lake, estuary, stream, vadose zone, ground water) or more specifically by name (e.g., Lucky Lake). Finally, identification of the cause of the problem and the source of that cause lend further definition to the problem statement. Table 2–1 summarizes some typical symptoms and problems and lists typical use impairments. Example water bodies are also summarized.

**Table 2–1** Water quality symptoms and problems

| Symptom | Problem | Use impairment | Water body | Cause | Source |
|---|---|---|---|---|---|
| Color | Algae, sediment, organic acids | Drinking | Lake | Erosion | Fields |
| Excess algae | Nutrients | Aesthetics | Lake | P, N | Animal waste |
| Excess macrophytes | Nutrients, abundant light | Recreation | Lake | P | Fertilizers |
| Hypoxia | Nutrients | Fishing | Estuary | N | Wastewater |
| Low biotic diversity | Toxics, nutrients | Fishing | Bay | PCB, pesticides | Contaminated sediment |
| Taste | Salinity, algae, metals | Drinking | Ground water | Salts | Geologic formation |
| Turbidity | Algae, sediment | Irrigation | Stream | Erosion | Return flows |

## 600.0202 Syntax

Based upon the characteristics of a water quality problem, a syntax for developing a water quality problem statement can be given. Thus, the water quality problem statement should include information about the problem, the use impairment, the specific water body, the cause of the problem, and the source of the causal agents. A suggested syntax for writing a water quality problem statement is:

**problem +**
**impaired use +**
**water body +**
**cause +**
**source**

A good example of a definition of a water quality problem is:

*The lack of recreation in St. Albans Bay is because of eutrophication caused by excessive phosphorus loading from agricultural sources.*

The problem has been stated with sufficient clarification to set monitoring and project objectives. The water quality problem is identified as eutrophication. A sympton of that problem, although not stated, might be algal blooms. The water body is St. Albans Bay. The cause identifies the driving factor for eutrophication, which in this case is phosphorus. A more complete discussion of causality is in part 2 of this handbook. Finally, the source of the pollutant is identified as agricultural in this case.

In many cases the actual source of the pollutant or the actual cause of the problem may not be known when designing the monitoring study. This is often the case where water quality data are limited or do not exist. In such cases the statement of the water quality problem may need to include some uncertainty. For example:

*The lack of recreation in St. Albans Bay is because of excess nutrients (N or P) from unknown sources.*

Another limitation may be knowledge of causality for the problem. The problem may be so new that a causal relationship has not been developed yet. As described in the preface, the actual purpose of monitoring may be to determine the source of the problem.

On the other hand, an example of a poor definition of a water quality problem is:

*Bad fishing.*

For this example, the real problem is unknown. Is fishing poor because of toxics, dissolved oxygen, sediment, food, or some other causal factor? Also, what is the source of the problem contributing to the causal factor? Therefore, to adequately define the problem, some knowledge of the condition of the resource must be available. Some data are needed. The problem must also be of a scale that is addressable by the project. For example, a study on a small plot in the watershed of a large lake will not allow determining whether the water quality problem of the lake has been corrected, but may address a water quality problem in a tributary to the lake.

The absence of a proper statement of the water quality problem is a common impediment to proper design and execution of a water quality monitoring study.

## 600.0203 References

Ehrman, R.L., M.L. Link, J.J. Gottala. 1990. Special protection areas: A new nonpoint source management option in Nebraska. J. Soil and Water Conserv. 45(2):263-264.

Terrell C.R., and P.B. Perfetti. 1989. Water quality indicators guide: Surface waters. USDA Soil Conserv. Serv., SCS-TP-161, Washington, DC.

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# Chapter 3 Objectives

# Chapter 3 Objectives

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# Chapter 3 Objectives

## 600.0300 Introduction

The second step in developing a water quality monitoring study, after defining the water quality problem, is to define the monitoring objectives. The objectives of a monitoring study must address the water quality problem. A well thought out objective or set of objectives drives the rest of the monitoring study design and is critical to a successful monitoring project. This chapter presents methods for formulating objectives and gives several examples of objectives. In addition, a process for organizing a multitude of objectives is provided.

Unfortunately, two types of objectives emerge when planning a monitoring project: management objectives and monitoring objectives. *Management objectives* refer to the goals of the project that monitoring is intended to assess. *Monitoring objectives* refer to obtaining knowledge about the system. Often these two types of objectives become confused; yet, both are important to the success of the project. Therefore, both types of objectives are presented in this chapter.

Setting objectives can be viewed as a series of three steps:

- Identifying the objective
- Developing an objective hierarchy
- Specifying attributes to measure the level of achievement of these objectives

## 600.0301 Forming objectives

Much time has been devoted to debating the differences among objectives, goals, and purposes. Although the distinction between goals and objectives has been made, the differences are subtle to most but the academician (Dickerson and Robershaw 1975, Keeney 1988, Keeney and Raiffa 1976). Therefore, for the purposes of this handbook, all these terms are grouped under the term *objective*.

### (a) Monitoring objectives

In general, an objective describes the answer to the following question: "What must be done?" It also states what is desired to accomplish. By definition, an objective includes an object as part of the statement. A useful syntax for writing an objective is:

*infinitive verb + object word or phrase + constraints*

The first component is the infinitive verb. An infinitive is a verb form that is usually preceded by the word *to*. An infinitive typically is used as a noun in objective statements. These infinitives allow determining whether or not they are achieved and are not subjective. Some examples for monitoring objectives are:

*To determine…*
*To evaluate…*
*To assess…*

The second component of an objective statement is the object. The object receives the action of the verb and answers the question, "What?" An example of a monitoring objective statement with an infinitive and a noun is:

*To determine the effects of implementing conservation practices…*

The third component of an objective statement is the constraints to the objective. This component is not necessary to make an objective statement. Constraints limit the objective statement to specified areas. The objective becomes constrained from the whole world

of opportunities or alternatives. Appropriate constraints can include the water quality variables to be sampled or the location of the study. For example, the completed monitoring objective could be:

*To determine + the effect of implementing conservation practices + on fecal coliform levels in Long Lake.*

Some constraints may be unnecessary and may overly limit the study design. For example, to limit the water quality variables to test for when the cause of pollution is unknown. The constraint would then interfere with determining the cause of the problem.

Coffee and Smolen (1990) suggest that monitoring objectives should specify the water quality variables, location of monitoring, the degree of causality, and the anticipated result of the management action.

### (b) Management objectives

For managment objectives, the infinitives show a direction of preference; however, achievement of these objectives may be more subjective, depending upon how they are stated. The infinitives for management objectives include:

*To reduce…*
*To increase…*
*To eliminate…*

An example of a management objective statement with an infinitive and a noun is:

*To reduce bacterial loading…*

The completed management objective somewhat related to the monitoring objectives described above is:

*To reduce fecal coliform loading to Long Lake.*

This management objective is subjective. An example of a nonsubjective management objective is:

*To implement fecal coliform controls on 75 percent of the farms in the Long Lake watershed.*

## 600.0302 Objectives tree

Most projects have several objectives. These objectives may be complementary or even sometimes competitive. To achieve some overall general objective, several subobjectives may be needed. Thus, the subobjectives might be viewed as hierarchical.

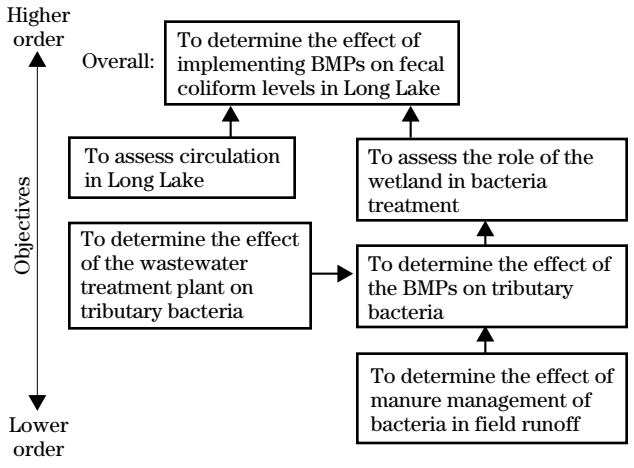
The relationships among objectives can be better understood by developing an objective tree. An objective tree displays all of the monitoring objectives in a hierarchical manner so that priorities can be established on which objective to tackle first. Two objectives in the tree are connected if *the achievement of one objective contributes directly to the achievement of the other objective*. Higher-order objectives are more general and stable than lower-order objectives. The lower-order objectives help to define the higher-level objectives more specifically and may change from time to time with expanding knowledge.

One way to develop the objective tree is to write each objective on a separate card and compare all possible combinations of card pairs using the statement: "Does the achievement of card A contribute directly to the achievement of card B?" If the answer is yes, the two objectives are connected in the direction indicated.

One of the advantages of developing the objective tree is that it shows the order in which objectives must be accomplished so that the overall objective can be attained.

An example of a monitoring objective tree is shown in figure 3–1. For this example, the system contains a wetland that receives tributary loadings before runoff outlets to the lake. The watershed has both point and nonpoint sources of bacteria. Also, the lake is not well-mixed and exhibits water quality gradients that appear to be influenced by wind-driven circulation patterns. In this case, before we could determine the effect of implementing BMPs in the watershed on the levels of bacteria in the lake, the circulation in the lake and the effect of the wetland would need to be assessed. Also, point and nonpoint sources of bacteria would need to be separated.

**Figure 3–1** Water quality monitoring objective tree




## 600.0303 Objective attributes

The final step in developing objective statements is to determine attributes for the objectives. Attributes define the level of achievement for each objective. Monitoring objectives are typically binary. They are either achieved or not achieved. For example, an assessment of the circulation patterns in Long Lake is either achieved or not. Another monitoring objective attribute could relate to time, such as:

> *To determine circulation patterns in Long Lake in 1 year.*

One of the problems associated with binary attributes is that they have no intermediate steps upon which to evaluate progress.

Management or programmatic objectives may use other scaler quantities as attributes to measure their achievement. For instance, for the Long Lake example, an appropriate attribute for a management objective could be:

> *…the percent of farms in the watershed receiving fecal coliform controls*

Another attribute could be:

> *…the percentage change in bacteria loading to Long Lake.*

The attribute should be so stated that it helps answer the question, "…how do you know when you have monitored enough?"

In conclusion, monitoring objectives are often redefined after going through these three steps as well as after gaining experience in the monitoring project. Such changes are appropriate, expected, and should be encouraged.

## 600.0304 References

Coffee, S.W., and M.D. Smolen. 1990. The nonpoint source manager's guide to water quality monitoring. NC State Univ. Water Quality Group, Raleigh, NC.

Dickerson, S.L., and J.E. Robershaw. 1975. Planning and design: the systems approach. Chapter 2: Defining the problem. Lexington Books, Lexington, MA.

Keeney, R.L. 1988. Value-focused thinking and the study of values. *In* Decision making: descriptive, normative, and prescriptive interactions, chapter 21. D.E. Bell, J. Raiffa, and A. Tversky (Eds.) Cambridge Univ. Press, Cambridge, NY, pp. 465-494.

Keeney, R.L., and H. Raiffa. 1976. Decisions with multiple objectives: preferences and value tradeoffs. Chapter 2: The structuring of objectives. John Wiley & Sons, New York, NY.

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# Chapter 4 Statistical Designs

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# Chapter 4 Statistical Designs

## 600.0400 Introduction

Several experimental designs can be used to evaluate the effect of a conservation practice or a number of practices on water quality. The design selected depends primarily on the study objective. The study design must be determined before the project begins because the design of the project dictates most other aspects of the project including the study scale, the number of sampling locations, the sampling frequency, and the station type.

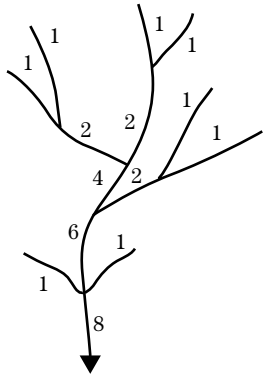
The study designs considered in this chapter include the reconnaissance, plot, single watershed, above-and-below, two watersheds, paired watershed, multiple watershed, and trend station. A more complete description of the statistical aspects of study designs is given in part 2 of this handbook.

## 600.0401 Reconnaissance

Reconnaissance or synoptic designs have been used to determine the magnitude and extent of the water quality problem or as a preliminary survey where no data exist. The term *synoptic* has been used to imply either obtaining a general view of water quality or obtaining samples at approximately the same time. Reconnaissance surveys differ greatly among the type of water body, whether stream, lake, or ground water. A properly stated objective also is critical for a reconnaissance survey. This type of monitoring is used to target critical areas as well.

Reconnaissance surveys are often grab sampling programs. For stream systems, one approach for determining sources of pollution was based on the number of contributing tributaries (Sanders, et al. 1983). In a downstream fashion, the number assigned to a stream segment is the sum of the numbers assigned to the upstream segments. The total number of segments at the most downstream station is used to select sampling locations. That number could be divided by two, four, and so forth, to obtain a desired number of sampling stations for the preliminary survey. The number obtained would describe which segment to sample. Example 4–1 illustrates this.

**Example 4–1** Sampling locations based on contributing tributaries




Determine the sampling locations for reconnaissance monitoring for the numbered stream segments. Assume two stations will be used.

$$\frac{8}{2} = 4$$

Sample segments 8 and 4

Other approaches might include designs based upon a percentage of the basin sampled, at known sources of pollution, and at shifts in land use or geology. One approach recommended by the World Health Organization (WHO) based the number of water quality stations on a percentage of the stream gaging stations, which in turn are based on a minimum density for different climate zones (WHO 1978). They also recommended "basic stations" to classify water quality and "auxiliary" stations to understand the assimilative capacity of streams. Basic stations were generally located at the mouth and major tributaries, at political boundaries, at water intakes, below outfalls, and below urban areas. In addition, when biological monitoring is being conducted, different stream habitats (riffle, pool) should be considered when selecting sampling stations.

Reconnaissance biological monitoring approaches, such as the Rapid Bioassessment Protocol I, must consider the major factors influencing aquatic organisms (Plafkin, et al. 1989). These factors include pollution sources, bottom types, stream habitats, flow characteristics, and other physical characteristics, such as shade (Klemm, et al. 1990). A biological reconnaissance is also important in determining ultimate sample sizes and taxa of importance. Reference stations are also recommended for reconnaissance biological monitoring.

The goal for stream reconnaissance surveys is often to locate the areas not meeting their intended uses and those that are the most polluted. Other design considerations in stream reconnaissance surveys are the frequency of sampling (chapter 9 and the number of locations needed per unit area.

Lake synoptic surveys typically involve collecting a large number of samples over a short time. Locations could be determined on an areal basis by overlaying a grid on the lake and sampling randomly located grid intersections. Other approaches include sampling bays or sampling longitudinally along lake gradients.

Design of ground water reconnaissance surveys depends on whether there is a local concern or more regional concern in knowledge about ground water quality. In local monitoring, monitoring wells are located above and below the potential pollution source. At a minimum the survey should have three wells located in a triangular array about the area of interest. This array allows the preliminary determination of flow direction. Additional wells could be added to further determine the extent of the contaminant plume. In regional reconnaissance surveys, wells could be located based on a grid bases as for lakes, or existing wells could be surveyed.

### (a) Advantages

Reconnaissance surveys are less expensive than fixed-station monitoring.

### (b) Disadvantages

Because of the frequent lack of statistical designs, reconnaissance surveys may miss important information. For example, stream grab sampling based on equal time intervals (e.g., weekly) often results in oversampling baseflow conditions and undersampling stormflow periods. As a result a smaller variability will be observed than actually exists. Also reconnaissance surveys have the potential to include judgment bias in the selection of sampling locations. Sampling just below outfalls, at tributaries, and at easily accessible locations, such as bridges, may give unrealistic representations of general water quality conditions.

## 600.0402 Plot

Plots have been used for conducting agricultural experiments in the United States since before 1900 (LeClerg, et al. 1962). They are generally small areas (fractions of an acre) that are replicated on the landscape or in the water. Plot size is a difficult decision. Generally, smaller plots that have many replicates are preferred to larger plots with fewer replicates (LeClerg, et al. 1962). For agronomy studies, three to six replicate plots have been recommended. A 0.01 acre plot might be 6 feet wide by 72.6 feet long (USDA 1979). On land, runoff plots might be used for studies of erosion, the surface transport of chemicals, or soil water nutrient status. In water, limnocorrals have been used in lakes to evaluate nutrient and acid additions. Plots are generally too small for ground water studies. The influence of the plot treatment on ground water below the plot may be insignificant in relation to other inputs to the ground water. However, field plots have been used to study water in the vadose zone.

For a plot design, all plots are treated alike except for the factor(s) under study. Plots are typically located across the slope in homogeneous areas, although such placement of plots can introduce a factor of bias (LeClerg, et al. 1962). Differences of an area can be accounted for by blocking. An example of blocking in a plot study is shown in figure 4–1. This example shows three replicates of four treatments. One treatment would be a control, the other three could be different rates of sludge applications, for example. Individual treatments would be randomly assigned to the plots. Blocking could be used to determine if there was an upslope-downslope effect.

### (a) Advantages

The greatest advantage to a plot study is that the treatments are replicated; most watershed studies have no true replicates. Also, plots generally allow control of several variables, such as soil type, including the treatment (Striffler 1965). Plots are generally small enough that precipitation should be uniform over the area. A major advantage of the plot design is that it has a control. A control is a plot that is monitored like all others, but does not receive the treatment.

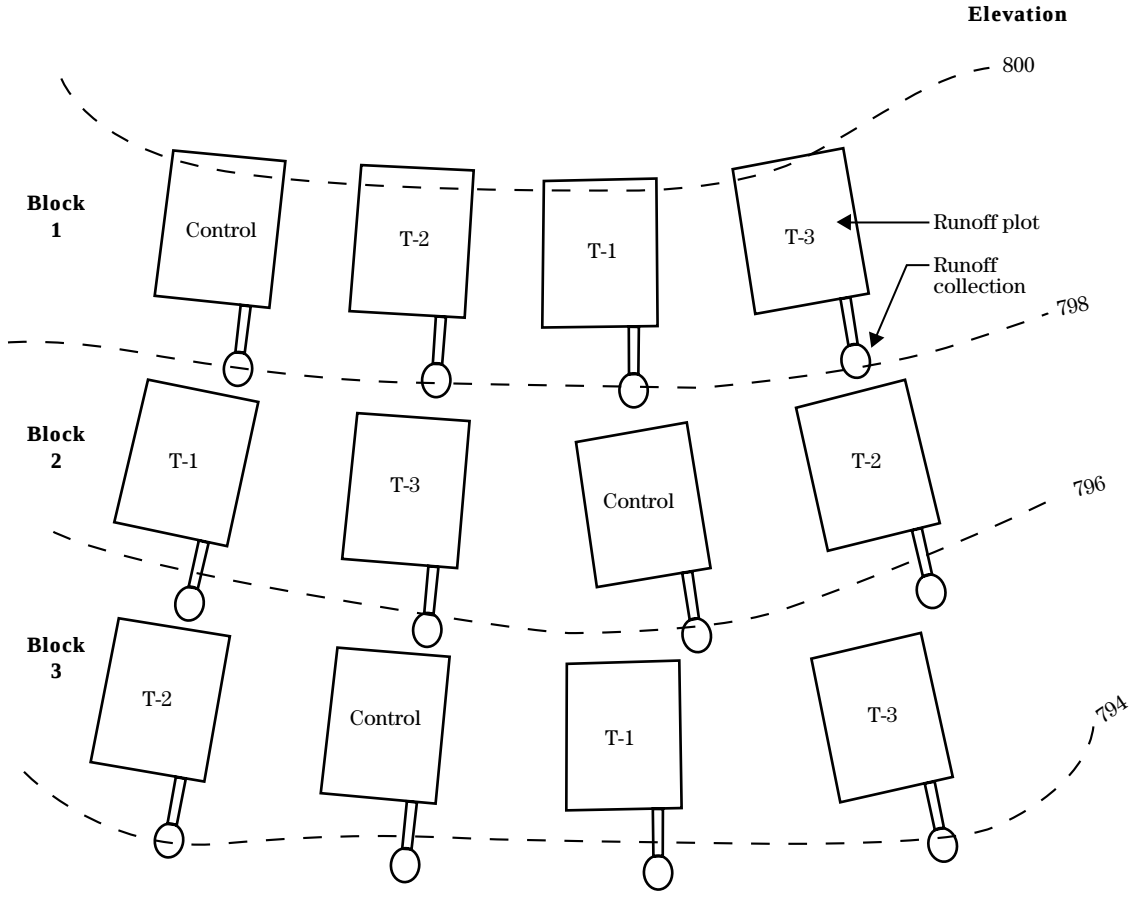
### (b) Disadvantages

The results from plot studies are not transferable to other watersheds, especially larger watersheds (Striffler 1965). Plots also may be too small a unit to adequately represent the hydro-ecosystem. Because of their small size, plots do not receive “real world” management. They must be separated from each other by some method to prevent cross-contamination of the treatment from one plot to another.

### (c) Statistical approach

The primary statistical approach is the analysis of variance of a randomized complete block design. The area where the plots are to be located is divided into blocks, with the number of blocks equal to the number of replicates chosen. Each block serves as a replication. Blocks are assumed to be homogeneous areas. For the example in figure 4–1, three blocks are shown at difference elevations. Each block contains all treatments. The treatments are assigned to plots within the blocks randomly. This design allows for the removal of the effect of the block that might be caused by differences in the field. Other more complicated designs are available including the Latin square and split plot designs, or a factorial arrangement of treatments (Snedecor & Cochran 1980). These designs are described in part 2 of this handbook.

**Figure 4–1** Layout example of a plot study with blocking

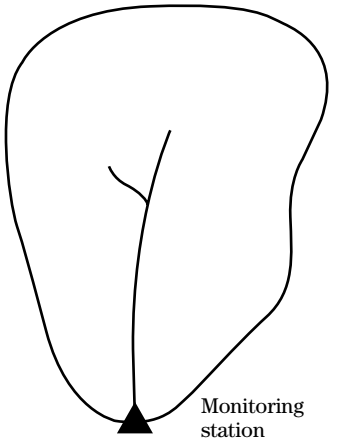


## 600.0403 Single watershed/ before-after

A single watershed has sometimes been used to evaluate the water quality effectiveness of a conservation practice (fig. 4–2). Water quality monitoring is conducted both before and after the practice is applied. The *before* period has sometimes been referred to as baseline data. Generally, this technique is not recommended and should be avoided (see 600.0403(b)).

However, a second manner in which a single watershed could be used was described by Striffler (1965). For this technique a water quality variable could be related to a climate variable(s), such as precipitation. The difference because of the conservation practice could be evaluated as a change in the relationship between the water quality characteristic and the climate variable. The interpretation of results would be somewhat constrained. For example, a result might be: "For an equal amount of monthly precipitation, the concentration declined." More specific results are generally needed, such as the percent reduction in a water quality variable resulting from the practice.

**Figure 4–2** Single watershed design




### (a) Advantages

The primary advantage of the single watershed design, with monitoring before and after a practice is implemented, is that it is the simplest of all designs. Only one monitoring station needs to be monitored. This design is applicable for most watersheds (Striffler 1965).

### (b) Disadvantages

This design should not be used because the effect by the practice cannot be separated from other confounding effects. As indicated in table 4–1 for the single watershed design, the effect because of the treatment (e.g., BMP) cannot be separated from year-to-year climate differences. If a dry year occurred when the practice was implemented, following a wet year when the watershed was in the pre-practice stage, stream concentration reduction would generally occur because of the climate differences. Also, an interaction would most likely occur between climate and the practice that could not be assessed by the study. For example, during a drought a field terrace might be expected to reduce sediment loading to a stream. However, during a wet year the terrace could be overtopped, resulting in increased suspended solids loading.

Using the alternative relationship approach described by Striffler (1965) on a single watershed is more complex, requires a longer calibration period, and is less precise than a paired watershed design. The single watershed design also has the disadvantage of not being able to transfer results to other areas.

**Table 4–1** Causal factors for alternative monitoring designs

| Design | Cause |
|---|---|
| Single watershed/ before-after | BMP or climate |
| Above-and-below watershed | BMP or watershed |
| Two watersheds | BMP or watershed |
| Paired watershed | BMP |

### (c) Statistical approach

The difference in water quality caused by the practice generally is expressed as the difference between the means for the two periods. A t-test is most often used for this type of comparison (Snedecor and Cochran 1980). An appropriate null hypothesis (Ho:) might be that the mean concentrations are equal between the two periods, for example:

$H_o$: *mean tss (period 1) = mean tss (period 2)*

As described further in part 2 of this handbook, rejection of the null hypothesis is desirable. Errors can be made in accepting the null hypothesis.

A paired t-test is not appropriate for this design because the samples collected are not paired in any meaningful way. For example, the water quality associated with months across years cannot be paired because of random components in water quality.

To perform a parametric t-test, the samples would need to be random, independent, normally distributed, and have equal variances. A nonparametric comparison of means could be used where data are not normally distributed.

The statistical approach for using the relationship between water quality and a climate variable would be similar to that described for the paired watershed below. The differences between the slopes and intercepts of the two regression relationships (one pre-practice, one post- practice) would be analyzed using analysis of covariance. Multivariate regressions that include flow or climate variables might improve these relationships.

Examples of the statistical approach to apply to a single watershed design are given in part 2 of this handbook.

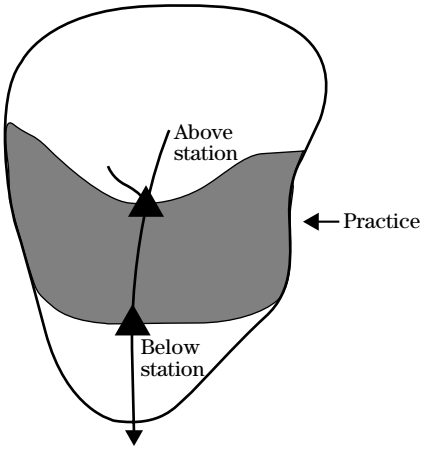
## 600.0404 Above-and-below watersheds

The above-and-below design is applied after the treatment is in place. This approach is sometimes viewed as a single watershed with monitoring above and below a practice (fig. 4–3), or in the case of ground water monitoring, upgradient and downgradient from the activity of interest. In actuality, two watersheds are being monitored, one nested within the other. In some cases the above station is erroneously thought of as "background water quality," and the below station is the one believed to be influenced by the practice.

This design is probably the most commonly used strategy in-ground water monitoring. Placement of the wells is important because ground water sites are three-dimensional. Gradients may occur in both vertical as well as horizontal directions.

If the above-and-below approach is applied both before and after the practice is installed, this approach can be analyzed as a paired watershed design as described below.

**Figure 4–3** Above-and-below watershed design



### (a) Advantages

The above-and-below approach is not as susceptible to year-to-year climatic differences as is the single watershed approach using before and after sampling. Also, it may be relatively easy to locate a watershed where a practice could be implemented between the above and below stations on a stream. This technique may be useful for isolating critical areas. The above-and-below design is well suited to biological as well as chemical/physical monitoring.

### (b) Disadvantages

Water quality measurements from nested watershed may not be independent. The water quality downstream is most likely a function of the upstream water quality. For example, a high concentration upstream would most likely result in a large concentration downstream.

A second major disadvantage of this design is that the differences between the above and below stations might be caused by inherent watershed differences (e.g., geology) or to some interaction between the practice and the watershed, and not only because of the practice itself (table 4–1). These various causal factors cannot be separated using this design; however, proper site selection may reduce this effect.

### (c) Statistical approach

The above-and-below design is analyzed as a t-test of the differences between paired observations at the above and below stations (see part 2). An appropriate null hypothesis might be:

$$H_o: \textit{difference} = 0$$

Parametric and nonparametric (distribution free) t-test approaches are available. A nonparametric analysis uses the rank of the data rather than the data itself (part 2).

Another approach would be to compare regressions between concentration and a climate variable, such as flow, for the above and below stations (Ponce 1980).

## 600.0405 Two watersheds

Two watersheds, one with the practice and one without, have been incorrectly used to evaluate the effects of a practice on water quality. This design should always be avoided. The two watershed design is not the same as the paired watershed design. There is no calibration period for the two watershed design when the two watersheds are in the identical treatment, but there is for the paired watershed approach.

### (a) Advantages

Two watersheds, each in a different land use, are relatively easy to locate.

### (b) Disadvantages

The differences in water quality between the two watersheds may be caused by the practice, inherent watersheds differences, or an interaction between these two factors, and there is no way to distinguish among these causal factors (table 4–1).

### (c) Statistical approach

Although a statistical examination of the water quality associated with two watersheds may not be appropriate, the water quality could be compared using the same approach as that for the nested watersheds. That is, a paired t-test or nonparametric t-test of treatment means could be used. In some cases regressions between water quality and a climate variable could be compared.

## 600.0406 Paired watersheds

Paired watersheds have been used for over 40 years to evaluate the effects of silvicultural practices on watershed quantity and quality (Wilm 1949). The basic approach requires a minimum of two watersheds and two periods of study. The two watersheds are called control and treatment; the two periods of study are referred to as calibration and treatment (fig. 4–4). The control watershed serves as a check over year-to-year or seasonal climate variations and receives no changes in management practices during the study.

During the calibration period, the two watersheds are treated identically and paired water quality data are collected. Such paired data could be annual means or totals, or for shortened studies, the observations could be seasonal, monthly, weekly, or event-based.

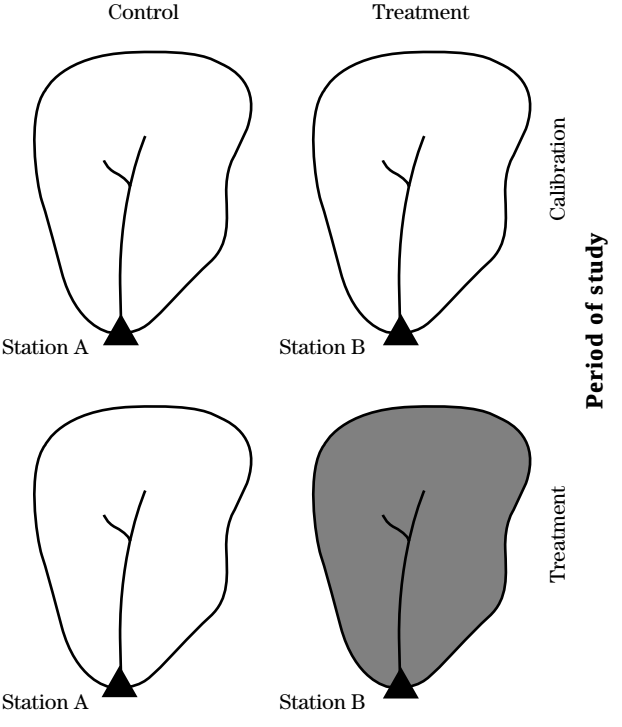
During the treatment period, one randomly selected watershed is treated with a practice while the control watershed remains in the original management. The reverse of this schedule is possible for certain practices. Both watersheds might already be treated with a conservation practice during the calibration period. During the treatment period, one of the watersheds could be treated with a traditional practice.

For ground water monitoring, an above-and-below approach to the paired watershed design is recommended. During the calibration period, monitoring would take place upgradient and downgradient for both the control and treatment portions of the ground water formation being studied. During the treatment period, one of the areas bounded by wells would receive a practice, while the other control area would remain as before.

Guidelines for paired watershed studies include:

- Steady-state—The control watershed should be at or near a steady-state condition during the life of the study (Reinhart 1967). Steady-state is used here to mean that there are no gradual changes that would result in a trend in water quality. For example, a watershed that had a gradual shift in crop types would not make a good control.
- Size—The watersheds should be small enough to obtain a uniform treatment over the entire area (Reinhart 1967). The size will vary depending on climatic region. In humid areas the watersheds generally would be less than 5 square miles in area. In arid climates, they could be larger.
- Range—The calibration period should encompass the full range of observations expected (Reinhart 1967, Wilm 1949). Normally, this refers to wet and drought years. This allows reasonable comparison of treatment data to calibration data.
- Calibration length—The calibration period should be long enough to develop significant regression relationships between the two watersheds so that data for the treatment watershed can be predicted knowing data from the control watershed within certain error limits (Striffler 1965). Methods for determining the length of calibration are described in part 2.
- Response—The designed treatment should be expected to have a large enough response to exceed prediction errors. At least a 10 percent change in the variable of interest is suggested (Hewlett & Pienaar 1973).

**Figure 4–4** Paired watershed design



- Watershed similarity—The watersheds should be similar in size, slope, location, soils, and land cover (Hewlett 1971, Striffler 1965). They should also have been in the same land cover for a number of years before the study (Hewlett 1971). Chemical characteristics of the soils should be similar. However, no two watersheds are identical, nor can they be considered representative.
- Monitoring suitability—Each watershed should have a stable channel, a stable control section for monitoring, and should not leak around the gaging station at the watershed outlet (Reinhart 1967).

### (a) Advantages

The greatest advantage of the paired watershed approach is that variation not associated with the treatment, such as climate differences over years, are statistically controlled (Kovner & Evans 1954). Also, the control watershed eliminates the need to measure and understand all the mechanisms generating the response (Hewlett & Pienaar 1973). The water quality of runoff from the two watersheds need not be identical. Finally, the calibration phase can be done in reverse with the treatment period preceding the calibration period (Reinhart 1967).

### (b) Disadvantages

Several disadvantages to the paired watershed approach also apply to all the study designs.

- The variances in water quality data are not likely to be equal between time periods because the treatment on one of the watersheds is often quite drastic. It is also difficult to satisfy the assumptions of normality and independence of observations. Shortened calibrations may increase the likelihood of serially correlated data (Reinhart 1967).
- The treatment effect may be gradual and not constant with time (Reinhart 1967; Hewlett & Pienaar 1973). Thus overall comparisons may mask interesting results.
- The paired watershed experiment is costly and time consuming (Hewlett & Pienaar 1973).
- Long-term changes in the soils or vegetation may occur in the control watershed. Other catastrophes, such as fires, dust storms, hurricanes, and insect infestations, could occur, which could destroy the meaning of results. This disadvantage applies to all watershed designs.

### (c) Statistical approach

The basis of the paired watershed approach is that there is a quantifiable relationship between paired water quality data for the two watersheds and that this relationship will persist until a major change is made in one of the watersheds (Hewlett 1971). This does not require that the quality of runoff be the same for the two watersheds; but rather that the relationship between the water quality of the two sites, except for the influence of the treatment (practice), remains the same over time. In fact, most often the water quality is different between the two watersheds. This inherent difference between all watersheds further substantiates the need to use the paired watershed approach.

The primary statistical approach is to develop significant regression relationships between the control and treatment watersheds during both the calibration and treatment periods (see part 2). These two regression relationships are then compared for identical slopes and intercepts using analysis of covariance (Reinhart 1967). During the calibration period the significance of the regression is tested using analysis of variance for regression (Snedecor & Cochran 1980). Procedures for determining the length of the calibration period have been described by Wilm (1949), Kovner and Evans (1954), and Reinhart (1967) and are presented in part 2 of this handbook. An alternative analysis approach has been presented by Green (1979), Bernstein and Zalinski (1983), and Carpenter, et al. (1989).

## 600.0407 Multiple watersheds

The multiple watershed approach involves more than two watersheds (Clausen and Brooks 1983, Striffler 1965, Wicht 1967). Watersheds with the treatments already in place are selected from across the region of interest. The region could be as large as a state or as small as an individual field. Sampling of the runoff is conducted from these watersheds over a period of time.

As an example, multiple watersheds could be used as a method to assess the water quality effect of storing manure during the winter and not daily spreading as a conservation practice. About 15 watersheds in each treatment could be selected. That is, 15 fields or watersheds where daily spreading was occurring during the winter, and 15 fields where no spreading occurred. During runoff periods, these fields could be sampled for the concentrations of appropriate pollutants, such as nitrogen and phosphorus.

Another example could be a test of irrigation water management. Runoff from fields in flood irrigation could be compared to runoff from sprinkler irrigated fields.

### (a) Advantages

The greatest advantage of the multiple watershed approach is that the results are transferable to the region included in the monitoring. A second major advantage is that the true variability among watersheds is included in the variance for each treatment.

### (b) Disadvantages

The multiple watershed approach is difficult to conduct using intermittent streams or field runoff because sampling must be timed with stormflow periods. Also, mass calculations would only be point estimates, and annual mass calculations would be expensive to obtain using a large number of watersheds. However, the probability approach has been used to determine annual mass estimates, which could reduce the number of samples that need to be collected (Richards 1989).

### (c) Statistical approach

The basic statistical approach is the comparison of the means of two populations using the t-test. The testing would be for unpaired samples that may be of unequal sizes.

## 600.0408 Trend stations

Trend stations are single watersheds monitored over time. A trend is a persistent change in the water quality variable(s) of interest over time. In many cases the most appropriate design may be the use of long-term trend stations. Trend stations are single, independent watersheds where a group of conservation practices might be implemented gradually over time or where the response to a practice might take a long time.

It is important for trend analysis that there not be gaps in the data set, that methods of water quality analysis not change during the study, that hydrologic control at the monitoring station is stable, and that a causal link can be made between water quality and the watershed treatments. This implies that collection of hydrologic data and land use activities are crucial to trend analysis. In addition, for some trend analysis techniques, water quality data must be collected or aggregated to fixed time intervals (Valiela & Whitfield 1989; Montgomery & Reckhow 1984; Hirsch, et al. 1982).

The use of a control watershed for trend detection cannot be emphasized enough. The control should have a stable land use and no changes in practices during the life of the trend investigation.

Although models are sometimes used to simulate long-term trends, the purpose of this handbook is to discuss the applicability of monitoring and not modeling.

### (a) Advantages

A long-term trend station is relatively easy to establish for watersheds drained by permanent streams. For complex watersheds, conservation practices are typically installed at different times over several years. This prevents use of short-term designs. For example, it may take many years for water quality to respond to practices because of the residual storage of nutrients.

### (b) Disadvantages

A true commitment to long-term (>10 years) monitoring is difficult to achieve because of changing priorities and changing personnel within funding and monitoring agencies. A significant effort must be made for land use data tracking. Over the long term, the potential is greater for unwanted disturbances, such as a new road or urban development, to affect water quality.

### (c) Statistical approach

A large number of parametric and nonparametric techniques are available for detecting trends in water quality data. Several techniques should be used before reaching a conclusion (WHO 1978). These techniques are described below and discussed in detail with examples in part 2 of this handbook.

**Time plot**—A graph of the water quality versus time is useful in detecting obvious trends (WHO 1978).

**Least square fit regression**—A linear or nonlinear regression could be fit through the data, which would allow quantification of the slope or trend rate (WHO 1978).

**Comparison of annual means**—A t-test could be used to compare averages for shorter, equal time periods within the trend total period (WHO 1978). For example, annual means could be compared. An analysis of variance, followed by a multiple comparison test, would be a more appropriate method because the overall variance would be pooled (Snedecor and Cochran 1980).

**Cumulative distribution curves**—Two cumulative distribution curves (which portray the percent cumulative distribution as a function of concentration) for two different time periods could be compared for shifts to determine trends (WHO 1978).

**Q-Q plo**t—A Q-Q plot is a comparison of the quartiles of one data set plotted against those of another data set for the variable of concern. By comparing the data from different time periods, a shift in the data as compared to a y=x line can be determined (WHO 1978).

**Double mass analysis**—Typically used for precipitation records, double mass analysis is a comparison of the accumulated data from one station plotted against the accumulated averages of data from several stations. A break in the slope would indicate a change in that one station as compared to the others, which could be interpreted as a trend (Dunne & Leopold 1978).

**Paired regressions**—A "before" period can be compared to an "after" period by the comparison of the regression equations between data from a control trend station and a treatment trend station. This analysis is identical to the paired watershed analysis described above.

**Time series analysis**—Because water quality data collected at the same station may be autocorrelated, time series analysis could be used to detect trends (McLeod, et al. 1983). However, the forecasting features of time series analysis are not likely to be relevant (Vandaele 1983).

**Seasonal Kendall test**—This nonparametric approach is especially useful where seasonality exists in the data set. A seasonal Kendall slope estimator is used to determine the magnitude of the trend (Hirsch, et al. 1982).

Generally, when applying several approaches to trend detection, the results rarely vary in direction, although the statistical significance of these techniques will vary. All of the methods, except paired regressions, only provide information on whether a trend exists and not why it exists. Only the paired regression approach allows linking the trend to causes other than hydrologic because a control is used. An alternative approach would be to adjust the trend data set for hydrologic influences. This is discussed in part 2 of this handbook.

## 600.0409 References

Bernstein, B.B., and J. Zalinski. 1983. An optimum sampling design and power tests for environmental biologists. J. Environ. Mgmt. 16(1):35-43.

Carpenter, S.R., T.M. Frost, D. Heisey, and T.K. Kratz. 1989. Randomized intervention analysis and the interpretation of whole-ecosystem experiments. Ecology 70(4):1142-1152.

Clausen, J.C., and K.N. Brooks. 1983. Quality of runoff from Minnesota peatlands: II. A method for assessing mining impacts. Water Resour. Bull. 19(5):769-772.

Dunne, T., and L.B. Leopold. 1978. Water in environmental planning. W.H. Freeman and Co., San Francisco, CA.

Green, R.H. 1979. Sampling design and statistical methods for environmental biologists. John Wiley and Sons, New York, NY.

Hewlett, J.D. 1971. Comments of the catchment experiment to determine vegetal effects on water yield. Water Resour. Bull. 7(2):376-381.

Hewlett, J.D., and L. Pienaar. 1973. Design and analysis of the catchment experiment. *In* Proc. Symp., Use of small watersheds, E.H. White (ed.), Univ. KY.

Hirsch, R.M., J.R. Slack, and R.A. Smith. 1982. Techniques of trend analysis for monthly water quality data. Water Resour. Res. 18(1):107-121.

Klemm, D.J., P.A. Lewis, F. Faulk, and J. Lazorcnak. 1990. Macroinvertebrate field and laboratory methods for evaluating the biological integrity of surface waters. U.S. Environmental Protection Agency. Office of Research and Development, Washington, DC. EPA/600/4-90/030.

Kovner, J.L., and T.C. Evans. 1954. A method for determining the minimum duration of watershed experiments. Trans. Amer. Geophys. Union. 35(4):608-612.

LeClerg, E.L., W.H. Leonard, and A.G. Clark. 1962. Field plot technique. 2nd ed., Burgess Publ. Co., Minneapolis, MN.

McLeod, A.I., K.W. Hipel, and F. Comancho. 1983. Trend assessment of water quality time series. Water Resour. Bull. 19(4):537-547.

Montgomery, R.H., and K.H. Reckhow. 1984. Techniques for detecting trends in lake water quality. Water Resour. Bull. 20(1):43052.

Plafkin, J.L., M.T. Barbour, K.D. Porter, S.K. Gross, and R.M. Hughes. 1989. Rapid bioassessment protocols for use in streams and rivers: benthic macroinvertebrates and fish. U.S. Environmental Protection Agency, Office of Water, Washington, DC. EPA/444/4-89-001.

Ponce, S.L. 1980. Water quality monitoring programs. USDA Forest Serv., Watershed Sys. Dev. Group. WSDG Tech. Pap. WSDG-TP-00002, Fort Collins, CO.

Reinhart, K.G. 1967. Watershed calibration methods. *In* Proc. Intern. Symp. on forest hydrology. W.E. Sopper and H.W. Lull (eds.), Pergamon Press, Oxford, pp. 715-723.

Richards, R.P. 1989. Determination of sampling frequency for pollutant load estimation using flow information only. *In* Proc. Symp., Design of water quality information systems. R.C. Ward, J.C. Loftis, and G.B. McBride (Eds.) CO Water Resour. Res. Inst. Inf. Ser. No. 61, Fort Collins, CO.

Sanders, T.G., R.C. Ward, J.C. Loftis, T.D. Steele, D.D. Adrian, and V. Yevjevich. 1983. Design of networks for monitoring water quality. Water Resour. Pub., Littleton, CO.

Snedecor, G.W., and W.G. Cochran. 1980. Statistical methods. 7th Ed. IA State Univ. Press, Ames, IA.

Striffler, W.D. 1965. The selection of experimental watersheds and methods in disturbed forest areas. Publ. No. 66. I.A.S.H. Symp. of Budapest. pp. 464-473.

United States Department of Agriculture. 1979. Field manual for research in agricultural hydrology. Agric. Handb. 224, Washington, DC.

Valiela, D., and P.H. Whitfield. 1989. Monitoring strategies to determine compliance with water quality objectives. Water Resour. Bull. 20(1):127-136.

Vandaele, W. 1983. Applied time series and Box-Jenkins models. Academic Press, Inc., New York, NY

Wicht, C.L. 1967. The validity of conclusions from South African multiple watershed experiments. *In* Proc. Int. symp. on forest hydrol. W.E. Sopper and H.W. Lull (eds.), pp. 749-760.

Wilm, H.G. 1949. How long should experimental watersheds be calibrated? Amer. Geophys. Union Trans., part II. pp.618-622.

World Health Organization. 1978. Water quality surveys—A guide for the collection and interpretation of water quality data. IHD-WHO Working Group on Quality of Water. UNESCO/WHO, Geneva, Switzerland.

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# Chapter 5 Scale of Study

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# Chapter 5 Scale of Study

## 600.0500 Introduction

The fourth step in developing a water quality monitoring study is to determine the size or scale of the area to monitor. The study scale depends in part on: 1) study objectives, 2) available resources, 3) study duration, 4) type of water resource, and 5) the complexity of the project to monitor. These individual factors are described later in this chapter.

Although considered as a separate step, study scale is actually coupled with the statistical design. However, scale is provided as a separate chapter to force consideration of this decision in the overall design of a water quality monitoring study.

This chapter recognizes four scale categories—point, plot, field, and watershed—although it is acknowledged that the latter three scale types are in reality all watersheds.

For lake systems, the terminology is different. Plots are limnocorrals, fields are bays or regions, and watersheds are lakes. In ecology, scales are referred to as either microcosm (e.g., point), mesocosm (e.g., plot, limnocorral), and macrocosm (e.g., field, watershed, lake) (Odum 1984).

One potential barrier to selecting the appropriate scale of the project is where the monitoring objectives are not clearly stated. Contemplating the scale of the project often results in a clarification of the objectives in a feedback sense.

## 600.0501 Point scale

Points are the smallest scale considered for water quality monitoring and are characterized by obtaining single observations. The term "point scale" means a point in space, but not a point in time. Examples of point-scale monitoring include precipitation gages, snow samples, soil samples, most vadose zone lysimeters, and many lake samples. Ground water wells and stream samples are considered watershed-scale samples and not point-scale samples even though they may be taken at one location.

Point sampling is appropriate for trend monitoring, for problem definition or compliance monitoring, for research and fate and transport monitoring, or for evaluating certain types of models (table 5–1). Point samples are used in both vadose zone and lake studies (table 5–2). Point sampling is considered cheaper than larger scales, but the frequency of visits and the duration of sampling will vary greatly depending on the study objectives.

**Table 5–1** Objective by study scale matrix

| Objective | Point | Plot | Field | Watershed |
|---|---|---|---|---|
| 1. Baseline | | | X | X |
| 2. Trends | X | | | X |
| 3. Fate and transport | X | X | X | X |
| 4. Problem definition | X | | X | X |
| 5. Critical areas | | | X | X |
| 6. Compliance | X | | X | X |
| 7. BMP effectiveness | | X | X | |
| 8. Program effectiveness | | | | X |
| 9. Wasteload allocations | | | X | X |
| 10. Model evaluation | X | X | X | X |
| 11. Research | X | X | X | |

## 600.0502 Plot scale

Plots are mesocosm sampling units (LeClerg, et al. 1962). They are appropriate monitoring units if the objective is to replicate several treatments as part of a fate and transport study or if the effectiveness of a conservation practice or a model is evaluated (table 5–1). When considering the type of water body being studied, a plot scale is appropriate when investigating soil solution water or overland flow, but not for ground water, streamflow or lake studies. This is because these systems are larger than plot boundaries (table 5–2). An exception to the use of plots for lakes and streams would be the use of limnocorrals or seepage meters and artificial stream channels, which are actually plots of a mesocosm scale. Limnocorrals are floating water column enclosures that do not allow mixing with lake water (Odum 1984). Seepage meters are barrels placed on the land bottom that allow sampling of the flux through lake sediment (Lee 1977). Artificial streams divert some stream water into a controllable, constructed channel.

Plot studies work well for short duration (<5 years) studies, but may require a greater investment of personnel time and funds than other study scales. This, of course, depends upon the complexity of the study (table 5–3). The number of plots needed for an experimental study is a function of the number of treatments applied. A single treatment requires twice the number of plots as the number of replications because an equal (recommended) number of control plots is needed. For example, if the number of replicates determined based on the variability in runoff data were 5 (see chapter 9), the total number of plots needed would be 10. For two treatments, an additional five plots would be needed (table 5–4). The plot design is appropriate for evaluating a large number of individual practices (table 5–5).

From a water quality perspective, a critical requirement for the design of plots is that the treatment on each plot is isolated from all the other plots, or through monitoring, the effects of one plot are separated from the other plots by subtraction. For example, plots should be separated far enough apart so that a spray treatment on one plot could not drift onto other plots. Plots also may need to be isolated from overland flow from upslope areas. If the plot is designed for soil solution monitoring (e.g., via lysimeters), the plots may need to be configured to allow measurements of the soil solution of subsurface water entering the plot from above as well as at the bottom of the plot.

Several studies have used single replication plots; for example, one plot in treatment A, one plot in treatment B, and one control, for a total of three plots. This design is insufficient to determine the effects of the treatment. One can determine that the plots are different, but cannot distinguish between the difference as a result of the treatment or the individual plot.

**Table 5–2** Type of water resource by study scale matrix

| Water body | Point | Plot | Field | Watershed |
|---|---|---|---|---|
| Overland flow | | X | X | |
| Vadose zone | X | X | X | |
| Ground water | | | X | X |
| Streamflow | | X | | X |
| Lakes | X | X | X | X |

**Table 5–3** Relative cost and time requirements of various study scales

| | Point | Plot | Field | Watershed |
|---|---|---|---|---|
| Cost | Low | High | Low | Moderate to high |
| Frequency of visits | varies | events | events-weekly | weekly + |
| Duration | varies | <5 years | <5 years | >5 years |

**Table 5–4** Number of plots required based on the number of treatments (assuming replicates=5)

| Treatments | Plots |
|---|---|
| 1 | 10 |
| 2 | 15 |
| 3 | 20 |

**Table 5–5** Practice by study scale matrix

| Practice | Plot | Field | Watershed |
|---|---|---|---|
| **Vegetative/tillage practices** | | | |
| Conservation cropping | X | X | |
| Conservation tillage | X | X | |
| Contour farming | | X | |
| Cover crop | X | X | |
| Crop residue | X | X | |
| Crop rotation | | X | |
| Filter strip | X | X | |
| Mulching | X | X | |
| Hayland planting | X | X | |
| Riparian buffer | X | X | |
| Stripcropping, contour | | X | X |
| **Structural practices** | | | |
| Grassed waterway | | X | |
| Streambank protection | | | X |
| Terrace | | X | |
| **Management practices** | | | |
| Animal waste mgmt | X | X | |
| Irrigation mgmt | X | X | |
| Pasture/hayland mgmt | X | X | |
| Pesticide management | X | X | |
| Plant nutrient mgmt | X | X | |
| Woodland mgmt | | X | X |

**Example 5–1** Plot scale

The University of Rhode Island established 18 plots to monitor the water quality associated with turfgrass management (Morton, et al. 1988). Plots were 7 by 50 feet, were sloped at 2 to 3 percent, and had a 5-foot sod alley between them. Soil solution water was collected from 18 plots using ceramic lysimeter plates. The plots received six treatments consisting of three rates of nitrogen application and two irrigation rates per each nitrogen treatment. Each treatment was replicated three times. Overland flow collection occurred on 12 plots using an orifice flow splitter (10% of flow) to collection barrels.

This plot study determined that overwatering concurrently with fertilization can result in significantly higher nitrogen losses than controls. However, with scheduled irrigation, nitrogen losses were not different from controls. The study took 2 years to complete.

## 600.0503 Field scale

Monitoring on a field scale implies a larger area than an individual plot, although the entire plot design taken together could cover an area larger than a single field. The area of a field is difficult to state because it varies greatly in different parts of the United States. A field in humid (precipitation > evapotranspiration) areas is an area smaller than that required to produce a first order stream. In subhumid and arid areas (precipitation < evapotranspiration), a field typically would be larger, and many fields may occupy the area required to produce a first order stream.

Identical to the plot scale, a field scale monitoring project is appropriate if the objective was to investigate the fate and transport of a substance or the effectiveness of an individual conservation practice or a model (table 5–1). Field scale studies also are appropriate for ground water, vadose zone, and overland flow studies (table 5–2). The cost of monitoring a field scale project generally is not as great as either plot studies or watershed scale projects. Field scale projects are usually of short duration (<5 years), but could be longer.

Field scale projects are most suitable for evaluating individual practices on a field. For example, the practices may include field nutrient management, erosion control, or conservation cropping (table 5–5). If a field scale project is selected, it is important that the appropriate design (chapter 4) be matched to this scale. Monitoring a single field before and after a practice is installed is not an acceptable design unless the effects of climate over time are accounted for.

The scale of filter strips and many other constructed conservation practices, such as wetlands, lies somewhere between plot and field scales. Monitoring is usually conducted above and below the practice and typically has not been replicated.

For lake systems, different regions of a lake are synonomous with different fields on the land. Lake regions may be represented by bays, areas near sources, such as beaches, or gradient zones.

**Example 5–2** Field scale

Two fields were used in Vermont to determine the effect of conversion from conventional tillage to conservation tillage on pesticides in runoff (Clausen, et al. 1990). The two fields were compared using the paired watershed technique (chapter 3). During the calibration period, the two fields were moldboard plowed. During the treatment period, one field was conventionally tilled, while the other field was disk harrowed and planted with a conservation tillage planter. The two fields were 1.6 and 2.1 acres in area and had slopes ranging from 3 to 7 percent.

Field runoff was continuously monitored with heated,1.5-foot H-flumes and water level recorders. Flow proportional samples (0.1% of total flow) were obtained by tubing connected to the throat of the flume and to a storage carboy.

Using the paired watershed technique, conservation tillage was found to reduce runoff from the field. Therefore sediment loss and the mass export of the pesticides atrazine and cyanazine also were decreased.

## 600.0504 Watershed scale

A project scale larger than either plots or fields is needed if the monitoring objectives are to determine long-term trends, identify critical areas, examine standard compliance, make wasteload allocations, or verify watershed scale models (table 5–1). In addition, where a number of BMP systems are being installed in a watershed with the intent of improving downstream water quality, watershed scale monitoring is a necessity.

Watershed scale monitoring also is desired if the water resource system of concern is either ground water, a stream, or a lake/estuary (table 5–2). Watershed scale monitoring costs range from moderate to high depending on the size of the system being monitored. Large streams or lakes are more costly to monitor than smaller water bodies. Watersheds are studied for longer durations than are either plots or fields. For most individual BMPs, watersheds are not an appropriate scale of study. However, exceptions might include riparian buffers and streambank protection, which could be evaluated on a watershed basis (table 5–5). The watershed scale would be more appropriate for biological and habitat monitoring than smaller scales.

The most difficult decision regarding watershed scale projects is the selection of watershed size. Several factors influence the selection of watershed size including: drainage pattern, stream order, stream permanence, climate region, the number of manageable landowners, the homogeneity of land uses, and watershed geology and geomorphology.

No real relationship exists between a watershed area and most stream characteristics, including stream order, stream length, and drainage density (stream length /watershed area) (Harlin 1984). For example, the relationship $L=1.4A^{0.6}$ (where L=stream length and A=watershed area) has been found to be regional. The primary reasons for the lack of relationships are the differences in climate regions and geology across the U.S. It is not surprising that watershed area and watershed discharge would vary from humid climate regions to arid or subhumid regions. The ratio of potential evapotranspiration to precipitation has been used to distinguish between climate regions, with a ratio of one separating humid from subhumid areas (Holdridge 1962). If precipitation equals or is less than evapotranspiration, very little runoff would be expected and a larger basin would be needed to generate a permanent stream. On the other hand, if precipitation exceeds evapotranspiration, runoff would most likely occur, and a smaller basin would be needed to generate streamflow.

Streams draining small watersheds in humid regions (precipitation > evapotranspiration) are usually first or second order, intermittent, and < 500 acres in area. Moderately sized watersheds are from 500 to 5,000 acres in area, are permanent, and have third or fourth order streams. Stream order, according to Strahler's method (Ruhe 1975), is determined by numbering the smallest streams highest in the watershed as first order streams. The joining of two first order streams results in a second order stream, and so on.

Humid watersheds larger than 5,000 acres and less than 50,000 acres are considered large. Watersheds larger than 50,000 acres are considered very large and may be inappropriate for monitoring because of their likely heterogeneity in land uses.

The size of the watershed selected influences the response to implementation of conservation practices. For example, the export of phosphorus from agricultural watersheds generally decrease per unit area as the watershed size increases (T.-Prairie & Kalff 1986). This effect was not observed for forested watersheds. Comparing different agricultural land uses, this decreasing phosphorus export with increasing watershed area occurred for row crop and pasture watersheds, but not for mixed agricultural or non-row crop basins. The authors attributed this difference to a combination of decreasing sediment delivery ratios, a reduction of drainage density, and decreasing slope with increasing watershed area. Because an average of 84 percent of the total phosphorus exported from agricultural watersheds was found in the particulate rather than dissolved form, the decreasing sediment delivery would result in decreasing phosphorus delivery. For forested watersheds, less than 50 percent was in the dissolved form (T.-Prairie & Kalff 1986). Phosphorus yield from watersheds less than 5,000 acres was particularly sensitive to watershed size.

The importance of these findings is twofold. First, using markedly different watershed sizes for control and treatment areas could introduce a bias in response. If the practice installed influenced sediment delivery, a smaller watershed will react differently from a larger one. Second, because sediment delivery per unit area is greater in smaller watersheds, there may be differences in flushing of sediment stored in channels of different sized watersheds.

A final consideration may be whether the stream is intermittent or permanent. Intermittent streams appear to exhibit a first flush phenomenon after extended dry periods where concentrations of nutrients are higher than anticipated based on discharge measurements. Also, the biotic community in an intermittent stream is controlled, in large part, by the periodic lack of flow. Some biotic community changes may be influenced more by flow than water quality changes. This is not to say that intermittent watersheds are inappropriate for study. Intermittent watersheds are smaller, and therefore greater control over watershed land activities can be exercised.

**Example 5–3** Watershed scale

One of the objectives of the St. Albans Bay watershed RCWP was to determine the effect of implementing BMPs on the water quality of the bay and its tributaries. Water quality monitoring, both chemical and biological, was conducted in the bay and four tributaries. At each stream monitoring location, flow was continuously recorded and samples were taken at 8-hour intervals and composited. Bacteria grab samples were taken weekly.

The watersheds were 3,400, 6,000, 3,800, and 14,400 acres in area. Trend analysis applied to the bacteria data revealed that bacteria abundance declined significantly in all tributary streams by 60 to 70 percent. The decline was attributed to bacterial dieoff during manure storage and greater incorporation of manure applied to fields, both of which were BMPs.

## 600.0505 References

Clausen, J.C., F.I. Potter, III, W.S. Douglas, W.E. Jokela, and J.W. Williams. 1990. Conservation tillage use of pesticides for corn: surface water contamination. Vermont Water Resour. Res. Cent., Burlington, VT.

Harlin, J.M. 1984. Watershed morphometry and time to hydrograph peak. J. of Hydrol. 67:141-154.

Holdridge, L.R. 1962. The determination of atmospheric water movements. Ecology. 43(1):1-9.

LeClerg, E.L., W.H. Leonard, and A.G. Clark. 1962. Field plot techniques. 2nd. Ed. Burgess Pub. Co. Minneapolis, MN.

Lee, D.R. 1977. A device for measuring seepage flux in lakes and estuaries. Limnol. Oceanog. 22(1):140-147.

Morton, T.G., A.J. Gold, and W.M. Sullivan. 1988. Influence of overwatering and fertilization on nitrogen losses from home lawns. J. Environ. Qual. 17(1):124-130.

Odum, E.P. 1984. The mesocosm. BioScience. 34(9):558-562.

Ruhe, R.V. 1975. Geomorphology: geomorphic processes and surficial geology. Houghton Mifflin Co., Boston, MA.

T.-Prairie, Y., and J. Kalff. 1986. Effect of catchment size on phosphorus export. Water Resour. Bull. 22(3):465-470.

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# Chapter 6 Variable Selection

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# Chapter 6 Variable Selection

## 600.0600 Introduction

The term *variable* is used in this handbook to denote water quality characteristics that exhibit variability (e.g., algae counts, dissolved oxygen, nutrient concentrations). Although the term *parameter* is often used interchangeably with the term variable, in this handbook parameter is meant to be quantities that characterize statistical samples (mean, variance).

The selection of water quality variables to include in a project requires consideration of several factors. The tendency is to sample for more variables than are generally needed. The major reason for not sampling "full suite" is that there are trade-offs in the study design. Water quality monitoring is expensive, and resources committed to unnecessary water quality characteristics may be at the expense of a successful experimental design. Where funding is limited, fewer stations, and the number of samples at each station, can be monitored when more water quality variables are added to a project. As a final test in considering which water quality variables to include in a project, a written justification statement is recommended for each variable. If the justification is weak, the variable may be of low priority and might not be essential.

This chapter discusses the various factors that affect the selection of water quality variables. Also several methods for prioritizing variables are presented including: variable matrices, variable cross-correlations, and the probability of exceeding standards.

Water quality variables receive various names and are classified differently in different references. For this chapter, the naming conventions that appear in American Public Health Association's standard methods (APHA 1989) were used. Two excellent references describe the meaning of various water quality variables. They are Hem (1970) and McKee and Wolf (1963). Additional descriptions are in IHD-WHO (1978), McNeely et al. (1979), and Stednick (1991). The importance of biological characteristics is described in Cairns et al. (1982), Plafkin et al. (1989), Terrell and Perfetti (1989), and Weber (1973).

## 600.0601 Factors affecting variables

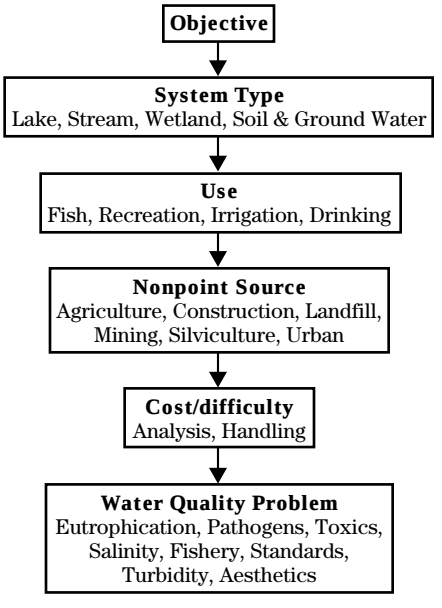
Considerations that influence the variables to sample include the study objectives, the type of water resource, the use or classification of the water body, the type of nonpoint source activity, the difficulty or cost in analysis of the variable, and the water quality problem. An overall schematic of these considerations is given in figure 6–1.

### (a) Objectives

A properly stated objective assists in defining the water quality variables to monitor. In fact, selecting the water quality variables may result in a redefinition or clarification of the objectives in a feedback manner. The *constraint* part of the objective may specifically mention the water quality variables (chapter 3). For example, the following objective statement from chapter 3 clearly indicates that the variable to measure is fecal coliform levels:

> *To determine the effect of implementing conservation practices on fecal coliform levels in Long Lake.*

**Figure 6–1** Water quality variable selection



## (b) System type

The type of water resource being studied also influences the variables selected. Table 6–1 indicates that the appropriate variables of interest differ primarily between subsurface systems, such as soil water and ground water, and surface water systems, including lakes, streams, and wetlands. For example, chemical nutrients may be important to all systems, but particulate forms of nutrients are meaningful only for lake, stream, and wetland systems and not for soil water or ground water systems.

In addition, different variable selections may be made for intermittent or permanent stream systems (USDA 1976). Generally, more variables can be justified for a perennial water body than for an intermittent one. The biota in intermittent streams is limited by the flow regime, and therefore may not be good water quality indicators in that situation.

Tables 6–1 through 6–8 provide a list of potential water quality variables to consider when designing a monitoring program.

**Table 6–1** Water quality variable groups by water resource system type matrix (general guidelines; in some circumstances variables that are not marked should be considered)

| Variable | System type | | | | |
|---|---|---|---|---|---|
| | Lake | Stream | Wetland | Soil water | Ground water |
| **Physical** | | | | | |
| Dissolved oxygen | X | X | X | | |
| Discharge | X | X | X | X | X |
| Embeddedness | | X | | | |
| Habitat assessment | | X | | | |
| Riffle/pool ratio | | X | | | |
| Salinity | X | X | X | X | X |
| Secchi disk transparency | X | | | | |
| Specific conductance | X | X | X | X | X |
| Substrate characteristics | X | X | | | |
| Suspended solids | X | X | X | | |
| Temperature | X | X | X | | |
| Total dissolved solids | X | X | X | X | X |
| Turbidity | X | X | X | | |
| **Chemical** | | | | | |
| $BOD_5$ | X | X | X | | |
| Inorganic nonmetals: Cl, F | | X | X | X | X |
| Nutrients - N, P dissolved | X | X | X | X | X |
| total or particulate | X | X | X | | |
| Metals: As, Ca, Cd, Cr, Co, Cu, Fe, Hg, K, Pb, Mg, Mn, Na, Ni, Zn | X | X | X | X | X |
| pH | X | X | X | X | X |
| **Biological** | | | | | |
| Bacteria | X | X | X | X | X |
| Chlorophyll 'a' | X | X | | | |
| Indices (SCI, BI, IBI)* | X | X | | | |
| Invertebrates | X | X | X | | |
| Fish | X | X | | | |
| Macrophyton | X | X | X | | |
| Periphyton | X | X | | | |
| Plankton (algae) | X | X | | | |
| Protozoa | X | X | | | |

* SCI = Sequential Comparison Index
BI = Beck's Biotic Index
IBI = Index of Biotic Integrity

## (c) Designated use

Variable selection may be modified by the intended or designated use of a water body (US EPA, 1981b). A water body being used for recreation, including aesthetic uses, might emphasize variables associated with sediment, nutrients, toxic and biological characteristics because all these are visual or affect visual characteristics of water bodies. However, water having an irrigation use might not include biological variables (table 6–2). Water intended to be used for drinking, recreation, or fisheries might include analysis of biological and toxic substances.

## (d) Pollutant source

The nonpoint source of the water quality problem also influences variable selection, as will certain activities for those sources. The major nonpoint source categories include:

- agriculture
- construction
- landfill
- mining
- silviculture
- urban

**Table 6–2** Water quality variable groups by intended water resource use (general guidelines; in some circumstances variables that are not marked should be considered)

| Variable | Intended use | | | | |
|---|---|---|---|---|---|
| | Fish | Recreation contact | Aesthetics | Irrigation | Drinking |
| **Physical** | | | | | |
| Dissolved oxygen | X | | X | | X |
| Discharge | | | | | |
| Salinity | X | | | X | X |
| Secchi disk transparency | X | X | X | | |
| Specific conductance | | | | X | X |
| Suspended solids | X | X | X | X | X |
| Temperature | X | | | | |
| Total dissolved solids | X | | | X | X |
| Turbidity | X | X | X | X | X |
| **Chemical** | | | | | |
| $BOD_5$ | X | | X | | |
| Inorganic nonmetals: Cl, F | X | | | X | X |
| Nutrients - N, P dissolved | X | | X | X | |
| total or particulate | X | | X | | |
| Metals: As, Ca, Cd, Cr, Co, Cu, Fe, Hg, K, Pb, Mg, Mn, Na, Ni, Zn | X | X | | X | X |
| pH | X | | | X | X |
| **Biological** | | | | | |
| Bacteria | | X | | | X |
| Chlorophyll 'a' | X | | X | | X |
| Indices (SCI, BI, IBI) | X | | X | | |
| Invertebrates | X | | | | |
| Fish | X | | | | |
| Macrophyton | X | | X | | |
| Periphyton | | | | | |
| Plankton (algae) | X | | X | | X |
| Protozoa | | X | | | |

Within each of these categories are specific activities that influence certain water quality variables. Agricultural activities are shown in table 6–3. Almost all agricultural activities justify monitoring dissolved oxygen or BOD, flow, suspended solids, nutrients in all forms, and invertebrates. Most agricultural activities might also influence turbidity and bacteria. Pesticide monitoring requires fewer variables to analyze, although the metabolites should also be monitored. In addition, metals can be added with certain pesticides, such as copper sulfate or a zinc fungicide.

Pesticides in field runoff are carried in both dissolved and particulate forms. Generally, the concentration of the pesticide is greater in the particulate form; however, the annual mass export may be greater in the dissolved form.

Three forms of nutrients (total, dissolved, and particulate) are appropriate for most agricultural activities. However, all three forms may not need to be analyzed since they are highly related. Including the other forms in the monitoring study would require justification.

**Table 6–3** Water quality variable groups by nonpoint source activity (general guidelines; in some circumstances variables that are not marked should be considered)

| Variable | Activity | | | | | | |
|---|---|---|---|---|---|---|---|
| | Field runoff* | Pesticide | Fertilizer | Barnyard/feedlot | Stream access | Pasture | Animal waste |
| **Physical** | | | | | | | |
| Dissolved oxygen | X | | X | X | X | X | X |
| Discharge | X | X | X | X | X | X | X |
| Salinity | | | | | X | | X |
| Secchi disk transparency | X | | X | X | X | X | X |
| Specific conductance | | | | | | | |
| Suspended solids | X | | | X | X | X | X |
| Temperature | | | | | | | |
| Total dissolved solids | X | | | X | X | X | X |
| Turbidity | X | | | X | X | X | X |
| **Chemical** | | | | | | | |
| $BOD_5$ | X | | X | X | X | | X |
| Inorganic nonmetals: Cl, F | | | | | | | |
| Nutrients - N, P dissolved | X | | X | X | X | X | X |
| total or particulate | X | | | X | X | X | X |
| Metals: As, Ca, Cd, Cr, Co, Cu, Fe, Hg, K, Pb, Mg, Mn, Na, Ni, Zn | | | | | | | |
| pH | | | | | | | |
| **Biological** | | | | | | | |
| Bacteria | X | | | X | X | X | X |
| Chlorophyll 'a' | X | X | X | X | X | X | X |
| Indices (SCI, BI, IBI) | X | X | X | X | X | X | X |
| Invertebrates | X | X | X | X | X | X | X |
| Fish | | X | | | | | |
| Macrophyton | X | X | X | X | X | X | X |
| Periphyton | X | X | X | X | X | X | X |
| Plankton (algae) | X | X | X | X | X | X | X |
| Protozoa | | X | | | | | |

* Includes runoff from hayland, rangeland, and cropland.

An activity by variable matrix for additional nonpoint source categories is given in table 6–4. Most of the activities have the potential to directly influence discharge, sediment and nutrients. Therefore, additional indirect effects may occur to oxygen, transparency, and several biological characteristics. Landfill leachate may contain a wide range of water quality constituents; therefore, a large number of physical, chemical, and biological variables are usually monitored.

The water quality variables selected for mining operations would change with the type of mining. Acid mine drainage, associated with coal mining, might involve monitoring several physical variables, as well as metals and biological characteristics. Mining of taconite, sylvite, rock phosphate, and sand and gravel might imply other, more specific variables.

**Table 6–4** Water quality variable groups by construction, landfill, and mining activities (general guidelines; in some circumstances variables that are not marked should be considered)

| Variable | Activity | | |
|---|---|---|---|
| | Construction | Landfill | Mining |
| **Physical** | | | |
| Dissolved oxygen | | X | X |
| Discharge | X | X | X |
| Salinity | | X | |
| Secchi disk transparency | X | X | |
| Specific conductance | | X | X |
| Suspended solids | X | X | X |
| Temperature | X | | X |
| Total dissolved solids | X | X | X |
| Turbidity | X | | X |
| **Chemical** | | | |
| $BOD_5$ | | X | |
| Inorganic nonmetals: Cl, F | | X | X |
| Nutrients - N, P dissolved | X | X | |
| total or particulate | X | X | |
| Metals: As, Ca, Cd, Cr, Co, Cu, Fe, Hg, K, Pb, Mg, Mn, Na, Ni, Zn | | X | X |
| pH | | X | X |
| **Biological** | | | |
| Bacteria | | X | |
| Chlorophyll 'a' | X | X | X |
| Indices (SCI, BI, IBI) | X | X | X |
| Invertebrates | X | X | X |
| Fish | X | X | X |
| Macrophyton | | X | X |
| Periphyton | | X | X |
| Plankton (algae) | | X | X |
| Protozoa | | X | |

Several activities are associated with silvicultural operations (table 6–5). Of these activities, road construction, grazing, and site preparation have the greatest potential to influence the most water quality characteristics. Timber harvesting alone only influences the water quality variables affected by riparian vegetation removal. Transporting the timber out of the forest causes most of the potential water quality effects. However, water yield changes associated with timber harvesting can have additional water quality impacts.

Urban activities may influence several physical, chemical, and biological variables, as indicated in table 6–6. Impervious areas and combined sewer overflows (CSOs) influence the same variables directly and indirectly because their primary sources of pollutants are runoff from impervious surfaces.

**Table 6–5** Water quality variable groups by silvicultural activity (general guidelines; in some circumstances variables that are not marked should be considered)

| Variable | Activity | | | | |
|---|---|---|---|---|---|
| | Harvesting | Roads | Site preparation | Grazing | Pesticide |
| **Physical** | | | | | |
| Dissolved oxygen | X | X | X | X | |
| Discharge | X | X | | X | |
| Salinity | | | | | |
| Secchi disk transparency | | X | | X | |
| Specific conductance | | | | | |
| Suspended solids | | X | X | X | |
| Temperature | X | | | | |
| Total dissolved solids | | X | X | X | |
| Turbidity | | X | X | X | |
| **Chemical** | | | | | |
| $BOD_5$ | | | | | |
| Inorganic nonmetals: Cl, F | | | | | |
| Nutrients - N, P dissolved | | X | X | X | |
| total and particulate | | X | X | X | |
| Metals: As, Ca, Cd, Cr, Co, Cu, Fe, Hg, K, Pb, Mg, Mn, Na, Ni, Zn | | | | | |
| pH | | | | | |
| **Biological** | | | | | |
| Bacteria | | | X | | |
| Chlorophyll 'a' | | X | X | X | X |
| Indices (SCI, BI, IBI) | | X | X | X | X |
| Invertebrates | X | X | X | X | X |
| Fish | X | X | X | X | X |
| Macrophyton | X | X | X | X | X |
| Periphyton | X | X | X | X | X |
| Plankton (algae) | X | X | X | X | X |
| Protozoa | | | | | X |

**Table 6–6** Water quality variable groups by urban activity (general guidelines; in some circumstances variables that are not marked should be considered)

| Variable | Impervious areas | Lawns | Combined sewer overflows | Pets |
|---|---|---|---|---|
| **Physical** | | | | |
| Dissolved oxygen | X | X | X | X |
| Discharge | X | X | X | |
| Salinity | | | | |
| Secchi disk transparency | X | X | X | X |
| Specific conductance | X | | | |
| Suspended solids | X | | X | |
| Temperature | | | | |
| Total dissolved solids | | | | |
| Turbidity | X | | X | |
| **Chemical** | | | | |
| $BOD_5$ | X | | X | |
| Inorganic nonmetals: Cl, F | X | | X | |
| Nutrients - N, P dissolved | X | X | X | X |
| total or particulate | X | | X | X |
| Metals: As, Ca, Cd, Cr, Co, Cu, Fe, Hg, K, Pb, Mg, Mn, Na, Ni, Zn | X | | X | |
| pH | | | | |
| **Biological** | | | | |
| Bacteria | X | | X | X |
| Chlorophyll 'a' | X | X | X | X |
| Indices (SCI, BI, IBI) | X | X | X | X |
| Invertebrates | X | X | X | |
| Fish | X | X | X | |
| Macrophyton | X | X | X | |
| Periphyton | X | X | X | X |
| Plankton (algae) | X | X | X | X |
| Protozoa | X | | X | X |

## (e) Analysis difficulty

The difficulty or cost of analysis should be considered when selecting water quality variables. Table 6–7 presents some relative costs of analysis for specific water quality variables. These costs are relative to the cost of analyzing the sample for either pH or conductance. When water quality characteristics are highly related, but the analysis cost of one is much cheaper than the other, the less expensive variable could be selected. For example, analysis of turbidity is less costly than suspended solids, both of which are less expensive than total solids. Also, nitrate nitrogen is cheaper than ammonia nitrogen or total Kjeldahl nitrogen because digestion of the sample is not required.

The range and level of accuracy are also important. For example, Inductively Coupled Plasma (ICP) emission spectroscopy will determine elements cheaper, but not as accurately, as atomic absorption. Sample holding times also influence parameter selections. For example, nitrate and ortho-phosphate are recommended by the Environmental Protection Agency (USEPA 1983) to be analyzed within 48 hours of collection, whereas nitrate+nitrite and total phosphorus can be held for 28 days before analysis if preserved (see table 11–1).

## (f) Water quality problem

Finally, the water quality problem itself influences the variables to sample. The major water quality problems are summarized in table 6–8 along with the appropriate water quality variables. Eutrophication problems require monitoring of several physical, chemical, and biologic characteristics. Excess algae might suggest sampling of dissolved oxygen and temperature, flow for mass balance purposes, turbidity or secchi disk transparency, nutrients, plankton abundance/type, and chlorophyll 'a' concentrations. Because many of these variables are related, not all would be needed to detect changes. Also, an index, such as Carlson's Trophic State Index (TSI) could be used (Carlson 1977). It combines some of these variables.

A problem associated with either a standard violation or a toxic substance might focus on monitoring that particular standard or toxicant.

**Table 6–7** Relative cost of analysis for water quality variables (based on Beetem et al. 1980)

| Variable | Cost ($/analysis) dissolved | total | particulate |
|---|---|---|---|
| **Ions** | | | |
| Ca, Mg | 4.70 | | 12.00 |
| Na, K, $SiO_2$ | 3.40 | | 10.00 |
| Cl | 5.35 | | |
| F | 5.25 | | |
| $SO_4$ | 5.80 | | |
| **Trace metals** | | | |
| As, Hg | 5.20 | | 22.70 |
| Cd, Co, Cu, Pb, Ni | 6.20 | | 10.00 |
| Cr | 10.50 | | 2.90 |
| Fe, Mn | 3.40 | | 10.00 |
| Zn | 4.20 | | 10.00 |
| **Physical** | | | |
| Alkalinity | | 3.55 | |
| pH | | 1.00 | |
| Specific conductance | | 1.00 | |
| Total solids | | 8.95 | |
| Turbidity | | 1.80 | |
| **Nutrients** | | | |
| $NH_3$, $NO_3$, $NO_2$ | | 3.40 | |
| TKN | | 8.90 | |
| Total P | | 9.55 | |
| $PO_4$ | | 3.40 | |

**Table 6–8** Water quality variable groups by water quality problem (general guidelines; in some circumstances variables that are not marked should be considered)

| Variable | Problem | | | | | | |
|---|---|---|---|---|---|---|---|
| | Aesthetics | Bacteria | Algae | Macrophytes | Salinity | Sediment | Toxics |
| **Physical** | | | | | | | |
| Dissolved oxygen | X | | X | | | | |
| Discharge | | | X | | | | |
| Salinity | | | | X | | | |
| Secchi disk transparency | X | | X | | | X | |
| Specific conductance | | | | | X | | |
| Suspended solids | X | | | | X | | |
| Temperature | | | | | | | |
| Total dissolved solids | | | | | X | | |
| Turbidity | X | | | | | X | |
| **Chemical** | | | | | | | |
| $BOD_5$ | | | | | | | |
| Inorganic nonmetals: Cl, F | | | | | X | | |
| Nutrients - N, P dissolved | X | | X | X | | | |
| total or particulate | X | | X | X | | | |
| Metals: As, Ca, Cd, Cr, Co, Cu, Fe, Hg, K, Pb, Mg, Mn, Na, Ni, Zn | | | | | | | |
| pH | | | | | | | |
| **Biological** | | | | | | | |
| Bacteria | | X | | | | | |
| Chlorophyll 'a' | X | | X | | | | X |
| Indices (SCI, BI, IBI) | X | | X | | X | | X |
| Invertebrates | | | | | X | | X |
| Fish | | | | | X | | X |
| Macrophyton | X | | | X | X | | |
| Periphyton | X | | X | | | | X |
| Plankton (algae) | X | | X | | | | X |
| Protozoa | | | | | | | X |

## 600.0602 Prioritizing variables

Because virtually hundreds of water quality variables exist and are therefore candidates for monitoring, a method for prioritizing their selection is important. The four basic approaches for prioritizing water quality variables are ranking, activity matrices, correlations, and probability of exceeding a standard.

### (a) Ranking

Sanders et al. (1983) suggest a hierarchical approach of:

- **Primary**—water quantity variables that serve as a carrier of water quality, e.g., discharge, volume, head
- **Secondary**—water quality variables that are the result of aggregated effects, e.g., temperature, pH, conduction, dissolved oxygen, turbidity, anions, cations
- **Tertiary**—water quality variables that produce aggregated effects, e.g., radioactivity, suspended matter

Variables higher in the hierarchy would be selected over lower-ranked variables. Greater priority should be placed on primary variables than on secondary variables when the number of variables to monitor need to be limited.

Another example of prioritizing suggests two levels of analysis (USEPA 1981 a, b). Level I is the minimum list of variables needed to evaluate program effectiveness associated with a particular water quality problem and use of the water resource. For example, chlorophyll ‘a’ would be the level I variable for a stream experiencing excessive algal growth and being used for drinking water. Level II includes more detailed, multiparameter variables. For the example above, nitrogen and phosphorus species would be added to the chlorophyll 'a' sampling.

### (b) Activity matrices

The water quality variable matrices given in tables 6–1 through 6–6 serve as a second method in selecting water quality variables. Ponce (1980) assigned values of 1, 2, or 3 to primary, secondary, and tertiary sampling priority codes in a forest management activity matrix with water quality variables. This method combines the ranking and activity matrices approaches. The activity matrix variable provides an initial list of variables to consider when planning the monitoring study.

### (c) Correlations

Correlations between variables can be used to reduce the variable list. A number of water quality variables are often correlated. Total phosphorus often is highly related to ortho-phosphorus. In lake systems, total phosphorus has been reported to be highly related to secchi disk transparency and chlorophyll 'a' (Reckhow & Chapra 1983). Other variables that might be expected to exhibit correlations are conductivity and dissolved solids and suspended solids and turbidity. Since these variables may be highly related, one variable could be dropped from the monitoring program or monitored less frequently.

Correlation coefficients are readily computed in most statistical packages. This topic is further discussed in part 2 of this handbook. The correlation coefficient (r) can be determined from:

$$r = \frac{\sum\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{\sqrt{\sum\left(X_i - \overline{X}\right)^2 \sum\left(Y_i - \overline{Y}\right)^2}} \qquad [6–1]$$

where:

$\overline{X}$ and $\overline{Y}$ = the means of the variables X and Y, respectively

$X_i$ and $Y_i$ = individual values of variables X and Y, respectively

To use correlation coefficients, some monitoring data would have to be available either from a previous study or from preliminary monitoring in the watershed of interest.

Another consideration for correlated variables is the proximity of the range in values to the detection limit for that variable. Values below detection limits, termed censored values, require adjustments when calculating means and variances. Variables that do not include censored values are preferred.

Example 6–1 illustrates variable correlations.

**Example 6–1** Variable correlations

Muddy Bay is experiencing impairment caused by excessive sedimentation and eutrophication. Both nitrogen and phosphorus are believed to contribute to the problem. Appropriate variables include:

- Turbidity
- Total Suspended Solids (TSS)
- Volatile Suspended Solids (VSS)
- Total Phosphorus (TP)
- Ortho-Phosphate (OP)
- Total Kjeldahl Nitrogen (TKN)
- Ammonia Nitrogen ($NH_3$)
- Nitrate Nitrogen ($NO_3$)

Based on cost data, these analyses would cost a total of $40.45 per site visit (1980 dollars). You have $25 budgeted to monitor water quality per sampling period. Which parameters would you monitor?

Note that based on sampling in Muddy Bay during 1 year, the following correlation matrix was developed.

**Correlation matrix (r)**

| | Turbidity | TSS | TKN | $NO_3$ | TP |
|---|---|---|---|---|---|
| TSS | 0.577 | 1.000 | --- | --- | --- |
| VSS | 0.764 | 0.855 | --- | --- | --- |
| $NH_3$ | --- | --- | 0.836 | 0.281 | --- |
| $NO_3$ | --- | --- | -0.057 | 1.000 | --- |
| OP | --- | --- | --- | --- | 0.915 |

The correlations between TP and OP, TKN and $NH_3$, and TSS and VSS are significant and very high. Adequate monitoring could be achieved by choosing TSS, total P, and TKN for less than $25 to meet sedimentation and eutrophication objectives. In nitrogen-limited systems, measurement of $NO_3$ should be included.

## (d) Probability of exceeding standard

An alternative method for determining the priority of variables to monitor would be to select those with the highest probability of exceeding a particular standard (Moser & Huibregtse, 1976). To determine this probability requires knowledge of the mean ($\overline{X}$), standard deviation (S), and numerical standard value ($X_{std}$) not to be exceeded. The probability is determined from the Z-statistic as:

$$Z = \frac{X_{std} - \overline{X}}{S} \qquad [6\text{–}2]$$

Using a standard Z-table (appendix A), the probability would be obtained. Not all variables have adopted numerical values for standards. For example, nitrogen and phosphorus generally are not included in lists of numeric standards. In such cases a eutrophication value, such as 0.05 mg/L for total phosphorus could be used. Another alternative would be to set a concentration goal to achieve and substitute that for a standard value.

Example 6–2 illustrates this approach.

**Example 6–2** Probability of exceeding a standard

Using the St. Albans Bay data, the mean fecal coliform bacteria count for Jewett Brook in 1989 was 149 organisms/100 mL. The standard deviation was 493 organisms/100 mL. Using a water quality standard of 200 organisms/100 mL, what is the probability of exceeding the fecal coliform standard?

$$Z = \frac{200 - 149}{493} = 0.10$$

From a standard Z-table (appendix A), the probability would be 0.4602 or 46 percent. This probability may be higher than that for other water quality variables, and therefore would be given higher priority.

## 600.0603 References

American Public Health Association. 1989. Standard methods for the examination of water and wastewater. 17th Ed. American Public Health Assoc. Washington, DC.

Beetem, W.A., L.C. Friedman, G.R. Perryman, and C.A. Wottersan (eds). 1980. 1981 Water quality laboratory services catelog. U.S. Geol. Surv. Open-file Rep. 80-1279.

Cairns, J., Jr., A.L. Buikema, Jr., D.S. Cherry, E.E. Herricks, R.A. Matthews, B.R. Niederlehner, J.H. Rodgers, Jr., and W.H. van der Schalie. 1982. Biological monitoring in water pollution. Pergamon Press, Elmsford, NY.

Carlson, R.E. 1977. A trophic state index for lakes. Limnol. Ocean. 22:361- 369.

Hem, J.D. 1970. Study and interpretation of the chemical characteristics of natural water. U.S.. Geol. Surv. Water-Supply Pap. 1473. US GPO, Washington, DC.

IHD-WHO Working Group on the Quality of Water. 1978. Water quality surveys—a guide for the collection and interpretation of water quality data. Stud. and Rep. in Hydrol. No. 23. United Nations Educational, Scientific, and Cultural Organization. Paris, France, and World Health Organization, Geneva, Switzerland.

McKee, J.E., and H.W. Wolf. 1963. Water quality criteria. 2nd Ed. California State Water Quality Control Board. Publ. No. 3-A. Sacramento, CA.

McNeely, R.N., V.P. Neimanic, and L. Dwyer. 1979. Water quality sourcebook—a guide to water quality parameters. Inland Water Directorate, Water Quality Branch. Ottawa, Canada. Cat. No. EN 37- 541.

Moser, J.H., and K.R. Huibregtse. 1976. Handbook for sampling and sample preservation of water and wastewater. USEPA 600/4-76-049.

Plafkin, J.L., M.T. Barbour, K.D. Portor, S.K. Gross, and R.M. Hughes. 1989. Rapid bioassessment protocols for use in streams and rivers: benthic macroinvertebrates and fish. USEPA 444/4-89-001. Office of Water. Washington, DC.

Ponce, S.L. 1980. Water quality monitoring programs. WSDG Tech Pap. No. WSDG-TP-00002. Watershed Systems Development Group, USDA Forest Service. Ft. Collins, CO.

Reckhow, K.N. and S.C. Chapra. 1983. Engineering approaches for lake management. Vol. 1: Data analysis and emphirical modeling. Butterworth Publ. Woburn, MA.

Sanders, T.G., R.C. Ward, J.C. Loftis, T.D. Steele, D.D. Adrian, and V. Yevjevich. 1983. Design of networks for monitoring water quality. Water Resourc. Pub. Littleton, CO.

Stednick, J.D. 1991. Wildland water quality sampling and analysis. Academic Press, Inc., San Diego, CA.

Terrell, C.R., and P.B. Perfetti. 1989. Water quality indicators guide: surface waters. USDA, Soil Conserv. Serv., SCS-TP-161. Washington, DC.

United States Department of Agriculture, Soil Conservation Service. 1976. A general guideline for the assessment of water quality. Tech. Rel. No. 58. Eng. Div., Washington, DC.

United States Environmental Protection Agency. 1981a. Conceptual framework for assessing agricultural nonpoint source projects. NC State Univ., Raleigh, NC.

United States Environmental Protection Agency. 1981b. Guidelines for evaluation of agricultural nonpoint source water quality projects. NC State Univ., Raleigh, NC.

United States Environmental Protection Agency. 1983. Methods for chemical analysis of water and wastes. US EPA 600/4-79-020. Environ. Monit. and Support Lab., Cincinnati, OH.

Weber, C.I. (Ed.) 1973. Biological field and laboratory methods for measuring the quality of surface waters and effluents. US EPA 670/4-73-001. Off. Res. and Dev., Cincinnati, OH .

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# Chapter 7 Sample Type

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# Chapter 7 Sample Type

## 600.0700 Introduction

If water quality did not vary in space or in time, there would be little reason to collect more than one sample to describe the quality of a particular water body. However, water quality does vary spatially and temporally. Both random and deterministic components (fig. 7–1) are found in most water quality data. Variations in water quality data are caused by seasonal differences, trends, and the randomness associated with rainstorms. For example, suspended solids concentrations increase during stormflow, especially during the early part of the storm (Shelly & Kirkpatric 1975). Therefore, because of these temporal and spatial variations, samples must be taken from the entire population of water quality data possible.

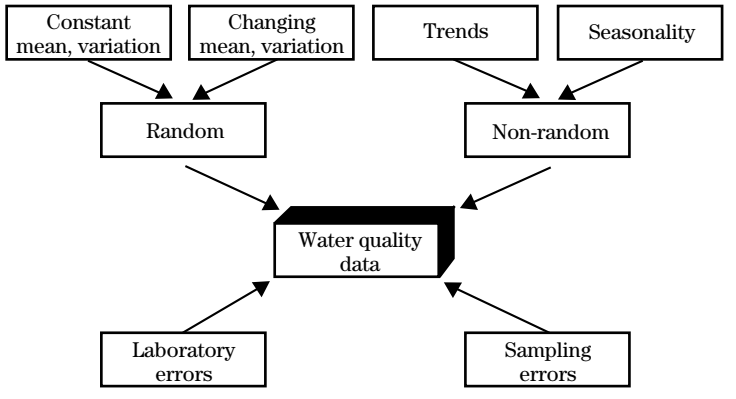
The four types of water quality samples that can be collected are grab, composite, integrated, or continuous. The sample type selected is governed by the study objectives, the variable to sample, and whether concentration or mass is the desired outcome. Composite samples are appropriate for most monitoring study objectives, whereas grab sampling is recommended for a few objectives directed toward reconnaissance sampling (table 7–1). Continuous samples are appropriate only for research and fate and transport studies.

The variable to sample influences the sample type as well. For example, bacteria samples must be taken as grab samples with sterilized bottles and cannot be stored in the field as a composite sample. The concentrations of other variables change dramatically during storage and therefore are inappropriate for compositing. These include all dissolved gases, chlorine, pH, temperature, and sulfide (APHA 1989). Water quality variables that correlate highly with stream velocity, especially those related to suspended sediment concentrations, may need to be sampled with depth integrated samplers. Grab samples may be insufficient to determine mass loading values unless the concentrations are correlated to discharge (Baun 1982).

**Table 7–1** Sample type as a function of monitoring study objective

| Objective | Grab | Integrated or composite | Continuous |
|---|---|---|---|
| 1. Baseline | X | X | |
| 2. Trend | X | X | |
| 3. Fate & transport | | X | X |
| 4. Problem definition | X | X | |
| 5. Critical areas | X | X | |
| 6. Compliance | X | X | |
| 7. Conservation practice effectiveness | | X | |
| 8. Program effectiveness | | X | |
| 9. Wasteload allocations | | X | |
| 10. Model evaluation | | X | |
| 11. Research | | X | X |

**Figure 7–1** Factors contributing to variability in water quality data



## 600.0701 Grab samples

A grab sample is a discrete sample that is taken at a specific point and time (APHA 1989; Ponce 1980). Grab samples may not be representative of the water quality of the body of water being sampled. For example, the water quality may vary with depth or distance from the streambank. Samples at a single location in a lake or a single well are really grab samples. For lakes and ground water, variable concentrations may vary with location and depth. For example, nitrate concentrations have been found to be stratified in some water table aquifers in the Midwest. Also, since water quality often varies with time, grab samples may not represent temporal variations.

Grab samples can be collected manually by hand or automatically with a sampler.

## 600.0702 Composite samples

A series of grab samples, usually collected at different times and lumped together, are considered composite samples. However, composite samples typically are taken only at one point. These samples can be either time-weighted or flow-weighted. The collection of composite samples generally is done with the aid of an automatic sampler, as described in chapter 9, although manual techniques could be used as well. A distinct advantage of the composite sample is that a savings in laboratory and field costs can be realized. Also, compositing will reduce sample-to-sample variability.

### (a) Time-weighted composite

Time-weighting is the most common type of water quality compositing. For this type of sample, a fixed volume of sample is collected at prescribed time intervals in either a large composite bottle or separate bottles for compositing later. With automatic samplers, the time interval can range from 1 minute to 100 hours, and the volume collected can range from 10 mL to 990 mL, although larger volumes are possible. Equation 8–1 in chapter 8 can be used to determine the number of samples (n) to take to make up a composite, where n is a function of the variability in the data and the desired precision. For water quality variables where the length of the composite time is greater than the prescribed holding times (USEPA 1983), the collection bottles may be pre-acidified for preservation.

### (b) Flow-weighted composite

Time-weighted compositing has been criticized as being inappropriate for mass loading calculations and inaccurate where the discharge and concentrations vary (Baun 1982; Shelly & Kirkpatric 1975). Also, the time interval may miss peak concentrations during peak discharges. Therefore, flow-weighted compositing is an alternative to time-compositing. Where flow-weighted compositing is used, a sample is taken after a specified volume ($l^3$) of flow has passed the monitoring station. This type of sampling requires automatic equipment that monitors stream stage and

calculates discharge. A number of automatic samplers offer this function, or a data logger can be used.

To sample in this manner, the stage-discharge relationship must be known for the monitoring location. Stage-discharge relationships require a great deal of effort to develop unless a calibrated flow devise, such as a weir or a flume, is used.

Flow-weighted compositing also can be achieved using certain types of passive samplers. A passive sampler is one that collects a water quality sample by action of the flow of water itself. A number of these types of devices are described further in chapter 9.

## 600.0703 Integrated samples

A specific type of grab sample is a depth-integrated sample (USGS 1977). Such a sample may account for velocity or stratification induced changes with depth, but temporal variations would not be integrated.

Multipoint sampling at a station may be necessary because of the horizontal and vertical variations in water quality. The U.S. Geological Survey recommends that streams should be sampled using a depth integrated sampler whenever practical (USGS 1977) except when the stream is too shallow to obtain that type of sample.

For variations across the stream, samples can be collected using either the Equal Width Increment (EWI) method or the Equal Discharge Increment (EDI) method. With the EWI method, depth integrated samples are collected at equally spaced intervals at the cross section. All subsamples are then composited. The EDI method requires knowledge of streamflow discharge by subsection in the cross section. The section is divided into equal discharge subsections, which are then sampled.

Depth-integrated samples may also be appropriate for both lake and ground water systems. In lakes, depth integration can be achieved by sampling each lake strata, by obtaining a sample of the entire water column with a hose, or by automatic devices or pulleys that collect at different depths over time.

Different ground water strata can be sampled with certain types of bailers or with multilevel wells and samplers.

## 600.0704 Continuous samples

Continuous sampling is rare in nonpoint source pollution studies and is typically used for research purposes (table 7–1). Continuous monitoring can be used for any water quality variable that is measured using electrometric methods (table 7–2). This would exclude analysis of metals and organics.

Several problems are encountered when using continuous sampling. Most electrodes are temperature dependent and have temperature limits beyond which they cease to function. Electrodes normally cannot be placed in areas of rapid water velocity, which influences readings by the probe. However, in-stream stilling wells can be used to reduce this effect.

Several manufacturers produce submersible, multiple recording probes for such variables as pH, dissolved oxygen, conductance, and depth. These probes have been widely used in lake systems.

**Table 7–2** The suitability of various water quality variables for continuous monitoring (based on APHA 1989)

| Suitable | Not suitable |
|---|---|
| Ammonia | Metals |
| Chloride | Organic compounds |
| Conductivity | Pesticides |
| Cyanide | |
| Dissolved oxygen | |
| Fluoride | |
| Inorganic nonmetals | |
| Nitrate | |
| pH | |
| Salinity | |
| Temperature | |

## 600.0705 References

American Public Health Administration. 1989. Standard methods for the examination of water and wastewater. 17th Ed. Amer. Pub. Health Assoc., Washington, DC.

Baun, K. 1982. Alternative methods of estimating pollutant loads in flowing water. Tech. Bull. No. 133. WI Dep. Nat. Res. Madison, WI.

Ponce, S.L. 1980. Water quality monitoring programs. WSDG Tech. Pap. WSDG-TP-0002. Watershed Systems Development Group, U.S. Dep. Agric., Forest Serv., Fort Collins, CO.

Shelley, P., and G. Kirkpatric. 1975. An assessment of automatic sewer flow samplers. U.S. Environ. Prot. Agency 600/2-75-065, pp. 327-330.

United States Environmental Protection Agency. 1983. Methods for chemical analysis of water and wastes. USEPA 600/4-79-020, Environmental Monitoring and Support Lab, Cincinnati, OH.

United States Geological Survey. 1977. National handbook of recommended methods for water-data acquisition. Chapter 5: Chemical and physical quality of water and sediment. Off. Water Data Coord., USGS, Reston, VA.

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# Chapter 8 Sampling Location

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# Chapter 8 Sampling Location

## 600.0800 Introduction

The question of where to sample is critical to a successful monitoring program. The factors that influence the location of sampling stations are:

- The study objectives and experimental design
- The type of water body (e.g., lake, stream, ground water)

Sampling locations may be viewed from two perspectives: macroscopic and microscopic. First, the overall watershed spatial locations must be determined. Second, the sampling locations within the system must be found. Because there are trade-offs between the number of sampling stations and the number of samples taken, some optimal sampling location strategies are based on travel distances and other such factors. Finally, when actually siting a station on the ground, some site selection criteria should be considered.

## 600.0801 Factors affecting locations

Definition of the study's objectives and the study design should aid in defining the general spatial sampling locations. As described in chapter 3, the monitoring study design indicates the basic sample locations. It is fairly obvious that needs differ in siting locations for plot studies versus a paired watershed design. Above-and-below or *nested* stations are particularly difficult to site. If these stations are too far apart, there may be no relationship between them. If they are located too close together, there may not be a detectable difference because of the treatment, especially in larger watersheds. Nested watersheds located too high in the watershed may exhibit poor relationships because the upper location may be intermittent. Above-and-below stations located lower in the watershed might be dominated by watershed processes not associated with the watershed treatment.

The most crucial element of sampling locations is siting the control station location. The control site must be stable and free from outside disturbances. For example, road ditch changes or repair must not be allowed to divert runoff into a control watershed. In biological monitoring this is termed the reference station.

The overall monitoring purpose, as described in the preface, influences sampling locations. For example, determining critical areas may require several watershed locations to isolate the major contributing sites. In contrast, long-term trend analysis or program evaluation may involve only one or two locations. Compliance monitoring would be located very close to the source. In contrast, fate and transport studies and wasteload allocations require downstream locations.

The type of water body also influences the sampling locations. To characterize a watershed outlet only requires one sampling station. To characterize ground water or the water quality of a lake would require several more sampling locations. Biological monitoring in any of these systems would require subsampling of different habitats or nitches in the system.

Some specific recommendations have been made for locating sampling stations for biological monitoring (Klemm, et al. 1990)

- Select sampling locations with similar substrates, depth, physical characteristics, and velocity. If it is not possible to locate stations with similar habitats, artificial substrate samplers may be necessary.
- Include at least one reference station away from all possible discharge points.
- Include a station directly below the source of pollution. If the discharge is not mixed, include left-bank, midchannel, and right-bank substrations.
- Establish stations at various distances downstream from the source.
- Sampling locations for macroinvertebrates should be close to sites used for chemical and physical monitoring.
- Locations used for sampling should not be atypical, such as at bridges or dams. However, in urban areas such structures may be typical.
- Sampling nonpoint sources of pollution may require a number of stations along the water body impacted.

## 600.0802 Site selection criteria

The criteria used to determine sampling locations will be specific to the individual project, and will obviously change with the type of system (lake, ground water, stream) and the scale of system (plot, field, watershed) being monitored. However, the following generalized criteria can serve as a beginning point.

All sites
- Accessible all weather
- Power available
- Cooperative landowner
- Equipment protected from vandals
- Close to problem area

Streams
- Appropriate habitat
- Impermeable streambed
- Stable streambed
- Sufficient stream gradient
- Straight, uniform cross-section and approach
- Not at obstructions
- Not at meander
- Control at all stages
- Confined channel
- No road drainage influence
- Obtain stage-discharge at all stages
- Appropriate land use

Ground water
- Water table divide definable
- Barrier locations (stream, strata) known
- Direction of flow appropriate
- Water levels high or low as needed
- Stratified or mixed concentrations as needed
- Depth to confining layer known
- Away from large volume well drawdown

Lakes
- Stratification depths known
- Longitudinal gradient defined
- Bays and beaches considered
- Water circulation patterns known

Field/Plot
- Homogeneous land use
- Definable watershed
- Homogeneous soil

## 600.0803 Within system locations

Once the overall sampling location has been determined, a more specific location is needed to collect a representative sample (Canter 1985; Ponce 1980; Sanders, et al. 1983). These locations vary with system type.

### (a) Streams

At a single stream cross section, water quality may vary vertically and horizontally for several reasons. Velocity profiles result in varying concentrations at a cross-section, especially for sediment and sediment-bound concentrations (fig. 8–1a). The stream velocity generally is greater in the center of the stream and just below the water surface. The mean velocity is considered to be at 0.6 times the depth from the water surface for water less than 1 foot deep and at the average of 0.2 and 0.8 times the depth for water more than 1 foot deep.

Lateral mixing below tributary junctions may be incomplete, resulting in a plume following one streambank (fig. 8–1b). Meanders result in increased velocity near the outside bank and reduced velocity inside the meander near the point bar. Thus at a meander, lateral homogeneity would be small. The location of meanders also changes with flow stage.

Sampling locations must account for these vertical, horizontal, and longitudinal differences in water quality. Vertical and horizontal concentration differences are minimized where the stream is completely mixed; therefore, chemical sampling should be conducted at locations expected to be well mixed. Mixing is better in high velocity, turbulent stream sections and well below tributary inputs.

Mixing distances can be determined using equation 8–1 (Sanders, et al. 1983):

$$L_y = 2.17\frac{\sigma_y^2}{d} \times \frac{\mu}{\mu^*} \qquad [8–1]$$

where:

$L_y$ = distance for complete lateral mixing
$\sigma_y$ = distance from farthest bank of stream to point of discharge
$d$ = depth of flow
$\mu$ = mean stream velocity
$\mu^*$ = shear velocity = $(gRS_e)^{0.5}$

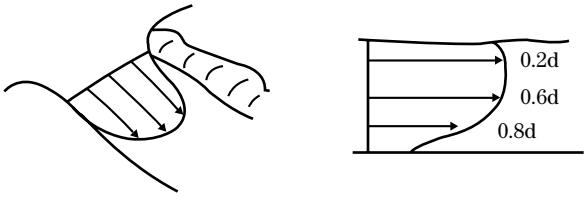
where:

g = acceleration because of gravity
R = hydraulic radius = A/P
A = cross-section area
P = wetted perimeter
$S_e$ = slope of the energy gradient = approximately the streambed slope

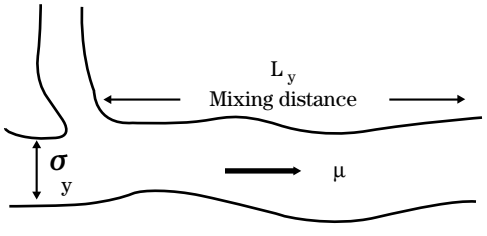
The sampling station should be located downstream of a tributary, or other discharge to the stream, by a distance equal to or greater than the mixing distance.

**Figure 8–1** Within stream sampling locations for physical/chemical monitoring

**a Velocity profiles**




**b Mixing zone**



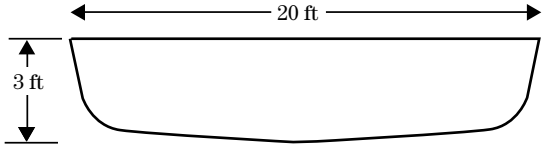
If differences in lateral concentrations still exist, compositing samples taken at locations across the stream can integrate these differences. Lateral locations can be width or flow integrated.

Differences in vertical gradients in streams also can be accounted for by the sampling technique. As described in chapter 10, a depth-integrating sampler, such as a DH-48, can be used to obtain a grab sample. For automatic samplers, a floating sampling tube can be used.

**Example 8–1** Mixing distances

A tributary to Mill River contains a large amount of sediment as compared to Mill River, which results in a sediment plume following one of the streambanks. How far downstream should a sampling station be located on Mill River to ensure complete mixing?

Mill River has a mean velocity ($\mu$) of 1.5 feet per second. The average depth (d) of the stream is 3 feet, and the average width ($\sigma_y$) is 20 feet. The streambed slope ($S_e$) is 0.005 foot per foot, based on information from a topographic map.




$$R = \frac{A}{P} = \frac{3ft \times 20ft}{3ft + 3ft + 20ft} = 2.31ft$$

$$\mu^* = \sqrt{\left(32.2ft/s^2\right)\left(2.31ft\right)\left(0.005\right)}$$

$$\mu^* = 0.61ft/s$$

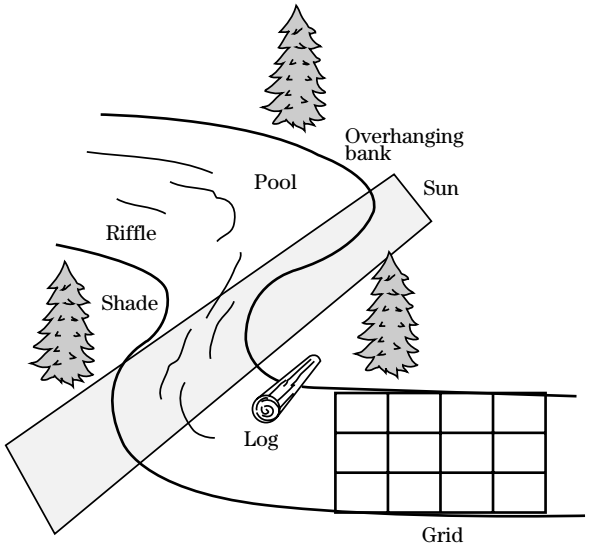
$$L_y = \frac{\left(2.17\right)\left(20ft\right)^2}{3ft}\frac{1.5ft/s}{0.61ft/s}$$

$$L_y = 711ft = 0.13\,mi$$

The monitoring station should be located at least 0.13 mile downstream from the tributary. This analysis assumes that the flow of the tributary is small in relation to the flow in Mill River.

Biological sampling within streams must consider the different stream habitats that occur as well as the mixing phenomena described. Stream systems contain pools, riffles, overhanging banks, logs, and debris that will all influence the biotic community (fig. 8–2). Within each of these habitats, stream velocity will further stratify biological communities. Shaded and sunny habitats will also differ. A good sampling program considers all of these habitats. For qualitative sampling, the biologist would make sure that each habitat was investigated. For quantitative sampling, a representative sample per unit area must be obtained from each habitat.

**Figure 8–2** Within stream sampling locations for biological monitoring

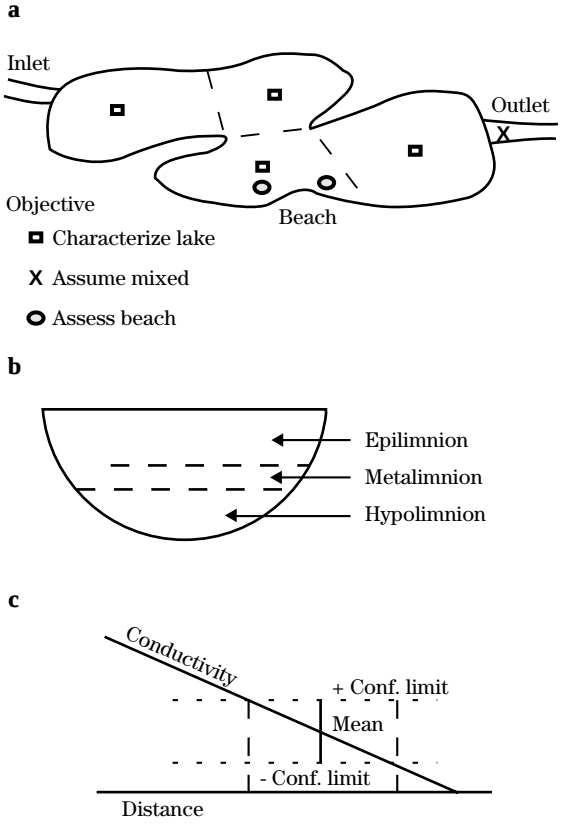


## (b) Lakes

The water quality of lake systems also is heterogeneous because of vertical stratification, longitudinal gradients, and currents caused by winds and density differences. Furthermore, many lake basins are actually a combination of sub-basins or bays that have varying water quality. Near-shore water quality might be expected to be different from open water concentrations. Also, biotic populations in lakes are impacted by sediment types and some species are colonial.

Spatial variation within a lake is often greater when the lake has many bays or coves. In such cases samples may need to be located within each bay or section of the lake (fig. 8–3a). The objective of the study becomes very important in selecting lake sampling locations. Is it necessary to sample within the lake or is the outlet sufficient to fulfill the objectives?

**Figure 8–3** Lake sampling locations




Because of temperature, and therefore density differences, lakes may stratify into three layers: epilimnion, metalimnion, and hypolimnion (fig. 8–3b). Samples are needed from each stratified layer in the system to describe lake water quality at a particular point. Ideally, stratified random sampling should be used to determine the number of samples to collect in each layer (see chapter 8).

If information regarding individual layers is not needed, individual samples could be composited. An alternative approach is to collect a depth integrated sample using a hose or other similar device.

Longitudinal gradients may exist in some lakes, particularly riverine lakes or lakes that are long and narrow. If the objective includes defining the water quality gradient, the station location can be determined based on the variability at a station (Potash and Henson 1978). The procedure is to develop a linear regression with the variable being a function of the distance longitudinally through the lake (fig. 8–3c). Using the mean value and the 95 percent confidence limits, the distance either side of the station location is calculated from:

$$\pm \text{ Distance} = \frac{\left[\left(\overline{X} \pm S_x t\right) - a\right]}{b} \qquad [8\text{–}2]$$

where:

a and b = the regression intercept and slope, respectively
$\overline{X}$ = the mean
$S_x$ = the standard deviation
$t$ = student's 't' at p = 0.05

Graphically, this represents the intercept of the upper and lower confidence limits with the regression line (fig. 8–3c). These intercepts could then be projected to the x-axis to determine the distances represented by the station. Stations with overlapping distances could be eliminated. Obviously, more stations will be needed in regions of greater concentration changes than in areas that have little gradient.

Biological monitoring in lakes must consider the spatial variability of biotic community of interest. Plankton will stratify within lakes. Blue-green algae may be more prevalent in surface water than in deeper water. Some zooplankton migrate diurnally from

shallow to deeper water. Fish seek layers of certain temperatures and dissolved oxygen concentrations. Horizontally, shallow, near-shore water contains different habitats than those of deeper water. Benthic organisms vary with lake sediment type. Certain species are colonial, growing in lake bottom villages.

Choice of biotic sampling locations must consider these variations. For plankton sampling, individual samples can be taken at different depths, or less accurately, a net can be towed vertically from a depth of no light to the surface. For quantitative benthic sampling, some estimate of spatial variability should be used to determine the number of samples needed. The same is true for macrophyte sampling.

**Example 8–2** Specific conductance of gradient

Conductivity data from Station #7 at Crown Point in Lake Champlain was used to determine the distance along Lake Champlain that the station represents (Potash & Henson 1978). The mean distance at the station was 112 miles. The value of $S_x t$ was 6.55.

The regression:

*Conductivity* = 110.3 – 0.13 (distance)

where distance is given in miles.

The confidence limits:

$$+\text{Distance} = \frac{(112 + 6.55) - 110.3}{-0.13}$$

$$+\text{Distance} = 63.5 \text{ mi}$$

$$-\text{Distance} = \frac{(112 - 6.55) - 110.3}{-0.13}$$

$$-\text{Distance} = 37.3 \text{ mi}$$

Station #7 would adequately describe the conductivity concentration gradient 63.5 miles in one direction and 37.3 miles in the other direction. Adjacent stations could be evaluated to determine if there is overlap with station #7. If there was, a station could be dropped while the gradient would still be adequately monitored.

## (c) Ground water

The location of sampling stations within ground water systems depends upon the objectives as well as the type of aquifer system being monitored. The objectives determine whether just the ground water concentrations or both concentration and flow for mass calculations are needed. For flow analysis, the well locations need to be expanded to determine the flow into and out of the area and the hydrogeologic properties of the aquifer. Several textbooks cover this subject (Davis & DeWiest 1970; Driscoll 1986; Domenico & Schwartz 1990; Freeze & Cherry 1979).

For concentration monitoring alone, the monitoring system is simplified as compared to flow monitoring. In siting ground water monitoring wells, the soils and geology, the direction of ground water flow, and the type of ground water system must be considered.

The two major types of aquifers are confined and unconfined (Davis & DeWiest 1970). Unconfined aquifers, also termed water table aquifers, are in direct contact with the atmosphere through the soil. Confined aquifers, also termed artesian aquifers, are separated from the atmosphere by an impermeable layer (fig. 8–4a).

Ground water monitoring also must consider vertical, horizontal, and longitudinal water quality differences. More commonly, ground water monitoring requires a two-staged approach. The first stage should be a hydrogeologic survey that determines the ground water surface elevations and flow directions. In some ground water investigations it may be important to locate the top of the ground watershed divide.

To investigate lateral ground water quality, sampling wells should be located upgradient and downgradient from the area of interest (fig. 8–4b). More than one well should be located above, within, and below the treatment area so that replications can be obtained. The actual number of wells needed to characterize the water quality of the aquifer can be determined from the formula in chapter 8. Before monitoring wells are sited, there must be knowledge of the general ground water flow direction. Preliminary estimates of flow direction can be obtained by triangulation using three driven well points.

The depth of the monitoring well also is important. If sampling nitrate in unconfined aquifers, it may be necessary to utilize multilevel wells because nitrate concentrations are often stratified with higher levels at the top of the aquifer (Eccles and Nicklen 1978). Such wells can be constructed in the same bore hole (fig. 8–4c) or in separate borings. Poor sealing between screens in the same borehold may make "nested" wells undesirable. For monitoring water table wells, the length of perforated screen should cover the full range of water levels anticipated.

It is important when locating the depth of all wells that the monitoring well be placed into the ground water of interest and not into a localized perched condition (fig. 8–4d).

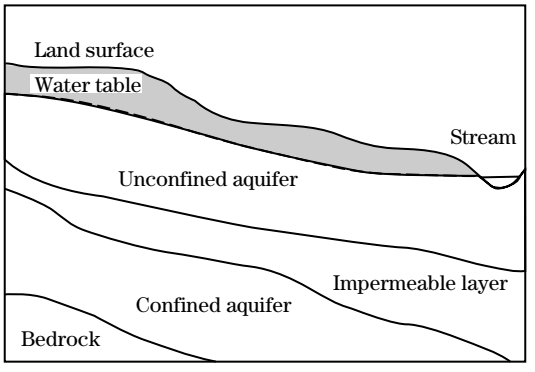
Using existing wells for monitoring presents several problems. Usually knowledge is lacking regarding well construction, screen length, and other such information. Also, the well could be contaminated. New monitoring wells, developed for the purpose of monitoring, are encouraged over existing wells.

Several geophysical techniques are available to characterize ground water conditions. Both surface and borehole techniques can be used. Surface techniques include (Driscoll 1986):

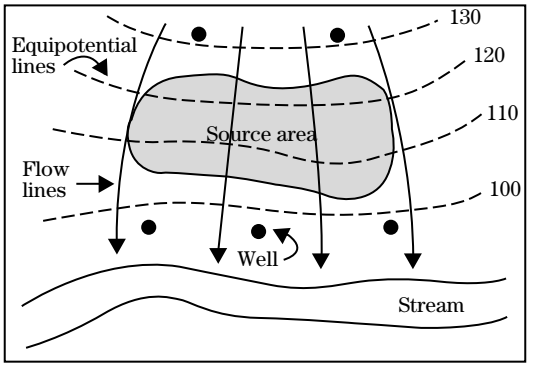
- seismic refraction/reflection
- gravimetric surveys
- electromagnetic surveys
- electrical resistivity

**Figure 8–4** Ground water sampling locations

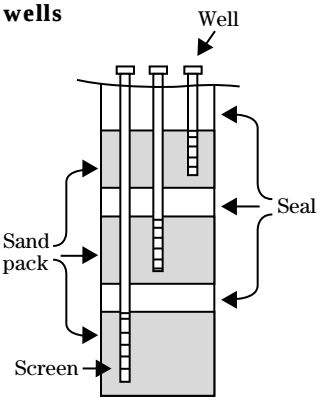
**A Ground water aquifers**



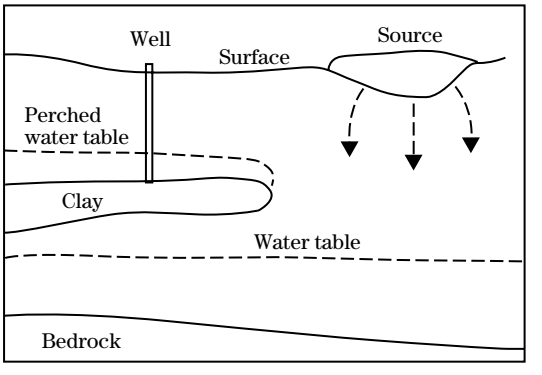

**B Monitoring source areas**




**C Multilevel wells**




**D Vertical locations**



All of these methods provide information on the geologic stratigraphy and presence of ground water. Seismic methods can be used to determine the depth to different geologic formations using a hammer and geophones. Gravity meters can be used to measure density differences in subsurface materials and are especially useful in locating bedrock.

Ground-penetrating radar is useful for shallow (<50 feet) investigations of subsurface materials. The device can be towed to obtain profiles of depths and distances. Resistivity is used to identify the depth to or thickness of subsurface strata. The depth to the water table can also be determined. Additional methods can be used in boreholes.

## 600.0804 Optimizing locations

Large monitoring programs generally include many sampling locations and many visits per location. The optimal number of stations and the number of visits per stations can be determined so that the variability about the mean is minimized. This has been described as a combination of a cost function and a statement of variability in the data (Hayne 1977; Mar, et al. 1986; Reckhow & Chapra 1983). A cost function could be:

$$C = C_o + SC_s + SpvC_v \qquad [8–3]$$

where:

$C$ = total cost of sampling
= total budget
$C_o$ = initial fixed cost
$C_s$ = cost of establishing site
$C_v$ = cost of visiting site
$S$ = number of sites
$pv$ = number of visits per site
= number of periods ($p$) times number of visits ($v$) per period

The number of visits ($v$) per site is a function of the variance caused by the number of sites, the number of visits, an interaction between site and visit, and an error term, such that:

$$v = \left( \frac{CK_v + C_s}{pC_v\left(pK_s + K_{S\cdot V}\right)} \right)^{\frac{1}{2}} \qquad [8–4]$$

where:

$$K_s = \frac{\sigma_s^2}{\sigma_e^2} \qquad [8–5]$$

$$K_v = \frac{\sigma_v^2}{\sigma_e^2} \qquad [8–6]$$

$$K_{S\cdot V} = \frac{\sigma_{S\cdot V}^2}{\sigma_e^2} \qquad [8–7]$$

where σ refers to the variance caused by the differences among sites (s), visits (v), a site by period interaction (s·v), and random error (e).

The number of sites can be determined based upon the optimum number of visits from:

$$S = \frac{C}{C_s + pvC_v} \qquad [8–8]$$

**Example 8–3** Optimizing sites and visits

A study was conducted by Hayne (1977) to determine the total number of small drainage basins that would describe the water quality in a river basin. Sampling sites were chosen randomly, and grab samples were collected and analyzed for total phosphorus.

A preliminary 1-year study using 13 4-week periods, 15 sites, and 2 randomly selected visits per period resulted in the following information:

Total cost = \$14,211.25
Per site cost = \$153.18
Per visit cost = \$79.47
Site variance = 0.01265
Visit variance = 0.06830
S· V variance = 0.04109
Error variance = 0.1153

Determine the optimum number of visits per site and the number of sites needed given the available budget. If the budget were doubled what would be the allocation between sites and visits?

$$\mathrm{K_s} = \frac{0.01265}{0.1153} = 0.1097$$

$$K_v = \frac{0.06830}{0.1153} = 0.5924$$

$$K_{S\cdot V} = \frac{0.04109}{0.1153} = 0.3564$$

$$v = \left[\frac{14,211.25\left(0.5924\right) + 153.18}{13\left(79.47\right)\left[13\left(0.1097\right) + 0.3564\right]}\right]^{\frac{1}{2}}$$

$$v = 2.16 = 3$$

$$S = \frac{14,211.25}{153.18 + 13\left(3\right)\left(79.47\right)} = 4.4 = 5$$

For the budget of \$14,211.25, the optimal number of sites would be 5 and the number of visits per period would be 3 rather than the 2 used in the preliminary study.

If the budget were doubled, the number of sites could be increased to 9 and the number of visits per period would remain 3.

## 600.0805 References

Canter, L.W. 1985. River water quality monitoring. Lewis Publ., Inc., Chelsea, MI.

Davis, S.N., and R.J.M. DeWiest. 1970. Hydrogeology. John Wiley and Sons, Inc., NY.

Domenico, P.A., and F.W. Schwartz. 1990. Physical and chemical hydrogeology. John Wiley and Sons, Inc., NY.

Driscoll, F.G. 1986. Ground water and wells. 2nd Ed. Johnson Div., St. Paul, MN.

Eccles, L.A., and R.R. Nicklen, 1978. Factors influencing the design of a ground water quality monitoring network. Proc. Establishing water quality monitoring programs. Amer. Water Resour. Assoc.

Freeze, R.A., and J.A. Cherry. 1979. Ground water. Prentice-Hall, Inc., Englewood Cliffs, NJ.

Hayne, D.W. 1977. Probability sampling of small streams: problems and results. *In* Watershed research in Eastern North America, A workshop to compare results, Vol. II, Rep. NSF/RA 770255. Smithsonian Inst., pp. 809-830.

Klemm, D.J., P.A. Lewis, F. Fulk, and J.M. Lazorchak. 1990. Macroinvertabrate field and laboratory methods for evaluating the biological integrity of surface waters. Office of Research and Development, Washington, DC, EPA/600/4-90/030.

Mar, B.W., R.R. Horner, J.S. Richey, R.N. Palmer, and D.P. Lettenmaier. 1986. Data acquisition. Environ. Sci. Technol. 20(6):545-551.

Ponce, S.L. 1980. Water quality monitoring programs. WSDG Tech. Pap. No. WSDG-TP-00002. Watershed Sys. Dev. Group, USDA, Forest Serv., Ft. Collins, CO.

Potash M., and E.B. Henson. 1978. Significance of geographic positioning for water quality monitoring in Lake Champlain. Proc. Establishing water quality monitoring programs. Amer. Water Resour. Assoc., pp. 58-73.

Reckhow, K.N., and S.C. Chapra. 1983. Engineering approaches for lake management. Vol. 1: Data analysis and empirical modeling. Butterworth Publ., Woburn, MA.

Sanders, T.G., R.C. Ward, J.C. Loftis, T.D. Steele, D.D. Adrian, and V. Yevjevich. 1983. Design of networks for monitoring water quality. Water Resour. Pub., Littleton, CO.

United States Department of Agriculture, Soil Conservation Service. 1985. National Engineering Handbook, Section 4, Hydrology., chapter 14.

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# Chapter 9 Sampling Frequency and Duration

# Chapter 9 Sampling Frequency and Duration

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# Chapter 9 Sampling Frequency and Duration

## 600.0900 Introduction

The most frequently asked questions when developing a water quality monitoring study are "How many samples and for how long?" Unfortunately, the correct response is: "It depends." Several factors affect the frequency of sampling. They include the objectives of the study, the type of water body being studied, the data variability, and the available resources. Table 9-1 summarizes general frequencies for various objectives for conducting a water quality study. Frequencies are given in relative terms to each other because a fixed time interval is inappropriate.

Long-term trend monitoring and programs evaluating program effectiveness on a watershed basis can use longer intervals between samples than other monitoring objectives. Frequent sampling or even a continuous recorder may be desirable for a study aimed at understanding a mechanism controlling certain water quality changes. The frequency of compliance monitoring should be approximately equal to the probability of exceeding a standard.

Sampling frequency is also affected by the aquatic system being studied. In general, the variance is greater; therefore, more samples are needed for studying streams than for lakes. Intermittent streams are often more variable than permanent streams. Ground water also is considered less variable than streams, but soil water samples can be highly variable (fig. 9–1).

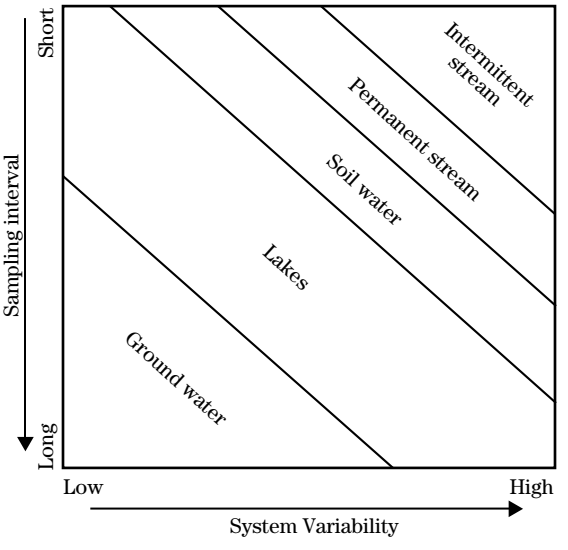
Financial resources typically limit the sampling frequency, although time, people, and laboratory capability can also limit sampling frequency. However, financial resources should not be allowed to dictate a sampling frequency. In cases where funds are limiting, a consideration should be given to eliminating extra parameters or stations. Compositing samples and passive sampling (chapter 10) can save substantial resources.

This chapter presents methods for calculating the sampling frequency. The primary sampling techniques described are simple random sampling and stratified random sampling.

**Table 9–1** Relative sampling frequency and objectives

| Objective | Relative interval between samples |
|---|---|
| 1. Baseline | Long |
| 2. Trends | Long |
| 3. Fate and transport | Short |
| 4. Problem definition | Short |
| 5. Critical areas | Short |
| 6. Compliance | Probability of exceeding standard |
| 7. BMP effectiveness | Short |
| 8. Program effectiveness | Long |
| 9. Wasteload allocations | Short |
| 10. Model evaluation | Short to long |
| 11. Research | Continuous to short |

**Figure 9–1** Sampling interval as a function of system type



## 600.0901 Simple random sampling

Sampling of water quality is needed to provide useful information about the entire population of water quality data that exists without measuring the entire population. Sampling saves time and money. Simple random sampling for water quality monitoring means that every water quality sample has an equal chance of being collected.

The calculation of sample size varies with the statistical objective of the monitoring study. Such objectives include an estimate of the mean, linear trend detection, and a step trend. The methods used to calculate sample sizes for each case are presented.

### (a) Estimate of the mean

One goal may be to be able to estimate the mean for a water quality variable with a certain amount of confidence in the estimate. The equation for calculating the sample size has been widely reported and is based on the variability and precision desired (Snedecor & Cochran 1980; Freese 1962; Moser & Huibregtse 1976; Ponce 1980; Rustagi 1983; Reckhow & Chapra 1983; Sanders, et al. 1983). The sample size can be calculated from the relationship:

$$n = \frac{t^2 S^2}{d^2} \qquad [9–1]$$

where:

*n* = the calculated sample size
*t* = Student's 't' (appendix B) at n-1 degrees of freedom and confidence level (p)
*S* = the estimate of the population standard deviation
*d* = the allowable difference from the mean

The standard deviation (S) is calculated as the square root of the variance ($S^2$) which is determined from (Snedecor & Cochran 1980):

$$S^2 = \frac{\Sigma X_i^2 - \frac{\left(\Sigma X_i\right)^2}{n}}{n-1} \qquad [9–2]$$

where:

n = the sample size
$X_i$ = the value of the $i^{th}$ observation

If the coefficient of variation rather than the standard deviation is known, the following relationship may be used (Koch, et al. 1982; Moser & Huibregtse 1976):

$$n = \frac{t^2 CV^2}{\%\overline{X}^2} \qquad [9–3]$$

where:

$CV$ = the coefficient of variation = $\frac{S}{\overline{X}}$

$\%\overline{X}$ = the percent deviation allowed from the true mean

Ranges in coefficients of variation for select system type are given in table 9–2 for certain water quality variables. This formula should be used with a double iterative procedure as shown in the following examples.

If the variance ($S^2$) is not known, an approximation can be made based on the range in the data using equation 9–4 (Ponce 1980; Sanders, et al. 1983):

$$S^2 = \frac{\left(\text{Range}\right)^2}{4^2} \qquad [9–4]$$

where:

Range = the range from the smallest to the largest values expected to be encountered during the sampling period

**Example 9–1** Sample size using simple random sampling based on estimate of the mean

Based on historical monitoring in a stream, how many samples are needed to be within 10 and 20 percent of the true annual mean total phosphorus concentration? The following information was obtained from the existing monitoring program for 1 year:

| | |
|---|---|
| mean | = 0.886 mg/L |
| standard deviation | = 0.773 mg/L |
| variance | = 0.597 mg/L |
| maximum | = 4.1 mg/L |
| minimum | = 0.074 mg/L |
| n | = 165 |

The difference (d) for 10 percent and 20 percent would be:

d = 0.1 x 0.886 mg/L = 0.09 mg/L
d = 0.2 x 0.886 mg/L = 0.18 mg/L

The t-value would be 1.96 for >120 degrees of freedom and p=0.05 (appendix B). A two-tailed t-value can be obtained from most statistics books, such as table A–4 in Snedecor and Cochran (1980).

1st Iteration—10%

$$n = \frac{(1.96)^2(0.773)^2}{(0.09)^2} = 283$$

Because the t-value would not change for n=283 degrees of freedom, no additional iterations are necessary.

1st Iteration—20%

$$n = \frac{(1.96)^2(0.773)^2}{(0.18)^2} = 71$$

This result is a fourth of the 10% result. However, the t-value must be adjusted for the degrees of freedom.

2nd Iteration—20%

$$n = \frac{(1.993)^2(0.773)^2}{(0.18)^2} = 73$$

Therefore 73 samples should be taken to estimate the mean annual total phosphorus concentration within 20% of the true mean.

The variance could have been estimated based on the range as follows:

$$S^2 = \frac{\text{Range}^2}{16} = \frac{(4.1 - 0.074)^2}{16} = 1.013 \text{ mg/l}$$

This estimate of the variance is greater than the measured variance listed above, and would result in a larger sample size being taken.

## (b) Linear trend detection

Another goal may be to determine the number of samples needed to detect a linear trend in the water quality data (Ward, et al. 1990). The sample size may be calculated from:

$$n = \frac{12t^2S^2}{d^2} \qquad [9–5]$$

where:

$S$ = the standard deviation of the water quality data collected over time with any trend removed from the data

$d$ = the minimum magnitude of the trend

**Example 9–2** Sample size for trend detection

Using example 9–1, determine the number of samples needed to detect a trend of at least 0.5 mg/L per year.

1st Iteration

$$n = \frac{12(1.96)^2(0.773)^2}{(0.5)^2} = 110$$

2nd Iteration

$$n = \frac{12(1.981)^2(0.773)^2}{(0.5)^2} = 113$$

Therefore, 113 samples per year would be needed to detect a linear trend of 0.5 mg/L per year. The greater the trend, the fewer samples that would be needed.

**Table 9–2** Coefficients of variation[1] (dashes indicate data not available)

| Parameter | Agricultural streams | Lakes | Ground water | Treatment plant | Edge-of-field |
|---|---|---|---|---|---|
| Temperature | 0.7-1.2 | 0.4-0.7 | | 0.4-0.7 | |
| Dissolved oxygen | 0.2-0.6 | 0.2-0.4 | | 0.2-0.7 | |
| pH | 0.03-0.1 | 0.05-0.1 | | 0.03-0.1 | |
| Conductivity | 0.2-0.7 | 0.1-0.5 | | 0.2-1.3 | |
| Secchi disk | --- | 0.1-0.7 | | --- | |
| Fecal coliform | 0.9-27.1 | 1.6-9.5 | | 0.6-39.2 | |
| Fecal streptococci | 1.2-94.0 | 1.5-32.0 | | 0.9-11.2 | |
| Turbidity | 0.7-5.5 | 0.6-2.5 | | 0.4-3.8 | |
| Total suspended solids | 1.0-9.0 | 0.1-3.7 | | 0.3-3.4 | |
| Volatile suspended solids | 0.7-4.4 | 0.5-2.8 | | 0.3-2.2 | |
| Total phosphorus | 0.6-2.2 | 0.3-2.4 | | 0.3-0.9 | |
| Ortho phosphorus | 0.5-2.1 | 0.4-3.3 | | 0.5-1.4 | |
| Total Kjeldahl nitrogen | 0.4-1.8 | 0.1-1.4 | | 0.3-1.1 | |
| Ammonia nitrogen | 0.8-4.0 | 0.3-3.9 | | 0.4-2.2 | |
| Nitrate nitrogen | 0.1-4.8 | 0.7-2.0 | | 0.4-4.4 | |
| Chlorophyll 'a' | --- | 0.2-4.0 | | --- | |

[1] St. Albans Bay RCWP

### (c) Step trend

The goal may be to determine if there has been a change in the mean water quality between two time periods. This would be equivalent to a step trend (Sanders, et al. 1983). The number of samples needed to detect a stated change is determined from:

$$n = \frac{2t^2S^2}{d^2} \qquad [9–6]$$

where:
- $n$ = the size of each sampling period, which is assumed to be equal
- $S$ = the pooled standard deviation for both periods
- $d$ = the allowable difference (precision) from the mean

The total number of samples needed to detect the difference would be 2n.

**Example 9–3** Sample size for step trend

For example 9–2, determine the number of samples needed to detect a change in the mean total phosphorus concentrations between a pre-implementation period and a post-implementation period with 20 percent precision. No changes in the original sampling data were assumed.

$$\text{d} = 0.2 \times 0.886 \text{ mg / L} = 0.18 \text{ mg / L}$$

$$\text{n} = \frac{2\left(1.96\right)^2\left(0.773\right)^2}{\left(0.18\right)^2} = 141$$

$$2\text{n} = 282$$

Therefore, 282 samples would need to be taken over the two time periods to detect a difference in the means between the two periods. Note that the level of precision would only be 20 percent; therefore, the difference would need to be greater than 20 percent to be detectable.

## 600.0902 Stratified random sampling

Instead of each water quality sample having the equal chance of being collected, there may be advantages to dividing the population of water quality samples into subgroups that are each more homogeneous than the whole data set. Samples could then be taken from each subgroup or strata. This type of sampling is termed *stratified random sampling* (Snedecor & Cochran 1980). More samples are allocated to subgroups that have greater variability. Two examples of appropriate applications of this technique would be:
- grouping by a flow period (snowmelt, summer low flow) or
- grouping by strata in a lake (epilimnion, hypolimnion).

The sample size for stratified random sampling can be calculated from the relationship (Reckhow & Chapra 1983):

$$n = \frac{t^2\left(\sum w_i S_i\right)^2}{d^2} \qquad [9–7]$$

where:
- $n$ = the total number of samples
- $t$ = Student's 't' at n–1 degrees of freedom
- $w_i$ = the proportional size of stratum $i$
- $S_i$ = the standard deviation of the water quality data for stratum $i$
- $d$ = the difference from the mean

The number of samples for each individual stratum is determined from:

$$n_i = \frac{nw_iS_i}{\sum\left(w_iS_i\right)} \qquad [9–8]$$

where:
- $n_i$ = the number of samples of stratum i

**Example 9–4** Stratified random sampling

Mudd Lake stratifies in the summer; therefore, it is desirable to subsample each layer to determine lake-wide phosphorus concentrations. Preliminary sampling resulted in the following information:

| | Thickness (ft) | Thickness (%) | Standard deviation (mg/L) |
|---|---|---|---|
| epilimnion | 14 | (35) | 0.012 |
| metalimnion | 6 | (15) | 0.005 |
| hypolimnion | 20 | (50) | 0.010 |

Determine the total number of samples and the number of samples within each stratum to be within 10 percent of the true mean at the 95 percent confidence level. The overall mean was 0.04 mg/L total phosphorus.

1st Iteration

$$n = \frac{(1.96)^2\left[(0.35)(0.012)+(0.15)(0.005)+(0.50)(0.010)\right]^2}{\left[(0.10)(0.04)\right]^2}$$

$$n = 23.8 = 24$$

2nd Iteration

$$n = \frac{(2.069)^2(0.00995)^2}{(0.004)^2}$$

$$n = 26.5 = 27$$

Allocate the 27 samples among the 3 strata by:

$$n_{epi} = \frac{27(0.35)(0.012)}{0.00995} = 11.4$$

$$n_{meta} = \frac{27(0.15)(0.005)}{0.00995} = 2.0$$

$$n_{hypo} = \frac{27(0.50)(0.010)}{0.00995} = 13.6$$

Therefore 11, 2, and 14 samples should be taken from the epilimnion, metalimnion, and hypolimnion, respectively.

## 600.0903 References

Freese, F. 1962. Elementary forest sampling. USDA Forest Serv., Agric. Handb. No. 232, Washington, DC.

Koch, R.W., T.G. Sanders, and H.J. Morel-Seytoux. 1982. Regional detection of change in water quality variables. Water Resour. Bull. 18(5):815-821.

Moser, J.H., and K.R. Huibregtse. 1976. Handbook for sampling and sample preservation of water and wastewater. U.S. Environ. Prot. Agency 600/4-76-049.

Ponce, S.L. 1980. Water quality monitoring programs. WSDG-TP-00002, Watershed Sys. Dev. Group, USDA Forest Serv., Ft. Collins, CO.

Reckhow, K.H., and S.C. Chapra. 1983. Engineering approaches for lake management. Volume 1: Data analysis and empirical modeling. Butterworth Publ., Woburn, MA.

Rustagi, K.P. 1983. Determination of sample size in simple random sampling. Forest Science. 29(1):190-192.

Sanders, T.G., R.C. Ward, J.C. Loftis, T.D. Steele, D.D. Adrian, and V. Yevjevich. 1983. Design of networks for monitoring water quality. Water Resour. Pub., Littleton, CO.

Snedecor, G.W., and W.G. Cochran. 1980. Statistical methods. 7th ed. IA State Univ. Press, Ames, IA.

Ward, R.C., J.C. Loftis, and G.B. McBride. 1990. Design of Water Quality Monitoring Systems. Van Nostrand Reinhold, NY, pp. 1-13.

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# Chapter 10 Station Type

# Chapter 10 Station Type

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# Chapter 10 Station Type

## 600.1000 Introduction

The purpose of this section is to provide guidance on the design, operation, and maintenance of hydrologic and water quality monitoring stations. This chapter is divided into the types of monitoring to be conducted:

- discharge
- concentration
- precipitation
- soil water
- biota
- bottom sediment

Generally, several optional methods for conducting the monitoring are available for each type of monitoring station needed. Also, the costs of installation and operation of these stations differ.

When designing monitoring stations, three principles are recommended: redundancy, simplicity, and quality. Important hydrologic variables, such as stage, should be measured in more than one way. Power failures and the unexpected seem to influence any monitoring record. Whenever possible, the most simple alternative is often the best. Complicated monitoring station designs invite problems. Finally, whatever is done should be installed with high quality. A neat and sturdy monitoring setup will be a safe and reliable one.

Agricultural Handbook No. 224 (USDA 1979) is an important reference for designing monitoring stations. The U.S. Geological Survey has published a series of Techniques of Water Resource Investigations (TWI) reports that addresses many of the issues related to designing monitoring stations. A listing of TWI 1 through TWI 8 is given following the references. Other references are also listed at the end of this chapter.

The type of station desired will, of course, depend on the objectivies as well as other components of the study design. Not all study designs require a fixed station, especially biological monitoring. This chapter is intended to give guidance on possible approaches and the equipment currently available to achieve certain monitoring goals.

## 600.1001 Discharge stations

The type of discharge station to construct is a function of the scale of the project (plot, field, or watershed), the project duration, and the project budget.

### (a) Plot discharge

Two types of devices for measuring the amount of plot runoff are shown in figure 10–1. A simple, small plot design is shown in figure 10–la. Sheet metal (18 gauge) cutoff walls are driven into the soil. Overland flow from just within the plot flows into a rain gutter installed flush with the soil surface, and then into a collection jug. The lip on the rain gutter can be inserted into the soil to prevent underflow. The plot can be sized based on expected overland flow so that the volume of the jug will not be exceeded. For example, a 3 by 6 foot plot has been used in the northeast United States. This type of plot can be installed in about 20 minutes and removed during field cultivation. A tipping bucket device (Chow 1976; Johnson 1942) can be used at the bottom of the plot instead of a collection jug. In some cases a large barrel could be installed to capture all the flow. This sampler determines flow based on the volume of sample collected.

Runoff volumes from such small runoff plots are highly variable plot to plot; therefore, a large number of plots may be necessary to obtain a good estimate of runoff (see chapter 9).

An example of a runoff plot used for research purposes is shown in figure 10–lb. This type of plot used a multislot divisor. The total runoff volume is computed from the sample volume collected by the divisor (USDA 1979). Dressing, et al. (1987) describe an expensive sampler that determined flow based on the volume of sample collected.

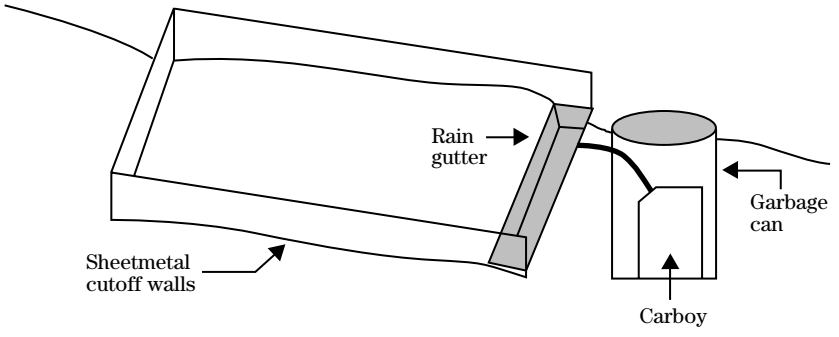
## (b) Edge-of-field discharge

Some of the devices described previously for plots can be enlarged for edge-of-field situations, especially that described by Dressing, et al. (1987). Because ponding of water on a field and high sediment and plant remains loads are undesirable, a flume, rather than a weir, is most often used for field discharge. The H-type flume is the most commonly used (fig. 10–2). This flume is so named because it was the eighth developed in a series starting with the A flume (Gwinn and Parsons 1976). The others include HS (small) and HL (large) flumes.

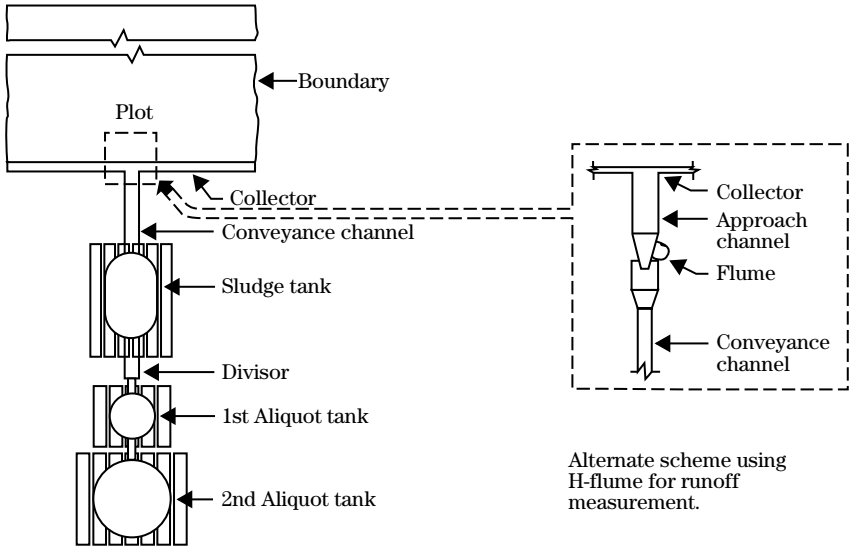
A complete description of the H-flume is given in Agricultural Handbook 224 (USDA 1979). The flume is often constructed of sheet metal; however, stainless steel flumes have been used for pesticide sampling (Smith, et al. 1985), and prefabricated fiberglass flumes are available as well. Rating tables and equa-

**Figure 10–1** Runoff plots

**a Small-scale runoff plot**




**b Larger-scale runoff plot**

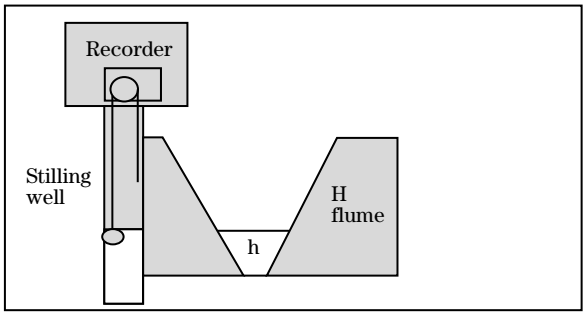


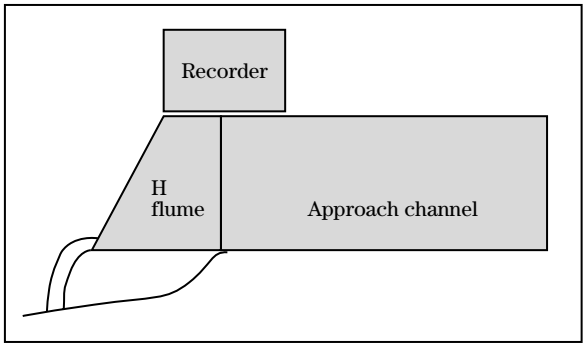

Alternate scheme using
H-flume for runoff
measurement.

tions are readily available (Gwinn and Parsons 1976; USDA 1979; Grant 1979). An approach channel to the flume is needed to reduce velocity and turbulence in the flow (fig. 10–2). A false side sloping floor (1:8) can be used when sedimentation in the flume is significant. The H-flume needs a method of recording stage, generally in a stilling well attached to the flume. Stage recording is described later in this chapter.

Other types of flumes have been used to measure edge-of-field runoff including Parshall and long-throated flumes (USDA 1979; Replogle & Clemmens 1981).

**Figure 10–2** Field runoff H-flumes




## (c) Stream discharge

Many options are available for determining discharge in streams. The selection of the type of station varies with individual site conditions, such as slope, sediment load, and stream size. The major options include flumes, wiers, and a natural channel. The use of existing structures, such as culverts, will also be discussed.

The practical limit to H-flumes is about a peak discharge of 100 cubic feet per second (5 ft. head); however, larger flumes can be built onsite. Specialized flumes have been developed for use in the Western States where streams may be flashy and ephemeral (USDA 1979). Sufficient slope in the streambed is needed to prevent backwater into the flume and allow the freefall of water at the outlet opening.

Wiers are another common device used in streams for discharge measurement. Figure 10–3b shows several configurations for weir types. They include v-notched, rectangular, and Cipolletti wiers. Wiers can be constructed of wood, sheet metal, or concrete.

The practical size for a prefabricated weir made of plywood with a metal or plastic sharp crest is 5 cubic feet per second (1.3 ft. head). Larger plywood weirs may fail. The weir must not leak. The weir plate should extend well into the streambed and be connected to a channel sill that extends upstream of the weir.

A natural channel is often necessary when flow is too large for an artificial structure. The basic features of recording discharge for a natural channel are shown in figure 10–4a. The cross-section is located at a control section; that is, a stable streambed and streambank location where the channel is straight. Also, stream gaging must be possible at or near the cross-section.

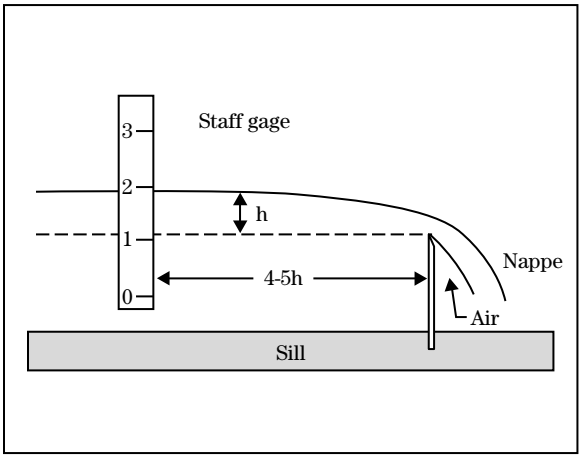
A basic setup for a natural channel includes a stilling well for stage measurement with intake pipes connected to the stream. The stilling well should not be placed in the stream because of velocity effects and icing problems, but rather should be installed in the streambank. The well diameter could range from a 12-inch PVC pipe to a 48-inch corrugated metal pipe (CMP). A gage house is either placed on top of the stilling well or, for large diameter culverts, is part of the well itself. The total cross-section area of the

intake pipes should be about 1 percent of the area of the stilling well. Venting the gage house helps to prevent moisture buildup.

For some study designs, using an open channel with point measurement of discharge may be sufficient to achieve the study objectives. However, such discharge monitoring does not give any information about the discharge between sampling dates. Existing structures, including culverts, dams, and spillways, are used for discharge measurements (USDA 1979). The author believes that culverts generally should be avoided for discharge measurements. At high flows, culverts can be submerged, a hydraulic jump may form at the culvert entrance, or the water level may drop because an entrance is constricted (fig. 10–4b). These conditions yield false stage values. Culverts also present problems by collecting debris and icing in winter.

**Figure 10–3** Weirs

**a Components of typical weir**




**b Weir types**

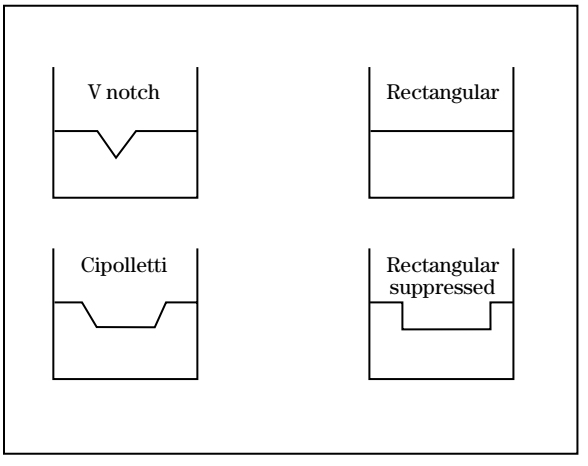
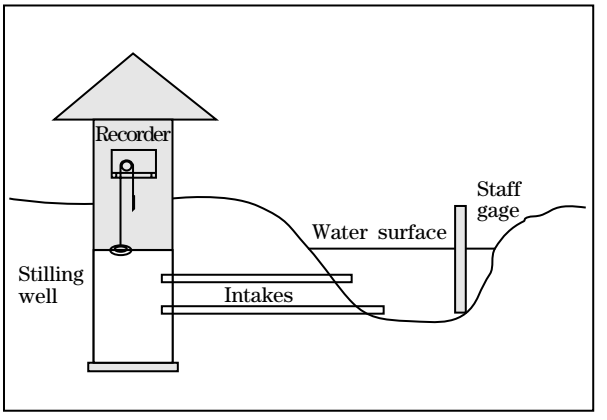
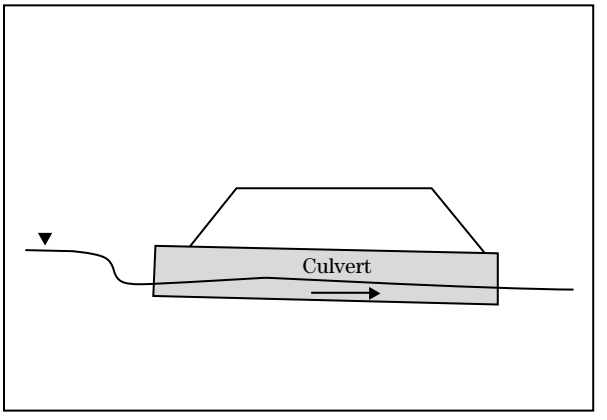



**Figure 10–4** Natural channel gaging station

**a Station cross-section**




**b Flow at culvert**



## (d) Staff gages

All discharge stations should include a staff gage. A staff gage is typically a vertical calibrated gage made of porcelain enameled steel (fig. 10–5). It should be so constructed or so placed as to not catch debris and to shift easily upward or downward. A point gage should be used in an instrument shelter, either with a separate float or using a graduated float tape. The outside staff gage reading is the true stage to which all recording gages should be set. The elevation of the staff gage should be checked periodically for shifts.

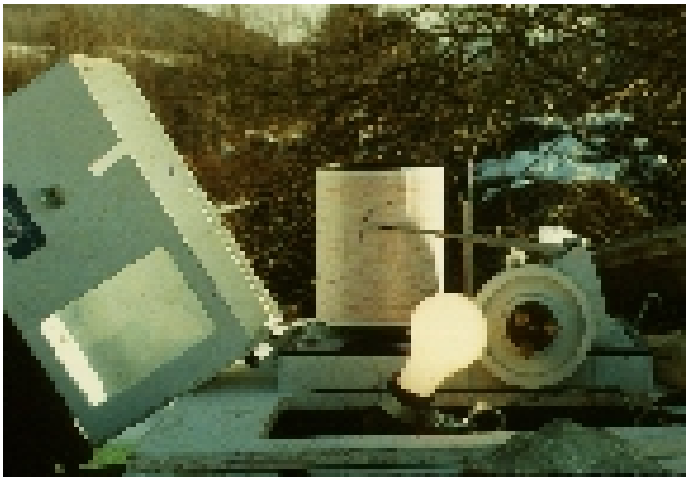
## (e) Stage recording

Stage is most often recorded in a stilling well, although bubbler gages have made this requirement unnecessary. The primary methods for recording stage are through the use of floats, bubblers, pressure transducers, and ultrasonic sensors (fig. 10–6). Several float-level recorders are highly reliable and remain the preferred method of stage recording for many hydrologists. Advantages of bubbler gages are that no stilling well is required and they can be easily combined with automatic water samplers. Almost all stage recorders available today allow for data logging. Those with programmable data loggers can control automatic water sampling. Pressure transducers and ultrasonic sensors are not widely used at this time; however, they are very useful for data logging.

**Figure 10–5** Porcelain staff gage

**Figure 10–6** Stage recorders (photos c, d, e, f courtesy Instrumentation Specialties Company)

**a Float-level**



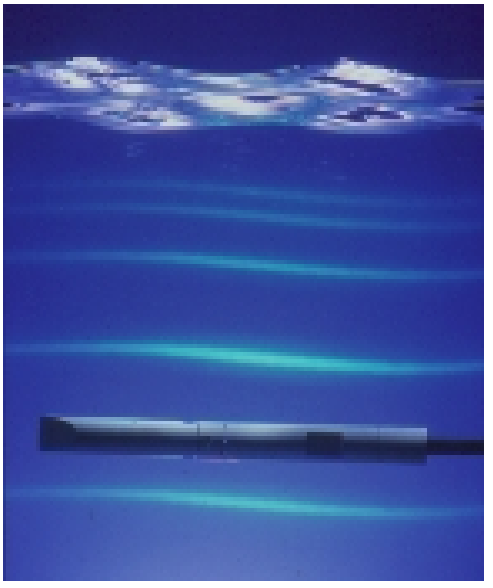
**b Punch tape**

**c Bubbler**

**Figure 10–6** Stage recorders—Continued

**d Ultrasonic**

**e Pressure transducer**



**f Bubbler**

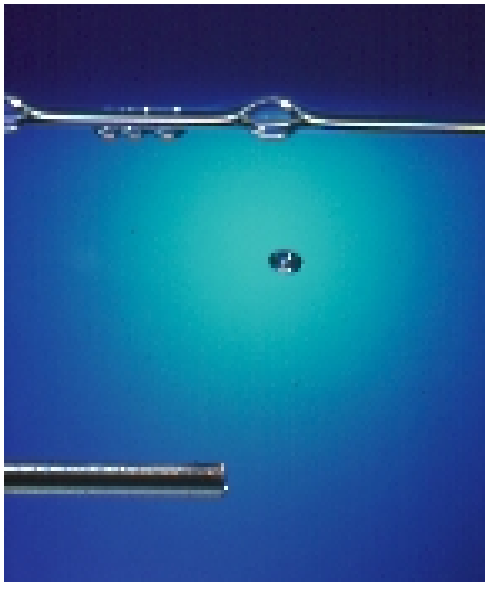
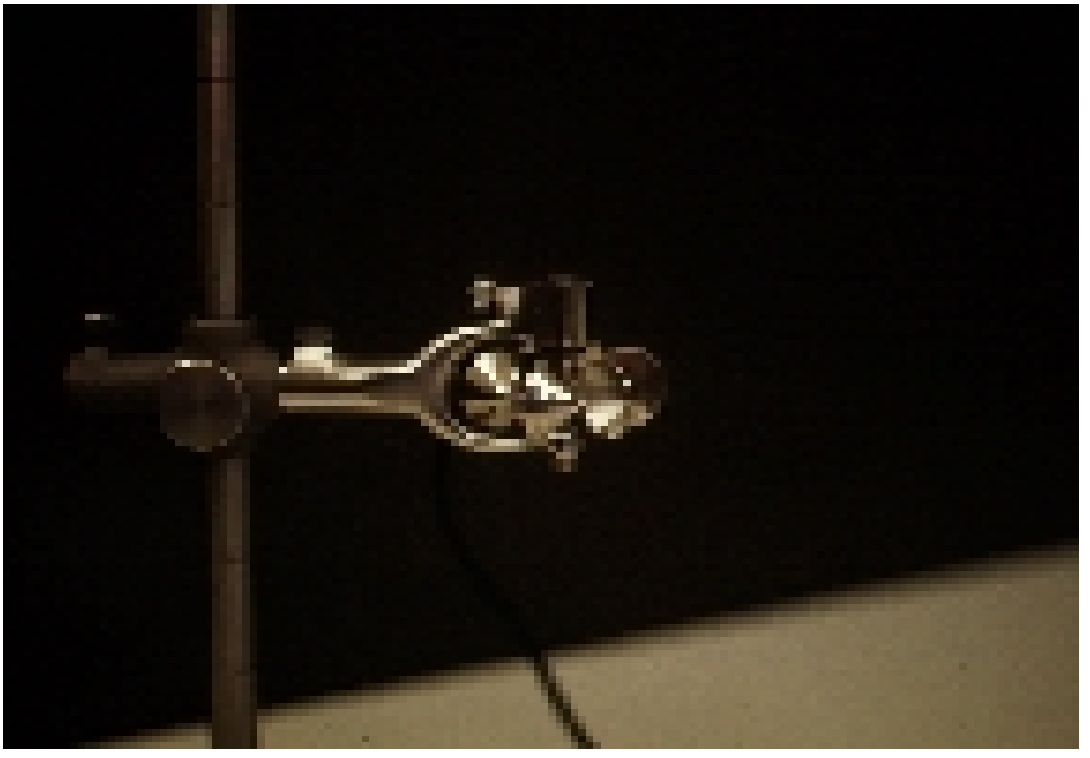
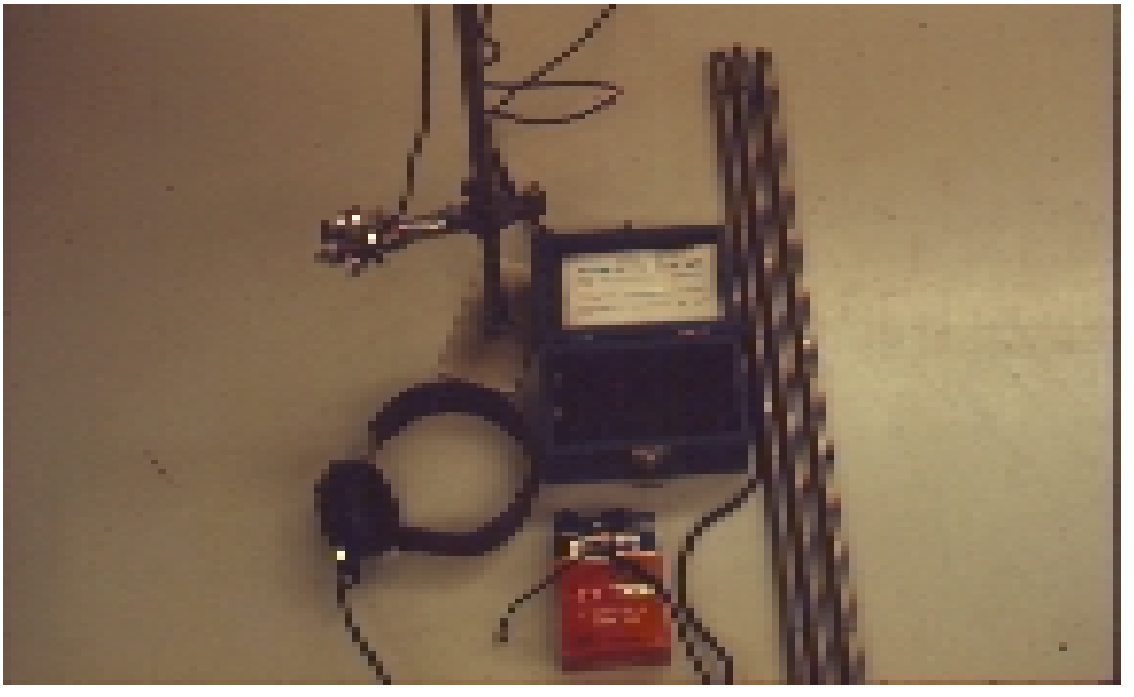


**Figure 10–7** Pygmy current meter





## (f) Stage-discharge relationship

$$Q = AV \qquad [10–1]$$

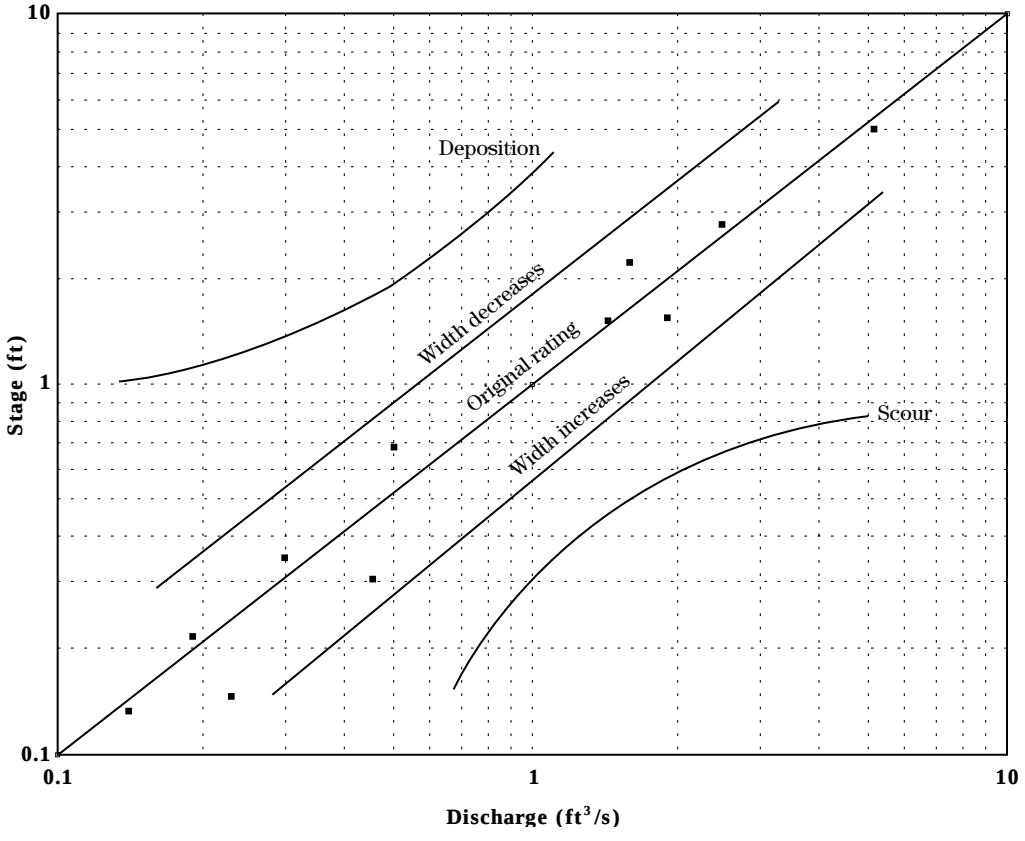
Because stage is only a measure of the height of the water, not the discharge in the stream, a stage-discharge relationship for the open channel station must be developed. Simultaneous measurement of stage and discharge is needed to develop the rating equation for an open channel stage recorder. Once the relationship is developed, stage measurements can be used to compute discharge. Discharge in open channels typically is determined using current meter measurements (fig. 10–7).

The primary method for determining discharge is the velocity-area method, although other techniques, such as the salt dilution method, exist as well (USDI, BOR 1977). The velocity-area method uses the equation:

where:
$Q$ = discharge
$A$ = cross-sectional area of stream
$V$ = stream velocity

When conducting a discharge measurement using a velocity meter, the stream cross-section is divided into subsections and velocity measurements are taken at each subsection. For sections deeper than 2.5 feet, two velocity measurements are taken at 0.2 and 0.8 times the depth; otherwise a single velocity measurement is taken at 0.6 times the depth.

**Figure 10–8** Stage-discharge rating curve



A good description of guidelines for making discharge measurements is given in Buchanan and Somers (1969) and the National Handbook for Recommended Methods for Water-Data Acquisition (USGS 1977). Example 10–1 shows the recommended steps for developing a rating equation.

The general form of the rating equation is:

$$Q = CH^b \qquad [10–2]$$

where:

$Q$ = the discharge ($ft^3/s$)
$C$ = the regression intercept, which is the discharge where $H = 1.0$
$H$ = the stage (ft)
$b$ = the slope of the regression

This equation should plot as a straight line on log-log paper. An example rating curve is given in figure 10–8. Note that, by convention, the discharge (Q) is plotted as the abscissa even though it is the dependent variable.

A minimum of 15 pairs of stage and discharge measurements should be used to develop the rating equation shown as points on figure 10–8. At times, two rating equations are developed; one for low flow and one for high flow. The ratings should be checked periodically because shifts in the equation may occur. Changes in the rating curve may be caused by scouring or filling the streambed, the growth of aquatic vegetation, or by icing. Figure 10-8 displays two of these cases. If scour occurs, the rating would be expected to move to the right and concave downward. That is, for an equal stage, the discharge would be greater after scouring. With filling, the rating would move left and concave upward (USGS 1977).

**Example 10–1** Developing a rating equation

Use the following steps to develop the rating equation:

1. Log transform paired values of Q and H

2. Perform a linear regression of Q vs. H with Q as the dependent variable.

2. Obtain intercept (C) and slope (b)

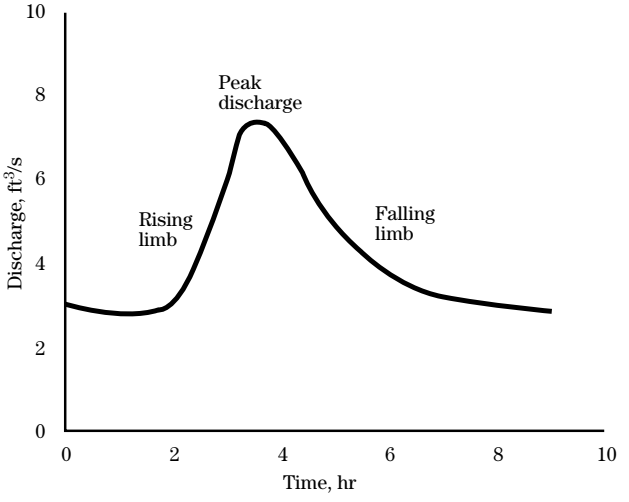
4. Add coefficients to the equation:
$$\log Q = \log C + b \log H$$

5. Transform equation to the form:
$$Q = CH^b$$
by taking the antilog of equation in step 4, so that:
$$Q = 10^c H^b$$
For example, if the intercept (C) was 0.05 and the slope (b) was 2.54, the equation would be:
$$Q = 10^{0.05} H^{2.54}$$
or
$$Q = 1.12 H^{2.54}$$

If the width of the downstream control section increased, the intercept would be expected to increase. That is, for an equal discharge, the stage would be lower if the width decreased. The opposite would happen if the width of the control decreased.

Several methods are available for extending the relationship for higher observed stages (Schulz 1976; USGS 1977). Also, additional adjustments can be made to the rating. For example, there is a histeresis effect of rising limb discharge exceeding falling limb discharge at the same stage (fig. 10–9). Assistance of agencies, such as the U.S. Geological Survey, may be necessary where large streams are involved.

**Figure 10–9** Stream hydrograph



## (g) Heating in cold climates

Year around monitoring is necessary in many cases. In cold climates, heating may be needed to guarantee sample collection. Heating design varies with the type of gaging station. Generally, heating requirements can be reduced by insulating. For many gaging stations, insulating means having the stilling well buried into the soil as far as possible. Weir plates can be kept open by covering with a wooden box during the winter. The box also can be heated for further protection.

Where electric power is present, heating is relatively easy. Heat lamps, light bulbs, space heaters, or stock tank heaters have all proven to prevent freeze-up. Sample lines to automatic samplers can be prevented from freezing by wrapping with electrical heat tape. When electric power is not present, propane can provide heat. A regulator with a "fail safe" must be used with the pilot light to prevent gas leakage and possible explosions in the stilling well. A pilot light propane heater is shown in figure 10–10a. This type of system could heat a stilling well and instrument shelter on little gas. Catalytic propane heaters can be used to provide a more directed heat source, such as needed at the mouth of an H-type flume (fig. 10–10b). However, these heaters require much more gas than the smaller pilot light heater.

**Figure 10–10** Heating devices

**a Pilot light propane heater**

**b Catalytic propane heater**

## 600.1002 Concentration sampling

A variety of devices have been developed for taking samples for water quality analysis. Sampling may be either attended or unattended, and unattended sampling may be either passive or automated. The type of sampling device varies with the scale of the project, the objectives, and the project budget.

### (a) Grab samples

A grab sample is a discrete sample that is taken at a specific place and time. A series of grab samples lumped together are considered composite samples. Grab samples may not be representative of the water quality of the body of water being sampled for several reasons. Water quality may vary with depth or distance from the streambank.

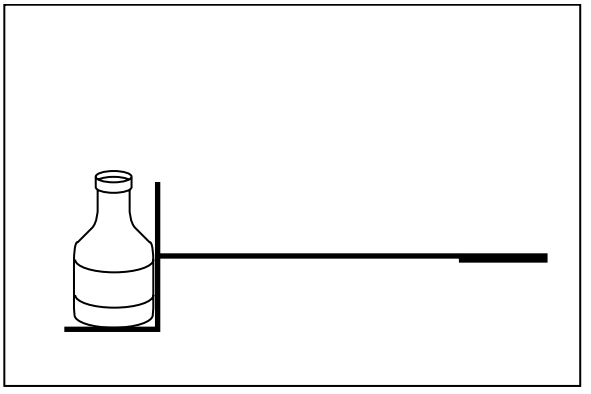
A grab sample typically is taken by hand with a sampling bottle. The bottle should be held just below the surface of the water to avoid contaminants in the surface film. The sample bottle can be connected to a holder on the end of a rod with plastic tubing to obtain a sample at some distance away (fig. 10–11a).

Sampling lake systems requires more specialized equipment. Frequently used samplers include Kemmerer, VanDoren, or Beta bottles. These samplers can obtain a sample from any depth in the water column. An inexpensive sampler consisting of a bottle with a pullable stopper (fig. 10–11b) has been described by Schwoerbel (1970) and WHO (1978). The same effect could be achieved by lowering a weighted, open bottle upside down, and inverting it with a second rope, allowing the air to escape and the bottle to fill with water.

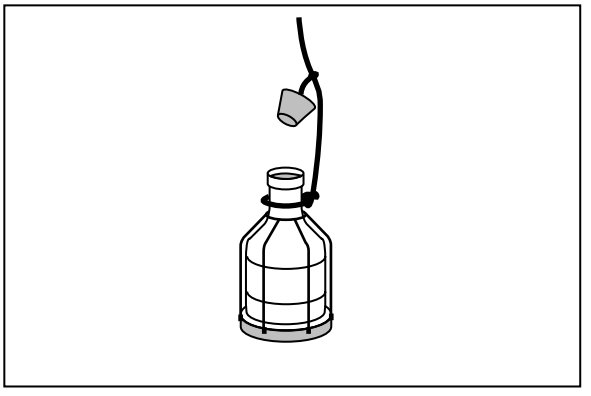
Depth integrating samplers have been used especially for sediment sampling. For example, the DH-48 sampler (fig. 10–12) is designed to continuously obtain a sample as it is lowered to the streambed and then raised to the surface. In lakes, hoses have been used to obtain a sample of the total column of water. The hose is lowered into the water and allowed to fill. A rope attached to the bottom end is used to raise the lower end of the hose to the surface thereby collecting the entire sample of water in the hose. Pumps also have been used to sample lake water.

**Figure 10–11** Grab samplers

**a Rod sampler**



**b Lake sampler**



## (b) Passive samplers

A passive sampler collects a water quality sample by action of the flow of water itself. A tipping bucket discharge station is well suited to passive sampling (fig. 10–13). Slots or funnels under the tipping bucket have been used to collect water samples (Chow 1976; Johnston 1942; Russell 1945). H-flumes also have been widely used for passive sample collection. The Coshocton wheel (fig. 10–14) has been used to sample 1 percent of discharge for sediment sampling (USDA 1979). A splitter below a Coshocton wheel has been used to reduce the size of the sample to 0.1 percent of discharge (Coote & Zwerman 1972). Holes drilled in the mouth of an H-flume also have been used to collect stage-integrated samples through tubing.

Passive devices have been used for plot runoff. Most involve some sort of divisor and collection tank (Coote & Zwerman 1972; Dressing, et al. 1987; Geib 1933; Kohnke & Hickok 1943; USDA 1978) unless the plot is sized to collect the entire sample in a collection jug, as shown in figure 10–1.

The primary advantages of a passive sampler are that it can be unattended, requires little maintenance, and no power.

Stage samplers are another type of unattended passive sampler. Originally devised for suspended sediment sampling, a stage sampler consists of a series of bottles attached to a board arranged vertically at different stages (fig. 10–15). Each bottle has two tubes at different heights, which creates a siphon when filling. The disadvantages of this type sampler include collection of debris, some bias in size of sediment collected, sample taken near the water surface during the rising stage, and a filled bottle may have some mixture with later water (USDA 1979).

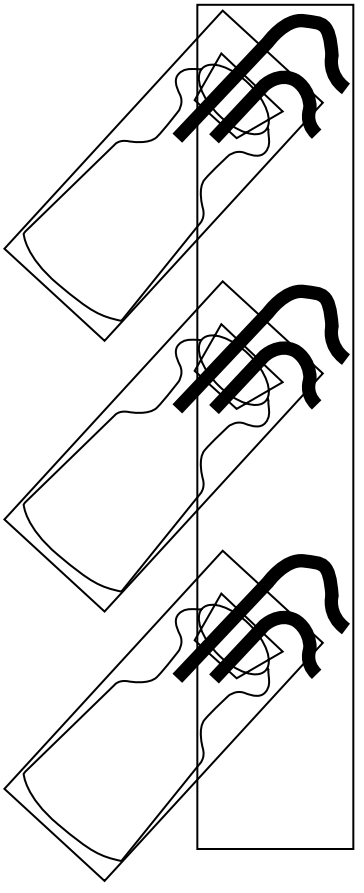
A single stage sampler was used by Schwer and Clausen (1989) to sample the outflow from dairy milkhouse waste pipes. Tubing was connected to the milkhouse drainage pipe with an extension collar. When the pipe flowed, part of the wastewater flowed through the tubing into a collection bottle. The bottle had a second tube as an air outlet.

**Figure 10–12** DH-48 sampler

**Figure 10–13** Tipping bucket with passive sampler

**Figure 10–14** Coshocton wheel

**Figure 10–15** Stage sampler



## (c) Automated samplers

Automated samplers are needed for larger streams and unattended sampling. These samplers typically allow programming of sample volume, time or flow interval between samples, and whether composite or discrete samples are taken. A summary of some of the older models available is in the National Park Service's publication "Automatic Water Samplers for Field Use" (NPS 1983). One of the common samplers in use is shown in figure 10–16. The ISCO sampler also can be connected to an ISCO flow meter to assist flow proportional sampling.

An inexpensive sampler developed in Canada is a submerged pipe section that has an opening operated by a solenoid. At timed intervals, a solenoid opens a port and allows a sample to enter the pipe. The volume of sample taken is proportional to the stage of the stream. The sample is removed by vacuum pump during a field visit.

The advantage of automated samplers is that they operate at all times, especially during runoff events, without attendance. However, these samplers are expensive and require maintenance.

One of the criticisms of pumping samplers is that a sample is taken from one point in the stream profile. Depth integrated intakes have been described by Eads and Thomas (1983) and McGuire, et al. (1980). These devices use a float to raise the intake with the stage and can collect a depth-integrated sample if the intake is perforated along its entire length (fig. 10–17).

**Figure 10–17** Depth-integrating intake

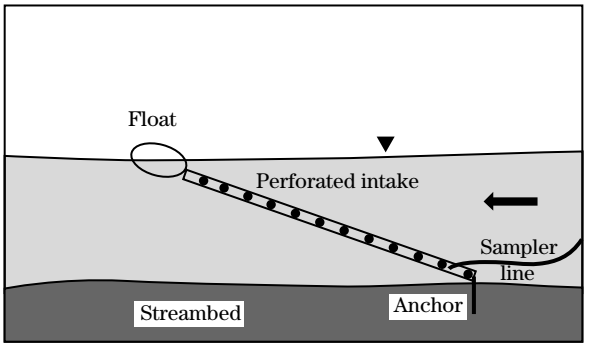



**Figure 10–16** ISCO automatic sampler (courtesy Instrumentation Specialties Company)

### (d) Actuated sampling

Actuated sampling is effective for sampling intermittent streams or for just sampling during storm events. Several options are available for initiating sampling during storms. Liquid level actuation has been used to initiate an ISCO sampling sequence (fig. 10–18). Precipitation sensors can also be used to initiate sampling. Programmable data loggers that also are monitoring stage could be used to initiate sampling. Various homemade float devices have been used to trip a switch and initiate samplers.

**Figure 10–18** ISCO liquid level actuator (courtesy Instrumentation Specialties Company)

## 600.1003 Precipitation monitoring

The extent of precipitation monitoring varies with the objectives of the study, but some precipitation monitoring is necessary in most monitoring projects. Precipitation data are useful for event sampling, for computing runoff coefficients for quality assurance programs, and for documenting rainfall conditions relative to a normal year. For most installations, both nonrecording and recording rain gages should be used. The nonrecording gage gives the total amount of precipitation; whereas the recording rain gage gives the time of precipitation. The total precipitation obtained by the recording rain gage should be adjusted to that measured in the nonrecording rain gage. A good background in precipitation monitoring is described in Agricultural Handbook 224 (USDA 1979), and guidance on maintenance is given in Weather Bureau Observing Handbook No. 2 (USWB 1970).

A variety of nonrecording and recording rain gages are commercially available. For the nonrecording gage, the National Weather Service standard 8-inch (20 cm) gage is most often used (fig. 10–19). For summer operation, a small amount of oil reduces evaporation. For winter operation, antifreeze can be added to the gage. The most common types of recording rain gages are either weighing bucket or tipping bucket (fig. 10–20). A weighing bucket gage can collect both rain and snow. For a tipping bucket gage to operate in the winter, it must be heated. However, the tipping bucket gage is easily adapted to data logging.

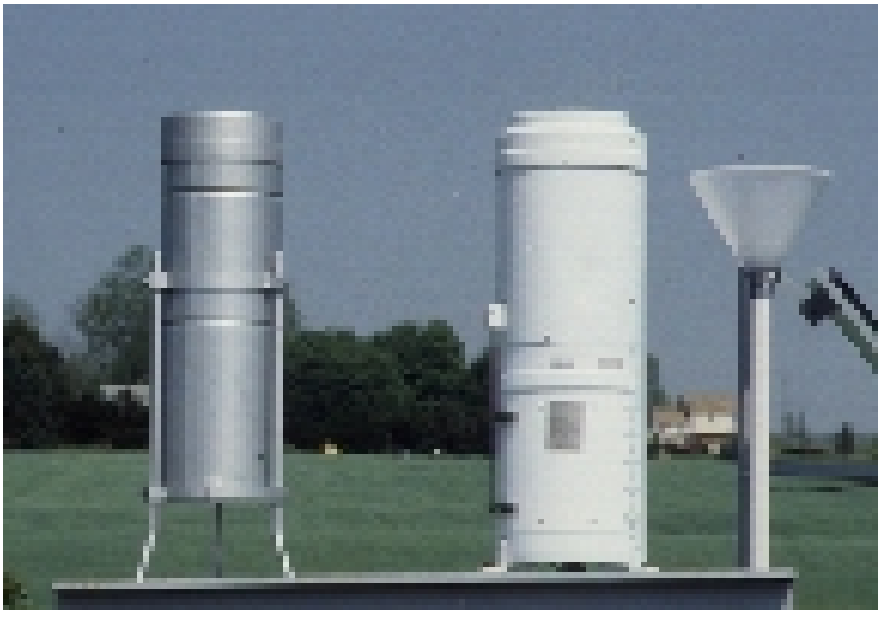
The location of the gage is important to precipitation monitoring. Recording and nonrecording gages should be placed at the same height and be leveled. The gages must be located in an opening where there is no obstruction within 45° of the lip of the gage. In areas of snowfall, the use of a windshield (fig. 10–21), such as an Alter shield, should be considered (USDA 1979). A windshield would be especially important in an open installation.

For some water quality studies, more than one gage may be necessary. The objective of precipitation monitoring must be considered when designing the

**Figure 10–19** Standard rain gage

**Figure 10–21** Standard rain gage altar shield

**Figure 10–20** Standard rain gage with tipping bucket and funnel gages



precipitation network. Other factors influencing the number and location of rain gages include topography, storm type, and the size of the area being studied. Monitoring in mountainous areas should definitely consider multiple gages.

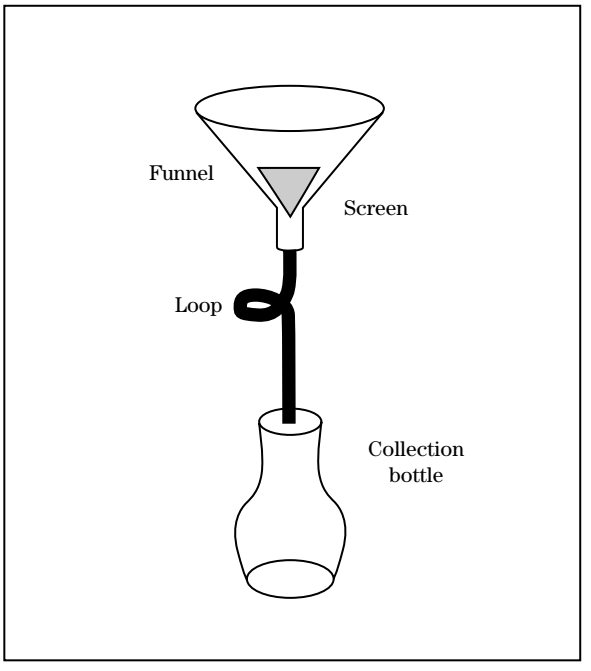
Knowledge of the quality of precipitation may be desired for some water quality studies. For example, studies examining the mass budget of nitrogen might consider N inputs in precipitation. Two common methods for sampling precipitation quality are wet-only collection and bulk precipitation.

Bulk precipitation can be easily sampled using a funnel gage (fig. 10–20) as described by Eaton et al (1973). A loop in the tubing leading from the funnel to the collection jug prevents evaporation (fig. 10–22a). A screen is recommended in the funnel opening to prevent large insects from entering the sample. Although this type of sampler is inexpensive and easy to construct, it collects any dry deposition that occurs on the funnel surface as well as rainfall. In addition, the funnel will not collect snow without bridging unless it is heated.

A wet-only sample can be obtained from a wet-dry deposition sampler as used by the NADP (Bigelow 1982). This sampler covers the precipitation bucket during dry periods thus preventing dry deposition from contaminating the sample (figure 10–22b). A precipitation sensor opens the wet bucket during rainfall. The time of opening and closing the lid can be recorded on a rain gage that has a second pen attachment.

**Figure 10–22** Gages for precipitation chemistry

**a Funnel collector**




**b Wet-dry deposition sampler**

## 600.1004 Soil water sampling

Sampling the soil water may be useful for determining nutrient concentrations and possibly mass fluxes in the vadose zone of soils. A number of sampling techniques have been used to sample soil water. These samplers generally can be classified as tension and zero-tension. Tension lysimeters extract a sample of soil water at some suction and include porous ceramic cups, plate lysimeters (fig. 10–23a), and capillary-wick samplers. The zero-tension lysimeters collect gravitational water and have included funnels, pans, and troughs (fig. 10–23b).

Volumes of water collected in lysimeters are highly variable; therefore, a large number of lysimeters may be needed to adequately represent soil solution fluxes in an area. Water quality concentrations collected by tension and zero-tension lysimeters are different (Haines, et al. 1982).

## 600.1005 Biotic sampling

Biologic sampling includes collection and analysis of plankton, periphyton, macrophyton, macroinvertebrates, and fish. In addition, several techniques are available for determining primary production. Although not discussed in this guide, biotic sampling also may include bioassay.

### (a) Plankton

Plankton are organisms that move with the currents. Two major types of plankton are phytoplankton (plants) and zooplankton (animals). Knowledge of the phytoplankton is particularly useful in water quality monitoring studies because they are good indicators of nutrient enrichment.

Plankton are influenced by currents, temperature, light, turbidity, and various chemical variables, such as salinity, nutrients, and toxics (USEPA 1973). Most of these factors vary with depth, except in well-mixed systems.

**Figure 10–23** Soil water samplers

**a Porous cup and plate lysimeters**

**b Outlet to funnel lysimeters**

Plankton samples can be obtained by net, water bottle, or with a pump (Schwoerbel 1970). Various plankton nets are available for sampling, the most common of which is the Wisconsin plankton net (fig. 10–24a). Plankton nets collect what is termed *net plankton* because some plankton may pass through the net. These nets are generally used for qualitative analysis.

Plankton also can be collected with a water bottle, such as a Kemmerer (fig. 10–24b), VanDorn, or Beta bottle. A quantitative sample of plankton can be obtained because the volume of water collected is known. Water bottles obtain a sample of plankton from a particular location and layer; therefore, the number of samples needed is subject to the variability in sampling (chapter 9).

Plankton samples collected with a pump can be obtained from any depth and of any volume. However, the pump tubing should be cleaned between samples, and the pump may break apart some plankton.

Once collected, plankton should be preserved and enumerated using standard techniques (USEPA 1973). In some cases chlorophyll analysis should be performed on the plankton as an indicator of the biomass.

### (b) Periphyton

The periphyton are organisms that mostly are attached to underwater substrates, such as rocks or macrophytes. These organisms may be predominant in shallow and running bodies of water. They also indicate water quality conditions.

Artificial substrates are used to quantitatively collect periphyton samples. They include glass microscope slides or the Hester-Dendy sampler (fig. 10–24c). Samplers are left in the field for about 2 weeks and then removed. Zooplankton and macroinvertebrates may graze on the periphyton, which will result in an underestimate of periphyton growth. The resulting samples should be preserved and enumerated. Biomass analysis is often used to express the amount of periphyton present.

### (c) Macrophyton

The large aquatic plants are termed macrophyton. In many cases these plants are what many perceive to be the water quality problem. Macrophytes are influenced by light (turbidity), nutrients, and sediment. Qualitatively, macrophytes may be identified to species and classified as to the relative cover. Quantitative sampling might involve small plots with an analysis of the number of stems or the biomass. Air photography often is used to delineate boundaries of plant communities.

### (d) Macroinvertebrates

Aquatic macroinvertebrates are animals that are large enough to be seen with the unaided eye and include insects, mollusks, worms, and crustaceans. Their presence is seasonally-dependant and influenced by type of substrate, light, oxygen content, water velocity, and various chemical constituents. They also are susceptible to various stressors. Because their locations vary, proper sampling is important. Quantitative sampling involves determining the numbers or biomass of macroinvertebrates per unit area. This type of information is often used to calculate an index, such as Beck's Biotic Index (Terrell & Perfetti 1989). Samples are collected using such devices as the Surber sampler (fig. 10–24d). These samplers are difficult to use in some habitats, such as rocky substrates.

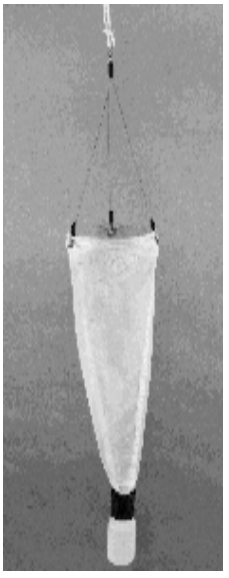
Qualitative samples of macroinvertebrates also are taken. Such sampling allows determining what is present and the diversity of the community. Samples are collected using a wide variety of devices, including sediment samplers in deep water, such as the Ekman or Peterson dredge (fig. 10-25 a & b). These types of samplers have several disadvantages (USEPA 1973).

Artificial substrates using baskets of rocks also have been used to collect macroinvertebrates. Drift nets are most commonly used to qualitatively assess the macroinvertebrate community. These nets come in various shapes (fig. 10–25c). Collected samples should be preserved before identification (Klemm et al., 1990).

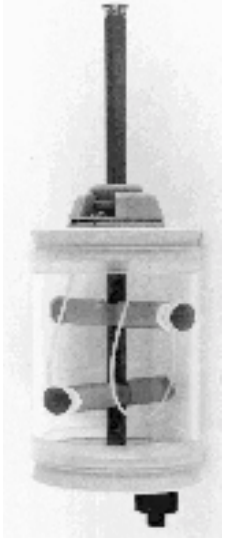
The EPA's Rapid Bioassessment Protocols (RBP) are methods for assessing the biotic condition of streams in comparison to reference stations (Plafkin, et al. 1989). Several indices are recommended using RBP level III.

**Figure 10–24** Biotic samplers (courtesy Wildlife Supply Company)

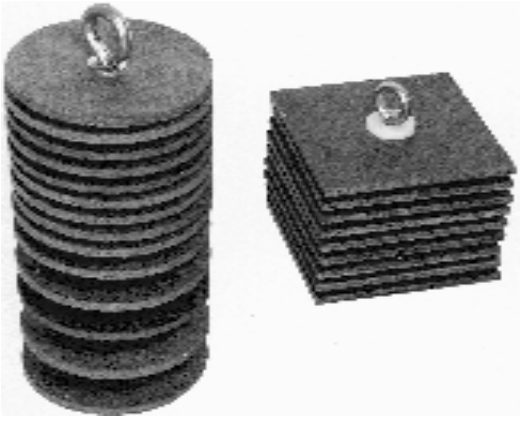
**a Wisconsin plankton net**



**b Kemmerer water bottle**



**c Hester-Dendy sampler**



**d Surber sampler**

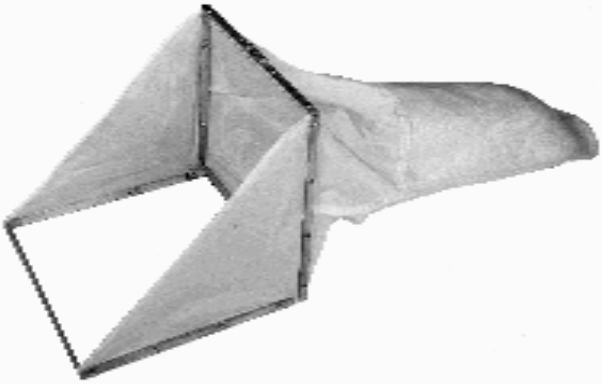
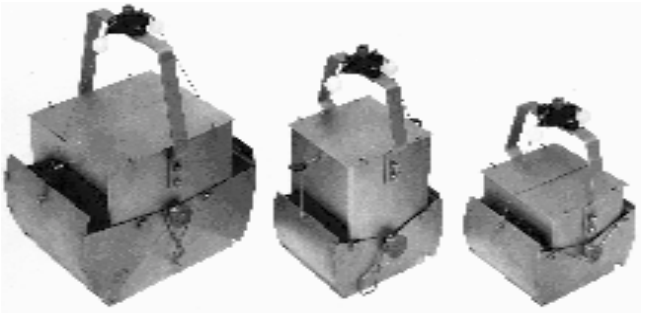


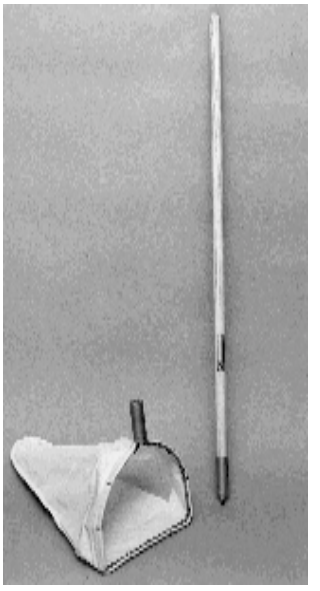
**Figure 10–25** Biotic and sediment samplers (courtesy Wildlife Supply Company)

**a Ekman dredge**



**b Peterson dredge**

**c D-type drift net**



### (e) Fish

Water quality influences fish species, abundance, and health. Certain species of fish are sensitive to pollutants and serve as indicators of water quality. The species, abundance by species, size, growth rate, condition, reproductive success, and disease are of interest where fish are used in biomonitoring (USEPA 1973). Sampling of fish has been classified as either active or passive. Active sampling includes electrofishing and seines. Passive collection includes gill nets and trap nets. The various methods used to collect fish samples usually result in somewhat different species being collected. Fish are not located randomly throughout the water body; therefore, sampling must be adjusted.

The Rapid Bioassessment Protocol level V for fish describes methods for electrofishing and calculation of the Index of Biotic Integrity (IBI) and other metrics (Plafkin, et al. 1989).

**Figure 10–26** Hand-held sediment corer (courtesy Wildlife Supply Company)

## 600.1006 Sediment sampling

The sampling of sediment varies between running water and standing water. In running water, sediment has been divided into suspended sediment and bedload. Suspended sediment is carried by the water above the bed of the stream (USGS 1977). Bedload sediment is heavier than suspended sediment and moves along the bed of the stream.

Sampling of suspended sediment was previously described in this chapter. Suspended sediment-bedload sediment rating curves can be developed to estimate bedload transport. Bedload sampling is conducted by using bedload traps in the streambed or net samplers of a certain height, or it can be conducted by measuring changing cross sections in the stream.

In edge-of-field runoff, sediment is best sampled in some type of proportional sampler, such as the Coshocton wheel. Other bedload samplers have been developed for use with flumes. They consist of a slot across the flume that traps the bedload.

Sampling of sediment in standing water, such as lakes and ponds, generally is conducted with a type of coring device. The type of corer used varies with the depth of the water and the thickness and type of substrate. An example of a hand-held corer is shown in figure 10–26. Other types of corers include piston or drive samplers for deeper water.

In some cases lake sediment samples are obtained by diving, so that the sample remains undisturbed. The force of a sampler hitting the sediment may disturb the upper organic deposits, thereby biasing the sample. Sediment samples collected from standing water bodies are often analyzed for particle sizes, organic matter content, chemical content, dry weight, and volume.

## 600.10007 References

Bigelow, D.S. 1982. NADP instruction manual. Site oper-ation. Natl. Atmos. Deposition Program, Nat. Resour. Ecol. Lab., CO State Univ., Ft. Collins.

Bodhaine, G.L. 1968. Measurement of peak discharge at culverts by indirect methods. United States Geological Survey, TWI 3-A3, 60 pp.

Buchanan, T.J., and W.P. Somers. 1969. Discharge measurement at gaging stations. Book 3, chap. A8 *in* Techniques of water-resources investigations of the United States Geological Survey.

Buchanan, T.J., et al. 1968, Stage measurements at gaging stations. United States Geological Survey, TWI 3-A7, 28 pp.

Carter, R.W., et al. 1968. General procedure for gaging streams. United States Geological Survey, TWI 3-A6, 13 pp.

Chow, T.L. 1976. A low-cost tipping bucket flowmeter for overland flow and subsurface stormflow studies. Can. J. Soil Sci. 56: 197-202.

Coote, D.R., and P.J. Zwerman. 1972. A conveniently constructed divisor for splitting low water flows. Soil Sci. Soc. Amer. Proc. 36:970-971.

Dressing, S.A., J. Spooner, J.M. Kreglow, E.O. Beasley, and P.W. Westerman. 1987. Water and sediment sampler for plot and field studies. J. Environ. Qual. 16(1):59.

Eads, R.E., and R.B. Thomas. 1983. Evaluation of a depth proportional intake device for automatic pumping samplers. Water Resour. Bull. 19(2):289-292.

Eaton, J.S., G.E. Likens, and F.H. Bormann. 1973. Throughfall and stemflow chemistry in a northern hardwood forest. J. Ecol. 61:495-498.

Geib, H.V. 1933. A new type of installation for measuring soil and water losses from control plots. J. Amer. Soc. Agron. 25(7):429-440

Grant, D.M. 1979. ISCO open channel flow measurement handbook. Instrumentation Spec. Co., Lincoln, NE.

Guy, H.P. 1969. Laboratory theory and methods for sediment analysis. United States Geological Survey, TWI 5-C1, 58 pp.

Guy, H.P., et al. 1970. Field methods of measurement of fluvial sediment. United States Geological Survey, TWI 3-C2, 59 pp.

Gwinn, W.R., and D.A. Parsons. 1976. Discharge equations for the HS, H, and HL flumes. J. Hydraul Div., Amer. Soc. Agric. Eng. 102:73-88.

Haines, B.L., J.B. Waide, and R.L. Todd. 1982. Soil solution nutrient concentrations sampled with tension and zero-tension lysimeters: Report of discrepancies. Soil Sci. Soc. Amer. J. 46:658-661.

Johnston, C .N. 1942. Tilt buckets for measuring runoff and erosion. Agric. Engr. 23:161-162.

Kennedy, E.J. 1985. Discharge ratings at gaging stations. United States Geological Survey, TWI 3-A10, 59 pp.

Kennedy, E.J. 1990. Levels at streamflow gaging stations. United States Geological Survey, TWI 3-A19, 27 pp.

Kilpatrick, F.A., et al. 1983. Use of flumes in measuring discharge. United States Geological Survey, TWI 3-A14, 46 pp.

Kilpatrick, F.A., et al. 1985. Measurement of discharge using tracers. United States Geological Survey, TWI 3-A16, 52 pp.

Klemm, D.J., P.A. Lewis, F. Fulk, and J.M. Lazorchak. 1990. Macroinvertabrate field and laboratory methods for evaluating the biological integrity of surface waters. Office of Research and Development, Washington, DC, EPA/600/4-90/030.

Kohnke, H., and R.B. Hickok. 1943. An automatic aliquot runoff sampler. Soil Sci. Soc. Amer. Proc. 8:444-447.

Laenen, A. 1985. Acoustic velocity meter systems. United States Geological Survey, TWI 3-A17, 38 pp.

McGuire, P.E., T.C. Daniel, D. Stoffel, and B. Andraski. 1980. Sample intake position and loading rates from nonpoint source pollution. Envir. Mgmt. 4(1):73-77.

National Park Service, Water Resources Field Support Laboratory. 1983. Automatic water samplers for field use. U.S. Dept. of the Int. Natl. Park Serv., Water Resourc. Field Sup. Lab. Rep. No. 83-1, Fort Collins, CO.

Plafkin, J.L., M.T. Barbour, K.D. Porter, .S.K. Gross, and R.M. Hughes. 1989. Rapid bioassessment protocols for use in streams and rivers: Benthic macro-invertebrates and fish. U.S. EPA EPAl444/ 4-89001, Off. of Water. Washington, DC.

Replogle, J.A., and A.J. Clemmens. 1981. Measuring flumes of simplified construction. Trans. Amer. Soc. Agric. Eng. pp. 362-366.

Russell, M.B. 1945. A portable runoff measuring device. J. Amer. Soc. Agron. 37(8):589-594.

Schulz, E.F. 1976. Problems in applied hydrology. Water Resourc. Publ., Fort Collins, CO.

Schwer, C.B., and J.C. Clausen, 1989. Vegetative filter treatment of dairy milkhouse wastewater. J. Environ. Qual. 18(4):446-451.

Schwoerbel, J. 1970. Methods of hydrobiology. Pergamon Press, New York, NY.

Skougstad, M.W., et al. 1979. Methods for determination of inorganic substances in water and fluvial sediments. United States Geological Survey, TWI 5-A1, 626 pp.

Smith, C.N., D.S. Brown, J.D. Dean, R.S. Parrish, R.F. Carsel, and A.S. Donigian, Jr. 1985. Field agricultural runoff monitoring (FARM) manual. EPA/ 600/385/043, Environ. Res. Lab., Athens, GA.

Terrell, C.R., and P.B. Perfetti. 1989. Water quality indicators guide: Surface waters. USDA Soil Conserv. Serv. SCS-TP-161, Washington, DC.

United States Department of Agriculture. 1979. Field manual for research in agricultural hydrology. Agric. Handb. 224, Washington, DC.

United States Department of Interior, Bureau of Reclamation. 1977. Water measurements manual. 2nd edition.

United States Environmental Protection Agency. 1973. Biological field and laboratory methods for measuring the quality of surface waters and effluents. USEPA 670/4-73-001. Off. Res. & Dev., Cincinnati, OH.

United States Geological Survey. 1977. Methods for collection and analysis of aquatic biological and microbiological samples. Edited by P.E. Greeson, et al., TWI 5-A4, 332 pp.

United States Geological Survey. 1977. National handbook of recommended methods for water-data acquisition. Chapter 1: Surface water, Off. Water Data Coord., Reston, VA.

United States Geological Survey. 1987. Methods for the determination of organic substances in water and fluvial sediments, edited by R.L. Wershaw, et al., TWI 5-A3, 80 pp.

United States Weather Bureau. 1970. Weather Bureau observing handbook No. 2. Substation observations. U.S. Dep. Com., Environ. Sci. Serv. Admin., Silver Spring, MD.

World Health Organization. 1978. Water quality surveys—A guide for the collection and interpretation of water quality data. IHD-WHO Working group on water quality. UNESCO/WHO, Geneva, Switzerland.

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# Chapter 11 Sample Collection and Analysis

# Chapter 11 Sample Collection and Analysis

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# Chapter 11 Sample Collection and Analysis

## 600.1100 Introduction

Obtaining high quality data requires following appropriate techniques for obtaining water quality samples and analyzing them for their constituents. Equally important is the need to describe in detail how the work is being conducted so that others can duplicate the information. This chapter describes suggested techniques for collecting a water sample, and recommended quality assurance and quality control procedures for both the lab and the field. Two references may be helpful for volunteer monitoring (US EPA 1990, Simpson, 1991)

## 600.1101 Sample Collection

Different sample collection procedures should be followed depending upon the type of sample (grab, automatic) and whether the system is a lake, stream, or ground water. Generally, a bottle used for a grab sample should be rinsed with the sample water two or three times before filling unless the bottle contains a preservative, in which case there should be no rinsing (APHA 1989). If samples are collected from pipes under pressure, make sure that the system has been flushed for a sufficient period to guarantee that new water is being sampled. Bacteria samples are collected in sterilized bottles.

Collection of samples from wells can be complicated. Water within the well may be stagnant and not representative of surrounding ground water. The well should be purged for a sufficient amount (3 to 10 well-bore volumes) to ensure that the sample is representative of the ground water. More than 5 minutes may be required to remove over 80 percent of the well-bore volume when pumped at 1.3 gpm. Some recommend that well purging should be conducted at the rate of well replenishment. This would not be the case for well-mixed aquifers. Sampling for volatile organics may require special precautions and possibly no purging.

Sampling of volatile substances requires special sampling equipment in wells. The release of gases during pumping can change the pH of the water and therefore the solubility of metals. Oxidation of the sample during pumping can influence organics, sulfur, iron, ammonium, and manganese (Driscoll 1986).

Generally, all samples should be collected so that the bottle is completely full. This reduces volatilization losses. An exception to this would be if the sample was to be frozen, in which case room for expansion upon freezing should be left in the container. Sampling of toxic substances require extra precautions, including gloves, coveralls, aprons, eye protection, and in the case of toxic vapors, a respirator may be necessary.

The quantity of sample to collect is dependent upon the type of analyses to be conducted. Suggested volumes are given in table 11–1. The total volume should include a summation of the recommended volumes plus amounts for the quality assurance program. In addition, the analysis of a sample may need to be repeated. Therefore, it is generally recommended that the total recommended volume be doubled (Shelley 1977).

**Table 11–1** Recommended methods for sample collection and preservation (US EPA 1983)

| Measurement | Vol. req. (mL) | Container P=plastic; G=glass | Preservative | Maximum holding time |
|---|---|---|---|---|
| **Physical properties** | | | | |
| Color | 50 | P,G[1/] | Cool, 4 °C | 48 hrs |
| Conductance | 100 | P,G | Cool, 4 °C | 28 days |
| Hardness | 100 | P, G | $HNO_3$ to pH < 2 | 6 mos |
| Odor | 200 | G only | Cool, 4 °C | 24 hrs |
| pH | 25 | P,G | None req. | Analyze immediately |
| Residue | | | | |
| Filterable | 100 | P,G | Cool, 4 °C | 7 days |
| Nonfilterable | 100 | P,G | Cool, 4 °C | 7 days |
| Total | 100 | P,G | Cool, 4 °C | 7 days |
| Volatile | 100 | P,G | Cool, 4 °C | 7 days |
| Settleable matter | 1,000 | P,G | Cool, 4 °C | 18 hrs |
| Temperature | 1,000 | P,G | None req. | Analyze immediately |
| Turbidity | 100 | P,G | Cool, 4 °C | 48 hrs |
| **Metals** | | | | |
| Dissolved | 200 | P,G | Filter on site<br>$HNO_3$ to pH <2 | 6 mos |
| Suspended | 200 | | Filter on site | 6 mos |
| Total | 100 | P,G | $HNO_3$ to pH <2 | 6 mos |
| Chromium | 200 | P,C | Cool, 4 °C | 24 hrs |
| Mercury dissolved | 100 | P,G | Filter<br>$HNO_3$ to pH <2 | 28 days |
| Total | 100 | P G | $HNO_3$ to pH <2 | 28 days |
| **Inorganics, nonmetallics** | | | | |
| Acidity | 100 | P,G | Cool, 4 °C | 14 days |
| Alkalinity | 100 | P,G | Cool, 4 °C | 14 days |
| Bromide | 100 | P,G | None req | 28 days |
| Cbloride | 50 | P,G | None req | 28 days |
| Chlorine | 200 | P,G | None req | Analyze immediately |
| Cyanides | 500 | P,G | Cool, 4 °C<br>NaOH to pH >12<br>0.6g ascorbic acid[6] | 14 days |
| Fluoride | 300 | P,G | None req | 28 days |
| Iodide | 100 | P,G | Cool, 4 °C | 24 hrs |

**Table 11–1** Recommended methods for sample collection and preservation (US EPA 1983)—Continued

| Measurement | Vol. req. (mL) | Container P=plastic; G=glass | Preservative | Maximum holding time |
|---|---|---|---|---|
| **Inorganics, nonmetallics** (continued) | | | | |
| Nitrogen | | | | |
| Ammonia | 400 | P,G | Cool, 4 °C $H_2SO_4$ to pH <2 | 28 days |
| Kjeldahl, total | 500 | P,G | Cool, 4 °C $H_2SO_4$ to pH <2 | 28 days |
| Nitrate plus Nitrite | 100 | PG | Cool, 4 °C $H_2SO_4$ to pH <2 | 28 days |
| Nitrate | 100 | P,G | Cool, 4 °C | 48 hrs |
| Nitrite | 50 | P,G | Cool, 4 °C | 48 hrs |
| Dissolved oxygen | | | | |
| Probe | 300 | G bottle & top | None req. | Analyze immediately |
| Winkler | 300 | G bottle & top | Fix on site and store in dark | 8 hrs |
| Phosphorus | | | | |
| Ortho-phosphate Dissolved | 50 | P,G | Filter on site Cool, 4 °C | 48 hrs |
| Hydrolyzable | 50 | P,G | Cool, 4 °C $H_2SO_4$ to pH <2 | 28 days |
| Total | 50 | P,G | Cool, 4 °C $H_2SO_4$ to pH <2 | 28 days |
| Total dissolved | 50 | P,G | Filter on site Cool, 4 °C $H_2SO_4$ to pH <2 | 24 hrs |
| silica | 50 | P only | Cool, 4 °C | 28 days |
| sulfate | 50 | P,G | Cool, 4 °C | 28 days |
| sulfide | 500 | P,G | Cool, 4 °C add 2 mL zinc acetate plus NaOH to pH >9 | 7 days |
| sulfite | 50 | P,G | None req. | Analyze immediately |
| **Organics** | | | | |
| BOD | 1,000 | P,G | Cool, 4 °C | 18 hrs |
| COD | 50 | P,G | Cool, 4 °C $H_2SO_4$ to pH <2 | 28 days |
| Oil & grease | 1,000 | G only | Cool, 4 °C $H_2SO_4$ to pH <2 | 28 days |
| Organic carbon | 25 | P,G | Cool, 4 °C $H_2SO_4$ / HCl to pH < 2 | 28 days |
| Phenolics | 500 | G only | Cool, 4 °C $H_2SO_4$ to pH <2 | 28 days |
| MBAS | 250 | P,G | Cool, 4 °C | 48 hrs |
| NTA | 50 | P,G | Cool, 4 °C | 24 hrs |

## 600.1102 Sample preservation and transport

Once a sample is collected, it has the opportunity to change its composition through chemical, physical, and biological processes. Some changes may not be preventable, so rapid analysis is recommended in those situations (USEPA 1983).

Examples of physical changes include settling of solids, adsorption of certain cations on container walls, and loss of dissolved gases. Chemical changes could include precipitation, dissolution from sediments, complexation with other ions, and changes in valence state. Biological reactions could result in both the uptake and release of certain constituents. Microbial activity may change the species of nitrogen present (APHA 1989).

Preservation techniques are aimed at slowing biological activity, hydrolysis, volatility, and absorption. The primary preservation methods are acidification, refrigeration, filtration, and preventing light from reaching the sample (USEPA 1983; APHA 1989). Recommended preservation methods for most chemical properties of water are summarized in table 11-1. The appropriate sample volume, type of sampling container, and maximum holding time also are listed. A similar listing is given in the "Standard methods for the examination of water and wastewater" (APHA 1989).

Using a sample bottle that has the preservative already added may be useful for composite sampling. The sample becomes preserved immediately upon collection. Preservation of biological samples is also important (Klemm, et al. 1990). Without preservation predation within the sample may occur or the specimens may degrade. Generally, adding an equal volume of 95 percent ethanol to the sample results in an ethanol strength of 70 percent, which is adequate to preserve the sample (USEPA 1973). Plankton can be preserved with Lugol's solution (APHA 1989).

The sample container is also important. Glass containers may leach sodium and silica, and plastic containers may sorb organics (APHA 1989). Certain pesticides may adsorb to silicone rubber and tygon, but not high-density polyethylene or acrylic plastic (Topp and Smith 1992). Teflon and stainless steel are appropriate containers in certain cases.

Transportation to the laboratory should be direct. Transport should be done following some methods of preservation, such as cooling and keeping in the dark. Using dry ice for cooling is not recommended (APHA 1989).

## 600.1103 Methods of laboratory analysis

It is not within the scope of this handbook to describe methods of laboratory analysis for water quality variables. Two important references on this subject are Standard Methods for the Examination of Water and Wastewater (APHA 1989) and Methods for Chemical Analysis of Water and Wastes (USEPA 1983).

**Table 11–2** Water quality variables for which field test kits are available (Kunkle and Ricketts 1984)

| Water quality variables |
|---|
| Alkalinity, hardness |
| Ag, Al, Ba, Ca, Cd, Co, Cr, Cu, |
| Fe, Hg, K, Mg, Mn, Na, Ni, Pb, Zn |
| Ammonia, nitrate, nitrite |
| Total phosphorus, ortho-phosphate |
| Acidity, COD, color, pH, salinity |
| Dissolved oxygen, carbon dioxide |
| Turbidity, dissolved solids |
| Arsenic |
| Bromine |
| Chloride, chlorine |
| Cyanide chromate |
| DEEA |
| Detergents |
| EDTA/NTA |
| Fluoride |
| Formaldehyde |
| Gasoline |
| Hydrogen peroxide |
| Hydrogen sulfide |
| Iodine |
| Lignin |
| Molybdate |
| Ozone |
| pH |
| Phenol |
| Silica |
| Sulfate, sulfide |
| Tannin |
| Temperature |

## 600.1104 Field test kits

Many test kits are available for field analysis of a wide variety of water quality variables (tables 11–2 & 11–3). These kits range in level of sophistication and price. Field test kits are not considered as accurate as laboratory analyses, but may be useful in many situations (Kunkle & Ricketts 1984).

Kits function in one of three ways.

- *Color comparator* kits use the addition of a reagent to a sample, which results in a color development. The intensity of the color is compared to a color wheel or color tubes.
- *Colorimeter and spectrophotometer* kits use color development, which is read in battery powered colorimeters. Colorimeter kits are the most expensive kit.
- *Titration* kits use the addition of a reagent until a color change occurs.

Electric meters for field pH, conductivity, and dissolved oxygen are also available.

**Table 11–3** Partial list of manufacturers of field test kits

| Manufacturers | |
|---|---|
| Bausch and Lomb | (716) 338-8317 |
| CHEMetrics, Inc. | (703) 788-9026 |
| Ecologic Instrument | (516) 567-9000 |
| EM Science | (609) 423-6300 |
| Hach Company | (303) 669-3050 |
| Hellige, Inc. | (516) 222-0300 |
| In-Situ, Inc. | (307) 742-8213 |
| Kahl Scientific | (619) 444-2158 |
| LaMotte Chemical | (301) 778-3100 |
| Millipore Corp. | (617) 875-2050 |
| Soiltest, Inc. | (312) 869-5500 |
| Solomat | (203) 849-3111 |
| Spectrum Technologies, Inc. | (815) 436-4440 |
| Taylor Chemicals, Inc. | (301) 472-4776 |

## 600.1105 Quality assurance

Quality Assurance (QA) is the total integrated program for assuring the reliability of monitoring and measurement data (USEPA 1988). Quality assurance programs should allow determining statistical limits of confidence in the data (Taylor 1984). The program also should document the procedures that are followed (Dillaha, et al. 1988). Quality assurance is composed of quality control and quality assessment. Quality Control (QC) refers to activities conducted to provide high quality data (Lawrence and Chau 1987). Quality assessment refers to techniques used to evaluate the effectiveness of the program (Taylor 1984).

An overall outline for a quality assurance plan is given in figure 11–1.

**Figure 11–1** Outline of a quality assurance plan (USEPA 1988)

1. Cover page
2. Table of contents
3. Project description
   a. Objectives and scope
   b. Data usage
   c. Design and rationale
   d. Monitoring parameters and collection frequency
   e. Parameter table
4. Project organization and responsibility
5. Data quality requirements
   a. Precision
   b. Accuracy
   c. Representativeness
   d. Comparability
   e. Completeness
6. Sampling and laboratory procedures
7. Sample custody procedures
8. Calibration procedures and preventive maintenance
9. Documentation, data reduction and reporting
10. Data validation
11. Performance and system audits
12. Corrective action
13. Reports
14. Literature cited

## 600.1106 Quality control

Table 11–4 summarizes the major components of a quality control program. Good Laboratory Practices (GLPs) refer to general practices, such as glassware cleaning and preparation. Standard Operating Procedures (SOPs) are recipes for conducting analyses. These would include standard methods (APHA 1989) and approved methods (USEPA 1983). SOPs would also exist for sample handling (chain of custody records) and calibration and maintenance procedures.

Education and training refer to procedures used to support and verify the training of sampling and analysis personnel. This is especially important for safety training. Supervision includes the monitoring and review of techniques and data to allow for timely corrective actions.

**Table 11–4** Components of a quality control program (after Taylor 1984)

| |
|---|
| Good Laboratory Practices (GLPs) |
| Standard Operating Procedures (SOPs) |
| Education/training |
| sample custody procedures |
| calibration and maintenance |
| Supervision |

## 600.1107 Quality assessment

Quality assessment allows feedback on how well the quality control program is operating. Table 11–5 summarizes the components of a quality assessment program, and table 11–6 shows the indicators of quality data. Indicators of data quality include:

- precision
- accuracy
- representativeness
- comparability
- completeness

A description of each indicator follows.

**Table 11–5** Components of a quality assessment program

**Internal**

Duplicate samples
Standard additions (spikes)
Tests of sampling frequency
Tests of reason with comparable data
Missing analysis records
Standard curves
Internal audit

**External**

Exchange sample with other lab
External known materials
External audit

### (a) Precision

Precision is a measure of the closeness by which repeated measures of a given sample agree with each other. The Relative Standard Deviation (RSD) of duplicate samples provides the overall precision of the study, including random sampling errors and errors associated with sample preparation and analysis.

#### (1) Frequency

Duplicate analysis should be performed for every 20th sample collected for which there is sufficient quantity for splitting or at least one per analytical run.

#### (2) Calculation

The relative standard deviation, which also is the coefficient of variation, between the duplicates can be calculated as follows:

$$RSD = \frac{S}{\overline{X}} \times 100 \qquad [11–1]$$

where:

$S$ = standard deviation
$\overline{X}$ = the mean

#### (3) Acceptance

An RSD of more than 10 percent could require notification of the onsite QA officer.

**Table 11–6** Quality control samples

| Indicator | Sample type | Frequency | Measure | Acceptance criteria (%) |
|---|---|---|---|---|
| Precision | Duplicate | 1/20 | RSD | 10 |
| Accuracy | Spike | 1/20 | % recovery | 90-110 |
| Representative | Multiple | Initial | n | ±20 |
| Completeness | All | Annual | % missing | <10 |
| Performance audit | EPA known | 4/yr | % recovery | 90-110 |

## (b) Accuracy

Accuracy (bias) is the degree of agreement between measured and true values. The percentage recovery of known standard additions to a sample provides the measure of accuracy for the study. The amount added should be sufficient to double the concentration.

### (1) Frequency

Every 20th sample collected in sufficient quantity for splitting should be spiked.

### (2) Calculation

Chemical recovery is calculated as follows:

$$\% \text{ Recovery} = \frac{A}{B+C} \times 100 \qquad [11\text{–}2]$$

where

$A$ = measured concentration of spiked sample
$B$ = measured concentration of unspiked sample
$C$ = concentration of known addition

### (3) Acceptance

A recovery of 90 to 110 percent is considered acceptable. Recovery less than this limit requires corrective action.

## (c) Representativeness

Representativeness refers to how well the results represent the sample and how well the samples represent the population. Representativeness can be assessed by examining the variability among samples. For example, to determine whether individual composite samples are sufficient to develop a weekly composite, the required number of samples could be calculated. Methods for calculating the number of samples are presented in chapter 9 and repeated here.

### (1) Calculation

Compute the required number of samples as follows:

$$n > \frac{t^2 S^2}{d^2} \qquad [11\text{–}3]$$

where:

$n$ = number of samples
$t$ = students 't' at a given confidence level
$d$ = acceptable difference from the mean
$S$ = sample standard deviation

## (d) Comparability

Certain data from the study can be compared to results obtained from other similar studies.

## (e) Completeness

Completeness can be measured as the percentage of total samples collected that were analyzed. Sufficient water volumes should be collected to allow re-analysis of a sample if beyond a standard curve or if lost in a laboratory accident. A measure of completeness is the percentage of missing data obtained in the study. The number of samples needed is governed by the study design.

## 600.1108 Sample custody procedures

Each sample should be dated and coded according to site, sample type, station number, and sample sequence. The actual sample containers should be labelled with a sample number for identification.

Transfer of sample custody takes place upon delivery of samples to the laboratory. At the time of delivery, the person delivering the samples signs over custody to a laboratory person receiving the samples. This transaction is recorded on forms for that purpose, and the records are maintained in the laboratory (fig. 11–2).

As part of the process of sample receipt, each sample is assigned a unique identification number that can include specific information on location, date, composite, and yearly sequence. For example, a sample numbered 10-011891-24-566 represents a sample taken at station 10, on January 18, 1991, a 24-hour composite, and is the 566th sample received by the laboratory in a calendar year. This final number, representing the sample received in a year, serves as the shorthand sample number and is used for overall tracking in the laboratory.

The sample number should be used in all laboratory books to identify the sample. Sample transfer forms may be needed for some studies where samples are sent to other labs. Some agencies employ the practice of prelabeling bottles before they go to the field.

## 600.1109 Calibration procedures and preventative maintenance

The primary pieces of laboratory equipment should be described in a quality assurance plan together with the calibration and maintenance procedures and schedules. Standard curves, using from 8 to 10 standards including blanks, should be developed the same day of analysis for most analyses. Each analytical run should include a set of standards.

The maintenance schedule should be included in a quality assurance plan. The options available if equipment breakdown occurs should be described.

**Figure 11–2** Laboratory chain of custody sheet

Custody sheet for samples collected on (date)_____
Relinquished by_____
Received by_____

Samples held until:
(+ 28 days)

| Lab No. | Sample Description | Procedure completed (indicate with date) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Acid | Filter | Digest | TKN | NH3 | NO3 | TP | CL | TSS |
| | | | | | | | | | | |
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Remarks:

## 600.1110 Performance and systems audits

The project should be subject to both performance audits and systems audits. The performance audit could consist of unknown samples submitted quarterly to the laboratory.

### (a) Calculation

Reported results are compared to known values. The percentage recovery for the known is calculated as:

$$\% \text{ Recovery} = \frac{R - T}{T} \times 100 \qquad [11\text{–}4]$$

where
$R$ = reported value
$T$ = true value

Performance within ± 25 percent should be acceptable. Performance beyond ± 25 is considered an out-of-control situation calling for corrective action.

Project supervisors should make unscheduled performance audits of all laboratory personnel to detect any deviations from standard operating procedures. A checklist of the audit should remain on file in the supervisor's office.

A systems audit consists of an onsite review of the entire project.

## 600.1111 Corrective action

Data quality assurance procedures should be designed to ensure that project personnel are able to quickly identify and correct analytical problems. Data failing to meet quality control requirements should be subject to repeated analysis where sufficient volume exists to retest the sample.

## 600.1112 Field quality assurance

### (a) Field equipment

Calibration of field equipment is necessary. In situ analysis of temperature, pH, dissolved oxygen, conductivity, and other ions use field instruments requiring maintenance and calibration. Some instruments, such as pH and dissolved oxygen meters, require daily or more frequent calibration. A record should be maintained of all calibrations.

Stage recorders should be calibrated against a permanent outside staff gage at every visit. The staff gages should be surveyed to a benchmark at least annually. Precipitation gages should be calibrated annually, and checked weekly. Well pressure transducers should be calibrated when they do not equal staff gage readings. Well top elevations should be surveyed annually to a temporary benchmark. Stage-discharge relationships should be constructed during the first year of the project by at least 15 discharge measurements using the velocity-area method. Annually, the stage-discharge relationship should be checked with at least five ratings. Annual runoff coefficients should be calculated as the percentage of precipitation that left the watershed as discharge. These coefficients could be compared to runoff coefficients calculated from U.S. Geological Survey water resources data collected from other watersheds in the same general area of the state.

### (b) Field logs

Daily field logs should be kept for each field visit. These logs record operating status, calibration checks, manual readings, and the name of the field visitor. They are often 1-page sheets (fig. 11–3) and are tailored to the individual project. A personal notebook (survey book) maintained by each field worker may be useful. Each field visit is recorded and additional notes are made on work to be done.

**Figure 11–3** Example daily field log

Riparian Zone

Technician _____
Date _____
Checked _____
Date _____

**Daily Field Log**

| | | Station 1 | Station 2 | Station 3 | Comments |
|---|---|---|---|---|---|
| General | Time of visit | | | | |
| | Weir clear/chop | | | | |
| | Solar panels Ok? | | | | |
| | Batterries Ok? | | | | |
| | | | | | |
| | | | | | |
| Sampler | Sample volume Ok? | | | | |
| | Intake line Ok? | | | | |
| | Dessicant Ok?/replace | | | | |
| | Line in bottle? | | | | |
| | Sampler on? | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| Stage | Recorder stage (ft) | | | | |
| | Staff stage (ft) | | | | |
| | Point gage (ft) | | | | |
| | Display | | | | |
| | Enough paper? | | | | |
| | | | | | |
| | | | | | |

### (c) Field quality control samples

The four types of samples needed to assess field quality control include (Burger 1987):

- **Field duplicate—**Samples collected simultaneously at a location used to determine the variability associated with sample collection.
- **Trip blank**—Sample container taken to field and filled with distilled or deionized water and returned. This sample assesses contamination during transport or storage.
- **Sampler blank—**Sample obtained by passing deionized water through a nondedicated sampler, such as a portable pump. This blank is used to test contamination by a sampler.
- **Filtration blank—**Sample collected by field filtering apparatus using deionized water. This blank tests contamination by a filter and apparatus.

### (d) Field chain of custody

The sample custody procedures actually begin in the field. Proper labeling of sample bottles is critical. Some laboratories use pre-numbered bottle labels (Burger 1987).

## 600.1113 References

American Public Health Association. 1989. Standard methods for the examination of water and wastewater. 17th Ed., American Public Health Assoc., Washington, DC.

Burger, Robert M. 1987. Design and implementation of a successful quality control program for ground water sampling events. Symp. on monitoring, modeling, and mediating water quality, pp. 49-58, Amer. Water Resour. Assoc.

Dillaha, T.A., S. Mostaghimi, C.D. Eddleton, and P.W. McClellan. 1988. Quality control/quality assurance for water quality monitoring. Amer. Soc. Agric. Eng. Pap. No. 88-2648, St. Joseph, MI.

Driscoll, F.G. 1986. Ground water and wells. 2nd. Ed. Johnson Div., St. Paul, MN.

Klemm, D.J., P.A. Lewis, F. Fulk, and J.M. Lazorchak. 1990. Macroinvertabrate field and laboratory methods for evaluating the biological integrity of surface waters. Office of Research and Development, Washington, DC, U.S. Environmental Protection Agency/600/4-90/030.

Kunkle, S.H., and T.E. Ricketts. 1984. Portable kits for water chemistry reconnaissance in the field. WRFSL Rep No. 84-2, Water Resour. Field Sup. Lab., Natl. Park Serv., Fort Collins, CO.

Lawrence J., and A.S.Y. Chau. 1987. Quality assurance for environmental monitoring. Symp. on monitoring, modeling, and mediating water quality, pp. 165-175. Amer. Water Resour. Assoc.

Shelley, P.E. 1977. Sampling of water and wastewater. US EPA-600/4-77-039. Off. Res. and Dev., Cincinnati, OH.

Simpson, J.T. 1991. Volunteer lake monitoring: a methods manual. US EPA 440/4-91-002. Off. Water. Washington, DC.

Taylor. J.E. 1984. Essential features of a laboratory quality assurance program. *In* Statistics in the environmental sciences, S.M. Gertz and M.D. London (Eds.). Amer. Soc. for Test. and Mat. pp. 66-73.

Topp, E., and W. Smith. 1992. Sorption of the herbicide Atrazine and Metolachlor to selected plastics and silicone rubber. J. Environ. Quality 21:316-317.

United States Environmental Protection Agency. 1973. Biological field and laboratory methods for measuring the quality of surface waters and effluents. EPA 670/4-73-001, Off. Res. and Dev., Cincinnati, OH.

United States Environmental Protection Agency. 1983. Methods for chemical analysis of water and wastes. EPA600/4-79-020, Off. Res. and Dev., Cincinnati, OH.

United States Environmental Protection Agency. 1988. Guide for the preparation of quality assurance project plans for the national estuary program. EPA 556/2-88-001, Off. Marine and Estuarine Prot., Washington, DC.

United States Environmental Protection Agency. 1990. Volunteer water monitoring: a guide for state managers. EPA 440/4-90-010. Off. Water. Washington, DC.

United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

National Handbook of
Water Quality Monitoring

# Chapter 12 Land Use and Management Monitoring

(450-vi-NHWQM, December 1996)

# Chapter 12 Land Use and Management Monitoring

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# Chapter 12 Land Use and Management Monitoring

## 600.1200 Introduction

An essential element of water quality monitoring is the tracking of land use and management activities in the watershed being monitored. Land use and management data are needed to explain any water quality changes that may occur. The water quality changes must be attributed to the management practice and not to other confounding influences, such as climate or a point source. For watershed scale monitoring, the proximity of the land practices to the monitoring location can directly influence the water quality observed. A poor practice near the watershed outlet or downgradient can mask the influence of good practices upstream or upgradient.

This chapter presents methods for monitoring and managing land use and management data and provides checklists of recommended activities to monitor for the major sources of the nonpoint pollutant.

## 600.1201 Methods of monitoring

The four basic approaches for monitoring land treatment data are personal observations, field logs, personal interviews, and remote sensing. Any one project may use some or all of these approaches to track activities on the land, depending on the scale and complexity of the project.

Land treatment data can be either static or dynamic, point or diffuse. Static land treatment data do not change with time. Examples of this type data include soil type and slope. Dynamic land treatment data can vary with time and include the number of animals, cover crop, nutrient applications, and irrigation schedules. Most land treatment activities are considered diffuse or nonpoint. However, some activities, such as feedlots, manure stacks, and silage bunkers, can be viewed as potential point sources from a watershed scale perspective.

### (a) Personal observations

For small scale projects, such as plots or individual fields, tracking may best be accomplished by project personnel using personal observations. Routine site visits can include an analysis of the site conditions at the time of the visit. The type of information that can be collected through personal observations includes counts, timing of certain activities, site characteristics, and tests. Some examples are:

**Counts**
- Number of animals
- Crop type

**Site characteristics**
- Slope
- Slope length
- Soil type

**Timing**
- Planting date
- Harvest date
- Tillage dates
- Fertilizer applications
- Pesticide applications
- Irrigation schedules

**Tests**
- Yield test
- Soil test
- Application rates

A form for recording personal observations is highly recommended. It should include required check-offs to assure certain questions are not overlooked.

The windshield survey is another type of personal observation. This survey is useful in identifying land uses for areas where ownership is unknown and information is difficult to collect from traditional methods.

**(1) Advantages**
A major advantage of the personal observation is that the quality of the data is controlled by the observer. This means that the timing of the visit can be scheduled as well. Personal observation-type data are relatively inexpensive to obtain.

**(2) Disadvantages**
Timing is critical to certain types of land use observations. For example, pesticide applications occur on a short time frame and will most likely be missed by less frequent than daily visits. Also, the amount of an application, such as nutrient loading, can only be determined by being present during the application.

The potential for "judgment bias" in personal observations is great. Different individuals will most likely make different observations. Bias also can be introduced by personal schedules. Quantitative and randomized observations may help to reduce bias. Generally, a reliance on personal observation alone results in an incomplete data set of land treatment activities.

## (b) Field logs

The term *field log* is meant to include the various forms that would be left with the landowner or manager. The manager ideally would keep a record of activities. A copy of a manure/fertilizer log used in the St. Albans Bay RCWP is shown in figure 12–1. This particular log was given to each cooperating and noncooperating farm producer in the watershed. The log was placed inside a checkbook cover with a farm map showing numbered fields. The field logs were recovered twice yearly.

Some states require that the producer maintain a field log as part of a permit condition.

**(1) Advantages**
The major advantage of the field log is that the person performing the activities is keeping the records. This person is often the only one who knows when certain activities occur and how much occurred. Picking up a field log allows for additional interaction with the producer.

**(2) Disadvantages.**
A 100 percent compliance in good record keeping in the watershed is unlikely. Some producers will not fill out the log. Others will not complete the log with the level of detail or precision needed. For example, instead of indicating the exact date of a manure application on field No. 10, a producer may indicate “early spring.”

## (c) Personal interviews

A personal interview or one-on-one contact is an effective way to obtain land treatment data. A direct visit is preferred over a telephone interview. A form is recommended as a guide for the interview. Based on experience obtained in the St. Albans Bay RCWP, two visits per year yields much more reliable data than an annual visit. Meetings with producers were timed with less busy periods on the farm (e.g., mid-summer and mid-winter).

**(1) Advantages**
The major advantage of the personal interview is that the data is obtained from the person responsible for the land activity. Also, the interview facilitates obtaining information on subtle land use changes, such as rental lands, field boundary changes, and shifts in animal numbers.

**(2) Disadvantages**
A major disadvantage of the personal interview is that the quality of data obtained varies with both the interviewer and the interviewee. Some people are adept at questioning farm producers, while others are not. Similarly, some farm producers are reluctant to share management information. Another disadvantage is that the personal interview relies on "reconstructed" data based on the memories of the person interviewed.

**Figure 12–1** Example of a field log

## A. Manure application

| Date | Field ID (see map) | Amount applied (full spreader load) | Date incorporated | Time (approx.) | Comments |
|---|---|---|---|---|---|
| Example 4/23/82 | 3b | 1 1/2 | 4/23 | 10:30 am | • Evenly spread except wet spot on NE corner<br>• Planted corn 4/28 |
| | | | | | |
| | | | | | |
| | | | | | |

## B. Commercial fertilizer application (including lime)

| Date | Field ID | Formulation | Amount applied/ac | How applied | Comments |
|---|---|---|---|---|---|
| Example 4/23/82 | 21 (or all corn fields) | 10-20-10 | 4 lb/ac | broadcast | disced on 4/23 |
| | | | | | |
| | | | | | |
| | | | | | |

### (d) Remote sensing

For certain types of land use and treatment data, remote sensing techniques may serve as a primary data source or verification of other data sources. For example, the 35mm slides of cropland areas taken annually by FSA can provide a source of land cover information on a field basis. Satellite data would generally not be sufficient for monitoring land treatment, although it has been used to assess critical areas (Sivertun, et al. 1988).

#### (1) Advantages

Remotely sensed data can give a permanent visual and spatial record of certain types of land use data, including land cover. Certain types of critical sources of nonpoint pollution, such as erosion, may be observable using remote sensing. Data that can be obtained by remote sensing eliminate reliance on the memories of individuals.

#### (2) Disadvantages

Remotely sensed data have limited applications. Low level air photos can be used to distinguish some crop covers, but it is difficult to distinguish between others, such as forest and residential. Remotely sensed data will not provide timing information, such as manure or fertilizer applications.

## 600.1202 Management of land treatment data

The method employed to keep track of land use data varies with the situation, but the method used must be defined at the beginning of the project. Without attention to management of land treatment data, records will most likely be insufficient and full of gaps. The three methods for management of land treatment and land use data are ad hoc files, spread sheets/data bases, and geographic information systems.

### (a) Ad hoc files

A good filing system can be effectively used to track land use and treatment data. It is important that the results of land treatment monitoring be reported routinely and often. Failure to do so will result in data gaps remaining hidden, possibly until the end of the project when it will be too late to recover the data. Spatial data from ad hoc files should be transferred to and displayed on maps as a quality control check on how much information is actually being obtained.

### (b) Spreadsheets/data bases

Various computer spreadsheet and data base programs can be used to track land treatment data. Such programs are particularly efficient in attaching attributes to field IDs. The EPA has developed a PC software program, the Nonpoint Source Management System (NPSMS), to track management activities and water quality and implementation data (US EPA 1991). NPSMS actually has several separate files for tracking information. The *management* file stores information about the water quality problem and project goals. The *monitoring plan* file holds descriptions of the monitoring design, including stations, variables, and frequencies. The *annual report* file includes the annual water quality and implementation data. The system also includes the water body system for identifying the individual body of water involved.

Data bases, in particular, allow relating data between different files, such as land treatment files and water quality files.

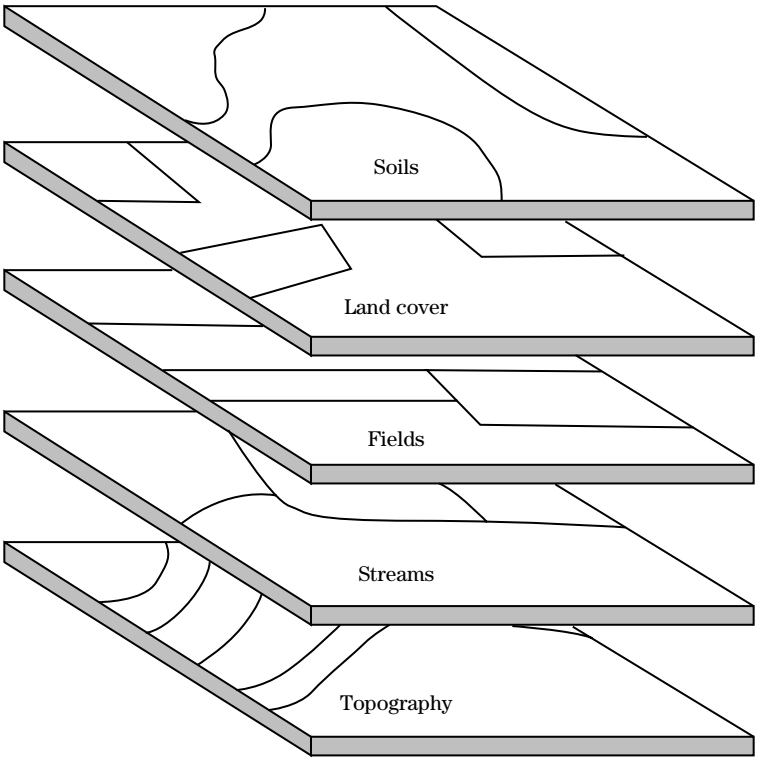
### (c) Geographic information system (GIS)

Geographic information systems are "…systems that integrate layers of spatially oriented information, whether manually or automatically…" (Walsh 1985). A GIS is ideally suited to track land use and treatment data. The primary advantage is that land treatment data can be displayed spatially and combined with other water quality related information.

GIS data can be stored as values for uniform grids (raster) or as strings of coordinates representing points, lines, and areas, including polygons (vector). Land treatment data, such as land cover, can be overlaid on stream courses, soil types, and topography (fig. 12–2). A GIS also allows displaying and calculating new information from the combined data layers, such as where and how much animal waste was applied within 50 feet of a stream or where and how much animal waste was applied on soil hydrologic group D.

Because all the files in a GIS are relational, that is, two-dimensional tables can be related to each other based on a common characteristic, such as field ID, a GIS also serves as a data base for managing and reporting land treatment data.

**Figure 12–2** Geographic information systems data layers



### (1) Data entry

The most difficult aspect of using a GIS for managing land treatment data is the initial digitizing of the spatial data layers. Quality control is an important consideration in GIS data entry, just as it is for water quality analysis. Digitized information should go through an error checking system to make sure that the layer has been appropriately geo-referenced and lines and points are properly located. Just closing polygons is insufficient quality control. Other information added should also receive error checking (see chapter 12).

Once the data layers have been entered, attributes are easily added and data management is enhanced and powerful. Although the appropriate data layers would vary with each situation, several useful data layers are given in table 12–1 along with suggested priorities for most water quality monitoring situations.

Farm and field boundaries are almost essential as a data layer. Such data can be obtained from the farm plan photos with verification from the farm operator.

**Table 12–1** Frequently used data layers for a GIS

| Priority | Data layer |
|---|---|
| 1 | quadrangle basemap |
| 1 | farm and field boundaries |
| 1 | stream courses and other water bodies (or proximity class) |
| 1 | watershed boundary |
| 1 | soil series (or attribute of field) |
| 2 | topography or slope (or attribute of soil) |
| 2 | land cover/land use |
| 3 | transportation |
| 3 | geology |
| 3 | political boundaries |
| 4 | archeology |
| 4 | precipitation (where variable) |

Stream courses can be digitized as lines or bands, polygons, or grids, or a proximity zone to the watercourse can be used. For example, Sivertun, et al. (1988) used proximity bands of 0 to 150, 150 to 650, 650 to 3,300, and >3,300 feet to help identify critical areas in a watershed.

Soils data could be entered as the soil series or as some more general textural class either as a separate layer or as a field attribute. However, a separate soils layer is recommended. Topography could be entered as a data layer, either as points, polygons, or grid information, or the percent slope could be entered either as an attribute of the field boundary or the soil series. Topographic information is not necessary to track land use data, but is useful for displaying results in a 3-D format and identifying critical areas.

Land cover could be entered as a separate data layer; however, it is best entered as an attribute of a farm field because it is easily updated. Good land cover/land use maps are not readily available. Therefore, these maps are often developed from aerial photo interpretations, satellite imagery, or on-the-ground observations.

For the St. Albans Bay RCWP, a land use/land cover data layer was created from individual farm 9 by 9 1:660 scale farm plan photos, verifications from the farm operator, supplemental ASCS 35mm slides, and ground truthing of gaps in the data layer.

The use of satellite results is not accurate enough at this time to determine land use/land cover for water quality monitoring purposes. However, satellite data may be very useful when determining critical areas of high pollution potential (Guilliland and Baxter-Potter 1987).

Precipitation is an appropriate data layer when highly variable across the watershed in some cases. Irrigation networks may be useful in certain areas (Walsh 1985).

For ground water projects, information on ground water withdrawals and piezometric surfaces may be important management information.

### (2) Analysis

After the data layers have become part of the GIS data base, attributes of dynamic data layers can be updated. For example, cover crop can be changed annually. The additions of nutrients, either as animal waste or fertilizers, can be updated on a weekly, monthly, or annual basis. From this data base, several types of land use and management information can be generated (table 12–2).

**Table 12–2** Land use and management data generated from a GIS

| | Units |
|---|---|
| **Land treatment data** | |
| Critical area under BMP | %, ac. |
| Animal units under BMP | %, No., No/ac |
| Fields under nutrient management | %, ac. |
| Fields under irrigation management | %, ac. |
| Area of land use (pasture, etc.) | %, ac. |
| Erosion control | %, ac. |
| **Animal waste data** | |
| Manure from storage | % |
| Manure incorporated | % |
| Barnyard management | No. |
| Milkhouse management | No. |

## 600.1203 Relationship between land use/treatment and water quality

The purpose in collecting land use and management information is to use that data to establish causal relationships with water quality. Causality involves several steps:

1. An association should exist between the water quality and land treatment data.
2. This association should be consistent across different data sets so that a general statement may be made about the relationship.
3. The association should be tested to make sure that one variable is responsive to the other variable. This responsiveness may require experimentation.
4. There must be a mechanism that logically explains the process that results in the relationship.

This section will focus on developing associations between land treatment and water quality data.

When developing a program for monitoring land treatment data for the purpose of relating that data to water quality, both temporal and spatial scales must be decided.

Water quality data are often collected at a much more frequent rate than land treatment data. For example, in the St. Albans Bay RCWP, water quality samples were collected every 8 hours, but land treatment information was collected twice a year. In one analysis associations were made of weekly phosphorus and manure application data (Hopkins & Clausen 1985). However, the danger in such associations is that they are confounded by the timing of agricultural practices. For example, animal waste is not applied to agricultural lands during wet seasons, but nutrient concentrations in streams are highest during the same wet periods. Thus a confounded association of manure applications and stream concentrations could exist. To resolve this problem, Meals (1992) used annual data for the associations.

The spatial scale of land treatment data also is important. Watershed-wide summaries were most useful in establishing land treatment-water quality relationships in Vermont (Meals 1992). However, an association of land use (corn, pasture, hay) and certain water quality variables for data summarized were within 150 feet of the streams for each watershed. Schlagel (1992) also pointed out that the spatial pattern within watersheds of changes in land treatment practices is important and could mask water quality changes.

The primary methods for establishing associations are described in part 2 of this handbook. Correlations serve as an initial tool.

When developing the monitoring plan, a list of land use and management data that will be used to relate to water quality data also should be developed. This list will obviously vary with the project.

## 600.1204 References

Gilliland, M.W., and W. Baxter-Potter. 1987. A geographic information system to predict non-point source pollution potential. Water Resourc. Bull. 23(2):281-291.

Hopkins, R.B., Jr., and J.C. Clausen. 1985. Land use monitoring and assessment for nonpoint source pollution control *In* Perspectives on nonpoint source pollution, EPA 440/5-85-001, Washington, DC, pp. 25-29.

Meals, D.W. 1992. Relating land use and water quality in the St. Albans Bay watershed, Vermont. Proc. Natl. RCWP Symp., EPA pp. 131-143.

Schlagel, J.D. 1992. Spatial and temporal change in animal waste application in the Jewett Brook watershed, Vermont: 1983-1990. Proc. Natl. RCWP Symp., EPA pp. 145-150.

Silvertun, A., L.E. Reinelt, and R. Castensson. 1988. A GIS method to aid in non-point source critical area analysis. J. Geogr. Inf. Sys. 2(4):365-378.

United States Environmental Protection Agency. 1991. Watershed monitoring and reporting for section 319 national monitoring program projects. Office of Water Washington, DC.

Walsh, S.J. 1985. Geographic information systems for natural resource management. J. Soil and Water Conserv. pp. 202-205.

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# Chapter 13 Data Management

# Chapter 13 Data Management

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**Figures**

# Chapter 13 Data Management

## 600.1300 Introduction

Data management in water quality monitoring projects refers to a series of steps for handling data (fig. 13–1). The management of data has become increasingly important because efficient means are needed to deal with a large amount of numbers and the integrity of those numbers must be guaranteed. The processes in a data management system include acquisition, storage, validation, retrieval, manipulation, and reporting of data (Canter 1985; Sanders, et al. 1983; Ward, et al. 1990). The interpretation of data will be further described in part 2.

Advances in computers and software have made the process of data management much easier. Therefore computer applications will be described in this chapter.

## 600.1301 Data acquisition

The acquiring of data is meant to include its collection and entry into the data management system. Entry may begin indirectly from data entry sheets (fig. 13–2), which could be completed by either field or laboratory personnel. More direct entry of data has been made possible via the use of data loggers. This latter process bypasses the steps of manually entering data and therefore avoids transcription errors. Data from a data logger can be input using storage modules, cassette tapes, or telecommunication devices that have an interface with a computer system.

**Figure 13–1** Data management system

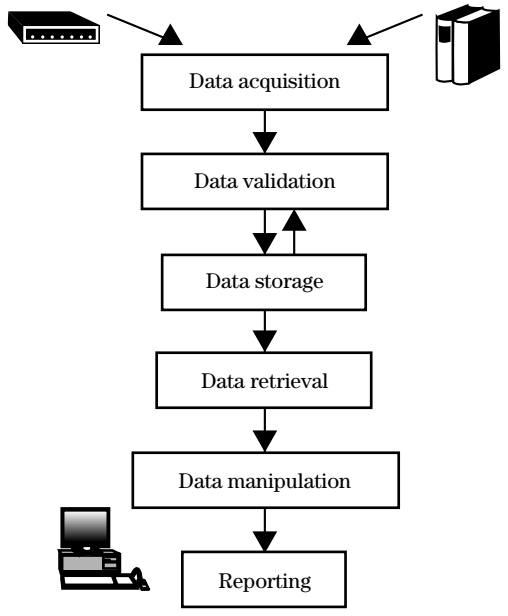


**Figure 13–2** Example data entry sheets

Data entry sheet
riparian zone restoration project

**Streams**

| STA | Date MM/DD/YY | Hours | Lab No. | Concentration (mg/l) | | | |
|---|---|---|---|---|---|---|---|
| | | | | TKN | $NH_3$ | $NO_2/NO$ | TP |
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## 600.1302 Data storage

The storage of data should be viewed as a multilevel effort using manual and computerized technologies. Manual efforts should include safe storage of original laboratory notebooks, field notebooks, daily field logs, and any paper tapes and strip charts. A manual copy of all computerized data files should be printed on high quality paper and placed in safe storage. Smoke destroys a floppy disk, but not paper.

Laboratory notebooks should be considered a permanent record of data. The notebooks should be bound with numbered pages so that pages cannot be substituted or deleted. Pages should be dated and signed by operators. Entries should be made in ink. Errors should be crossed out so that they are legible, but not erased. The correction should be initialed and dated. Large blank spaces in the notebooks should have lines drawn through them. Standard curves should be drafted within the lab notebook.

Computerized data storage also is highly recommended. In the past, computerized data management systems were developed specifically for individual projects onsite, and could not be transferred to other locations. The availability of general spreadsheet software, such as Lotus 1-2-3, Quattro Pro, or Excel, has greatly changed the need to develop individual data management systems. In addition, data base management software is available. The following are recommendations for computerized spreadsheets and data base management systems use:

- Store data in ASCII format, preferably formatted in columns.
- Store data on floppy disks, not hard drives.
- Backup disks are essential; maintain one set onsite and one set offsite (at home).
- Store data in files of "convenient" blocks of data, such as annually. One disk could represent 1 year of data.
- Plan file naming conventions. A file name could include such information as project or study area, data type, data manipulations, and project year. For example, the file "SAQ23.S85" refers to the St. Albans Bay RCWP project (SA), flow data (Q), for the Level 2 tributary stations (2), for the third quarter of the year (3), sorted by station number and date (S), and for project year 1985. For this study separate formatted ASCII files were created for flow (Q) files, concentration data (C), mass data (M), stage data (S), and precipitation data (P) using the same file naming convention. Because knowing that the data files have been error checked is important, checking was done quarterly. However, many spreadsheets use their own filename extensions, such as XXXXXXXX.WQ1 for Quattro.
- Decide how to record missing data in the computer files. A -9.0 could be a code for missing data in cases where negative data does not exist (e.g., concentration, flow). The statistical package SAS uses a single period, '.' as an indicator of missing data.

Geo-referencing the location of water quality sampling stations by latitude and longitude (degrees, minutes, seconds) is further recommended. Such referencing is required by some data storage systems, such as STORET.

Data that are below detection limits are termed *censored* data. Data should be entered in the data management system that codes the data as below the detection limit. For example, a -8.0 could be used where negative data is not possible. The elimination of data below detection limits or the entry of the below detection limit data as either a 0, half the limit, or the limit itself is not recommended (Newman, et al. 1989).

## 600.1303 Data validation

All data reported should receive a 100 percent error check. Transcription errors can be checked by entering the data twice, preferably by two individuals. A computer program can compare the two data files and flag any inconsistencies for correction.

Also, the **COMP** command in DOS allows the comparison of the contents of two files in either the same or different directories. If the **COMP** command finds any mismatches, an error statement will be displayed.

Laboratory notebook calculations should be checked by a supervisor, who initials the notebooks as verified. Sample custody sheets should be reviewed to ensure that holding times, preservation, sample integrity, and equipment calibration requirements have been met.

Additional tests of reason can be applied to concentration values. For example, ammonia concentrations cannot exceed total Kjeldahl nitrogen values, and ortho-phosphorus cannot exceed total phosphorus values. Also, limits can be used as flags in the data set. For example, appropriate limits for pH are 0 to 14. A maximum limit for total phosphorus might be 5 mg/L for a lake. Standard laboratory curves should be analyzed for warning and control limits as described in Standard Methods (APHA 1989).

Data not meeting the requirements described above could be rejected and noted in the data files as missing data.

## 600.1304 Data retrieval

The retrieval of data from the data management system must consider the form of retrieval (paper report, data file, graph) as well as the intended use (statistical, quality control, share with others). Good records must be maintained on format for data storage so that others can review the data files. Readme.txt files stored on disks containing the data files are highly recommended.

## 600.1305 Data manipulation

Data generally require some form of manipulation before being reported. Common manipulations include:

- calculations of average values or mass exports
- sorting
- graphical presentations
- statistical analysis/ transformations

Common spreadsheet and data base programs facilitate the calculation of averages and mass exports. For example, Quattro Pro and Lotus allow entering a formula, i.e., equation, to apply to stored data or the use of functions (internal formulas) to apply to the data. These functions include mathematical, statistical, and logical operations.

The sorting of data is a common manipulation in a data management system. Frequently, data must be arranged by date or station number to report the results, input to a graph, or perform statistical analysis. Most spreadsheets have sorting commands. It may be desirable to search through the data system as well as sort the data.

Graphical presentations also are facilitated by spreadsheets, or a number of graphics packages are available.

Statistical manipulation of data will be very specific to the study design. However, most data receive routine univariate analysis, including the number of samples, mean, maximum, minimum, and standard deviation. These simple statistics can be determined in most spreadsheets. More sophisticated statistical analysis may require the use of other statistical packages.

If censored (below detection limits) data are in the data set, the mean and standard deviation for the data are strongly influenced by the manner in which the censored data is handled and the percentage of data that is censored. This is discussed further in part 2.

## 600.1306 Data reporting

Reporting data at the end of a monitoring study may seem obvious, but reporting during the progress of the study is very important for several reasons. Interim reporting encourages (requires) identifying data errors and data gaps. Frequent reporting aids in solving problems. Although it seems like it takes too much time, reporting should be at a minimum of quarterly either formally or informally. Progress reports should include data that have been screened, analyzed statistically, summarized and plotted. A few copies of the raw data should be made available to project sponsors and cooperators. The data could be shared as ASCII files on diskettes.

Guidelines for preparing reports are beyond the scope of this handbook. However, following the guidelines of an appropriate professional journal, especially regarding tables and figures, is recommended.

## 600.1307 References

American Public Health Association. 1989. Standard methods for the examination of water and wastewater. 17th ed., American Public Health Assoc., Washington, DC.

Canter, L.W. 1985. River water quality monitoring. Lewis Pub., Inc. Chelsea, MI.

Newman, M.C., P.M. Dixon, B.B. Looney, and J.E. Pinder, III. 1989. Estimating mean and variance for environmental samples with below detection limit observations. Water Resourc. Bull. 25(4):905-916.

Sanders, T.G., R.C. Ward, J.C. Loftis, T.D. Steele, D.D. Adrian, and V. Yevjevich. 1983. Design of networks for monitoring water quality. Water Resourc. Pub., Littleton, CO.

Ward, R.C., J.C. Loftis, and G.B. McBride. 1990. Design of water quality monitoring systems. Van Nostrand Reinhold. New York, NY.

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# National Handbook of Water Quality Monitoring

# Glossary

(450-vi-NHWQM, draft March 1994)

# Glossary

**Aerobic** The presence of oxygen.

**Anaerobic** The absence of oxygen.

**Aquifer** A geologic formation containing water, usually able to yield appreciable water.

**Baseflow** A part of stream discharge not attributed to direct runoff from precipitation or snowmelt and usually contributed by subsurface flow.

**Baseline** Initial or background water quality conditions. Also a surveyed line.

**Bed load** Sediment moving along the stream bed not in suspension by rolling or bouncing.

**Benthos** The assemblage of organisms living on or at the bottom of a body of water.

**Best Management Practice** A practice or combination of practices found to be the most effective, practicable (including economic and institutional considerations) means of preventing or reducing the amount of pollution generated by nonpoint sources to a level compatible with water quality goals.

**Catchment** The area providing runoff to a lake, stream, or well (drainage area, drainage basin, watershed).

**Coliform bacteria** A group of bacteria predominantly found in the intestines of animals, but also occasionally found elsewhere.

**Composite sample** A combination of individual samples taken at selected intervals or volumes to minimize variability.

**Concentration** The amount of a substance dissolved or suspended in a unit volume of water.

**Conductance** The measure of the conducting ability of a solution that is equal to the reciprocal of the resistance.

**Confined aquifer** An aquifer that is surrounded by formations of less permeable or impermeable material that is isolated from the atmosphere. (Artesian aquifer)

**Conservation practice** An engineered structure or management activity that eliminates of reduces an adverse environmental effect of a pollutant and conserves soil, water, plant, or animal resources.

**Contamination** An introduction of a substance into water in a sufficient concentration to make the water unfit for its intended use.

**Control** In a study, a standard for comparison against which other treatments are compared, but is either untreated or receives a standard treatment. Also, a stable cross section in a stream that controls flow upstream.

**Critical area** An area within a watershed determined to be an important source of a pollutant.

**Current meter** A devise for measuring the velocity of flowing water.

**Discharge rating curve** A curve showing the relationship between the stage at a cross section and the discharge at that cross section.

**Discharge** The rate or volume of water flowing at a specific cross section within a specified time.

**Dispersion** The mixing of the concentration of a substance in the water with another body of water due to the flow of water.

**Dissolved oxygen** The oxygen dissolved in water, expressed in milligrams per liter or percentage saturation.

**Drainage basin** See catchment.

**Drainage density** The density of natural drainage channels in a given area, expressed as length per unit area.

**Effluent stream** A stream that receives water from saturated ground water.

**Epilimnion** The upper waters of a thermally stratified lake.

**Equipotential line** A contour line that connects points of equal head for the water table or equipotential surface.

**Field** A small agricultural unit implying a management area.

**Filter strip** A conservation practice that is a strip of vegetated land established downslope of a nonpoint source of pollution with the purpose of reducing the pollutant.

**Flow line** Line indication the direction of ground water flow toward the point of discharge. Flow lines are perpendicular to equipotential lines and together they form a flow net.

**Flume** An open conduit for flow.

**Gage** A device for determining the water level.

**Grab sample** A single sample taken at a certain time and place.

**Ground water** Subsurface water in the saturated zone below the water table.

**Hydrograph** A graph showing discharge as a function of time for a given location on a stream.

**Hypolimnion** The bottom waters of a thermally stratified lake.

| | |
|---|---|
| **Intermittent stream** | A stream or portion that flows only in direct response to precipitation. |
| **Limnocorral** | A device used in lakes that isolates the water column from surrounding waters. |
| **Load** | The quantity of material entering a receiving body of water. |
| **Lysimeter** | A device used to measure the water quantity or quality draining through the soil. |
| **Macroinvertebrates** | A large animal without a backbone that can be observed without the aid of magnification. |
| **Macrophyton** | A large plant that can be observed without the aid of magnification. |
| **Mesocosm** | |
| **Metalimnion** | The middle layer of a thermally stratified lake. |
| **Model** | |
| **Nonpoint source** | A diffuse location with no particular point of origin. |
| **Objective** | |
| **Perennial stream** | A stream that flows continuously all seasons of a year and during both wet and dry years. |
| **Periphyton** | Small or microscopic aquatic plants attached to submerged objects. |
| **Phytoplankton** | Small or microscopic aquatic plants. |
| **Piezometer** | An instrument for measuring pressure head in the soil. |
| **Plankton** | Small or microscopic aquatic organisms that are floating, or weakly motile and generally considered to be at the mercy of the currents. |
| **Plot** | |
| **Pollutant** | |
| **Pollution** | A condition caused by the presence of harmful or objectionable substances in water. |
| **Rating** | A relation between stage and discharge of a stream. |
| **Reconnaissance survey** | |
| **Resource management system** | A combination of conservation practices and management identified by the primary use of land or water. |

| | |
|---|---|
| **Runoff coefficient** | The ratio of the depth of runoff from a watershed to the depth of precipitation. |
| **Runoff** | That portion of precipitation or irrigation found in surface channels and streams. |
| **Sampler** | A device used to obtain an aliquot of water. |
| **Specific conductance** | |
| **Stage** | The elevation of the water surface above some datum. |
| **Stage-discharge relation** | The relationship between stream stage and discharge at a gaging station. |
| **Steady-state** | Conditions that are averaging constant over time. |
| **Stilling well** | A chamber with small inlets connected to a water body used for measuring the water level. |
| **Streamflow** | Water flowing in a stream channel. (Stream discharge) |
| **Surface runoff** | The portion of runoff that reaches a stream by traveling over the surface of the land. (Overland flow) |
| **Suspended solids** | Solids in suspension in water. |
| **Synoptic survey** | |
| **Tensiometer** | An instrument filled with water with a porous cup used for measuring the soil water potential. |
| **Turbidity** | A condition in water caused by suspended matter that causes the scattering and absorption of light. |
| **Unconfined aquifer** | An aquifer where the water table is exposed to the atmosphere. (Water table aquifer) |
| **Vadose zone** | Zone of soil between the surface and the water table that is not saturated. |
| **Velocity meter** | A meter used to measure stream velocity. |
| **Water quality management** | |
| **Water quality monitoring** | |
| **Water quality standards** | |
| **Water quality** | The physical, chemical, and biological properties of water with respect to its suitability for an intended use. |

**Water table** The upper surface of the saturated zone in a soil that is at atmospheric pressure.

**Water-level recorder** A device used for recording the water elevation over time.

**Watershed** The area contributing water to a stream, lake, or well.

**Weir** A device used in a stream with a damming crest and an opening of some known geometric shape, such as a V-notch.

**Zooplankton** Small or microscopic aquatic animals.

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# Appendixes

(450-vi-NHWQM, December 1996)

# Appendixes

**Contents:**

## Appendix A Distribution of Z [1]

Probability of a random value of $Z = (X - \mu)/s$ being greater than the values tabulated in the margins

| Z | .00 | .01 | .02 | .03 | .04 | .05 | .06 | .07 | .08 | .09 |
|---|---|---|---|---|---|---|---|---|---|---|
| .0 | .5000 | .4960 | .4920 | .4880 | .4840 | .4801 | .4761 | .4721 | .4681 | .4641 |
| .1 | .4602 | .4562 | .4522 | .4483 | .4443 | .4404 | .4364 | .4325 | .4286 | .4247 |
| .2 | .4207 | .4168 | .4129 | .4090 | .4052 | .4013 | .3974 | .3936 | .3897 | .3859 |
| .3 | .3821 | .3783 | .3745 | .3707 | .3669 | .3632 | .3594 | .3557 | .3520 | .3483 |
| .4 | .3446 | .3409 | .3372 | .3336 | .3300 | .3264 | .3228 | .3192 | .3156 | .3121 |
| .5 | .3085 | .3050 | .3015 | .2981 | .2946 | .2912 | .2877 | .2843 | .2810 | .2776 |
| .6 | .2743 | .2709 | .2676 | .2643 | .2611 | .2578 | .2546 | .2514 | .2483 | .2451 |
| .7 | .2420 | .2389 | .2358 | .2327 | .2296 | .2266 | .2236 | .2206 | .2177 | .2148 |
| .8 | .2119 | .2090 | .2061 | .2033 | .2005 | .1977 | .1949 | .1922 | .1894 | .1867 |
| .9 | .1841 | .1814 | .1788 | .1762 | .1736 | .1711 | .1685 | .1660 | .1635 | .1611 |
| 1.0 | .1587 | .1562 | .1539 | .1515 | .1492 | .1469 | .1446 | .1423 | .1401 | .1379 |
| 1.1 | .1357 | .1335 | .1314 | .1292 | .1271 | .1251 | .1230 | .1210 | .1190 | .1170 |
| 1.2 | .1151 | .1131 | .1112 | .1093 | .1075 | .1056 | .1038 | .1020 | .1003 | .0985 |
| 1.3 | .0968 | .0951 | .0934 | .0918 | .0901 | .0885 | .0869 | .0853 | .0838 | .0823 |
| 1.4 | .0808 | .0793 | .0778 | .0764 | .0749 | .0735 | .0721 | .0708 | .0694 | .0681 |
| 1.5 | .0668 | .0655 | .0643 | .0630 | .0618 | .0606 | .0594 | .0582 | .0571 | .0559 |
| 1.6 | .0548 | .0537 | .0526 | .0516 | .0505 | .0495 | .0485 | .0475 | .0465 | .0455 |
| 1.7 | .0446 | .0436 | .0427 | .0418 | .0409 | .0~01 | .0392 | .0384 | .0375 | .0367 |
| 1.8 | .0359 | .0351 | .0344 | .0336 | .0329 | .0322 | .0314 | .0307 | .0301 | .0294 |
| 1.9 | .0287 | .0281 | .0274 | .0268 | .0262 | .0256 | .025n | .0244 | .0239 | .0233 |
| 2.0 | .0228 | .0222 | .0217 | .0212 | .0207 | .0202 | .0197 | .0192 | .0188 | .0183 |
| 2.1 | .0179 | .0174 | .0170 | .0166 | .0162 | .0158 | .0154 | .0150 | .0146 | .0143 |
| 2.2 | .0139 | .0136 | .0132 | .0129 | .0125 | .0122 | .0119 | .0116 | .0113 | .0110 |
| 2.3 | .0107 | .0104 | .0102 | .0099 | .0096 | .0094 | .0091 | .0089 | .0087 | .0084 |
| 2.4 | .0082 | .0080 | .0078 | .0075 | .0073 | .0071 | .0069 | .0068 | .0066 | .0064 |
| 2.5 | .0062 | .0060 | .0059 | .0057 | .0055 | .0054 | .0052 | .0051 | .0049 | .0048 |
| 2.6 | .0047 | .0045 | .0044 | .0043 | .0041 | .0040 | .0039 | .0038 | .0037 | .0036 |
| 2.7 | .0035 | .0034 | .0033 | .0032 | .0031 | .0030 | .0029 | .0028 | .0027 | .0026 |
| 2.8 | .0026 | .0025 | .0024 | .0023 | .0023 | .0022 | .0021 | .0021 | .0020 | .0019 |
| 2.9 | .0019 | .0018 | .0018 | .0017 | .0016 | .0016 | .0015 | .0015 | .0014 | .0014 |
| 3.0 | .0013 | .0013 | .0013 | .0012 | .0012 | .0011 | .0011 | .0011 | .0010 | .0010 |
| 3.1 | .0010 | .0009 | .0009 | .0009 | .0008 | .0008 | .0008 | .0008 | .0007 | .0007 |
| 3.2 | .0007 | .0007 | .0006 | .0006 | .0006 | .0006 | .0006 | .0005 | .0005 | .0005 |
| 3.3 | .0005 | .0005 | .0005 | .0004 | .0004 | .0004 | .0004 | .0004 | .0004 | .0003 |
| 3.4 | .0003 | .0003 | .0003 | .0003 | .0003 | .0003 | .0003 | .0003 | .0003 | .0002 |
| 3.6 | .0002 | .0002 | .0001 | .0001 | .0001 | .0001 | .0001 | .0001 | .0001 | .0001 |
| 3.9 | .0000 | | | | | | | | | |

1/ Steel, R.G.D., and J.H. Torrie. 1960. Prnciples and procedures of statistics. McGraw-Hill, Inc., New York, NY. (Reproduced with permission of the McCraw-Hill Companies.)

**Appendix B** Distribution of *t* (two-tailed) [1]

| Degrees of Freedom | Probability of a Larger Value, Sign Ignored | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0.500 | 0.400 | 0.20 | 0.10 | 0.050 | 0.025 | 0.010 | 0.005 | 0.001 |
| 1 | 1.000 | 1.376 | 3.078 | 6.314 | 12.706 | 25.452 | 63.657 | | |
| 2 | 0.816 | 1.061 | 1.886 | 2.920 | 4.303 | 6.205 | 9.925 | 14.089 | 31.598 |
| 3 | .765 | 0.978 | 1.638 | 2.353 | 3.182 | 4.176 | 5.841 | 7.453 | 12.941 |
| 4 | .741 | .941 | 1.533 | 2.132 | 2.776 | 3.495 | 4.604 | 5.598 | 8.610 |
| 5 | .727 | .920 | 1.476 | 2.015 | 2.571 | 3.163 | 4.032 | 4.773 | 6.859 |
| 6 | .718 | .906 | 1.440 | 1.943 | 2.447 | 2.969 | 3.707 | 4.317 | 5.959 |
| 7 | .711 | .896 | 1.415 | 1.895 | 2.365 | 2.841 | 3.499 | 4.029 | 5.405 |
| 8 | .706 | .889 | 1.397 | 1.860 | 2.306 | 2.752 | 3.355 | 3.832 | 5.041 |
| 9 | .703 | .883 | 1.383 | 1.833 | 2.262 | 2.685 | 3.250 | 3.690 | 4.781 |
| 10 | .700 | .879 | 1.372 | 1.812 | 2.228 | 2.634 | 3.169 | 3.581 | 4.587 |
| 11 | .697 | .876 | 1.363 | 1.796 | 2.201 | 2.593 | 3.106 | 3.497 | 4.437 |
| 12 | .695 | .873 | 1.356 | 1.782 | 2.179 | 2.560 | 3.055 | 3.428 | 4.318 |
| 13 | .694 | .870 | 1.350 | 1.771 | 2.160 | 2.533 | 3.012 | 3.372 | 4.221 |
| 14 | .692 | .868 | 1.345 | 1.761 | 2.145 | 2.510 | 2.977 | 3.326 | 4.140 |
| 15 | .691 | .866 | 1.341 | 1.753 | 2.131 | 2.490 | 2.947 | 3.286 | 4.073 |
| 16 | .690 | .865 | 1.337 | 1.746 | 2.120 | 2.473 | 2.921 | 3.252 | 4.015 |
| 17 | .689 | .863 | 1.333 | 1.740 | 2.110 | 2.458 | 2.898 | 3.222 | 3.965 |
| 18 | .688 | .862 | 1.330 | 1.734 | 2.101 | 2.445 | 2.878 | 3.197 | 3.922 |
| 19 | .688 | .861 | 1.328 | 1.729 | 2.093 | 2.433 | 2.861 | 3.174 | 3.883 |
| 20 | .687 | .860 | 1.325 | 1.725 | 2.086 | 2.423 | 2.845 | 3.153 | 3.850 |
| 21 | .686 | .859 | 1.323 | 1.721 | 2.080 | 2.414 | 2.831 | 3.135 | 3.819 |
| 22 | .686 | .858 | 1.321 | 1.717 | 2.074 | 2.406 | 2.819 | 3.119 | 3.792 |
| 23 | .685 | .858 | 1.319 | 1.714 | 2.069 | 2.398 | 2.807 | 3.104 | 3.767 |
| 24 | .685 | .857 | 1.318 | 1.711 | 2.064 | 2.391 | 2.797 | 3.090 | 3.745 |
| 25 | .684 | .856 | 1.316 | 1.708 | 2.060 | 2.385 | 2.787 | 3.078 | 3.725 |
| 26 | .684 | .856 | 1.315 | 1.706 | 2.056 | 2.379 | 2.779 | 3.067 | 3.707 |
| 27 | .684 | .855 | 1.314 | 1.703 | 2.052 | 2.373 | 2.771 | 3.056 | 3.690 |
| 28 | .683 | .855 | 1.313 | 1.701 | 2.048 | 2.368 | 2.763 | 3.047 | 3.674 |
| 29 | .683 | .854 | 1.311 | 1.699 | 2.045 | 2.364 | 2.756 | 3,.038 | 3.659 |
| 30 | .683 | .854 | 1.310 | 1.697 | 2.042 | 2.360 | 2.750 | 3.030 | 3.646 |
| 35 | .682 | .852 | 1.306 | 1.690 | 2.030 | 2.342 | 2.724 | 2.996 | 3.591 |
| 40 | .681 | .851 | 1.303 | 1.684 | 2.021 | 2.329 | 2.704 | 2.971 | 3.551 |
| 45 | .680 | .850 | 1.301 | 1.680 | 2.014 | 2.319 | 2.690 | 2.952 | 3.520 |
| 50 | .680 | .849 | 1.299 | 1.676 | 2.008 | 2.310 | 2.678 | 2.937 | 3.496 |
| 55 | .679 | .849 | 1.297 | 1.673 | 2.004 | 2.304 | 2.669 | 2.925 | 3.476 |
| 60 | .679 | .848 | 1.296 | 1.671 | 2.000 | 2.299 | 2.660 | 2.915 | 3.460 |
| 70 | .678 | .847 | 1.294 | 1.667 | 1.994 | 2.290 | 2.648 | 2.899 | 3.435 |
| 80 | .678 | .847 | 1.293 | 1.665 | 1.989 | 2.284 | 2.638 | 2.887 | 3.416 |
| 90 | .678 | .846 | 1.291 | 1.662 | 1.986 | 2.279 | 2.631 | 2.878 | 3.402 |
| 100 | .677 | .846 | 1.290 | 1.661 | 1.982 | 2.276 | 2.625 | 2.871 | 3.390 |
| 120 | .677 | .845 | 1.289 | 1.658 | 1.980 | 2.270 | 2.617 | 2.860 | 3.373 |
| ∞ | .6745 | .8416 | 1.2816 | 1.6448 | 1.9600 | 2.2414 | 2.5758 | 2.8070 | 3.2905 |

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## Appendix C Significance of r [1]

| df | 10% | 5% | 2% | 1% |
|---|---|---|---|---|
| 3 | 0.805 | 0.878 | 0.934 | 0.959 |
| 4 | .729 | .811 | .882 | .917 |
| 5 | .669 | .754 | .833 | .874 |
| 6 | .622 | .707 | .789 | .834 |
| 7 | .582 | .666 | .750 | .798 |
| 8 | .549 | .632 | .716 | .765 |
| 9 | .521 | .602 | .685 | .735 |
| 10 | .497 | .576 | .658 | .708 |
| 11 | .476 | .553 | .634 | .684 |
| 12 | .458 | .532 | .612 | .661 |
| 13 | .441 | .514 | .592 | .641 |
| 14 | .426 | .497 | .574 | .623 |
| 15 | .412 | .482 | .558 | .606 |
| 16 | .400 | .468 | .542 | .590 |
| 17 | .389 | .456 | .528 | .575 |
| 18 | .378 | .444 | .516 | .561 |
| 19 | .369 | .433 | .503 | .549 |
| 20 | .360 | .423 | .492 | .537 |
| 25 | .323 | .381 | .445 | .487 |
| 30 | .295 | .349 | .409 | .449 |
| 35 | .275 | .325 | .381 | .418 |
| 40 | .257 | .304 | .358 | .393 |
| 45 | .243 | .288 | .338 | .372 |
| 50 | .231 | .273 | .322 | .354 |
| 60 | .211 | .250 | .295 | .325 |
| 70 | .195 | .232 | .274 | .302 |
| 80 | .183 | .217 | .256 | .283 |
| 90 | .173 | .205 | .242 | .267 |
| 100 | .164 | .195 | .230 | .254 |
| 150 | .134 | .160 | .189 | .208 |
| 200 | .116 | .138 | .164 | .181 |
| 300 | .095 | .113 | .134 | .148 |
| 400 | .082 | .098 | .116 | .128 |
| 500 | 0.073 | 0.088 | 0.104 | 0.115 |

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## Appendix D Table for testing skewness (one-tailed percentage points of the distribution of $\sqrt{b_1} = g_1 = \frac{m_3}{m_2^{\frac{3}{2}}}$) 1/

| Size of sample *n* | - - Percentage points - - 5% | 1% | Standard deviation |
|---|---|---|---|
| 25 | .711 | 1.061 | .4354 |
| 30 | .661 | .982 | .4052 |
| 35 | .621 | .921 | .3804 |
| 40 | .587 | .869 | .3596 |
| 45 | .558 | .825 | .3418 |
| 50 | .533 | .787 | .3264 |
| 60 | .492 | .723 | .3009 |
| 70 | .459 | .673 | .2806 |
| 80 | .432 | .631 | .2638 |
| 90 | .409 | .596 | .2498 |
| 100 | .389 | .567 | .2377 |
| 125 | .350 | .508 | .2139 |
| 150 | .321 | .464 | .1961 |
| 175 | .298 | .430 | .1820 |
| 200 | .280 | .403 | .1706 |
| 250 | .251 | .360 | .1531 |
| 300 | .230 | .329 | .1400 |
| 350 | .213 | .305 | .1298 |
| 400 | .200 | .285 | .1216 |
| 450 | .188 | .269 | .1147 |
| 500 | .179 | .255 | .1089 |

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## Appendix E Values of F [1/]

| Denominator *df* | Probability of a larger *F* | Numerator *df* 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.100 | 39.66 | 49.50 | 53.59 | 55.83 | 57.24 | 58.20 | 58.91 | 59.44 | 59.86 |
| | 0.050 | 161.40 | 199.50 | 215.70 | 224.60 | 230.20 | 234.00 | 236.80 | 238.90 | 240.50 |
| | 0.025 | 647.80 | 799.50 | 864.20 | 899.60 | 921.80 | 937.10 | 948.20 | 9567.00 | 963.50 |
| | 0.010 | 4052.00 | 4999.50 | 5403.00 | 5625.00 | 5764.00 | 5859.00 | 5928.00 | 5982.00 | 6022.00 |
| | 0.005 | 16211.00 | 20000.00 | 21615.00 | 22500.00 | 23056.00 | 23437.00 | 23715.00 | 23925.00 | 24091.00 |
| 2 | 0.100 | 8.53 | 9.00 | 9.16 | 9.24 | 9.29 | 9.33 | 9.35 | 9.37 | 9.38 |
| | 0.050 | 18.51 | 19.00 | 19.16 | 19.25 | 19.30 | 19.33 | 9.35 | 19.37 | 19.38 |
| | 0.025 | 38.51 | 39.00 | 39.17 | 39.25 | 39.30 | 39.33 | 39.36 | 39.37 | 39.39 |
| | 0.010 | 98.50 | 99.00 | 99.17 | 99.25 | 99.30 | 99.33 | 99.36 | 99.37 | 99.39 |
| | 0.005 | 198.50 | 199.00 | 199.20 | 199.20 | 199.30 | 199.30 | 199.40 | 199.40 | 199.40 |
| 3 | 0.100 | 5.54 | 5.46 | 5.39 | 5.34 | 5.31 | 5.28 | 5.27 | 5.25 | 5.24 |
| | 0.050 | 10.13 | 9.55 | 9.28 | 9.12 | 9.01 | 8.94 | 8.89 | 8.85 | 8.81 |
| | 0.025 | 17.44 | 16.04 | 15.44 | 15.10 | 14.88 | 14.73 | 14.62 | 14.54 | 14.47 |
| | 0.010 | 34.12 | 30.82 | 29.46 | 28.71 | 28.24 | 17.91 | 27.67 | 27.49 | 27.35 |
| | 0.005 | 55.55 | 49.80 | 47.47 | 46.19 | 45.39 | 14.84 | 44.43 | 44.13 | 43.88 |
| 4 | 0.100 | 4.54 | 4.32 | 4.19 | 4.11 | 4.05 | 4.01 | 3.98 | 5.95 | 3.94 |
| | 0.050 | 7.71 | 6.94 | 659.00 | 6.39 | 6.26 | 6.16 | 6.09 | 6.04 | 6.00 |
| | 0.025 | 12.22 | 10.65 | 9.98 | 9.60 | 9.36 | 9.20 | 9.07 | 8.98 | 8.90 |
| | 0.010 | 21.20 | 18.00 | 16.69 | 15.98 | 15.52 | 15.21 | 4.98 | 14.80 | 14.66 |
| | 0.005 | 31.33 | 26.28 | 2426.00 | 23.15 | 22.46 | 21.97 | 11.62 | 21.35 | 21.14 |
| 5 | 0.100 | 4.06 | 3.78 | 3.62 | 3.52 | 3.45 | 3.40 | 3.37 | 3.34 | 3.52 |
| | 0.050 | 6.61 | 5.79 | 5.41 | 5.19 | 5.05 | 4.95 | 4.88 | 4.82 | 4.77 |
| | 0.025 | 10.01 | 8.43 | 7.76 | 7.39 | 7.15 | 6.98 | 6.85 | 6.76 | 6.68 |
| | 0.010 | 16.26 | 13.27 | 12.06 | 11.39 | 10.97 | 10.67 | 10.46 | 10.29 | 10.16 |
| | 0.005 | 22.78 | 18.31 | 16.53 | 1556.00 | 14.94 | 14.51 | 14.20 | 13.96 | 13.77 |
| 6 | 0.100 | 3.78 | 3.46 | 3.29 | 3.18 | 3.11 | 3.05 | 3.01 | 2.98 | 2.96 |
| | 0.050 | 5.99 | 5.14 | 4.76 | 4.53 | 4.39 | 4.28 | 4.21 | 4.15 | 4.10 |
| | 0.025 | 8.81 | 7.26 | 6.60 | 6.23 | 5.99 | 5.11 | 5.70 | 5.60 | 5.52 |
| | 0.010 | 13.75 | 10.92 | 9.78 | 9.15 | 8.75 | 6.47 | 8.26 | 8.10 | 7.98 |
| | 0.005 | 18.63 | 14.54 | 12.92 | 12.03 | 11.46 | 11.07 | 10.79 | 10.57 | 10.39 |
| 7 | 0.100 | 3.59 | 3.26 | 3.07 | 2.96 | 2.88 | 2.83 | 2.78 | 2.75 | 2.72 |
| | 0.050 | 5.59 | 4.74 | 4.35 | 4.12 | 3.97 | 3.87 | 3.79 | 3.73 | 3.68 |
| | 0.025 | 8.07 | 6.54 | 5.89 | 5.52 | 5.29 | 5.12 | 4.99 | 4.90 | 4.82 |
| | 0.010 | 12.25 | 9.55 | 8.45 | 7.85 | 7.46 | 7.19 | 6.99 | 6.84 | 6.72 |
| | 0.005 | 16.24 | 2.40 | 10.88 | 10.05 | 9.52 | 9.16 | 8.89 | 8.68 | 8.51 |

**Appendix E** Values of F [1/] —Continued

| Numerator *df* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 12 | 15 | 20 | 24 | 30 | 40 | 60 | 120 | ∞ | P |
| 60.19 | 60.71 | 61.22 | 61.74 | 62.00 | 62.26 | 62.53 | 62.79 | 63.06 | 63.33 | 0.100 |
| 241.90 | 243.90 | 245.90 | 248.00 | 249.10 | 250.10 | 251.10 | 252.20 | 253.30 | 254.30 | 0.050 |
| 968.60 | 976.70 | 984.90 | 993.10 | 997.20 | 1001.00 | 1006.00 | 1010.00 | 1014.00 | 1018.00 | 0.025 |
| 6056.00 | 6106.00 | 6157.00 | 6209.00 | 6235.00 | 6261.00 | 6287.00 | 6313.00 | 6339.00 | 6366.00 | 0.010 |
| 24224.00 | 24426.00 | 24630.00 | 24836.00 | 24940.00 | 25044.00 | 25148.00 | 23253.00 | 25359.00 | 25465.00 | 0.005 |
| 9.39 | 9.41 | 9.42 | 9.44 | 9.55 | 9.46 | 9.47 | 9.47 | 9.48 | 9.49 | 0.100 |
| 19.40 | 19.41 | 19.43 | 19.45 | 19.45 | 19.46 | 19.47 | 19.48 | 19.49 | 19.50 | 0.050 |
| 39.40 | 39.41 | 39.43 | 39.45 | 39.46 | 39.46 | 39.47 | 39.48 | 39.49 | 39.50 | 0.025 |
| 99.40 | 99.42 | 99.43 | 99.45 | 99.46 | 99.47 | 99.47 | 99.48 | 99.49 | 99.50 | 0.010 |
| 199.40 | 199.40 | 199.40 | 199.40 | 199.50 | 199.50 | 199.50 | 119.50 | 199.50 | 199.50 | 0.005 |
| 5.23 | 5.22 | 5.20 | 5.18 | 5.18 | 5.17 | 5.16 | 5.15 | 5.14 | 5.13 | 0.100 |
| 8.79 | 8.74 | 8.70 | 8.86 | 8.64 | 8.62 | 8.59 | 8.57 | 8.55 | 8.53 | 0.050 |
| 14.42 | 14.34 | 14.25 | 14.17 | 14.12 | 14.08 | 14.04 | 13.99 | 13.95 | 13.91 | 0.025 |
| 2.23 | 27.05 | 26.87 | 5.69 | 26.6 | 26.50 | 26.41 | 26.32 | 26.22 | 26.13 | 0.010 |
| 43.69 | 43.39 | 43.08 | 42.78 | 42.62 | 42.47 | 42.31 | 42.15 | 41.99 | 41.83 | 0.005 |
| 3.92 | 3.90 | 3.87 | 3.84 | 3.83 | 3.82 | 3.80 | 3.79 | 3.78 | 3.76 | 0.100 |
| 5.96 | 5.91 | 5.86 | 5.80 | 5.77 | 5.75 | 5.72 | 5.69 | 5.66 | 5.63 | 0.050 |
| 8.84 | 8.75 | 8.86 | 8.56 | 8.51 | 8.46 | 8.41 | 8.36 | 8.31 | 8.26 | 0.025 |
| 14.55 | 14.37 | 14.20 | 14.02 | 13.93 | 13.84 | 13.75 | 13.63 | 13.56 | 13.46 | 0.010 |
| 20.97 | 20.97 | 20.44 | 20.17 | 20.03 | 19.89 | 19.75 | 19.61 | 19.47 | 19.32 | 0.005 |
| 3.30 | 3.27 | 3.24 | 3.21 | 3.19 | 3.17 | 3.16 | 3.14 | 3.12 | 3.10 | 0.100 |
| 4.74 | 4.88 | 4.62 | 4.56 | 4.53 | 4.50 | 4.46 | 4.43 | 4.40 | 4.36 | 0.050 |
| 6.62 | 6.52 | 6.43 | 6.33 | 6.28 | 6.23 | 6.18 | 6.12 | 6.07 | 6.02 | 0.025 |
| 10.05 | 9.89 | 9.72 | 9.55 | 9.47 | 9.38 | 9.29 | 9.20 | 9.11 | 9.02 | 0.010 |
| 13.62 | 13.38 | 13.15 | 12.90 | 12.78 | 12.66 | 12.53 | 12.40 | 12.27 | 12.14 | 0.005 |
| 2.94 | 2.90 | 2.87 | 2.84 | 2.82 | 2.80 | 2.78 | 2.76 | 2.74 | 2.72 | 0.100 |
| 4.06 | 4.00 | 3.94 | 3.87 | 3.84 | 3.81 | 3.77 | 3.74 | 3.70 | 3.67 | 0.050 |
| 5.46 | 5.37 | 5.27 | 5.17 | 5.12 | 5.07 | 5.01 | 4.96 | 4.90 | 4.85 | 0.025 |
| 7.87 | 7.72 | 7.56 | 7.40 | 7.31 | 7.23 | 7.14 | 7.06 | 6.97 | 6.88 | 0.010 |
| 10.25 | 10.03 | 9.81 | 9.59 | 9.47 | 9.36 | 9.24 | 9.12 | 9.00 | 8.88 | 0.005 |
| 2.70 | 2.67 | 2.63 | 2.58 | 2.58 | 2.56 | 2.54 | 2.51 | 2.49 | 2.47 | 0.100 |
| 3.84 | 3.57 | 3.51 | 3.41 | 3.41 | 3.38 | 3.34 | 3.30 | 3.27 | 3.23 | 0.050 |
| 4.76 | 4.67 | 4.57 | 4.42 | 4.42 | 4.36 | 4.31 | 4.25 | 4.20 | 4.14 | 0.025 |
| 6.62 | 6.47 | 6.31 | 6.07 | 6.07 | 5.99 | 5.91 | 5.82 | 5.74 | 5.65 | 0.010 |
| 8.38 | 8.18 | 7.97 | 7.65 | 7.65 | 7.53 | 7.42 | 7.31 | 7.19 | 7.08 | 0.005 |

**Appendix E** Values of F [1/] —Continued

| Denominator *df* | Probability of a larger *F* | Numerator *df* 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 8 | 0.100 | 3.46 | 3.11 | 2.92 | 2.81 | 2.73 | 2.67 | 2.62 | 2.59 | 2.56 |
| | 0.050 | 5.32 | 4.46 | 4.07 | 3.84 | 3.69 | 3.58 | 3.50 | 3.44 | 3.39 |
| | 0.025 | 7.57 | 6.06 | 5.42 | 5.05 | 4.82 | 4.65 | 4.53 | 4.43 | 4.36 |
| | 0.010 | 11.26 | 8.65 | 7.59 | 7.01 | 6.63 | 6.37 | 6.11 | 6.03 | 5.91 |
| | 0.005 | 14.69 | 1.04 | 9.60 | 8.81 | 8.30 | 7.95 | 7.69 | 7.50 | 7.54 |
| 9 | 0.100 | 3.36 | 3.01 | 2.81 | 2.69 | 2.61 | 2.55 | 2.51 | 2.47 | 2.44 |
| | 0.050 | 5.12 | 4.26 | 3.86 | 3.63 | 3.48 | 3.37 | 3.29 | 3.23 | 3.18 |
| | 0.025 | 7.21 | 5.71 | 5.08 | 4.72 | 4.41 | 4.32 | 4.20 | 4.10 | 4.03 |
| | 0.010 | 10.56 | 8.02 | 6.99 | 6.42 | 6.06 | 5.80 | 5.61 | 5.47 | 5.35 |
| | 0.005 | 13.61 | 10.11 | 8.72 | 7.96 | 7.47 | 7.13 | 6.88 | 6.69 | 6.54 |
| 10 | 0.100 | 3.29 | 2.92 | 2.73 | 2.61 | 2.52 | 2.46 | 2.41 | 2.38 | 2.35 |
| | 0.050 | 4.96 | 4.10 | 3.71 | 3.41 | 3.33 | 3.22 | 3.14 | 3.07 | 3.02 |
| | 0.025 | 6.94 | 5.46 | 4.83 | 4.47 | 4.24 | 4.07 | 3.95 | 3.85 | 3.78 |
| | 0.010 | 10.04 | 7.56 | 6.55 | 5.99 | 5.64 | 5.39 | 5.20 | 5.06 | 4.94 |
| | 0.005 | 12.83 | 9.43 | 8.08 | 7.34 | 6.87 | 6.54 | 6.30 | 6.12 | 5.97 |
| 11 | 0.100 | 3.23 | 2.86 | 2.66 | 2.54 | 2.45 | 2.39 | 2.34 | 2.30 | 2.27 |
| | 0.050 | 4.84 | 3.98 | 3.59 | 3.36 | 3.20 | 3.09 | 3.01 | 2.95 | 2.90 |
| | 0.025 | 6.72 | 5.26 | 4.63 | 4.28 | 4.04 | 3.88 | 3.76 | 3.66 | 3.59 |
| | 0.010 | 9.65 | 7.21 | 6.22 | 5.67 | 5.32 | 5.07 | 4.89 | 4.74 | 4.63 |
| | 0.005 | 12.23 | 8.91 | 7.60 | 6.88 | 6.42 | 6.10 | 5.86 | 5.68 | 5.54 |
| 12 | 0.100 | 3.18 | 2.81 | 2.61 | 2.46 | 2.39 | 2.33 | 2.28 | 2.24 | 2.21 |
| | 0.050 | 4.75 | 3.89 | 3.49 | 3.26 | 3.11 | 3.00 | 2.91 | 2.85 | 2.80 |
| | 0.025 | 6.55 | 5.10 | 4.47 | 4.12 | 3.89 | 3.73 | 3.61 | 3.51 | 3.44 |
| | 0.010 | 9.33 | 6.93 | 5.95 | 5.41 | 5.06 | 4.82 | 4.64 | 4.50 | 4.39 |
| | 0.005 | 11.75 | 8.51 | 7.23 | 6.52 | 6.07 | 5.76 | 5.52 | 5.35 | 5.20 |
| 13 | 0.100 | 3.14 | 2.76 | 2.56 | 2.43 | 2.35 | 2.28 | 2.23 | 2.20 | 2.16 |
| | 0.050 | 4.67 | 3.81 | 3.41 | 3.18 | 3.03 | 2.92 | 2.83 | 2.77 | 2.71 |
| | 0.025 | 6.41 | 4.97 | 4.35 | 4.00 | 3.77 | 3.60 | 3.48 | 3.39 | 3.31 |
| | 0.010 | 9.07 | 6.70 | 5.74 | 5.21 | 4.86 | 4.62 | 4.44 | 4.30 | 4.19 |
| | 0.005 | 11.37 | 6.19 | 6.93 | 6.23 | 5.79 | 5.48 | 5.25 | 5.08 | 4.94 |
| 14 | 0.100 | 3.10 | 2.73 | 2.52 | 2.39 | 2.31 | 2.24 | 2.19 | 2.15 | 2.12 |
| | 0.050 | 4.60 | 3.74 | 3.34 | 3.11 | 2.96 | 2.85 | 2.76 | 2.70 | 2.65 |
| | 0.025 | 6.30 | 4.86 | 4.24 | 3.89 | 3.66 | 3.50 | 3.38 | 3.29 | 3.21 |
| | 0.010 | 8.86 | 6.51 | 3.56 | 5.04 | 4.69 | 4.46 | 4.21 | 4.14 | 4.030 |
| | 0.005 | 11.06 | 7.92 | 6.68 | 6.00 | 5.36 | 5.26 | 5.03 | 4.86 | 4.720 |

**Appendix E** Values of F [1/] —Continued

| Numerator *df* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 12 | 15 | 20 | 24 | 30 | 40 | 60 | 120 | ∞ | P |
| 2.54 | 2.50 | 2.46 | 2.42 | 2.40 | 2.38 | 2.36 | 2.34 | 2.32 | 2.29 | 0.100 |
| 3.35 | 3.28 | 3.22 | 3.15 | 3.12 | 3.08 | 3.04 | 3.01 | 2.97 | 2.93 | 0.050 |
| 4.30 | 4.20 | 4.10 | 4.00 | 3.95 | 3.89 | 3.84 | 3.78 | 3.73 | 3.67 | 0.025 |
| 5.81 | 5.67 | 5.52 | 5.36 | 5.28 | 5.20 | 5.12 | 5.03 | 4.95 | 4.86 | 0.010 |
| 7.21 | 7.01 | 6.81 | 6.61 | 6.50 | 6.40 | 6.29 | 6.18 | 6.06 | 5.95 | 0.005 |
| 2.42 | 2.38 | 2.34 | 2.3 | 2.28 | 2.25 | 2.23 | 2.21 | 2.18 | 2.16 | 0.100 |
| 3.14 | 3.07 | 3.01 | 2.94 | 2.90 | 2.86 | 2.83 | 2.79 | 2.75 | 2.71 | 0.050 |
| 3.96 | 3.87 | 3.77 | 3.67 | 3.61 | 3.56 | 3.51 | 3.45 | 3.39 | 3.33 | 0.025 |
| 5.26 | 5.11 | 4.96 | 4.81 | 4.73 | 4.65 | 4.57 | 4.48 | 4.40 | 4.31 | 0.010 |
| 6.42 | 6.23 | 6.03 | 5.83 | 5.73 | 5.62 | 5.52 | 5.41 | 5.30 | 5.19 | 0.005 |
| 2.32 | 2.28 | 2.24 | 2.20 | 2.18 | 2.16 | 2.13 | 2.11 | 2.08 | 2.06 | 0.100 |
| 2.98 | 2.91 | 2.85 | 2.77 | 2.74 | 2.70 | 2.66 | 2.62 | 2.58 | 2.54 | 0.050 |
| 3.72 | 3.62 | 3.52 | 3.42 | 3.37 | 3.31 | 3.26 | 3.20 | 3.14 | 3.08 | 0.025 |
| 4.85 | 4.71 | 4.56 | 4.41 | 4.35 | 4.25 | 4.17 | 4.08 | 4.00 | 3.91 | 0.010 |
| 5.85 | 5.66 | 5.47 | 5.27 | 5.17 | 5.07 | 4.97 | 4.86 | 4.75 | 4.64 | 0.005 |
| 2.25 | 2.21 | 2.17 | 2.12 | 2.10 | 2.08 | 2.05 | 2.03 | 2.00 | 1.97 | 0.100 |
| 2.85 | 2.79 | 2.72 | 2.65 | 2.61 | 2.57 | 2.53 | 2.49 | 2.43 | 2.40 | 0.050 |
| 3.53 | 3.43 | 3.33 | 3.23 | 3.17 | 3.12 | 3.06 | 3.00 | 2.91 | 2.88 | 0.025 |
| 4.54 | 4.40 | 4.25 | 4.1 | 4.02 | 3.94 | 3.86 | 3.78 | 3.69 | 3.60 | 0.010 |
| 5.42 | 5.24 | 5.05 | 4.86 | 4.76 | 4.65 | 4.55 | 4.44 | 4.31 | 4.23 | 0.005 |
| 2.19 | 2.15 | 2.10 | 2.06 | 2.04 | 2.01 | 1.99 | 1.96 | 1.93 | 1.90 | 0.100 |
| 2.75 | 2.69 | 2.62 | 2.54 | 2.51 | 2.47 | 2.43 | 2.38 | 2.34 | 2.30 | 0.050 |
| 3.37 | 3.28 | 3.18 | 3.07 | 3.02 | 2.96 | 2.91 | 2.05 | 2.79 | 2.72 | 0.025 |
| 4.30 | 4.16 | 4.01 | 3.86 | 3.78 | 3.70 | 3.62 | 3.54 | 3.45 | 3.36 | 0.010 |
| 5.09 | 4.91 | 4.72 | 4.53 | 4.43 | 4.33 | 4.23 | 4.12 | 4.01 | 3.90 | 0.005 |
| 2.14 | 2.10 | 2.05 | 2.01 | 1.98 | 1.96 | 1.93 | 1.90 | 1.81 | 1.85 | 0.100 |
| 2.67 | 2.60 | 2.53 | 2.46 | 2.42 | 2.38 | 2.34 | 2.30 | 2.25 | 2.21 | 0.050 |
| 3.25 | 3.15 | 3.05 | 2.95 | 2.89 | 2.84 | 2.78 | 2.72 | 2.66 | 2.60 | 0.025 |
| 4.10 | 3.96 | 3.82 | 3.66 | 3.50 | 3.51 | 3.43 | 3.34 | 3.25 | 3.17 | 0.010 |
| 4.82 | 4.64 | 4.46 | 4.27 | 4.17 | 4.07 | 3.97 | 3.87 | 3.76 | 3.65 | 0.005 |
| 2.10 | 2.05 | 2.01 | 1.96 | 1.94 | 1.91 | 1.89 | 1.86 | 1.83 | 1.80 | 0.100 |
| 2.60 | 2.53 | 2.46 | 2.39 | 2.35 | 2.31 | 2.27 | 2.22 | 2.18 | 2.13 | 0.050 |
| 3.15 | 3.05 | 2.95 | 2.84 | 2.79 | 2.73 | 2.67 | 2.61 | 2.55 | 2.49 | 0.025 |
| 3.94 | 3.80 | 3.66 | 3.51 | 3.43 | 3.35 | 3.27 | 3.18 | 3.09 | 3.00 | 0.010 |
| 4.60 | 4.43 | 4.25 | 4.06 | 3.96 | 3.86 | 3.76 | 3.66 | 3.55 | 3.44 | 0.005 |

**Appendix E** Values of F [1/] —Continued

| Denominator *df* | Probability of a larger *F* | Numerator *df* 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 15 | 0.100 | 3.07 | 2.70 | 2.49 | 2.36 | 2.27 | 2.21 | 2.16 | 2.12 | 2.09 |
| | 0.050 | 4.54 | 3.68 | 3.29 | 3.06 | 2.90 | 2.79 | 2.71 | 2.64 | 2.59 |
| | 0.025 | 6.20 | 4.77 | 4.15 | 3.80 | 3.58 | 3.41 | 3.29 | 3.20 | 3.12 |
| | 0.010 | 8.66 | 6.36 | 5.42 | 4.89 | 4.56 | 4.32 | 4.14 | 4.00 | 3.89 |
| | 0.005 | 10.60 | 7.70 | 6.48 | 5.80 | 5.37 | 5.07 | 4.85 | 4.67 | 4.54 |
| 16 | 0.100 | 3.05 | 2.67 | 2.46 | 2.33 | 2.24 | 2.18 | 2.13 | 2.09 | 2.06 |
| | 0.050 | 4.49 | 3.83 | 3.24 | 3.01 | 2.85 | 2.74 | 2.66 | 2.59 | 2.54 |
| | 0.025 | 6.12 | 4.69 | 4.08 | 3.73 | 3.50 | 3.34 | 3.22 | 3.12 | 3.05 |
| | 0.010 | 8.53 | 6.23 | 5.29 | 4.77 | 4.44 | 4.20 | 4.03 | 3.89 | 3.78 |
| | 0.005 | 10.58 | 7.51 | 6.30 | 5.64 | 5.21 | 4.91 | 4.69 | 4.52 | 4.38 |
| 17 | 0.100 | 3.03 | 2.64 | 2.44 | 2.31 | 2.22 | 2.15 | 2.10 | 2.06 | 2.03 |
| | 0.050 | 4.45 | 3.59 | 3.20 | 5.96 | 2.81 | 2.70 | 2.61 | 2.55 | 2.49 |
| | 0.025 | 6.04 | 4.62 | 4.01 | 3.66 | 3.44 | 3.28 | 3.16 | 3.06 | 2.95 |
| | 0.010 | 8.40 | 6.11 | 5.18 | 4.67 | 4.34 | 4.10 | 3.93 | 3.79 | 3.88 |
| | 0.005 | 10.38 | 7.35 | 6.16 | 5.50 | 5.07 | 4.78 | 4.56 | 4.39 | 4.25 |
| 18 | 0.100 | 3.01 | 2.62 | 2.42 | 2.29 | 2.20 | 2.13 | 2.08 | 2.04 | 2.00 |
| | 0.050 | 4.41 | 3.35 | 3.16 | 2.93 | 2.77 | 2.66 | 2.58 | 2.51 | 2.46 |
| | 0.025 | 5.98 | 4.56 | 3.95 | 3.61 | 3.38 | 3.22 | 3.10 | 3.01 | 2.93 |
| | 0.010 | 8.29 | 6.01 | 5.09 | 4.58 | 4.25 | 4.01 | 3.84 | 3.71 | 3.60 |
| | 0.005 | 10.22 | 7.21 | 6.03 | 5.37 | 4.98 | 4.66 | 4.44 | 4.28 | 4.14 |
| 19 | 0.100 | 2.99 | 2.61 | 2.40 | 2.27 | 2.18 | 2.11 | 2.06 | 2.02 | 1.98 |
| | 0.050 | 4.38 | 3.52 | 3.13 | 2.90 | 2.74 | 2.63 | 2.54 | 2.48 | 2.42 |
| | 0.025 | 5.92 | 4.51 | 3.90 | 3.56 | 3.33 | 3.17 | 3.05 | 2.96 | 2.88 |
| | 0.010 | 8.18 | 5.93 | 5.01 | 4.50 | 4.17 | 3.94 | 3.77 | 3.63 | 3.52 |
| | 0.005 | 10.07 | 7.09 | 5.92 | 5.27 | 4.85 | 4.56 | 4.34 | 4.18 | 4.04 |
| 20 | 0.100 | 2.97 | 2.59 | 2.38 | 2.25 | 2.16 | 2.09 | 2.04 | 2.00 | 1.96 |
| | 0.050 | 4.35 | 3.49 | 3.10 | 2.87 | 2.71 | 2.60 | 2.51 | 2.45 | 2.39 |
| | 0.025 | 5.87 | 4.46 | 3.86 | 3.51 | 3.29 | 3.13 | 3.01 | 2.91 | 2.84 |
| | 0.010 | 8.10 | 5.85 | 4.94 | 4.43 | 4.10 | 3.87 | 3.70 | 3.56 | 3.46 |
| | 0.005 | 9.94 | 6.99 | 5.62 | 5.17 | 4.76 | 4.47 | 4.26 | 4.09 | 3.96 |
| 21 | 0.100 | 2.96 | 2.57 | 2.36 | 2.23 | 2.14 | 2.08 | 2.02 | 1.98 | 1.95 |
| | 0.050 | 4.32 | 3.47 | 3.07 | 2.84 | 2.68 | 2.57 | 2.49 | 2.42 | 2.37 |
| | 0.025 | 5.83 | 4.42 | 3.82 | 3.48 | 3.25 | 3.09 | 2.97 | 2.87 | 2.80 |
| | 0.010 | 8.02 | 5.78 | 4.87 | 4.37 | 4.04 | 3.81 | 3.64 | 3.51 | 3.40 |
| | 0.005 | 9.83 | 6.89 | 5.73 | 5.09 | 4.68 | 4.39 | 4.18 | 4.01 | 3.88 |

**Appendix E** Values of F [1/] —Continued

| Numerator *df* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 12 | 15 | 20 | 24 | 30 | 40 | 60 | 120 | ∞ | P |
| 2.06 | 2.02 | 1.97 | 1.92 | 1.90 | 1.87 | 1.85 | 1.82 | 1.79 | 1.76 | 0.100 |
| 2.56 | 2.48 | 2.40 | 2.33 | 2.29 | 2.25 | 2.20 | 2.16 | 2.11 | 2.07 | 0.050 |
| 3.06 | 2.96 | 2.86 | 2.76 | 2.70 | 2.64 | 2.59 | 2.52 | 2.46 | 2.40 | 0.025 |
| 3.80 | 3.67 | 3.52 | 3.37 | 3.29 | 3.21 | 3.13 | 3.05 | 2.96 | 2.87 | 0.010 |
| 4.42 | 4.25 | 4.07 | 3.88 | 3.79 | 3.69 | 3.58 | 3.48 | 3.12 | 3.26 | 0.005 |
| 2.03 | 1.99 | 1.94 | 1.89 | 1.87 | 1.84 | 1.81 | 1.78 | 1.75 | 1.72 | 0.100 |
| 2.49 | 2.42 | 2.35 | 2.28 | 2.24 | 2.19 | 2.15 | 2.11 | 2.06 | 2.01 | 0.050 |
| 2.99 | 2.89 | 2.79 | 2.68 | 2.63 | 2.57 | 2.51 | 2.45 | 2.38 | 2.32 | 0.025 |
| 3.69 | 3.35 | 3.41 | 3.26 | 3.18 | 3.10 | 3.02 | 2.93 | 2.18 | 2.75 | 0.010 |
| 4.27 | 4.10 | 3.92 | 3.73 | 3.64 | 3.54 | 3.44 | 3.33 | 3.22 | 3.11 | 0.005 |
| 2.00 | 1.96 | 1.91 | 1.86 | 1.84 | 1.81 | 1.78 | 1.75 | 1.72 | 1.69 | 0.100 |
| 2.45 | 2.38 | 2.31 | 2.23 | 2.19 | 2.15 | 2.10 | 2.06 | 2.01 | 1.96 | 0.050 |
| 2.92 | 2.82 | 2.72 | 2.62 | 2.56 | 2.50 | 2.44 | 2.38 | 2.32 | 2.25 | 0.025 |
| 3.39 | 3.46 | 3.31 | 3.16 | 3.08 | 3.00 | 2.92 | 2.83 | 2.71 | 2.65 | 0.010 |
| 4.14 | 3.97 | 3.79 | 3.61 | 3.31 | 3.41 | 3.31 | 3.21 | 3.10 | 2.98 | 0.005 |
| 1.98 | 1.93 | 1.89 | 1.84 | 1.81 | 1.78 | 1.75 | 1.72 | 1.69 | 1.66 | 0.100 |
| 2.41 | 2.34 | 2.27 | 2.19 | 2.15 | 2.11 | 2.06 | 2.02 | 1.97 | 1.92 | 0.050 |
| 2.87 | 2.77 | 2.67 | 2.56 | 2.50 | 2.44 | 2.38 | 2.32 | 2.26 | 2.19 | 0.025 |
| 3.51 | 3.37 | 3.23 | 3.08 | 3.00 | 2.92 | 2.84 | 2.75 | 2.66 | 2.57 | 0.010 |
| 4.03 | 3.86 | 3.66 | 3.50 | 3.40 | 3.30 | 3.20 | 3.10 | 2.99 | 2.87 | 0.005 |
| 1.96 | 1.91 | 1.86 | 1.81 | 1.79 | 1.76 | 1.73 | 1.70 | 1.67 | 1.63 | 0.100 |
| 2.38 | 2.31 | 2.23 | 2.16 | 2.11 | 2.07 | 2.03 | 1.98 | 1.93 | 1.88 | 0.050 |
| 2.82 | 2.72 | 2.62 | 2.51 | 2.45 | 2.39 | 2.33 | 2.27 | 2.20 | 2.13 | 0.025 |
| 3.43 | 3.30 | 3.15 | 3.00 | 2.92 | 2.84 | 2.76 | 2.67 | 2.58 | 2.49 | 0.010 |
| 3.93 | 3.76 | 3.59 | 3.40 | 3.31 | 3.21 | 3.11 | 3.00 | 2.89 | 2.78 | 0.005 |
| 1.94 | 1.89 | 1.84 | 1.79 | 1.77 | 1.74 | 1.71 | 1.68 | 1.64 | 1.61 | 0.100 |
| 2.35 | 2.28 | 2.20 | 2.12 | 2.08 | 2.04 | 1.99 | 1.95 | 1.90 | 1.84 | 0.050 |
| 2.77 | 2.58 | 2.57 | 2.46 | 2.41 | 2.35 | 2.29 | 2.22 | 2.16 | 2.09 | 0.025 |
| 3.37 | 3.23 | 3.09 | 2.94 | 2.86 | 2.78 | 2.69 | 2.61 | 2.52 | 2.42 | 0.010 |
| 3.85 | 3.88 | 3.50 | 3.32 | 3.22 | 3.12 | 3.02 | 2.92 | 2.81 | 2.69 | 0.005 |
| 1.02 | 1.87 | 1.83 | 1.78 | 1.75 | 1.72 | 1.69 | 1.66 | 1.62 | 1.59 | 0.100 |
| 2.32 | 2.25 | 2.18 | 2.10 | 2.05 | 2.01 | 1.96 | 1.92 | 1.87 | 1.81 | 0.030 |
| 2.73 | 2.64 | 2.53 | 2.42 | 2.37 | 2.31 | 2.25 | 2.18 | 2.11 | 2.04 | 0.025 |
| 3.31 | 3.17 | 3.03 | 2.88 | 2.80 | 2.72 | 2.64 | 2.55 | 2.46 | 2.36 | 0.010 |
| 3.77 | 3.60 | 3.43 | 3.24 | 3.15 | 3.05 | 2.95 | 2.84 | 2.73 | 2.61 | 0.005 |

**Appendix E** Values of F [1/] —Continued

| Denominator *df* | Probability of a larger *F* | Numerator *df* 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 22 | 0.100 | 2.95 | 2.56 | 2.35 | 2.22 | 2.13 | 2.06 | 2.01 | 1.97 | 1.93 |
| | 0.050 | 4.30 | 3.44 | 3.05 | 2.82 | 2.66 | 2.55 | 2.48 | 2.40 | 2.34 |
| | 0.025 | 5.79 | 4.38 | 3.78 | 3.44 | 3.22 | 3.05 | 2.93 | 2.84 | 2.76 |
| | 0.010 | 7.95 | 5.72 | 4.62 | 4.31 | 3.99 | 3.76 | 3.59 | 3.45 | 3.35 |
| | 0.005 | 9.73 | 6.81 | 5.65 | 5.02 | 4.61 | 4.32 | 4.11 | 3.94 | 3.81 |
| 23 | 0.100 | 2.94 | 2.55 | 2.34 | 2.21 | 2.11 | 2.05 | 1.99 | 1.95 | 1.92 |
| | 0.050 | 4.28 | 3.42 | 3.03 | 2.80 | 2.64 | 2.53 | 2.44 | 2.37 | 2.32 |
| | 0.025 | 5.75 | 4.35 | 3.75 | 3.41 | 3.18 | 3.02 | 2.90 | 2.81 | 2.73 |
| | 0.010 | 7.88 | 5.66 | 4.76 | 4.26 | 3.94 | 3.71 | 3.54 | 3.41 | 3.30 |
| | 0.005 | 9.63 | 6.73 | 5.58 | 4.95 | 4.54 | 4.26 | 4.05 | 3.88 | 3.75 |
| 24 | 0.100 | 2.93 | 2.54 | 2.33 | 2.19 | 2.10 | 2.04 | 1.98 | 1.94 | 1.91 |
| | 0.050 | 4.26 | 3.40 | 3.01 | 2.78 | 2.62 | 2.51 | 2.42 | 2.36 | 2.30 |
| | 0.025 | 5.72 | 4.32 | 3.72 | 3.38 | 3.15 | 2.99 | 2.87 | 2.78 | 2.70 |
| | 0.010 | 7.82 | 5.61 | 4.72 | 4.22 | 3.90 | 3.67 | 3.50 | 3.36 | 3.26 |
| | 0.005 | 9.55 | 6.66 | 5.52 | 4.89 | 4.49 | 4.20 | 3.99 | 3.83 | 3.69 |
| 25 | 0.100 | 2.92 | 2.53 | 2.32 | 2.18 | 2.09 | 2.02 | 1.97 | 1.93 | 1.89 |
| | 0.050 | 4.24 | 3.39 | 2.99 | 2.76 | 2.60 | 2.49 | 2.40 | 2.34 | 2.28 |
| | 0.025 | 5.69 | 4.29 | 3.69 | 3.35 | 3.13 | 2.97 | 2.85 | 2.75 | 2.68 |
| | 0.010 | 7.77 | 5.57 | 4.68 | 4.18 | 3.85 | 3.63 | 3.46 | 3.32 | 3.22 |
| | 0.005 | 9.48 | 6.60 | 5.46 | 4.84 | 4.43 | 4.15 | 3.94 | 3.78 | 3.64 |
| 26 | 0.100 | 2.91 | 2.52 | 2.31 | 2.17 | 2.08 | 2.01 | 1.96 | 1.92 | 1.88 |
| | 0.050 | 4.23 | 3.37 | 2.98 | 2.74 | 2.59 | 2.47 | 2.39 | 2.32 | 2.27 |
| | 0.025 | 5.66 | 4.27 | 3.67 | 3.33 | 3.11 | 2.94 | 2.02 | 2.73 | 2.65 |
| | 0.010 | 7.72 | 5.53 | 4.64 | 4.14 | 3.82 | 3.59 | 3.42 | 3.29 | 3.18 |
| | 0.005 | 9.41 | 6.54 | 5.41 | 4.79 | 4.38 | 4.10 | 3.89 | 3.73 | 3.60 |
| 27 | 0.100 | 2.90 | 2.51 | 2.30 | 2.17 | 2.07 | 2.00 | 1.95 | 1.91 | 1.87 |
| | 0.050 | 4.21 | 3.35 | 2.96 | 2.73 | 2.57 | 2.46 | 2.37 | 2.31 | 2.25 |
| | 0.025 | 5.63 | 4.24 | 3.65 | 3.31 | 3.08 | 2.92 | 2.80 | 2.71 | 2.63 |
| | 0.010 | 7.68 | 5.49 | 4.60 | 4.11 | 3.78 | 3.56 | 3.39 | 3.26 | 3.15 |
| | 0.005 | 9.34 | 6.49 | 5.36 | 4.71 | 4.34 | 4.06 | 3.65 | 3.69 | 3.56 |
| 28 | 0.100 | 2.89 | 2.50 | 2.29 | 2.16 | 2.06 | 2.00 | 1.94 | 1.90 | 1.87 |
| | 0.050 | 4.20 | 3.34 | 2.95 | 2.71 | 2.56 | 2.45 | 2.36 | 2.29 | 2.24 |
| | 0.025 | 5.61 | 4.22 | 3.63 | 3.29 | 3.06 | 2.90 | 2.78 | 2.69 | 2.61 |
| | 0.010 | 7.64 | 5.45 | 4.57 | 4.07 | 3.75 | 3.53 | 3.36 | 3.23 | 3.12 |
| | 0.005 | 9.28 | 6.44 | 5.32 | 4.70 | 4.30 | 4.02 | 3.81 | 3.65 | 3.52 |

**Appendix E** Values of F [1/] —Continued

| Numerator *df* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 12 | 15 | 20 | 24 | 30 | 40 | 60 | 120 | ∞ | P |
| 1.90 | 1.86 | 1.81 | 1.76 | 1.73 | 1.70 | 1.67 | 1.64 | 1.60 | 1.57 | 0.100 |
| 2.30 | 2.23 | 2.15 | 2.07 | 2.03 | 1.98 | 1.94 | 1.89 | 1.84 | 1.78 | 0.050 |
| 2.70 | 2.60 | 2.50 | 2.39 | 2.33 | 2.27 | 2.21 | 2.14 | 2.08 | 2.00 | 0.025 |
| 3.26 | 3.12 | 2.98 | 2.83 | 2.73 | 2.67 | 2.58 | 2.50 | 2.40 | 2.31 | 0.010 |
| 3.70 | 3.34 | 3.36 | 3.18 | 3.08 | 2.98 | 2.88 | 2.77 | 2.66 | 2.55 | 0.005 |
| 1.89 | 1.84 | 1.80 | 1.74 | 1.72 | 1.69 | 1.66 | 1.62 | 1.59 | 1.55 | 0.100 |
| 2.27 | 2.20 | 2.13 | 2.05 | 2.01 | 1.96 | 1.91 | 1.86 | 1.81 | 1.76 | 0.050 |
| 2.67 | 2.57 | 2.47 | 2.36 | 2.30 | 2.24 | 2.18 | 2.11 | 2.01 | 1.97 | 0.025 |
| 3.21 | 3.07 | 2.93 | 2.78 | 2.70 | 2.62 | 2.54 | 2.45 | 2.33 | 2.26 | 0.010 |
| 3.64 | 3.47 | 3.30 | 3.12 | 3.02 | 2.92 | 2.82 | 2.71 | 2.60 | 2.48 | 0.005 |
| 1.88 | 1.03 | 1.78 | 1.73 | 1.70 | 1.67 | 1.64 | 1.61 | 1.57 | 1.53 | 0.100 |
| 2.25 | 2.18 | 2.11 | 2.03 | 1.98 | 1.94 | 1.89 | 1.84 | 1.79 | 1.73 | 0.050 |
| 2.64 | 2.54 | 2.44 | 2.33 | 2.27 | 2.21 | 2.15 | 2.08 | 2.01 | 1.94 | 0.025 |
| 3.17 | 3.03 | 2.89 | 2.74 | 2.66 | 2.58 | 2.49 | 2.40 | 2.31 | 2.21 | 0.010 |
| 3.59 | 3.42 | 3.25 | 3.06 | 2.97 | 2.87 | 2.77 | 2.66 | 2.55 | 2.43 | 0.005 |
| 1.87 | 1.82 | 1.77 | 1.72 | 1.70 | 1.66 | 1.63 | 1.59 | 1.56 | 1.52 | 0.100 |
| 2.24 | 2.16 | 2.09 | 2.01 | 1.98 | 1.92 | 1.87 | 1.82 | 1.77 | 1.71 | 0.050 |
| 2.61 | 2.51 | 2.41 | 2.30 | 2.24 | 2.18 | 2.12 | 2.05 | 1.98 | 1.91 | 0.025 |
| 3.13 | 2.99 | 2.11 | 2.70 | 2.62 | 2.54 | 2.45 | 2.36 | 2.27 | 2.17 | 0.010 |
| 3.34 | 3.37 | 3.20 | 3.01 | 2.92 | 2.11 | 2.72 | 2.61 | 2.50 | 2.38 | 0.005 |
| 1.86 | 1.81 | 1.76 | 1.71 | 1.68 | 1.65 | 1.61 | 1.58 | 1.54 | 1.50 | 0.100 |
| 2.22 | 2.15 | 2.07 | 1.99 | 1.95 | 1.90 | 1.85 | 1.80 | 1.75 | 1.69 | 0.050 |
| 2.59 | 2.49 | 2.39 | 2.28 | 2.22 | 2.16 | 2.09 | 2.03 | 1.95 | 1.88 | 0.025 |
| 3.09 | 2.96 | 2.11 | 2.66 | 2.58 | 2.50 | 2.42 | 2.33 | 2.23 | 2.13 | 0.010 |
| 3.49 | 3.33 | 3.13 | 2.97 | 2.87 | 2.77 | 2.67 | 2.56 | 2.45 | 2.33 | 0.005 |
| 1.85 | 1.80 | 1.75 | 1.70 | 1.67 | 1.64 | 1.60 | 1.57 | 1.53 | 1.49 | 0.100 |
| 2.20 | 2.13 | 2.06 | 1.97 | 1.93 | 1.88 | 1.84 | 1.79 | 1.73 | 1.67 | 0.050 |
| 2.57 | 2.47 | 2.36 | 2.25 | 2.19 | 2.13 | 2.07 | 2.00 | 1.93 | 1.85 | 0.025 |
| 3.05 | 2.93 | 2.71 | 2.63 | 2.33 | 2.47 | 2.38 | 2.29 | 2.20 | 2.10 | 0.010 |
| 3.45 | 3.28 | 3.11 | 2.93 | 2.83 | 2.73 | 2.63 | 2.52 | 2.41 | 2.29 | 0.005 |
| 1.84 | 1.79 | 1.74 | 1.69 | 1.66 | 1.63 | 1.59 | 1.57 | 1.52 | 1.48 | 0.100 |
| 2.19 | 2.12 | 2.04 | 1.96 | 1.91 | 1.87 | 1.82 | 1.77 | 1.71 | 1.65 | 0.050 |
| 2.55 | 2.43 | 2.34 | 2.23 | 2.17 | 2.11 | 2.05 | 1.98 | 1.91 | 1.83 | 0.025 |
| 3.03 | 2.90 | 2.75 | 2.60 | 2.52 | 2.44 | 2.35 | 2.26 | 2.17 | 2.06 | 0.010 |
| 3.41 | 3.25 | 3.07 | 2.89 | 1.79 | 2.69 | 2.59 | 2.48 | 2.37 | 2.25 | 0.005 |

**Appendix E** Values of F [1/] —Continued

| Denominator *df* | Probability of a larger *F* | Numerator *df* 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 29 | .100 | 2.89 | 2.50 | 2.28 | 2.15 | 2.06 | 1.99 | 1.93 | 1.89 | 1.86 |
| | .050 | 4.18 | 3.33 | 2.93 | 2.70 | 2.55 | 2.43 | 2.35 | 2.28 | 2.22 |
| | .025 | 5.59 | 4.20 | 3.61 | 3.27 | 3.04 | 2.88 | 2.76 | 2.67 | 2.59 |
| | .010 | 7.60 | 5.42 | 4.54 | 4.04 | 3.73 | 3.50 | 3.33 | 3.20 | 3.09 |
| | .005 | 9.23 | 6.40 | 5.28 | 4.66 | 4.26 | 3.98 | 3.77 | 3.61 | 3.48 |
| 30 | .100 | 2.88 | 2.49 | 2.28 | 2.14 | 2.05 | 1.98 | 3.93 | 1.88 | 1.85 |
| | .050 | 4.17 | 3.32 | 2.92 | 2.69 | 2.53 | 2.42 | 2.33 | 2.27 | 2.21 |
| | .025 | 5.57 | 4.18 | 3.59 | 3.25 | 3.03 | 2.87 | 2.75 | 2.65 | 2.57 |
| | .010 | 7.56 | 5.39 | 4.51 | 4.02 | 3.70 | 3.47 | 3.30 | 3.17 | 3.07 |
| | .005 | 9.18 | 6.35 | 5.24 | 4.62 | 4.23 | 3.95 | 3.74 | 3.58 | 3.45 |
| 40 | .100 | 2.84 | 2.44 | 2.23 | 2.09 | 2.00 | 1.93 | 1.87 | 1.83 | 1.79 |
| | .050 | 4.08 | 3.23 | 2.84 | 2.61 | 2.45 | 2.34 | 2.25 | 2.18 | 2.12 |
| | .025 | 5.42 | 4.05 | 3.48 | 3.13 | 2.90 | 2.74 | 2.62 | 2.53 | 2.45 |
| | .010 | 7.31 | 5.18 | 4.31 | 3.83 | 3.51 | 3.29 | 3.32 | 2.99 | 2.89 |
| | .005 | 5.83 | 6.07 | 4.98 | 4.37 | 3.99 | 3.71 | 3.51 | 3.35 | 3.22 |
| 60 | .100 | 2.79 | 2.39 | 2.18 | 2.04 | 1.95 | 1.87 | 1.82 | 1.77 | 1.74 |
| | .050 | 4.00 | 3.15 | 2.76 | 2.33 | 2.37 | 2.25 | 2.17 | 2.10 | 2.04 |
| | .025 | 5.29 | 3.95 | 3.34 | 3.01 | 2.79 | 2.63 | 2.51 | 2.41 | 2.33 |
| | .010 | 7.08 | 4.98 | 4.13 | 3.65 | 3.34 | 3.12 | 2.95 | 2.82 | 2.72 |
| | .005 | 5.49 | 5.79 | 4.73 | 4.14 | 3.76 | 3.49 | 3.29 | 3.13 | 3.01 |
| 120 | .100 | 2.75 | 2.35 | 2.13 | 1.99 | 1.90 | 1.82 | 1.77 | 1.72 | 1.88 |
| | .050 | 3.92 | 3.07 | 2.68 | 2.45 | 2.29 | 2.17 | 2.09 | 2.02 | 1.96 |
| | .025 | 5.15 | 3.80 | 3.23 | 2.89 | 2.67 | 2.52 | 2.39 | 2.30 | 2.22 |
| | .010 | 6.85 | 4.79 | 3.95 | 3.48 | 3.17 | 2.96 | 2.79 | 2.66 | 2.36 |
| | .005 | 8.18 | 5.54 | 4.50 | 3.92 | 3.55 | 3.28 | 3.09 | 2.93 | 2.81 |
| ∞ | .100 | 2.71 | 2.30 | 2.08 | 1.94 | 1.85 | 1.77 | 1.72 | 1.67 | 1.63 |
| | .050 | 3.84 | 3.00 | 2.60 | 2.37 | 2.21 | 2.10 | 2.01 | 1.94 | 1.88 |
| | .025 | 5.02 | 3.69 | 3.12 | 2.79 | 2.57 | 2.41 | 2.29 | 2.19 | 2.11 |
| | .010 | 6.63 | 4.61 | 3.78 | 3.32 | 3.02 | 2.80 | 2.64 | 2.51 | 2.41 |
| | .005 | 7.88 | 5.30 | 4.28 | 3.72 | 3.35 | 3.09 | 2.90 | 2.74 | 2.62 |

**Appendix E** Values of F 1/ —Continued

| Numerator *df* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 12 | 15 | 20 | 24 | 30 | 40 | 60 | 120 | ∞ | P |
| 1.83 | 1.78 | 1.73 | 1.65 | 1.68 | 1.62 | 1.58 | 1.55 | 1.51 | 1.47 | .100 |
| 2.18 | 2.10 | 2.03 | 1.94 | 1.90 | 1.85 | 1.81 | 1.75 | 1.70 | 1.64 | .050 |
| 2.53 | 2.43 | 2.32 | 2.21 | 2.15 | 2.09 | 2.03 | 1.96 | 1.89 | 1.81 | .025 |
| 3.00 | 2.87 | 2.73 | 2.57 | 2.49 | 2.41 | 2.33 | 2.23 | 2.14 | 2.03 | .010 |
| 3.38 | 3.21 | 3.04 | 2.86 | 2.76 | 2.66 | 2.56 | 2.45 | 2.33 | 2.21 | .005 |
| 1.82 | 1.77 | 1.72 | 1.67 | 1.64 | 1.61 | 1.57 | 1.54 | 1.50 | 1.46 | .100 |
| 2.16 | 2.09 | 2.01 | 1.93 | 1.89 | 1.84 | 1.79 | 1.74 | 1.68 | 1.62 | .050 |
| 2.51 | 2.41 | 2.31 | 2.20 | 2.14 | 2.07 | 2.01 | 1.94 | 1.87 | 1.79 | .025 |
| 2.98 | 2.84 | 2.70 | 2.55 | 2.47 | 2.39 | 2.30 | 2.2l | 2.30 | 2.18 | .010 |
| 3.34 | 3.18 | 3.01 | 2.82 | 2.73 | 2.63 | 2.52 | 2.42 | 2.30 | 2.18 | .005 |
| 1.76 | 1.71 | 1.66 | 1.61 | 1.57 | 1.54 | 1.51 | 1.47 | 1.42 | 1.38 | .100 |
| 2.08 | 2.00 | 1.92 | 1.84 | 1.79 | 1.74 | 1.69 | 1.64 | 1.58 | 1.51 | .050 |
| 2.39 | 2.29 | 2.18 | 2.07 | 2.01 | 1.94 | 1.88 | 1.80 | 1.72 | 1.64 | .025 |
| 2.80 | 2.66 | 2.52 | 2.37 | 2.29 | 2.20 | 2.11 | 2.02 | 1.92 | 1.80 | .010 |
| 3.12 | 2.95 | 2.78 | 2.60 | 2.50 | 2.40 | 2.30 | 2.18 | 2.06 | 1.93 | .005 |
| 1.71 | 1.66 | 1.60 | 1.54 | 1.51 | 1.48 | 1.44 | 1.40 | 1.35 | 3.29 | .100 |
| 1.99 | 1.92 | 1.84 | 1.75 | 1.70 | 1.65 | 1.59 | 1.53 | 1.47 | 1.39 | .050 |
| 2.27 | 2.17 | 2.06 | 1.94 | 1.88 | 1.82 | 1.74 | 1.67 | 1.58 | 1.48 | .025 |
| 2.63 | 2.50 | 2.35 | 2.20 | 2.12 | 2.03 | 1.94 | 1.84 | 1.73 | 1.60 | .010 |
| 2.90 | 2.74 | 2.57 | 2.39 | 2.29 | 2.19 | 2.08 | 1.96 | 1.83 | 1.69 | .005 |
| 1.65 | 1.60 | 1.55 | 1.48 | 1.45 | 1.41 | 1.37 | 1.32 | 1.26 | 1.19 | .100 |
| 1.91 | 1.83 | 1.75 | 1.66 | 1.63 | 1.55 | 1.50 | 1.49 | 1.35 | 1.25 | .050 |
| 2.16 | 2.05 | 1.94 | 1.82 | 1.76 | 1.69 | 1.61 | 1.53 | 1.43 | 1.31 | .025 |
| 2.47 | 2.34 | 2.19 | 2.03 | 1.95 | 1.86 | 1.76 | 1.66 | 1.53 | 1.38 | .030 |
| 2.71 | 2.54 | 2.37 | 2.19 | 2.09 | 1.98 | 1.87 | 1.73 | 1.61 | 1.43 | .005 |
| 1.60 | 1.55 | 1.49 | 1.42 | 1.38 | 1.34 | 1.30 | 1.24 | 1.17 | 1.00 | .100 |
| 1.83 | 1.75 | 1.67 | 1.57 | 1.52 | 1.46 | 1.39 | 1.32 | 1.22 | 1.00 | .050 |
| 2.05 | 1.94 | 1.83 | 1.71 | 1.64 | 1.57 | 1.48 | 1.39 | 1.27 | 1.00 | .025 |
| 2.32 | 2.18 | 2.04 | 1.88 | 1.79 | 1.70 | 1.59 | 1.47 | 1.32 | 1.00 | .010 |
| 2.52 | 2.36 | 2.19 | 2.00 | 1.90 | 1.79 | 1.67 | 1.53 | 1.36 | 1.00 | .005 |

1/ Steel, R.G.D., and J.H. Torrie. 1960. Prnciples and procedures of statistics. McGraw-Hill, Inc., New York, NY. (Reproduced with permission of the McCraw-Hill Companies.)

**Appendix F** Critical Values of the Kruskal-Wallis *H* Distribution[1/]

| $n_1$ | $n_2$ | $n_3$ | a = | 0.10 | 0.05 | 0.02 | 0.01 | 0.005 | 0.002 | 0.001 |
|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 2 | 2 | | 4.571 | | | | | | |
| 3 | 2 | 1 | | 4.286 | | | | | | |
| 3 | 2 | 2 | | 4.500 | 4.714 | | | | | |
| 3 | 3 | 1 | | 4.571 | 5.143 | | | | | |
| 3 | 3 | 2 | | 4.556 | 5.361 | 6.250 | | | | |
| 3 | 3 | 3 | | 4.622 | 5.600 | 6.489 | (7.200) | 7.200 | | |
| 4 | 2 | 1 | | 4.500 | | | | | | |
| 4 | 2 | 2 | | 4.458 | 5.333 | 6.000 | | | | |
| 4 | 3 | 1 | | 4.056 | 5.208 | | | | | |
| 4 | 3 | 2 | | 4.511 | 5.444 | 6.144 | 6.444 | 7.000 | | |
| 4 | 3 | 3 | | 4.709 | 5.791 | 6.564 | 6.745 | 7.318 | 8.018 | |
| 4 | 4 | 1 | | 4.167 | 4.967 | (6.667) | 6.667 | | | |
| 4 | 4 | 2 | | 4.555 | 5.455 | 6.600 | 7.036 | 7.282 | 7.855 | |
| 4 | 4 | 3 | | 4.545 | 5.598 | 6.712 | 7.144 | 7.598 | 8.227 | 8.909 |
| 4 | 4 | 4 | | 4.654 | 5.692 | 6.962 | 7.654 | 8.000 | 8.654 | 9.269 |
| 5 | 2 | 1 | | 4.200 | 5.000 | | | | | |
| 5 | 2 | 2 | | 4.373 | 5.160 | 6.000 | 6.533 | | | |
| 5 | 3 | 1 | | 4.018 | 4.960 | 6.044 | | | | |
| 5 | 3 | 2 | | 4.651 | 5.251 | 6.124 | 6.909 | 7.182 | | |
| 5 | 3 | 3 | | 4.533 | 5.648 | 6.533 | 7.079 | 7.636 | 8.048 | 8.727 |
| 5 | 4 | 1 | | 3.957 | 4.985 | 6.431 | 6.955 | 7.364 | | |
| 5 | 4 | 2 | | 4.541 | 5.273 | 6.505 | 7.205 | 7.573 | 8.114 | 8.591 |
| 5 | 4 | 3 | | 4.549 | 5.656 | 6.676 | 7.445 | 7.927 | 8.481 | 8.795 |
| 5 | 4 | 4 | | 4.619 | 5.657 | 6.953 | 7.760 | 8.189 | 8.868 | 9.168 |
| 5 | 5 | 1 | | 4.109 | 5.127 | 6.145 | 7.309 | 8.182 | | |
| 5 | 5 | 2 | | 4.623 | 5.338 | 6.446 | 7.338 | 8.131 | 6.446 | 7.338 |
| 5 | 5 | 3 | | 4.545 | 5.705 | 6.866 | 7.578 | 8.316 | 8.809 | 9.521 |
| 5 | 5 | 4 | | 4.523 | 5.666 | 7.000 | 7.823 | 8.523 | 9.163 | 9.606 |
| 5 | 5 | 5 | | 4.940 | 5.780 | 7.220 | 8.000 | 8.780 | 9.620 | 9.920 |
| 6 | 1 | 1 | | - - - - - | | | | | | |
| 6 | 2 | 1 | | 4.200 | 4.822 | | | | | |
| 6 | 2 | 2 | | 4.545 | 5.345 | 6.182 | 6.982 | | | |
| 6 | 3 | 1 | | 3.909 | 4.855 | 6.236 | | | | |
| 6 | 3 | 3 | | 4.682 | 5.348 | 6.227 | 6.970 | 7.515 | 8.182 | |
| 6 | 3 | 3 | | 4.538 | 5.615 | 6.590 | 7.410 | 7.872 | 8.628 | 9.346 |

**Appendix F** Critical Values of the Kruskal-Wallis *H* Distribution[1/]—Continued

| $n_1$ | $n_2$ | $n_3$ | | a = | 0.10 | 0.05 | 0.02 | 0.01 | 0.005 | 0.002 | 0.001 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6 | 4 | 1 | | | 4.038 | 4.947 | 6.174 | 7.106 | 7.614 | | |
| 6 | 4 | 2 | | | 4.494 | 5.340 | 6.571 | 7.340 | 7.846 | 8.494 | 8.827 |
| 6 | 4 | 3 | | | 4.604 | 5.610 | 6.725 | 7.500 | 8.033 | 8.918 | 9.170 |
| 6 | 4 | 4 | | | 4.595 | 5.681 | 6.900 | 7.795 | 8.381 | 9.167 | 9.861 |
| 6 | 5 | 1 | | | 4.128 | 4.990 | 6.138 | 7.182 | 8.077 | 8.515 | |
| 6 | 5 | 2 | | | 4.596 | 5.338 | 6.585 | 7.376 | 8.196 | 8.967 | 9.189 |
| 6 | 5 | 3 | | | 4.535 | 5.602 | 6.829 | 7.590 | 8.314 | 9.150 | 9.669 |
| 6 | 5 | 4 | | | 4.522 | 5.661 | 7.018 | 7.936 | 8.643 | 9.458 | 9.960 |
| 6 | 5 | 5 | | | 4.547 | 5.729 | 7.110 | 8.028 | 8.859 | 9.771 | 10.27I |
| 6 | 6 | 1 | | | 4.000 | 4.945 | 6.286 | 7.121 | 8.165 | 9.077 | 9.692 |
| 6 | 6 | 2 | | | 4.438 | 5.410 | 6.667 | 7.467 | 8.210 | 9.219 | 9.752 |
| 6 | 6 | 3 | | | 4.558 | 5.625 | 6.900 | 7.725 | 8.458 | 9.458 | 10.150 |
| 6 | 6 | 4 | | | 4.548 | 5.724 | 7.107 | 8.000 | 8.754 | 9.662 | 10.342 |
| 6 | 5 | 5 | | | 4.542 | 5.765 | 7.152 | 8.124 | 8.967 | 9.948 | 10.524 |
| 6 | 6 | 6 | | | 4.643 | 5.801 | 7.240 | 8.222 | 9.170 | 10.187 | 10.889 |
| 7 | 7 | 7 | | | 4.594 | 5.819 | 7.332 | 8.378 | 9.373 | 10.516 | 11.310 |
| 8 | 8 | 8 | | | 4.595 | 5.805 | 7.385 | 8.465 | 9.495 | 10.805 | 11.705 |
| 2 | 2 | 1 | 1 | | ----- | | | | | | |
| 2 | 2 | 2 | 1 | | 5.357 | 5.679 | | | | | |
| 2 | 2 | 2 | 2 | | 5.667 | 6.167 | (6.667) | 6.667 | | | |
| 3 | 1 | 1 | 1 | | ----- | | | | | | |
| 3 | 2 | 1 | 1 | | 5.143 | | | | | | |
| 3 | 2 | 2 | 1 | | 5.556 | 5.833 | 6.500 | | | | |
| 3 | 2 | 2 | 2 | | 5.544 | 6.333 | 6.978 | 7.133 | 7.533 | | |
| 3 | 3 | 1 | 1 | | | | | | | | |
| 3 | 3 | 2 | 1 | | 5.689 | 6.244 | 6.689 | 7.200 | 7.400 | | |
| 3 | 3 | 2 | 2 | | 5.745 | 6.527 | 7.182 | 7.636 | 7.873 | 8.018 | 8.455 |
| 3 | 3 | 3 | 1 | | 5.655 | 6.600 | 7.109 | 7.400 | 8.055 | 8.345 | |
| 3 | 3 | 3 | 2 | | 5.879 | 6.727 | 7.636 | 8.105 | 8.379 | 8.803 | 9.030 |
| 3 | 3 | 3 | 3 | | 6.026 | 7.000 | 7.872 | 8.538 | 8.897 | 9.462 | 9.513 |
| 4 | 1 | 1 | 1 | | ----- | | | | | | |
| 4 | 2 | 1 | 1 | | 5.250 | 5.833 | | | | | |
| 4 | 2 | 2 | 1 | | 5.533 | 6.133 | 6.667 | 7.000 | | | |
| 4 | 2 | 2 | 2 | | 5.755 | 6.545 | 7.091 | 7.391 | 7.964 | 8.291 | |
| 4 | 3 | 1 | 1 | | 5.067 | 6.178 | 6.711 | 7.067 | | | |

**Appendix F** Critical Values of the Kruskal-Wallis *H* Distribution[1/]—Continued

| $n_1$ | $n_2$ | $n_3$ | | a = | 0.10 | 0.05 | 0.02 | 0.01 | 0.005 | 0.002 | 0.001 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 3 | 2 | 1 | | 5.591 | 6.309 | 7.018 | 7.455 | 7.773 | 8.182 | |
| 4 | 3 | 2 | 2 | | 5.750 | 6.621 | 7.530 | 7.871 | 8.273 | 8.689 | 8.909 |
| 4 | 3 | 3 | 1 | | 5.589 | 6.545 | 7.485 | 7.758 | 8.212 | 8.697 | 9.182 |
| 4 | 3 | 3 | 2 | | 5.872 | 6.795 | 7.763 | 8.333 | 8.718 | 9.167 | 8.455 |
| 4 | 3 | 3 | 3 | | 6.016 | 6.984 | 7.995 | 8.659 | 9.253 | 9.709 | 10.016 |
| 4 | 4 | 1 | 1 | | 5.182 | 5.945 | 7.091 | 7.909 | 7.909 | | |
| 4 | 4 | 2 | 1 | | 5.568 | 6.386 | 7.364 | 7.886 | 8.341 | 8.591 | 8.909 |
| 4 | 4 | 2 | 2 | | 5.808 | 6.731 | 7.750 | 8.346 | 8.692 | 9.269 | 9.462 |
| 4 | 4 | 3 | 1 | | 5.692 | 6.635 | 7.660 | 8.231 | 8.583 | 9.038 | 9.327 |
| 4 | 4 | 3 | 2 | | 5.901 | 6.874 | 7.951 | 8.621 | 9.165 | 9.615 | 9.945 |
| 4 | 4 | 3 | 3 | | 6.019 | 7.038 | 8.181 | 8.876 | 9.495 | 10.105 | 10.467 |
| 4 | 4 | 4 | 1 | | 5.564 | 6.725 | 7.879 | 8.588 | 9.000 | 9.478 | 9.758 |
| 4 | 4 | 4 | 2 | | 5.914 | 6.957 | 8.157 | 8.871 | 9.486 | 10.043 | 10.429 |
| 4 | 4 | 4 | 3 | | 6.042 | 7.142 | 8.350 | 9.075 | 9.742 | 10.542 | 10.929 |
| 4 | 4 | 4 | 4 | | 6.088 | 7.235 | 8.515 | 9.287 | 9.971 | 10.809 | 11.338 |
| 2 | 1 | 1 | 1 | 1 | ----- | | | | | | |
| 2 | 2 | 1 | 1 | 1 | 5.785 | | | | | | |
| 2 | 2 | 2 | 1 | 1 | 6.250 | 6.750 | | | | | |
| 2 | 2 | 2 | 2 | 1 | 6.600 | 7.133 | (7.533) | 7.533 | | | |
| 2 | 2 | 2 | 2 | 2 | 6.982 | 7.418 | 8.073 | 8.291 | (8.727) | 8.727 | |
| 3 | 1 | 1 | 1 | 1 | ----- | | | | | | |
| 3 | 2 | 1 | 1 | 1 | 6.139 | 6.583 | | | | | |
| 3 | 2 | 2 | 1 | 1 | 6.511 | 6.800 | 7.400 | 7.600 | | | |
| 3 | 2 | 2 | 2 | 1 | 6.709 | 7.309 | 7.836 | 8.127 | 8.327 | 8.618 | |
| 3 | 2 | 2 | 2 | 2 | 6.955 | 7.682 | 8.303 | 8.682 | 8.985 | 9.273 | 9.364 |
| 3 | 3 | 1 | 1 | 1 | 6.311 | 7.111 | 7.467 | | | | |
| 3 | 3 | 2 | 1 | 1 | 6.600 | 7.200 | 7.892 | 8.073 | 8.345 | | |
| 3 | 3 | 2 | 2 | 1 | 6.788 | 7.591 | 8.258 | 8.576 | 8.924 | 9.167 | 9.303 |
| 3 | 3 | 2 | 2 | 2 | 7.026 | 7.910 | 8.667 | 9.115 | 9.474 | 9.769 | 10.026 |
| 3 | 3 | 3 | 1 | 1 | 6.788 | 7.576 | 8.242 | 8.424 | 8.848 | (9.455) | 9.455 |
| 3 | 3 | 3 | 2 | 1 | 6.910 | 7.759 | 8.590 | 9.051 | 9.410 | 9.769 | 9.974 |
| 3 | 3 | 3 | 2 | 2 | 7.121 | 8.044 | 9.011 | 9.505 | 9.890 | 10.330 | 10.637 |
| 3 | 3 | 3 | 3 | 1 | 7.077 | 8.000 | 8.879 | 9.451 | 9.846 | 10.286 | 10.549 |
| 3 | 3 | 3 | 3 | 2 | 7.210 | 8.200 | 9.267 | 9.876 | 10.333 | 10.838 | 11.171 |
| 3 | 3 | 3 | 3 | 3 | 7.333 | 8.333 | 9.467 | 10.200 | 10.733 | 10.267 | 11.667 |

1/ Zar, J.H. 1996. Biostatistical analysis. 3rd ed., Prentice Hall, Upper Saddle River, NJ 07458.

## Appendix G Upper Percentage Points of the Studentized Range, $q_\alpha = \frac{\bar{x}_{max} - \bar{x}_{min}}{s_{\bar{x}}}$ 1/

| Error df | | p = number of treatment means | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| 5 | .05 | 3.64 | 4.60 | 5.22 | 5.67 | 6.03 | 6.33 | 6.58 | 6.80 | 6.99 | 7.17 | 7.32 | 7.47 | 7.60 | 7.72 | 7.83 | 7.93 | 8.03 | 8.12 | 8.21 |
| | .01 | 5.70 | 6.97 | 7.80 | 8.42 | 8.91 | 9.32 | 9.67 | 9.97 | 10.24 | 10.48 | 10.70 | 10.89 | 11.08 | 11.24 | 11.40 | 11.55 | 11.68 | 11.81 | 11.93 |
| 6 | .05 | 3.46 | 4.34 | 4.90 | 5.31 | 563 | 5.89 | 6.12 | 6.32 | 6.49 | 6.65 | 6.79 | 6.92 | 7.03 | 7.14 | 7.24 | 7.34 | 7.43 | 7.51 | 7.59 |
| | .01 | 5.24 | 6.33 | 7.03 | 7.56 | 7.97 | 8.32 | 8.61 | 8.87 | 9.10 | 9.30 | 9.49 | 9.65 | 9.81 | 9.95 | 10.08 | 10.21 | 10.32 | 10.43 | 10.54 |
| 7 | .05 | 3.34 | 4.16 | 4.68 | 5.06 | 5.36 | 5.61 | 5.82 | 6.00 | 6.16 | 6.30 | 6.43 | 6.55 | 6.66 | 6.76 | 6.85 | 6.94 | 7.02 | 7.09 | 7.17 |
| | .01 | 4.95 | 5.92 | 6.54 | 7.01 | 7.37 | 7.68 | 7.94 | 8.17 | 8.37 | 8.55 | 8.71 | 8.86 | 9.00 | 9.12 | 9.24 | 9.35 | 9.46 | 9.55 | 9.65 |
| 8 | .05 | 3.26 | 4.04 | 4.53 | 4.89 | 5.17 | 5.40 | 6.60 | 5.77 | 5.92 | 6.05 | 6.18 | 6.29 | 6.39 | 6.48 | 6.57 | 6.65 | 6.73 | 6.80 | 6.87 |
| | .01 | 4.74 | 5.63 | 6.20 | 6.63 | 6.96 | 7.24 | 7.47 | 7.68 | 7.87 | 8.03 | 8.18 | 8.31 | 8.44 | 8.55 | 8.66 | 8.76 | 8.85 | 8.94 | 9.03 |
| 9 | .05 | 3.20 | 3.95 | 4.42 | 4.76 | 5.02 | 5.24 | 5.43 | 5.60 | 5.74 | 5.87 | 5.98 | 6.09 | 6.19 | 6.28 | 6.36 | 6.44 | 6.51 | 6.58 | 6.64 |
| | .01 | 4.60 | 5.43 | 5.96 | 6.35 | 6.66 | 6.91 | 7.13 | 7.32 | 7.49 | 7.65 | 7.78 | 7.91 | 8.03 I | 8.13 | 8.23 | 8.32 | 8.41 | 8.49 | 8.57 |
| 10 | .05 | 3.15 | 3.88 | 4.33 | 4.65 | 4.91 | 5.12 | 5.30 | 5.46 | 5.60 | 5.72 | 5.83 | 5.93 | 6.03 | 6.11 | 6.20 | 6.27 | 6.34 | 6.40 | 6.47 |
| | .01 | 4.48 | 5.27 | 5.77 | 6.14 | 6.43 | 6.67 | 6.87 | 7.05 | 7.21 | 7.36 | 7.48 | 7.60 | 7.71 | 7.81 | 7.91 | 7.99 | 8.07 | 8.15 | 8.22 |
| 11 | .05 | 3.11 | 3.82 | 4.26 | 4.57 | 4.82 | 5.03 | 5.20 | 5.35 | 5.49 | 5.61 | 5.71 | 5.81 | 5.90 | 5.99 | 6.06 | 6.14 | 6.20 | 6.26 | 6.33 |
| | .01 | 4.39 | 5.14 | 5.62 | 5.97 | 6.25 | 6.48 | 6.67 | 6.84 | 6.99 | 7.13 | 7.25 | 7.36 | 7.46 | 7.56 | 7.65 | 7.73 | 7.81 | 7.88 | 7.95 |
| 12 | .05 | 3.08 | 3.77 | 4.20 | 4.51 | 4.75 | 4.95 | 5.12 | 5.27 | 5.40 | 5.51 | 5.62 | 5.71 | 5.80 | 5.88 | 5.95 | 6.03 | 6.09 | 6.15 | 6.21 |
| | .01 | 4.32 | 5.04 | 5.50 | 5.84 | 6.10 | 6.32 | 6.51 | 6.67 | 6.81 | 6.94 | 7.06 | 7.17 | 7.26 | 7.36 | 7.44 | 7.52 | 7.59 | 7.66 | 7.73 |
| 13 | .05 | 3.06 | 3.73 | 4.15 | 4.45 | 4.69 | 4.88 | 5.05 | 5.19 | 5.32 | 5.43 | 5.53 | 5.63 | 5.71 | 5.79 | 5.86 | 5.93 | 6.00 | 6.05 | 6.11 |
| | .01 | 4.26 | 4.96 | 5.40 | 5.73 | 5.98 | 6.19 | 6.37 | 6.53 | 6.67 | 6.79 | 6.90 | 7.01 | 7.10 | 7.19 | 7.27 | 7.34 | 7.42 | 7.48 | 7.55 |
| 14 | .05 | 3.03 | 3.70 | 4.11 | 4.41 | 4.64 | 4.83 | 4.99 | 5.13 | 5.25 | 5.36 | 5.46 | 5.55 | 5.64 | 5.72 | 5.79 | 5.85 | 5.92 | 5.97 | 6.83 |
| | .01 | 4.21 | 4.89 | 5.32 | 5.63 | 5.88 | 6.08 | 6.26 | 6.41 | 6.54 | 6.66 | 6.77 | 6.87 | 6.96 | 7.05 | 7.12 | 7.20 | 7.27 | 7.33 | 7.39 |
| 15 | .05 | 3.01 | 3.67 | 4.08 | 4.37 | 4.60 | 4.78 | 4.94 | 5.08 | 5.20 | 5.31 | 5.40 | 5.49 | 5.58 | 5.65 | 5.72 | 5.79 | 5.85 | 5.90 | 5.96 |
| | .01 | 4.17 | 4.83 | 5.25 | 5.56 | 5.80 | 5.99 | 6.16 | 6.31 | 6.44 | 6.55 | 6.66 | 6.76 | 6.84 | 6.93 | 7.00 | 7.07 | 7.14 | 7.20 | 7.26 |
| 16 | .05 | 3.00 | 3.65 | 4.05 | 4.33 | 4.56 | 4.74 | 4.90 | 5.03 | 5.15 | 5.26 | 5.35 | 5.44 | 5.52 | 5.59 | 5.66 | 5.72 | 5.79 | 5.84 | 5.90 |
| | .01 | 4.13 | 4.78 | 5.19 | 5.49 | 5.72 | 5.92 | 6.00 | 6.22 | 6.35 | 6.46 | 6.56 | 6.66 | 6.74 | 6.82 | 6.90 | 6.97 | 7.03 | 7.09 | 7.15 |
| 17 | .05 | 2.98 | 3.63 | 4.02 | 4.30 | 4.52 | 4.71 | 4.86 | 4.99 | 5.11 | 5.21 | 5.31 | 5.39 | 5.47 | 5.55 | 5.61 | 5.68 | 5.74 | 5.79 | 5.84 |
| | .01 | 4.10 | 4.74 | 5.14 | 5.43 | 5.66 | 5.85 | 6.01 | 6.15 | 6.27 | 6.38 | 6.48 | 6.57 | 6.66 | 6.73 | 6.80 | 6.87 | 6.94 | 7.00 | 7.05 |
| 18 | .05 | 2.97 | 3.61 | 4.00 | 4.20 | 4.49 | 4.67 | 4.82 | 4.96 | 5.07 | 5.17 | 5.27 | 5.35 | 5.43 | 5.50 | 5.57 | 5.63 | 5.69 | 5.74 | 5.79 |
| | .01 | 4.07 | 4.70 | 5.09 | 5.38 | 5.60 | 5.79 | 5.94 | 6.08 | 6.20 | 6.31 | 6.41 | 6.50 | 6.58 | 6.65 | 6.72 | 6.79 | 6.85 | 6.91 | 6.96 |
| 19 | .05 | 2.96 | 3.59 | 3.98 | 4.25 | 4.47 | 4.65 | 4.79 | 4.92 | 5.04 | 5.14 | 5.23 | 5.32 | 5.39 | 5.46 | 5.53 | 5.59 | 5.65 | 5.70 | 5.75 |
| | .01 | 4.05 | 4.67 | 5.05 | 5.33 | 5.55 | 5.73 | 5.89 | 6.02 | 6.14 | 6.25 | 6.34 | 6.43 | 6.51 | 6.58 | 6.65 | 6.72 | 6.78 | 6.84 | 6.89 |
| 20 | .05 | 2.95 | 3.58 | 3.96 | 4.23 | 4.45 | 4.62 | 4.77 | 4.90 | 5.01 | 5.11 | 5.20 | 5.28 | 5.36 | 5.43 | 5.49 | 5.55 | 5.61 | 5.66 | 5.71 |
| | .01 | 4.02 | 4.64 | 5.02 | 5.29 | 5.51 | 5.69 | 5.84 | 5.97 | 6.09 | 6.19 | 6.29 | 6.37 | 6.45 | 6.52 | 6.59 | 6.65 | 6.71 | 6.76 | 6.82 |
| 24 | .05 | 2.92 | 3.53 | 3.90 | 4.17 | 4.37 | 4.54 | 4.611 | 4.81 | 4.92 | 5.01 | 5.10 | 5.18 | 5.25 | 5.32 | 5.38 | 5.44 | 5.50 | 5.54 | 5.59 |
| | .01 | 3.96 | 4.54 | 4.91 | 5.17 | 5.37 | 5.54 | 5.69 | 5.81 | 5.92 | 6.02 | 6.11 | 6.19 | 6.26 | 6.33 | 6.39 | 6.45 | 6.51 | 6.56 | 6.61 |

**Appendix G** Upper Percentage Points of the Studentized Range, $q_\alpha = \frac{\bar{x}_{max} - \bar{x}_{min}}{s_{\bar{x}}}$ 1/ — Continued

| Error df | ∞ | p = number of treatment means | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| 30 | .05 | 2.89 | 3.49 | 3.84 | 4.10 | 4.30 | 4.46 | 4.60 | 4.72 | 4.83 | 4.92 | 5.00 | 5.08 | 5.15 | 5.21 | 5.27 | 5.33 | 5.38 | 5.43 | 5.48 |
| | .01 | 3.89 | 4.45 | 4.80 | 5.05 | 5.24 | 5.40 | 5.54 | 5.65 | 5.76 | 5.85 | 5.93 | 6.01 | 6.08 | 6.14 | 6.20 | 6.26 | 6.31 | 6.36 | 6.41 |
| 40 | .05 | 2.86 | 3.44 | 3.79 | 4.04 | 4.23 | 4.39 | 4.52 | 4.63 | 4.74 | 4.82 | 4.91 | 4.98 | 5.05 | 5.11 | 5.16 | 5.22 | 5.27 | 5.31 | 5.36 |
| | .01 | 3.82 | 4.37 | 4.70 | 4.93 | 5.11 | 5.27 | 5.39 | 5.50 | 5.60 | 5.69 | 5.77 | 5.84 | 5.90 | 5.96 | 6.02 | 6.07 | 6.12 | 6.17 | 6.21 |
| 60 | .05 | 2.83 | 3.40 | 3.74 | 3.98 | 4.16 | 4.31 | 4.44 | 4.55 | 4.65 | 4.73 | 4.81 | 4.88 | 4.94 | 5.00 | 5.06 | 5.11 | 5.16 | 5.20 | 5.24 |
| | .01 | 3.76 | 4.28 | 4.60 | 4.82 | 4.99 | 5.13 | 5.25 | 5.36 | 5.45 | 5.53 | 5.60 | 5.67 | 5.73 | 5.79 | 5.84 | 5.89 | 5.93 | 5.98 | 6.02 |
| 120 | .05 | 2.80 | 3.36 | 3.69 | 3.92 | 4.10 | 4.24 | 4.36 | 4.48 | 4.56 | 4.64 | 4.72 | 4.78 | 4.84 | 4.90 | 4.95 | 5.00 | 5.05 | 5.09 | 5.13 |
| | .01 | 3.70 | 4.20 | 4.50 | 4.71 | 4.87 | 5.01 | 5.12 | 5.21 | 5.30 | 5.38 | 5.44 | 5.51 | 5.56 | 5.61 | 5.66 | 5.71 | 5.75 | 5.79 | 5.83 |
| ∞ | .05 | 2.77 | 3.31 | 3.63 | 3.86 | 4.03 | 4.17 | 4.29 | 4.39 | 4.47 | 4.55 | 4.62 | 4.68 | 4.74 | 4.80 | 4.85 | 4.89 | 4.93 | 4.97 | 5.01 |
| | .01 | 3.64 | 4.12 | 4.40 | 4.60 | 4.76 | 4.88 | 4.99 | 5.08 | 5.16 | 5.23 | 5.29 | 5.35 | 5.40 | 5.45 | 5.49 | 5.54 | 5.57 | 5.61 | 5.65 |

1/ Steel, R.G.D., and J.H. Torrie. 1960. Prnciples and procedures of statistics. McGraw-Hill, Inc., New York, NY. (Reproduced with permission of the McCraw-Hill Companies.)

## Appendix H Wilcoxon two-sample rank test (Mann-Whitney test) 1/

| $n_2$ = larger $n$ | $P$ | $n_1$ = smaller $n$ | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 4 | .05 | | | 10 | | | | | | | | | | | |
| | .01 | | | --- | | | | | | | | | | | |
| 5 | .05 | | 6 | 11 | 17 | | | | | | | | | | |
| | .01 | | --- | --- | 15 | | | | | | | | | | |
| 6 | .05 | | 7 | 12 | 18 | 26 | | | | | | | | | |
| | .01 | | --- | 10 | 16 | 23 | | | | | | | | | |
| 7 | .05 | | 7 | 13 | 20 | 27 | 36 | | | | | | | | |
| | .01 | | --- | 10 | 17 | 24 | 32 | | | | | | | | |
| 8 | .05 | 3 | 8 | 14 | 21 | 39 | 38 | 49 | | | | | | | |
| | .01 | --- | --- | 11 | 17 | 25 | 34 | 43 | | | | | | | |
| 9 | .05 | 3 | 8 | 15 | 22 | 31 | 40 | 5I | 63 | | | | | | |
| | .01 | --- | 6 | 11 | 18 | 26 | 35 | 45 | 56 | | | | | | |
| 10 | .05 | 3 | 9 | I5 | 23 | 32 | 42 | 53 | 65 | 78 | | | | | |
| | .01 | --- | 6 | 12 | 19 | 27 | 37 | 47 | 58 | 71 | | | | | |
| 11 | .05 | 4 | 9 | 16 | 24 | 34 | 44 | 55 | 68 | 81 | 96 | | | | |
| | .01 | --- | 6 | 12 | 20 | 28 | 38 | 49 | 61 | 74 | 87 | | | | |
| 12 | .05 | 4 | 10 | 17 | 26 | 35 | 46 | 58 | 71 | 85 | 99 | 115 | | | |
| | .01 | --- | 7 | 13 | 21 | 30 | 40 | 51 | 63 | 76 | 90 | 106 | | | |
| 13 | .05 | 4 | 10 | 18 | 27 | 37 | 48 | 60 | 73 | 88 | 103 | 119 | 137 | | |
| | .01 | --- | 7 | 14 | 22 | 31 | 41 | 53 | 65 | 79 | 93 | 109 | 125 | | |
| 14 | .05 | 4 | 11 | 19 | 28 | 38 | 50 | 63 | 76 | 91 | 106 | 123 | 141 | 160 | |
| | .01 | --- | 7 | 14 | 22 | 32 | 43 | 54 | 67 | 81 | 96 | 112 | 129 | 147 | |
| 15 | .05 | 4 | 11 | 20 | 29 | 40 | 52 | 65 | 79 | 94 | 110 | 127 | 145 | 164 | 185 |
| | .01 | --- | 8 | 15 | 23 | 33 | 44 | 56 | 70 | 84 | 99 | 115 | 133 | 151 | 171 |
| 16 | .05 | 4 | 12 | 21 | 31 | 42 | 54 | 67 | 82 | 97 | 114 | 131 | 150 | 169 | |
| | .01 | --- | 8 | 15 | 24 | 34 | 46 | 58 | 72 | 86 | 102 | 119 | 137 | 155 | |
| 17 | .05 | 5 | 12 | 21 | 32 | 43 | 56 | 70 | 84 | 100 | 117 | 135 | 154 | | |
| | .01 | --- | 8 | 16 | 25 | 36 | 47 | 60 | 74 | 89 | 105 | 122 | 140 | | |
| 18 | .05 | 5 | 13 | 22 | 33 | 45 | 58 | 72 | 87 | 103 | 121 | 139 | | | |
| | .01 | --- | 8 | 16 | 26 | 37 | 49 | 62 | 76 | 92 | 108 | 125 | | | |
| 19 | .05 | 5 | 13 | 23 | 34 | 46 | 60 | 74 | 90 | 107 | 124 | | | | |
| | .01 | 3 | 9 | 17 | 27 | 38 | 50 | 64 | 78 | 94 | 111 | | | | |
| 20 | .05 | 5 | 14 | 24 | 35 | 48 | 62 | 77 | 93 | 110 | | | | | |
| | .01 | 3 | 9 | 18 | 28 | 39 | 52 | 66 | 81 | 97 | | | | | |
| 21 | .05 | 6 | 14 | 25 | 37 | 50 | 64 | 79 | 95 | | | | | | |
| | .01 | 3 | 9 | 18 | 29 | 40 | 53 | 68 | 83 | | | | | | |
| 22 | .05 | 6 | 15 | 26 | 38 | 51 | 66 | 82 | | | | | | | |
| | .01 | 3 | 10 | 19 | 29 | 42 | 55 | 70 | | | | | | | |
| 23 | .05 | 6 | 15 | 27 | 39 | 53 | 68 | | | | | | | | |
| | .01 | 3 | 10 | 19 | 30 | 43 | 57 | | | | | | | | |
| 24 | .05 | 6 | 16 | 28 | 40 | 55 | | | | | | | | | |
| | .01 | 3 | 10 | 20 | 31 | 44 | | | | | | | | | |
| 25 | .05 | 6 | 16 | 28 | 42 | | | | | | | | | | |
| | .01 | 3 | 11 | 20 | 32 | | | | | | | | | | |
| 26 | .05 | 7 | 17 | 29 | | | | | | | | | | | |
| | .01 | 3 | 11 | 21 | | | | | | | | | | | |
| 27 | .05 | 7 | 17 | | | | | | | | | | | | |
| | .01 | 4 | 11 | | | | | | | | | | | | |
| 28 | .05 | 7 | | | | | | | | | | | | | |
| | .01 | 4 | | | | | | | | | | | | | |

1/ Steel, R.G.D., and J.H. Torrie. 1960. Prnciples and procedures of statistics. McGraw-Hill, Inc., New York, NY. (Reproduced with permission of the McCraw-Hill Companies.)

**Appendix I** Wilcoxon's signed rank test (tabulated values of T are such that smaller values, regardless of sign, occur by chance with stated probability) 1/

| Pairs | - - Probability - - .05 | .02 | .01 |
|---|---|---|---|
| 6 | 0 | — | — |
| 7 | 2 | 0 | — |
| 8 | 4 | 2 | 0 |
| 9 | 6 | 3 | 2 |
| 10 | 8 | 5 | 3 |
| 11 | 11 | 7 | 5 |
| 12 | 14 | 10 | 7 |
| 13 | 17 | 13 | 10 |
| 14 | 21 | 16 | 13 |
| 15 | 25 | 20 | 16 |
| 16 | 30 | 24 | 20 |
| 17 | 35 | 28 | 23 |
| 18 | 40 | 33 | 28 |
| 19 | 46 | 38 | 32 |
| 20 | 52 | 43 | 38 |
| 21 | 59 | 49 | 43 |
| 22 | 66 | 56 | 49 |
| 23 | 73 | 62 | 55 |
| 24 | 81 | 69 | 61 |
| 25 | 89 | 77 | 68 |

1/ Steel, R.G.D., and J.H. Torrie. 1960. Prnciples and procedures of statistics. McGraw-Hill, Inc., New York, NY. (Reproduced with permission of the McCraw-Hill Companies.)

**Appendix J** Quantiles (p-values) for Kendall's tau correlation coefficient (p = Prob[S ≥ x] = Prob [S≤ –x]) 1/

| x | Number of data pairs = n | | | | x | Number of data pairs = n | | |
|---|---|---|---|---|---|---|---|---|
| | 4 | 5 | 8 | 9 | | 6 | 7 | 10 |
| 0 | 0.625 | 0.592 | 0.548 | 0.540 | 1 | 0.500 | 0.500 | 0.500 |
| 2 | 0.375 | 0.408 | 0.452 | 0.460 | 3 | 0.360 | 0.386 | 0.431 |
| 4 | 0.167 | 0.242 | 0.360 | 0.381 | 5 | 0.235 | 0.281 | 0.364 |
| 6 | 0.042 | 0.117 | 0.274 | 0.306 | 7 | 0.136 | 0.191 | 0.300 |
| 8 | | 0.042 | 0.199 | 0.238 | 9 | 0.068 | 0.119 | 0.242 |
| 10 | | 0.0083 | 0.138 | 0.179 | 11 | 0.028 | 0.068 | 0.190 |
| 12 | | | 0.089 | 0.130 | 13 | 0.0083 | 0.035 | 0.146 |
| 14 | | | 0.054 | 0.090 | 15 | 0.0014 | 0.015 | 0.108 |
| 16 | | | 0.031 | 0.060 | 17 | | 0.0054 | 0.078 |
| 18 | | | 0.016 | 0.038 | 19 | | 0.0014 | 0.054 |
| 20 | | | 0.0071 | 0.022 | 21 | | 0.0002 | 0.036 |
| 22 | | | 0.0028 | 0.012 | 23 | | | 0.023 |
| 24 | | | 0.0009 | 0.0063 | 25 | | | 0.014 |
| 26 | | | 0.0002 | 0.0029 | 27 | | | 0.0083 |
| 28 | | | <0.0001 | 0.0012 | 29 | | | 0.0046 |
| 30 | | | | 0.0004 | 31 | | | 0.0023 |
| 32 | | | | 0.0001 | 33 | | | 0.0011 |
| | | | | | 35 | | | 0.0005 |
| | | | | | 37 | | | 0.0002 |

1/ Helsel, D.R., and R.M. Hirsch. 1992. Chapter 12, Trend analysis. *In* Statistical methods in water resources, Studies in Environmental Science 49, Elsevier, New York, NY.

## Appendix K Conversion Factors

### Length

| From: | To: | Multiply by: |
|---|---|---|
| foot | inch | 12 |
| foot | meter | .3048 |
| inch | centimeter | 2.54 |
| kilometer | mile | 0.621 |
| meter | yard | 1.094 |
| mile | kilometer | 1.6093 |
| yard | inch | 36 |

### Area

| From: | To: | Multiply by: |
|---|---|---|
| acre | $ft^2$ | 43,560 |
| acre | hectare | 0.405 |
| $ft^2$ | $m^2$ | 0.0929 |
| hectare | acre | 2.471 |
| hectare | $m^2$ | $10^4$ |
| $mile^2$ | $kilometer^2$ | 2.59 |

### Volume

| From: | To: | Multiply by: |
|---|---|---|
| $ft^3$ | liter | 28.317 |
| $ft^3$ | gallon | 7.481 |
| gallon | liter | 3.785 |
| $m^3$ | $ft^3$ | 35.314 |
| $m^3$ | liter | 1,000 |

### Discharge

| From: | To: | Multiply by: |
|---|---|---|
| $ft^3/s$ | gpm | 448.83 |
| $ft^3/s$ | $m^3/s$ | .0283 |
| $m^3/s$ | liter/s | 1,000 |
| $m^3/s$ | gpm | 15,850 |

### Mass

| From: | To: | Multiply by: |
|---|---|---|
| pound | kilogram | 0.4536 |
| ton | pound | 2,000 |
| tonnes | pound | 2,205 |
| pound/ac | kg/ha | 1.1208 |
| $ft^3$ - water | pound | 62.4 |

### Temperature

$$^{\circ}F = \frac{9}{5}\left(^{\circ}C\right) + 32$$

$$^{\circ}C = \frac{5}{9}\left(^{\circ}F - 32\right)$$

### Concentration

| From: | To: | Multiply by: |
|---|---|---|
| mg/L | ppm | 1.0 |
| ppm | ppb | 1,000 |
| mg/L | mg/kg | 1.0 |
| ug/L | $mg/m^3$ | 1.0 |
| $g/m^3$ | mg/L | 1.0 |
| lb/ac | kg/ha | 1.120851 |
| % solution | mg/L | 1 x 104 |

### Metric

To convert SI prefixes

| From: | To: | Multiply by: |
|---|---|---|
| Suffix | mega (M) | $1 \times 10^6$ |
| Suffix | kilo (k) | 1,000 |
| Suffix | hecto (c) | 100 |
| Suffix | deca | 10 |
| Suffix | Suffix | 1 |
| Suffix | deci | .1 |
| Suffix | centi | .01 |
| Suffix | milli | .001 |
| Suffix | micro | .000001 |

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## P



## Q



## R



## S



## T



## V



## W