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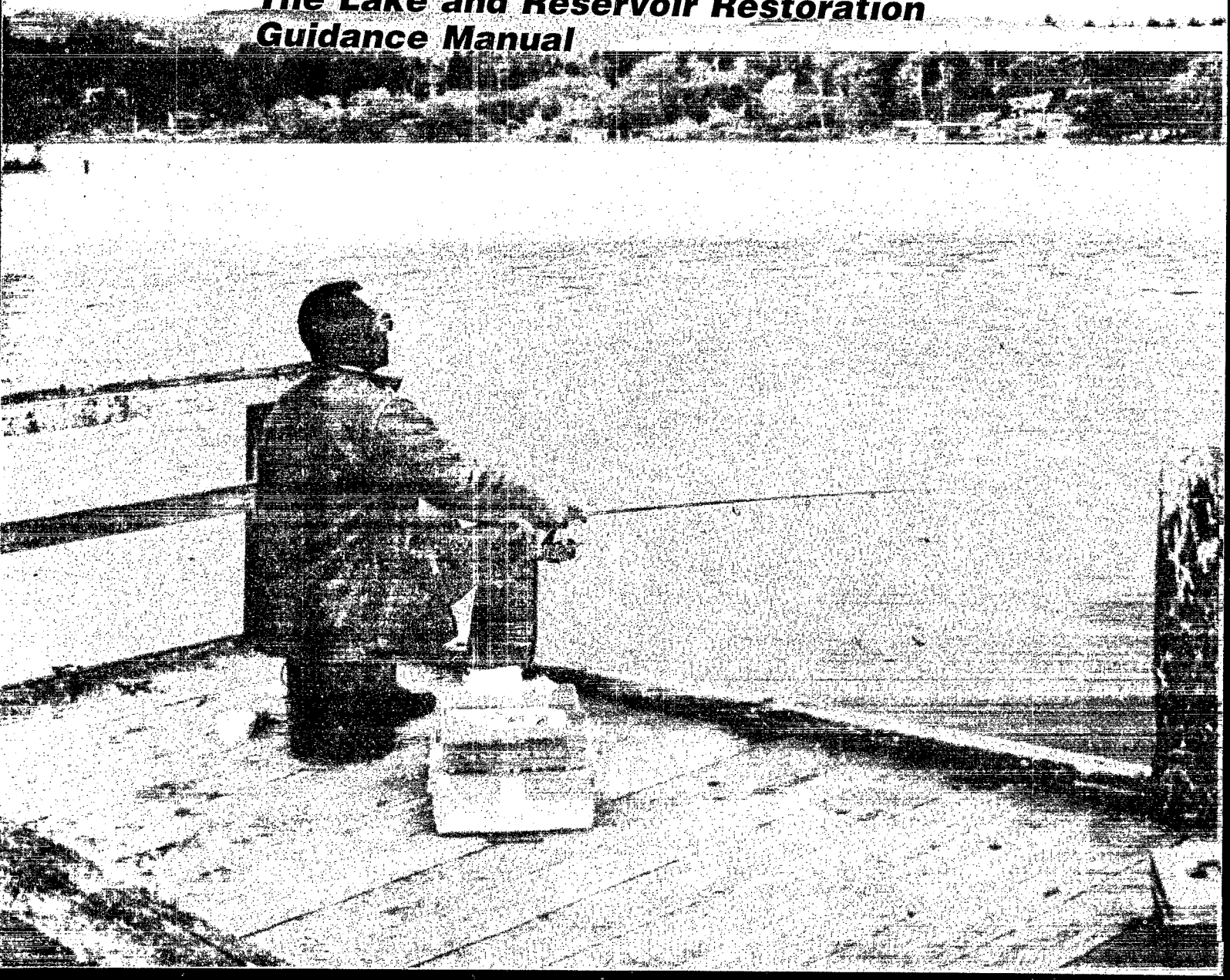
Fish and Fisheries Management in Lakes and Reservoirs

TECHNICAL SUPPLEMENT TO

The Lake and Reservoir Restoration Guidance Manual



Fish and Fisheries Management in Lakes and Reservoirs

TECHNICAL SUPPLEMENT TO

The Lake and Reservoir Restoration Guidance Manual

Prepared by the

Terrene Institute

in cooperation with the

U.S. Environmental Protection Agency
Office of Water
Office of Wetlands, Oceans, and Watersheds
Assessment and Watershed Protection Division
Washington, DC

1993

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Courtesy of Dave Wagner, Devils Lake Water Improvement District, Lincoln City, Oregon.

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This manual represents a summary of existing knowledge on fish and fisheries managed in lakes and reservoirs. It was written by Joan P. Baker, Harvey Olem, Clayton S. Creager, and Benjamin R. Parkhurst. Significant contributions to the manual were made by Robert W. Wiley, Steve McComas, and Gareth Goodchild. Editors were Gretchen Flock and Roberta F. Shulman.

The manual draws on the many good books, papers, and reports on fish biology, fisheries, and ecology cited in the references. In particular, substantial background material was extracted from the two previous manuals in this series: *The Lake and Reservoir Restoration Guidance Manual* and *Monitoring Lake and Reservoir Restoration.*

The quality and scope of this document benefited greatly from discussions of a preliminary draft at a 1992 peer review workshop in Denver, CO, attended by Les Ager (Georgia Department of Natural Resources), Mike Alexander (U.S. Army Corps of Engineers), Tom Davenport (U.S. Environmental Protection Agency), Joe Eilers (E & S Environmental Chemistry, Inc.), Bill Funk (Washington State University), Frank Lapensee (U.S. Environmental Protection Agency), Dave Marshall (Wisconsin Department of Natural Resources), Pat Marinez (Colorado Division of Wildlife), Spence Peterson (U.S. Environmental Protection Agency), Susan Ratcliffe (U.S. Environmental Protection Agency), Dick Wedepohl (Wisconsin Department of Natural Resources), Ray White (Trout Unlimited), and Bob Wiley (Wyoming Game and Fish Department). Written comments were also received from Sandy Engel (Wisconsin Department of Natural Resources), Rick Hoopes (Pennsylvania Fish Commission), Mike Jones (Ontario Ministry of Natural Resources), Tom Powell (Colorado Division of Wildlife), and Richard Ryder (Ontario Ministry of Natural Resources).

Completion of this manual would not have been possible without the advice and assistance of these many scientists and resource managers. In addition, many State and provincial resource agencies provided helpful written materials including the Alabama Department of Conservation and Natural Resources, Arkansas Game and Fish Commission, Delaware Division of Fish and Wildlife, Georgia Department of Natural Resources, Idaho Fish and Game, Illinois Department of Conservation, Iowa Department of Natural Resources, Kansas Department of Wildlife and Parks, Louisiana Department of Wildlife and Fisheries, Maine Department of Inland Fisheries and Wildlife, Minnesota Department of Natural Resources, New York Department of Environmental Conservation, Oklahoma Department of Wildlife Conservation, Ontario Ministry of Natural Resources, Pennsylvania Fish Commission, and Wyoming Game and Fish Department. Useful reference materials were also provided by the Sport Fishing Institute, Flathead River Basin Commission, and Devils Lake Water Quality Improvement District.

PREFACE

This document is part of a series of technical guidance manuals on lake restoration and management prepared for state and local use under a cooperative agreement with the U.S. Environmental Protection Agency's Clean Lakes Program. *The Lake and Reservoir Restoration Guidance Manual* (EPA 440/4-90-006) provides an overview of the principles and techniques of lake restoration. *Monitoring Lake and Reservoir Restoration* (EPA 440/4-90-007) presents more detailed guidance on designing and implementing a lake monitoring program, necessary for characterizing lake problems and evaluating the success and effectiveness of restoration projects. This manual focuses on one component of lake ecosystems: fish. Historically, fisheries management and lake water quality management have been treated as separated disciplines and handled by separate agencies or departments in both state and federal governments. An important objective of this manual is to encourage the development of an integrated lake management program that addresses fish, other biota, the physical and chemical characteristics of the lake habitat, and the associated watershed as an interdependent unit.

Additional technical guidance manuals for state and local use are planned on other topics of interest. The staff of the Terrene Institute would welcome your suggestions and comments. Please address your comments and requests for the manuals to:

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CHAPTER 1

Introduction

Purpose of the Manual

Historically, fish populations in lakes have been managed by fisheries managers interested primarily in increasing the number and size of fish caught by anglers. Fish stocking to introduce new fish species or supplement reproduction was the major management tool used to increase fishery yields, with relatively little consideration given to the potentially adverse effects of these stocking programs on other fish species and biota or alternative lake uses. In a similar manner, water quality managers focused on improving water clarity, decreasing noxious algal blooms, and other aspects of lake water quality. They paid relatively little attention to the potential effects of lake restoration efforts on fishing quality. Training programs for fisheries and water quality management were distinct, emphasizing different management objectives, types of expertise, and techniques. Furthermore, in most States fisheries and water quality have been and continue to be managed by separate agencies or departments.

Biota are all plant and animal species occurring in a specified area.

Fish, however, are an integral component of lake and reservoir ecosystems. In addition to being a desired resource for lake users, they play important roles in energy flows, nutrient cycling, and maintaining community balance. The physical, chemical, and biological characteristics of a lake or reservoir are major determinants of the types, number, and size of fish available for harvest. At the same time, fisheries management affects not only fish and the quality of fishing but also the ecosystem as a whole. The introduction of a new fish species, for example, can have a cascading effect on the abundance of other organisms and, indirectly, nutrient levels and water clarity. Fisheries management, therefore, cannot be considered in isolation but must be viewed as one part of an overall lake management program. Fishing is only one of many often conflicting lake uses. An important goal of lake management is to achieve the appropriate balance among these uses.

An ecosystem consists of interrelated organisms and their physical–chemical environment including the lake and surrounding land and streams that drain into the lake.

This manual is written to provide

- water quality managers with a better understanding of the concepts and techniques of fisheries management as well as the role of fish in the lake ecosystem and the potential use of fish management as one method for improving and maintaining water quality;
- fisheries managers with a better appreciation for the broader, ecological consequences of fisheries management activities; and
- both water quality and fisheries managers with a basis for incorporating fisheries management into an integrated lake management program.

[F]isheries management affects not only fish and the quality of fishing but also the ecosystem as a whole.

Integrating fisheries management into a lake management program can serve three important purposes:

- Maintain the health of the fish community, an important component of the overall health of the lake.
- Enhance public support for lake management and restoration activities by addressing the concerns of the fishing public.
- Publicly — and explicitly — recognize the interdependency between fish, water quality, and the lake ecosystem as a whole.

An integrated program will ensure that management decisions consider the full range of options and effects as well as potential trade-offs among alternative objectives and all lake uses.

Scope of the Manual

Lakes and Reservoirs

This manual focuses on the management of fish and fisheries in lakes and reservoirs. The term "lake" is used generically to include both natural lakes and those made by humans, which are called "reservoirs." Because reservoirs are constructed for different purposes, such as flood control, water supply, and recreation, their design and characteristics vary greatly. On average, however, reservoirs tend to have larger drainage areas, shorter water retention times, and more convoluted shorelines than natural lakes. Distinctions between natural lakes and reservoirs are discussed only when the management implications are important. Special considerations required to manage small farm ponds (generally less than five acres and privately owned) are not included in this manual.

Whole-basin Approach

A lake's quality and productivity depend largely on conditions in the surrounding lands that drain into it, either directly or through feeder streams or rivers.

A lake's quality and productivity depend largely on conditions in the surrounding lands that drain into it, either directly or through feeder streams or rivers. Most of the silt, nutrient, and organic matter inputs to a lake often derive from human disturbances in these surrounding lands or upstream waters rather than from direct discharges to the lake or in-lake sources. Furthermore, many fish species rely on areas in connecting streams for reproduction or as nurseries for young fish. Migrations of fish are common between a lake and its inflowing streams and also among interconnected lakes in the same drainage basin.

For these reasons, effective lake management requires a whole-basin approach. This encompasses not only the lake itself but also land uses and activities in the surrounding watershed as well as the coordinated management of all lakes and streams in the basin. A whole-basin approach to water quality management has recently been adopted by some States (for example, see Creager and Baker, 1991). This manual emphasizes the importance of a whole-basin approach to both water quality and fisheries management.

Management = Protection + Restoration

Lake protection is the most cost-effective and long-term approach to lake management; that is, management actions that prevent the degradation of lake quality or attainable lake uses. Once degraded, however, a lake restoration project may be needed to improve lake quality and bring it back to (or closer to) its natural state and natural attainable uses (see Natl. Res. Counc. 1991). The term "lake management" in this document refers to a comprehensive program that incorporates both protection and restoration activities, as appropriate, to effectively improve and maintain the quality of the lake ecosystem.

Fish and Fisheries Management

A fishery is the act or occupation of fishing — the harvesting of fish from waterbodies for either commercial or recreational purposes. Recreational fisheries, which are the primary focus of this document, are managed to maximize and sustain the overall quality of the "fishing experience." Although the definition of a quality experience varies among anglers, it incorporates more than simply the quantity and type of fish caught. Likewise, fisheries management involves much more than just managing fish. Managing a fishery requires not only managing the fish populations being harvested but also the habitat and food supplies required to sustain those fish populations, the anglers participating in the fishery, and the broader environment in which the fishing experience occurs.

A fishery is the act or occupation of fishing — the harvesting of fish from waterbodies for either commercial or recreational purposes.

This manual discusses both fish and fisheries management. The objective of fisheries management is to achieve and sustain the optimal level of fishing quality that is consistent with the overall lake management objectives and desired balance among lake uses. By contrast, fish can be managed for multiple purposes: to improve the quality of fishing, to control unwanted growths of aquatic plants, to improve water clarity, or other objectives intended to improve and maintain lake quality and a variety of lake uses.

Additional References

This manual is an up-to-date technical summary of the state-of-the-science of fish and fisheries management in lakes and reservoirs. It provides a scientific and technical foundation for the development of workable and practical lake management plans that can be approved by a governing body, funding agency (such as EPA's Clean Lakes Program), or private organization or individual. Material from other supplements in this series (Olem and Flock, 1990; Wedepohl et al. 1990) is summarized as needed to comprehensively cover all relevant topics.

This supplement is not intended to serve as a stand-alone reference on fish and fisheries management, however, or as a how-to manual with step-by-step instructions for implementing management techniques. Additional sources of information are listed in the reference section for readers interested in obtaining more detailed guidance on specific topics.

Intended Audience

The primary users of this manual are likely to be

- lake managers (water quality managers, fisheries managers, and lake associations);
- local lake restoration project managers and their sponsors;
- state personnel involved in lake restoration and management activities;
- Federal employees involved in lake management; and
- consultants and contractors participating in lake management and restoration projects.

[I]n most waters, fish are a public resource, the management of which is the responsibility of State and tribal fisheries agencies.

It is important to note that, in most waters, fish are a public resource, the management of which is the responsibility of State and tribal fisheries agencies. Thus, State and tribal fisheries management personnel must be contacted before any of the activities or management techniques discussed in this book are implemented and should be actively involved in project planning. Many of the

management techniques presented require permits; some can be conducted only by State agencies. Additional information on the role of State biologists and associated State regulations and requirements is noted in appropriate sections throughout this manual.

EPA's Clean Lakes Program addresses problems in lakes and reservoirs in the United States. The information in this manual, however, is widely applicable to lake and fisheries management in general. Case studies, references, and contacts are included to assist with design and implementation of projects in Canada.

Manual Organization

The manual is divided into five parts: background (Chapters 2 and 3); project planning and design (Chapters 4 through 7); techniques and management tools (Chapters 8 through 11); case studies (Chapter 12); and Appendices A through C.

- **Chapters 2 and 3,** which provide background information on terms and basic scientific principles and concepts, are designed for readers with relatively little technical training in ecology, limnology (the scientific study of freshwaters) or fish biology. Other readers may wish to turn directly to Chapter 4.

- **Chapters 4 through 7** introduce concepts of fish and fisheries management and outline a framework for developing comprehensive management plans that integrate fisheries and water quality management and address the underlying causes of lake problems. People and organizations who can help with fisheries management are also identified.

- **Chapters 8 through 11** describe methods and management tools used in fish and fisheries management.

- **Chapter 12** presents case study examples to illustrate how problems in lake and fisheries management have been approached and resolved.

- **The glossary** supplements the text with terms pertaining to fisheries and lakes.

- **The reference section** lists citations by chapter as well as additional reports and papers that might prove useful.

- **Three appendices** are included: Appendix A: Background Information on Selected Fish Species; Appendix B: Sampling Methods; and Appendix C: Sources of Information and Assistance.

Units of Measurement

As with the other technical supplements in this series, most of the units presented in this manual are in British/U.S. form. Most scientific publications, however, use metric units. Table 1-1 provides a listing of metric to English conversions for units of measurement commonly used in lake and fisheries management.

Table 1-1—Metric to English conversions.

METRIC UNIT	SYMBOL		ENGLISH UNIT	CONVERSION FACTOR*
Length				
Millimeter	mm	= 0.001 m	inch	0.03937
Centimeter	cm	= 0.01 m	inch	0.3937
Meter	m	= 1.0 m	yard	1.094
Kilometer	km	= 1,000 m	mile	0.6214
Weight				
Microgram	µg	= 0.000001 g	(no reasonable equivalent)	
Milligram	mg	= 0.001 g	grain	0.015432
Gram	g	= 1.0 g	ounce (avoir)	0.03527
Kilogram	kg	= 1,000 g	pound	2.205
Volume				
Milliliter	mL	= 0.001 L	ounce	29.57
Liter	L	= 1.0 L	quart	1.057
Cubic meter	m^3	= 1,000 L	cubic yard	1.308

* To convert metric to English units, multiply by the conversion factor; to convert English to metric, divide by the factor.

Other Useful Conversions:

1 gallon = 3.785 liters
1 milligram/Liter = 1 part per million
1 hectare = 2.47 acres
1 acre-foot = 32,590 gallons
1 cubic meter = 264 gallons

CHAPTER 2

Lake and Reservoir Ecosystems

Chapter Objective

The focus of this manual is on managing fish resources. However, informed decisions regarding fish and fisheries management require a basic understanding of the major physical, chemical, and biological processes that influence lake and reservoir ecosystems. The environment within which fish live plays a major role in determining the types of species able to survive and reproduce, fish production and growth rates, and the management problems likely to be encountered. This chapter provides a brief overview of the ecological processes of greatest importance to fish and also of the role of fish in the lake ecosystem. Several basic texts on limnology and freshwater ecology are listed in the reference section for the reader interested in more detailed discussions of ecological concepts relevant to lake and reservoir management. *The Lake and Reservoir Restoration Guidance Manual* (Olem and Flock, 1990) provides further background information on many of these topics; many sections in this chapter summarize discussions in that publication.

Morphometry relates to a lake's physical structure (e.g., depth, shoreline length).

Lake Morphometry

Lakes come in many different shapes and sizes, and morphological characteristics, such as a lake's area, maximum depth, mean depth, and total water volume, have a significant effect on nearly all of the major physical, chemical, and biological processes in lakes. For this reason, development of a bathymetric map (Fig. 2-1), showing the shape of the shoreline, water depth contours, and locations of any inflowing streams (tributaries) and lake outflow(s), is an important first step for most lake management programs.

[M]orphological characteristics . . . have a significant effect on nearly all of the major physical, chemical, and biological processes in lakes.

The shallow, nearshore region of a lake, where adequate light can penetrate to the lake bottom to allow for the growth of rooted aquatic plants (presuming other conditions are suitable), is the littoral zone. Because it often receives high nutrient inputs that run off the surrounding land and may support rooted plant growth, the littoral zone can contribute significantly to total lake production. All else being equal, shallow lakes with large littoral areas (relative to the total lake area) tend to be more productive than deeper lakes or those with steep-sided basins and little or no littoral zone. Many fish species live, feed, or reproduce in littoral zones; therefore, the extent and nature of a lake's littoral zone directly affect fish community composition and productivity.

All else being equal, shallow lakes with large littoral areas tend to be more productive than deeper lakes or those with steep-sided basins and little or no littoral zone.

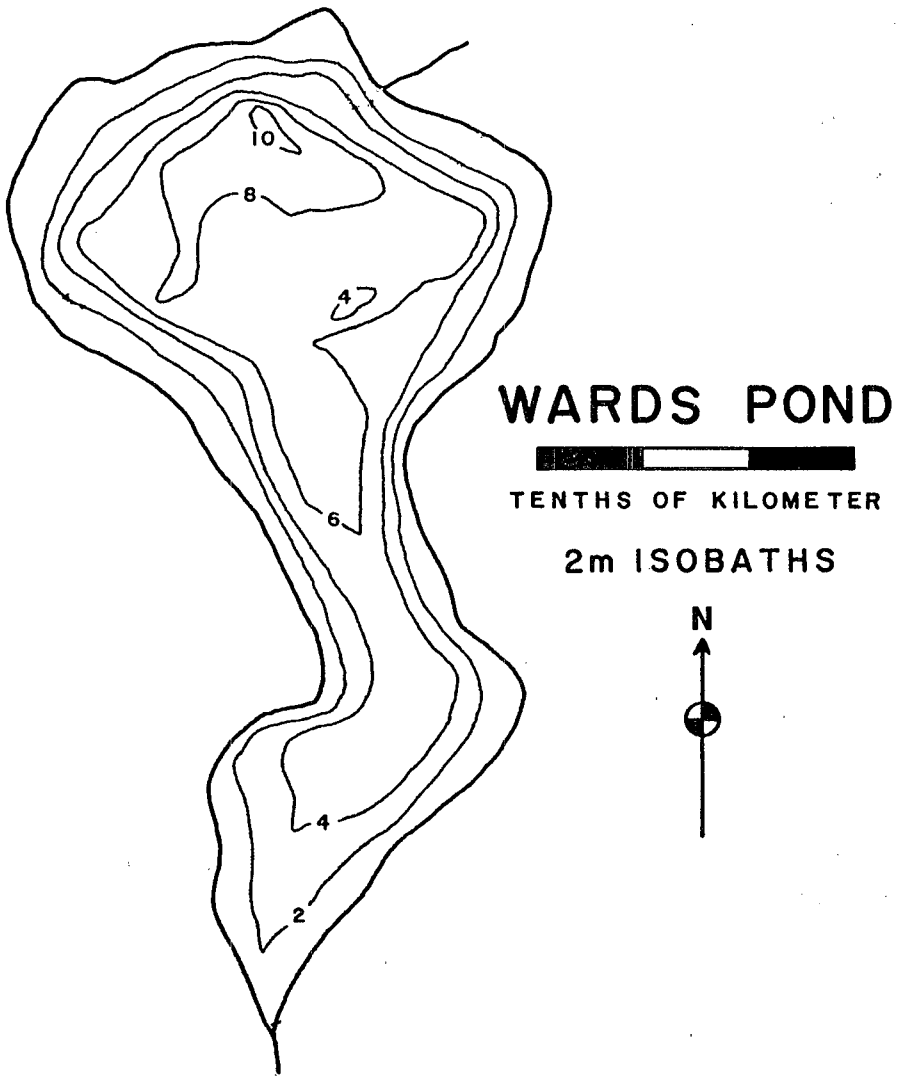

Figure 2-1.—Example of a bathymetric map for Wards Pond, Maine, showing the shape of the shoreline, locations of tributaries and lake outflow, and depth contours (lines connecting points in the lake of equal depth) at 2-m intervals (about 6 feet) (source: Davis et al. 1978).

The pelagic zone is the open-water area not directly influenced by the shore or the bottom. The profundal area is the deeper part of a lake that lies below the light-controlled limit of plant growth. Lakes that have a large fraction of the total water volume in the profundal zone generally have relatively low productivity per unit volume.

Another aspect of lake morphometry often correlated with productivity is referred to as "shoreline development." In limnology, shoreline development (SD) is the ratio of the length of the shoreline to the circumference of a circle with the same area as the lake:

$$SD = \frac{\text{length of shoreline}}{2\sqrt{(\text{area of lake}) \cdot \pi}}$$

It describes the degree of shoreline convolutions, that is, the extent to which the shoreline shape departs from a circle. A lake shaped like a perfect circle would have a shoreline development factor of one; lakes with highly convoluted shorelines have much greater values. Generally, lakes with a high shoreline development value have disproportionately large littoral areas and high littoral-to-lake area ratios and tend to be more productive.

Lake Hydrology

Hydrology is the science dealing with the distribution and circulation of water on the surface of the land, in the soil and underlying rocks, and in the atmosphere. Lakes and reservoirs represent one component of the hydrologic cycle (Fig. 2-2), the process by which water is circulated from the atmosphere to the earth (as precipitation) and then back to the atmosphere (through evaporation and transpiration) in a continuous cycle. The subsections that follow summarize two important hydrologic concepts: (1) water balance and residence time within lakes and reservoirs and (2) the role and importance of a lake's watershed.

Surface water is standing or flowing water on the land surface, such as streams, rivers, lakes, and oceans.

Groundwater is water that infiltrates the soil and underlying rock layers, eventually flowing into lakes and other surface waters.

Surface runoff is excess precipitation or snowmelt that does not infiltrate the soil but flows over the land surface.

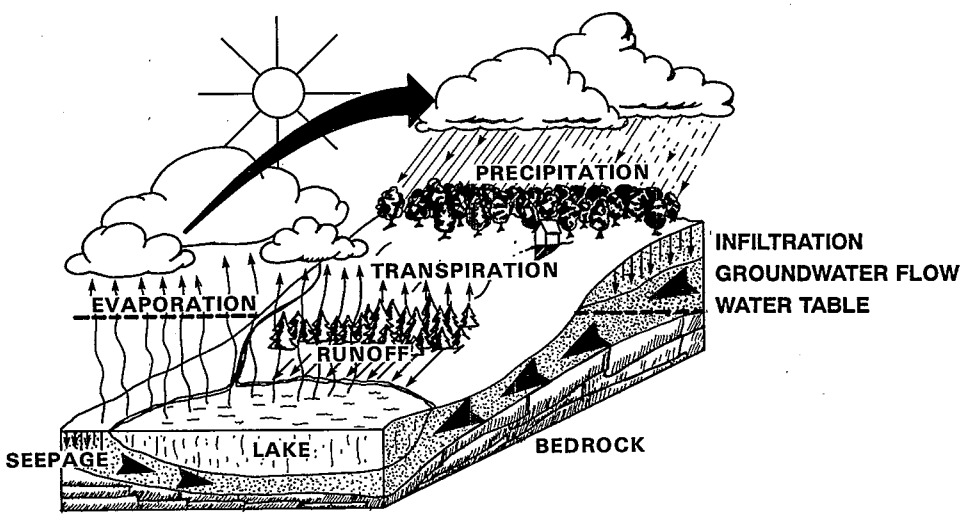

Figure 2-2.—The hydrologic cycle (source: Olem and Flock, 1990).

Water Balance and Hydraulic Residence Time

Important physical characteristics that influence the lake and reservoir ecosystem include its quantity (volume) of water, the rate these waters are replaced and replenished, and the sources of water entering the lake.

A lake's volume is determined by the shape of its basin and by the relative balance of water inputs and outputs. Water inputs include direct precipitation, groundwater, surface stream inflow, surface runoff during storms or snowmelt events, and any point source discharges of wastewaters (e.g., from sewage treatment facilities). Water outputs include discharges through the lake outflow(s), evaporation, losses to groundwater, and water withdrawals for domestic, agricultural, and industrial uses. If inputs exceed outputs, lake volume will increase and the lake level will rise. Conversely, when lake outputs exceed inputs (for example, during a summer drought period), the lake level will fall.

Lakes that experience large fluctuations in lake volume as a result of either natural or human-related causes have unique management problems. Large drops in lake level can hinder user access to the lake, and the exposed shoreline may be aesthetically unpleasing. The shoreline may be subject to greater erosion from wave action and runoff, increasing the silt load in the lake or reservoir. Plants and animals that live in shallow nearshore areas may be adversely affected by exposure and desiccation. For fish species that spawn in nearshore areas, decreased water levels that coincide with periods of egg laying and incubation can affect reproductive success. Large changes in lake level are common

Lakes that experience large fluctuations in lake volume as a result of either natural or human-related causes have unique management problems.

problems in some reservoirs and in arid regions where evaporation rates are high and water inputs are low. At the same time, however, controlled changes in water level, at the right time and of the appropriate magnitude, can be a useful fisheries management tool (see Chapter 8).

A second important lake characteristic is its hydraulic residence time, defined as the average time required to completely replace a lake's water volume. In simple systems where the inflow and outflow rates are equal and water in the lake is completely mixed, the water residence time (T_W) equals the amount of time that would be required for the water inflow or outflow (Q) to replace the volume of water in the lake (V):

$$T_W = V / Q$$

Lakes with large inflows and outflows relative to the lake volume have short residence times. Water in the system is replaced rapidly, generally within days or months (e.g., Fig. 2-3). Large lakes with relatively small inputs and outflows, on the other hand, have long residence times, on the order of several years or decades.

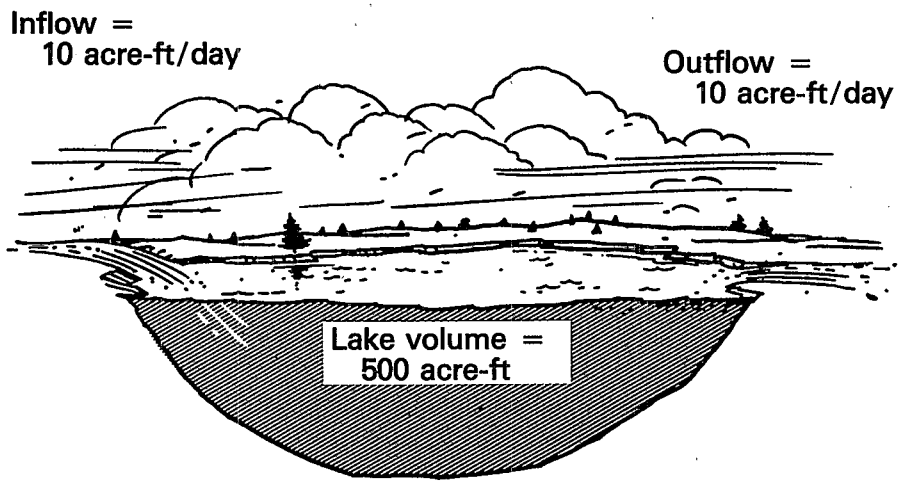

Figure 2-3.—Hydraulic residence time is the average time required to completely renew a lake's water volume. The simple formula given in the example above assumes that inflow is equal to outflow (source: Olem and Flock, 1990).

A lake's hydraulic residence time influences management decisions in two major ways:

1. Lakes with longer residence times will generally exhibit longer lag times; that is, a longer period of time will pass before restoration efforts (such as reductions in external nutrient loads) will result in discernible changes or improvements in lake quality. Such lakes have relatively poor ability to "cleanse" themselves by flushing.

2. In-lake processes (such as internal nutrient cycling) are more important in lakes with longer residence times, while lakes with short residence times are influenced more by the quantity and types of external inputs. All else being equal, lakes with longer residence times are generally more productive than lakes with shorter residence times. In waters with very short residence times, the development of plankton communities (small plants and animals that live suspended in the water column) may be hindered by the rapid flushing rate.

All else being equal, lakes with longer residence times are generally more productive than lakes with shorter residence times.

The Lake and its Watershed

The land area that surrounds a lake and drains into it (either directly or through feeder streams or rivers) is called the lake's watershed. Water and the dissolved and particulate materials it carries enter the lake from its watershed. If a lake is dominated by surface inflows, the characteristics of its watershed and activities occurring there play important roles in determining water quality and productivity. Important natural features include watershed topography, vegetation, and soil fertility and erodibility.

Land uses in the watershed also directly affect both lakewater quality and quantity. For example, large areas of impervious surfaces (paved areas or packed dirt) decrease the infiltration of water into the soil and groundwater system, thereby increasing the quantity of stormwater discharged directly into the receiving lake or stream as surface runoff. Watershed disturbances that remove natural vegetation, such as farming or construction, can greatly increase the amount of silt and nutrients exported from the land to the lake. Managing land uses and activities within the watershed is, therefore, an important component of a comprehensive lake management and restoration program.

Managing land uses and activities within the watershed is, therefore, an important component of a comprehensive lake management and restoration program.

Sediment Loads and the Bottom Substrate

Waters entering a lake generally carry suspended particles, including organic matter, clays, and silt washed from the watershed and carried downstream to the lake in rivers and streams. These particles settle once they reach the relatively quiescent lake environment; as a result, lakes are extremely efficient sediment traps. Although filling with sediments is a part of a lake's natural aging process, poor land management practices can speed this process significantly. Watersheds that have soils with a high clay content, more erodible soils, and more exposed soil and disturbance contribute greater quantities of suspended sediments. In addition, sediments can carry substantial quantities of adsorbed nutrients and chemical contaminants. Thus, lakes receiving high sediment loads frequently also receive excessive inputs of nutrients and toxic contaminants.

Although filling with sediments is a part of a lake's natural aging process, poor land management practices can speed this process significantly.

Much of the sediment load entering a lake, together with the particulate matter produced internally (primarily dead organic particles from plants and animals living within the lake), eventually settles to the bottom. The rate of sedimentation and the types of materials deposited determine the physical characteristics of the bottom substrate (see Table 2-1), which, in turn, influence oxygen levels in and near the bottom sediments and the types and productivity of organisms that live there. Many fish species deposit their eggs in these bottom sediments; different fish species prefer or require different substrate types. For example, lake trout require well-oxygenated, gravel-rubble substrate with little silt or clay. High sedimentation rates, resulting from large inputs of suspended sediments to the lake, may smother and kill eggs deposited on the bottom.

Table 2-1.—Substrate types and general characteristics.

Bedrock:	All exposed rock
Boulder:	All rock over 10 inches (25 cm) in diameter (approximately)
Rubble:	Rock material between 3 and 10 inches (8–25 cm) in diameter
Gravel:	Rock material between 1/8 inch and 3 inches (0.2–8 cm) in diameter
Sand:	Material of crystalline rock origin less than 1/9 inch (0.3 cm) in diameter but still large enough to be palpable as grit
Silt:	Inorganic material of various origins but finer than sand
Clay:	A material of organic origin (aluminum silicates) with a greasy feel between the fingers and no apparent structure
Muck:	A soft material largely of organic origin with silt and clay intermingled
Marl:	A light gray, calcerous material derived principally from agal activity and mollusk shells
Detritus:	An organic material in which large pieces (sticks, leaves, remnants of decayed aquatic plants, etc.) are common

Light in Lakes

Light is essential for primary production. It is also the primary source of heat for lakes. Thus, the amount of light available and the depth to which it penetrates are major driving forces that directly and indirectly affect lake productivity and a wide range of other lake properties and processes.

In lakes with a high concentration of suspended particulates, most of the incoming light is absorbed or backscattered in the first few feet of water.

A portion of the light reaching a lake is reflected off its surface; the greater the angle of the sun, the higher the percentage of light reflected. Near noon on a clear, calm summer day, about 5 percent of the incident light is reflected, while over 50 percent is reflected by late afternoon (Wetzel, 1983).

The light that enters a lake is

- absorbed by the water and converted into heat;
- absorbed by plants and converted, through photosynthesis, into organic matter;
- absorbed by inorganic particles in the water and converted into heat;
- scattered back out of the lake by particulates in the water; or
- reflected or absorbed and converted to heat by sediments on the lake bottom, if it penetrates through the water column.

In photosynthesis, light energy is converted into chemical energy and stored as organic compounds to support biological growth and production.

In lakes with a high concentration of suspended particulates, most of the incoming light is absorbed or backscattered in the first few feet of water. Deeper waters receive little heat input and have inadequate levels of light for plant growth. Low light may, in such waters, be a major factor limiting plant growth and lake productivity.

[L]ight energy with shorter wave lengths penetrates deeper into the water column.

Water strongly absorbs light in the infrared and red range of the light spectrum (range with longer wave lengths); and 40 to 90 percent of the light energy at these wave lengths is absorbed by pure water within the first three feet (Hutchinson, 1957). By contrast, the same depth of water absorbs less than three percent of the green, blue, and ultraviolet light. Thus, light energy with shorter wave lengths penetrates deeper into the water column. One result of this differential absorption of light is that deeper waters and lakes with relatively low levels of suspended solids generally appear bluish green.

Dissolved organics increase the absorption of ultraviolet, blue, and green light. While all waters absorb infrared and red light, waters with high concentrations of dissolved organics absorb all wave lengths of light and, as a result, all or most of the incoming light may be absorbed in the upper few feet of the water column. Heat input is concentrated in the top layer of water and plant growth inhibited in deeper waters.

Light availability may vary seasonally (see Fig. 2-4). Algal blooms in the summer may prevent light from penetrating into deeper waters. Immediately following rainstorms or snowmelt, water clarity and light penetration may be reduced by large influxes of suspended sediments in surface runoff, especially in watersheds where soils and the natural vegetation cover have been disturbed.

During periods of heavy snow and ice cover, very little light penetrates into the lake to support plant growth.

Snow and ice cover during winter may also reduce light levels. The percentage of light reflected by and transmitted through clear, colorless ice is not greatly different than that for water. Light absorption increases greatly, however, if the ice is cloudy (with air bubbles) or stained with organic matter. Snow cover also markedly increases both light reflection (about 75 percent) and light absorption (90 percent by four inches of new snow). During periods of heavy snow and ice cover, very little light penetrates into the lake to support primary production.

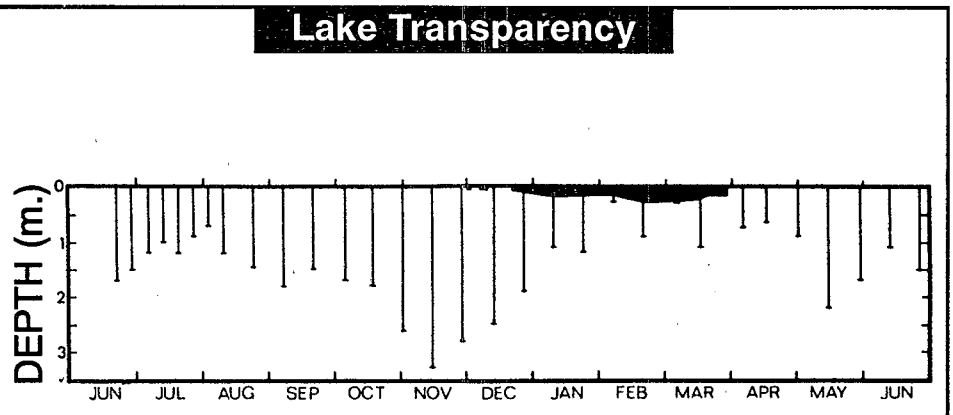

Figure2-4.–Variations in the Secchi disk transparency of Wintergreen Lake in southwestern Michigan in 1970-71 (source: Wetzel, 1975). Water clarity and the depth of light penetration can be measured in several ways. One of the simplest and most common is with the Secchi disk. Secchi depth transparency is the greatest depth at which a disk 20 cm in diameter is visible when lowered into the lake around midday. Seasonal changes in Secchi depth transparency or over time provide a good indication of trends in water clarity and the approximate depth to which light levels are adequate for plant growth.

Lake Circulation and Thermal Regimes

The movement and mixing of waters within a lake or reservoir also are key factors that influence lake productivity as well as the suitability of lake habitat for various fish species. Wind is the primary energy source that drives water movement and mixing. Differences in water density, caused by differences in temperature and/or the concentration of dissolved solids, may limit the depth and extent of wind-driven water circulation.

The density (weight per unit mass) of water is temperature-dependent. As waters become colder (down to 39°F or 4°C), they also become heavier. Because sunlight is the major heat source, waters near the surface that receive direct heat inputs warm faster than deeper waters. During the summer, this process often creates a stable thermal stratification pattern (Fig. 2-5): a warmer, lighter layer of water, the epilimnion, floats on a colder, heavier water layer, the hypolimnion. The intermediate area of rapid temperature change is the metalimnion.

The differences in water density between the epilimnion and hypolimnion provide an effective barrier to lake mixing. The greater the temperature differences, the more energy is needed to circulate the water. During summer thermal stratification, waters in the epilimnion circulate but little water exchange occurs between the epilimnion and hypolimnion. When the lakewater cools, as in the fall, this temperature-controlled zonation breaks down and water mixes throughout the lake (fall overturn). Likewise, in many lakes thermal differences also are small in the spring and the water column mixes completely (spring overturn).

The differences in water density between the epilimnion and hypolimnion provide an effective barrier to lake mixing. The greater the temperature differences, the more energy is needed to circulate the water.

Water reaches its maximum density at 39°F (4°C). At lower temperatures, density decreases slightly until the freezing point (32°F, 0°C) is reached. When water freezes, ice forms and the density decreases sharply (Fig. 2-5). Because of this decrease in density at temperatures near and at the freezing point, ice forms at the top of lakes rather than at the bottom. During the winter, this ice cover insulates the lake from the wind. Thus, even though the density gradients are relatively minor, little water column mixing occurs.

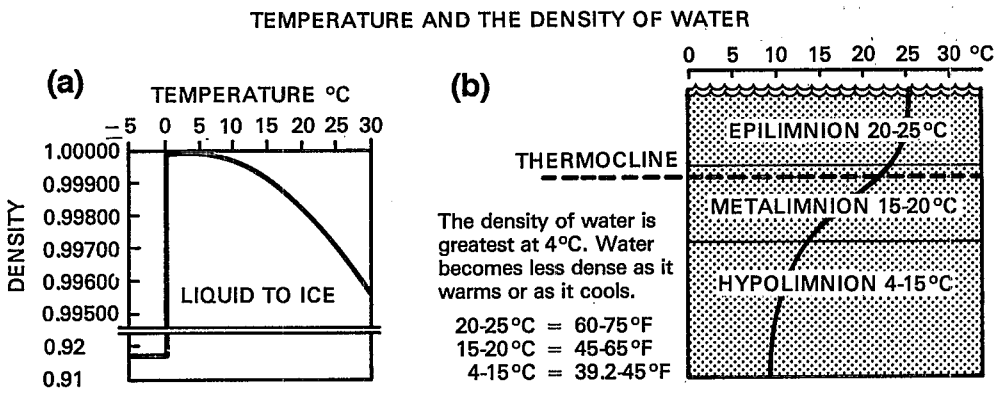

Figure 2-5.—The temperature-density relationship of water (a) enables deep lakes to stratify during summer (b) (source: Olem and Flock, 1990).

Mixing occurs throughout the water column twice a year, in the spring and fall.

Most lakes in temperate regions undergo a fairly predictable seasonal pattern, alternating between stratification and complete mixing. During the summer and winter (in ice-covered waters), lakes are generally thermally stratified, with minimal mixing of surface and deeper waters. Mixing occurs throughout the water column twice a year, in the spring and fall. Shallow lakes, however, especially those lakes in areas with strong winds, may circulate continually or periodically even during summer. By contrast, very deep lakes, especially small, deep lakes in steep-sided watersheds that limit wind speeds, may mix only once a year, infrequently, or not at all. (Mixing and stratification patterns in reservoirs are discussed further in the subsection, *Special Issues in Reservoirs*.)

[A] lake's thermal regime and temperature variations are important factors that influence the types of species and fish communities able to survive and reproduce in that environment.

Lake stratification has direct and indirect effects on fish communities. The colder, deeper waters of the hypolimnion, if well-oxygenated, can serve as a refugium for fish species that prefer (or require) cold water temperatures. Different fish species prefer to live at different temperatures (see Table 2-2); thus, a lake's thermal regime and temperature variations are important factors that influence the types of species and fish communities able to survive and reproduce in that environment. However, because of the limited water exchange between the epilimnion and hypolimnion during summer, nutrients tend to accumulate in the hypolimnion. Also, the lake's deeper waters can become depleted of oxygen. Low levels of dissolved oxygen may restrict fish distributions and limit the types and numbers of fish in the hypolimnion.

Table 2-2.—Fish species are often classified as coldwater, coolwater, or warmwater fish, depending on their preferred water temperatures. Example species in each class and the approximate midpoints of the preferred temperature range (Magnuson et al. 1979) are noted below.

COLDWATER FISH (50–60°F)	COOLWATER FISH (68–77°F)	WARMWATER FISH (77–86°F)
Brook trout	Walleye	Largemouth bass
Lake trout	Yellow perch	Bluegill
Rainbow trout	Northern pike	Channel catfish
Kokanee salmon	Muskellunge	Carp

Water density is also affected by the concentration of total dissolved solids (TDS). . . .

Water density is also affected by the concentration of total dissolved solids (TDS): waters with higher TDS are heavier than waters with lower TDS (Table 2-3). If deeper waters have substantially higher TDS than surface waters, a stable pattern of lake stratification may result. Often, in such cases, the stratification is permanent; the lake rarely if ever mixes completely.

Lakes that are permanently stratified as a result of differences in TDS are referred to as "meromictic lakes." Meromictic lakes are relatively rare, however. Most fresh waters have TDS levels between 0.01 and 0.5 g/L (Wetzel, 1983), con-

centrations that have comparatively little effect on water density. Generally, differences in water density and patterns of lake stratification are determined primarily by differences in water temperature; TDS concentrations play a secondary role.

Table 2-3.—Changes in the density of water (at 39°F, 4°C) with total dissolved solids (TDS) (source: Ruttner, 1963).

TDS (g/L)	DENSITY
0	1.00000
1	1.00085
2	1.00169
3	1.00251
10	1.00818
35 (mean seawater)	1.02822

Organic Matter Production and Consumption and Nutrient Cycling

Photosynthesis and Primary Productivity

Chlorophyll is a green pigment in algae and other green plants essential for the conversion of sunlight, carbon dioxide, and water to sugar — photosynthesis.

Chlorophyll-bearing plants in aquatic ecosystems (e.g., planktonic algae, benthic algae, epiphytic algae, and rooted aquatic plants in the littoral zone) use the energy from sunlight to convert carbon dioxide, water, and nutrients into organic matter, oxygen, and water (Fig. 2-6). This process, called photosynthesis, converts light energy into chemical energy (stored as organic compounds), which can then be used to support biological growth and production. The rate of photosynthetic uptake of carbon to form sugars and other organic compounds is called primary productivity. The amount of plant material produced and remaining in the system is called primary production and is also referred to as the standing crop or biomass (total weight) of plants in a farmer's field. The molecular oxygen produced during photosynthesis is the primary source of dissolved oxygen in the water and oxygen in the atmosphere.

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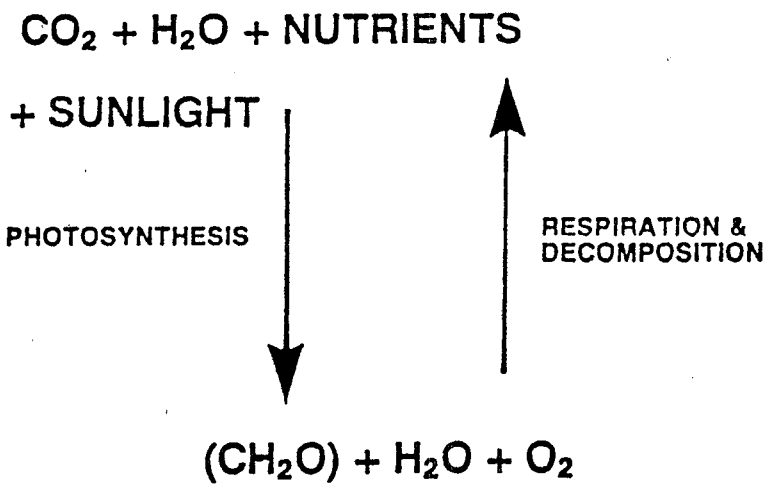

Figure 2-6.—The equilibrium relationship between photosynthesis and respiration-decomposition processes (source: Olem and Flock, 1990).

Because of the requirement for light, primary production by aquatic plants is restricted to that portion of the lake that receives adequate light for photosynthesis, referred to as the photic zone. The thickness of the photic zone depends upon the transparency of the water and generally corresponds to the depth to which at least 1 percent of the surface light penetrates.

Primary production of planktonic algae is controlled mainly by water temperature, light and nutrient availability, hydraulic residence time, and the rate at which they are consumed. When light is adequate, nutrient availability frequently is the major limiting factor. Production of rooted aquatic plants is controlled more by temperature, light, and bottom substrate type because most rooted plants obtain nutrients from the bottom sediments.

While in-lake photosynthesis is the dominant source of organic matter for the lake's food web, most lakes also receive significant inputs of energy in the form of dissolved and particulate organic matter from their watersheds. Watershed characteristics, lake type, and hydraulic residence time determine the importance of these external inputs relative to in-lake photosynthesis.

Respiration and Decomposition

The chemical energy stored in organic molecules is released through the processes of respiration and decomposition.

The chemical energy stored in organic molecules is released through the processes of respiration and decomposition (Fig. 2-6). Plants and animals break down organic molecules to produce the energy needed for their survival and growth in a process called "respiration." Organic matter decomposition is a collective term for the net conversion of organic material back to inorganic compounds through the respiratory activities of all organisms, including bacteria, fungi, and other microbes. Both processes consume oxygen and release energy, carbon dioxide, water, and nutrients.

Decomposition occurs throughout the water column but is often concentrated in deeper waters and in the bottom sediments.

Decomposition occurs throughout the water column but is often concentrated in deeper waters and in the bottom sediments. Dead organic matter (detritus) accumulates on the lake bottom, and in productive lakes, the amount can be substantial. Under these conditions, the quantity of oxygen consumed in deeper waters by decomposition can exceed that available or produced through photosynthesis (Fig. 2-7). Oxygen depletion can be particularly severe in thermally stratified, productive lakes during summer. Then the deeper waters of the hypolimnion are isolated from the epilimnion where photosynthesis and water circulation recharge the oxygen supply. In severe cases, dissolved oxygen may be

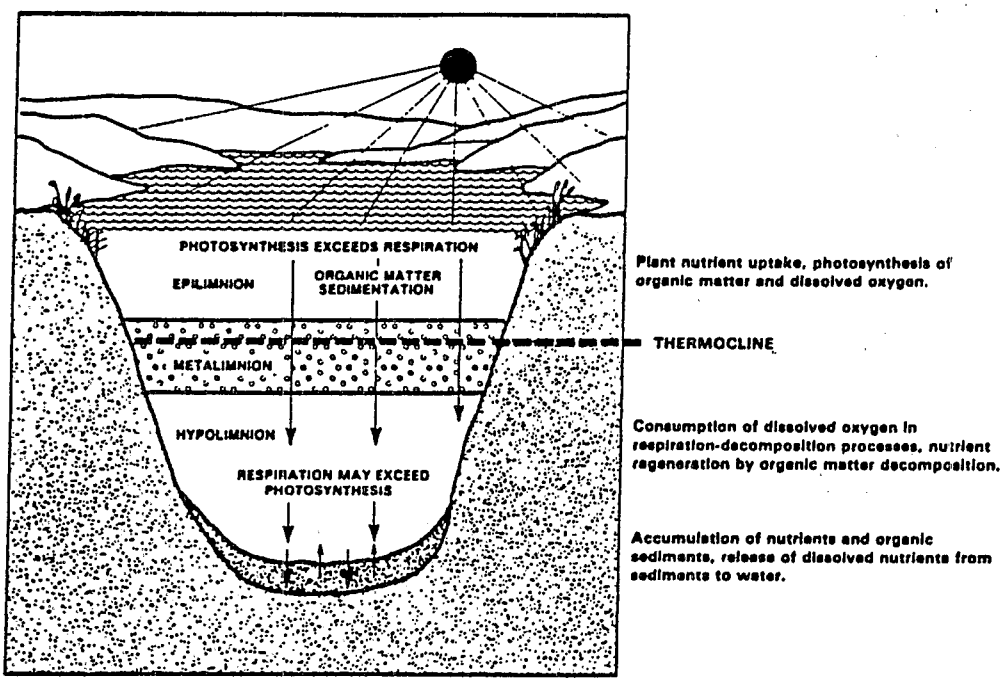

Figure 2-7.—Influence of photosynthesis and respiration-decomposition processes and organic matter sedimentation on the distribution of nutrients, organic matter, and dissolved oxygen in a lake during summer thermal stratification (source: Olem and Flock, 1990).

depleted completely in waters near the lake bottom or in the entire hypolimnion. Similar conditions may occur in productive lakes during winters with prolonged ice and snow cover that limit both water mixing and light penetration.

Oxygen concentrations not only affect the suitability of the habitat for aquatic animals but also control many important chemical and physical reactions. For example, under anoxic conditions (no dissolved oxygen), some metals, nutrient compounds, and gases (e.g., hydrogen sulfide [H_2S] and methane [CH_4]) become increasingly soluble and are released from the bottom sediments into the hypolimnion. At fall overturn, the nutrients and other compounds may reenter the photic zone and stimulate algal productivity. Nutrients that reenter the water column from sediments constitute an internal nutrient load to the lake.

Oxygen concentrations not only affect the suitability of the habitat for aquatic animals but also control many important chemical and physical reactions.

Nutrients that reenter the water column from sediments constitute an internal nutrient load to the lake.

Limiting Nutrients

Of the various elements required for cell growth, nitrogen and phosphorus often limit lake productivity. Nitrogen occurs in several forms, as nitrate (NO_3-), ammonium (NH_4+), and molecular nitrogen gas (N_2). Some algal species, particularly blue-green algae, can satisfy their nitrogen requirements by using N_2 from the atmosphere. As a result, phosphorus is most often the limiting nutrient in lakes (Hecky and Kilham, 1988).

Many human activities produce waste products with high concentrations of phosphorus, such as agricultural drainage waters, some detergents, and municipal sewage. If allowed to enter lakes, these wastewaters can artificially stimulate algal production and result in nuisance algal blooms, noxious tastes and odors, and oxygen depletion in the water column. Therefore, lake management and restoration projects often focus on controlling phosphorus loads.

If allowed to enter lakes, these wastewaters can artificially stimulate algal production and result in nuisance algal blooms, noxious tastes and odors, and oxygen depletion in the water column.

Some systems are nitrogen-limited, however, and some lakes need to be managed for both phosphorus and nitrogen. For example, many of the high-elevation lakes in the western United States are nitrogen-limited (Morris and Lewis, 1988; Eilers, 1991). For these systems, the nitrogen dissolved in precipitation (as NO_3- and NH_4+) is the dominant nitrogen source (Likens and Bormann, 1972). As a result, increases in nitrogen deposition from atmospheric emissions of nitrous oxides from power plants, industrial sources, and motorized vehicles can increase both the availability of nutrients and productivity of these lakes.

Trophic State and Eutrophication

Lakes are frequently characterized according to their trophic state:

Trophic state is the degree of a lake's eutrophication.

- **Oligotrophic** lakes are nutrient poor and relatively unproductive. Insufficient organic matter is produced in the epilimnion to reduce hypolimnetic oxygen concentrations; thus, the hypolimnion remains relatively oxygenated throughout the year.
- **Mesotrophic** lakes have intermediate nutrient availability and biological productivity.
- **Eutrophic** lakes are nutrient rich and highly productive. Decomposition of the abundant organic matter may often exhaust the dissolved oxygen in unlighted zones, leading to anoxia in the hypolimnion.
- **Hypereutrophic** lakes, which are extremely productive and rich, often experience pea-soup conditions because of high concentrations of algae and/or excessive densities of rooted aquatic plants.

Multiple trophic states can exist within large lakes and reservoirs; for example, the upper reaches of a reservoir may be oligotrophic while lower reaches or regions receiving tributary inflows with high nutrient loads may be eutrophic.

A lake's trophic state has a major influence on the potential fish production and types of fish communities best suited to the water.

Lake eutrophication is a natural process that results from the gradual accumulation of nutrients, increased productivity, and a slow filling-in of the lake basin, generally over hundreds of years, with accumulated sediments and organic matter from the watershed. Human activities can greatly accelerate this process, however, by dramatically increasing nutrient, soil, or organic matter loads to the lake in a process called "cultural eutrophication." Some lakes and reservoirs are naturally eutrophic because they are located in naturally fertile watersheds. Other lakes are naturally oligotrophic and, if undisturbed, will remain so for thousands of years. A lake's trophic state has a major influence on the potential fish production and types of fish communities best suited to the water. Therefore, natural differences in trophic state must be recognized and accounted for when designing a fisheries and lake management program.

Aquatic Biota

Habitat is a place where plants or animals live and grow.

Most of the major groups (taxa) of biota are represented in the biological communities that occur in lakes and reservoirs, from one-celled bacteria and algae to the birds and mammals that rely on aquatic ecosystems for food or habitat. For convenience, many of these taxa are grouped according to their primary habitat and/or lifeform. For example:

- **Microbes** refers collectively to some bacteria, fungi, and other microscopic organisms involved in organic matter decomposition.
- **Plankton** are microscopic organisms that live suspended in the water column. The plankton community includes both plants (phytoplankton) and animals (zooplankton) and several different major taxa (phyla, classes, families, and species of organisms).
- **Periphyton** are organisms associated with submerged substrates, such as bottom sediments, aquatic vegetation, docks, and other surfaces. The periphyton community includes periphytic algae as well as the microscopic animals and microbes that feed on that algae.
- **Macrophytes** refers to the larger, macroscopic aquatic plants and algae, most of which grow rooted in the bottom sediments. Some, however, are free-floating forms.
- **Macroinvertebrates** are the larger, multi-celled animals without backbones, including many species of mollusks, insects, other crustaceans, and worms (oligochaetes), which generally live on or in the bottom sediments (benthic invertebrates) or attached to macrophytes in the littoral zone.

Fish feed on all of these organisms, although different species prefer different types of prey. Brief descriptions follow of each of these major components of the biological community in lakes and reservoirs.

Microbes

Freshwater microbial communities are composed of a diverse array of bacteria, fungi, yeasts, mold, protozoans, and other microorganisms that are found free-living in the water column, associated with suspended organic matter, mixed in with bottom sediments, and on submerged surfaces, such as plants, rocks, and decaying organic matter. These communities play a major role in the breakdown of organic substances and nutrient recycling as well as the nutrition of animals that feed on detritus and other organic materials. The activity of microbes (termed "conditioning") makes detritus more digestible; and the microbes themselves are an energy source for detritus-feeding organisms, which include many benthic invertebrates and some fish species (e.g., carp and some members of the sucker family).

Phytoplankton

Phytoplankton are microscopic algae that live suspended in the water column. Most phytoplankton are slightly heavier than water and will gradually sink or settle out of the water column if not maintained by water turbulence or wind-driven water circulation. A few species have buoyant, gelatinous coatings and float to the surface, forming algal scums. These phytoplankton occur primarily in nutrient-rich, highly productive waters where light is the major factor that limits algal growth.

The taxonomically diverse phytoplankton community is composed of a number of different kingdoms and phyla, such as the green algae (Chlorophyta), blue-green "algae" (Cyanobacteria), and diatoms (Chrysophyta). Different species tend to thrive under particular types of conditions. Blue-green "algae" often dominate in productive eutrophic or hypereutrophic lakes because they can fix nitrogen gas from the atmosphere.

Seasonal changes in environmental conditions within a given lake generally result in seasonal changes in the types and abundance of algae (Fig. 2-8). Algal production and biomass usually are low in the winter because of low water temperatures and low light availability. In the spring and early summer, phytoplankton biomass tends to be high as a result of increasing water temperatures and light availability, relatively high nutrient availability, and low losses to zooplankton grazing (consumption by microscopic animals). As grazing pressure increases and nutrients in the epilimnion are depleted by continued algal growth, the algal biomass generally declines from early to midsummer, only to rise again in the late summer and fall when water column mixing increases the supply of nutrients. Diatoms often dominate the phytoplankton in the spring and fall, green algae in midsummer, and blue-greens in late summer.

Phytoplankton serve as a food source for zooplankton and other animals, including some fish species (e.g., many minnows) that feed directly on planktonic algae. Phytoplankton standing crops are generally a good indicator of a lake's trophic state and nutrient loadings that, in turn, influence potential fish production.

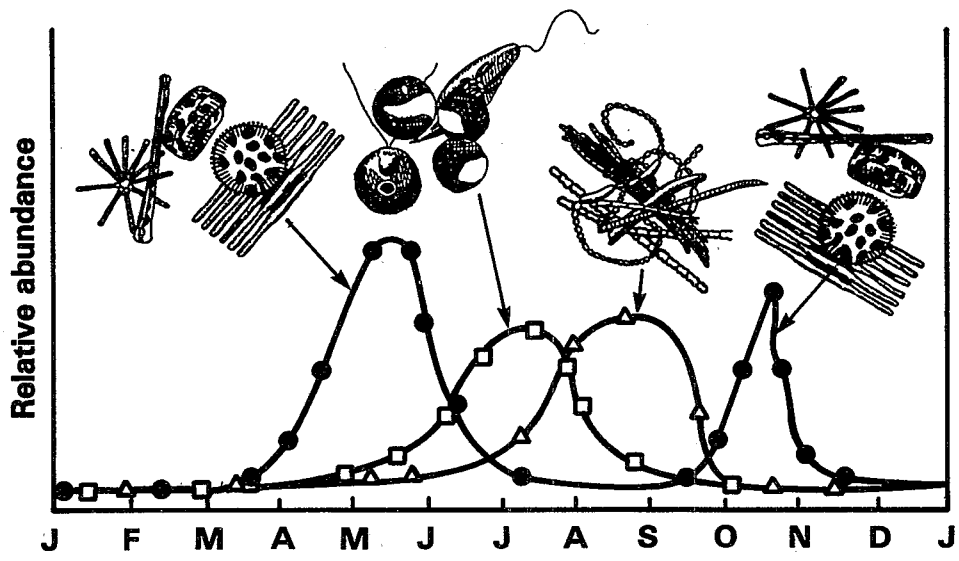

Figure 2-8.—A typical seasonal succession of lake phytoplankton communities. Diatoms (solid circles) dominate the phytoplankton in the spring and fall, green algae (open squares) in midsummer, and blue-green algae (open triangles) in late summer (source: Olem and Flock, 1990).

Periphyton

Periphytic algae typically contribute a rather insignificant amount to the energy budget of lakes; for example, generally less than 6 percent of the total in-lake primary production in oligotrophic lakes (Schindler et al. 1973; Jordan and Likens, 1975; Sondergaard and Sand-Jensen, 1978; Kairesalo, 1980). Their relative contribution to primary production is greater in shallower lakes. Most species are single-celled or exist in small, microscopic colonies. Some periphytic algae, however, grow in long filaments, visible to the naked eye. Excessive growths of periphyton can occur in highly productive waters as well as acidic lakes, can alter the bottom habitat, and are unattractive. Few fish in temperate lakes feed primarily on periphyton. However, large growths of filamentous algae can provide a sheltered habitat for small, young fish.

Macrophytes

Macrophytes serve as breeding, feeding, and nursery grounds for many fish species and are an important food source for waterfowl, some mammals (e.g., muskrat, moose), invertebrates, and detritus-based organisms. Macrophytes also serve as sites for egg deposition by insects, zooplankton, and some fish; as substrate for periphytic algae and various attached invertebrates; and as microhabitats for small fish and invertebrates avoiding predation. Finally, macrophytes help to stabilize bottom sediments by binding them and reducing wave action.

Rooted macrophytes are classified into three groups based on their life-form: emergent, floating-leaved, and submersed.

Rooted macrophytes are classified into three groups based on their life-form: emergent, floating-leaved, and submersed. Emergent macrophytes, which grow on water-saturated or submerged soils and extend mature leaves into the air, include cattails (*Typha* spp.), pickerelweed (*Pontederia cordata*), and arrowheads (*Sagittaria* spp.). Floating-leaved macrophytes also are rooted in the sediment, but their leaves float on the surface of the water when mature, for example, the water-lillies (*Nuphar* spp.). Submersed rooted macrophytes grow entirely below the water's surface and include numerous mosses and macroalgae (*Chara*) as well as vascular plants such as watermilfoil (*Myriophyllum* spp.), bladderwort (*Utricularia* spp.), and pipewort (*Eriocaulon* spp.). Free-floating macrophytes, such as duckweed (*Lemna* spp.), occur in sheltered areas of some lakes.

Many macrophytes grow through the spring and summer and then die back when water temperatures cool in the fall. In shallow lakes with large, extensive beds of macrophytes, decomposition of this dead organic matter can deplete oxygen levels and may, in extreme cases, result in fishkills. Low levels of dissolved oxygen may also occur periodically in dense beds of macrophytes during summer, following extended periods of cloud cover and low light input, or during the night, when the oxygen consumed by plant respiration exceeds that produced by photosynthesis.

Zooplankton

Zooplankton are a diverse group of aquatic invertebrates, generally smaller than 2 mm (less than one-tenth of an inch). The three most numerically dominant taxonomic groups are the rotifers, copepods, and cladocerans (water fleas) (Fig. 2-9). The zooplankton community includes both herbivores (animals that feed on plants, primarily the phytoplankton) and predators, which feed on other animals. Zooplankton grazing can have a significant influence on phytoplankton species composition and productivity through selective grazing (e.g., feeding on larger or smaller phytoplankton, depending on the size of the zooplankton) and by recycling nutrients. Zooplankton, in turn, are eaten by fish, waterfowl, and other larger animals and thus play an important role in the transfer of energy from phytoplankton to higher trophic levels.

Trophic level is a step in the trophic pyramid, the hierarchical classification based on the types of organisms other organisms eat and that eat them.

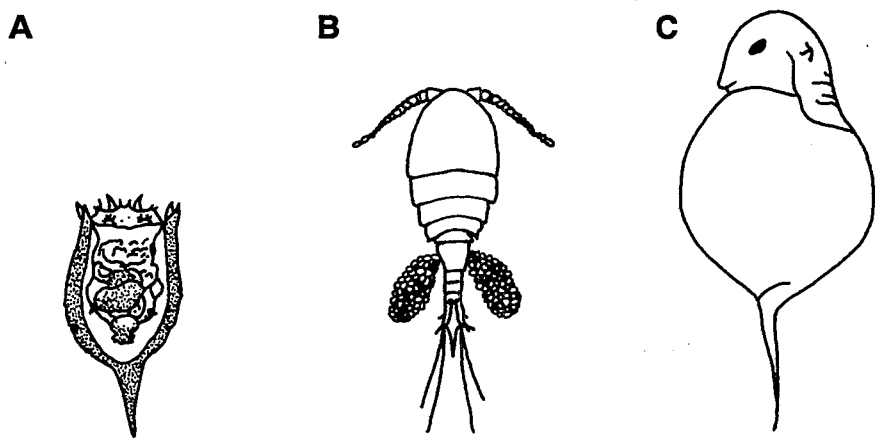

Figure 2-9.—Examples of zooplankton: (a) rotifer, (b) copepod, and (c) cladoceran (adapted from Wetzel, 1975).

Because fish feed on zooplankton, which feed on phytoplankton, changes in fish species composition and abundance may cause marked changes in both zooplankton and phytoplankton communities. Fish tend to feed selectively on large zooplankton. Therefore, the introduction of plankton-feeding fish (planktivores) into a lake can result in the rapid decline of large-bodied zooplankton species, an increase in smaller-bodied forms, and in some cases, an overall decline in zooplankton abundance and biomass. This, in turn, may lead to a shift in phytoplankton species composition (favoring larger forms on which the smaller-bodied zooplankton feed less efficiently) and a net increase in phytoplankton abundance.

To avoid fish predation, some species of zooplankton, particularly large, predacious zooplankton, exhibit a diel vertical migration in lakes. During the day, these organisms remain near the lake bottom; at night, however, they move up into the metalimnion and epilimnion to feed on phytoplankton in the photic zone.

Macroinvertebrates

Most macroinvertebrates live on or in the bottom sediments or attached to macrophytes in the littoral zone. Some species (called "nekton," as a group) live on or immediately under the lake surface, in association with the water's surface film. Benthic macroinvertebrates feed mostly on the detrital matter that settles to the lake bottom. They play an important role in the mechanical breakdown of dead organic matter and the associated release and recycling of nutrients bound in these organic materials. Other macroinvertebrates are herbivores and feed on periphyton. Predators feed on other invertebrates or even small fish. Many fish, waterfowl, and other bird species rely on macroinvertebrates as their primary food resource.

Common macroinvertebrates in lakes include many species of aquatic worms (oligochaetes), leeches, insects (e.g., mayflies, dragonflies, damselflies), other crustaceans (e.g., crayfish, amphipods), and mollusks (e.g., snails, clams). Some species of insects live their entire life cycle in aquatic environments. Many, however, occur in fresh waters only as immature forms. Upon metamorphosizing into adults, they emerge from the water, mate, and then lay eggs in aquatic habitats. Often, these terrestrial adult stages are short-lived. For example, immature forms of mayflies develop for one to two years in aquatic environments but live only one to three days as terrestrial adults. Adult emergence frequently occurs over a fairly short period for a given insect species and in a given lake. During this hatch, fish feed heavily on the emerging adults.

[T]he occurrence of red bloodworms (Tubificidae) in bottom sediments is indicative of low levels of dissolved oxygen because these organisms can survive at much lower oxygen levels than most other animals.

Different species of benthic invertebrates have varying tolerances of environmental stress, such as low levels of dissolved oxygen or high concentrations of toxic substances. Therefore, benthic community composition is often used as an indicator of environmental condition. For example, the occurrence of red bloodworms (Tubificidae) in bottom sediments is indicative of low levels of dissolved oxygen because these organisms can survive at much lower oxygen levels than most other animals. Substrate type also has major impact on benthic community composition.

Fish

All of the previously mentioned organisms are eaten by fish; however, different fish species have different preferred food types and mechanisms of food capture (Table 2-4). An animal taken by a predator as food is referred to as its prey.

Table 2-4.—Preferred types of prey consumed by adults of selected fish species.*

DOMINANT PREY	EXAMPLE FISH SPECIES
Phytoplankton	Gizzard shad, brassy minnow
Zooplankton	Alewife, American shad, cutthroat trout, rainbow trout, kokanee salmon, golden shiner (plus juvenile fish of many species)
Benthic invertebrates	Lake whitefish, bluntnose minnow, lake sturgeon, white sucker, shorthead redhorse, brown bullhead, channel catfish, slimy sculpin
Macroinvertebrates associated with macrophytes	Bluegill, white crappie, yellow perch (plus juvenile fish of many species)
Fish	Longnose gar, grass pickerel, muskellunge, largemouth bass, striped bass, walleye, lake trout

* Most fish, however, are opportunistic feeders and can eat a diversity of prey, depending on the types that are most readily available. In addition, dominant prey types often change as fish grow and become larger.

Fish that are planktivores — for example, alewifes, cisco (lake herring), smelt, and kokanee salmon — feed primarily on zooplankton and, to a lesser degree, on phytoplankton and other organic particles suspended in the water column. Many planktivores filter fairly large quantities of water through their gill rakers (Fig. 2-10), which act as sieves to collect the larger particles. The mesh size of these gill

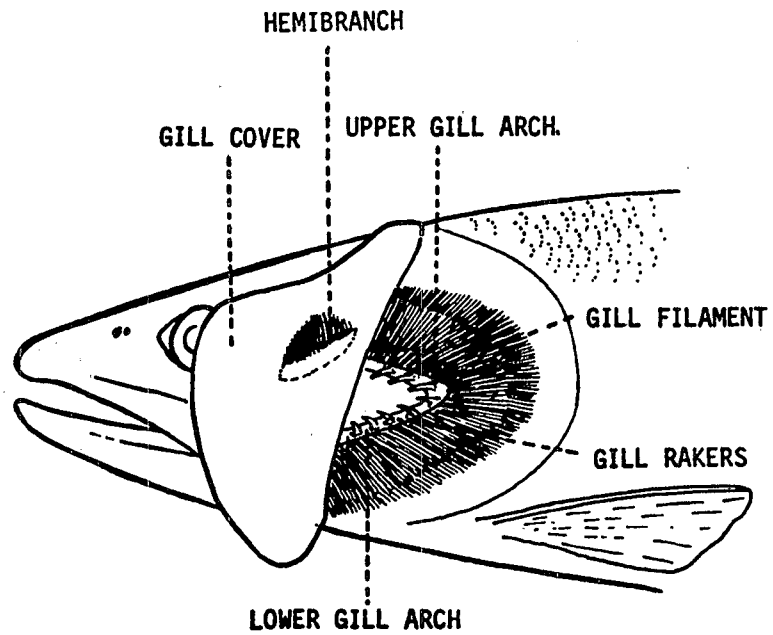

Figure 2-10.—Fish gills and gill rakers. The gill rakers act as a sieve to collect plankton filtered from the water (adapted from Scott and Crossman, 1973).

raker sieves varies among species and by fish size; thus, some species are able to capture smaller plankton than are others. All planktivores also rely to some degree on visual contact and pursuit to capture zooplankton prey. Planktivores that actively select their prey tend to feed on larger, more visible zooplankton species and also can feed more effectively in waters with higher transparency.

Other fish species — for example, suckers, carp, bullheads, and sculpin — feed primarily on organisms on the lake bottom, including benthic macroinvertebrates and periphytic algae as well as detritus. For some, but not all of these species, their benthic feeding habits are evident from their mouth morphology (Fig. 2-11). Some of these fish species (such as carp) feed fairly passively, sucking up large volumes of bottom sediments and then expelling all but the edible particles. Most fish, however, rely on sight or other senses to identify individual prey items, which are then removed from the bottom. Bullheads, for example, seek out food by using the tastebuds on their barbels (Fig. 2-12).

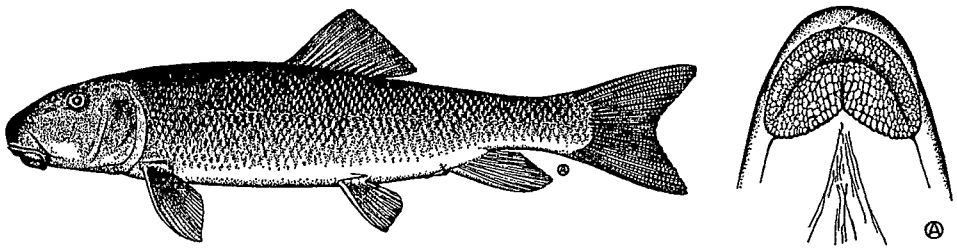

Figure 2-11.—Side and bottom views of the mouth of a white sucker, which feeds primarily on benthos (source: Scott and Crossman, 1973).

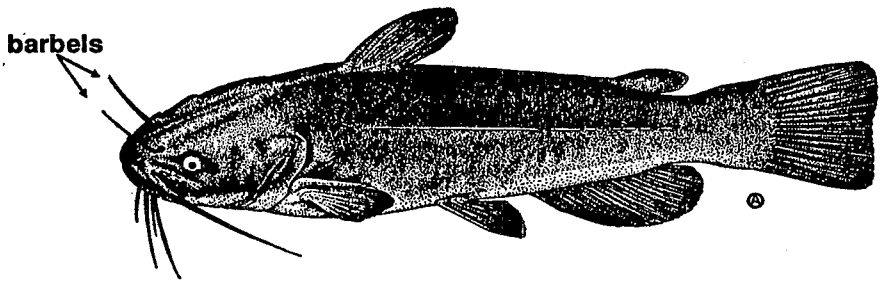

Figure 2-12.—Brown bullhead, illustrating the barbels near the fish's mouth used to help locate prey (adapted from Scott and Crossman, 1973).

Finally, some fish (called piscivores) feed primarily on other fish, often referred to as forage fish. Most large sport fish species are piscivores, including lake trout, largemouth bass, walleye, northern pike, and muskellunge. Piscivores can, if necessary, feed on other food resources, although such a shift in dominant prey generally results in substantially slower growth rates. Changes in diet also occur as the fish ages and grows; when young, most fish species feed primarily on plankton and/or macroinvertebrates.

Although fish have preferred prey, most species are fairly omnivorous and adaptable; they feed most heavily on the types of prey and groups of organisms that are readily available. The quantity and quality of available prey and the effort required for fish to obtain sufficient food are major factors determining fish survival, growth rates, and reproductive success (see Chapter 3). At the same time, fish predation affects the composition and abundance of plankton and benthic communities as a result of their selective feeding on preferred food items and prey species.

The quantity and quality of available prey and the effort required for fish to obtain sufficient food are major factors determining fish survival, growth rates, and reproductive success.

Other Animals

A diversity of other animals — amphibians, reptiles, birds, and mammals — play important roles in lake and reservoir ecosystems. Some, such as kingfishers, eagles, and loons, are important fish predators. Others compete with fish for food; for example, duckling growth can be inversely affected by fish that feed on the same benthic macroinvertebrates as the waterfowl (Hunter et al. 1986). A few animals, such as amphibian larvae and tadpoles, are eaten by fish. Beaver activity in small lakes can alter the lake's physical habitat as well as that of inflowing tributaries and affect the suitability of the lake for fish survival or reproduction. Lastly, lake restoration and fisheries management actions may have both direct and indirect effects on amphibian, reptile, bird, and mammal populations that rely on lakes and reservoirs for food, habitat, or as sites for breeding and nesting.

The Trophic Pyramid

The transfer and general progression of energy from primary producers to herbivores, planktivores, and then to large predators constitutes the lake's trophic pyramid (Fig. 2-13). The actual complex of feeding interactions that exists among all of the lake's organisms is called the food web.

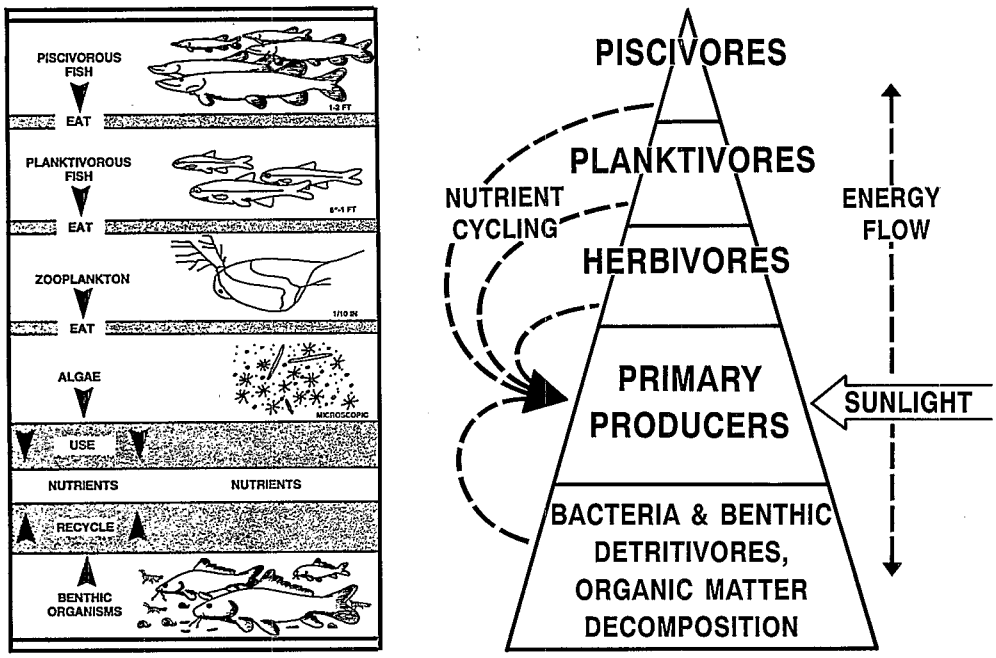

Figure 2-13.—The trophic pyramid illustrates the progression of feeding (or trophic) levels from primary producers, to herbivores, to higher predators. This process involves both the transfer of energy among lake organisms and the recycling of nutrients. Because the available energy decreases at each trophic level, a large food base of primary producers, herbivores, and planktivores is required to support a few large game fish (source: Olem and Flock, 1990).

The energy supporting the trophic pyramid originates with the light energy from the sun, which is converted by photosynthetic organisms into the chemical bond energy represented by the organic matter produced by plants. Each subsequent consumer level (also called trophic level) transfers only a fraction (usually about 10 to 20 percent) of the energy received up the trophic pyramid to the next trophic level. In practice, this means that a relatively small number of large sport fish depend on a large supply of smaller forage fish, which depend on a very large supply of smaller herbivores, which depend on a successively larger base of photosynthetic production by phytoplankton and other aquatic plants.

By constantly producing wastes and eventually dying, all of these organisms provide nourishment for detritivores (detritus-feeding organisms) and to bacteria and fungi, which derive their energy by decomposing organic matter. Detritivores and microbes are, themselves, often eaten by higher level organisms, which recycle a portion of the stored energy. In addition, organic matter transported into the lake from the watershed can decompose and supplement in-lake production. Decomposition releases the nutrients tied up in organic matter, making them available for further plant production (nutrient recycling).

Top-Down Versus Bottom-Up Lake Management

Historically, the central paradigm of limnology has been that the productivity and dynamics of lake ecosystems are regulated almost exclusively by the inputs of nutrients and energy at the bottom of the trophic pyramid (Magnuson, 1991). Efforts to improve water quality focused on reducing internal and external nutrient and organic loads. Increasingly in recent years, however, scientists have recognized that these bottom-up approaches to lake management may not be sufficient nor necessarily the only means for achieving desired management objectives and levels of lake quality.

Shapiro et al. (1975), Carpenter et al. (1985), and others have proposed using top-down management as a complementary approach to bottom-up lake management. The underlying principle of top-down management (also called biomanipulation) is that human-controlled manipulations of the food web, especially of top predators such as fish, can control the abundance and productivity of lower trophic levels, such as algae, which in turn can affect water clarity, nutrient recycling, and other physical and chemical lake characteristics. Given a typical trophic structure, such as that illustrated in Figure 2-14, the basic hypothesis of top-down management is that an increase in the biomass of large piscivorous fish should cause a decrease in the biomass of the small planktivorous fish on which they feed. This increases the biomass of herbivorous zooplankton on which the planktivorous fish feed and finally decreases the biomass of phytoplankton on which the herbivorous zooplankton feed (Fig. 2-15). Carpenter et al. (1985) refer to this sequence of interactions as the trophic cascade. Bottom-up factors (nutrient loading and organic energy transfer) establish the potential lake productivity, while top-down factors (predation and food web processes) determine the realization of that potential (Carpenter et al. 1985; Carpenter and Kitchell, 1988). Both are important; neither, by itself, is sufficient.

The underlying principle of top-down management (also called biomanipulation) is that human-controlled manipulations of the food web, especially of top predators such as fish, can control the abundance and productivity of lower trophic levels . . . .

Lake ecosystems are highly complex. Rarely, if ever, are food web interactions as simple as those described in the previous paragraph. Examples of factors or processes that contribute to this complexity include, in addition to predation, competition among species for limited resources, behavioral responses, physical mixing patterns, the spatial heterogeneity of lakes, temporal variations in environmental conditions (such as climate), and the lag times in response that commonly occur (e.g., between a change in the abundance of piscivorous fish and the subsequent change in abundance of its prey) (Carpenter, 1988; Wetzel, 1983). Recognition and understanding of these factors can lead to more accurate predictions of lake responses to management actions and, ultimately, to more effective lake management.

Further details on top-down management are provided in Chapter 9. The biomanipulation techniques and example applications presented there illustrate the usefulness of these approaches as well as the complexity of and variations in lake responses.

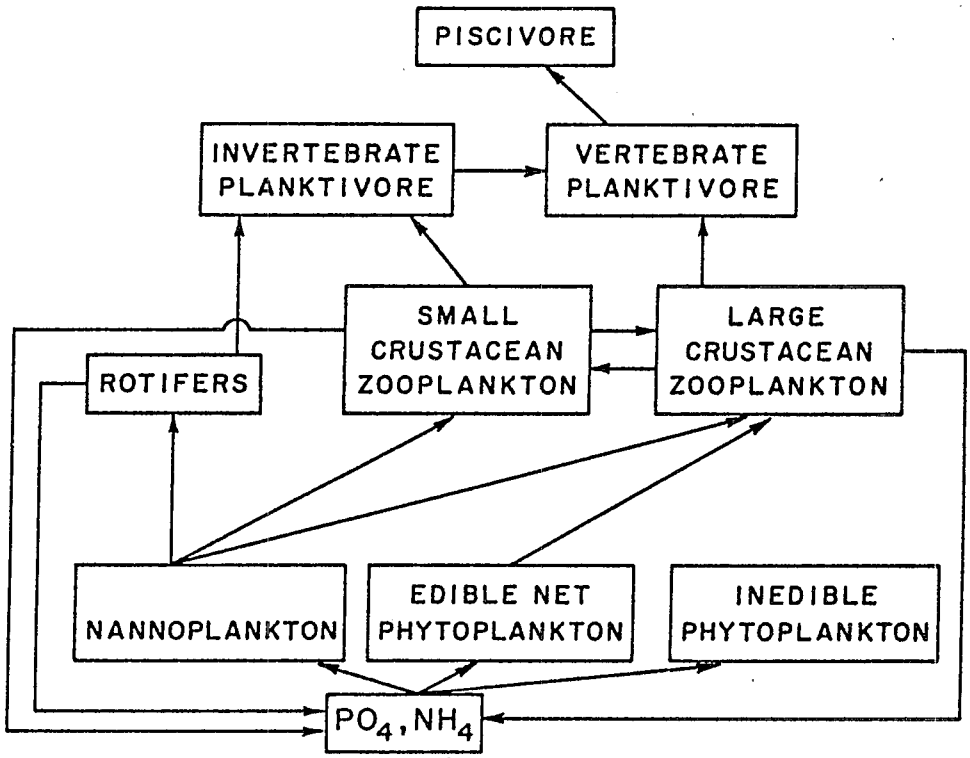

Figure 2-14.—Conceptual model of trophic structure in a typical lake (source: Carpenter et al. 1985).

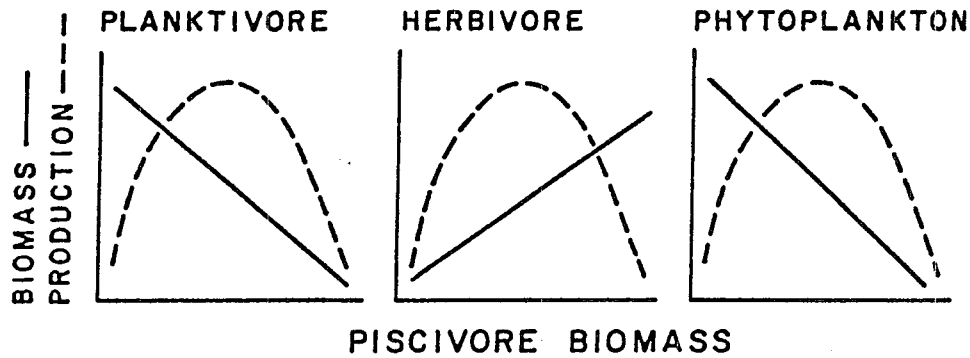

Figure 2-15.—Hypothetical relationship between piscivore biomass and the biomass (solid line) and production (dashed line) of vertebrate zooplanktivores, large herbivores, and phytoplankton, assuming a trophic structure similar to that in Figure 2-14 (source: Carpenter et al. 1985).

Special Issues in Reservoirs

Although all of the preceding physical, chemical, and biological processes also apply to reservoirs, they have several unique features that deserve note. The major distinctions relate to reservoir hydrology and water circulation patterns.

Typically, reservoirs have one or two major tributaries, very large watersheds compared to the lake surface area, relatively short hydraulic residence times, and a high shoreline development factor. The inputs of dissolved and particulate organic and inorganic materials from the watershed are also likely to be very high. In some

ways, reservoirs occupy an intermediate position between rivers and natural lakes in terms of their hydraulic residence time, degree of riverine influence, and other environmental factors that control water quality and biotic productivity.

More so than in most natural lakes, the volume of the inflowing water from major tributary(ies) can be an important factor in determining water circulation patterns and flows in the reservoir (Fig. 2-16). Often, the inflowing river water and the reservoir water differ in temperature or total dissolved solids and, therefore, in density. If the river inflow is warmer than the reservoir, the less dense river water will spread over the reservoir surface as an overflow. If the river is of intermediate density because of intermediate temperatures or moderately high levels of TDS, the inflow will plunge from the surface and proceed "downstream" as an interflow at the depth at which the river and reservoir water densities are equal. If the river inflow is denser (cooler or having substantially higher TDS) than the entire reservoir water mass, the inflowing river water will plunge and flow along the reservoir bottom as an underflow. This downstream flow of water usually controls the transport and distribution of dissolved and suspended particles.

Under stratified conditions, cooler, more dense water may pass through an entire reservoir along the bottom or at an intermediate depth without contributing significant amounts of nutrients or oxygen to the upper waters in the epilimnion. This short-circuiting underflow allows the often nutrient-laden water from the watershed to flow through the reservoir without contributing significantly to algal productivity in the epilimnion.

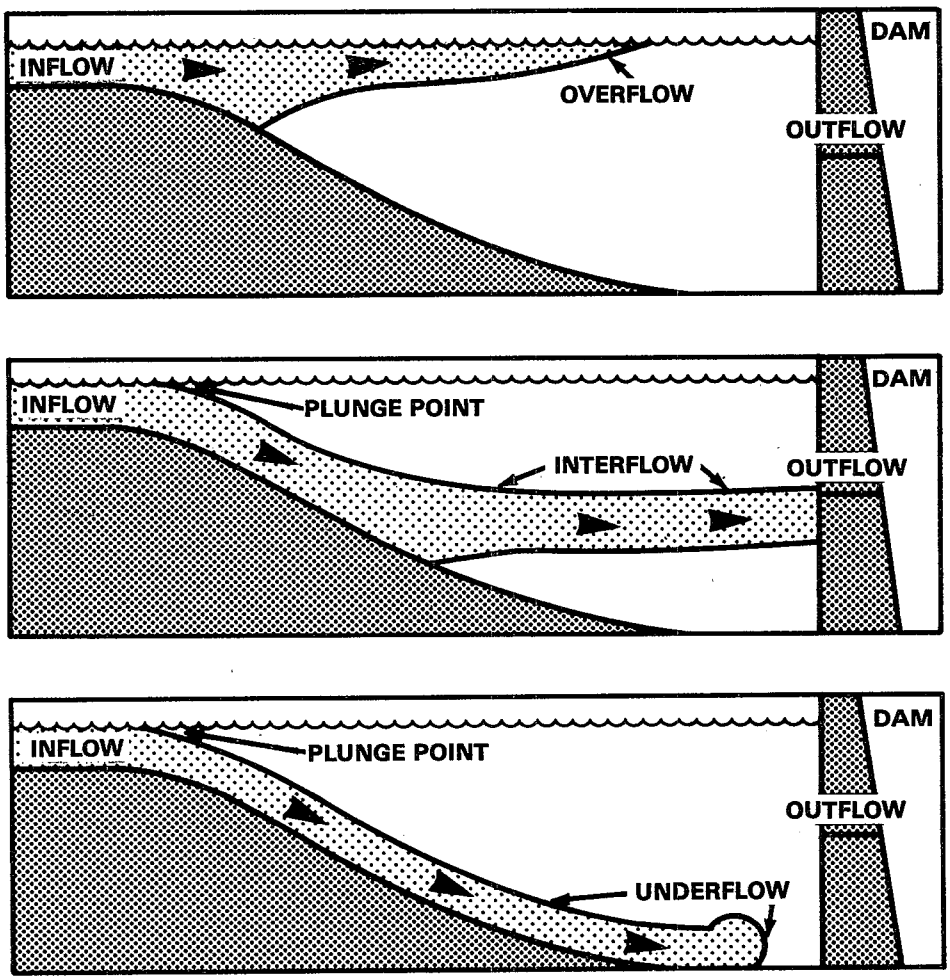

Figure 2-16.—Types of density flows in reservoirs (source: Olem and Flock, 1990).

In most reservoirs, the deepest point is just above the dam, near the lake outflow. This unique basin morphometry can also affect water circulation and stratification patterns.

A distinctive feature of some reservoirs is their subsurface outlet. While in natural lakes the lake outflow draws primarily from the lake epilimnion (during stratification), reservoir subsurface outflows generally draw from the hypolimnion. As a result, the waters exported are colder and often have higher nutrient concentrations and lower plankton biomass. Subsurface outflows also tend to promote subsurface density flows and, thus, the short-circuiting of inflowing tributary waters. Discharge of colder waters downstream may allow for the creation of a coldwater trout fisheries in the reservoir's "tailwaters."

Reservoirs, especially those constructed for flood control or water supply, frequently undergo fairly large changes in water level. As discussed earlier in this chapter, water level fluctuations can cause a myriad of problems; however, if conducted at the right time and of the appropriate magnitude, they can be an effective part of a lake's management program. Reservoirs can have extensive littoral zones but relatively little macrophyte growth because of both water-level fluctuations and high turbidity (and associated light limitations).

Reservoirs, especially those with subsurface outlets, are more efficient at trapping sediments than at retaining nutrients. Therefore, sedimentation and the filling of the reservoir basin with riverborne silts and clays is the dominant aging process.

Finally, reservoirs on average tend to become eutrophic more rapidly than do natural lakes because, as a rule, most of them receive higher sediment and nutrient loads. Newly filled impoundments may go through a relatively short period of trophic instability. Initially, reservoir productivity may be quite high because nutrients are received both from external sources (i.e., the watershed) and internal sources (leaching of nutrients from the flooded soils of the reservoir basin and from decomposition of the submerged terrestrial vegetation and litter). As these internal sources are depleted, reservoir productivity declines from this initial "trophic upsurge" and stabilizes. Reservoirs, especially those with subsurface outlets, are more efficient at trapping sediments than at retaining nutrients. Therefore, sedimentation and the filling of the reservoir basin with riverborne silts and clays is the dominant aging process.

For additional information on the characteristics and ecology of reservoirs, see Thornton et al. (1990).

CHAPTER 3

Fish Ecology

Chapter Objective

Chapter 2 of this book provided an overview of the basic concepts of lake and reservoir ecology — the major physical, chemical, and biological processes that influence the quality of the environment for fish and the role of fish in the lake ecosystem. Chapter 3 also provides a general review of basic ecological concepts but focuses more specifically on the biology and ecology of fish. This chapter steps through the processes and factors that influence fish growth, reproductive success, mortality, and population dynamics; fish genetics; habitat considerations; fish communities; and finally, a discussion of special issues in reservoirs. An understanding of the basic principles of fish ecology is required to effectively assess problems and identify appropriate solutions to managing fish and fisheries in lakes and reservoirs. Additional information on fish biology and ecology and the scientific basis for fisheries management can be found in the texts and references listed in the reference section.

An understanding of the basic principles of fish ecology is required to effectively assess problems and identify appropriate solutions to managing fish and fisheries in lakes and reservoirs.

Definitions

A fish population is a group of fish of the same species that occurs within a given lake or reservoir. In very large systems, a single population may consist of multiple fish stocks; that is, subsets of the population that are reproductively isolated from other fish stocks. The fish community within a lake or reservoir is the collection of all fish populations; i.e., all fish species. The terms "population" and "community" are used similarly for biota other than fish to refer to single-species and multiple-species assemblages, respectively, within a given ecosystem. Finally, fish habitat is the place or type of area where a fish normally lives and grows — the physical and chemical features of the environment on which fish depend, directly or indirectly, to carry out their life processes.

A fish population is a group of fish of the same species that occurs within a given lake or reservoir.

Fish Growth Rates

Most people like to catch big fish. Faster growth rates mean that fish reach larger sizes (length and weight) at a younger age, which may translate into more big fish in the angler's catch. Understanding and manipulating the factors that control fish growth rates, therefore, are important aspects of fisheries management.

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Humans and most other warm-blooded animals attain a maximum size after a definitive period of time, generally soon after sexual maturity. After that time, little further growth occurs except for the addition of fatty tissue if feeding conditions are good. By contrast, fish growth is relatively indeterminate. Fish can

continue to grow, in length and weight, throughout life (Fig. 3-1). On the other hand, if conditions are poor (e.g., limited food intake), fish grow very slowly, if at all. Populations may "stunt," with fish reaching sexual maturity and very old ages at a relatively small size. For example, bluegills as small as 0.5 ounces have been known to successfully reproduce and may reach only 3 to 4 inches in length by 5 to 6 years of age in slow-growing populations. Although fish near starvation may stay the same size for an indefinite period of time or, in extreme cases, actually lose weight, they still retain the capacity to grow rapidly, with no long-term ill effects, should an abundance of food suddenly become available.

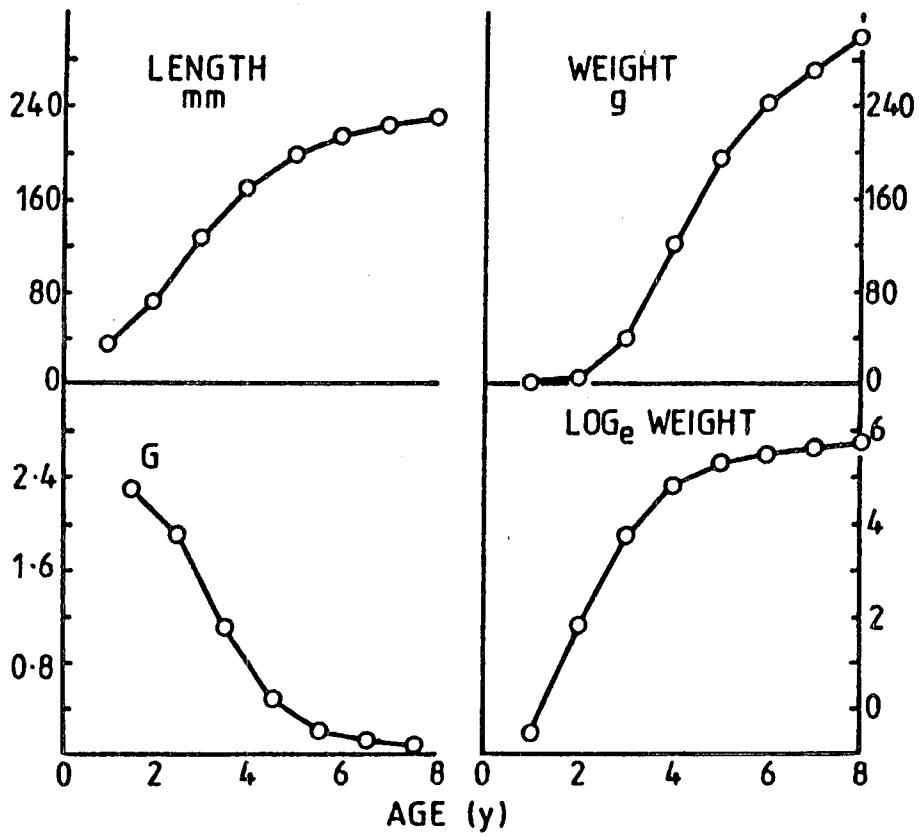

Figure 3-1.—Growth (increase in average length and weight with age) and specific growth rate (G, the instantaneous rate of growth per unit weight, expressed as percent per year) for a population of bluegill sunfish in Spear Lake, Indiana (source: Ricker, 1975; Wootton, 1990).

The Energy Balance

The rate at which fish grow is a direct function of the amount of energy consumed as food and the efficiency with which it is used.

The rate at which fish grow is a direct function of the amount of energy consumed as food and the efficiency with which it is used. Specifically, the energy available for growth equals the caloric content of the food consumed, adjusted for the fraction of the food ingested that is actually digested, minus the energy required to maintain the fish's basic metabolism (i.e., the basic biological functions of respiration, blood circulation, excretion, etc.) and minus the energy expended gathering the food and also on reproductive functions.

Growth = f [(food intake)(fraction digested) – metabolism – food collection – reproduction]

Factors that Influence Growth Rates

Each of the components in the general growth equation is influenced by a number of environmental variables that influence, in turn, fish growth rates. The single most important factor is food availability. However, food availability is more than

simply a measure of the total quantity or biomass of suitable prey organisms that occurs within the lake or reservoir. Instead, the amount of food consumed will be determined equally by both the quantity of prey available and the total number of fish and other predators competing for the same food supply. Competition for food may be both intraspecific (among members of the same fish species) and interspecific (among different species with the same feeding habits). Problems with slow growth rates result as often from overcrowded fish populations as from inadequacies in the food supply.

[T]he amount of food consumed will be determined equally by both the quantity of prey available and the total number of fish and other predators competing for the same food supply.

Food quality and the types of prey available also affect the energy available for fish growth. Fish species are adapted to efficiently capture and digest preferred types of prey. In general, larger prey items provide more net energy for growth per unit of energy expended in prey capture. Thus, fish feeding on other fish tend to grow faster than do those of the same species feeding on zooplankton or other smaller prey (see Box 3-A). Prey at low densities as well as prey that are hard-to-find or difficult to capture also result in lower growth efficiencies because of the greater amount of energy required for food collection per unit of food consumed.

Problems with slow growth rates result as often from overcrowded fish populations as from inadequacies in the food supply.

Another important factor influencing fish growth rates is water temperature. Temperature directly affects the rate and efficiency of food digestion and the energy required to maintain a fish's basic metabolism and indirectly affects prey availability, capture efficiency, and fish reproduction.

Fish are cold-blooded animals; that is, their body temperature varies as a function of the temperature of their environment. At colder temperatures, their metabolism slows. Thus, the amount of energy required to maintain basic metabolic functions decreases. At the same time, however, their digestive rate also slows and they tend to become lethargic, feeding less actively. As a result, fish growth rates (especially for warmwater fish species) are generally slower in colder environments — for example, fish living in lakes at high elevations or northern latitudes.

Different fish species have adapted to different temperature regimes and, as a result, have different optimum temperatures for growth. At temperatures higher or lower than optimum, growth efficiency will decline. The classification of fish species as coldwater, coolwater, and warmwater reflects these general differences in preferred temperatures. Extreme temperatures above or below the optimum range may also be lethal and will be discussed in the subsection on fish mortality later in this chapter.

Different fish species have adapted to different temperature regimes and, as a result, have different optimum temperatures for growth.

Other factors also influence fish growth rates. For example, different fish species inherently have different growth rates or growth potentials. Some species will never grow as fast or large as others, even under equivalent conditions. Likewise, in some species, one sex may grow faster than the other; males may consistently grow faster than females or vice versa. Age also influences growth rate. In general, very young fish and old fish tend to grow somewhat slower in absolute terms (i.e., the incremental increase in fish length or weight per year) than do fish of intermediate age. As a result, the annual growth curve for a species, especially for fish weight, may be sigmoidal (S-shaped, see Fig. 3-1).

Finally, stressful water quality conditions can also decrease fish growth. Small decreases in dissolved oxygen or increases in the concentration of toxic substances in the water may be too small to be lethal but can sublethally stress fish, affecting growth efficiency as well as feeding activity and other behaviors. These sublethal effects may be masked, however, if poor water quality conditions also decrease fish survival. In such instances, food availability for the fish that remain may increase because of decreased competition (fewer fish competing for the same or even lower food supplies). As a result, even though growth efficiency declines, the absolute growth rates of the surviving fish may increase.

[S]tressful water quality conditions can also decrease fish growth.

Box 3-A.—Influence of Food Type and Availability on Fish Growth Rates

Differences in fish growth rates occur not only among lakes and years but also among individual fish within a given lake and year. Shelton et al. (1979) examined growth rates of largemouth bass in West Point Reservoir on the Alabama-Georgia border. Substantial variations were observed in the growth of individual yearling bass during the first year of impoundment 1975-76 (Fig. 3-2). In general, largemouth bass longer than 4 to 5 cm (total length) feed increasingly on fish. However, some individual fish begin to feed on forage fish earlier than do others. This tendency, though not initially size-related, results in a growth advantage for those fish able to prey on forage fish at an earlier age.

In West Point Reservoir, these natural variations in prey utilization were amplified by the relative shortage of smaller forage fish that could be consumed by smaller bass. As a general rule, a largemouth bass can swallow shad up to one-half its total length and sunfish up to one-third its length. In West Point Reservoir, shad < 10 cm and sunfish < 7 cm were scarce during the 1975-76 study period. Therefore, preferred prey for bass shorter than 10 to 15 cm was practically nonexistent but abundant for bass longer than about 15 to 20 cm. The result was a bimodal size distribution for the 1975 bass year in the reservoir (Fig.3-3). Growth rates for bass < 10 to 15 cm were slow, while those bass able to take advantage of the available forage fish grew rapidly during their first year of life, attaining lengths of 30 to 40 cm.

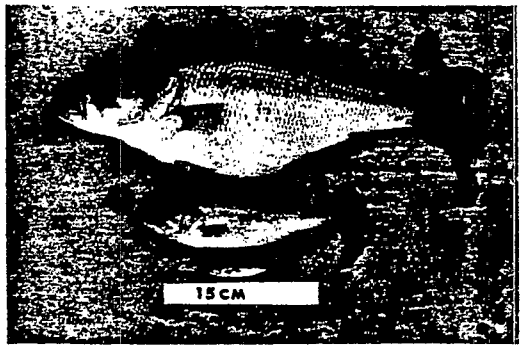

Figure 3-2.—Largemouth bass of the 1975 year class in April 1976 (source: Shelton et al. 1979).

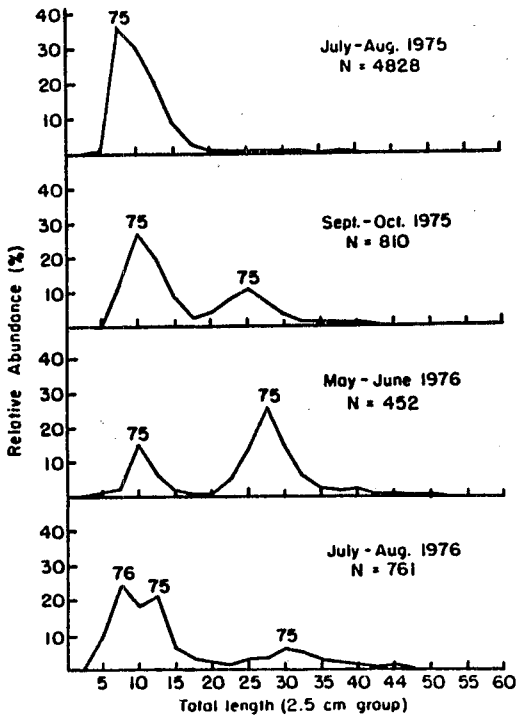

Figure 3-3.—Length-frequency of the 1975 year class of largemouth bass from West Point Reservoir (source: Shelton et al. 1979).

Seasonal Growth Patterns

Fish tend to grow at faster rates during certain times of the year.

Fish tend to grow at faster rates during certain times of the year. These differences are particularly pronounced at northern latitudes, where cold temperatures result in little to no fish growth during the winter. Periods of rapid growth coincide with increased food supplies and optimum temperatures, while periods of slow growth are associated with cold temperatures and scarce food. These seasonal patterns in growth rate generally provide the basis for determining a fish's age (See App. B, Fig. B-12). Furthermore, the length of the growing season as an index of a lake's thermal regime plays an important role in determining fish growth rates.

Weight-Length Relations

Fish that are longer also tend to be heavier; a strong correlation exists between the length (L) and weight (W) of a fish:

$$W = a L^b$$

where the constants a and b are determined for a fish population or other group of fish by linear regression analysis, using the logarithmic transformation of each fish's length and weight [log (W) = log(a) + blog(L)].

Often, the increase in weight is proportional to approximately the cube (or third-power) of a fish's length. That is,

$$W = a L^3$$

The constant, a in this case, is referred to as the condition coefficient or condition factor, abbreviated as C for English units of measurements or K for metric units. The condition factor for any given fish can be calculated, therefore, as follows:

$$C = W / L^3$$

For ease of reporting, C in the above equation is generally multiplied by 10,000 when length is measured in inches and weight in pounds; K is multiplied by 100,000 when length and weight are in millimeters and grams, respectively.

The condition factor is widely used as an index of the well-being of a fish or fish population. Fish that are plumper and heavier relative to their length have higher condition factors and are generally considered "healthier."

However, condition factors are influenced by a number of extraneous variables that must be considered to properly interpret the condition factor as an index of fish well-being. Different fish species have different "typical" condition factors simply because of their different body shapes. Robust (wide-bodied) fish, such as bass and sunfish, tend to have higher condition factors than narrow-bodied species, such as northern pike and trout. For many trout species (for example, brook, rainbow, brown, and cutthroat trout), a C value near 3.6 (or K = 1) indicates trout in "normal" or "good" condition. On the other hand, C values of 4.6 to 5.5 and 7.1 to 8.0 have been suggested to be indicative of "average" or "normal" condition for largemouth bass and bluegills, respectively. A fish's condition factor is also influenced by sex, season of the year, stage of sexual maturity, stomach fullness, and fish length. For example, immediately before spawning, mature fish, especially females, have higher condition factors because of the weight of eggs or milt (sperm) ready to be spawned.

The condition factor is widely used as an index of the well-being of a fish or fish population.

A fish's condition factor is also influenced by sex, season of the year, stage of sexual maturity, stomach fullness, and fish length.

Comparison of the condition factor (or the length-weight regression equation) for a fish population in a lake or reservoir to "expected" or "typical" values for healthy fish populations in the region (e.g., statewide average values for the species, accounting for the confounding factors noted above) provides a simple and easy-to-use tool for fish population assessment. Fish in poor condition (relatively low condition factors) may be indicative of overpopulation, starvation, or disease. High condition factors may result from a high temporary food supply (such as during insect hatches) or indicate that fish densities are low relative to the total food supply available, perhaps because of overfishing or poor reproductive success.

Fish in poor condition (relatively low condition factors) may be indicative of overpopulation or disease.

Two other weight-length indices are also commonly used as indices of fish well-being. The relative condition factor (Kn) (LeCren, 1951) explicitly recognizes the fact that b in the first weight-length equation does not always equal 3. The relative condition factor is calculated for each individual fish as follows:

$$Kn = W / (a L^b)$$

where W and L are the weight and length, respectively, of an individual fish and a and b are the constants from the weight-length relationship calculated for the population of fish or for some other standard group of fish of that species. An example is a statewide average weight-length relationship or a weight-length

relationship for fish considered to be in "good" condition. Kn equals 1 if the weight of the individual fish is the same as that for a fish of the same length in the standard group. Values less than 1 indicate weights less than expected or desired.

The relative weight index (Wr) (Wege and Anderson, 1978) is a further refinement of the concept Kn. Wr is given by the equation:

$$Wr = (W/Ws) \times 100$$

where W is the weight of an individual fish and Ws is a length-specific standard weight.

The standard weight functions are of the form:

$$Ws = a' L^{b'}$$

a' and b' are constants for an ideal population of the species, selected so that a well-fed, healthy fish would have a Wr value of 100. Wr values well below 100 indicate an inadequate food supply or other related problems. Standard weight functions for calculating Ws are presented in Table 3-1 for selected fish species.

All three of these indices of well-being, based on the relationship between fish length and weight, have their limitations. Cone (1989, 1990) provides a discussion of the assumptions and common pitfalls encountered in applying and interpreting each index.

Table 3-1.—Standard weight functions used in the calculation of relative weights for selected fish species: intercept (a') and slope (b') constants for equations using English units (inches and pounds) and the recommended minimum length for application (source: Murphy et al 1991).

SPECIES	INTERCEPT (a')	SLOPE (b')	MINIMUM LENGTH
Rainbow trout	-3.499	3.098	7.9
Brook trout	-3.467	3.043	5.1
Chinook salmon	-3.243	2.901	7.9
Northern pike	-3.727	3.059	3.9
Striped bass	-3.358	3.007	5.9
White bass	-3.394	3.081	4.5
Largemouth bass	-3.490	3.191	5.9
Smallmouth bass	-3.347	3.055	7.1
Bluegill	-3.371	3.316	3.1
Black crappie	-3.576	3.345	3.9
White crappie	-3.618	3.332	3.9
Walleye	-3.642	3.180	5.9
Sauger	-3.669	3.157	2.8
Yellow perch	-3.506	3.230	3.9

Fish Longevity

The maximum age to which fish live varies among species. Because fish growth is indeterminate, fish species that live longer also tend to be those that grow to larger sizes. For example, many of the large sport species, such as largemouth bass, walleye, and northern pike, in northern latitudes may live to be 10 to 25 years old. Lake trout frequently live 25 to 50 years, and lake sturgeon 50 to 80 years. By contrast, many small species, including most minnow species, generally live only one to three years. Typical life spans for selected fish species are presented in Table 3-2.

Variations in longevity occur even within a given fish species. Fast-growing fish populations tend to have shorter life spans than do slow-growing populations of the same species. The exact reasons for this inverse correlation between growth rate and longevity are not known. Many hatchery strains of fish also tend to have

shorter life spans than do wild strains of the same species, perhaps because historically faster-growing fish were selected in the hatchery as brood stock for subsequent generations. Hatchery strains of brook trout, for example, often have maximum ages of two to four years, while wild strains in the same waters may live five to eight years.

Table 3-2.—Approximate life spans of selected fish species (source: McComas, in press; Scott and Crossman, 1973).

SPECIES	REGIONS	LIFE SPAN IN YEARS
Lake trout	north	25 to 50
Largemouth bass	north	14 to 16
	central and south	9 to 12
Walleye	north	15 to 16
	south	10 to 12
Northern pike	north	16 to 17
Muskellunge	north	16 to 17
Bluegill		5 to 8
Brook and rainbow trout		5 to 8
White and black crappie		4 to 7
White bass		2 to 5

Fish Reproduction

The ability of a fish population to reproduce itself is clearly critical for population success. For a population to maintain itself at steady-state (with no long-term change in fish abundance), one pair of adults (male and female) must produce sufficient numbers of young to replace themselves with a new pair of mature adults. Otherwise, the population will decline and/or natural reproduction must be supplemented through artificial means, such as fish stocking.

The ability of a fish population to reproduce itself is clearly critical for population success.

Most fish species are oviparous with external egg fertilization. That is, mating partners come into close proximity within the waterbody and then spawn simultaneously. They release their sperm and eggs (spawn) directly into the water, where chance collisions result in egg fertilization. The embryos develop essentially on their own, food being supplied by the yolk within each egg. Eventually, the embryos hatch into larvae. For a period, these larvae continue to rely on yolk for food and are called "yolk-sac fry." As the yolk sac is depleted, the larvae begin to feed. At the same time, they also begin to swim actively in the water column. Thus, at this stage, the young fish are referred to as "feeding fry" or "swim-up fry."

Most fish species are oviparous with external egg fertilization.

Fish Fecundity

The number of eggs produced by a single female fish is termed "fecundity" and is generally determined by counting the number of eggs contained within the fish's ovaries just before spawning. Larger fish typically produce more eggs; thus, fecundity is often expressed as a function of fish size: the number of eggs per unit length or weight of the female fish. An estimate of fish fecundity times the estimated number of spawning females provides an index of the reproductive potential of the population.

Reproductive Strategies

In general, fish spawn large numbers of eggs per female. Largemouth bass, for example, each year typically produce between 2,000 and 7,000 eggs per pound of female; some very large females may spawn up to 100,000 eggs. A single, large

female northern pike may spawn 500,000 to 600,000 eggs. Salmonids generally have somewhat lower fecundity; the number of eggs per female brook trout, for example, ranges from about 100 for a small female (6 inches in length) up to 5,000 eggs for a 20-inch brook trout.

Although large numbers of eggs may be spawned, relatively few of these embryos survive through their first year of life or even to the swim-up stage. The reproductive strategy of fish, in general, is to produce large numbers of eggs but provide their young with relatively little or no protection. As a result, mortality rates are high during these early life stages. For many fish species, typically fewer than 1 percent (or even less than 0.01 percent) of the eggs spawned survives to one year of age. Survival rates for salmonids tend to be somewhat higher but are still generally 10 percent or less. Most mammals and many warm-blooded vertebrates, by contrast, have very different reproductive strategies. Compared with fish, mammals produce few young, expend considerable energy nurturing and protecting the young, and survive at relatively high rates.

The reproductive strategy of fish, in general, is to produce large numbers of eggs but provide their young with relatively little or no protection.

Reproductive strategies do vary, however, among fish species. Some species randomly deposit their eggs in the spawning area, with absolutely no follow-up parental care. In general, these species tend to have the highest fecundity and lowest early life stage survival rates. Examples include northern pike, common carp, yellow perch, alewifes, and striped bass. At the other extreme, sticklebacks build quite complicated nests within which their eggs are deposited, and the male actively guards the young until they swim away from the nest. Likewise, males of most centrarchid species (including largemouth and smallmouth bass and sunfish species) also build nests for spawning and actively guard their schools of young for several days or weeks after swim-up. Salmonids also spawn in nests (referred to as redds), although the female rather than the male develops the site and, in most species, provide no parental care after the eggs are spawned. Salmonid eggs, however, are relatively large, with large quantities of yolk. As a result, salmonid larvae are larger, more motile, and less susceptible to predation, compared to the larvae of many other fish species. As a general rule, fish species that provide some parental care and/or have larger eggs have lower fecundity and relatively higher early life stage survival rates.

Appendix A provides further information on the reproductive habits and strategies of specific fish species.

Spawning Habitats

Many fish species require certain types of physical habitat or habitat characteristics for reasonable survival of their eggs and yolk-sac fry (Table 3-3; App. A). Many trout species, for example, spawn only in clean gravel substrates in tributary streams, rather than in the lake proper. Northern pike spawn in shallow, weedy areas along the lake edge or in flooded areas in tributary streams. If such habitats are not available or rare, reproductive success may be poor or nonexistent. The availability of suitable spawning areas and substrate, therefore, is an important lake characteristic to consider when selecting fish species to be targeted for fisheries management. If natural reproduction is insufficient, the population will have to be supplemented or maintained through stocking, requiring substantial added expense and effort. In some instances, it may be possible to artificially construct additional spawning substrate in the lake or reservoir, which may also improve reproductive success (see Chapter 8).

The availability of suitable spawning areas and substrate, therefore, is an important lake characteristic to consider when selecting fish species to be targeted for fisheries management.

Spawning Periods

Different fish species also spawn at different times of the year (Table 3-3). Furthermore, some species have very short spawning seasons, lasting only a few days; others may spawn for one to two weeks; still others spawn intermittently over a period as long as three to four months. Temperature and photoperiod are the two

Table 3-3.—Spawning habitats, times, and water temperatures for selected fish species (source: McComas, in press; Scott and Crossman, 1973).

SPECIES	TIME	TEMP. (°F)	PREFERRED SPAWNING HABITAT
Bluegill	late May to early August	65 to 70	sand and gravel areas with some vegetation near shorelines of ponds and lakes
Largemouth bass	early May to late June	62 to 70 (north)	sand and gravel areas with some vegetation near shorelines of ponds and lakes
Crappies	late May to late July	60 to 70 (north)	sand and gravel areas with some vegetation in water usually less than 10 feet deep
Channel catfish	late spring/summer	75 to 80	undercut banks, log jams, or rock piles, either in the littoral zone or in slow-moving tributaries
Yellow perch	mid-March to mid-May	45 to 50	weedy or brushy areas in shallow to deeper water of ponds and lakes
Northern pike	early spring	35 to 50	shallow, weedy areas of lakes; also migrate up tributaries to flooded areas
Muskellunge	April to June	48 to 60	shallow bays of lakes in muddy, stumpy bottom
Brown trout	October to February	50 to 65	tributary streams or rocky, shallow areas of lakes
Brook trout	September to December	48 to 55	small gravel brooks or gravel shorelines of lakes
Lake trout	early October to late November	37 to 50	gravel or rocky bottoms of lakes or reefs at varying depths
Rainbow trout	mid-April to late June	50 to 60	beds of fine gravel in inlet or outlet streams
Cutthroat trout	three to five weeks after ice breakup	about 50	areas in small inlet and outlet streams with clean, gravel substrate
Walleye	spring, after ice breaks up	45 to 50	shoal areas of lakes or tributary streams

most important cues that trigger spawning. As a result at more northern latitudes and in colder waters, fish that spawn in the spring tend to spawn later in the year and fall-spawning fish do so earlier in the year, compared to spawning times at more southern latitudes and in warmer waters.

Many coolwater species (see Table 2-2), such as northern pike, walleye, and yellow perch, typically spawn soon after the ice goes out in early spring at temperatures of 45 to 50°F (7 to 12°C). Warmwater species, including most centrarchids (bass and sunfish) and ictalurids (bullheads and catfish), generally initiate spawning in late spring or early summer when water temperatures reach 55 to 75°F (13 to 24°C), depending on the species. Some, such as the bluegill, will continue to spawn intermittently throughout most of the summer. Some coldwater species, such as rainbow and cutthroat trout, spawn in the spring just before or soon after ice-out in the lake (at 50 to 60°F, 10 to 15°C). Most coldwater fish, however, including brook trout, lake trout, and kokanee salmon, are fall spawners, depositing their eggs as water temperatures decline (generally at about 40 to 55°F, 4 to 13°C). The eggs hatch in late winter, and the young fry swim-up and begin feeding as the ice recedes from the lake. Additional information on spawning times for individual fish species is provided in Appendix A.

The rate of embryo development and time from spawning to hatching and larval swim-up are also dependent on temperature. Thus, in warm years or in warm lakes (e.g., at more southern latitudes), not only does spawning occur earlier (for spring and summer spawners), but early life stages tend to grow and develop more rapidly. Because these early life stages are particularly susceptible

The rate of embryo development and time from spawning to hatching and larval swim-up are also dependent on temperature.

to environmental stresses and predation, the rate and timing of embryo/larval development relative to the timing and occurrence of stressful conditions (e.g., cold spells or episodic incursions of toxic substances), water level fluctuations, heavy predator concentrations, or food limitations may be critical for reproductive success.

Age at Sexual Maturity

[T]he age of sexual maturity varies with latitude, elevation, lake productivity, and other factors that affect fish growth rates.

The age at which fish reach sexual maturity also may influence fisheries management decisions; for example, in setting size limits for fish populations with a shortage of reproducing fish. Again, different species reach maturity at different ages, ranging from ages 1 to 2 years for short-lived species, such as many minnows, up to 15 to 25 years for a long-lived species like the lake sturgeon. Fast-growing populations tend to mature at an earlier age than do slow-growing populations of the same species. Thus, the age of sexual maturity varies with latitude, elevation, lake productivity, and other factors that affect fish growth rates (see Fig. 3-4). Not all fish within a given population reach maturity at the same age or size; furthermore, once a fish is mature, it may not spawn every year. The age and size at which fish reach sexual maturity can be easily determined by collecting a sample of fish during or immediately preceding the spawning season and identifying, measuring, and aging those fish that are sexually mature, as described in Appendix B.

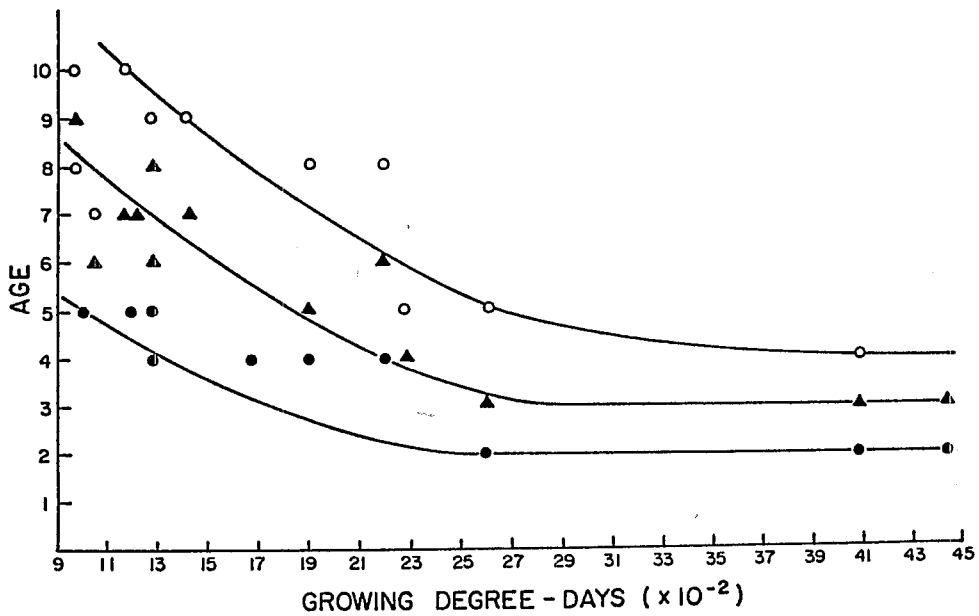

Figure 3-4.—Relationship between the age at which female walleyes become sexually mature and the length of the growing season, expressed as centigrade degree-days above 5°C (41°F). The lower line and solid circles indicate the age at which mature females first appear in the population. The middle line and solid triangles indicate the first age at which 50 percent or more of the females in the population are mature. Finally, the upper line and open circles represent the first age at which all surviving females are sexually mature. Data presented are for 22 lakes ranging from Texas to the Northwest Territories in Canada (source: Ont. Ministry Nat. Res. 1983).

Factors Affecting Reproductive Success

The ultimate measure of reproductive success is the number of new fish or recruits introduced into the population each year. Recruitment is the addition of new members to the population or fish stock of interest; recruitment success is deter-

mined by not only the numbers of eggs produced and hatched but also the number of young that survive until a given age or size, generally when they can first be collected and evaluated using available fish sampling techniques. Recruitment success can vary substantially from year to year as well as among different lakes. Strong year classes (relatively large numbers of new recruits in a single year) and weak year classes are common, and a wide diversity of factors may limit fish reproduction and young-of-the-year survival in any one year or lake.

Differences in recruitment success among lakes result from variations in both the intensity of spawning activity (i.e., fecundity, the number of fish spawning, and total number of eggs spawned) and the survival of eggs and young fish. For species with fairly specific spawning requirements such as many salmonids, the quantity and quality of suitable spawning habitat may be an important limiting factor. For example, brook trout require areas of groundwater upwelling and/or well-oxygenated gravel substrate in small tributary streams or along the lake shoreline for spawning and adequate survival of eggs and yolk-sac fry. Little to no brook trout reproduction will occur in lakes without such areas. In lakes with suitable spawning habitat, limiting environmental conditions (e.g., high acidity, low oxygen levels), high rates of predation, or overcrowding and competition for food among young may result in low early life stage survival rates and poor recruitment success.

Because of the large number of eggs spawned per female, year-to-year variations in recruitment success (year-class strength) are determined more often by differences in egg and larval survival than by the level of spawning activity. Strong year classes in previous years may result in poor young survival and a weak year class because of cannibalism or increased competition for food. A sudden cold snap or rapid decline in lake level soon after spawning may cause high levels of egg or larval mortality and, subsequently, a weak year class. Several studies have shown that the severity of wind and wave action, which may mechanically damage eggs and yolk-sac fry, is a major determinant of year-class strength in some largemouth bass populations. Thus, fluctuations in a number of environmental and biological factors can result in natural year-to-year variations in year-class strength.

[F]luctuations in a number of environmental and biological factors can result in natural year-to-year variations in year-class strength.

Problems with fisheries production may be traced, in many cases, to problems associated with fish reproduction and young fish survival. Thus, efforts to determine recruitment success and the major factors limiting recruitment success are important components of the process of problem identification and diagnosis in overall fisheries management (described in Chapter 6).

Hybridization

Hybrids are the offspring of parents of different species; for example, a cross between bluegill and green sunfish. Naturally produced hybrids are common among members of the sunfish family. A variety of other crosses have been artificially induced in hatcheries, such as the splake (a cross between lake trout and brook trout), tiger musky (a cross between northern pike and muskellunge), and the white bass–striped bass hybrid cross. Generally, hybrids are infertile or have reduced viability, and reproduction is minimal. Hybrids continued presence in a waterbody depends, therefore, on continued natural crosses between the parent species or on stocking. Frequently, hybrids grow faster and have greater vigor than the parent species, making them desirable targets for fisheries management in some situations and types of waterbodies. The introduction of hybrid species may, however, adversely affect native fish populations through competition or by interfering with natural reproduction. While hybrids do not successfully reproduce, they do spawn and may spawn with native populations of either species, reducing the reproductive success of the native populations.

Frequently, hybrids grow faster and have greater vigor than the parent species, making them desirable targets for fisheries management . . . .

Fish Mortality

Fish die as a result of diverse causes, both natural and human-induced. Examples of important sources of fish mortality include predation, starvation (although fish weakened by starvation usually die of other causes, such as predation, before they actually starve to death), disease, fishing, and lethal water quality conditions (such as low oxygen levels, high temperatures, or high concentrations of toxic substances).

Fish mortality rates (i.e., the proportion of fish dying over a given period of time) and major sources of mortality vary with fish age and among lakes. Mortality rates are highest during early life stages, as eggs and fry. In some populations, high levels of fish mortality also occur immediately after spawning. Immune systems are weakened by the stress of spawning, making the fish more susceptible to infections and diseases. Predation and competition for food are especially important for young, small fish, while fishing mortality becomes increasingly important for large, old fish. Fishing mortality also tends to be higher in waters that are more heavily fished. Mortality rates resulting from predation, starvation, or disease, on the other hand, are likely to be highest in waters with high fish densities and overcrowded conditions. Marginal water quality because of pollution or natural causes (e.g., when a coldwater species lives at the southern edge of its range and temperature tolerance) can also be a significant factor limiting fish survival in some lakes and reservoirs.

Compensatory Mortality

Some types of mortality are density-independent; that is, the proportion of fish dying is not affected by the number or density of fish in the population. For example, mortality caused by a toxic pollutant is likely to be density-independent. If one of every 10 fish is sensitive to the toxicant, then 10 percent of the fish will die whether the fish population is 10 or 1,000 fish.

By contrast, other types of mortality are density-dependent. In some instances, as with competition for food, the more fish in the population, the higher the percentage of fish that are likely to die. In a few cases, as for some types of predation, the reverse may also occur; higher densities of fish may mean that a lower proportion of the population is lost to predation. Deaths resulting from food shortages, diseases, and cannibalism are almost always density-dependent, with the proportion of fish dying increasing with fish density. Predation, on the other hand, may be density-independent or density-dependent and either positively or negatively correlated with fish density.

If fish mortality rates increase as fish density increases, then, to some degree, a population may be able to self-adjust itself.

If fish mortality rates increase as fish density increases, then to some degree, a population may be able to self-adjust itself. Theoretically, with perfectly balanced density-dependent mortality, population abundance would remain constant over time. While natural populations are far from perfectly balanced and typically experience large fluctuations in abundance as a result of short-term changes in both mortality and reproductive success, they do tend to regulate themselves in the direction of some long-term average density.

Density-dependent mortality also may counterbalance, to some degree, changes in density-independent mortality rates. For example, if more fish are removed from the population by fishing (higher fishing mortality), the fewer fish that remain may have more to eat per fish, decreasing the number of deaths resulting from starvation or inadequate food with little or no change in the total mortality rate. Such shifts in density-dependent mortality that serve to moderate the effects of density-independent mortality are referred to as compensatory mortality.

The degree to which populations are able to compensate, by decreasing their natural mortality rates, for increases in mortality caused by fishing or toxic pol-

lutants is one of the major uncertainties in fisheries management and an active area of research. Clearly by itself, compensatory mortality is not adequate in all circumstances, since many examples can be found of long-term fish population declines caused by overfishing and/or pollution. Uncertainties regarding the occurrence and magnitude of compensation, however, limit our ability to quantitatively predict fish population responses to environmental stresses.

Compensatory mechanisms in fish populations are not restricted to changes in density-dependent mortality rates. Growth and fecundity also vary as a function of fish density. At lower densities (given a constant food supply), fish grow faster, mature earlier, and usually produce more eggs, all of which act to increase the biomass and abundance of fish in the lake. At high fish densities, growth and fecundity are reduced, limiting or decreasing population size. This balancing of forces — processes of increase and growth versus forces that work to limit or decrease population size — is a fundamental concept of fish population dynamics, discussed in greater detail later in this chapter.

Fishing Mortality

Fishing activities increase fish mortality, either by the direct removal of "keepers" or as an incidental result of the added stress on fish associated with capture and handling (see Box 3-B). Fishing mortality rates are a function, therefore, of the total fishing effort and the types of fishing methods allowed. If fishing mortality rates are high, it may be necessary to reduce fishing effort (e.g., by limiting lake access) or alter fishing regulations; for example, by initiating a catch-and-release fishery or establishing minimum and/or maximum size limits (see Chapter 8).

The effects of fishing mortality on fish populations can be distinctly different than those from other mortality sources. Mortality rates that result from fishing generally increase with fish size and age; anglers preferentially remove large, old fish. By contrast, other types of mortality act primarily on early life history stages; mortality rates decrease with age or remain relatively constant at ages above 1 to 2 years. Many natural mortality factors are also density-dependent and thus, to some degree, are self-regulating. As a result of these differences, fishing mortality cannot be viewed as a substitute or replacement for natural mor-

Box 3-B.—Response of Largemouth Bass to Angling Stress (source: Gustaveson et al. 1991)

The stress associated with hooking, playing, and handling, by itself, can result in increased fish mortality, even if all fish caught are released (e.g., in a catch-and-release fishery or for fish smaller or larger than the allowable size limit). Hooking mortalities up to 98 percent have been reported for largemouth bass caught and released during tournaments and can also be high in nontournament public fishing (Champeau and Densen, 1989). Improvements in tournament procedures have reduced mortality from capture and handling, but rates of 20 to 60 percent can still occur (Chapman and Fish, 1985). Lee (1989) reported mortality rates as low as 2 percent in recent bass tournaments regulated by the California Department of Fish and Game.

Gustaveson et al. (1991) evaluated physiological stress responses in bass caught at different temperatures and with varying amounts of hooking and playing time. The level of stress increased with both increasing temperature and increased playing time. Stress responses were low for fish hooked and played for 1 to 5 minutes in the coldest water (11 to 13°C, 52 to 55°F); moderate for fish hooked and played at 16 to 20°C (61 to 68°F), and severe for fish played for five minutes at 28 to 30°C (82 to 86°F). Thus, mortality caused by angling stress is likely to be higher for fish caught at higher temperatures. Lee (1989) also observed relatively high mortality in early summer, which was attributed to a decrease in fish tolerance immediately following spawning; and in winter, as a result of decompression when bass were caught in deep water.

tality. Relatively low natural mortality rates but high levels of fishing mortality may lead to a number of management problems, including stunted populations dominated by large numbers of small, young fish.

Acute and Chronic Lethal Limits

To establish water quality regulations or evaluate the effects of pollution on fish populations, it is necessary to know what levels of toxicants and other water quality variables are likely to cause significant fish mortality. These concentrations or values are commonly referred to as lethal limits. An acute lethal limit is the concentration or level that will cause toxic effects (increased mortality) after just short-term exposures (typically four days or less). Chronic lethal limits are those that affect fish only after longer periods of exposure. In general, the shorter the period of exposure, the higher the toxic substance concentration, the higher the temperature, and the lower the oxygen level that fish are able to tolerate.

Lethal limits for water quality parameters vary greatly among fish species and with fish age (e.g., Fig. 3-5; Boxes 3-C and 3-D). Young fish (eggs, fry, and juveniles) tend to be much more sensitive to all environmental stresses than older fish. Thus, these early life stages may be particularly critical times for determining the impacts of pollutants and natural stresses on fish population success. Relative species sensitivities vary depending on the type of pollutant or stress. For example, brook trout are relatively tolerant of lake acidity compared to other fish species, but brook trout eggs and fry are relatively sensitive to low levels of dissolved oxygen.

Young fish tend to be much more sensitive to all environmental stresses than older fish.

Clearly, a fish's lethal limits and preferred ranges of temperature, dissolved oxygen, and other water quality variables should be carefully considered in selecting target species for fisheries management. Water quality conditions are likely to vary spatially within a lake or reservoir. Thus, assessing a lake's suitability for a given fish species requires information on the range of water quality conditions likely to be encountered in the specific areas of the lake inhabited by the species during each life stage.

Winterkill and Summerkill

High levels of fish mortality occur in some lakes during the summer (summerkill) and/or winter (winterkill) (see Boxes 3-E and 3-F). Frequently, the cause of death is suffocation as a result of low levels of dissolved oxygen that tend to occur in the hypolimnion of eutrophic lakes during summer and in some lakes over winter during long periods of snow and ice cover (see Chapter 2). High temperatures, rapid temperature changes during cold or warm spells, and epidemic diseases or parasites may also cause periodic summerkills.

Fish Population Dynamics

Fish population dynamics is the study of the combined processes of fish growth, reproduction, and mortality and their impact on the total numbers and biomass of fish of a given species in a particular ecosystem. The status of a population at any given time depends on the dynamic balance between the forces of population increase (growth and reproduction) and decrease (mortality). All these processes are highly interactive with important feedback mechanisms. While fish have an extremely large reproductive potential, a number of physical and biological checks act to keep this potential and the population in balance. For example, as populations increase in abundance, competition for available food increases, increasing fish mortality and decreasing growth rates that, in turn, cause a delay in sexual maturity and reduced fecundity. A population subject to increased mortality as a result of increased fishing mortality may respond by increasing individual fish

While fish have an extremely large reproductive potential, a number of physical and biological checks act to keep this potential and the population in balance.

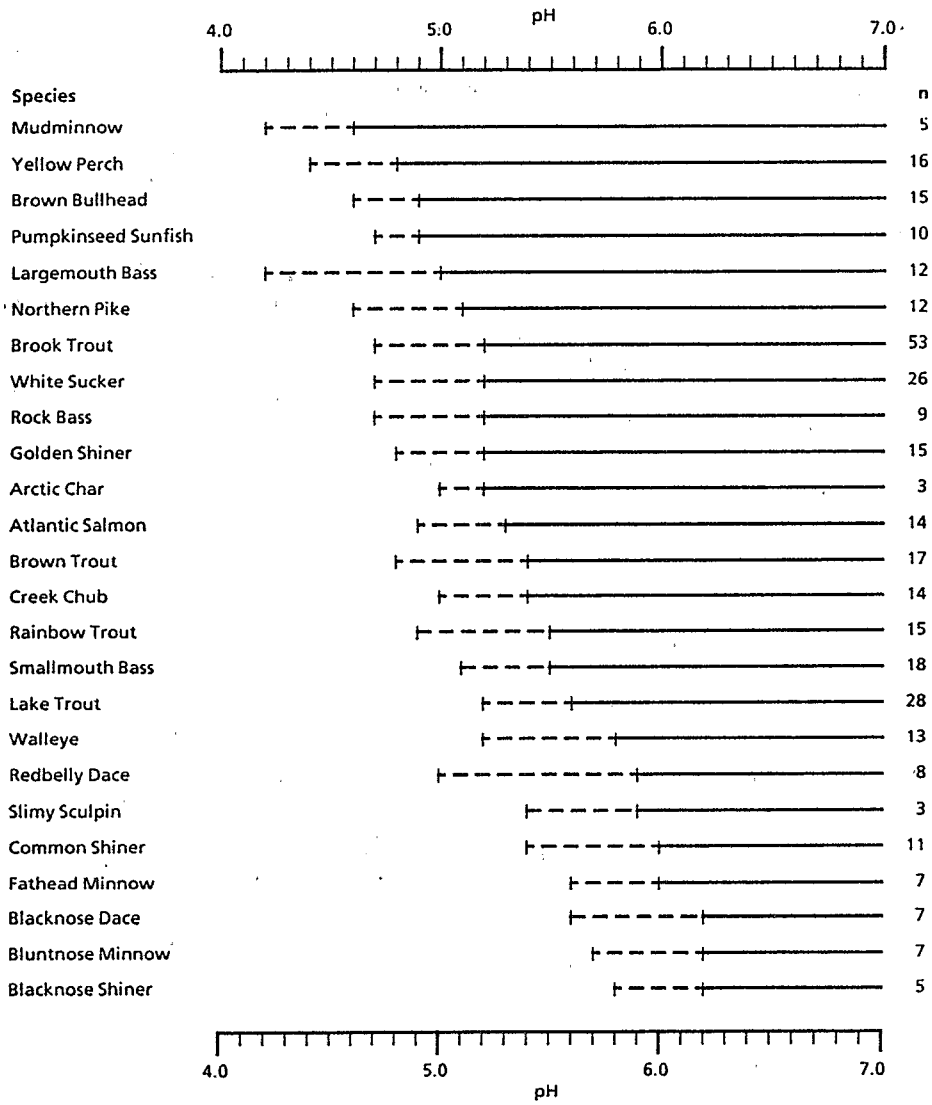

Figure 3-5.—Estimated critical pH values for effects on fish populations. Dashed lines represent the approximate range of uncertainty in the critical pH. Number of studies (n) used to derive the estimate are noted (source: Baker and Christenson, 1991).

growth, reproduction, and subsequently, survival. As noted earlier, the result of these compensatory mechanisms are that fish populations in stable environments generally tend toward some long-term average population biomass that reflects the carrying capacity of the system.

Population Age Structure

A population's age structure — that is, the numbers of fish in each age or year class — is determined by the relative magnitudes of the annual birth and death rates. If birth and mortality rates are constant year to year, then the numbers of fish in each age class will decline logarithmically with increasing fish age (see Fig. 11-5, Chapter 11). Unusually large numbers of fish in any given age group indicate either higher than average reproductive success or lower mortality. Missing year classes or age groups may result from complete reproductive failure or mass mortality within a particular year. Populations with only old, large fish have experienced successive reproductive failures or mass mortalities in recent

Unusually large numbers of fish in any given age group indicate either higher than average reproductive success or lower mortality.

Box 3-C.—Effects of Low Dissolved Oxygen on Fish

Fish and other animals require oxygen to survive, as discussed in Chapter 2. When levels of oxygen dissolved in the water become too low, fish mortality may increase dramatically. At moderately low oxygen levels, fish may be sublethally stressed, experiencing decreased growth and increased susceptibility to other causes of mortality. Table 3-4 summarizes dissolved oxygen concentrations associated with varying levels of effects on fish. Salmonids, on average, are more sensitive to low levels of dissolved oxygen than are other fish species (especially warmwater fish species) and thus are considered separately in Table 3-4. Oxygen solubility is temperature dependent; in waters at equilibrium with the atmosphere, lower concentrations of dissolved oxygen occur at higher temperatures (Fig. 3-6). The rate of organic matter decomposition, which consumes oxygen (see Fig. 2-6), also increases at higher temperatures. Thus in general, oxygen depletion is more prevalent in warmer waters and during summer. Low levels of oxygen may also occur, however, during winter in lakes with long periods of snow and ice cover.

Table 3-4.—Summary of dissolved oxygen concentrations (mg/L) generally associated with effects on fish in salmonid waters and nonsalmonid waters (source: U.S. Environment Protection Agency, 1987).

LEVEL OF EFFECT	SALMONID	NONSALMONID
Early Life Stages (eggs and fry)		
No production impairment	11 (8)[a]	6.5
Slight production impairment	9 (6)	5.5
Moderate production impairment	8 (5)	5.0
Severe production impairment	7 (4)	4.5
Limit to avoid acute mortality	6 (3)	4.0
Other Life Stages		
No production impairment	8.0	6.0
Slight production impairment	6.0	5.0
Moderate production impairment	5.0	4.0
Severe production impairment	4.0	3.5
Limit to avoid acute mortality	3.0	3.0

[a] Values for salmonid early life stages are water column concentrations recommended to achieve the required concentration of dissolved oxygen in the gravel spawning substrate (shown in parentheses).

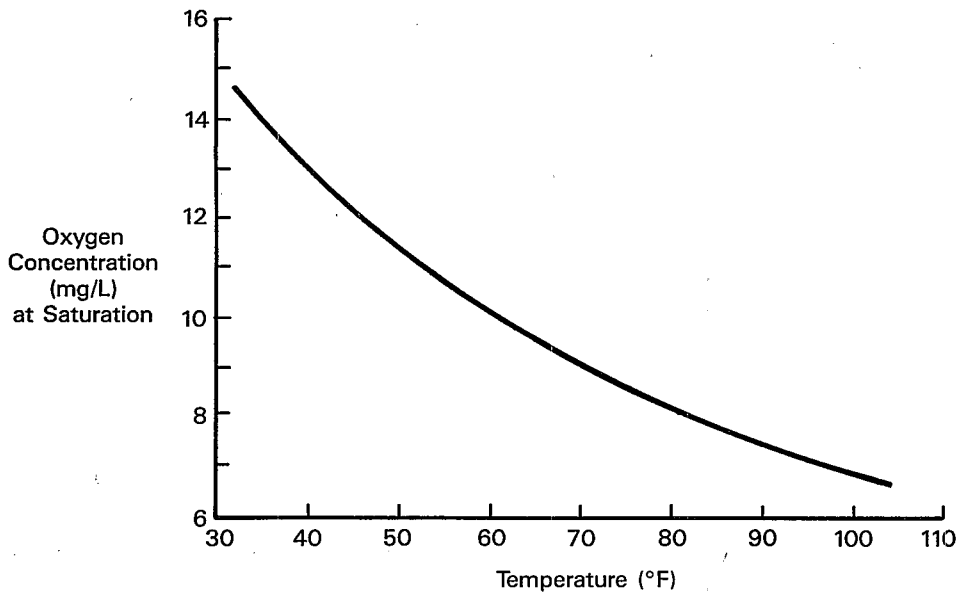

Figure 3-6.—Solubility of oxygen in freshwater as a function of temperature (source: Stand. Methods, 1971). Oxygen levels in lakes are often presented as percent saturation; that is, the measured oxygen concentration divided by the maximum oxygen concentration possible (i.e., oxygen solubility) at that temperature times 100.

Box 3-D.—Temperature Limits for Fish

As discussed in Chapter 2, fish are cold-blooded vertebrates; their body temperature and metabolism are determined by the temperature of the surrounding environment. Thus, temperature directly influences fish growth rates, activity levels, reproduction, and most other aspects of fish biology. In addition, temperatures that are too high or too low can be lethal. A fish's upper and lower temperature limits are not fixed but are influenced by the temperature to which the fish has been acclimated by being held at that temperature for several weeks (Fig. 3-7). Some fish are able to tolerate a wide temperature range (eurythermal species); for example, goldfish with proper acclimation can tolerate a temperature range from 32 to 100°F (0° to 40°C). Other fish species are stenothermal and have a narrow zone of temperature tolerance. Examples of the approximate maximum temperatures to which adult and juvenile fish can be exposed for short periods of time during summer (i.e., when fish are acclimated to relatively high temperatures) without excessive fish mortality are listed in Table 3-5.

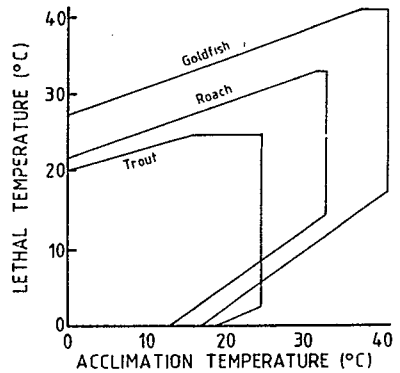

Figure 3-7.—Relationship between lethal temperatures (upper and lower) and fish acclimation temperature for goldfish, roach (a European roughfish), and brown trout (source: Wootton, 1990; Elliot, 1981).

Table 3-5.—Calculated short-term maximum temperature for survival of juveniles and adults during summer (source: U.S. Environ. Prot. Agency, 1987).

FISH SPECIES	WATER TEMPERATURE
	°F (°C)
Channel catfish	95 (35)
Bluegill	95 (35)
Largemouth bass	93 (34)
Northern pike	86 (30)
Lake herring (Cisco)	77 (25)
Coho salmon	75 (24)
Rainbow trout	75 (24)
Atlantic salmon	73 (23)
Sockeye salmon	72 (22)

years. In long-lived fish species, such conditions could continue for several years with no apparent decline in fishing success. However if the cause of the reproductive failure or mortality is not corrected, eventually the population will be lost. Population age structures, therefore, provide important information on population status and trends. Furthermore, by comparing age structure patterns to data on year-to-year fluctuations in environmental conditions, it may be possible to identify factors contributing to variations in population success or long-term declines (Box 3-G).

Population age structures, therefore, provide important information on population status and trends.

Length-Frequency Distributions

Gathering data on fish ages for large numbers of fish can be fairly time-consuming and difficult in some waters and for some species. A quick alternative that may be adequate in some cases is the length-frequency distribution (Fig. 3-9). Because fish age and length are correlated, general information on the population age structure can be obtained by examining the relative frequency of occurrence of fish of varying lengths. The absence of very small fish may again be indicative of reproductive failures in recent years. A truncated age or length distribution with a sudden decrease in the numbers of fish present above some particular size suggests a high mortality among older fish; for example, as a result of fishing mortality. Many methods for sampling fish are less efficient at collecting small

Box 3-E.—Conditions Associated with Summer Mortality of Striped Bass in Keystone Reservoir, Oklahoma (source: Zale et al. 1990)

Striped bass have been introduced into many inland reservoirs, especially in the southeastern and southcentral United States. Although generally these populations support productive sport fisheries, summer mortality of adults is common and widespread (Matthews, 1985). Coutant (1985) hypothesized that such mortality results from a temperature-oxygen squeeze. During summer stratification, the upper waters in the epilimnion become too hot for adult striped bass, while the deep, cool waters lack adequate dissolved oxygen. Zale et al. (1990) evaluated this hypothesis in Keystone Reservoir, a large, 26,000-acre impoundment for hydroelectric power generation on the Arkansas and Cimmaron rivers in northern Oklahoma. During the summer, Keystone Reservoir is characterized by a strong, chemically induced stratification (Fig. 3-8) caused by the differential total dissolved solids levels in the Arkansas and Cimmaron river inflows. Summer mortalities of striped bass frequently occur.

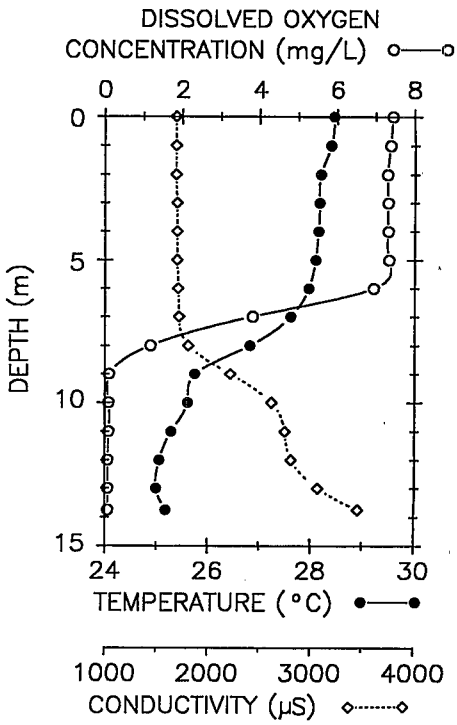

Figure 3-8.—Water column profiles of water temperature, dissolved oxygen concentration, and conductivity (an indicator of the total dissolved solids content) in the main pool of Keystone Reservoir, Oklahoma, on July 13, 1988 (source: Zale et al. 1990).

During the period of study, 1986-88, significant mortality (based on the occurrence of large numbers of dead fish found along the shoreline) occurred in late summer/early fall in both 1987 and 1988, but not in 1986. During summer, striped bass were restricted to a thin (3 to 6 feet) layer of the stratified water column consisting of the coolest waters available at which dissolved oxygen concentrations exceeded 2 mg/L. Fish stopped feeding when minimum water temperatures in this zone reached about 80°F (27° C). Observations at Keystone Reservoir indicate that adult striped bass can tolerate exposure to 80 to 82°F (27 to 28°C) for about one month (as in 1986) but die (probably from malnutrition) when they are exposed to slightly higher temperatures (about 84°F or 29°C, as in 1987) for a similar period or when exposure to 82° is prolonged (as in 1988).

fish or are selective for certain size classes (see App. B). These size-related differences in capture efficiency must be accounted for in interpreting fish age or length distributions in the sample of fish examined.

Because most anglers prefer to catch large fish, the length-frequency distribution is also of direct interest as an index of the quality of fishing and the relative balance between small and large fish in the population. For a number of species, standard length classes have been designated (Table 3-6), based on percentages of the world record lengths. The percentage of the sample or population falling within each designated size class is referred to as relative stock density (RSD). Alternatively, the proportional stock density (PSD) index is calculated as follows:

PSD = (number of fish ≥ minimum quality length / number ≥ minimum stock length) x 100

Index values range from 0 to 100. For example, if 50 largemouth bass are ≥ 30 cm (12 inches) long (quality size) in a sample of 100 fish ≥ 20 cm (8 inches) long

Box 3-F.—Consequence of Winterkill in Wintergreen Lake, Michigan (source: Hall and Ehlinger, 1989)

Wintergreen Lake is a small (37-acre), shallow (21 feet maximum depth, 11 feet mean depth) hypereutrophic, hardwater lake in southern Michigan. Most of the nutrient inputs to the lake come from migrant and resident waterfowl feces (Manny et al. 1975). Runoff from cultivated fields and an intermittent stream from a dairy farm feedlot also contribute to the large nutrient load.

Currently, nearly 40 percent of the lake's surface is covered with macrophytes, and phytoplankton blooms are common. Historically, fish in the lake were typical of those in warmwater lakes in the region; the fish community was dominated by centrarchids with largemouth bass as the top predator. The lake was subject to an occasional partial winterkill. But before 1977, individuals of each fish species survived the periods of low dissolved oxygen or were able to recolonize the lake from downstream Gull Lake, connected to Wintergreen Lake by an outlet stream during periods of high flow.

The winters of 1977 and 1978, however, were particularly severe in Michigan, with four months of continuous ice and snow cover. Dissolved oxygen levels in the lake dropped to below 1 mg/L and massive fish kills resulted. At ice-out in 1977, over 7,000 dead fish were collected along the shoreline; 70 percent of these dead fish were bluegill and largemouth bass. Since that time (through 1987), no bluegills or largemouth bass have been caught in any angling or netting surveys in the lake. At the same time, the golden shiner population has increased dramatically. Golden shiners, which were relatively rare before 1977-78, are now by far the dominant species. Yellow perch, pumpkinseed sunfish, and yellow bullhead also occur. All of these species are more tolerant of prolonged, very low oxygen levels than are bluegill or largemouth bass (Cooper and Washburn, 1946; Moore, 1942).

Hall and Ehlinger (1989) concluded that (a) the loss of the top predator, largemouth bass, was responsible for the explosion in the golden shiner population; and (b) the increase in golden shiners, a planktivorous fish species, resulted in the observed sharp decline in the abundance of large zooplankton, especially *Daphnia pulex* and *Daphnia galeata mendotae*. Although in some lakes an increased abundance of planktivores has been associated with decreased water clarity (see Chapter 9), no change was evident in the transparency of Wintergreen Lake, based on measurements of Secchi depth transparency in 1971-72 and 1982. Both before and after the 1977-78 lake winterkill, lake transparency was low (Secchi depth is generally 3 to 6 feet or less during the summer).

(stock size), the PSD is 50. Fisheries management goals may then be defined in terms of the RSD or PSD for target fish species. Changes in the RSD or PSD over time for one or more species (e.g., Fig. 3-10) can be used to track the progress towards achieving those goals.

Table 3-6.—Proposed minimum total length (in centimeters, 10 cm equals about 4 inches) for each designated size class: stock, quality, preferred, memorable, and trophy, for selected fish species (source: Gablehouse, 1984; Anderson and Gutreuter, 1983).

	SIZE DESIGNATION				
SPECIES	STOCK	QUALITY	PREFERRED	MEMORABLE	TROPHY
Largemouth bass	20	30	38	51	63
Smallmouth bass	18	28	35	43	51
Walleye	25	38	51	63	76
Muskellunge	51	76	97	107	127
Northern pike	35	53	71	86	112
Channel catfish	28	41	61	71	91
Bluegill	8	15	20	25	30
Black and white crappie	13	20	25	30	38
White bass	15	23	30	38	46
Common carp	28	41	53	66	84

Box 3-G.—Factors Influencing Year-Class Strength of Walleye in Lake Burton, Georgia (source: Rabern, 1989)

From 1960 to 1968, over six million fry and fingerling walleye were stocked into Lake Burton, Georgia, and a naturally reproducing population was established. In the 1970s, Lake Burton supported a strong walleye fishery. By 1985, however, fishing success rates for walleye in the lake had declined sharply by nearly 90 percent relative to creel surveys in 1978-79. In response, the Georgia Department of Natural Resources initiated a comprehensive study of walleye in Lake Burton to identify the major factors responsible for the fishery decline. Trends in walleye abundance, size of the spawning stock, spawning times and locations, age and size distributions, food habits, and growth rates were evaluated relative to trends in prey abundance, predator abundance, temperature, rainfall, lake discharge, and water levels. The decline in walleye catch and harvest from 1976 to 1988 was accompanied by an upward shift in the age and length distribution (Table 3-6) and increased growth rates. During the 1970s, age-1 fish dominated the walleye population in the lake, while older age classes (ages 3 and 4) dominated in the 1980s.

Neither food limitations nor excessive losses to predators or fishing could account for the observed fishery decline. Rather, variations in walleye year class strength were most strongly correlated with rainfall levels in February ($r = 0.90$) and the minimum March water level in the reservoir ($r = 0.81$). Based on these results, Rabern (1989) concluded that walleye in Lake Burton were limited primarily by their reproductive success and the variable quality of the spawning habitat among years.

Walleye in Lake Burton spawn in tributary streams. However, rising water levels in the spring following the winter water-level drawdown gradually inundate these areas so that the spawning habitat shifts from a stream to a lake habitat during egg incubation and larval development. Favorable conditions for strong year classes occur when water levels are drawn down 10 feet or more during the winter and heavy winter rains scour the stream beds, removing the silt and debris accumulated during the preceding year and exposing significant quantities of rubble/gravel. Recommendations for improving the walleye fishery included (a) water-level drawdowns greater than 10 feet through February, (b) allowing the water level to rise in late February and March to inundate all spawning areas, (c) erosion control in the watershed to reduce siltation of the spawning beds, (d) stocking with fry to supplement natural reproduction in years when the spawning habitat quality is poor, and (e) creating artificial spawning reefs of rubble at the mouths of tributary streams to supplement natural spawning areas.

Table 3-7.—Age frequency (%) of walleye collected in November from Lake Burton, Georgia (source: Rabern, 1989).

		AGE							
YEAR	N	1	2	3	4	5	6	7	8
1976	4	25.0	0.0	0.0	50.0	25.0			
1977	27	22.2	7.4	11.1	7.4	11.1	18.5	14.8	11.1
1978	33	97.0	3.0						
1982	22	0.0	13.6	18.2	22.7	13.6	18.2	4.5	9.1
1983	14	0.0	0.0	42.9	14.3	21.4	14.3	0.0	7.1
1984	34	5.9	5.9	17.6	41.2	14.7	2.9	8.8	2.9
1985	27	14.8	0.0	11.1	55.6	11.1	7.4	0.0	0.0
1986	30	6.7	10.0	10.0	43.3	3.3	13.3	10.0	3.3
1987	19	0.0	0.0	21.1	73.7	0.0	0.0	5.3	0.0
1988	11	0.0	0.0	27.3	36.4	36.4			

The number of fish present in a lake or reservoir at a given time per unit area or volume is referred to as fish density or standing stock.

Fish Production

The number of fish present in a lake or reservoir at a given time per unit area or volume is referred to as fish density or standing stock. This number times the mean weight per fish is the fish population biomass or total weight of fish present per unit area or volume. The gross or total fish production in a given lake or reservoir is the total elaboration of new biomass over a specified period (e.g., one year)

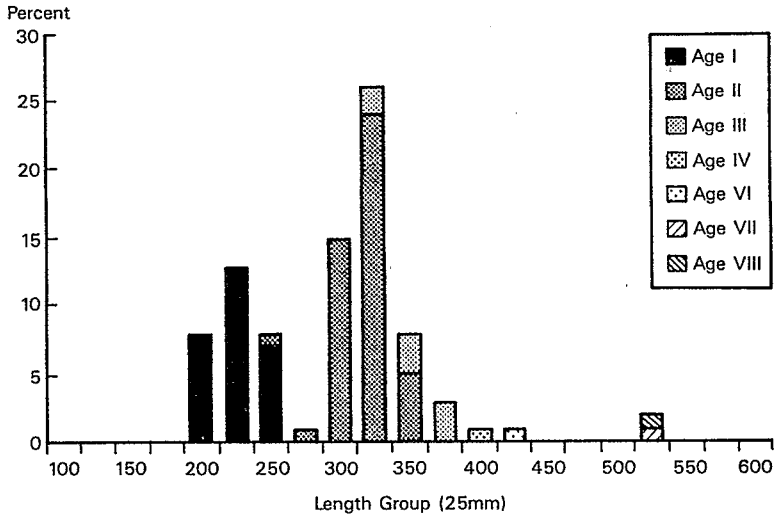

Figure 3-9.—Length-frequency distribution of largemouth bass in Lake Eufaula, Alabama, in spring 1988. Shadings indicate fish age in years (source: Newman et al. 1989).

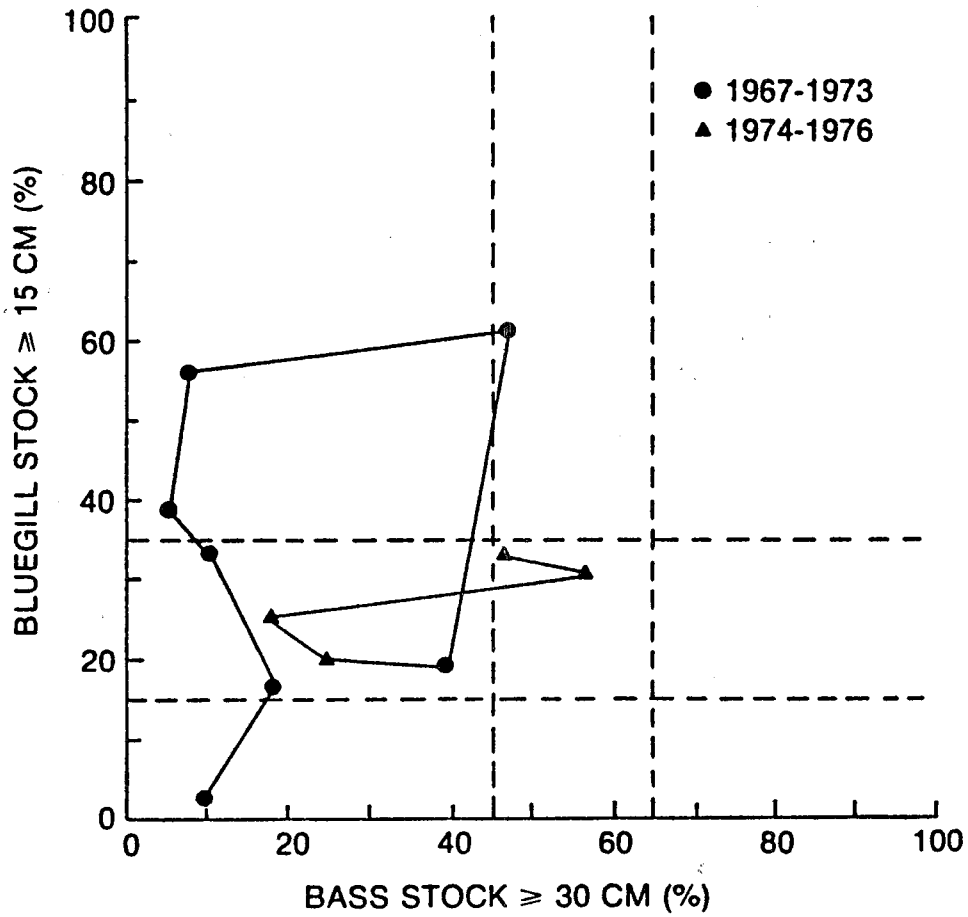

Figure 3-10.—Proportional stock densities of largemouth bass and bluegill in Phillips Lake, Missouri, 1967-76, plotted on a tic-tac-toe graph. The sequence of points represent samples collected 3/67, 4/68, 3/69, 5/70, 5/71, 5/72, 6/73, 5/74, 6/75, 10/75, and 5/76. The zone between the parallel dashed lines defines satisfactory conditions for bass and bluegill populations in small Missouri impoundments. A 30-cm (12-inch) minimum size limit on bass was evaluated from 1966-73 and may be responsible for the observed increase in the relative abundance of large bluegills. In 1974, the fishing regulation was changed to a slot size limit, protecting bass 30 to 38 cm (12 to 15 inches) (source: Anderson, 1976).

from both growth and reproduction, regardless of whether or not the biomass lives through the period under consideration. Net fish production equals the total production minus losses resulting from mortality; that is, the net change in fish population biomass between the beginning and end of the time period of interest. Depending on the relative balance among growth, reproduction, and mortality, the net production in a lake in any one year may be positive (increase in the population biomass), negative (population decrease), or zero (no change in the population biomass).

Fisheries Yield

Yield refers specifically to that portion of a fish population (in terms of fish numbers or weight) harvested by humans through recreational or commercial fisheries over some specified period of time and per unit area or volume (e.g., pounds per year per acre). The yield (Y), or catch from a fishery, is a direct function of the size of the population (P, population density or biomass), the level of fishing effort (f), and the "catchability" of the species (q):

$$Y = q \cdot f \cdot P$$

To ensure the long-term viability of a population, the quantity of fish harvested should never exceed the sustainable yield.

An important concept in fisheries management is the optimum sustainable yield, where sustainable yield refers to any level of yield that could be sustained indefinitely by the fish population without causing any long-term decline in population density or biomass. To ensure the long-term viability of a population, the quantity of fish harvested should never exceed the sustainable yield. An optimum sustainable yield is both sustainable and optimal in terms of the benefit derived from the fishery by humans. Maximum sustainable yield is the maximum quantity of biomass that could be harvested from a population each year without causing a long-term population decline. Optimum sustainable yield considers not only the quantity of fish harvested but also the level of effort and expense required to collect these fish and, in recreational fisheries, a wide range of other characteristics relating to angler values and the overall quality of the fishing experience (see Roedel, 1975).

The maximum and optimum sustainable yields for a fishery in a given lake or reservoir are dependent on the fish population's annual net production, which is affected in turn by the relative rates of fish growth, reproduction, and mortality. Lakes with higher productivity can support larger harvests without causing long-term population declines. Various methods and models exist for estimating fish production and maximum sustainable yield, some of which are discussed in Chapter 11. Optimum sustainable yields are difficult to formally quantify, however, because of the diverse array of variables that must be evaluated simultaneously. As a general rule, the optimum sustainable yield is less than the maximum sustainable yield.

Natural Factors that Influence Fish Production and Fisheries Yield

[M]ost of the fish species sought for recreational fishing occupy a relatively high position in the trophic pyramid.

All of the factors discussed in previous sections that influence the processes of growth, reproduction, and mortality also affect fish production and the potential fishery yield: food availability, temperature, levels of dissolved oxygen, toxic substances, availability of suitable spawning habitat, competition from other species, predation, and the occurrence of diseases and parasites. Furthermore, most of the fish species sought for recreational fishing occupy a relatively high position in the trophic pyramid. The elements of the trophic pyramid that lead to largemouth bass production, for example, generally include phytoplankton and/or bacteria, zooplankton, aquatic insects, and small fish species. Production at each of these levels and the efficiency of energy transfer between levels will ultimately influence the production of largemouth bass. Because only a fraction of the available energy

(about 10 to 20 percent) is transferred at each trophic level (see Chapter 2), generally fish species with the shortest food chains (e.g., plant-feeding fish) have the highest total production potential.

Fish production and yield are influenced, therefore, by a vast number of physical, chemical, and biological factors and interactions, most of which are difficult or impossible to observe or directly measure. Because of these complexities, several fisheries researchers have attempted to develop relatively simple indices for estimating potential production or yield as a function of general lake characteristics. Physical characteristics considered have included lake area, mean depth, maximum depth, shoreline development, littoral-area-to-lake-area ratio, water residence time, and many others. Physicochemical characteristics of interest include mean temperature, the highest average daily temperature, minimum oxygen levels, alkalinity, conductivity, and total dissolved solids. Some studies have also considered biological factors, such as the available biomass of plankton or benthic invertebrates.

Fish production and yield are influenced, therefore, by a vast number of physical, chemical, and biological factors and interactions, most of which are difficult or impossible to observe or directly measure.

One of the earliest and most widely cited indices was developed in the 1960s by Richard A. Ryder (1965, 1982). Using data for 34 northern temperate lakes subject to comparable fishing intensities, Ryder found that over 70 percent of the variability in fishing yield (Y) among lakes could be accounted for by a lake's mean depth (z) and total dissolved solids (TDS), when combined to form the morphoedaphic index (MEI):

$$MEI = \sqrt{(TDS / z)}$$

For Ryder's lakes,

$$Y = 1.4\ (MEI)0.45$$

where Y and MEI are in metric units, kg/ha/yr and mg/L/m, respectively.

The morphoedaphic index and various modifications of this index and approach have been widely applied in fisheries management to provide a quick, first-order estimate of a lake's potential fisheries yield. The best such predictor of fisheries yield is dependent, however, on the specific fish species, lake type, and region of interest. Chapter 11 provides further information on the available empirical models for estimating fish production and potential yield as a function of a lake's general physical, chemical, and biological characteristics.

Population Genetics

Individual fish within a given species and even within the same population have a high degree of phenotypic variability; that is, variations in characteristics such as growth rates, age at sexual maturity, fecundity, and resistance to environmental stresses. Much of this variability is environmentally determined; as discussed in earlier sections, fish are very "plastic" and responsive to environmental conditions (e.g., differences in food availability and temperature). However, some portion of this variability is also genetically determined. Heritability is the proportion of the total phenotypic variation within a species that results from genetic differences among individuals.

Inherited differences in potential growth rates, resistance to environmental stresses, and the like have allowed fish populations over many generations to become better adapted to their local environment. Fish species occur over wide geographic regions with relatively little, if any, natural interbreeding between populations in lakes separated by large distances. This reproductive isolation can lead to the development of separate subspecies, strains, or stocks of fish that can be genetically distinguished within a region or even within an individual lake or drainage system by using protein electrophoresis and other techniques (see Utter et al. 1987; Whitmore, 1990). Thus, two individuals from the same species but

Fish species occur over wide geographic regions with relatively little, if any, natural interbreeding between populations in lakes separated by large distances.

Some lake populations spawn only in inlet streams, while others have adapted over time to spawn in lakes or lake outlets.

Genetic diversity within a given population of fish increases the likelihood of the long-term population survival....

from different populations (or different stocks, strains, or subspecies) may have subtle but important differences in their innate characteristics. For example, hatchery strains of brook trout have distinctly different characteristics (e.g., survival and growth potential) than do wild strains of brook trout. Even among wild strains, some populations are adapted to living in lakes, others in streams. Some lake populations spawn only in inlet streams, while others have adapted over time to spawn in lakes or lake outlets. Transplants of one population or strain into another environment for which they are poorly suited (e.g., an inlet-spawning population into a lake with no inlets) will often fail.

Genetic diversity within a species has two major advantages. First, locally adapted populations or fish stocks have presumably evolved over multiple generations to be better suited to survive and reproduce in their immediate environment. Genetic diversity, therefore, reflects the adaptation of the species to the variety of environments in which it occurs. Second, environmental conditions fluctuate over time, randomly year to year as well as long-term trends (e.g., long-term climatic trends). Genetic diversity within a given population of fish increases the likelihood of the long-term population survival; that is, at least some members of the population will be able to survive and reproduce given a change in water quality or periodic extremes in environmental conditions.

Fisheries management activities and fishing can impact fish population genetics and genetic diversity in several ways:

- **Transplants of fish among different lakes and regions,** a common practice historically in fisheries management, break down this system of semi-isolated, locally adapted native populations. Genetically distinct strains or stocks may be lost as a result of interbreeding with fish of the same species but from different regions or drainage systems.

- **Hatchery stocks of fish** have often been maintained for generations, inadvertently selecting fish better adapted for life in the hatchery than in the wild. Hatchery strains tend to be more docile and less frightened by humans (and thus easier for anglers to catch). They also feed better on the pelletized food used in the hatchery than on natural prey and grow faster but do not live as long as wild strains of fish of the same species. When stocked, hatchery fish may compete with wild fish for limited food supplies and also interbreed with native populations, again resulting in the loss of genetically distinct, locally adapted strains or fish stocks.

- **Anglers prefer large fish.** Thus, in heavily fished waters, those fish that grow faster are more likely to be harvested, while fish that grow slower tend to live longer, reproduce for more years, and contribute more offspring to subsequent generations. Heavy fishing pressure may select, therefore, for slow-growing individuals that become sexually mature at smaller sizes and may eventually lead to long-term changes in fish population characteristics. While theoretically sound, relatively few studies have been conducted to demonstrate the effects of fisheries selection on fish population genetics (Nelson and Soule, 1987).

- **Heavy fishing pressure,** especially in small lakes, may greatly reduce the number of fish in the population at any one time. Very small population sizes increase the potential for problems associated with inbreeding and the likelihood of reduced intra-population genetic diversity. As for the effects of fisheries selection, however, the effects of small population size on fish population genetics are theoretically sound, but little direct evidence is available (Nelson and Soule, 1987).

Ryman and Utter (1987) provide additional information on the relationship between fisheries management and population genetics. Also of interest are papers from the 1990 International Symposium on The Ecological and Genetic Implications of Fish Introductions, presented in the *Canadian Journal of Fisheries and Aquatic Sciences* (see Hebert, 1991).

Fish Habitat

Mention has been made in many of the previous sections of the importance of a lake's physical and chemical attributes in determining both the suitability for a particular fish species as well as the potential total fish production and yield. The purpose of this section is to reiterate and elaborate on several key points regarding fish habitats. An understanding of fish habitat requirements can serve two important purposes: (1) to evaluate the degree to which specific habitat features may be limiting fish population success or productivity within a given lake and (2) to design and evaluate fish habitat protection and management projects (see Chapter 8).

Fish require habitats in which they can complete their life cycle and reproduce. The types of habitats required vary among species and also among life stages. As a result, assessments of fish habitat suitability must be specific to species and life stage. The U.S. Fish and Wildlife Service has proposed Habitat Suitability Indices for many of the common fish species and most sportfish in fresh waters of the United States. These habitat evaluation approaches and models are discussed further in Chapter 11.

Some habitats are of critical importance to fish populations because of the essential functions they support and because the availability of these habitats is often limited. Two common classes of critical fish habitat are

- spawning areas, which are essential for reproduction and survival of early life stages; and
- nursery areas, which provide cover and feeding areas for young fish.

Some habitats are of critical importance to fish populations because of the essential functions they support and because the availability of these habitats is often limited.

Tributary streams and wetlands provide critical spawning habitats for many fish species (see Table 3-3 and App. A). The absence or degradation of these habitats may limit the types and diversity of species able to maintain self-sustaining populations in the lake or reservoir. Substrate type also is an important determinant of an area's suitability for spawning for many fish. In addition, substrate type influences the composition and productivity of benthic invertebrate communities and, thus, the availability of food for fish.

A lake's physical features also serve as areas of escape and cover for smaller fish to avoid or minimize the potential for predation. Extensive beds of aquatic vegetation are one of the most important refugia for juvenile and small fish in many lakes and reservoirs. In some waters, overly abundant cover and/or the occurrence of too few fish predators may result in relatively high survival rates among young fish and subsequent overcrowding and stunted populations. Therefore, as in most management issues, maintaining an appropriate balance between too little and too much cover and protection is important.

Extensive beds of aquatic vegetation are one of the most important refugia for juvenile and small fish in many lakes and reservoirs.

Fish — smaller fish seeking cover as well as larger predatory fish searching for prey — tend to congregate around areas that provide cover. Adding structures such as brush piles or cribs to lakes with relatively little natural cover may serve to attract and concentrate sportfish, thereby improving fishing success. The potential benefits and use of such "attraction" habitats for fisheries management are discussed further in Chapter 8.

Changes in water level may have a marked effect on the quantity and quality of suitable habitat. For example, with a decrease in water level, beds of aquatic vegetation in the littoral zone may be exposed and no longer available as cover

Changes in water level may have a marked effect on the quantity and quality of suitable habitat.

for juvenile and small fish. The result may be an increase in predation, benefiting the larger predatory fish while decreasing the survival of smaller fish. Thus, although somewhat drastic, periodic water drawdowns are one approach to addressing problems with overcrowded populations of small, stunted fish (see Chapter 8).

The construction of seawalls, beaches, and docks, and other physical alterations of the shoreline and littoral area environment may also impact the availability of suitable fish habitat and cover. They are discussed further in Chapter 8.

The colder waters of a lake's metalimnion and hypolimnion provide important habitat for coldwater fish species such as brook trout, lake trout, and other salmonids (see Table 2-2) and also for coolwater species such as striped bass, alewife, and blueback herring in southern reservoirs (e.g., see Box 3-E). Lake restoration activities that affect the stability of a lake's thermal stratification or the temperature or levels of dissolved oxygen in these deep waters would directly affect the suitability of the lake for coldwater or coolwater fisheries and/or the maintenance of a two-story fishery (with both warmwater and cold- or coolwater fish species).

Maintenance of suitable habitats for fish is fundamental to successful fish management. Yet, many human activities alter or degrade these habitats. Common threats to fish habitats include increased silt loads as a result of construction, farming, or lumbering activities within the watershed; dredging; and barriers to migration, in particular dams on lake inlets and outlets that may block spawning runs. Threats also include alterations of flow and stream diversions and industrial and municipal liquid waste discharges and nonpoint sources of nutrients and toxic substances that may directly and indirectly affect the suitability of the lake or reservoir for fish survival and reproduction. Managing the quality of the habitat is a prerequisite to maintaining a quality fishing experience and productive fisheries.

Managing the quality of the habitat is a prerequisite to maintaining a quality fishing experience and productive fisheries.

Fish Communities

Historically, fisheries management has focused on managing individual fish species and populations of greatest interest or value for recreational or commercial fisheries. However, just as fish cannot be managed in isolation from their environment and the quality of the fish habitat, individual fish species cannot be effectively managed without considering the broader biological community in which they coexist. The abundance and success of any particular fish species is clearly affected by the abundance of other species that compete with, prey upon, or are prey for the species of interest. Maintaining an optimal yield of the target species requires appropriate population levels of competitors, predators, and prey species. The advantages of abundant prey are obvious. Reasonably abundant predators also can be advantageous because of their selective removal of younger, weaker fish, decreasing the potential for overcrowding and stunted growth. However, an overabundance of predators or competitors may limit the productivity and yield of the target fish species.

The abundance and success of any particular fish species is clearly affected by the abundance of other species that compete with, prey upon, or are prey for the species of interest.

Chapter 2 provides further discussion on the nature and importance of interactions between fish and other biota and among fish species. Three additional topics are briefly reviewed here: (1) fish community types, (2) factors that influence fish species distributions and fish community composition, and (3) the role of fish community analysis in fish and fisheries management.

Fish Community Types

Some fish species frequently occur together; others are negatively associated. Based on these patterns, fish communities are often classified into fish community types, generally denoted by the characteristic or dominant fish species in the community. For example, Tonn et al. (1983) classified fish communities in small lakes

in northern Wisconsin into three types: mudminnow, bass, and pike. Mudminnow lakes typically had populations of stunted yellow perch and one or more minnow species in addition to the dominant species, the central mudminnow *(Umbra limi)*. Frequently occurring species in bass lakes included largemouth bass, yellow perch, and bluegill and/or pumpkinseed sunfish. Lakes dominated by northern pike typically also contained one or more species of bullhead, white sucker, pumpkinseed and/or bluegill sunfish, and yellow perch. The composition and frequency of occurrence of common fish community types vary among regions.

Two approaches have been used to define fish community types. Many State fisheries agencies categorize lakes according to their major fishery(ies); for example, as walleye lakes, bass-bluegill lakes, lake trout lakes, two-story fisheries, and so on. Alternatively, fish community types can be determined based on statistical associations among species (e.g., using ordination analyses; see Gauch 1982; Hill and Gauch, 1980). Examples include the Tonn et al. (1983) study previously mentioned, Minns (1989), and Hinch et al. (1991).

Natural patterns of fish species distribution tend to follow major drainage systems . . . .

Factors That Influence Fish Community Composition

Many factors work together to determine the composition of a fish community in a given lake or reservoir. All of the species that occur must have naturally emigrated to the lake from waterbodies connected currently or historically or been introduced, accidentally or on purpose, by human activities. Natural patterns of fish species distribution tend to follow major drainage systems; fish communities in lakes interconnected within the same major drainage system tend to be more similar to each other than to communities in other systems or regions. In some areas, especially northern regions influenced by glaciation, historic drainage patterns were distinctly different from those of today. Large meltwater lakes formed at the edge of the retreating ice sheet over major portions of Wisconsin, Ontario, and other areas. Lakes that today are geographically isolated may have been interconnected during this post-glacial period and, as a result, have similar species composition. In general, lakes that are geographically isolated (for example, seepage lakes with no inlets or outlets and lakes at high elevations) tend to support fewer fish species (i.e., have a lower species richness) than do drainage lakes (with inlets and outlets), reservoirs, and lakes at lower elevations.

Colonization opportunities and human introductions define the pool of species that potentially occur in a lake. Habitat characteristics and biotic interactions determine the actual species composition and relative species abundance. For a species to persist, the lake or reservoir must provide suitable habitat for reproduction, survival, and growth. Fish species with similar habitat requirements (e.g., largemouth bass and bluegill) frequently co-occur, while species that prefer distinctly different types of habitat (e.g., smallmouth bass and bullheads) are often negatively associated or occur together only in large lakes with diverse habitats.

Colonization opportunities and human introductions define the pool of species that potentially occur in a lake.

Because large lakes and reservoirs generally provide a greater variety of habitats, they also tend to support more fish species than do smaller lakes. Sporadic events, such as winterkill, can also have a long-term impact on fish community composition (as discussed in Box 3-F) especially if the lake is currently isolated from other waterbodies, preventing or slowing the natural recolonization of the lake by fish.

Predation and competition among fish species also influence fish community composition. Predation, in particular, may limit species co-occurrence. For example, soft-bodied, small fish species (e.g., minnows) that are readily captured and eaten by predators tend to be absent or rare in lakes with large piscivorous

Predation and competition among fish species also influence fish community composition.

species, such as northern pike and largemouth bass (Tonn and Magnuson, 1982; Jackson, 1988). Inskip and Magnuson (1983) speculated that predation of northern pike on young-of-the-year muskellunge is the primary reason for the sharp decline in muskellunge abundance in Big Pine Lake, Wisconsin, following the introduction of northern pike in the 1940s. Biotic interactions are likely to be of greater importance in small lakes with relatively little fish cover than in larger lakes or those with abundant macrophytes or other fish cover.

Role of Community Analyses in Fisheries Management

Tonn et al. (1983) and Magnuson (1991) identify several ways in which fish community analyses may benefit a fisheries management program:

- The delineation of common fish community types in a region identifies sets of species that commonly co-occur and those that rarely, if ever, occur together, providing guidelines for reasonable assemblages of species to target in any given lake or reservoir.

- For regional planning (e.g., State fisheries programs), classification of lakes by fish-community type facilitates the evaluation and tracking of available fish resources; the number of lakes within each class provides an indicator of the types and distribution of fishing opportunities available.

- Associations between easily measured lake characteristics (e.g., area, depth, summer temperatures, total dissolved solids) and fish-community type are more consistent than those for individual fish species. Multivariate analyses can be used to identify lake characteristics highly correlated or associated with the occurrence of a particular fish-community type. Results from these analyses can be used as follows:

  - Relatively simple models or dichotomous keys (e.g., Fig. 3-11) can be developed to predict the type of fish community most likely to occur in a lake based on measurements of physical and chemical variables.
  - Information on lake characteristics can be used to help establish reasonable fish management goals, identify lake characteristics that may be limiting the fish community and fisheries, and avoid inappropriate and wasteful management procedure (e.g., stocking fish into lakes where the fish species is unlikely to survive over the long term).

1a. Lakes with total watershed size < 10 km2(3.9 square miles) and surface area < 45 ha (111 acres) 2

1b. Lakes with total watershed size 10-340 km^2(3.9-131 sq. miles) and surface area 45-100 ha (111-247 acres) 3

2a. Lakes with maximum depth < 4 m (13 ft) . . . . . .mudminnow lakes

2b. Lakes with maximum depth 4 to 8 m (13-26 ft) . . . . . .bass lakes

3a. Lakes with pH 5 to 6.5 or conductivity 7 to 50 µS/cm . . . .bass lakes

3b. Lakes with pH 6.5 to 9 or conductivity 51 to 200 µS/cm . . pike lakes

Figure 3-11.—Dichotomous key for predicting fish-community type for small lakes in forested areas in northern Wisconsin (source: Magnuson, 1991; Tonn et al. 1983).

Special Issues in Reservoirs

The concepts and underlying principles of managing reservoir fisheries are no different than those for fisheries in natural lakes. Furthermore, most fisheries management problems and approaches are common to both lakes and reservoirs. Nevertheless, some features, problems, and approaches are unique or occur more frequently in reservoirs than in natural lakes. Issues of special concern or interest for managing fisheries in reservoirs include the following:

[M]ost fisheries management problems and approaches are common to both lakes and reservoirs.

- **Reservoir design and construction.** Unlike natural lakes, reservoirs can be designed and constructed specifically with fish habitat requirements and preferences in mind. It may be possible to favor particular target fish species, enhance productivity, minimize the potential for certain types of management problems, and also improve boater and angler access. Factors to consider in the design and construction of reservoirs are discussed further in Chapter 8.

- **Fisheries and fish community development.** When filled, the reservoir provides a new lake habitat with little to no pre-existing fish community. Therefore, both the fish community and fishery must be, in essence, developed "from scratch." New species must be introduced and appropriate balances established among prey, predators, and fish populations.

- **Aging.** As noted in Chapter 2, new impoundments typically experience an initial peak in productivity (trophic upsurge) followed by a trophic depression and longer-term, gradual maturation and aging process. Fish populations may fluctuate sharply during the trophic disequilibrium phase but usually stabilize within 5 to 10 years. Changes in target species and management approaches may be warranted over time in response to changes in the reservoir habitat.

- **Water level fluctuations.** Water level fluctuations tend to be greater in many reservoirs than in natural lakes. Periodic exposures of the littoral zone during water drawdowns may have both positive and negative effects on the lake ecosystem and fish community. Reservoir outlet designs that allow for multiple water level discharges facilitate the use of water level management as a fisheries management tool (see Chapter 8). To protect the fish community, minimal water levels that provide a fish conservation pool should be designated.

- **Hypolimnetic discharges.** Hypolimnetic discharges from reservoirs promote subsurface density flows and allow creation of downstream coldwater fisheries, as discussed in Chapter 2. At the same time, mainstream reservoirs are frequently constructed in series. Hypolimnetic discharges from upstream reservoirs may adversely affect the reproductive success and growth of warmwater fisheries in downstream reservoirs.

- **Spatial heterogeneity.** Many reservoirs are large, complex, and diverse systems. This spatial heterogeneity may lead to the development of discrete fish stocks with distinct growth and life history characteristics. Variations among fish stocks and the size and spatial heterogeneity of the reservoir environment increase the difficulty of obtaining an adequate sample for assessing fish community status and trends.

- **Limited natural cover.** Frequent changes in water level together with the high levels of turbidity that occur in some reservoirs may limit growths of aquatic macrophytes. As noted in Chapter 2, macrophyte beds provide important spawning habitats and nursery areas for a number of fish species. In waters without macrophytes, the addition of structures to enhance fish cover may be beneficial to the fish community (see Chapter 8).

- **Energy development.** Many reservoirs are constructed specifically for energy development for hydroelectric power or as cooling ponds for electrical generating facilities. Both uses introduce a unique set of problems, including entrainment, impingement, thermal discharges, and effluents from ash basins. Problems in fisheries management are discussed further in Chapter 6.

Hall and Van Den Avyle (1986) discuss additional issues and problems relating to managing fish and fisheries in reservoirs.

CHAPTER 4

Key Concepts in Fish and Fisheries Management

Chapter Objective

This chapter introduces the major components of and key concepts underlying a fish or fisheries management program. Subsequent chapters provide further details on each of these topics and also describe specific management techniques and approaches.

As discussed in previous chapters, the emphasis is on fish and fisheries management within the context of an integrated lake management program. Fishing is only one of many human uses of lakes and reservoirs, and fisheries management must be viewed within the broader context of managing the quality and multiple uses of aquatic resources. Water quality management is critical to fisheries management because (a) sustainable fisheries yields and the types of fish resources that a lake can support are highly dependent on the quality and characteristics of the lake habitat, and (b) the quality of the lake environment as a whole (e.g., aesthetics) has a major influence on the level of enjoyment derived from a fishing experience. Likewise, fish are of interest to water quality managers because (a) fisheries management activities and fishing can indirectly affect water quality and other lake uses, and (b) manipulations of the fish community are one of a number of available tools for water quality management. A joint management program recognizes the interrelationships among fish, other biota, water quality, and the physical habitat. Decisions regarding lake management can consider the full range of effects associated with a proposed action and the potential trade-offs among all alternative objectives, lake uses, and human values.

A joint management program recognizes the interrelationships among fish, other biota, water quality, and the physical habitat.

Important Underlying Principles

The Lake and Reservoir Restoration Guidance Manual (Olem and Flock, 1990) presents several underlying principles and conclusions regarding lake restoration efforts. Because of their importance, these major conclusions are repeated here, modified slightly to better reflect the issues and objectives of primary concern for fish and fisheries management:

- Fisheries or lake management problems have no simple, ready-made solutions; different situations require different approaches. Applying the wrong management technique can often make problems worse or more intransigent, difficult, and expensive to resolve.

- Management and restoration efforts must treat the cause of the problem, not the symptom. Actions that address only symptoms are unlikely to be successful or cost effective over the long-term.
- The physical, chemical, and biological components of lake ecosystems are intricately linked. As a result, identifying causal linkages and causes of management problems are often difficult. Furthermore, any management action is likely to have a series of indirect consequences that must be anticipated and considered as part of the decision-making process.
- Biological communities and fish populations are dynamic and exist in an environment that is highly variable and largely uncontrollable. These natural fluctuations must be accounted for in management decisions and in interpreting the results from lake monitoring programs. Responses to management actions may occur over a long time frame and require long-term data sets to detect.
- Habitat protection is essential to successful fisheries management; suitable fish habitat is a prerequisite for productive fisheries. In a similar manner, a lake and its watershed are tightly coupled. Good management practices in the watershed are essential for improving and protecting the physical and chemical quality of the lake environment. Thus, lake and watershed management must be incorporated within a fisheries management program.
- To be successful, fisheries and lake management objectives must be compatible with the uses that the natural condition of the lake (and its watershed) can support most readily. For example, some lakes are naturally highly productive (eutrophic) because of the types of soils and geology of their surrounding watershed. To attempt to manage or transform such a system to an unproductive, clear-water (oligotrophic) state or manage the fisheries in the lake for fish species that do best in oligotrophic waters would be ill-advised.
- Lakes and reservoirs are used for multiple, often conflicting purposes. Even among the fishing public, conflicting desires, objectives, and fishing preferences frequently arise. Lake management decisions must reflect the need to set priorities, compromise, and establish an optimal balance among multiple uses.
- Management decisions and actions must be cost effective. Cost considerations must be incorporated directly into fisheries planning and management decisions.
- Because of the complexity of the issues involved and the potential adverse consequences of making a mistake, professionals trained in fisheries science and limnology must be involved during each phase of the planning process, program implementation, and management evaluation. In particular because the fish in most lakes are pubic resources, personnel from State fisheries agencies should be contacted before any of the management activities described in this manual are undertaken. Some of these management techniques and fish sampling methods can be conducted only by State personnel or require State permits (see Chapter 7 and Appendix C for information on contacting State agencies).
- Finally, minimal management is often the best management approach: protection of the resource rather than intervention. To the degree possible, management objectives should be achieved by enhancing and managing native fish populations rather than through large-scale manipulations and alterations of the existing fish community in the lake or reservoir.

Importance of Recreational Fisheries

Fishing is one of the most popular and widespread recreational uses of lakes and reservoirs. In 1985, 38.4 million individuals 16 years and older participated in angling on fresh waters in the United States (excluding the Great Lakes), for a total of 786 million angling days (U.S. Fish Wildl. Serv., 1988). In Canada in 1985, 6.5 million active anglers 16 years and older — close to one out of every five Canadians — fished a total of approximately 69 million days on fresh waters (Can. Dep. Fish. Oceans, 1988). In the U.S. survey, 15 million people reported fishing on natural lakes and 22 million on reservoirs, the latter divided fairly equally among smaller reservoirs (35 percent on waters < 10 acres in size) and larger systems (45 percent on waters > 40 acres). Fish species and groups preferred by anglers in the United States and Canada are listed in Table 4-1.

Fishing is one of the most popular and widespread recreational uses of lakes and reservoirs.

Table 4-1.—Fish species and groups preferred by anglers in the United States and Canada in 1985 (source: U.S. Fish Wildl. Serv. 1988; Can. Dep. Fish. Oceans, 1988).

	PERCENTAGE OF FISHING EFFORT OR CATCH*	
FISH SPECIES OR GROUP	UNITED STATES	CANADA
Black bass	19	7
White bass	4	—
Striped bass and striped bass hybrids	4	—
Panfish	15	—
Crappie	13	—
Catfish and bullheads	16	—
Walleye and sauger	4	12
Perch	—	21
Northern pike and pickerel	4	10
Muskie and muskie hybrids	1	—
Trout	9	22
Salmon	1	2
Steelhead	1	—
Whitefish	—	1
Smelt	—	7
Other	3	18
Fishing for anything	7	—

* Dashes (—) indicate fish species or groups not listed as a separate category in the U.S. and Canadian national survey summary reports.

Direct expenditures on freshwater fishing in 1985 totalled $17.8 billion in the United States and $2.5 billion in Canada (U.S. Fish Wildl. Serv. 1988; Can. Dep. Fish Oceans, 1988). Canadian anglers also spent an estimated additional $1.9 million for durable goods (e.g., boats, motors, camping gear) related directly to sport fishing activities; similar data for U.S. anglers were not available.

Since 1955, when the U.S. National Survey of Fishing, Hunting, and Wildlife Associated Recreation was initiated, the numbers of anglers and angling days have more than doubled (U.S. Fish Wildl. Serv. 1988). While the number of individuals participating in angling continues to increase, the total fish resource and acres of surface waters available for fishing have remained relatively constant in recent years. Thus, sustaining a high level of fishing enjoyment, including a reasonable level of fishing returns and fish caught, will require careful management of the existing resource.

Historical Perspectives

The science and objectives of fisheries management have changed over the years. In the late 1800s and early 1900s, when many State fisheries agencies were first established, restrictive fishing regulations and fish stocking were the major management techniques. Most funding was spent on hatchery operations, with

In the late 1800s and early 1900s, . . . [f]ish were considered a resource to be exploited.

the emphasis on producing the maximum amount of fish biomass for harvest by anglers. Fish were considered a resource to be exploited. To increase the available quantity, fish were stocked into waters with relatively little attention paid to the suitability of the habitat, the potential for long-term survival of the fish population, and the impacts on other fish species and biota. Exotic species imported from other countries or other regions of the United States were widely distributed in an attempt to increase and diversify fishing opportunities. Examples include the common carp and brown trout, imported from Europe in the 1800s, and rainbow trout, which are native to the western United States but have been stocked extensively throughout much of North America.

[S]imple approaches to the management of fish resources have often caused more harm than good....

Through time, simple approaches to the management of fish resources have often caused more harm than good, and the science of freshwater fish management has developed considerably. Important lessons learned and trends in fisheries management have included the following (Radonski and Martin, 1985; Magnuson, 1991):

- Stocking is cost effective only if the stocked fish have a reasonable chance of survival and the habitat into which they are stocked is suitable. Stocking programs have become increasingly sophisticated, developing approaches for optimizing the size, numbers, and types of fish stocked for the greatest returns and improvement in fishing quality.

[S]tocking is no longer viewed as a panecea....

- Stocking, especially introductions of non-native species, can cause serious adverse effects to fishing quality and other lake uses. While still playing a role in fisheries management as one of a number of management options, stocking is no longer viewed as a panacea, the emphasis on and relative funding of stocking programs have decreased, and the potential adverse effects of stocking are carefully considered before initiating any new stocking program.

Currently, management programs recognize the benefits and role of managing and protecting both water quality and the physical habitat.

- Habitat improvement and protection activities can be more effective than stocking and can result in long-term increases in fishing quality at relatively low cost. Interest in fish habitat improvements began in the 1930s and primarily involved the installation of physical structures in streams to stabilize shorelines, deepen pools, and provide fish cover, and fish attraction features in lakes to concentrate fish for angling. Attention shifted to the adverse effects of pollution, especially chemical pollutants and eutrophication, in the 1960s and 1970s. Currently, management programs recognize the benefits and role of managing and protecting both water quality and the physical habitat.

- Many of the fishing regulations used initially — creel limits, minimum size limits, closed seasons — have been proven ineffective or even counterproductive in some instances in controlling fish populations. Substantial research since the 1960s has lead to the development of more targeted and effective regulatory approaches (e.g., slot size limits, discussed in Chapter 8). Furthermore, current management philosophy is to implement only those regulations that have a clearly demonstrated need.

[F]isheries management requires an understanding of lake ecology as well as fish biology and fish population dynamics.

- Fisheries management in the 1950s and 1960s, in particular, focused on individual fish species; fisheries science was largely the study and modeling of fish population dynamics to estimate maximum sustainable yields. While important, an understanding of fish population dynamics, by itself, is not sufficient. Fisheries management has advanced through an appreciation for predator-prey balances to a recognition of the importance and complexity of the interactions between the targeted fish species and all other ecosystem components. As discussed in Chapters 2 and 3, fisheries management requires an understanding of lake ecology as well as fish biology and fish population dynamics.

- Anglers are interested in more than just maximizing the biomass of fish caught. In fact in a 1985 survey of Canadian anglers, quality of the water and beauty of the surroundings were rated as the two most important factors affecting the enjoyment of a day of fishing. Number of fish caught, size of fish caught, and fish catch as a source of food were rated 9, 10, and 11, respectively, behind a variety of environmental and sociological factors such as escape from routine, privacy, and angling for wild fish (Can. Dep. Fish. Oceans, 1988). While the relative importance of these factors varies regionally, the scope of fisheries management objectives has broadened substantially.
- Fish and fishing can affect other lake uses and lake characteristics. The increasing recognition, starting in the 1960s and 1970s, of the role of fish predators in the lake ecosystem has lead to (a) a better appreciation for the indirect effects of fisheries management activities on other aspects of lake quality and other lake uses; (b) use of biomanipulation as a tool for water quality management; and (c) increasing emphasis, as in this manual, on the integration of fisheries and water quality management programs.
- Many of today's environmental problems are regional or global in scale (e.g., acidic deposition, global climate change) and cannot be effectively addressed by site-specific research and management programs.
- To better address the diversity of environmental problems and concerns, lake managers must have an increased understanding of the underlying mechanisms of fish response, ecological processes, human motivations and values, and more sophisticated analysis tools. Studies of fish physiology, behavior, genetics, community ecology, ecosystem ecology, and statistics and mathematical modeling have become increasingly important. The science of fisheries management has evolved from one founded largely in biology to an interdisciplinary science encompassing biology, chemistry, physics, ecology, mathematics, and statistics as well as economics, sociology, and psychology.

Components of a Management Program

A comprehensive lake management program includes six major components (Fig. 4-1):

1. Determine the current status of the lake ecosystem and fisheries by sampling and assessing each of the following (see Appendix B):
   - sportfish in the lake (i.e., the fish populations exploited directly by recreational fishing);
   - other fish species and biota that may prey upon, be prey for, or compete with the target species;
   - other biota that may be indicative of the condition of the biological community as a whole in the lake or reservoir;
   - the fish's habitat, in particular the physical, chemical, and biological characteristics of the lake that are most critical for fish survival, reproduction, and growth; and
   - the fisheries and fishing success.
2. Characterize the user population; for example, the characteristics and desires of individuals likely to be involved in recreation (fishing,

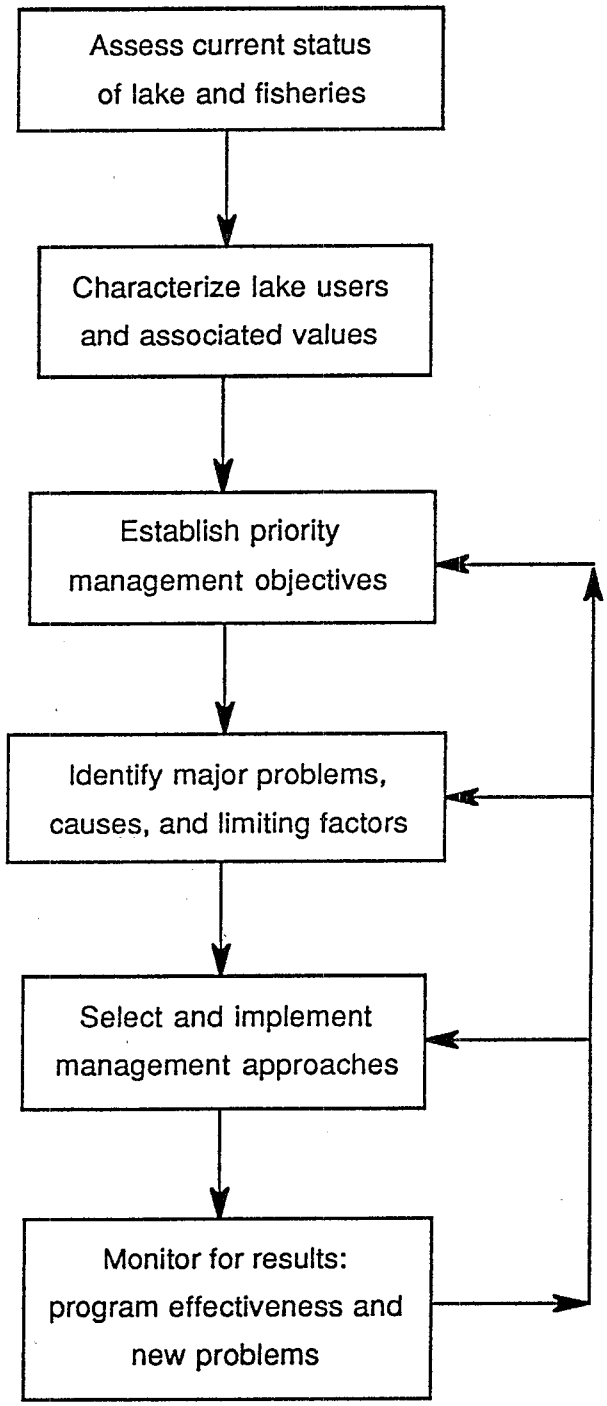

Figure 4-1.—Major components of a comprehensive lake management program.

swimming, boating) in the lake or reservoir and also the full range of environmental values associated with the lake or reservoir by both users and nonusers (Chapter 5).

3. Establish priority objectives and targets for the management program that consider the preferences of the fishing public, potential competing uses, and the environmental characteristics of the lake or reservoir that may influence or limit the optimal lake uses or target fish species (Chapter 5).

4. Identify the major factors or problems that may be limiting fisheries success, the quality of the fishing experience, or other lake uses (Chapter 6).
5. Select and implement optimal approach(es) to resolving these problems (Chapters 8 and 9). For fish and fisheries management problems, actions may include one or more of the following:
   - direct manipulation of the fish population or fish community (e.g., stocking, removing undesirable fish);
   - increasing food supplies (e.g., by prey introductions or increasing lake productivity);
   - habitat protection and management (e.g., by modifying a lake's physical features or improving water quality); and
   - fishing regulations and associated activities (e.g., controlling lake access) to improve the quality of fishing by adjusting fishing pressure and harvest.
6. Monitor changes in the fish community, fisheries, and lake ecosystem to determine the effectiveness of the management actions, and identify any new problems that may arise.

Based on the monitoring data collected, new or modified management actions may be warranted. In addition, the application of a management action itself is a learning process. By observing the response of the lake and lake's fisheries, further insight can be gained regarding the nature of the problem, the system constraints, and the optimal management approach to alleviate the problem. This process, whereby information is gained and management strategies are improved through direct experience with applying management techniques, is referred to as "adaptive management" (Walters, 1986). Thus, lake management, including the six components of a management program in Figure 4-1, is not a linear process but is highly interactive with multiple feedback loops. Models are frequently used as part of the adaptive management process to help organize the accumulated information and evaluate the remaining uncertainties (see Chapter 11).

By observing the response of the lake and lake's fisheries, further insight can be gained regarding the nature of problem, the system constraints, and the optimal management approach to alleviate the problem.

Regional Perspectives

As noted in Chapter 1, the object of this manual is to provide useful guidance on fish and fisheries management appropriate for lakes and reservoirs in the United States and Canada. To cover such a diverse area in a single manual is a challenge that, admittedly, can be only partially fulfilled. Priority management objectives, the types of problems encountered, and optimal management approaches tend to vary widely among lakes in different regions, of different sizes and lake types, and with different types of fish communities and fisheries. For example, while the basic principles and underlying processes are the same, management strategies commonly used for warmwater fish communities (e.g., bass and bluegill) differ from those for coldwater fish communities (e.g., trout). Coldwater and coolwater fish species represent the major sport fish at northern latitudes; warmwater fish species occur in most areas but are of greater importance at southern latitudes (see Table 4-1). Many management techniques, especially in-lake treatments, are more feasible in small lakes than in large lakes. Large lakes and reservoirs are also more spatially heterogeneous, with a greater diversity of habitats, fish species, conditions, and problems in any given lake. Winterkill problems occur predominately in small lakes at northern latitudes or high elevations, while summerkill is more common in warmer climates or at the southern edge of the distribution for coolwater species.

Some of these lake-to-lake differences in management strategy can be better understood by classifying lakes by region, lake type, or fish-community type. State fisheries agencies, by default, manage by political boundaries. Within a given State, however, management activities are often organized by subregion and/or by fish-community type. For example, Omernik (1987) used regional differences in climate, rainfall, topography (hills, valleys, plains), soils, geology, and land use to define ecoregions within the United States. A number of States use ecoregions or other ecologically relevant subregion boundaries to delineate management areas likely to have relatively similar natural biological communities and lake characteristics and as the basic unit to establish attainable lake uses and biocriteria (i.e., numeric or narrative water quality criteria describing the reference biological integrity of aquatic communities of a given designated use).

This manual attempts to describe management approaches in generic terms. The discussions are not region-specific for the most part. However, case studies are provided in Chapter 12 and elsewhere throughout the text to illustrate applications of these techniques and procedures in different regions and for different types of lake problems and fish communities.

CHAPTER 5

Setting Goals, Specific Objectives, and Priorities

Chapter Objectives

Before proceeding, you must first decide what you are trying to achieve and what actions to take. Thus, the first step in any lake or fisheries management program is to establish program goals, specific objectives, and priorities. Goals describe in general terms what your program is designed to achieve. For example, for a fishery in an urban area, important goals may be to provide the maximum possible fisheries yield, a high catch rate per unit of angling effort, and self-sustaining fish populations that can support heavy fishing pressure. Specific technical objectives should then be defined for each goal, delineating explicit targets and metrics for tracking progress toward achieving that result. For these goals, appropriate objectives might include target values for the total number of angling hours on the lake per year, the average catch per unit effort (e.g., the number and weight of fish caught per hour fished), and the total yield for one or more selected target fish species. Often, some goals and specific objectives conflict and cannot be optimized simultaneously. Furthermore, funding is frequently limited, preventing completion of all desirable projects and specific objectives. As a result, you must make choices and define priorities. Priority setting is an integral part of establishing a program's goals and specific objectives.

[T]he first step in any lake or fisheries management program is to establish goals, specific objectives, and priorities.

This chapter provides an overview of the process — that is, the activities and issues associated with defining a program's goals, specific objectives, and priorities — and briefly describes the types of goals that may be of interest or value for fish and fisheries management programs in lakes and reservoirs.

Who Should Be Involved?

All too often in the past, fisheries management objectives have been defined primarily by fisheries biologists working in relative isolation from the user community (i.e., the fishing public and other groups of lake users). A program's effectiveness and likelihood of success can be greatly enhanced, however, by actively involving lake users in the planning process. For example, people who currently fish (or may fish) at the lake can best define factors that contribute to a quality fishing experience. Moreover, the fishing public is generally keenly aware of existing problems, user conflicts, and constraints on fishing and other recreational activities (see Chapter 6).

A program's effectiveness and likelihood of success can be greatly enhanced, however, by actively involving lake users in the planning process.

The planning process should include not only anglers but also representatives from all groups of lake users such as cabin owners, boaters, and swimmers. As discussed in Chapter 1, the goal is to develop an integrated lake management program that considers fisheries, water quality, and all lake uses simultaneously. Even when the primary topic is fisheries management, many decisions may indirectly affect other lake uses, and trade-offs may be necessary. Excluding representatives from any faction can arouse animosity and diminish the broad public support needed for the program's success. Therefore, it is important to systematically identify all current and planned lake uses, the interactions between these uses and the lake's fisheries and fish community, and the associated user populations.

[N]onuser values and concerns should also be considered during the lake planning process.

People who currently use the lake for fishing, swimming, or other purposes generally take the greatest interest in lake management. However, nonusers also appreciate a lake for its intrinsic values, which can include both option values (keeping available possible future use of the lake) and existence values (associated with simply knowing that the lake exists). This applies to future generations or those with a general concern for nature but with no immediate plans to use the lake (Bishop et al. 1987). To the degree possible, nonuser values and concerns should also be considered during the lake planning process.

State fisheries agencies, in particular, should be actively involved in developing and implementing a fish or fisheries management program.

Finally, State, Federal, and local agencies typically have regulatory or management responsibilities that affect the lake or will be affected by the lake management program. State fisheries agencies, in particular, should be actively involved in developing and implementing a fish or fisheries management program. State water quality agencies should also be contacted because fish and fisheries management activities may directly or indirectly affect other biota and water quality. In some instances, multiple agencies may have jurisdiction over the fish in a lake, with markedly different goals and objectives (e.g., in lakes used for both recreational and commercial fishing). Although this supplement focuses on encouraging public involvement in lake planning together with the appropriate State agency(ies), many of the same principles and basic approaches can be used to foster interagency cooperative management programs. Pinkerton (1989) presents several case studies illustrating the development of co-management plans for sharing fisheries management authority between two or more agencies.

Gathering Information on User Characteristics and Public Values

Information on public values and user characteristics can help define and prioritize lake management goals.

Information on public values and user characteristics can help define and prioritize lake management goals. Mail surveys, telephone interviews, and personal contact interviews such as creel surveys can obtain data for a representative sample of the user population and/or interested nonusers. Questionnaire and interview survey designs and techniques are described in Appendix B.

Various types of information can be collected — for instance, answers to specific questions regarding possible management goals or approaches; qualitative rankings of the relative merits of different options; or quantitative data on personal values. Contingent valuation (Bishop et al. 1987; Hoehn, 1987) is frequently used to assign monetary values to nonmarket goods and services such as recreational fishing. The respondent's willingness to pay (or assign a value) for such activities as better fishing or protecting bald eagles is determined by a series of "yes-no" questions. Travel cost methods (Talheim et al. 1987) also provide estimated monetary values for nonmarket goods and services. Gregory (1987) presents several nonmonetary approaches to valuing fish resources, including measures of attitude and social well-being. Talhelm and Libby (1987) emphasize the importance of a total value assessment that considers basic human values (e.g., existence values) as well as monetary and assigned monetary values. Finally, Yarbrough (1987) and Stoffle et al. (1987) discuss the importance of distinguishing

public attitudes and opinions from underlying public values: the former tend to be unstable and change in response to a specific situation or concern, while the latter are generally highly stable and persistent. Simple preference questions may reveal superficial attitudes rather than underlying values (Talheim et al. 1987; see also the Social Assessment of Fisheries Resources Symposium published in the *Transactions of the American Fisheries Society*, 1987).

Building Consensus and Public Support

Two keys to the planning process are (1) communication and education and (2) public participation and debate. People involved in the planning process must be made fully aware of the management options and their consequences so they can contribute to the decisionmaking process. Public participation and debate can clarify issues and help people better understand and appreciate alternative points of view. Open debate often leads to compromise and resolution. The objective of the planning process is to resolve conflicts and differences of opinion on appropriate management objectives by building a consensus among competing interests. This process involves forming an information network to facilitate two-way communication and education, representing all sides in disputes, channeling debate in fruitful directions, and focusing expert advice on important problems. Also, always keep the big picture in mind: focus on the whole ecosystem and all lake uses and values to build an integrated management plan (Engel, 1989; Hance et al. 1990).

Public participation and debate can clarify issues and help people better understand and appreciate alternative points of view.

The best approach to the planning process (in particular, how best to involve the public in setting goals and priorities) depends on (1) the number and complexity of the various management options and goals; (2) the level of interactions and conflicts among users; and (3) the size of the affected user community and the number of persons who want to be actively involved. The following general guidelines apply to all situations, however:

- Carefully explain the planning process — what you are trying to achieve, the procedures you will follow, and the program constraints.
- In a clear, straightforward manner, outline the alternative goals, specific objectives, and approaches for managing the lake, including a discussion of the likelihood of success, uncertainties, and possible consequences of each alternative.
- Elicit input from all interested parties; recognize each individual's contribution and make everyone feel part of the process. People who are included in the decisionmaking process are more likely to support the final decisions and ultimate program plan.
- Maintain a constructive and cooperative atmosphere; remain objective and avoid confrontation.
- Hold one or more small group workshops (maximum 15 to 20 participants) with representatives from each interested user group, or break down larger meetings into smaller working groups to facilitate discussions and communication. Face-to-face discussions and interactions in a small group setting are needed to build consensus and define priorities for the user group as a whole.
- Form a central planning team consisting of lake experts trained in fisheries management and limnology (see Chapter 7) and a representative from each major lake user group, interested nonusers, and appropriate State, Federal, or local agency. Ad hoc committees or satellite teams can also be useful to deal with specific aspects of the management program or planning process (Engel, 1989).

Elicit input from all interested parties; recognize each individual's contribution and make everyone feel part of the process.

Although specifics will vary, in general, the planning process consists of six major steps or phases of activity:

1. **Public notification.** The public should be notified through announcements in local newspapers and/or a broad-scale mailing of the initiation of the planning process and how and when citizens can participate.

2. **Identification of potential alternatives and their consequences.** A fisheries biologist or limnologist with experience in lake and fisheries management should prepare a brief written summary of alternative management goals and specific objectives currently being considered, as well as their possible consequences, and distribute it to people who expressed an interest in further involvement during Step 1. This initial option summary should be used only to stimulate further discussion and debate, not to propose a preferred approach or goal.

3. **Compilation of public opinions, ideas, and responses.** Encourage all interested parties to express their opinions and ideas regarding the proposed lake management program. The objectives are to identify the full range and diversity of ideas and priorities and to actively include and provide a sense of involvement for as large a group as possible. As noted earlier, each contribution must be formally recognized. For example, for large groups, surveys or questionnaires may be mailed to each participant together with the option summary discussed in Step 2. A summary of responses to this questionnaire and the revised option summary document would then be distributed during Phase 4. For smaller groups and simpler problems, it may be possible to combine Steps 3, 4, and 5 into one or more group meetings. Suggestions for the meeting format and procedures are presented in Box 5-A.

Encourage all interested parties to express their opinions and ideas regarding the proposed lake management program.

4. **Group communication and exchange of ideas.** Having developed a reasonably complete listing of alternative goals, objectives, and priorities in Step 3, the planning team should initiate active face-to-face discussions and debates on the various options in a public meeting or forum — the larger the group, the more formal and structured this initial meeting. The meeting should be announced publicly, with separate notices mailed to those who participated in Steps 1 to 3. The purpose of the meeting is to fully air all points of view regarding the pros and cons of each alternative goal and objective without attempting to achieve consensus.

5. **Group prioritization and consensus building.** If conflicts exist among users or user priorities, the planning team should attempt to develop a group consensus or compromise. Again, this will require face-to-face meeting(s) and discussions. At this stage, however, smaller working groups or workshops with no more than 15 to 20 people are essential. Several workshops may be needed if the number of interested participants is large and/or the issues are complex or contentious. Pointers for leading such a workshop are presented in Box 5-A.

6. **Final priority goals and objectives.** Publish and distribute the final decisions on program goals and objectives. Follow through and make sure that these goals and objectives focus the direction of the program. Invite additional comment and continued input and, as appropriate, request assistance with implementation or other phases of the planning process (see Chapter 6).

Box 5-A.—Helpful Hints for Successful Meetings

Small meetings with no more than 15 to 20 participants per group are an effective way to move toward resolving conflicting opinions and developing consensus on priorities, goals, and objectives. These meetings should be moderated by a neutral "facilitator" who ensures that the discussions remain focused, everyone has an opportunity to contribute and be heard, and progress is made toward the specific meeting objective—developing a set of priority management goals and objectives for the lake. At the beginning of the meeting, the facilitator should outline the issues/questions to be discussed as well as the meeting format and schedule. The ground rules for group discussions and the meeting function and process must be clearly established. To the degree possible, isolate different issues/questions and deal with them one at a time in a logical order. As you proceed through each topic, a useful sequence of events is as follows:

1. Develop a full list of alternatives or opinions.
2. Merge, simplify, and organize participants' options and ideas.
3. Discuss and evaluate each item so that all participants fully understand the alternatives.
4. Prioritize the alternatives and options.
5. Summarize the group decision(s).

First, compile a full list of opinions; for example, a complete list of participants' ideas on the major goals for the lake management program. Each idea should be listed on a flip chart to be referred to and discussed later. Discussions on the merits of each suggestion should be avoided; the objective at this stage is simply to develop the list. Record all ideas suggested by the group. Overlapping or duplicate items can be identified and merged during the next stage. Allow sufficient time to extract all relevant ideas and proposals and try to get everyone to contribute; for example, go around the table one or more times and ask each participant for his or her suggestions and ideas.

After developing a full list, ask the group to identify similar or overlapping items and merge any duplicates. If appropriate, establish a hierarchy, listing some items as subheads under others. As part of this process, discuss and explain each item so that all participants fully understand it.

Having developed a manageable list of alternatives, ask the group to identify those with highest priority. It may be useful to open the discussion by simply going around the table and asking participants to vote on their top three priorities. This activity provides a good indication of areas of agreement and disagreement (as well as the overall level of agreement) and focuses subsequent discussion. The entire group may rank some goals or specific objectives high priority.

When participants express differences of opinion, ask individuals to fully explain their viewpoint. Explore the reasons why people think differently to determine whether some underlying common ground exists. Conceptual models are often useful because they illustrate interactions and linkages between system components or alternative approaches and goals. If strong areas of disagreement exist, it may be best to table further discussion and reinitiate discussions later in the workshop or even at another workshop, thereby giving participants and the facilitator a chance to reflect on the different opinions and options for resolution.

Emphasize areas of agreement and consensus. In particular, frequently summarize discussions, group decisions, and the meeting progress. At the end of each session, the facilitator should summarize the workshop conclusions and identify areas of consensus, decisions, and the remaining issues to be addressed at future meetings or through other activities. A written summary of the discussions and meeting outcome should be distributed to meeting participants no more than one to two weeks after the meeting.

Additional guidance on organizing and facilitating group meetings can be found in Delbecq et al. (1975), Doyle and Strauss (1982), Renton (1980), Nathan (1979), Beale and Fields (1987), and Carpenter (1988).

Alternative Goals in Fish and Fisheries Management

Fish and fisheries management goals can be grouped into three broad categories:

1. maintaining ecological integrity and protecting natural systems as part of the public trust;
2. improving and maintaining the quality of the fishing experience (fisheries management); and
3. improving and maintaining water quality by managing fish.

The list of goals presented for each category is not intended to be comprehensive but only to illustrate the types of management goals of potential interest. In addition, no goal is necessarily mutually exclusive. In one lake, multiple goals may be appropriate. Some fish species may be managed for one type of fishery (e.g., trophy fishing), while others could be managed for increased water clarity or high angling yields. In many cases, however, trade-offs may be necessary. For example, high levels of angling pressure on top predator species may result indirectly in a decrease in water clarity (see Chapters 2 and 9). Ecosystem interactions and potential user conflicts must be considered to select a realistic set of complementary goals and specific objectives.

Ecosystem interactions and potential user conflicts must be considered to select a realistic set of complementary goals and specific objectives.

In selecting the management goals for a given lake, one must take into account not only public preferences but also the lake's physical, chemical, and biological characteristics that affect the types of fish species, fisheries, and uses for which it is best suited (see Chapters 2 and 3). Lakes in warmer climates, for example, will never support self-sustaining coldwater fisheries. Likewise, some fish species (such as lake trout whose preferred habitat is the deeper, colder waters of the hypolimnion) will do poorly in shallow lakes that do not thermally stratify. Some lakes naturally have low levels of dissolved oxygen and periodically experience winterkill or summerkill. While oxygen levels may be artificially enhanced, it may make more sense to manage these lakes for fish species that can tolerate relatively low levels of dissolved oxygen.

Management goals must also be consistent with established water quality standards for a lake, including designated attainable uses and associated water quality criteria.

Selection of the appropriate target species for fish or fisheries management is an important element of defining program goals and specific objectives and developing the lake management plan. Management goals must also be consistent with established water quality standards for a lake, including designated attainable uses and associated water quality criteria.

Ecological Integrity and the Public Trust

The primary responsibility of most State fisheries agencies is resource protection — to preserve for future use all fish community options that we currently enjoy (Dochoda and Fetterolf, 1987). Fisheries resources are held in trust for society by government. Only within the constraints of this public trust can managers consider how best to use and allocate the available resources for optimum present-day social and economic benefit.

Similar goals are incorporated within water quality legislation. The Water Quality Act Amendments of 1972 explicitly set as a national goal "to restore and maintain the physical, chemical, and biological integrity of the Nation's waters." Biological criteria (also called "biocriteria") are now included within EPA's water quality standards program (U.S. Environ. Prot. Agency, 1988), and all States are required to adopt narrative biological criteria during fiscal years 1991 to 1993 (U.S. Environ. Prot. Agency, 1990). Biological criteria are indicators of biological or ecological integrity compared to some least-disturbed reference site (Karr, 1991). Karr and Dudley (1981) defined biological integrity as the ability to support and

maintain "a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of the natural habitat of the region."

The conservation of genetic diversity has also been identified as an important fish management goal. As discussed in Chapter 3, intraspecies variations in fish characteristics, such as resistance to environmental stress and potential growth rate, increase the likelihood of long-term fish population survival and reflect the adaptation of populations, over multiple generations, to be better suited to survive and reproduce in their local environment. Just as the extinction of an endangered species is an irreversible loss, the elimination through extinction or interbreeding of a genetically unique fish strain or fish stock cannot be reversed. Conserving genetic diversity, restoring and maintaining ecological integrity, and protecting and preserving fisheries and other aquatic resources are clearly important goals for a lake management program.

Fisheries Management

The overall goal of fisheries management is to improve and maintain the quality of the fishing experience and to sustain yields. However, the attributes of a quality fishing experience can incorporate many things, such as a peaceful and natural fishing environment, easy access, and socializing with family members as well as catching an adequate number and size of fish (Brown, 1987). Examples of specific fisheries management goals that may be appropriate in some waters include the following:

- **Maximize yield.** Provide the maximum level of harvestable fish that can be sustained over the long term and is optimal in terms of the effort and expense required to sustain the yield. Although populations may be supplemented by stocking, the majority of the catch is comprised of fish that grow to catchable size in the wild. Management efforts are directed toward providing fishing opportunities of a general nature, rather than managing for especially large "trophy" fish.

- **Maximize catch rates per unit of effort.** While similar to the concept of maximum yield, maximizing catch per unit effort also considers the distribution of this yield among anglers and per unit of time spent fishing. On lakes with very heavy fishing pressure, the total yield may be high even though the catch per unit effort may be somewhat lower.

- **Maximize the "bites per hour."** For fisheries that attract large numbers of small children, it may be desirable to maximize the level of activity. The total quantity, size, and types of fish caught would be of lesser importance.

- **Maximize the number and size of trophy fish.** Management efforts in this case are directed primarily toward providing anglers an opportunity to catch a larger than average fish. In some waters, catch-and-release fishing regulations may be required to expand the number of available trophy fish (see Chapter 8).

- **Provide fishing opportunities for a particular fish species or strain that is unique and/or highly desirable.** For example, in western States this may include cutthroat trout in their native range, golden trout, or grayling. Other examples include heritage strains of brook trout and other salmonids (i.e., strains of fish native to the region that have never been commingled with hatchery strains) or rare or exotic species that may be introduced experimentally or permanently.

Conserving genetic diversity, restoring and maintianing ecological integrity, and protecing and perserving fisheries and other aquatic resources are clearly important goals for a lake management program.

The overall goal of fisheries management is to improve and maintain the quality of the fishing experience. . . .

- **Provide fishing opportunities for "wild" fish.** Some anglers prefer to catch fish from populations that are totally supported by natural reproduction. The goal to catch "wild" fish is often accompanied by the desire to catch native fish strains (rather than hatchery strains that have subsequently established a naturally reproducing population) and to fish in a relatively pristine environment.

- **Maximize the diversity of fishing opportunities.** Given a highly diverse fishing community, it may be desirable to purposely diversify the types of fish and fishing experiences available within the lake (e.g., trophy fish of some species, maximum "bites per hour" for others). More often, however, a high degree of diversity can be better achieved by managing different waters within a region for different types of fisheries. Thus, in establishing the goals and specific objectives for any one lake, the types of fishing opportunities available in other nearby, accessible waters may be an important consideration.

Provide a relatively pristine, natural, undisturbed environment for fishing . . . .

- **Provide a relatively pristine, natural, undisturbed environment for fishing.** For many anglers, being out-of-doors in a natural, undisturbed environment, in relative solitude, is an important part of the quality of a fishing experience. In some regions, this may mean fishing in remote, high mountain lakes. In others, "relatively pristine" and "undisturbed" may be interpreted as free from interference from boaters and waterskiers, with few to no other anglers in sight. Also implicitly incorporated within this goal is the satisfaction gained from fishing on waters with natural, undisturbed ecosystems that support a diversity of fish species and other biota.

- **Maximize the ease and convenience of fishing.** Important goals for some fisheries may be to facilitate lake access, to have stores and other support facilities conveniently located, and/or to locate the lake near large concentrations of people who may then take advantage of the fishing opportunities with minimal difficulty and effort.

Provide edible fish, with little to no health risk from bioaccumulated toxic substances . . . .

- **Provide edible fish, with little to no health risk from bioaccumulated toxic substances.** For some anglers, obtaining fish to eat is a major reason for fishing. In areas contaminated by toxic chemicals through direct discharges, nonpoint sources in the watershed, or atmospheric transport and deposition, toxic substances may bioaccumulate in fish to levels unsuitable for human consumption.

Management goals for commercial fisheries are not explicitly addressed in this supplement.

Using Fish Management for Water Quality Management

Additional management goals may be appropriate if fish communities are to be manipulated and managed for purposes not directly related to the quality of the fishing experience. Examples of how fish management may be used in lake restoration and management include the following:

- **Control and reduce the extent of aquatic macrophytes.** Grass carp and a few other fish species that feed on aquatic macrophytes have been used in some lakes to reduce the extent and density of aquatic weed beds. Reductions in aquatic macrophytes may be needed to improve fishing, aesthetics, boating, or swimming.

- **Reduce water turbidity.** Some fish species, such as the common carp, can extensively disturb the lake bottom as they feed, increasing water turbidity (i.e., increasing the levels of suspended solids). High turbidity may make a lake aesthetically unpleasing and reduce its desirability for swimming. Thus, to control the lake's turbidity problems, one goal of fish management may be to reduce the abundance of carp or other nuisance fish species.

- **Increase water clarity.** The potential indirect effects of fish predation on the aquatic food chain were discussed in Chapter 2. The abundance of planktivorous fish may influence the abundance of zooplankton, which influences in turn the abundance of phytoplankton and water clarity. As a result, reductions in the numbers of planktivorous fish may indirectly increase water clarity. Reductions in planktivorous fish may be achieved directly through removal or increased fishing pressure on planktivorous species or indirectly by increasing the abundance of larger fish predators that feed on the smaller planktivorous fish (see Chapter 9).

Many factors affect the abundance of aquatic macrophytes, water turbidity, and water clarity and often may override any indirect effects on these lake parameters resulting from changes in the fish community. Fish management to control aquatic weeds, reduce turbidity, or increase water clarity will work only in some circumstances. In addition, fish management may not be the most cost-effective means of achieving these goals. Potential applications of fish management for water quality goals are discussed further in Chapter 9.

CHAPTER 6

Problem Identification and Diagnosis

Chapter Objectives

Having established a reasonable set of lake management goals and specific objectives (Chapter 5), the next step is to determine what factors currently limit or prevent the achievement of these goals and objectives. A lake problem can be defined as "a limitation on a desired use of a lake or the inability to attain a desired goal or objective"; for example, catch rates that are too low or fish that are uniformly too small. Many lake management problems can be identified simply by compiling complaints from anglers and other lake users. However, to be successful over the long term, lake management must focus on and remedy the underlying cause of a problem, not just treat the symptoms. Thus, problem diagnosis, which involves a thorough investigation of the cause or causes of an identified problem, must precede program design and initiation of lake restoration activities.

A lake problem can be defined as "a limitation on a desired use of a lake or the inability to attain a desired goal or objective."

This chapter discusses the process of problem identification and diagnosis (Fig. 6-1) and common problems in managing fish and fisheries in lakes and reservoirs. Potential solutions (lake management techniques) are presented in Chapters 8 and 9. This manual emphasizes problems associated with the quality and types of fishing opportunities as well as water quality problems that might be alleviated by manipulating the fish community. *The Lake and Reservoir Restoration Guidance Manual* (Olem and Flock, 1990) provides a more general discussion of the full range of problems that can be encountered in lake management.

Problem Statement

The best starting point for gathering information on lake problems is to ask lake users (e.g., see Box 6-A). If catch rates or size of desirable fish species have declined markedly over the years, a lake restoration project might alleviate or correct the problem. A problem exists if excessive numbers of anglers, boaters, and waterskiers interfere with the quality of the fishing experience. The types and quantity of fish caught may be poor relative to other similar lakes in the region suggesting that conditions in the lake are preventing the lake's fisheries from achieving their full potential. Lastly, there may not be a problem, per se, but local anglers may express the desire to improve fishing opportunities — for example, by introducing new species or enhancing natural reproduction.

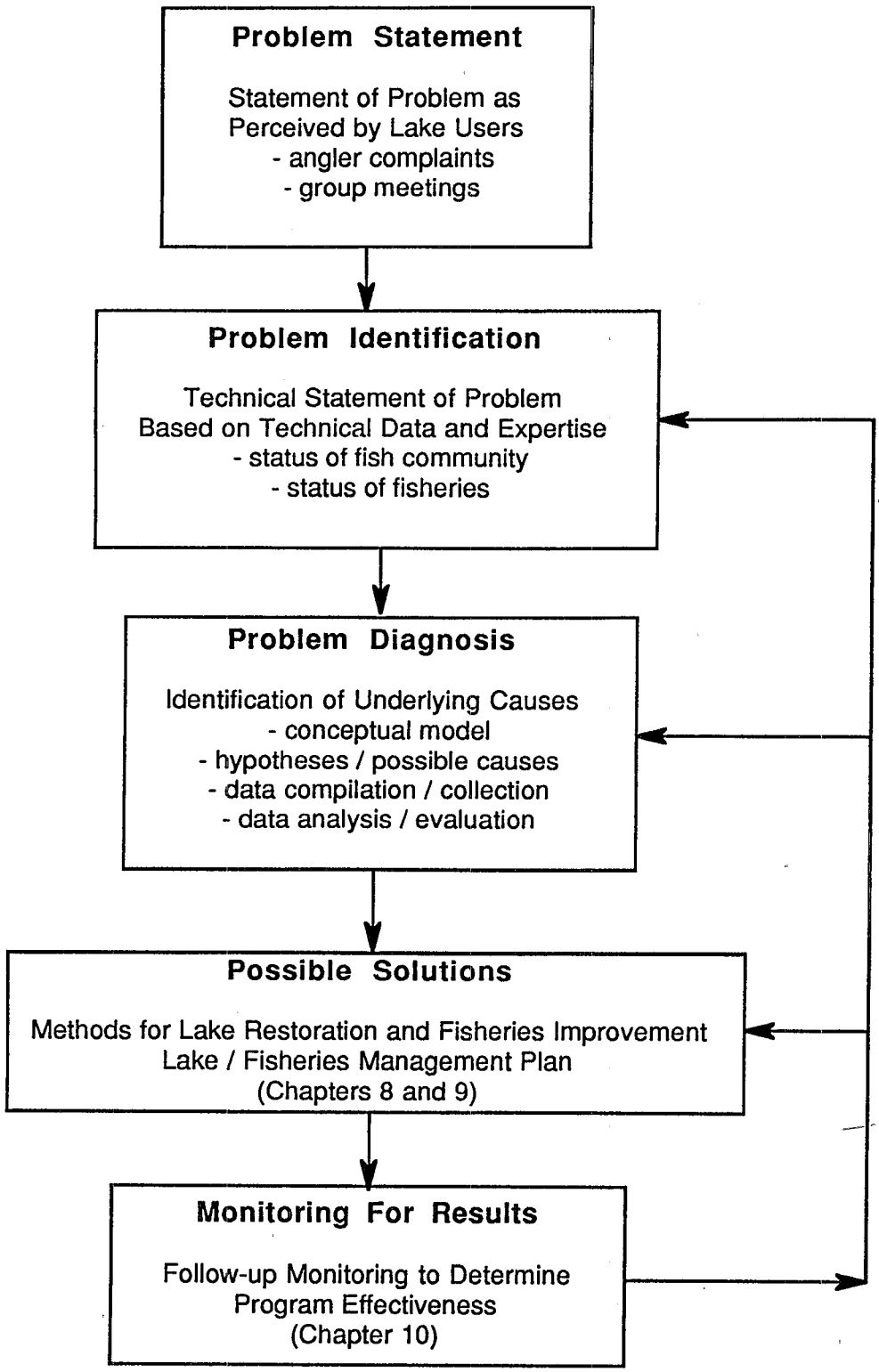

Figure 6-1.—Major steps in the process of problem identification and diagnosis as part of the development of a lake management program.

Box 6-A.—Community Involvement Program — Erie and Campbell Lakes, Washington, Restoration Program (source: Entranco Engineers, 1983 and 1987)

Erie and Campbell lakes are located on Fidalgo Island in Skagit County, Washington. Both suffered from dense blooms of blue-green algae; Erie Lake also experienced occasional fishkills.

In 1981, a Phase I Diagnostic Study was funded by the EPA Clean Lakes Program, State of Washington, and Skagit County to assess the nature and extent of water quality and fishing problems in the lakes. As part of this effort, a community involvement program was initiated to obtain input from lake users on perceived water quality problems, fishing problems, and affected beneficial uses, and to invite public participation in decisions on restoration alternatives. A Lake Study Review Committee comprised of local residents and interested agency officials met quarterly to review the status of the project and provide guidance to the technical project team. In addition, watershed property owners and people attending the first lake study citizens information meeting in January 1982 received a questionnaire designed to sample public attitudes about lake conditions, recreational uses, fishing, and lake problems.

Lake Erie respondents stated that exposed aquatic plants were the most serious problem, followed by gradual lake filling (lower water depth), submerged aquatic plants, algae blooms, swimmer's itch, erosion, and bad odors. Campbell Lake respondents noted that the most serious problems in order were algae blooms, submerged aquatic plants, lake filling, flooding, exposed aquatic plants, bad odors, and swimmer's itch. In response to the question of which lake uses were adversely affected by lake quality deterioration, Lake Erie respondents ranked fishing and swimming as most seriously impacted; Campbell Lake respondents noted that swimming was the most adversely affected use, followed by appreciation of the lake's beauty, fishing, and boating/canoeing.

Subsequent lake sampling and diagnostic analyses identified phosphorus as the nutrient controlling algal growth and sediment phosphorus release as the most significant controllable source of phosphorus to both lakes. Therefore, in 1985, Skagit County initiated a Phase II Implementation Program, including alum treatments to reduce internal phosphorus loading from the sediments (see Chapter 8) and mechanical harvesting of aquatic plants.

Compiling a list of problems, concerns, and desired improvements is generally relatively easy and may be best achieved by incorporating the task directly into the six-phase planning process described in Chapter 5. Questionnaires and group meetings may also be used to compile, discuss, and prioritize lake problems as perceived by the lake users. After establishing what the user community wants (i.e., the priority goals and specific objectives), you can then ascertain to what degree and in what ways current lake conditions fall short. These differences between a reasonable set of objectives and current conditions define the lake's problems, which can then be prioritized using the techniques described in Box 5-A (also see Appendix 3-A in *The Lake and Reservoir Restoration Guidance Manual*).

Actively involving the public will

- facilitate identification and prioritization of lake problems because lake users have direct, day-to-day experience with fishing quality and other lake uses and
- help to educate users about the lake ecosystem and their role in contributing to some lake problems (for example, those resulting from overfishing or lake eutrophication from nutrient-rich urban runoff).

Actively involving the public will help to educate users about the lake ecosystem and their role in contributing to some lake problems.

Greater understanding and awareness of problems will generally lead to increased cooperation in their solution and thus a greater likelihood of program success.

One type of lake problem cannot be readily detected by anglers and other lake users; specifically, bioaccumulation of toxic substances in fish that may pose a health hazard. Early detection of this problem requires routine monitoring of the contaminant levels in fish tissues, the water, and/or lake sediments. However, because of the expense of analyzing for the myriad of potential chemical contaminants, these monitoring programs are often initiated only if other sources of information suggest a cause for concern; for example, if a known contaminant source exists in the watershed or similar problems occur in other nearby lakes. A supplement on toxic substances in lakes and reservoirs is being prepared for EPA's Clean Lakes Program that will provide further information on when, where, and how to monitor for the bioaccumulation of contaminants.

Problem Identification

While lake users may be able to identify the symptoms of a problem or limitations on lake uses, technical data and expertise are needed to confirm and better define the problem.

While lake users may be able to identify the symptoms of a problem or limitations on lake uses, technical data and expertise are needed to confirm and better define the problem. Anglers may complain that they catch too few fish, too few large fish, or not enough fish of a particular preferred species; however, are these real problems that can be alleviated through lake restoration or management efforts? Are there really fewer fish than expected for a lake of that size and physical and chemical characteristics? Are there too few fish, or are anglers just having difficulty catching fish? Only after you clearly define the problem can you develop a detailed plan for problem diagnosis to determine why fish abundance is low or why anglers are having trouble catching fish.

A professional fisheries biologist and/or limnologist should assist with problem identification and diagnosis as well as the subsequent design of a lake management program. In some cases for publicly owned lakes, State fisheries agencies and State biologists may be able to provide substantial assistance and direction. For privately owned lakes, private consultants, local university staff, or other private organizations may be more appropriate. Chapter 7 discusses the types of assistance available and offers guidance on selecting a consultant.

Putting Problems in the Proper Perspective

Lake problems need to be clearly distinguished from natural constraints on the types and quality of fisheries and users that a lake can support.

Lake problems need to be clearly distinguished from natural constraints on the types and quality of fisheries and uses that a lake can support. A lake's natural physical, chemical, and biological characteristics play a major role in determining the types of fish species that will survive and reproduce, fish production and growth rates, potential fishery yields, and the nature of the fishing experience (see Chapters 2 and 3). While these natural features can be modified to some degree (e.g., through habitat management efforts), to attempt to drastically alter a lake's basic characteristics would be technically difficult, very expensive, often short-lived, and generally unwise. Therefore in this manual, lake problems are defined specifically as "the failure of a lake to achieve its full natural potential and potential uses." Most lake problems result from human-related causes.

Most lake problems result from human-related causes.

Regional patterns of lake conditions and fish communities provide an important source of information for distinguishing between natural and human-caused lake problems. If the symptom also occurs in other similar lakes in the region with undisturbed watersheds or with lower levels of fishing pressure, the perceived "problem" may actually be a natural constraint or phenomenon. For example, oligotrophic lakes naturally have relatively low levels of sustainable fisheries yield because of lower levels of nutrients and productivity. Thus, lakes in northern Minnesota, where the soils and bedrock are naturally low in nutrients, generally support lower fish biomass and yield than lakes in southern Minnesota, where soils are naturally more fertile. As a result, lakes are naturally more productive.

Periodic year-class failures of largemouth bass may result in some cases from year-to-year fluctuations in weather (such as cold spells or strong winds and wave action during the reproductive period) rather than from human-related causes that can be ameliorated through a lake or fisheries restoration program. Natural constraints are particularly important for fish populations in marginal habitat or at the edge of their natural range.

Natural constraints are particularly important for fish populations in marginal habitat or at the edge of their natural range.

Indicators of Fish Community Status and Fisheries Problems

Identifying fisheries management problems requires technical information on the status of the fish community and fisheries in the lake. Generally, a routine field survey of the fish community is warranted, using the methods described in Appendix B. Data collected in previous lake studies should also be compiled to supplement the field survey data and provide historical perspective.

Data collected in previous lake studies and surveys should also be compiled to supplement the field survey data and provide historical perspective.

What, however, should you look for in a fish community or fisheries survey? What metrics or symptoms indicate a problem? The development of simple, easy-to-measure, and reliable indicators of fish community "health" and fisheries condition is being actively researched (see Spigarelli, 1990). While a number of indicators are available, all have advantages and disadvantages. No single indicator can provide definitive evidence of a problem; rather, multiple indicators should be evaluated and considered in combination (see Box 6-B) and together used to judge the current status of a fish community, fish population, or fisheries.

No single indicator can provide definitive evidence of a problem; rather, multiple indicators should be evaluated and considered in combination . . . .

The types of fish community and population characteristics of interest were introduced in Chapter 3 and involve, for the most part, direct or indirect measures of important population and fisheries parameters; for example:

- **Fish abundance** — the density and/or biomass of fish present per unit area or volume, by species. Because taking absolute measures of fish abundance can be difficult and time-consuming, especially in large lakes (see Appendix B), measures of relative abundance (i.e., the numbers and biomass of fish caught per some standard unit of sampling effort) are often more practical and generally adequate.
- **Fishing pressure** — the total number of hours (or other suitable unit) of angling effort.
- **Catch per unit and harvest per unit efforts** — the number or biomass of fish caught and harvested, respectively, per unit of angling effort.
- **Fisheries yield** — the total numbers or biomass of fish removed from the lake through angling (per unit area or volume and period of time), estimated from the measures of fishing pressure and harvest per unit effort.

Most problems in fisheries management are associated with low or declining fish abundance, catch per unit effort, and fisheries yield.

Most problems in fisheries management are associated with low or declining fish abundance, catch per unit effort, and fisheries yield. However, changes in these parameters are often detectable only when the problem is fairly advanced and severe. Other parameters may provide an early warning of change or adverse effects before abundance or yield measurably decline. Examples of useful indicators of fish population status include the following:

- **Year-to-year variability in fish population abundance** — In some instances, an environmental stressor may initially decrease population stability and only later, with continued or increased stress, result in a long-term population decline.

[I]n some instances, an environmental stressor may initially decrease population stability and only later, with continued or increased stress, result in a long-term population decline.

Box 6-B.—Framework for detecting the effects of chemical contaminants on fish populations

(source: Munkittrick and Dixon, 1989)

Effects of stressors on fish populations can be direct (acting on growth, reproduction and/or survival) or indirect (operating through effects on predators or food resources). Colby (1984) identified five patterns of population response to heavy fishing pressure based on 10 different indicators of fish population status; Munkittrick and Dixon (1989) adapted this framework for examining fish population responses to chemical stressors (Tables 6-1 and 6-2). For example, increased adult mortality caused by acutely lethal toxicant concentrations or heavy fishing pressure would decrease population size and increase food availability for the fish remaining, presuming that the food base is not adversely affected by the toxicant. Such a change should result in an increased growth rate for survivors as well as a decreased age at maturation and increased fecundity and condition factor because of increased food resources (Pattern I, Table 6-2).

Removal of a significant number of adults would also result in a decreased mean age of the population and a shift in the size distribution toward younger fish. Similar patterns of response involving multiple interacting population characteristics can be identified for other ecosystem alterations such as reproductive failure or elimination of food resources. Munkittrick and Dixon (1989) provided several case histories demonstrating the applicability of these indicators and indicator patterns for assessing effects of mining wastes and atmospheric deposition on white sucker populations.

Table 6-1.—Five mechanisms of chemically induced alterations in ecosystem quality: consequences on fish populations and food resources (source: Munkittrick and Dixon, 1989).

RESPONSE PATTERN	TARGET SOURCE	CONTAMINANT EVENT	OTHER COMPARABLE STRESSORS	EFFECT ON POPULATION	EFFECT ON RESOURCE BASE	INITIAL POP. RESPONSES
I	Direct on adults	Acutely lethal spill away from nursery areas or a response to chronic mortality	Fisheries exploitation	Reduced abundance of adults	Increased food availability	Increased survivor growth rate
II	Direct on eggs or larvae	Spawning failure or increased larval mortality (reproductive problems, contamination of spawning areas or yolk-associated burdens)	Loss or disturbance of spawning grounds	Reduced abundance of young fish	Decreased use of food and habitat resources	Gradual shift in age distribution toward older fish
III	Direct on juveniles	Metabolic impacts or restricted food supply decrease energy flow through juveniles	Size-selective mortality of small fish induced by habitat change or loss of food supply	Reduced abundance of young fish	Decreased replacement of adult fish	Gradual shift in age distribution; decrease in fish condition
IV	Indirect, above indicator organism	Predator removal by chemical events or chronic food availability problems	Overstocking of fish or overexploitation of predators controlling population	Increased population size or increased competition for food	Decreased food availablity	Decreased growth rate
V	Indirect, below indicator organism	Habitat restriction; reduction or loss of food supply	Habitat destruction or introduction of exotic species	Increased food competition	Food web restructuring	Decrease in feeding efficiency

Box 6-B.—Continued

Table 6-2.—Five alternative patterns of fish population response to environmental stressors, depending on the mechanism of effect (see Table 6-1). An increase in the population characteristic in the stressed population compared to a reference population in a similar environment but not exposed to the environmental stressor is denoted by a plus sign (+); a decrease by a minus sign (–); and the absence of change by a zero (0) (source: Colby, 1984; Munkittrick and Dixon, 1989).

PATTERN	MEAN AGE	AGE DISTRIB.	GROWTH RATE	CONDITION FACTOR[a]	AGE AT MATURATION	RLS[b]	FECUNDITY	EGG SIZE	CPUE[c]	POP. SIZE
I	–	–	+	+	–	–, 0[d]	+	–,+	–	–
II	+	+	0,+[d]	0	0	+	0	0	–	–
II	+	+	–	–	+	0	–	–,0	–	–
IV	0	0	–	–	+	–	–	–	+	+
V	0	0	–	0	+	–	–	–	–,0	–,0

[a] Condition factor (K) = 100(wt/length^3)
[b] Reproductive life span (RLS) = mean age – (age at maturation)
[c] Catch per unit effort
[d] Change can vary with degree of stress

- **Population age structure** — the numbers of fish in each age group. Unusually low numbers of older, larger fish may be indicative of high fishing mortality or other causes of high death rates among older fish. Unusually low numbers of young fish or missing year-classes are indicative of problems affecting fish reproductive success. Information on population age structure can also be used to estimate other potentially useful indicators of fish population status, including
  - annual total mortality rates,
  - mean age of catch, and
  - variability in year-class strength.

- **Population size structure** — the numbers of fish in each length or weight interval. Length-frequency distributions can be summarized as proportional stock density (PSD) or relative stock density (RSD) indices, as discussed in Chapter 3.

- **Growth rates, condition factors, and relative weight** — the average length and weight of fish in each age group and the relationship between fish length and weight. Low growth rates, condition factors, and relative weights may be indicative of overcrowded fish populations, limited food supplies or prey availability, or stresses caused by toxic substances and other water quality problems that may adversely affect fish growth.

- **Reproductive potential** — based on measures of the age at sexual maturity and fecundity (numbers of eggs per unit weight of female fish). In some instances, fish populations may respond to stressful conditions by increasing reproductive potential; the age at which fish become sexually mature may decline and fecundity increase. Alternatively, adverse conditions may cause a decline in reproductive potential, primarily by decreasing fish fecundity and delaying sexual maturation.

- **Periodic fishkills or periods of high mortality** — for example, during summer or over winter. Fishkills are graphic evidence of a serious problem in the lake ecosystem. Causes include poor water quality, such as low levels of dissolved oxygen, high temperatures, or high concentrations of toxic substances, and infectious agents, including parasites and viral, bacterial, and fungal agents.

Fishkills are graphic evidence of a serious problem in the lake ecosystem.

- **Physiological or biochemical indicators of stress,** such as changes in body salt content or the levels of various hormones and enzymes, and associated histological changes (microscopic changes in body tissues) — A wide array of physiological, biochemical, and histological indicators, termed "biomarkers," have been proposed. Some are general indicators of stress, while others are specific to particular types of stress or conditions (e.g., lead exposure reduces the activity of the enzyme delta-ALAD). DiGiulio (1989), Adams (1990), and Niimi (1990) review the use and types of available biomarkers.

- **Incidence of tumors or physical deformities** — Some toxic contaminants or poor water quality conditions may cause tumors or body deformities in fish. Standard procedures have been developed to assess fish health based on external and internal examinations as well as physiological, biochemical, and histological indicators (Goede, 1988; Goede and Barton, 1990).

Additional indicators of fish community health or status include:

Adverse conditions may result in the loss of sensitive species of fish in marginal habitats and, thus, an overall decline in species richness.

- **Fish species richness** — the number of fish species in the lake. Adverse conditions may result in the loss of sensitive species or fish in marginal habitats and, thus, an overall decline in species richness.

- **Species diversity** — summary index that reflects both the number of species in the lake and the relative numbers of fish of each species. Lakes with numerous species and a more equitable distribution of fish among species have higher species diversity. As for species richness, stressful conditions often result in lower species diversity.

- **Community composition,** especially the status of selected sentinel species — species that are particularly sensitive to environmental stressors or critical to the maintenance of a healthy fish community. For example, Ryder and Edwards (1985) proposed using lake trout and the invertebrate amphipod, *Pontoporeia hoyi,* as sentinel species for large lakes in the Great Lakes basin, providing the basis for the Lake Trout Ecosystem Health Index (Box 6-C). Rapport (1990) defined two categories of species expected to change markedly in abundance in response to environmental stress. Type 1 species are those with narrow tolerance ranges that are among the first to disappear when conditions deviate from those found in their natural environment. Exemplary Type 1 species in oligotrophic lakes include lake trout, deepwater sculpin, and *P. hoyi;* for mesotrophic lakes, walleye and the burrowing mayfly, *Hexagenia limbata;* and for eutrophic systems, smallmouth bass has been suggested.

  As cultural stress increases, Type 2 species tend to replace Type 1. Type 2 species are usually present in low numbers in unstressed environments, but because of their wide tolerance ranges, they rapidly reproduce and expand in stressed environments. The result is a marked shift in community composition: a decrease in the abundance of sensitive, Type 1 species and an increase in tolerant, Type 2 species. Type 2 species are often exotics that are not native to the lake or drainage basin.

- **Index of Biotic Integrity (IBI)** — a summary index that combines information on the types of fish species present, their relative abundance, and in some cases, the types and abundance of benthic macroinvertebrates. The IBI was originally developed by Karr (1981) for midwestern streams but has since been adapted for streams in other regions (e.g., Karr et al. 1986; Leonard and Orth, 1986; Miller et al. 1988; Steedman, 1988). To date, applications in lakes are limited, and specific indices for lakes in most regions are still being developed. Over the next several years, however, the IBI or other similarly constructed indices are likely to play an increasing role in evaluating and regulating the health of aquatic communities (Karr, 1991).

Over the next several years, the IBI or other similarly constructed indices are likely to play an increasing role in evaluating and regulating the health of aquatic communities.

Box 6-C.—Lake Trout Ecosystem Health Index

(source: Marshall, 1992; Edwards et al. 1990)

The Lake Trout Ecosystem Health Index is an update of the Dichotomous Key developed by Marshall et al. (1987) to assess the health of oligotrophic aquatic ecosystems in Ontario lakes. The index takes the form of a user-friendly computer program that functions by posing a series of questions regarding the status of lake trout, the lake trout environment (e.g., spawning redds and food), and potential stressors that may adversely affect lake trout within the lake of interest (Table 6-3). Lake trout are used as a sentinel species, serving as a surrogate for the well-being of the lake ecosystem as a whole (Ryder and Edwards, 1985).

Table 6-3.—Examples of questions included within the Dichotomous Key, which has 47 questions in all (Edwards et al. 1990).

- Is the annual salmonid harvest less than the long-term mean?
- Is the cost/benefit ratio for the fisheries decreasing?
- Is the total annual lake trout mortality < 50 percent?
- Do lake trout older than 10 years (males) or 11 years (females) represent > 20 percent of the total standing stocks?
- Do *Mysis relicta* and *Pontoporeia hoyi* constitute > 80 percent of the diet offshore for lake trout < 200 mm in length?
- Do fish comprise > 50 percent of the diet for lake trout 50 to 60 cm in length?
- Is the mean condition factor > 0.90 for lake trout > 50 cm?
- Are oxygen levels in the hypolimnion during late summer at 100 percent saturation?
- During spring, is the interstitial pH on lake trout spawning beds > 5.0 and aluminum < 25 μg/L?
- Is the ratio of lakewide total spring phosphorus (μg/L) to mean depth (m) < 1?
- Is the spawning substrate affected by ice scouring?
- Is the concentration of PCB in lake trout < 0.1 μg/g?
- Are sperm counts > 10 billion/mL or higher?

The questions are designed to detect deleterious changes in the environment from those conditions necessary to maintain healthy lake trout stocks. Each question is answered with a simple "yes," "no," or "I don't know," and a degree of uncertainty is assigned to each answer. The answers are then processed by the computer, including an established ranking scheme that rates the relative importance of each question, and an index of ecosystem health is computed. A series of printouts provide detailed summaries of the stresses detected. In addition, a rationale for each question can also be called up within the computer program, including supportive information and a list of citations.

Thus, the computer program and index serve several important purposes. The index provides a quantitative assessment of the relative health of lake trout stocks and the ecosystem in which they reside and promotes both temporal and interlake comparisons of values. The program also compels the lake manager to consider a wide array of possible stressors that may be affecting the ecosystem and helps identify information inadequacies and data needs. Finally, the computer program is an educational tool, explaining the current scientific principles and concepts associated with each question.

Copies of the Ecosystem Health Index are available from Terry Marshall, Fisheries Research Section, Ontario Ministry of Natural Resources, Box 2089, Thunder Bay, Ontario P7B 5E7.

To adequately assess all of the above indicators would require an extensive survey and data collection effort. Therefore generally (at least in the initial stages of problem identification), a subset of parameters are selected that are likely to provide the most useful information for a reasonable level of sampling and analysis.

The best suite of indicators depends on the management objectives and environmental problems of greatest concern. The indicators listed reflect responses at various levels of organization, from individual fish (e.g., biomarkers — biochemical, physiological, or histological indicators), to population-level (e.g., fish population abundance, growth rates, reproductive potential), community-level (e.g., species richness), and ecosystem-level (e.g., the IBI) responses. Evans et al. (1990) suggest that monitoring and assessment efforts should focus on the level of organization at which the stressors of greatest concern act most directly (Fig. 6-2).

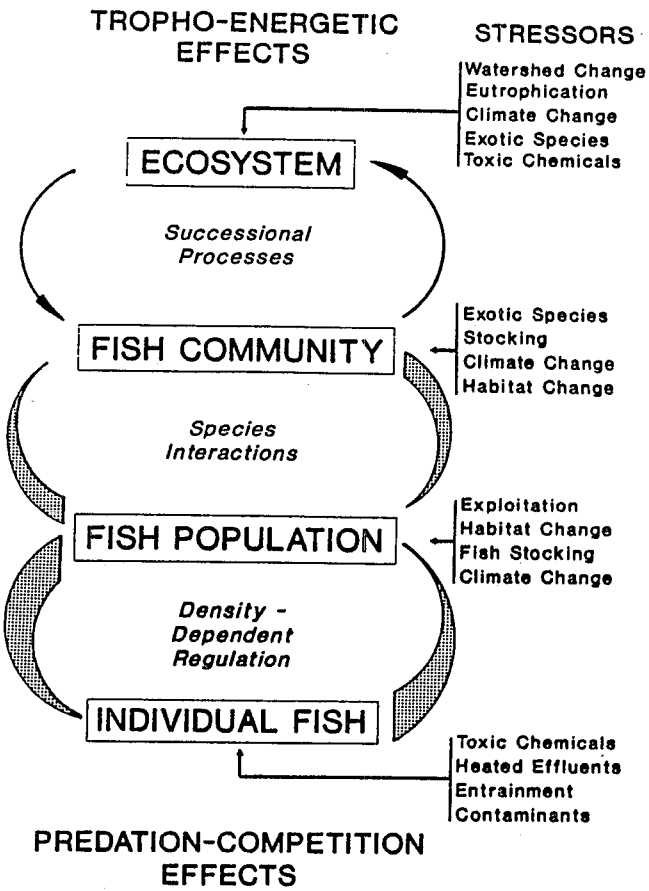

Figure 6-2.—Hierachical structure of levels of organization within aquatic ecosystems. Examples of external anthropogenic influences are shown that operate at each level of organization; homeostatic processes are shown that act at the interfaces between levels (source: Evans et al. 1990).

Indicators of individual fish response tend to be, on the whole, less expensive to measure, but their significance relative to effects at the population- or community-level is often unclear. Indicators at the population-, community-, or ecosystem-level generally relate more directly to lake management objectives, but data collection requires more time and effort. Many are also difficult to measure precisely or are naturally quite variable, and as a result, changes may not be detected until significant damage has already occurred.

What levels of each indicator signify a problem or reason for concern? There are no magic values, only a general principle: observed deviations from expected norms deserve further investigation. Reference values or ranges can be defined from historical (pre-disturbance) data for the lake or by comparison to relatively undisturbed lakes with similar natural features in the same ecoregion. The major difficulty in interpreting indicators of fish community and fisheries status is distinguishing between natural variability and deviations from the norm caused by problems or adverse effects of concern. Models and data analysis approaches that can aid data interpretation are discussed in Chapter 11.

What levels of each indicator signify a problem or reason for concern? There are no magic values, only a general principle: observed deviations from expected norms deserve further investigation.

Problem Diagnosis

Problem diagnosis involves the identification of the underlying cause or causes of the observed problem or use limitation. In addition to information on fish community and fisheries status, data are required on the potential sources of stress or adverse effects, including the physical and chemical characteristics of the fish habitat and biotic interactions (e.g., the abundance of important predators and prey).

Most problems are not unique to a particular lake but commonly occur in a number of lakes in the region. As a result, the general causes and approaches for solving them are often known. In addition, depending on the nature of the problem, some causes are likely to be more important than others. Thus, in most cases, a substantial amount of existing knowledge and expertise are available to aid in focusing diagnostic analyses and data collection.

Problem diagnosis is an iterative process (Fig. 6-3). Generally, the more complex and unusual the problem, the greater the number of iterations needed to determine the major cause or contributing factors with a reasonable degree of confidence.

Before initiating data collection or analysis, three tasks should be completed that formalize expert understanding of the problem and serve to focus subsequent efforts. First, develop a complete list of the possible causes of the observed problem and the expected symptoms or diagnostic clues of each cause. Second, develop a conceptual model illustrating the important interactions among system components that may influence data interpretation (e.g., Fig. 2-14). Because the physical, chemical, and biological components of lake ecosystems are intricately linked, stressors may have both direct and indirect effects. Recognizing these system interactions will greatly assist in identifying and evaluating potential causal linkages. After developing the conceptual model, the list of possible causes should be reassessed and updated as appropriate. Finally, based on the list of possible causes and the conceptual model, define specific testable hypotheses regarding likely causes and linkages. Data collection and analysis activities should then be designed to address and test each of these alternative hypotheses.

Because the physical, chemical, and biological components of lake ecosystems are intricately linked, stressors may have both direct and indirect effects. Recognizing these system interactions will greatly assist in identifying and evaluating potential causal linkages.

Having provided a framework for problem diagnosis, the next stage is to compile and analyze existing data on the lake, watershed, fish community, and fisheries relevant to the problem(s) of concern. Substantial data may be available in the files of the State fisheries agency or from previous lake studies. In some instances, the existing information may be sufficient to diagnose the problem and evaluate alternative hypotheses and potential remediation actions; however, in most cases, additional data will be required. The results from analyses of existing data should be used to update, as needed, the conceptual model and hypotheses, identify important remaining uncertainties and data gaps, and aid in designing a cost-effective and efficient data collection program. Subsequent data collection and analysis activities also may be iterative, providing more definitive, quantitative resolution on the sources and causes of the problem at each step (see Fig. 6-3).

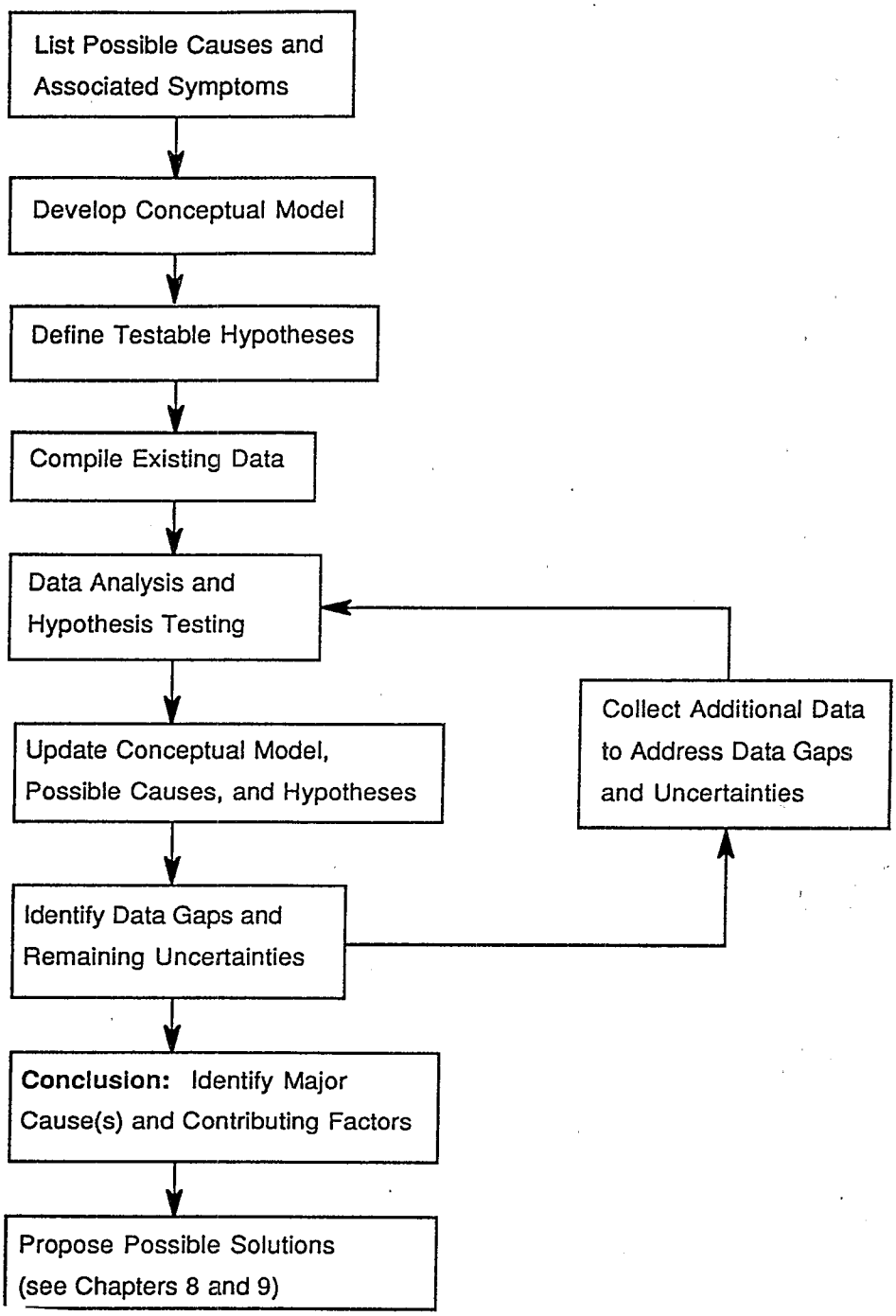

Figure 6-3.—Major steps in the iterative process of problem diagnosis.

The types and extent of data required will vary depending on the type and severity of the problem. Unfortunately, most of the problem symptoms and indicators of fish community and fisheries status are nonspecific; that is, similar changes occur in response to a broad range of different causes (Table 6-4). In some cases, substantial investigative work may be needed. For example, six years of intensive study were required to determine that selenium leaching from the fly ash disposal pond for the Roxboro Steam Electric Plant was the primary cause of largemouth bass population declines and poor reproductive success observed in Hyco Reservoir, North Carolina (Woock, 1984; Woock and Summers, 1984). In

Table 6-4.—Common problems in fisheries management and associated indicators of fish population and fisheries status.

COMMON PROBLEMS	LOW YIELD	LOW ABUNDANCE	TOO FEW OLDER FISH	TOO FEW YOUNG FISH	FISHKILLS	SLOW GROWTH	REDUCED FECUNDITY	BIO-MARKERS	TUMORS
Habitat degradation	X	X		XX*		X			
Inadequate spawning habitat	X	X		XX					
Water level fluctuations	X	X		XX		X			
Low oxygen	X	X			XX				
High temperatures	X	X			XX				
Excessive turbidity	X	X		X		X			
Entrainment/ impingement	X	X	X	X					
Acidity	X	X		X	X	X	X	X	
Toxic substances	X	X		X	X	X	X	X	X
Excessive macrophytes	XX					XX			
Low lake fertility	XX	X				XX			
Low prey availability	X	X				XX			
Undesirable fish species	X	X				X			
Overfishing		X	XX						
Underutilization	XX								

* XX indicate more commonly occurring and reliable indicators of the problem

other instances, expert judgment that relies on analyses of other similar problems in the region may be sufficient. Several case study examples of the process of problem identification and diagnosis and the design of fisheries restoration programs are provided in Chapter 12. In addition, Meyer and Barclay (1990) provide a comprehensive how-to manual on investigating and determining the causes of fishkills.

Common Causes of Fisheries Management Problems

Common causes of problems encountered in fisheries management include the following:

[P]oorly designed shoreline and watercourse development can destroy wetlands and other nearshore habitats that may serve as important spawning and nursery areas for fish.

- **Loss and degradation of fish habitat.** A wide variety of activities in the watershed and lake proper can result in the general degradation or loss of important fish habitat. For example, poorly designed shoreline and watercourse development can destroy wetlands and other nearshore habitats that may serve as important spawning and nursery areas for fish. Dam building and stream channeling may eliminate important spawning areas in tributary streams or lake outlets. Improper logging and construction practices can increase erosion and sediment transport into receiving streams and lakes, increasing lake turbidity, altering the bottom substrate, and potentially smothering fish eggs and fry. Habitat degradation is an all-encompassing term that includes any adverse change to the chemical, physical, and biological environment in which a fish lives. Therefore, many of the other fisheries problems noted in these paragraphs are actually subsets or special cases of problems associated with habitat degradation.

Cultural eutrophication . . . is one of the most obvious and pervasive problems that affects lakes.

- **Cultural eutrophication.** Cultural eutrophication, caused by marked increases in nutrient, organic, and/or sediment loadings as a result of human activities, is one of the most obvious and pervasive problems that affects lakes (Cooke et al. 1986). Oxygen deficits and high water temperatures that commonly accompany eutrophication can adversely impact fish both directly and indirectly. Anglers generally consider the types of fish that do best in highly eutrophic waters (e.g., carp, bullhead) less desirable compared to the natural, pre-eutrophication species. Algal blooms, noxious odors, turbidity, and excessive growths of rooted aquatic plants, which also typically increase with eutrophication, decrease the quality of the fishing environment.

- **Inadequate or poor spawning habitat.** Limitations on the quality and/or quantity of suitable spawning habitat are often important factors limiting the productivity of particular fish species within a given water. Spawning habitat is more likely to be an important limiting factor for species with fairly specific habitat requirements, such as many salmonids (see Appendix A).

- **Water level fluctuations.** Large fluctuations in water level may increase fish mortality by exposing eggs and fry in nearshore habitats and also concentrating fish into smaller volumes of water, often with limited cover, making them more susceptible to predation.

- **Low levels of dissolved oxygen.** Problems with oxygen depletion occur principally in the hypolimnion during summer stratification and over winter under ice and snow cover. Low levels of oxygen also occur

periodically in macrophyte beds during summer, at night, or after long periods of cloud cover. Some lakes naturally experience anoxic conditions or levels of dissolved oxygen too low to support fish in some habitats. Problems with low dissolved oxygen can be aggravated, however, by nutrient enrichment and eutrophication. Winterkill caused by oxygen depletion is relatively common in small, shallow productive lakes in northern climates (e.g., Box 3-F). Summerkill generally results from the combined effects of low oxygen and high temperatures (e.g., Box 3-E).

- **High water temperatures.** Each fish species has a preferred temperature range. Temperatures that exceed the fish's upper thermal tolerance can cause significant fish mortality. On occasion, fishkills may also result from sudden drops in temperature when temperature changes occur too rapidly to allow thermal acclimation. Fish species living in waters at the extremes of their geographic range and near their upper or lower thermal tolerance limits are more likely to experience problems associated with water temperature. Large thermal discharges into waterbodies from electrical generating facilities with once-through water cooling can create environments where sudden shifts in temperature are more likely to occur. Finally, decreases in water transparency resulting from eutrophication or increased turbidity may increase water heating and water temperatures in the upper surface layers of the lake.

- **Excessive turbidity.** High levels of turbidity can result from watershed disturbances or occur naturally in lakes and reservoirs having large watersheds with highly erodible soils. As noted, high levels of turbidity limit light penetration, thereby reducing primary productivity and increasing temperatures in the upper surface waters. High turbidity may also alter the bottom substrate and can smother eggs and fry on the lake bottom. In addition, excessive turbidity may decrease feeding efficiency of predators that rely on visual cues to capture prey.

- **Entrainment and impingement.** Hydroelectric generating facilities, electric generating units with once-through cooling, pumpback projects, city water treatment plants, and other similar operations may withdraw large quantities of water from lakes and reservoirs. Small fish, especially eggs and larvae with little or no swimming ability, can be entrained in these water withdrawals and carried directly into the facility where most or all these organisms die before being discharged. Larger fish that are caught in the strong currents created by these water withdrawals and impinged on to water intake screens also can experience high mortality rates. These problems are of concern principally in lakes and reservoirs where a relatively high percentage of the total water volume is withdrawn and discharged daily; for example, in reservoirs constructed to serve as water storage or cooling reservoirs for large electrical generating facilities or where water intakes are located in important fish nursery or spawning habitats.

- **Acidity.** High levels of acidity (low pH) are toxic to fish. Different fish species have varying pH tolerance ranges, although most prefer pH levels ranging from 6 to 8. High levels of acidity may result from acid mine drainage and, for waters with relatively low buffering capacity, from acidic deposition.

- **Toxic substances.** Toxic materials, such as pesticides and heavy metals, may be introduced into waterbodies through point source discharges of industrial or municipal wastes, nonpoint sources in runoff and groundwater from agricultural and other activities in the watershed, or atmospheric transport and deposition. Elevated concentrations of toxic substances may increase fish mortality rates, especially for early life stages, decrease fish growth and fecundity, and cause a number of other sublethal stresses and responses (e.g., physiological and biochemical changes), resulting eventually in decreased fish abundance and lower fisheries yield.

- **Bioaccumulation of toxic substances in fish tissues.** In some waters, toxic substances may have little direct adverse effect on fish or the fish community. However, bioaccumulations of toxic substances within fish tissues may make the fish unsuitable for human consumption.

- **Excessive aquatic weeds (macrophytes).** Beds of aquatic macrophytes provide important cover and nursery areas for young fish and spawning habitat for some fish species. As a result, the occurrence of macrophytes is generally advantageous for fish survival and production. However, excessive growths of aquatic macrophytes that provide extensive cover for small fish may severely reduce predation, and thus mortality, resulting in overcrowding, reduced growth rates, and stunted populations. In addition, periodic depletion of oxygen in weed beds at night during summer or in the late summer and fall as quantities of aquatic weeds die and decompose may kill fish or cause them to leave the area.

- **Low lake fertility and fish production.** As discussed earlier, excessive nutrient inputs and eutrophication can cause a variety of adverse effects on lake ecosystems. However, some lakes are naturally very low in nutrients and unproductive. If fishing is the primary use in these lakes, moderate increases in nutrient loads and fertility may be advantageous, resulting in a significant increase in sustainable fisheries yield. From the perspective of a lake's fisheries, therefore, conditions of low fertility and production may be a problem for some lakes and reservoirs.

- **Low prey availability.** Inadequate food supplies can limit fish growth rates. In unproductive lakes, the total quantity and productivity of prey available are low. However, even in fairly productive systems, fish growth rates may be less than desired or possible because of the absence or limited supply of certain preferred prey. For example, many game species are piscivorous: they feed primarily on smaller fish. When small fish species such as minnows or other suitable forage fish are lacking or in short supply, predator growth rates may be slow.

- **Excessive predation.** Heavy losses of desirable fish species to predators, such as larger fish and piscivorous waterfowl and mammals, may measurably limit the quantity of harvestable fish. However, both too little and too much predation can cause population imbalances. Maintaining an appropriate balance between predators and prey is an important component of managing the fish community and fisheries quality.

- **Introduction of undesirable fish species and nonnative fish strains.** Exotic and nonnative fish species or strains introduced into surface waters purposely or accidentally may compete with or prey upon the native species, modify the environment (e.g., carp can increase water turbidity), introduce parasites or diseases, interbreed with native fish, and cause deterioration of gene pools (see Chapter 3 as well as Billington and Hebert, 1991). The result may be a loss of native species and wild strains of fish and an overall decline in genetic diversity.

- **Overfishing.** Excessive fishing pressure may cause high levels of fish mortality and subsequently a decline in fish abundance and fishery yield. Fishing increases fish mortality both directly and indirectly. Even in a catch-and-release fishery, some fraction of the fish caught eventually die from the added stress and injuries associated with hooking and playing the fish on the line.

- **Underutilization.** Harvest levels substantially below long-term optimum sustainable yields may also be viewed as a problem if the specific objective is to maximize the value and use of the fishery.

- **Accessibility.** Fishery harvests in some hard-to-access lakes may be limited not by biological productivity but by low levels of fishing pressure. Improved access by improving roads, trails, or boat launching facilities or obtaining a right-of-way over private land may increase the number of anglers and, therefore, the total fishery yield.

- **Conflicts among users and stakeholders.** People rely on fish resources to satisfy different needs. They may fish for food or recreation, they may derive their employment and income from fish, or they may consider fish an important indicator of the overall health of the ecosystem. Conflicts may arise among users or stakeholders who do not have a common set of values and consequently do not agree on how best to allocate and share the fish resource.

- **User expectations not met.** Finally, while the lake may be providing an adequate and productive fishery, it may not be fulfilling specific expectations of some or all of the lake users; for example, in terms of the size and number of trophy fish or species available. These perceived fishery inadequacies may result from one or more lake problems or may simply require redirection of the fisheries management program and/or education of the lake users.

Water Quality Problems that Can Be Alleviated by Fish Management

Chapter 5 discusses three water quality management goals that can be achieved through a number of viable approaches, including biomanipulation. These same three topics define water quality problems that may be alleviated through fish management: (1) excessive growths of aquatic macrophytes; (2) high levels of water turbidity caused by fish disturbing the lake bottom as they feed or spawn; and (3) poor water clarity that results from high concentrations of phytoplankton and periodic algal blooms. The mechanisms by which changes in fish communities affect these lake characteristics are discussed in Chapter 2; specific management techniques as well as case studies of biomanipulation are presented in Chapter 9.

CHAPTER 7

Who Can Help?

Chapter Objectives

Throughout this manual, we emphasize the need for advice and assistance from professional fisheries biologists and limnologists in assessing the cause(s) of lake problems and identifying the most effective solution. Because of the highly interactive nature of lake ecosystems, management actions can often have unexpected, indirect, and potentially negative side effects. Designing and implementing a cost-effective and environmentally sound lake management program requires substantial expertise and experience. The objectives of Chapter 7 are to provide guidance on how best to obtain this expert assistance as well as information on specific organizations and government agencies that may be able to help.

State and Provincial Agencies

State and provincial agencies responsible for fisheries and water quality management are the best places to go for advice. Appendix C includes addresses and telephone numbers for the central office of relevant agencies in the States and Canadian provinces. Usually, each agency has several regional offices and separate program offices that deal with various aspects of lake and fisheries management. The best approach is to contact the central office and ask for recommendations on the most appropriate individual, office, or program for your specific needs. Requests for information and assistance should be made by a single representative of the lake association or organized group of concerned citizens. Before contacting the agency, you should have a clear idea of your group's needs and goals.

State and provincial agencies responsible for fisheries and water quality management are the best places to go for advice.

State and provincial agencies must be involved in all lake management programs. Management objectives and activities must be consistent with State water quality criteria and designated uses. Furthermore, fish are a public resource. Landowners can control access to a lake, but control and management of the fish community are the responsibility of State and provincial fisheries agencies. Many management actions (e.g., stocking and fish collection) require permits, and some of the methods described in Chapter 8 such as rotenone treatments and stocking of exotics are prohibited in some States and provinces or in specific waters or drainage basins. Because water quality and fisheries regulations vary widely among States and provinces, you should obtain an up-to-date listing of all relevant regulations and permit requirements.

Management objectives and activities must be consistent with State water quality criteria and designated uses.

For lakes that are publicly owned or have public access, State and provincial agencies also can often provide useful background information, including results from physical, chemical, and biological surveys, fish stocking records, or records

of other lake management activities conducted in the past. At a minimum, State and provincial biologists should be able to provide general advice on target fish species and the types of management efforts that have been successful in similar lakes in the area. Many agencies distribute pamphlets or handouts on common problems in local waters and recommended approaches for lake and fisheries management.

State and provincial biologists oversee activities in many waters and have many responsibilities; therefore, they usually can devote only limited time to individual lake management projects. The project's size and nature determine whether a State or provincial biologist can become actively involved in either the planning process or project implementation. Nevertheless, the appropriate State or provincial agency must be informed of the proposed program early in the process. If State or provincial biologists are unable to assist, they may have lists of or information on qualified consultants or other professionals.

Some States and provinces fund lake and fisheries restoration projects through community assistance programs and should be asked about the availability of and eligibility requirements for such assistance.

Some States and provinces fund lake and fisheries restoration projects through community assistance programs and should be asked about the availability of and eligibility requirements for such assistance.

Federal Agencies

Some lakes and reservoirs fall under Federal jurisdiction, are managed by Federal agencies, or are adjacent to lands or waters managed or regulated by a Federal agency. In addition, a number of Federal agencies conduct research and technology transfer programs relevant to fish and fisheries management. The primary Federal agencies in the United States involved in research or management activities related to freshwater fish are:

- **U.S. Fish and Wildlife Service.** The lead Federal agency in the conservation and management of the Nation's sport fishes as well as migratory birds, endangered species, and some mammals. Responsibilities include the operation of Federal hatcheries, management of national wildlife refuges, and an extensive research program on fish and wildlife conservation and management.

- **Army Corps of Engineers.** The agency responsible for the management, including fisheries management, of the large number of reservoirs constructed by the Corps.

- **Tennessee Valley Authority.** The Tennessee Valley Authority is also responsible for the overall management of a large number of reservoirs, all in the southeastern United States.

- **U.S. Environmental Protection Agency.** The Environmental Protection Agency has a broad range of responsibilities for Federal environmental protection regulations and research and administers the Clean Lakes Program.

- **Bureau of Land Management.** The Bureau of Land Management administers 48 percent of all federally owned lands — most of them in the western United States.

- **Bureau of Reclamation.** This agency is responsible for overseeing a number of regional reclamation projects, some involving fisheries improvements, on arid lands in the western United States.

- **U.S. Forest Service.** The Forest Service administers national forests and grasslands and is responsible for the management of these resources; it also conducts research on forestry and wildlife (including fish) management and protection.

- **National Park Service.** The National Park Service administers natural resources on designated, federally protected lands.

In Canada, relevant Federal agencies include:

- **Department of Fisheries and Oceans.** The agency responsible in Canada for fisheries development and management and conducting fisheries and environmental research. DFO administers the federal Fisheries Act, the prime fisheries legislative tool, but shares many fisheries management responsibilities with provincial environmental agencies.

- **Environment Canada** — This agency's responsibilities include the acquisition and preservation of natural areas. Conservation and Protection, part of Environment Canada, includes the Inland Waters Directorate responsible for planning and managing national and international water programs, conducting research, and gathering data relating to the Canada Water Act; the Canadian Wildlife Service, which administers the Canada Wildlife Act and other regulations and conducts research on migratory birds, endangered species, and other wildlife; and the Environmental Protection Directorate, responsible for programs to mitigate toxic chemicals, acid rain, and hazardous wastes, and assessing environmental impacts.

This manual cannot provide a full listing or discussion of all the offices and programs that provide useful advice, assistance, or information on designing and implementating a fish or fisheries management program. Two programs deserve special note, however.

- **The U.S. Fish and Wildlife Service** supports cooperative research units at land grant universities within most States. The leader of the Fish and Wildlife Service Cooperative Research Unit in your State may be a useful source of information on researchers and consultants working in relevant areas.

- **The Clean Lakes Program** is administered through the U.S. Environmental Protection Agency's regional offices and associated State programs. This program provides assistance and funding for the evaluation of lake problems and the implementation of lake restoration programs on waters with public access. Information on the Clean Lakes Program may be obtained from:

Clean Lakes Program (WH-553)
U.S. Environmental Protection Agency
401 M Street, SW
Washington, DC 20460

The Lake and Reservoir Restoration Guidance Manual (Olem and Flock, 1990: Chapter 8) provides further information on Federal sources of funding and advice.

Private Organizations

A number of private organizations also provide information on organizing citizens groups, obtaining lists of potential volunteers and interested individuals, determining angler preferences, establishing fisheries goals and objectives, and identifying fish and fisheries management techniques and possible funding sources. Organizations whose primary focus deals with issues relating to freshwater fish and water quality are listed in Table 7-1; their addresses are provided in Appendix C. Additional information on these and other organizations can be found in the Conservation Directory, published periodically by the National Wildlife Federation, 1400 Sixteenth Street, NW, Washington, DC 20036-2266.

Table 7-1.—Selected private organizations interested in freshwater fisheries and water quality (source: Natl. Wildl. Fed. 1991).

ORGANIZATION	PRIMARY INTERESTS
American Bass Association, Inc.	Protecting and enhancing fishery resources and promoting bass fishing as a major sport
Anglers for Clean Water, Inc.	Educating the general public about water pollution and promoting the need for conservation of water and fisheries resources
Bass Anglers Sportsman Society	Conserving water resources, fighting pollution, and teaching young people good conservation practices
Bass Research Foundation	Encouraging results-oriented research aimed at improving the quantity and quality of America's bass fishery resources
Clean Water Fund	Helping to build citizen leadership and organizations for more effective public participation in policy debates regarding environmental and consumer protection
Environmental Defense Fund, Inc.	Involving interdisciplinary teams of scientists, economists, and attorneys in the development of economically viable solutions for a broad range of environmental problems
Federation of Fly Fishers	Promoting fly fishing and preserving all species of fish through local stream and fishery restoration projects and conservation grants
Freshwater Foundation	Supporting research and education on the proper use and management of surface and ground waters for human consumption, industry, and recreation
Izaak Walton League of America	Educating the public to conserve, protect, and restore the soil, forest, water, air, and other natural resources
Muskies Inc.	Establishing hatcheries and introducing the muskellunge into suitable waters, abating water pollution, and promoting research and a high quality muskellunge sport fishery
National Audubon Society	Promoting science, lobbying, and citizen action to protect air, land, and water resources
National Wildlife Federation	Encouraging public awareness of the need for the wise use and proper management of natural resources
Natural Resources Defense Council, Inc.	Monitoring government agencies, bringing legal action, and disseminating citizen information to protect natural resources and improve the quality of the environment
North American Native Fishes Association	Promoting the study and conservation of North American native fishes and restoring and protecting fish habitat
Sierra Club	Promoting the responsible use of the earth's ecosystems and resources through public education; exploring and protecting wild places
Smallmouth Bass, Inc.	Promoting research, education, restoration, and conservation of smallmouth bass fisheries
Soil and Water Conservation Association	Advancing the science of good land and water use; conducting multidisciplinary forums to identify and formulate workable recommendations on land and water management policies and issues
Sport Fishing Institute	Promoting high-quality recreational fishing through an integrated program of ecological research, fish conservation education, and aquatic sciences advisory service
Trout Unlimited	Protecting clean water and enhancing trout, salmon, and steelhead fishery resources
Water Environment Federation	Developing and disseminating technical information on the preservation and enhancement of water quality and water resources

Professional Societies

Professional societies are private organizations of individuals with advanced training and experience in specific scientific or technical disciplines. Two professional societies with particular relevance to fisheries and lake management are the American Fisheries Society and the North American Lake Management Society. The membership directories for both organizations serve as a readily accessible source of names and addresses of knowledgeable experts, some of whom may be willing to consult and advise on a lake restoration project (see discussion of private consultants).

The North American Lake Management Society maintains a list of members who provide such services, sorted by specialty area and region. The American Fisheries Society supports a certification program for fisheries biologists and can provide a list of certified fishery biologists as well as all society members and their area of expertise. Both organizations publish books, journals, and magazines with useful information; in particular, *Fisheries*, published by the American Fisheries Society, and *Lake Line*, published by the North American Lake Management Society, are designed for a broad audience.

Additional professional organizations involved in lake and fisheries management and research are listed in Table 7-2; Appendix C lists their addresses.

Table 7-2.—Selected professional societies relating to lake and fisheries management (source: Natl. Wildl. Fed. 1991).

ORGANIZATION	PRIMARY SCIENTIFIC AREAS OF INTEREST
American Fisheries Society	Conservation, development, and wise use of fisheries, both recreational and commercial
American Society of Limnology and Oceanography	Physical, chemical, and biological processes in freshwaters and oceans
American Water Resources Association	Water resources research, planning, development, and management to establish a common ground for engineers and physical, biological, and social scientists
Ecological Society of America	Terrestrial and aquatic ecology; scientific study of organisms in relation to their environment
North American Benthological Society	Biotic communities in lake and stream bottoms and their role in aquatic ecosystems
North American Lake Management Society	Protection, restoration, and management of lakes and reservoirs and their watersheds
Society of Environmental Toxicology and Chemistry	Environmental toxicology and chemistry and the application of these sciences to hazard assessment and risk analysis

Environmental Consultants

Some lake management programs may find it necessary to hire an environmental consultant to perform in-depth analyses of data and assist with field sampling and project implementation. In some cases, faculty in fisheries or limnology departments at local universities may be willing to serve as consultants for individual lake projects. Alternatively, communities can hire environmental consulting firms individually or as teams of experts for complex projects involving a diversity of disciplines. To get information on candidate consultants, contact

- other lake associations;
- local and State environmental agencies and groups;

- the North American Lake Management Society consultant referral service; and
- the American Fisheries Society, which has a listing of certified fisheries biologists and members in most regions.

The Lake and Reservoir Restoration Guidance Manual (Table 3-3 and pages 42 and 192) discusses how to select a consultant or team of consultants for a lake restoration project; most of these recommendations are relevant for fish and fisheries management programs. Important criteria for selecting a consultant to assist *specifically* with the fisheries management aspects of a lake restoration project include:

- **Expertise**
  - Demonstrated training and qualifications in the principles of fishery science and fisheries management (e.g., education, advanced degrees, certifications).
  - Familiar with a broad range of fisheries management problems, the alternative management approaches discussed in Chapters 8 and 9, and the ecological consequences of these activities.
  - Knowledgeable about relevant local, State, and Federal regulations and permit requirements.
  - Adequate staff and equipment to complete all tasks.
- **Experience**
  - Prior hands-on experience working with similar management problems and fish communities in other lakes in the area.
  - Demonstrated ability to identify and implement practical cost-effective solutions to fisheries management problems.
  - Prior projects working with a lake association or citizens group demonstrating the capability to interact effectively with individuals with diverse backgrounds.
- **Past Performance**
  - References that vouch for the performance of the consultant(s) on prior projects.
  - Prior projects of high quality, completed on time and within budget.
  - Completion of one or more projects that involved the design and implementation of long-lasting and effective management solution(s) at reasonable cost.

CHAPTER 8

Management Techniques for Improving and Maintaining Fisheries in Lakes and Reservoirs

Chapter Objective

This chapter provides an overview of the various management techniques to improve and maintain fisheries in lakes and reservoirs. It is not intended to be a how-to guide with step-by-step instructions on implementation but rather a general description of the types of tools and methods available and their advantages and limitations. Greater detail on each of these management techniques can be found in the references cited. Information for some techniques was summarized from EPA's *Lake Maintenance Handbook* (McComas, in press) and *The Lake and Reservoir Restoration Guidance Manual* (Olem and Flock, 1990).

Management methods that use fish to improve water quality are discussed in Chapter 9. However, Chapters 8 and 9 should be considered as a unit, of interest to both fisheries and water quality managers. The fisheries management methods in Chapter 8 involve physical, chemical, and biological manipulations of the lake and watershed that can not only improve the lake's fisheries but also affect water quality, other ecosystem components, and other lake uses. The discussions in Chapter 9 provide insight into the ecological consequences of fish and fisheries management, which must be evaluated as part of any decision regarding lake management.

Selecting the Appropriate Management Technique

Managing a fishery is a delicate operation. Mistakes made are often difficult to correct, and the wrong type of management action may be worse for the fishery and lake ecosystem than no management at all. To be effective, management action must address key limiting factor(s) or major problem(s) affecting the lake's fisheries; otherwise, money and effort will be expended with little to no positive

[N]one of the methods described in this manual should be attempted without first consulting a professional fisheries biologist familiar with fish communities and fisheries problems in the area.

returns. For these reasons, none of the methods described in this manual should be attempted without first consulting a professional fisheries biologist familiar with fish communities and fisheries problems in the area. Furthermore, some activities (e.g., fish introductions, liming) require permits or are prohibited by State regulatory authorities (see Chapter 7).

A number of the techniques described are suitable only in limited or certain circumstances. For example, in many regions of the country, fertilizing a lake to increase fish productivity is considered highly undesirable and therefore not a viable management option because other lake uses and water quality would be adversely affected. However, for some waters where fishing is the dominant lake use and fisheries yields are clearly limited by low nutrients levels, lake fertilization may be appropriate.

This manual provides a comprehensive review of all possible management approaches; its scope is not limited by any specific management objective or philosophy. Nevertheless, in selecting the techniques to apply in any given lake, careful thought and analysis are necessary to ensure that the management program (a) addresses the cause of lake problems and major use limitations to ensure an effective expenditure of funds and effort, (b) will not result in unexpected adverse effects on other lake uses or ecosystem components, and (c) is consistent with public values and the long-term management goals for the lake as a whole.

As part of the planning process, cost estimates should be obtained for the subset of management options being considered.

Costs are another important consideration in selecting a management approach. The cost of implementing a given management technique can vary widely, depending on the region, lake size, accessibility, and other lake-specific conditions and factors. Because of this variability, this manual does not provide cost estimates, although relative costs are discussed for some techniques. As part of the planning process, cost estimates should be obtained for the subset of management options being considered. Both implementation costs and long-term operation and maintenance costs over the life of the project must be evaluated. How long will the treatment or beneficial effects last? How often will management actions need to be repeated? How much effort and expense will be required for routine upkeep and monitoring?

The size of the lake, watershed, and associated drainage system can have a major influence on the feasibility and effectiveness as well as the cost of various management techniques.

The size of the lake, watershed, and associated drainage system can have a major influence on the feasibility and effectiveness as well as the cost of various management techniques. In-lake treatments such as alum additions to reduce internal nutrient loads may have relatively little effect in lakes with short hydraulic residence times and can be very expensive in large lakes. The larger and more diverse a lake's watershed, the more difficult it may be to control nonpoint source inputs of nutrients and sediment. For lakes interconnected to other lakes, rivers, and streams, special consideration must be given to the potential for effects downstream or in adjacent waters. Stocked fish may migrate to other lakes where they may not be wanted. Exotic plants and animals may rapidly disperse throughout a drainage basin, becoming a regionwide nuisance. If undesirable fish species such as carp also occur in adjacent, connected waters, efforts to reduce or eliminate them in just one lake are likely to fail. As noted in Chapter 1, a whole-basin approach is needed for effective fisheries and water quality management.

[S]pecial consideration must be given to the potential for effects downstream or in adjacent waters.

It is not possible to provide simple rules for designing a management program — matching specific management techniques to certain types of problems or conditions. The most appropriate method(s) depends on

- the full suite of management goals,
- natural and existing conditions in the lake, watershed, and drainage basin,
- State regulations,
- available funding, and
- other site-specific factors.

The types of methods described do, however, correspond generally to the types of problems discussed in Chapter 6 (Table 8-1) and fall within three major categories (Fig. 8-1):

1. managing the fish's habitat;
2. manipulating the fish community directly; and
3. managing fishing pressure and harvests.

Table 8-1.—Categories of management approaches used to address common fisheries management problems.

MANAGEMENT APPROACH	COMMON FISHERIES MANAGEMENT PROBLEMS															
	Habitat degradation	Toxic substances	Eutrophication	Low lake fertility	Low oxygen	Acidity	Inadequate spawning habitat	Excessive macrophytes	Water level fluctuations	High temperature	Entrainment/ impingement	Excessive turbidity	Undesirable fish species	Low prey availability	Overfishing	Underuse
Habitat protection	X									X	X	X				
Reduce/eliminate toxicants	X	X														
Reduce nutrient loads	X		X		X					X						
Lake fertilization				X												
Aerate/ increase DO	X		X		X											
Liming	X					X										
Spawning habitat improvements	X						X									
Aquatic plant management	X						X	X								
Water level management	X							X	X							
Addition of fish cover																X
Game fish stocking							X			X						
Control undesirable species												X	X			
Prey enhancements														X		
Fishing regulations															X	
Fishing tournaments													X			X
User conveniences																X

(see Table 6-4)

Habitat Management

Habitat quality is the single most critical factor that determines the types and abundance of fish in a lake as well as the quality of a fishing experience. Without suitable habitat for fish survival, reproduction, and growth, attempts to manage

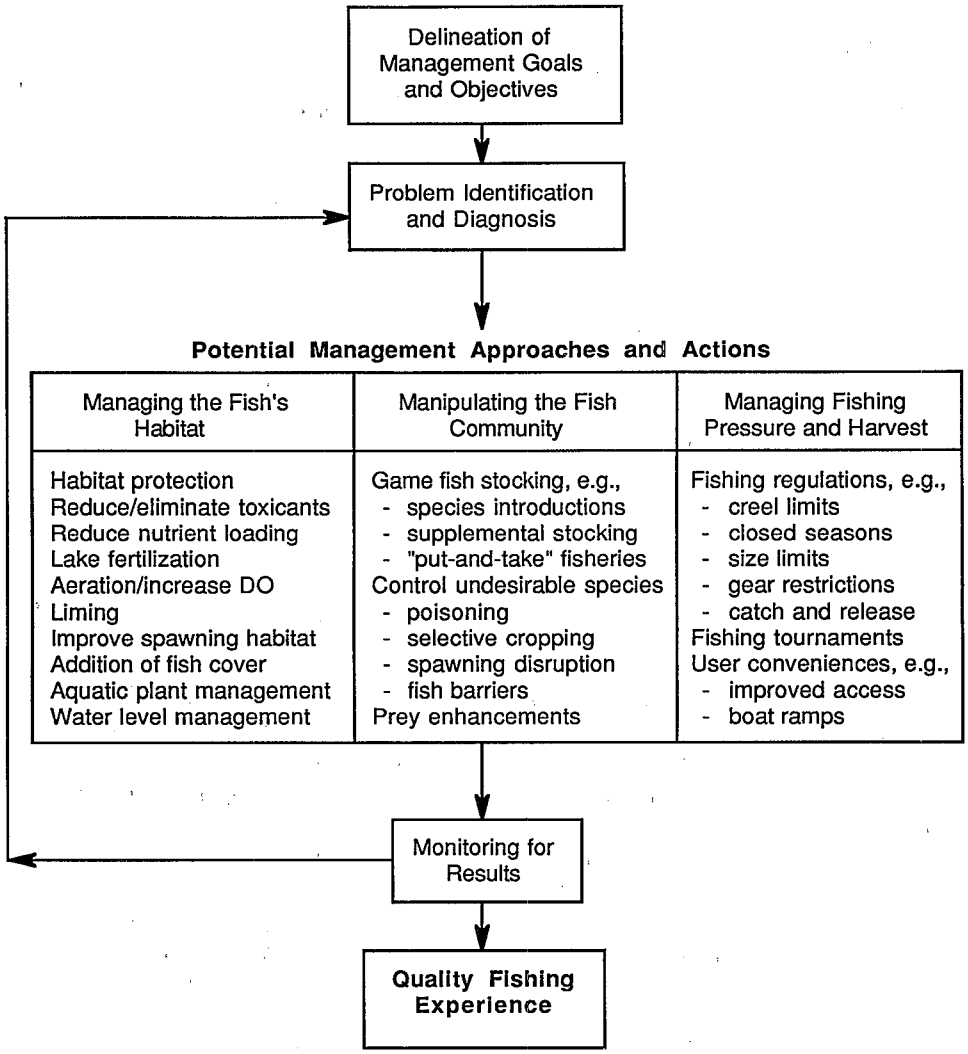

Figure 8-1.—Potential approaches and management actions for improving and maintaining fisheries in lakes and reservoirs. The appropriate management approach for any given lake will depend on the nature of the problem and the management goals and objectives. In addition, monitoring to evaluate the results and success of management actions should be an integral part of any fisheries management program.

Habitat quality is the single most critical factor that determines the types and abundance of fish in a lake as well as the quality of a fishing experience.

and sustain a fishery will be expensive and difficult — if not impossible. Many techniques available for protecting and restoring a lake's habitat have already been described in *The Lake and Reservoir Restoration Guidance Manual* (also see reviews in Cooke et al. 1986; Jorgensen and Vollenweider, 1989). For completeness, however, relevant information from the aforementioned manual is summarized briefly in the subsections that follow, emphasizing the usefulness of these approaches within the context of a fisheries management program. A number of additional habitat management activities are also presented that are unique to fisheries concerns.

The types of activities that may be useful for improving and maintaining a lake's fisheries include the following (see Fig. 8-1):

- habitat protection,
- methods for reducing or eliminating problems with toxic substances,
- methods for reducing nutrient loads and nutrient availability,
- lake fertilization to enhance fish productivity,

- lake aeration and other approaches for increasing levels of dissolved oxygen in critical fish habitats,
- lake liming and associated techniques for decreasing water acidity,
- spawning habitat enhancements or improvements,
- the addition of physical structures to provide increased fish cover and shelter,
- aquatic plant management, and
- water level management.

Finally, many fisheries management problems for artificial lakes (reservoirs) can be avoided or reduced if fish habitat requirements are considered during lake design. Thus, factors to consider in the design and construction of reservoirs are also summarized.

Habitat Protection

The most cost-effective and long-term approach to habitat management is habitat protection; that is, preventing the degradation or loss of important fish habitats through the application of best management practices, controlled watershed and lake development, and pollution prevention and treatment. Habitat protection activities should be a top priority for all fisheries management programs.

The most cost-effective and long-term approach to habitat management is habitat protection. . . .

Fish habitat includes not just the lake proper but also inflowing tributaries, lake outlet(s), adjacent wetlands, and the shoreline, all of which can provide important spawning, nursery, and feeding areas for fish. Furthermore, in many cases, habitat protection begins on the land in the surrounding watershed. Chapter 5 and Appendix D of *The Lake and Reservoir Restoration Guidance Manual* provide a detailed discussion on watershed management, including the use of best management practices to reduce erosion and the export of sediments, nutrients, and toxic contaminants to receiving waters. Best management practices have been developed for agricultural, silvicultural, urban, and construction activities (U.S. Environ. Prot. Agency, 1987). The effectiveness, cost, and chance of negative side effects associated with selected watershed best management practices are summarized in Table 8-2.

Additional habitat protection guidelines for local property owners and developers include the following (Ontario Ministry of Natural Resources, 1991):

- Disallow dredge and fill operations in or near areas with critical fish habitat (e.g., wetlands, spawning beds, and tributary streams used for spawning or nursery areas). Dredge and fill operations not only destroy fish habitat directly but also can result in increased water turbidity and siltation, which degrade fish habitat.
- Maintain buffer strips of natural vegetation along the banks of streams and lakes to stabilize the shoreline, reduce sediment inputs, and provide shading for cooler water temperatures during the summer. In cases where natural vegetation is not sufficient to stabilize shorelines, structural devices may be needed. Banks of riprap (carefully arranged large stones) with shrubs or other vegetation planted over them are preferable to solid shore walls of steel or cement.
- Boathouses and docks should not disturb river or lake beds or restrict water movement near the shoreline. Build cantilever, floating, or post-supported structures where possible. Crib foundations are acceptable if bridging is constructed between the cribs to allow water to circulate. All wood preservatives contain compounds toxic to fungi; therefore, preservatives should be used with caution or avoided.

Table 8-2.—Summary of the effectiveness, cost, and chance of negative side effects associated with select watershed best management practices (source: Olem and Flock, 1990).

	EFFECTIVENESS					CHANCE OF NEGATIVE EFFECTS
	SEDIMENT	NITROGEN	PHOS-PHORUS	RUNOFF	COST	
Agriculture:						
Conservation tillage	G-E	P	F-E	G-E	F-G	F-G
Contour farming	F-G	U	F	F-G	G	P
Contour stripcropping	G	U	F-G	G-E	G	P
Range & pasture mgt.	G	U	U	G	G	P
Crop rotation	G	F-G	F-G	G	F-G	P
Terraces	G-E	U	U	F	F-G	F
Animal waste mgt.	N/A	G-E	G-E	N/A	P	F
Urban:						
Porous pavement	F-G	F-G	F-G	G-E	P-G	F
Street cleaning	P	P	P	P	P	U
Silviculture:						
Ground cover maint.	G	G	G	G	G	P
Road & skid trail mgt.	G	U	U	U	P	F
Construction:						
Nonveg. soil stabilization	E	P	P	P-G	F-G	F
Surface roughening	G	U	U	G	F	P
Multicategory:						
Streamside mgt. zones	G-E	G-E	G-E	G-E	G	F
Grassed waterways	G-E	U	P-G	F-G	F-G	P
Interception or diversion	F-G	F-G	F-G	P	P-F	P
Streambank stabilization	G	U	U	P	P-G	F
Detention/sedimentation basins	G-E	P	P	G-E	F-G	F

E = excellent; G = good; F = fair; P = poor; U = unknown; N/A = no answer.

- Avoid building beaches in areas with critical fish habitat. Alternatives, such as dry beaches (built above the high water mark) and swimming platforms are preferable. Instead of sand, consider building beaches with coarse or pea-sized gravel.
- Maintain a diversity of habitats (e.g., riffles and pools in streams, littoral areas with a complex physical structure) that can support a wide range of fish species and sizes. Channelized streams and boat channels in littoral areas are relatively poor fish habitat.

Control of Toxic Contaminants

Elevated levels of [toxic] substances can reduce fish survival and growth and may bioaccumulate in fish tissues, limiting the suitability of fish for human consumption.

Toxic contaminants in lakes can include metals, pesticides, oils, and other pollutants in agricultural, industrial, and urban wastes. Elevated levels of these substances can reduce fish survival and growth and may bioaccumulate in fish tissues, limiting the suitability of fish for human consumption. Possible corrective actions include

- eliminating the source of the contaminants by treating effluents (for point sources) or applying best management practices (for nonpoint sources);
- dredging and removing contaminated lake sediments;
- isolating contaminants concentrated in the bottom sediments from the overlying water column by covering the sediments with a relatively impermeable layer, such as betonite (a form of clay) or a plastic liner;

- on-site water treatments — for example, diluting the contaminated water with "clean" water pumped in from other sources or withdrawing and treating the lakewater (e.g., by chemical precipitation/coagulation and filtration) and then returning the treated water to the lake;
- the addition of chemicals such as alum (aluminum sulfate) to the lake, which may accelerate the precipitation of toxic substance(s) out of the water column into the bottom sediments;
- deepwater aeration, for contaminants (e.g., some metals and ammonia) that precipitate or become nontoxic in the presence of dissolved oxygen;
- controlling changes in water level if the exposure and suspension of contaminated sediments tend to increase the solubility and mobilization of the toxic substance; and
- biomanipulation if the potential for human exposure to bioaccumulated toxics can be reduced by altering the food chain or target fish species for fisheries management (e.g., avoiding game fish, such as lake trout, that are top predators and have high levels of body fat).

Relatively few field tests have been conducted to evaluate the long-term effectiveness of most of these techniques; in addition, a number of techniques can have potentially serious negative side effects (e.g., dredging operations may resuspend toxic contaminants and actually increase bioavailability). Not infrequently, no action is the most environmentally sound and cost-effective approach, allowing natural processes, such as sedimentation, to gradually reduce the concentration and availability of toxic substances after the source of contaminants has been eliminated. A technical guidance manual on toxic substances in lakes and reservoirs for EPA's Clean Lakes Program is currently in preparation and will provide further details on designing a management program to control and reduce toxic contaminants.

Not infrequently, no action is the most environmentally sound and cost-effective approach, allowing natural processes, such as sedimentation, to gradually reduce the concentration and availability of toxic substances after the source of contaminants has been eliminated.

Reducing Nutrient Loads and Nutrient Availability

As discussed in Chapter 2, eutrophication can adversely affect fish communities by decreasing dissolved oxygen levels, increasing water temperatures, decreasing water clarity, and altering the types and abundance of phytoplankton, zooplankton, and other organisms available as fish prey. Increased nutrient loadings generally increase lake productivity, in many cases including the total production of fish. However, the accompanying changes in physical and chemical habitat often result in an undesirable shift in the types of fish species able to survive and flourish in these waters. As an indirect effect of high nutrient loads, lakes may become unsuitable for game species of particular interest to local anglers.

Much of *The Lake and Reservoir Restoration Guidance Manual* (Olem and Flock, 1990) is devoted to methods for evaluating and controlling problems with lake eutrophication. Two basic approaches are described for reducing nutrient inputs and availability: managing the watershed (Chapter 5, Olem and Flock, 1990) and various in-lake treatments (parts of Chapter 6, Olem and Flock, 1990). Managing the watershed may involve the construction or upgrading of wastewater treatment facilities and changes in land use or land use practices in the watershed — in particular, application of best management practices (see Table 8-2). The relative merits and effectiveness of best management practices depend on the relative importance of point and nonpoint nutrient sources to the lake (see "How To Assess Potential Sources," pages 104 to 106, Olem and Flock, 1990).

Watershed management of both point and nonpoint sources reduces external nutrient loadings.

[I]n-lake treatments will only be effective over the long-term if accompanied or preceded by efforts to reduce external nutrient loads.

Watershed management of both point and nonpoint sources reduces external nutrient loadings. In-lake treatment procedures, on the other hand, eliminate internal nutrient sources or reduce nutrient availability. In general, in-lake treatments will only be effective over the long-term if accompanied or preceded by efforts to reduce external nutrient loads. In conjunction with a plan for improved watershed management, in-lake treatments may serve to accelerate the process of lake recovery.

Many of the in-lake treatments noted previously for reducing toxics also can reduce nutrients. The following types of in-lake treatments effectively reduce nutrient availability in at least some circumstances:

- **Chemical treatments to precipitate and inactivate phosphorus.** Aluminum salts, such as aluminum sulfate (alum) and sodium aluminate, have a strong affinity to adsorb and absorb inorganic phosphorus and remove phosphorus-containing particulate matter from the water column as part of the floc (loose precipitate) that forms. After the floc settles, the result is not only a reduction in phosphorus availability but also generally a substantial increase in water clarity. Adverse effects may occur, however, if the dosage is too high. Excessive inputs of aluminum salts can result in concentrations of dissolved aluminum in the water column that are toxic to fish and other biota. Example applications of alum treatments to reduce nutrient levels in lakes include Horseshoe and Snake Lakes, Wisconsin (Peterson et al. 1973; Garrison and Knauer, 1984); Medical Lake, Washington (Gasperino et al. 1980; Soltero et al. 1981); Annabessacok Lake, Maine (Dominie, 1980); and Dollar and West Twin Lake, Ohio (Cooke et al. 1982).

- **Sediment removal.** Sediments with high concentrations of phosphorus or nitrogen may serve as an internal nutrient source. If nutrients are concentrated within the upper sediment layers, dredging and the removal of these nutrient-rich sediments may substantially reduce nutrient recycling and availability (see Figs. 6-1 and 6-2, Olem and Flock, 1990). At the same time, however, dredging operations can cause extensive damage to the benthic community, which can be an important food source for fish, and may disturb fish spawning habitats if not carefully designed and implemented. Example applications include Lake Trummen, Sweden (Andersson et al. 1975; Bengtsson et al. 1975; Cronberg et al. 1975) and Lilly Lake, Wisconsin (Dunst et al. 1984).

- **Dilution and flushing.** For small lakes, it may be possible to reduce nutrient concentrations in the water column by adding sufficient amounts of low-nutrient waters from other sources, thereby diluting and flushing the high-nutrient water out of the lake. Applications of this technique are limited, however, by the general absence of suitable alternative water supplies. Examples include Moses Lake, Washington (Welch and Patmont, 1980) and Green Lake, Washington (Perkins, 1983).

- **Aeration.** Phosphorus remobilization from lake sediments is generally higher in anaerobic waters (with no dissolved oxygen) than in well-aerated waters because the oxygenated forms of iron and manganese in natural waters form an insoluble precipitate with phosphorus. Thus, aeration techniques that increase oxygen levels in deeper waters may decrease nutrient recycling and availability. Increases in dissolved oxygen also have a direct positive effect on fish. Specific aeration methods are discussed later in this chapter.

- **Sediment oxidation.** Oxidation of the lake's sediments may also reduce the remobilization of phosphorus into the water column. Rather than air, however, a solid such as calcium nitrate is added to the sediments as an oxidizing agent. The procedure is termed "RIPLOX," after its originator (Ripl, 1976) and is considered still experimental. Example applications include Lake Lillesjon, Sweden (Ripl and Lindmark, 1978) and Long Lake, Minnesota (Willenbring et al. 1984).

■ **Water withdrawals from the hypolimnion.** The colder, deeper layers of a thermally stratified lake or reservoir generally have higher nutrient concentrations than waters in the epilimnion or metalimnion. Selectively withdrawing these nutrient-rich waters by using a siphon or deepwater outlet in a dam can decrease the quantity of nutrients stored and recycled in the waterbody. However, hypolimnetic withdrawals may also trigger thermal instability and lake turnover. In addition, the discharge of these nutrient-rich, often anaerobic waters from the hypolimnion of eutrophic lakes may adversely affect downstream receiving waters. Example applications include Lake Wononscopomuc, Connecticut (Kortmann et al. 1983) and Mauensee in Switzerland (Gächter, 1976; Cooke et al. 1986).

All these in-lake treatments require significant funding for equipment, chemicals, and labor and are generally short term. Case studies as well as additional information on the methods, costs, and potential negative side effects of each approach can be found in Chapter 6 of *The Lake and Reservoir Restoration Guidance Manual* (Olem and Flock, 1990) and Cooke et al. (1986).

Lake Fertilization

Lakes and reservoirs that are naturally oligotrophic (i.e., have low nutrient loads) generally also have relatively low levels of fish production and yield. In some cases, it may be desirable to increase fisheries yields in these waters through controlled additions of nutrients — in essence, fertilizing the lake to enhance productivity. However, this increase in nutrient loads will also alter other lake characteristics, for example, increasing algal growths and decreasing water clarity. Thus, while fertilization may be beneficial for fisheries, it is likely to have detrimental effects on other lake uses. As a result, fertilization as a fisheries management tool is generally restricted to lakes and reservoirs used only or primarily for fishing where nutrient additions will not adversely affect downstream waters. Once a lake is fertilized, returning the system to its original oligotrophic, clear-water condition can be difficult, expensive, and a lengthy process, especially for lakes with long retention times.

[W]hile fertilization may be beneficial for fisheries, it is likely to have detrimental effects on other lake uses.

Many commercially available fertilizers are suitable for lake fertilization projects. The optimal application rate and technique depend on current nutrient loads and concentrations, the desired increase in productivity, the fertilizer type, and target fish species. As a general rule, McComas (in press) recommends 50 lb/acre of 8-8-2 emergence fertilizer (8 parts nitrogen, 8 parts phosphorus, and 2 parts potassium). The Georgia Department of Natural Resources recommends applying approximately 40 lb/acre of 20-20-5 fertilizer every two to three weeks beginning in the spring when water temperatures reach 60°F (Ga. Dep. Nat. Resour. 1988). In waters that are naturally slightly acidic, simultaneous additions of agricultural limestone (e.g., one to two tons per acre) may further enhance productivity. Once fertilizer additions are initiated, they must be continued at regular intervals throughout the growing season. Do not add the total amount of fertilizer required for an entire season all at one time.

The fertilizer should be spread or dispersed evenly throughout the lake. One application approach uses submerged wooden platforms anchored about 12 inches below the water surface near the shore. The appropriate quantity of fertilizer is placed on each platform; the fertilizer gradually dissolves and is distributed through the lake by wave action and water currents. Alternatively, liquid fertilizer can be used to facilitate mixing.

An increase in phytoplankton productivity is the major, direct effect of fertilizer additions. Thus, fish species that feed on phytoplankton and zooplankton experience a larger increase in production than do species that feed primarily on benthic organisms, macrophytes, or other fish. In addition, fertilizer applications

will result in a measurable response only if food availability is the major factor limiting fish production — as opposed to temperature, natural reproduction, or other variables.

A number of State resource agencies have published guides for lake fertilization, including Alabama, Arkansas, Georgia, Illinois, Iowa, Minnesota, New York, and others (e.g., Iowa Dep. Nat. Resour. undated; Ga. Dep. Nat. Resour. 1988). State resource agencies are listed in Appendix C.

Lake Aeration and Other Approaches for Increasing Levels of Dissolved Oxygen in Critical Fish Habitats

Low levels of dissolved oxygen may occur in lakes as a result of natural conditions and cultural eutrophication.

Low levels of dissolved oxygen may occur in lakes as a result of natural conditions and cultural eutrophication. The lowest concentrations tend to occur in the deeper waters of the hypolimnion during thermal stratification in late summer, during long periods of snow and ice cover in winter, or in dense macrophyte beds at night or following long periods of cloud cover (see Chapter 2).

One important option for lakes with dissolved oxygen problems is to manage the fisheries for species able to tolerate relatively low levels of dissolved oxygen or that do not inhabit areas of the lake (such as the hypolimnion) that experience oxygen depletion.

One important option for lakes with dissolved oxygen problems is to manage the fisheries for species able to tolerate relatively low levels of dissolved oxygen or that do not inhabit areas of the lake (such as the hypolimnion) that experience oxygen depletion. For example, many salmonid species require both relatively high levels of dissolved oxygen and, because of their intolerance of warmer water temperatures, must reside in the cooler waters of the hypolimnion during summer. Therefore, to sustain a fisheries for salmonids may require an expensive and continuing effort to aerate the lake's hypolimnion during some or all of the summer. Alternatively, if the problems with oxygen depletion are moderate, the lake may be able to support coolwater or warmwater fisheries without extensive restoration efforts. Dissolved oxygen and temperature limits for fish are discussed in Boxes 3-C and 3-D in Chapter 3.

Problems with low dissolved oxygen can also be alleviated by doing one or more of the following:

- Decreasing the quantity of organic matter decomposing in the lake (the major process-consuming oxygen) by (a) limiting the export of organic materials from the watershed to the lake, in particular excessive exports associated with human activities, such as runoff from feedlots or direct discharges of wastewaters; (b) dredging to remove organic-rich sediments; and (c) decreasing in-lake productivity by reducing nutrient loads and nutrient availability.
- Increasing photosynthesis (an oxygen-generating process) by increasing light penetration, especially during winter and in areas (deeper waters of the hypolimnion) subject to oxygen depletion.
- Destratifying the lake (artificial circulation), bringing low oxygen waters in the hypolimnion in contact with the lake surface and the well-oxygenated waters of the epilimnion.
- Directly aerating the lake.

During winter, the goal is not to aerate the entire waterbody but instead to create an oxygen-rich refuge area for fish, generally near the lake surface.

The approaches and optimal design criteria for lake aeration projects vary somewhat for systems installed to alleviate problems with winterkill (oxygen depletion during winter) as opposed to low levels of dissolved oxygen in the hypolimnion during summer. During winter, the goal is not to aerate the entire waterbody but instead to create an oxygen-rich refuge area for fish, generally near the lake surface. Major design concerns include problems with equipment ice-up and the need to minimize the loss or weakening of the lake's ice cover for safety reasons. Hypolimnetic aeration systems must deal with the more difficult problem

of aerating waters at greater depths. Where the objective is to establish or maintain a coldwater fishery, hypolimnetic aeration must be achieved without disturbing the lake's thermal stratification. Otherwise, low levels of dissolved oxygen may be avoided by preventing thermal stratification through artificially circulating the water column. In both cases, during both winter and summer, maximum reliability at minimal cost are important design features.

■ **Pump and baffle aeration system.** One type of winter aeration system is the pump and baffle. Oxygen-poor water is extracted from a nearshore area of the lake, pumped to the top of a chute on shore, and then allowed to cascade over a set of baffles constructed from wooden boards (Fig. 8-2). The turbulence created as the flow passes over the baffles helps to reaerate the water. The reoxygenated water is then returned to a different part of the lake away from the intake area to create a zone of oxygen-rich water.

Generally, approximately 10 percent of the lake's volume should be aerated (McComas, in press). Thus, for a 100-acre lake with an average depth of 6 feet (volume of 600 acre-feet), the objective would be to aerate 60 acre-feet or about 19.5 million gallons of water. A typical rig uses a 10 hp motor with a 6- or 8-inch

Figure 8-2.—Photograph of the pump and baffle system used for lake aeration to prevent winterkill. The aerator pumps lake water to the top of a staircase and then the water cascades down back to the lake (source: McComas, in press).

pump that delivers between 1,600 and 3,000 gallons per minute or 2.3 to 4.3 million gallons per day. Thus, a suitable refuge area for this lake could be created within 5 to 10 days. For larger lakes, multiple rigs may be needed; therefore, the pump and baffle technique could be too expensive.

The level of oxygen that must be maintained depends on the fish species in the lake.

The level of oxygen that must be maintained depends on the fish species in the lake (see Box 3-C). The velocity of water discharged into the lake must be neither too low nor too high. At low velocities, the amount of water released would be too small to produce an oxygen-rich zone of sufficient size. At high velocities, the reoxygenated water discharged will mix too thoroughly with the oxygen-poor lake water, elevating the entire lake's oxygen level only slightly (and too little to significantly improve fish survival), rather than creating a smaller refuge area with higher oxygen levels.

Freeze-up can be a major problem with pump and baffle systems during especially cold winter days. Freeze-up may occur at the water intake, on the chute, or at the water discharge. For example, when ice builds up, the chute may become top-heavy and fall over. Thus, the system must be checked daily to ensure proper operation.

Pump and baffle systems have several major advantages over other aeration techniques. In particular, when properly operated, only a small area of the lake's ice cover is opened. Open areas and thin ice are safety hazards for which the operator of an aeration system is liable. All of the major pieces of equipment are on shore. In addition, the chute can be mounted on a trailer and moved from one lake to another or to different areas of the lake as needed. Generally, to prevent winterkill, aeration will be required for about two months, depending on winter conditions. By monitoring dissolved oxygen levels in the lake, the system can be operated during only those times and winters when needed.

Some lake associations have built their own pump and baffle systems; however, these systems can be purchased as a unit from a number of manufacturers (e.g., Crisafulli Pump Company, Glendive, Montana; H&H Pump, Inc., Clarksdale, Mississippi). McComas (in press) provides further information on the construction and operation of pump and baffle aeration units.

■ **Artificial circulation.** Artificial circulation eliminates thermal stratification or prevents its formation either by mechanical pumping or through the injection of compressed air from a pipe or ceramic diffuser at the lake's bottom (Fig. 8-3). The rising column of bubbles, if sufficiently powered, will produce lakewide mixing. As a result, the conditions that create hypolimnetic oxygen depletion (i.e., isolation of the deeper areas from the atmosphere with little to no primary production in these darker waters) are eliminated.

The most common cause of failure in artificial circulation projects is the lack of sufficient air flow to produce satisfactory mixing.

The most common cause of failure in artificial circulation projects is the lack of sufficient air flow to produce satisfactory mixing. On average, about 1.3 cubic feet per minute of air flow is required per acre of lake surface to adequately mix the lake and elevate levels of dissolved oxygen (Lorenzen and Fast, 1977). In general, it is easier and more effective to apply the mixing energy early enough to prevent stratification, rather than attempting to turn over an already stratified lake (Burns, 1988).

Artificial circulation is one of the most commonly used lake restoration techniques (Cooke et al. 1986). An example of its usefulness for improving fisheries yields is presented in Box 8-A. Other applications include Parvin Reservoir, Colorado (Lackey, 1972) and Corbett Lake, British Columbia (Halsey, 1968). The technique is best used in lakes that are not nutrient limited; nutrient concentrations are often higher in the hypolimnion, and as a result, mixing can stimulate increased algal growth. In addition, artificial circulation is not a viable option for coldwater fish species, which use the hypolimnion as a thermal refuge during summer.

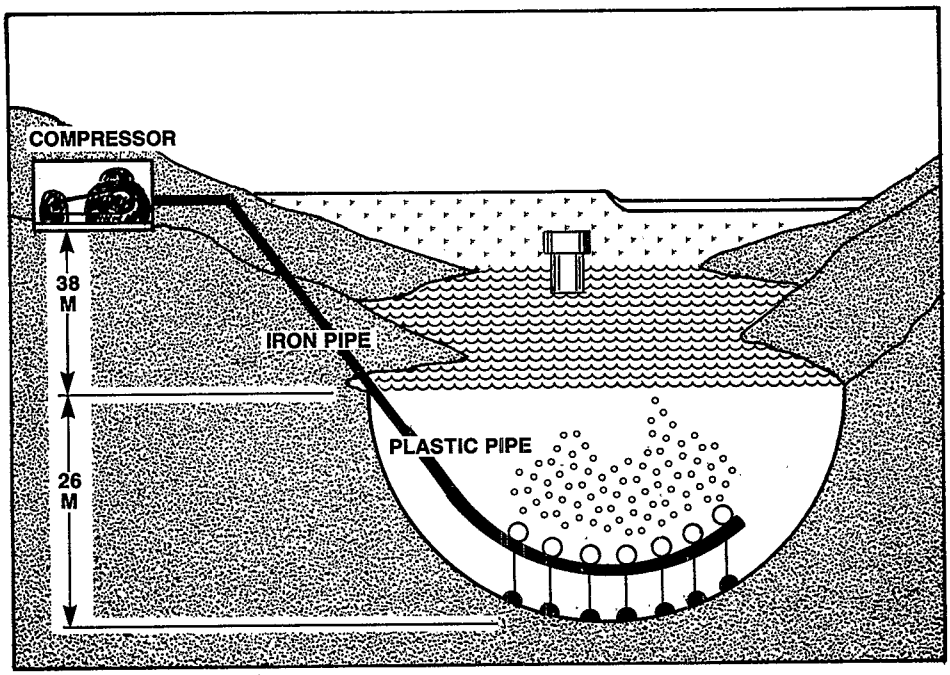

Figure 8-3.—Artificial circulation system installed at El Capitan Reservoir, California (source: Lorenzen and Fast, 1977).

■ **Hypolimnetic aeration.** Hypolimnetic aerators may be used to increase oxygen levels in the hypolimnion without disturbing the lake's thermal stratification. An airlift device (see Fig. 6-5, Olem and Flock, 1990) brings cold hypolimnetic water to the surface. The water is aerated by contact with the atmosphere; gases such as methane, hydrogen sulfide, and carbon dioxide that may accumulate under anaerobic conditions are dispersed; and the water is returned to the hypolimnion.

Hypolimnetic aerators require a large hypolimnion to work properly and are generally ineffective in shallow lakes and reservoirs. Costs depend on the amount of compressed air needed, which is a function, in turn, of the area of the hypolimnion, the rate of oxygen consumption in the lake, and the degree of thermal stratification (Kortmann, 1989). Example applications include Waccabuc Lake, New York (Fast et al. 1975), Larson and Mirror Lakes, Wisconsin (Smith et al. 1975), and Tory Lake, Ontario (Taggart and McQueen, 1981).

Box 8-A.—Effects of Artificial Circulation on Angling Success (Mosher, 1983)

Pottawatomie State Fishing Lake No. 1 (24 acres, maximum depth 20 feet) in northcentral Kansas had problems with severe oxygen depletion at depths below 13 feet during thermal stratification. As a result, during summer 89 percent of the fish were restricted to the upper 10 feet of the water column. In 1976 and 1977, a helixor-type aeration unit was installed to prevent stratification. Consequently, dissolved oxygen levels remained above 4 mg/L throughout the water column and 64 percent of the fish occurred in deeper lake waters (below the 10-foot isopleth). Angler days of fishing increased by 16 percent from 1975 to 1976 and an additional 17 percent in 1977. Channel catfish harvest increased 227 percent from 1975 to 1976, and 48 percent from 1976 to 1977. The aeration unit was removed in 1978 and conditions returned to those of the pre-circulation period; fishing pressure and harvest of channel catfish declined. Although circulation increased the channel catfish harvest at Pottawatomie State Fishing Lake No. 1, no such increase (in fisheries yield or dissolved oxygen) was observed when the same operation was transferred to a larger nearby lake. Apparently, the efficiency of the circulation unit was insufficient for the larger lake volume (3.7 times larger than Pottawatomie State Fishing Lake No. 1).

■ **Oxygen injection.** Recent studies have shown that it is often more cost effective and practical to inject pure oxygen into the hypolimnion than to inject air or aerate the hypolimnion through air-lift systems (Aquat. Syst. Eng. 1990). At Richard B. Russell Reservoir, Georgia, dissolved oxygen levels in the hypolimnion have been increased from < 3 mg/L to > 9 mg/L, with an oxygen transfer efficiency of about 75 percent (Gallagher and Mauldin, 1987; Mauldin et al. 1988). Liquid oxygen is stored in tanks on site and connected to several supply heads submerged and anchored in the reservoir. Flexible membrane diffusers mounted on the supply heads are used to maximize absorption efficiency and minimize maintenance requirements. Flexible membrane systems should last two to six years (or 10 years or more if operated ≤ 6 months per year); the compressor and distribution system should last substantially longer (an estimated 30-year life).

■ **Snowplowing to increase light penetration.** Snow removal from the lake surface to increase light penetration and photosynthesis (oxygen generation) under the ice is a low-tech, low-cost alternative to aerators and may be sufficient to prevent winterkill in lakes with marginal levels of dissolved oxygen (McComas, in press). Snow absorbs light much more effectively than ice. While 85 percent of the available light will penetrate 5 inches of clear ice, 5 inches of snow over 3 inches of ice will block out almost all light. Even thin layers of snow can greatly decrease light penetration, which decreases primary productivity and can lead to oxygen depletion and winterkill.

Even thin layers of snow can greatly decrease light penetration, which decreases primary productivity and can lead to oxygen depletion and winterkill.

If lake associations use volunteers, they can remove snow at relatively low cost. Snow should be removed from 30 percent or more of the lake surface, alternating between strips of cleared area and snow, rather than clearing the entire area. In general, snow removal prevents winterkill more effectively in shallow lakes with abundant rooted macrophytes than in deep lakes where phytoplankton are the dominant primary producer (McComas, in press).

Additional information on lake aeration systems can be found in Olem and Flock (1990), Cooke et al. (1986), Lorenzen and Fast (1977), and McComas (in press). The most cost-effective approach for increasing dissolved oxygen levels depends on the size (area and depth) of the lake, nature and causes of the problem, and fisheries management objectives.

Lake Liming and Other Methods for Decreasing Water Acidity

Waters may be naturally acidic (e.g., in regions with naturally acidic soils and large inputs of organic acids) or become acidified as a result of acid mine drainage, acidic deposition, or runoff from other anthropogenic sources of acids. Extensive research has been conducted recently to refine and test methods for neutralizing lake waters, using a variety of neutralizing agents as well as application techniques. *The Lake and Reservoir Restoration Guidance Manual* (pages 155 to 159, Olem and Flock, 1990) lists the following five basic approaches to treating acidic lakes:

Waters may be natural acidic or become acidified as a result of acid mine drainage, acidic deposition, or runoff from other anthropogenic sources of acids.

■ **Limestone addition to the lake surface.** Small limestone particles, limestone powder, or a limestone slurry are dispersed by boat, plane, or helicopter over the lake. Alternatively during winter, limestone can be spread on the ice by truck, enabling it to enter the lake in the spring as the ice melts. Direct addition of limestone to the lake surface is the most commonly employed method for decreasing lake acidity. Because limestone is used for agricultural purposes, it is usually available at low cost. However, the cost of limestone dispersal can be significant, particularly for remote lakes without road access. In addition, repeated applications are needed; lakes with short water retention times may need to be treated annually.

Direct addition of limestone to the lake surface is the most commonly employed method for decreasing lake acidity.

■ **Injection of base materials into the lake sediment.** Limestone, hydrated lime, or sodium carbonate can be injected into the lake sediments, resulting in a gradual decrease in lake acidity. This technique is largely experimental, however,

and limited to small, shallow lakes with soft organic sediments and road access for transport of application equipment. The treatment may last substantially longer than surface applications; however, it disturbs the lake's benthic community, increases turbidity, and costs more.

- **Mechanical stream doser.** Lake acidity may be decreased by neutralizing the acidic waters in upstream tributaries. Mechanical dosers are automated devices that release dry powder or slurried limestone directly into the stream, with the quantity of material added controlled by monitors of stream flow or chemistry. The treatment is continuous, expensive, and generally not recommended for lakes unless all other alternatives have been ruled out.

- **Limestone addition to the watershed.** Limestone is spread on all or parts of the lake's watershed, decreasing the acidity of runoff and shallow groundwater flow into the lake. Although the costs of one application are higher, the overall costs may be lower than for limestone applications to surface waters because the effects are much more long lasting. Watershed liming may be especially appropriate for lakes with short retention times (less than six months).

- **Pumping of alkaline groundwater.** Where abundant supplies of alkaline groundwater are available, these waters may be discharged directly into lakes or lake tributaries, decreasing acidity. Applications of this method have been limited, however, and the costs and effectiveness of this approach are not well known.

Many reports and books have been published on methods for liming lakes and streams, including Fraser et al. (1982), Fraser et al. (1985), Olem (1991), and Brocksen et al. (1992). Additional information can also be found in Olem and Flock (1990).

Spawning Habitat Management

Fish production in some waters may be limited by the availability of suitable sites for natural reproduction or the poor quality of available sites, resulting in relatively low reproductive success. The types of habitats required for spawning and the factors that influence spawning and reproductive success vary greatly among species (see Appendix A). Thus, the methods employed for spawning site management are also, to some degree, species-specific. The types of management activities fall within three broad categories: (1) efforts to protect existing spawning habitat, (2) spawning habitat improvements, and (3) construction of new spawning sites.

The first task required to protect or improve spawning habitat is to locate existing sites used by target fish species in the lake or associated streams. Some species spawn in dispersed areas throughout the lake, while others concentrate activities within fairly localized sites used consistently year after year. Potential areas should be visited regularly during the spawning season by trained observers to look for spawning adults, nests, or egg masses. However, finding spawning areas for species that spawn in deeper waters or that provide little noticeable evidence of spawning activity (e.g., do not build nests or lay eggs in visible masses) is much more difficult and time consuming. It will generally require SCUBA for underwater observations or sampling gear (see Appendix B) to detect the presence of eggs in the bottom sediments or water column.

- **Protection of spawning habitat.** Many fish species spawn in relatively shallow nearshore areas that are subject to disturbance from swimmers, boat traffic, and runoff from the adjacent watershed. It may be necessary to limit construction, land uses, or fertilizer applications in watersheds adjacent to critical spawning areas, including tributary streams used for spawning, or to divert and treat runoff that is high in suspended solids (to prevent excessive siltation that would decrease egg and larval survival).

It may be necessary to limit construction, land uses, or fertilizer applications in watersheds adjacent to critical spawning areas. . . .

Fish species that guard their spawning nest, such as largemouth and smallmouth bass and most sunfish species, are particularly susceptible to disturbances from swimming and boating. If repeatedly disturbed, males may eventually desert their nests, resulting in poor survival of eggs and fry. During spawning season, important spawning sites can be identified with buoys, and boat traffic and swimming should be restricted from these areas.

Waves rebounding off retaining walls may also drive off bass and sunfish males guarding nests. Shoreline structures that better absorb wave energy, such as riprap and vegetation, are preferable near important spawning areas.

■ **Spawning habitat improvements.** Siltation is a major cause of degraded spawning habitat. Some species such as bass, crappies, and bluegill sweep the nest area off with their tails before spawning; thus moderate siltation is not a major concern. Other fish such as walleye do not mechanically clean the lake bottom before spawning; therefore, the buildup of silt in walleye spawning areas can significantly decrease egg survival and may limit or prevent spawning activity.

Silt can be removed from spawning areas by using a water pump to blow the silt and algal growth off the rocks.

Silt can be removed from spawning areas by using a water pump to blow the silt and algal growth off the rocks. For example, a three-inch pump can generate enough force to remove silt from the rock face or turn cobble-sized rocks over to expose a new face. If mounted on a pontoon or raft, a water pump can clean several spawning sites in half a day (McComas, in press).

Brook trout have fairly restrictive spawning requirements, and as a result, the availability of suitable spawning areas is often an important factor limiting brook trout natural reproduction and productivity. Brook trout prefer to spawn in areas with upwelling, well-oxygenated groundwater in the littoral zone, tributary streams, or the lake outlet. Plants and sediments can accumulate on these underwater springs, obstructing groundwater flow and preventing brook trout spawning. The locations of underwater springs can be confirmed by inserting a small diameter pipe, such as two-inch PVC-type pipe, into the lake bottom. If upwelling groundwater is present, the water level in the pipe will rise above the lake level. Small-scale dredging techniques may then be used to remove the blanket of material obstructing the flow (see Chapter 4, Olem and Flock, 1990; McComas, in press). Carline (1980) provides examples of the success of this technique for spawning site improvements in Wisconsin lakes.

Finally, some fish species — including muskellunge and northern pike — spawn in flooded marshes and other heavily vegetated areas in bays or river floodplains. These heavily vegetated flooded areas also serve as important nurseries for young fish of many species. Therefore, in lakes and reservoirs with controlled water levels, reproductive success can be increased by raising water levels in spring to coincide with fish spawning and species' early life stages. The role of water level management for managing fisheries in lakes and reservoirs is discussed later in this chapter.

■ **Construction of new spawning sites.** In some instances, it may be worthwhile to add or construct new sites where important fish species can spawn. However, even the best-looking spawning habitat is not always used for spawning. Thus, the construction of new sites alone does not ensure that natural reproduction will be measurably increased.

The best time to build the reef is during winter, when it can be assembled on the ice and left until spring to fall into place as the ice melts.

Walleye spawn on rocky shoals in lakes or rocky areas in the white water below impassible falls and dams in rivers. Thus, rock reefs constructed at water depths of 1.5 to 4 feet may enhance walleye reproduction. The best time to build the reef is during winter, when it can be assembled on the ice and left until spring to fall into place as the ice melts (McComas, in press). Areas that receive silt-laden runoff should be avoided, since siltation will quickly make the reef unusable. In addition, the lake bottom in the area should be firm so that the added rubble will not sink. If extra support is needed, first deploy 4 to 6 inches of large-sized gravel

1/2 to 1 inch in diameter. The reef should be a mixture of rock sizes, with about 10 percent of the reef consisting of rock 3 to 5 inches in diameter, 50 percent 5- to 7-inch rock, and 40 percent 7- to 9-inch rock. In total, the reef should be about 12 inches thick. The Minnesota Department of Natural Resources (1975) distributes additional information on constructing walleye spawning shoals.

Spawning areas for lake trout have been constructed in a similar manner with quantities of large rocks at selected sites. The Maine Department of Inland Fisheries and Game dumped 170 tons of rock in a lake at a depth of 15 feet to provide a suitable spawning area for lake trout (Everhart and Youngs, 1981). Boxes of gravel or graveling large areas have been used in warmwater lakes as spawning aids for nest-building species such as smallmouth bass. To encourage minnow spawning and production, a variety of devices have been employed, including cut brush along the shore, spawning slabs, and floating boards for those species that lay their eggs underneath logs or other debris. Depending on conditions in the lake and the target fish species, construction of new spawning sites may be a cost-effective approach for improving fish production and yields.

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Addition of Physical Structures for Fish Cover

Some lakes and reservoirs lack sufficient structural features and areas for fish to hide — in particular, areas where younger, smaller fish can find cover to escape from larger fish and other predators. Without adequate cover, survival rates of young fish are often low, and high natural mortality rates can be an important factor limiting fisheries yields in some lakes. Structural features provide safety from predators, substrate for food organisms, and in some cases spawning habitat. Also, predators, which include most game species, tend to concentrate around structural features in search of prey. By concentrating fish into specific areas, the addition of fish cover, such as artificial reefs, can increase fishing success and angler satisfaction. In fact, the major impact of artificial reefs is often on fishing success. The effects of increased cover on game fish numbers and growth are less clear.

Fish cover can be provided by a variety of biological as well as physical structures. For example, macrophyte beds and flooded marsh areas provide excellent nursery areas for young fish. For a discussion of aquatic plant management for fish cover, see the next subsection.

Common types of physical structural habitat include docks and piers, fallen logs, brush piles, rock reefs, and drop-offs as well as constructed artificial reefs. The best reef design depends on the target fish species, available building materials, and lake morphometry. However, three general design characteristics should be incorporated:

- Maximum structural complexity to increase the number and variety of hiding places and attachment surfaces for food organisms.
- Sufficient weight for stability so that the reef stays in place.
- Non-toxic materials that do not deteriorate in a short period of time.

Examples of construction techniques include the following:

- **Brush piles.** Brush may be held together using a frame constructed of heavy wood or simply bundled together and weighted down with a concrete block to sink (Fig. 8-4a). Although easy to construct, brush piles degrade relatively quickly, releasing nutrients into the water column. Piles consisting of green trees and brush with thicker branches are sturdier and longer lasting. Largemouth bass, bluegill, and other panfish, in particular, may use brush piles for cover. For example, Pierce and Hooper (1979) found 4 to more than 10 times higher densities and biomass of largemouth bass, channel catfish, bluegill, and white crappie near brush piles installed in Barkley Lake, Kentucky, than in control areas.

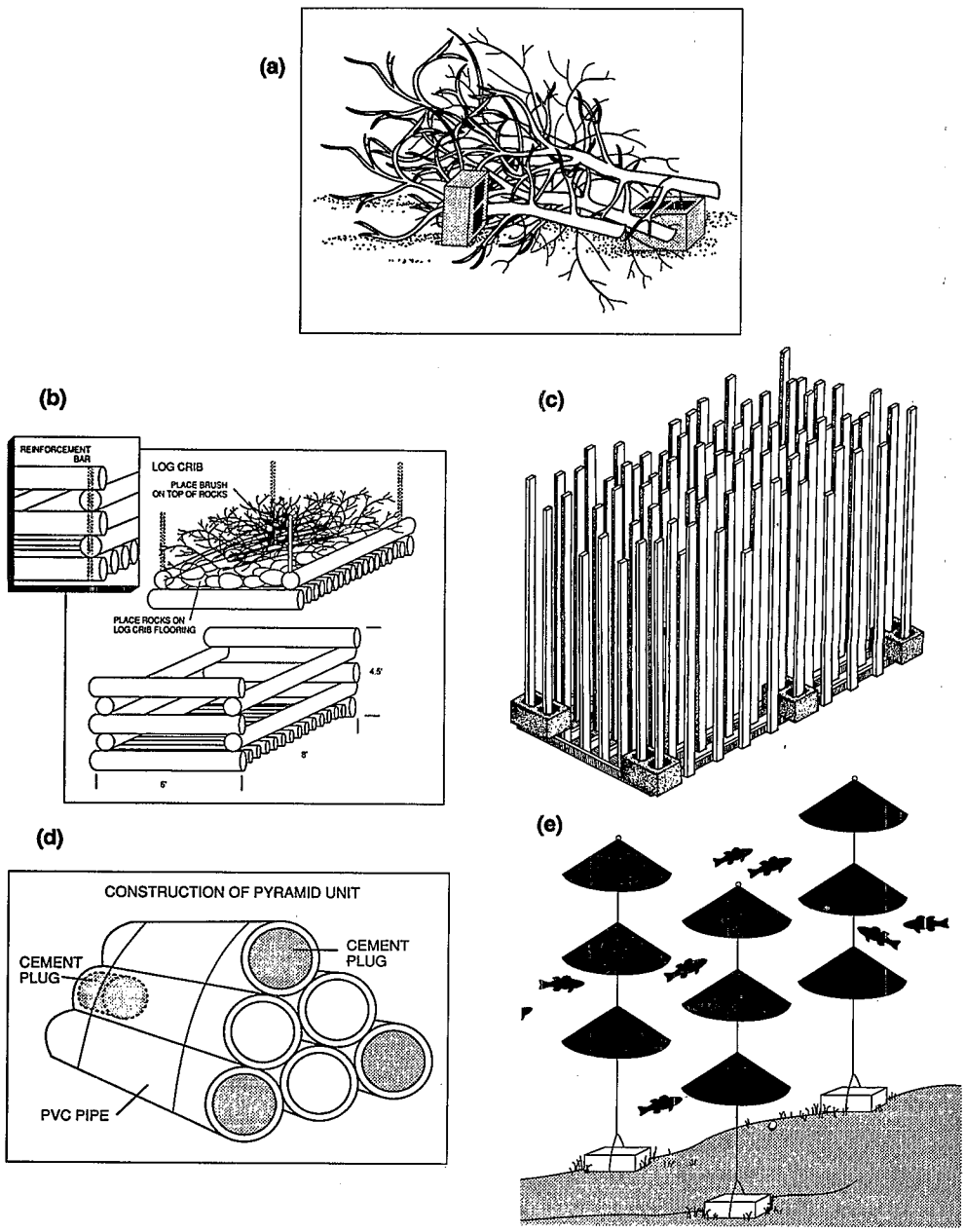


Figure 8-4.—Construction techniques for artificial reefs: (a) brush pile, (b) crib, (c) stake bed, (d) piping, and (e) plastic structures (source: Phillips, 1990).

■ **Cribs.** (Fig. 8-4b) Cribs are wooden frames constructed of heavy logs and generally filled with large rocks and brush. Target fish species include walleye, bass, panfish, and catfish.

■ **Stake beds.** (Fig. 8-4c) Stake beds, generally constructed of green lumber, consist of sawmill stakes and two-by-fours weighed down by concrete construction blocks. Primary target fish are largemouth bass, crappie, and panfish species.

■ **Piping.** (Fig. 8-4d) Suitable fish cover can be made from vitrified clay, PVC, or corrugated polyethylene pipes bundled together in a pyramid shape with a cement plug for ballast. Catfish and bullhead, in particular, use reefs made from pipes.

■ **Concrete block/rubble/rock piles.** Small piles of rock and broken concrete blocks of various sizes attract a variety of fish, including catfish, bass, panfish, and walleye.

■ **Plastic structures.** A variety of structures made of plastic have been designed specifically to serve as fish cover (see Fig. 8-4e).

Artificial reefs should be placed in areas that lack natural cover where they will be used by the targeted species of fish and are accessible to anglers. In addition, the reef must not pose a hazard to boat and skier traffic. Thus, reefs should be located out of boating lanes and at sufficient depth to allow safe passage. The reef location should also have a firm substrate such as sand, stone, or clay. Soft bottoms of silt or mud are not recommended because the heavier reef materials may eventually subside and disappear. Finally, artificial reefs should not be placed directly on existing productive bottom habitat, such as natural shoals or submerged trees or brush. Generally, several smaller reefs at a range of water depths and locations are preferable to one large unit.

[R]eefs should be located out of boating lanes and at sufficient depth to allow safe passage.

Because artificial reefs increase angler efficiency and can aggravate problems associated with overfishing, they should not be installed in small or heavily fished lakes. Furthermore, most of the research on artificial reefs has involved warmwater or coolwater species; relatively little is known about the response of trout and other salmonids. Guidelines for constructing and installing artificial reefs have been prepared by the Sport Fishing Institute (Phillips, 1990) and also many state fisheries agencies. Brown (1986) provides a review of the use of artificial structures in reservoirs (also see Box 8-B).

Aquatic Plant Management

While fish and fisheries generally benefit from adequate areas of fish cover, too much cover can be detrimental. Smaller fish may have too many areas in which to hide. As a result, survival rates will be high, possibly leading to overcrowding, slow growth rates, stunted populations, and low yields of piscivorous game fish, such as largemouth bass (see Chapter 3).

The most common cause of excessive fish cover is extensive growths of aquatic macrophytes. In lakes and reservoirs where thick beds of macrophytes cover a high proportion of the lake bottom, an aquatic plant control program may be needed to improve yields of large predatory game fish and increase the growth rates of panfish species, such as bluegill and white and black crappie. For fisheries management, however, the goal is to reduce but not eliminate macrophyte growths. More so than for other lake uses such as swimming and boating, fisheries are enhanced by moderate growths of aquatic plants. The complete elimination of macrophyte beds may be as harmful as excessive plant growths.

The specific objective of aquatic plant management, therefore, is to provide the appropriate amount of aquatic plants, taking into account the effects of macrophytes on fish communities (e.g., Fig. 8-5), other lake uses (e.g., swimming and boating), nutrient cycles, and aesthetics. Macrophytes and terrestrial vegetation also help stabilize the lake bed and shoreline, reducing problems with lake shore erosion and high turbidity.

For fisheries management, however, the goal is to reduce but not to eliminate macrophyte growths.

Excessive plant growths as a result of eutrophication or the inadvertent introduction of an exotic macrophyte species are a common lake problem. *The Lake and Reservoir Restoration Guidance Manual* (pages 135-151, Olem and Flock, 1990) provides a thorough discussion of the various approaches to control nuisance plant growths:

■ **Sediment removal and sediment tilling.** Lakes can be dredged to remove sediment and deepened so less of the lake bottom receives adequate light for macrophyte growth. The maximum depth at which macrophytes can grow

Box 8-B.—The Use of Brush Shelters as Cover by Spawning Bass in Bull Shoals Reservoir

(Vogele and Rainwater, 1975)

Black bass, including largemouth, smallmouth bass, and spotted bass, prefer nesting sites with cover. In some reservoirs with fluctuating water levels, the amount of available cover varies with the spring water elevation. Often natural cover is scarce in years when water levels are low but abundant when water levels are relatively high. Successful bass reproduction in these reservoirs appears to correlate with high springtime water levels.

Brush shelters were added to selected areas in coves of Bull Shoals Reservoir in the spring of 1972, when the water level was low. Observations indicated that spotted bass consistently preferred to spawn near these sheltered habitats; largemouth bass preferred nesting sites near the brush shelters early in the spawning season. Smallmouth bass, on the other hand, exhibited no preference for areas with brush shelters, but instead spawned primarily in areas with specific substrate types of rock and gravel. Although the overall effect of the brush shelters on bass abundance was not assessed, additions of brush piles and other structures may be a useful management tool for improving bass reproductive success during years when springtime water levels are low.

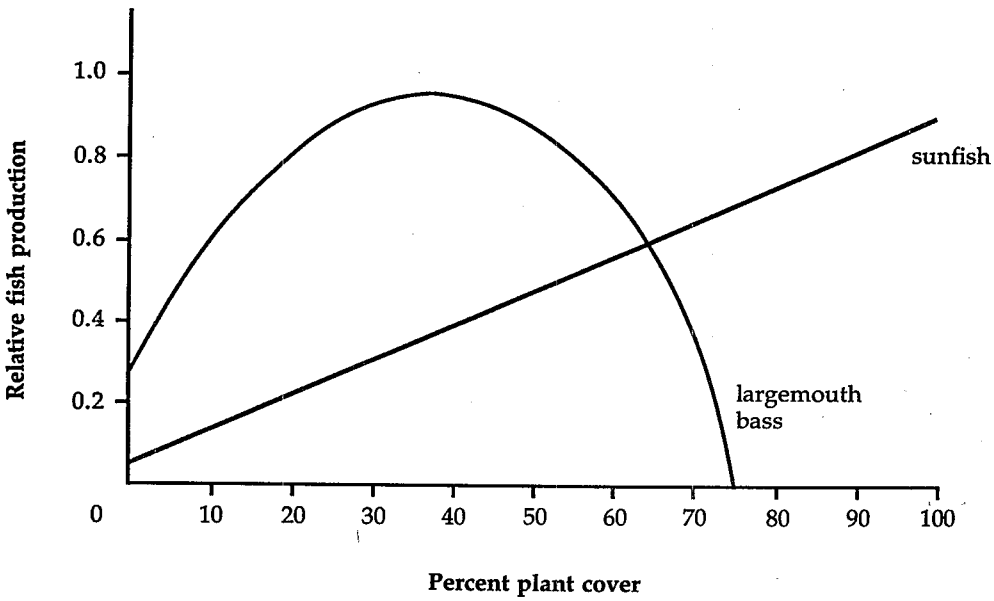


Figure 8-5.—Relative production of largemouth bass and sunfish as a function of aquatic plant cover. Optimal plant cover for bass production is 36 to 40 percent, based on a trophic model (source: Wiley et al. 1987).

depends on water transparency and the plant species. *Hydrilla*, a nuisance exotic plant in southern waters, can grow at lower light intensities than native plants (Canfield et al. 1985), making control through lake deepening a difficult task. Reductions in nutrient loads to control eutrophication can increase lake transparency, increasing the depth at which macrophytes can grow and countering the effectiveness of dredging to reduce macrophyte growth. Sediment removal and tilling — e.g., rototilling using cultivation equipment (Newroth and Soar, 1986) — can also be used to disturb the lake bottom and tear out plant roots for short-term macrophyte control. Both dredging and tilling can have negative side effects, including destruction of the benthic community and an increase in turbidity and siltation (Olem and Flock, 1990).

■ **Water level drawdown.** In lakes where water levels can be controlled, lake levels can be lowered to expose macrophytes in the littoral zone to prolonged drying and/or freezing. Some species of plants are permanently damaged by these conditions, which can kill the entire plant including roots and seeds after exposures of two to four weeks. Other plant species are unaffected or even increase (Table 8-3). Water level management to control macrophyte growths and for other purposes is discussed further in the next section.

Table 8-3.—Response of common aquatic plants to water drawdown (source: Olem and Flock, 1990).

DECREASE	INCREASE	VARIABLE
coontail (*Ceratophyllum demersum*)	alligatorweed (*Alternanthera philoxeroides*)	waterhyacinth (*Eichhornia crassipes*)
Brazilian elodea (*Egeria densa*)	hydrilla (*Hydrilla verticillata*)	common elodea (*Elodea canadensis*)
watermilfoil (*Myriophyllum* spp.)	bushy pondweed (*Najas flexilis*)	cattail (*Typha latifolia*)
southern naiad (*Najas guardalupensis*)		
yellow waterlily (*Nuphar luteum*)		
waterlily (*Nymphaea* spp.)		
Robbin's pondweed (*Potamogeton robbinsii*)		

■ **Shading and sediment covers.** Covers can be placed on the water or sediment surface as a physical barrier to plant growth or to block light (Engel, 1984). Sediment covers made of polypropylene, fiberglass, or other similar material can effectively prevent growths in small areas, such as near docks and swimming areas, but are generally too expensive to install over large areas. Applications of silt, sand, clay, or gravel have also been used, but plants eventually root in them. Shading to reduce growth rates can be provided by floating sheets of polyethylene (Mayhew and Runkel, 1962) or by planting evergreen trees along the lake shore (Engel, 1989).

■ **Introduction of grass carp.** Grass carp is an exotic fish species that feeds on macrophytes. The use of grass carp for aquatic plant management is discussed in Chapter 9.

■ **Introduction of insects that infest macrophytes.** Several exotic insect species have been imported to the United States and approved by the U.S. Department of Agriculture (USDA) for use in macrophyte control. Each insect species grows and feeds on only select target plant species. In particular, insects have been used in southern waters to aid control of alligatorweed and waterhyacinth (Sanders and Theriot, 1986; Haag, 1986). Because insect populations tend to grow more slowly than the plants, insects work best when used in conjunction with another plant control technique, such as harvesting or herbicides. No significant negative side effects from insect infestations have been documented (Olem and Flock, 1990).

■ **Mechanical harvesting.** Mechanical harvesters constructed on low-draft barges can be used to cut and remove rooted plants. Cutting rates range from 0.2 to 0.6 acres per hour, depending on machine size; Cooke et al. (1986) provide a listing of commercially available plant cutters. Harvesters can effectively clear an area of vegetation, although the benefits are only temporary. Rates of plant regrowth can be rapid (within weeks) but can be slowed if the cutter blade is lowered into the upper sediment layer (Conyers and Cooke, 1983). Removing cut plants eliminates an internal source of nutrients and organics and can have long-

[H]arvesting operations should precede spawning periods and/or avoid important spawning and nursery areas.

term benefits. However, some plant species, such as watermilfoil (Nicholson, 1981) that can be fragmented and dispersed, actually increase in abundance after harvesting operations. Also, small fish can be caught and killed by mechanical harvesters. Thus, harvesting operations should precede spawning periods and/or avoid important spawning and nursery areas.

■ **Herbicides.** Herbicides used to kill aquatic plants include Diquat, endothall, 2,4-D, glyphosate, and fluridone (Olem and Flock, 1990). Although herbicide treatments can rapidly reduce macrophyte growths, the benefits are short term and the potential for negative side effects is high. Plants are left in the lake to die; decomposition releases plant nutrients and, in some cases, causes oxygen depletion and algal blooms. Plants generally regrow after several weeks or months or may be replaced by other more tolerant macrophyte species.

Most chemicals currently approved are toxic to aquatic organisms and humans only at relatively high doses. Little information is available, however, on the long-term ecological consequences of herbicide use. Herbicide applicators must be licensed, have adequate insurance, wear protective gear, use only EPA-approved chemicals, and follow label directions exactly. Generally, because they do not remove nutrients or organics from the lake or address the cause of the aquatic plant problem, herbicides should be used only where other techniques are unacceptable or ineffective. Westerdahl and Getsinger (1988) provide guidelines for herbicide use and application.

Table 8-4.—Comparison of lake restoration and management techniques for control of nuisance aquatic weeds (source: Olem and Flock, 1990).

TREATMENT (ONE APPLICATION)	SHORT-TERM EFFECTIVENESS	LONG-TERM EFFECTIVENESS	COST	CHANCE OF NEGATIVE EFFECTS
Sediment removal	E	E	P	F
Drawdown	G	F	E	F
Sediment covers	E	F	P	L
Grass carp	P	E	E	F
Insects	P	G	E	L
Harvesting	E	F	F	F
Herbicides	E	P	F	H

E = excellent; F = fair; G = good; P = poor; H = high; and L = low, based on the consensus judgment of 12 lake restoration experts.

The relative effectiveness, costs, and potential for negative side effects for each of these techniques is summarized in Table 8-4.

In some lakes, especially newly impounded reservoirs, the problem may be too few rather than too many macrophytes. In such cases, it may be desirable to introduce (transplant) suitable plants — such as sago pondweed, wildcelery, and lily pads — or raise water levels to flood vegetated areas. In lakes with fluctuating water levels, terrestrial plants such as winter wheat or ryegrass can be planted in the exposed lake bed during periods of water drawdown. These plants provide both erosion control during drawdown and fish cover when the lake is reflooded, with no risk of developing nuisance levels or excessive plant growths. Howells (1986) and Evans (1989) provide guidelines for establishing plants in water fluctuation zones and managing plant communities in southern reservoirs. The joint use of plant and water level management to improve fish habitat is discussed further in the next section.

Water Level Management

For many years, large fluctuations in water level were believed detrimental to fish communities and fisheries. While large, uncontrolled fluctuations may be detrimental, controlled changes in water level at the right time, place, and mag-

nitude can be beneficial and provide an important management tool for maintaining and improving a lake ecosystem and fisheries. Water level management can be used for a number of purposes:

[C]ontrolled changes in water level at the right time, place, and magnitude can be beneficial and provide an important management tool for maintaining and improving a lake ecosystem and fisheries.

■ **Water level drawdowns to control aquatic macrophytes and periphyton.** As noted in the previous section, water level drawdowns are one of a number of approaches for controlling growths of aquatic plants. Not all plants are equally susceptible, however, and growths of resistant species may actually increase (Table 8-3). Generally, both desiccation and freezing are required to kill the roots and, in some cases, seeds of aquatic plants. Thus, drawdowns for vegetation control are usually conducted during winter, and programs are consistently successful only in areas where winter temperatures are sufficiently low. For example, growths of Eurasian watermilfoil were actually more extensive after a winter drawdown on a lake in Oregon where the mild, wet winter of the Pacific Northwest did not provide adequate freezing (Geiger, 1983). By contrast, winter drawdown in Murphy Flowage, Wisconsin, significantly decreased the extent of macrophyte beds with an associated improvement in fishing. Winter drawdowns have also been used to reduce growths of periphyton in walleye spawning areas.

■ **Water level drawdowns to control overcrowded, stunted fish populations.** Water level drawdowns also may be used to counter the effects of too much fish cover, which can result in overcrowded, slow-growing fish populations. When the water level is lowered, fish are forced out of macrophyte beds in the littoral zone and into the open water. As a result, small fish are more susceptible to predation; increased predation reduces the number of small fish, alleviating overcrowding problems. In addition, at least in the short term growth rates and condition factors of predatory fish are improved. Increased feeding immediately after drawdown has been reported for northern pike, largemouth bass, smallmouth bass, white bass, walleye, white crappie, and flathead catfish (Willis, 1986). To be most effective, drawdowns for fish control should be conducted when lake waters are warm (above 55°F) and fish are actively feeding and should last two to three months. However, after prolonged drawdown, fish growth may decline as concentrations of prey diminish and invertebrate productivity and fish reproduction remain low.

■ **Water level drawdowns to construct or enhance fish cover.** In lakes and reservoirs where the quantity of fish cover is inadequate, fisheries managers may take advantage of water level drawdowns to enhance fish cover by building artificial reefs or planting or allowing terrestrial vegetation to grow, which then serve as spawning and nursery areas when water levels rise. Growths of terrestrial vegetation on emerged shoals may be especially useful in reservoirs with high turbidity and inadequate light penetration for aquatic macrophytes.

■ **High water levels in the spring to provide increased spawning and nursery areas.** For some fish species, strong year-classes (i.e., high reproductive success) occur most often in years with rising or high water levels during and for several months after the spawning season. The flooded vegetation and marshy areas around the lake provide increased spawning substrate for species like northern pike and muskellunge and nursery areas for the young of the year of many fish species. Rapidly rising water levels also often result in at least a temporary increase in food supplies and increased growth rates for opportunistic fish — such as largemouth bass, sunfish, bullheads, and white catfish — that take advantage of the influx of terrestrial invertebrates.

■ **Water level drawdowns during spawning to reduce the reproductive success of undesirable fish species.** If desired, water level management also can be used to decrease the quantity of spawning substrate and nursery areas, thus reducing reproductive success. Mortality of eggs and young-of-the-year fish stranded by water level drawdowns has been reported for many fish

species. However, shifts in water level to either reduce or promote reproductive success will have measurable impacts on fish abundance only if spawning and early life-stage survival are critical limiting factors for the population. Water level management as an approach to controlling year-class strength has been successful only in some cases.

In lakes with a well-maintained outlet structure and drawdown capability, the dollar costs of a water level management program are minimal, and any or all of these actions may be useful for fisheries management. However, potential adverse side effects include

- impacts on other lake uses, such as swimming and boating;
- damage to shore banks, shorelines, and shoreline retaining walls;
- reduced numbers and diversity of benthic invertebrates in the littoral zone that are important prey items for some fish species; and
- an increased likelihood of winterkill during winter drawdowns.

Drawdowns should be conducted only in lakes with a steady water inflow sufficient to refill the lake when needed.

Drawdowns should be conducted only in lakes with a steady water inflow sufficient to refill the lake when needed. Ploskey (1982, 1986) presents additional information on the benefits and design of water level management programs.

Reservoir Construction

Physical features that can be altered only slightly once a lake is constructed may drastically affect the fish community and cost of maintaining quality fishing. Factors such as watershed area, watershed usage, and the erodibility of soils in the watershed will impact lakewater quality. Lake volume, mean and maximum depth, watershed topography, shoreline development, and basin slope will influence the degree of thermal stratification and other lake characteristics that indirectly affect the suitability of the lake habitat for fish. For example, Hill (1986) identified three primary physical characteristics associated with the quality of fishing in small reservoirs in Iowa:

1. the mean basin slope;
2. the watershed to lake area ratio; and
3. an adjusted siltation index based on the watershed to lake area ratio, soil erosion rates for soil types in the watershed, and the proportion of the watershed farmed using approved soil conservation practices.

All of these physical features can be determined before lake construction and should influence site selection, lake design, and construction methods.

The following factors are relevant specifically to fisheries management and important to consider when designing and constructing small lakes and reservoirs:

- The watershed should be well vegetated to prevent excessive siltation and free of pesticides and other pollutants. Runoff from row crops, livestock operations, and industrial sites (or from areas where erosion cannot be controlled) should be treated or diverted around the lake. Limited lakeshore development and no septic discharges into the lake should be allowed.
- The optimal watershed size and watershed-to-lake-area ratio depends on the lake volume, rate of rainfall, and topography and land uses in the watershed. In Georgia, the recommended watershed size for a small, one-acre lake is about 10 acres of pasture or 25 acres of forested watershed (Ga. Dep. Nat. Resour. 1988). Illinois recommends 20 acres of watershed per surface acre of water as a rule of thumb (Ill. Dep. Conserv.).

- The amount of timber and brush that should be cleared from the lake basin before filling depends on the lake's size and planned uses. In small lakes (< three acres), all trees, stumps, and brush should be removed to produce the maximum harvestable fish biomass. In larger reservoirs on the other hand, it is often desirable to leave small blocks of well-placed timber and brush near the shoreline in coves and embayments to provide fish cover. Timber should be cleared, however, in the area of the dam in recreational and boating areas. It should be cleared in the deeper parts of the reservoir where it is unlikely to improve fishing and may aggravate problems with oxygen depletion as the organic matter left behind gradually decomposes. Too much standing timber and brush can provide excessive fish cover and should be avoided.

In larger reservoirs . . . it is often desirable to leave small blocks of well-placed timber and brush near the shoreline in coves and embayments to provide fish cover.

- If natural spawning areas and fish cover must be supplemented, spawning sites and artificial reefs can be constructed more easily before the lake fills than afterward.
- Extensive shallow areas will encourage growths of aquatic macrophytes, an undesirable feature in most small lakes designed for fishing and fish production. Recommended slope ratios along the shoreline are generally 2:1 or 3:1. Also, sand blankets, gravel beds, or fiberglass mats may be used to inhibit rooted plant growth in selected areas.

Recommended slope ratios along the shoreline are generally 2:1 or 3:1.

- Water depths should be sufficient to minimize problems with low levels of dissolved oxygen in the winter and late summer. Illinois, for example, recommends that lakes be at least one acre in area and 10 to 12 feet deep in 25 percent of the basin for successful fish management.
- The dam and water overflow should be constructed to allow easy control of water levels by using a drain pipe or gate valve. In most cases, a standpipe overflow is recommended to draw water from deeper areas of the lake.
- Upstream migration of undesirable fish and, to a lesser degree, the downstream migration of game fish can be hindered by constructing the emergency spillway with a substantial vertical fall of at least 4 feet and sufficiently wide so that water depths over the spillway never exceed 2 inches.

Additional guidelines on the design and construction of small lakes and reservoirs are available from most State fisheries agencies (e.g., Okla. Dep. Wildl. Conserv. 1984; Ill. Dep. Conserv.; USDA Soil Conservation Service, 1982).

Manipulating the Fish Community

Many fisheries management techniques involve the direct manipulation of the fish community and other organisms that may serve as prey for or be predators or competitors with the fish species of interest. Three of these activities are discussed here: game fish stocking, control of undesirable fish species and stunted fish populations, and prey enhancements to supplement food supplies.

Game Fish Stocking

Stocking was once considered the panacea of fisheries management. If catch rates declined or were too low, more fish were stocked. If anglers wanted bigger fish or different kinds of fish and fishing opportunities, new, larger species were stocked. Unfortunately, as a result of overzealous stocking programs in the past, native fish communities have been disrupted, wild strains of fish have been lost, genetic

Stocking is not a panacea or remedy for all problems, but it does have a role in fisheries management when used in the right manner and in the right locale.

diversity has declined, and what were once considered desirable fish species and stocked widely (e.g., the common carp) are now nuisance fish difficult to eradicate in many waters and regions (Hebert, 1991; Allendorf, 1991).

Stocking is not a panacea or remedy for all problems, but it does have a role in fisheries management when used in the right manner and in the right locale. If reproductive success is limited by the absence or poor quality of available spawning habitat, stocking of young fish can supplement those produced naturally, thereby increasing fish abundance and fisheries yields. If the lake is suitable for fish survival and growth during only some parts of the year yet demands for fishing opportunities are high, it may be worth the cost to establish a put-and-take fishery, stocking large, catchable-sized fish each spring. Finally, introductions of new species through stocking to increase and diversify fishing opportunities may be appropriate and beneficial in some waters.

Stocking is not always successful, however, and can be an expensive error if the returns from stocked fish are low and fishing quality is improved little, if at all. Because of habitat constraints, food limitations, or an abundance of predators and competitors, few of the fish stocked may survive or growth rates may be slow. Additionally, the fish added to the lake may simply replace an already existing population and fishery, with no net increase in total yield or fishing opportunities. Thus, before initiating a stocking program, carefully consider the following:

- Are there other management measures, aside from stocking, that could achieve the fisheries goals and specific objectives at lower cost, with longer-term benefits or with less disruption of the existing biological community?
- What are the characteristics of the fishing demands? What kind(s), sizes, and abundance of fish are desired?
- What are the characteristics of the species and strain(s) of fish being considered for stocking — their habitat requirements, growth potential, longevity, reproductive potential, and vulnerability to angling?
- What species and strains are best suited to the lake environment (physical, chemical, and biological characteristics of the habitat) and the fishing demands?
- What impact will stocking have on resident wild fish and on other fish and biological populations in the lake? Fish should never be stocked where populations of suitable fish are already at the carrying capacity of the waterbody. In addition, particular care should be taken to avoid introducing species that will prey on desired species already present or compete with them for food, shelter, or spawning habitat, or where native wild strains of the species still exist. Potential effects of fish introductions on other biota and water quality are discussed in Chapter 9.
- Is the introduced species or strain likely to migrate into other waters in the drainage basin where it is not wanted and may cause harmful effects to existing fish communities?
- What are the likely returns? What proportion of the stocked fish is likely to survive and eventually be caught by anglers? By how much will fisheries yields increase? To what degree will the quality of fishing increase as a result of the stocking? How confident and reliable are these projections?
- How long will the benefits last? Will the introduced fish reproduce or must stocking be repeated annually?
- How many fish of what age and size should be stocked for maximum return at the least cost?

- When and where should fish be stocked in the lake?
- How much will the stocking program cost, and how do the overall benefits and costs compare? How do the net benefits (benefits minus costs) of stocking compare to the net benefits from alternative management measures for improving the fishery, such as habitat improvement?

Allendorf (1991) summarized the following concerns regarding the introduction of nonnative fish species or strains through stocking programs: (1) Introduced fish can adversely affect native fish and other biota through predation, competition, hybridization, and the introduction of diseases (see Chapter 3). (2) All fish introductions involve some ecological costs, and in general, current understanding of natural systems is not sufficient to accurately predict what these ecological costs and damages will be. (3) The benefits of fish introductions occur immediately, while harmful effects are often delayed. Furthermore, (4) most of the harmful effects, including the loss of native fish populations and decline in genetic diversity, are irreversible. Therefore, (5) the potential benefits and risks associated with fish introductions must be carefully weighed.

Li and Moyle (1981) recommended that introductions of nonnative species or strains be considered only for systems that have been so altered by human activity that it is necessary to create a new biological community to take advantage of the change in environmental conditions (e.g., in reservoirs or eutrophied lakes) and also are isolated from other bodies of water so that uncontrolled spread of the species is unlikely. Leach and Lewis (1991), Stanley et al. (1991), and Wingate (1991) review Federal and State/provincial policies and regulations regarding fish introductions in the United States and Canada.

[I]ntroductions of nonnative species or strains (should) be considered only for systems that have been so altered by human activity that it is necessary to create a new biological community to take advantage of the change in environmental conditions . . . .

Additional guidelines on fish stocking and fish culture can be found in Stroud (1986).

- **Uses.** Stocking may be used to
  - supplement an existing population (e.g., where natural reproduction is not sufficient to satisfy angler demands);
  - maintain a population that exists in a lake but cannot reproduce itself;
  - add a new species to an existing fish community complex;
  - restock waters after some natural or human-made catastrophe, such as winterkill or pollution, or after chemical reclamation (fish poisoning), discussed later in this chapter; or
  - introduce fish into a newly constructed lake that is currently fishless.

Depending on the circumstances, the design of the stocking program and major factors of concern will vary.

For lakes that are currently fishless, the need for stocking is obvious if a fishery is desired. The major design objective is simply to select the species or group of species best suited to the habitat that will best fulfill the fishing demands (the goals and objectives of the fisheries management program; see Chapter 5). The introduction of fish will, however, have major implications for other ecosystem components, causing a shift in the abundance and composition of amphibian, benthic, zooplankton, and other biological communities.

An introduced species or strain may adversely affect existing fish populations, resulting in a net negative effect.

Likewise, for maintenance stocking of an already established population, the need is clear (as long as it is desirable to maintain the current fisheries). The major design concern in this instance is selecting the most cost-effective combination of how many fish, what size, and when and where to stock to produce the maximum return at the lowest cost.

Box 8-C.—Lake Characteristics Associated with Successful Walleye Introductions (Bennett and McArthur, 1990)

Attempts to introduce walleye into lakes and reservoirs where they do not already exist have met with varying success, ranging from highly successful to complete failure. Historically, only about one in three attempts has resulted in the establishment of a self-sustaining walleye population. Because of the expense and difficulties involved, walleye should be stocked only into waters with a high probability of success. Analyses by Bennett and McArthur (1990) identified three lake characteristics that were significantly correlated with the success of walleye introductions:

- **Larger lake area** — The probability of success was higher in larger lakes and reservoirs. In general, walleyes prefer lakes larger than 1,000 acres.
- **Greater maximum depth** — Success rates were higher in deeper lakes. Other researchers have noted that walleye prefer thermally stratified lakes or moderately shallow waters where shelter, turbidity, or water color shield their eyes from light. Large, deep waters occlude light and thermally stratify.
- **Higher pH** — Walleye can successfully reproduce in waters with a pH of 6.0 to 9.0. The correlation between stocking success and higher pH may reflect the direct effects of lake pH and also serve as a surrogate for other chemical characteristics associated with pH, such as water hardness and calcium levels.

Walleye introductions were also more likely to be successful in older reservoirs than in newly constructed reservoirs. Older reservoirs tend to have accumulated more nutrients and generally are more mesotrophic.

Bennett and McArthur (1990) present predictive models to estimate *a priori* the likelihood of successful stocking and identify target waters for walleye introductions.

On the other hand, for stocking new species into an existing fish community and supplemental stocking, the value of stocking may be less certain. An introduced species or strain may adversely affect existing fish populations, resulting in a net negative effect. Supplemental stocking may or may not increase fish abundance and fisheries yields. Only if stocking addresses key factors currently limiting fish production in the lake will a supplemental stocking program have any likelihood of success.

Stocking also can be used to introduce fish prey or predators and competitors that may aid in controlling undesirable fish species. The emphasis in this section, however, is on stocking target game fish. Stocking programs for prey, predators, and competitors are discussed later in the chapter.

■ **How to determine the best species to stock.** The species must be well suited to the lake environment in terms of temperature preferences, oxygen requirements, physical habitats for feeding and spawning, available prey, occurrence of predators and competitors, and all of the other physical, chemical, and biological habitat characteristics that influence fish population success (see Chapter 3 and Box 8-C). In addition, to the degree possible the species should reflect angler preferences for particular types of fishing opportunities. Species highly desired by local anglers should only be stocked, however, if they have a high probability of surviving and growing in the lake's environment without significantly disrupting other important fish populations and biological communities.

It is preferable to stock only species and strains native to the region or those routinely used in fisheries management programs in nearby waters.

It is preferable to stock only species and strains native to the region or those routinely used in fisheries management programs in nearby waters. Introductions of fish species that do not currently occur in other similar waters in the region are less likely to succeed and more likely to result in unexpected adverse repercussions, including the inadvertent invasion of the species into other waters in the area. Stocking nonnative species is discouraged and should be done only with caution and when consistent with the overall lake management goals.

Some combinations of species tend to work better than others, and most State fisheries agencies have a pre-established set of recommended fish combinations or types. For example, many warmwater fisheries programs rely on the combination of largemouth bass and bluegill sunfish, sometimes accompanied by channel catfish and other sunfish species. Fish species may be selected because they fill a particular niche in the environment or satisfy a specific fishing demand. For example, striped bass stocking has been used to create a late fall and winter fishery in many southern reservoirs. Striped bass and striped bass hybrids also have produced midsummer pelagic fisheries on large open water reservoirs as well as deep-water trolling in mountain reservoirs.

Special hybrids or species strains are stocked in some cases because they are more robust, faster growing, or have other desirable characteristics (e.g., low reproductive potential for species that tend to overpopulate waters). Examples include the striped bass-white bass hybrid, the tiger musky (northern pike-muskellunge cross), and a variety of sunfish hybrids. The Florida subspecies of largemouth bass generally grows faster and larger than its northern counterpart but is also less tolerant of low water temperatures. In southern States as far north as Oklahoma, Florida largemouth bass have been stocked into high quality bass waters to provide trophy fishing.

Appendix A provides additional information on the preferred habitats and characteristics of important game fish that may be used in selecting fish species for stocking. However, consult a professional fisheries biologist before stocking any fish. Most State fisheries agencies can provide expert advice on the best types of fish to stock in a given region and lake type.

[C]onsult a professional fisheries biologist before stocking any fish.

■ **Hatchery versus wild fish strains.** Trout species, in particular, have been raised for many years in hatcheries — so long, in fact, that distinct hatchery strains of fish have developed. For generation after generation, those fish that survived and grew best in the hatchery environment were selected for breeding, eventually resulting in hatchery strains of fish better adapted for life in the hatchery than in the wild. For example, compared to wild strains, hatchery strains of brook trout

- feed better on hatchery diets (i.e., food pellets distributed on the surface or sinking through the water column) than on natural diets;
- are more docile, with reduced fright reactions and territoriality (because hatchery fish are reared in the presence of humans and fed by them, they are also much more easily caught by anglers);
- have less stamina and less ability to adapt to and withstand environmental stresses (thus, hatchery strains are less robust than wild strains when exposed to stressful conditions and environmental fluctuations); and
- are faster growing and mature earlier, which generally means a shorter life span (while wild strains of brook and rainbow trout often live to be four to six years old, the maximum age for hatchery strains is typically two to three years).

Similarly, years of selection in the wild have resulted in resident wild strains of fish highly adapted for survival in their specific environment. A single species of fish may have a number of recognizable strains from different regions or different types of waters, each with subtle but important differences in their basic characteristics that may affect their survival and growth in a given lake or reservoir.

When hatchery strains are stocked into waters that currently support wild strains of the species, the added competition and interbreeding may result in the decline and loss of the native wild strain. The characteristics of the wild strain that made them especially robust and well adapted to their environment may be irreversibly lost. Therefore, fish should be stocked into waters with existing

[F]ish should be stocked into waters with existing populations of the species only after careful consideration of the potential for long-term detrimental impacts on native populations and the loss of fishing opportunities for unique wild strains.

Many stocking programs rely primarily on stocking fingerlings.

High stocking rates may lead to interspecies competition and reduced growth rates; low stocking rates may produce fewer fish of larger size.

populations of the species only after careful consideration of the potential for long-term detrimental impacts on native populations and the loss of fishing opportunities for unique wild strains.

■ **What size fish should be stocked?** Fish can be stocked into lakes and reservoirs as eggs, fry (1 to 4 months old and less than 1.5 inches), fingerlings (4 to 11 months old, finger length), yearlings (1-year-old fish), or adults. For any given water and species, the selection of an optimal size for stocking depends on (a) the availability and cost of obtaining fish of different sizes (some species are easier and cheaper to rear than others) and (b) the abundance of predators and other factors likely to result in poor survival of smaller, younger fish.

Many stocking programs rely primarily on stocking fingerlings. Poor survival rates limit the usefulness of stocking eggs or fry. Fry stocking may be preferable, however, in lakes that are currently fishless or for fish species that are difficult and expensive to rear to the fingerling stage. The higher costs per fish often prevent extensive stocking of yearlings or adults. In some waters, however, the higher return rates for larger fish more than make up for the higher initial costs per fish, so that stocking yearlings or young adults may be more cost effective than stocking fingerlings. It may be necessary to stock older fish in lakes with poor food supplies for young fish or very large predator populations. Also, if suitable spawning sites are available, it may be cost effective to transplant sexually mature adults from other nearby lakes.

Where fishing pressure is heavy and fishing opportunities are scarce, put-and-take fisheries may be appropriate. Older fish of "catchable size" (generally 6 to 7 inches) are stocked into waters where they will be caught within a short period of time. Survival for more than a year or even all of the year is not expected. Most put-and-take fisheries target trout because of the comparative ease with which these fish can be raised in the hatchery. The costs per fish are relatively high, however. Therefore, stocking of catchable-sized trout is justified only when

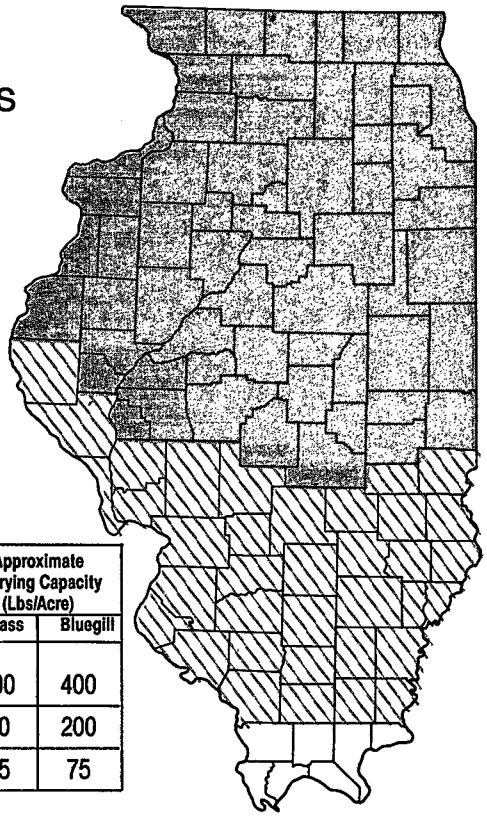
- a high proportion of the fish planted will be caught by anglers, with anglers' fees covering the costs; and
- in the absence of a put-and-take fishery, fishing opportunities would be minimal or inadequate to support the demand because the lake can support fish during only some parts of the year and/or fishing pressure is extremely heavy (e.g., lakes near large population centers or in popular recreational areas).

■ **How many fish should be stocked?** The optimal number of fish stocked depends on

- the size of fish stocked,
- the size and productivity of the lake or reservoir,
- the fish species,
- the availability of suitable prey and habitat, and
- the objectives of the fisheries management program.

The smaller and younger the fish, the lower the expected survival and, thus, the greater the number of fish that must be stocked. High stocking rates may lead to intraspecies competition and reduced growth rates; low stocking rates may produce fewer fish of larger size. Generally, the more productive the lake, the greater the number of fish that the lake can reasonably support and the greater the recommended stocking rate. Easily measured surrogates for lake productivity — such as mean depth, total dissolved solids, and lake alkalinity — are often used to estimate lake-specific stocking rates.

FERTILITY MAP OF ILLINOIS IMPOUNDMENTS BASED ON ALKALINITY OF THE WATER



Alkalinity	Fertility Rating	Fertility Key	Approximate Carrying Capacity (Lbs/Acre) LM Bass	Bluegill
More than 100 PPM*	Good		100	400
50 to 100 PPM*	Average		50	200
Less than 50 PPM*	Fair		25	75

*Parts per million

Locate your pond in the black, crosshatched, or clear areas in the map above. Use the following chart as a guide for its initial stocking.

Initial Fish Stocking Guide

Fertility Key*									
Soil Type of Pond	Black	Light	Forest	Black	Light	Forest	Black	Light	Forest
Number of fingerling fish stocked per surface acre									
Largemouth Bass	100	80	60	90	70	50	80	60	40
Channel Catfish	100	80	60	90	70	50	80	60	40
Bluegill	1000	700	500	800	600	400	700	500	300
Bluegill/Redear Combination									
Bluegill	700	560	490	490	420	350	350	310	245
Redear	300	240	210	210	180	150	150	140	105

Figure 8-6.—Recommended fish stocking rates for small lakes in Illinois, based on surface water alkalinity, soil type, and fish species (source: Ill. Dep. Conserv. 1989).

For many species and regions, general guidelines have been developed for estimating stocking rates from basic information on the lake's characteristics. State fisheries agencies are the best source of information on procedures for your region and target fish species. Figure 8-6 provides an example for stocking fish in small lakes in Illinois and Box 8-D, a method for calculating stocking rates for rainbow trout in lakes in west-central North America.

Box 8-D.—Stocking Density and Growth of Rainbow Trout in Mountain Lakes of West-Central North America (Donald and Anderson, 1982)

Based on data for 24 small lakes in west-central North America at elevations of 1,000 to 11,000 feet, lake-to-lake variations in the size of age 2 rainbow trout were correlated with the level of total dissolved solids, fish stocking densities, and the mean depth of the lake. Total dissolved solids and mean depth are frequently used as indices of potential fish production (see Chapter 3). Models derived from these analyses can be used to determine optimal stocking densities for rainbow trout in similar waters to achieve a given growth rate and size by age 2. For example, for lakes that were historically fishless and have little to no capability for natural reproduction, individual rainbow trout weight (W, in grams) was predicted as follows:

$$W = -1.20(SD) + 6.34(TDS) - 90.77(MD) + 758$$

where, SD = stocking density of fingerling rainbow trout, in terms of the number of fish per hectare; TDS = the concentration of total dissolved solids (mg/L); and MD = the mean lake depth in meters.

Thus, if the desired weight of an age 2 trout is 1,000 grams (2.2. lb) and the lake has a TDS of 200 mg/L and mean depth of 5 meters (16.4 ft), then the recommended stocking density would be 570 fish/hectare (or 230 fish/acre). Lakes with TDS of less than 50 mg/L rarely produce large fish and should be stocked with fewer than 100 fish/hectare (40 fish/acre).

Fish should be stocked at times and locations where survival rates are likely to be highest.

The cost-effectiveness of any stocking program should be continually reevaluated.

■ **When, where, and how should fish be stocked?** Fish should be stocked at times and locations where survival rates are likely to be highest. Most stockings occur during the spring or fall when water temperatures are cooler because high water temperatures combined with handling stress increase fish mortality rates. If possible, avoid stocking in areas where predators concentrate. Fish can be trucked to the lake or stocked from the air using a helicopter or fixed-wing aircraft.

The cost-effectiveness of any stocking program should be continually reevaluated. If the returns do not justify the costs, the stocking program should be discontinued or modified appropriately. As a general rule, catchable-sized fish should be stocked only where at least 50 percent of these fish will eventually be caught by anglers. For smaller fish, their total weight when harvested by anglers should equal or exceed the initial weight of fish stocked.

Controlling Undesirable Fish Species and Stunted Fish Populations

Within a given lake, some fish species may be "undesirable" because they interfere with the survival and growth of "desirable" fish species or with other lake uses. The term "rough fish" is frequently used to refer to these undesirable species. The species categorized as rough fish vary from place to place and even over time. For example, the common carp was originally introduced into the United States in the late 1800s as a prized food fish. Yet today, carp are ignored by most anglers and considered a nuisance fish in most waters. Northern pike are generally considered game fish. However, in some waters pike compete with or prey upon other more desirable game fish and therefore are considered undesirable rough fish. Many of today's rough fish are nonnative species introduced inadvertently or purposely into the drainage system in earlier years.

Fish control programs should be initiated only when clearly demonstrated that reducing or eliminating rough fish will yield a cost-effective improvement in the quality of fishing or other lake uses. In many cases, rough fish in reasonable numbers do little or no harm, and spending time and effort on controls would

produce little benefit in return. Simply because a species does not contribute directly to a fisheries does not make it undesirable. Ecological diversity by itself is an appropriate and beneficial management goal (see Chapter 5).

Fish control programs may be warranted when

- common carp in a lake disturb the lake bottom during feeding and spawning, increasing suspended solids and decreasing water clarity (see Chapter 9),
- abundant populations of nongame species (or less desirable game species) that compete with or prey upon desirable species (game fish or prey species for game fish) funnel productivity away from target species and decrease fisheries yields or fishing quality,
- populations of fish ordinarily considered desirable become undesirable when they occur in such large numbers and small sizes (stunted populations) that they are of little sporting value,
- heavy infections of parasites in a species ruin the aesthetic qualities of a fish population for human consumption, and
- lamprey (Petromyzon marinus) — a parasite on valuable commercial and sport fishes in the Great Lakes and adjacent waters that can decrease fisheries yields — are present in large numbers.

Several alternative approaches, which can be used alone or in combination to control undesirable fish species and stunted fish populations, are:

- fish poisoning,
- extreme water drawdown,
- selective cropping,
- disruption of spawning behavior and reproduction,
- increased predation, and
- barriers to prevent the immigration of rough fish into a lake or reservoir.

■ **Fish poisoning.** Poisoning all or most of the fish in the lake and then starting over by reintroducing only desirable fish species (a process often referred to in fisheries management as lake "reclamation" or "rehabilitation") is one of the most extreme approaches to rough fish control. Because of the severity of the treatment, fish poisoning should be used only as a last resort, only under conditions where adverse side effects can be minimized, and only when it is likely to successfully restore a quality fisheries over the long term. In all cases, State authorities require a permit; in some areas fish poisoning is allowed only in special circumstances, in others not at all.

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Rotenone is most commonly used to poison fish. A natural substance that comes from the stems and roots of a number of tropical plants, rotenone acts by inhibiting a biochemical process at the cellular level, making it impossible for fish to use oxygen. Thus, fish suffocate even though the water contains sufficient dissolved oxygen. At recommended doses, it is reasonably specific to fish. Humans and other animals, with the exception of swine, can drink the treated water with no ill effects; fish-eating birds and mammals can safely consume rotenone-poisoned fish, and plants are not harmed. Snails, clams, and crayfish are also quite tolerant. Rotenone applications do, however, dramatically reduce populations of zooplankton and aquatic insects. In addition, although adult frogs and other amphibians are not affected, tadpoles and juvenile salamanders are usually killed.

Rotenone is manufactured under several trade names, and application rates are product-specific. Generally, a concentration of about 2 ppm is toxic to fish, although sensitivity varies by fish species (Fig. 8-7). Because rotenone is fairly expensive, larger lakes with water level controls should be drawn down before applications, reducing water volume and concentrating the fish in the center of the lake.

The most popular way of applying rotenone is spraying the solution from pumps mounted in boats. Other methods include pouring the toxicant into the prop wash of an outboard motor, towing bags of toxicant designed to dissolve slowly, and spraying from planes and helicopters. Backpack pumps are used to disperse the chemical in vegetated or swampy areas. If the lake is stratified or sufficiently deep, the mixture should be pumped into deep-water areas through hoses suspended from the boat. The toxicant should be distributed to all areas where fish may occur or escape, including lake tributaries and marshy shorelines.

Some fish will begin to die within a matter of minutes; most will start showing effects within an hour. More resistant species, however, may die over several days. As many fish as possible should be collected and disposed of by burying in suitable disposal areas (e.g., county landfills).

Rotenone is an unstable compound that breaks down quickly when exposed to light, heat, oxygen, and alkaline water. At 80°F, the water will detoxify in less than four days; at 45°F, the water may remain toxic to fish for about 30 days. To detoxify the lake more rapidly, add 5.5 percent potassium permanganate or chlorinated lime to the water at a concentration approximately equal to the original rotenone concentration applied. The lake can be restocked after the water is determined to be no longer toxic, using in situ toxicity tests.

For most fish species, the toxicity of rotenone is greatest between 50° and 75°F. The rate of detoxification increases with increasing temperature. All else being equal, late summer may be the optimal time for rotenone applications. However, for better public relations and to minimize interferences with other lake uses, lake managers often apply rotenone in September or early October. Because fish eggs are tolerant of rotenone, it should not be applied when rough fish species are spawning.

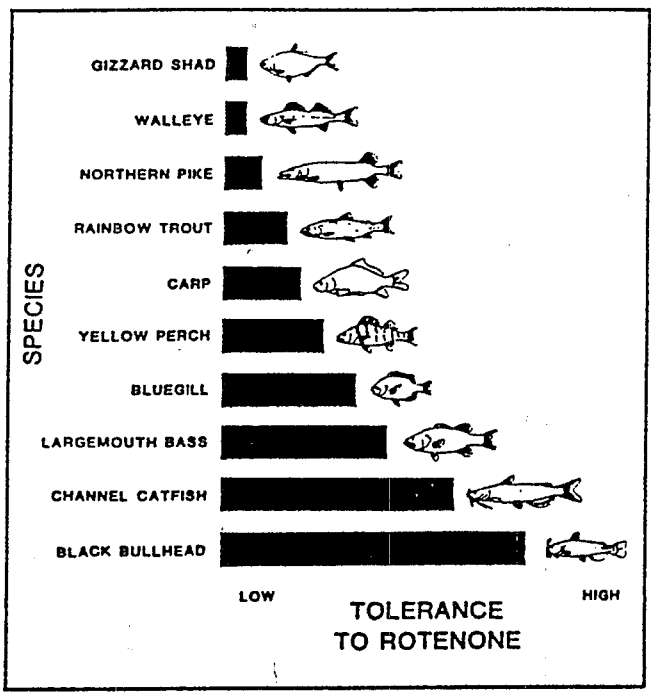

Figure 8-7.—Relative fish species' sensitivity to rotenone, for selected species (source: Sousa et al. 1991).

A number of publications provide more detailed guidance on the use of rotenone for rough fish control, including Sousa et al. (1991), California Department of Fish and Game (1985), Eschmeyer (1975), and Illinois Department of Conservation (undated b). Both rotenone and potassium pemanganate are hazardous substances; therefore, care in handling is required to avoid contact with the skin and especially with the eyes, nose, and throat. All persons applying pesticides, including rotenone, must be certified.

Various other poisons have also been used in fish control programs, although none as widely as rotenone. Antimycin, an antibiotic produced in cultures of the mold *Streptomyces*, is absorbed through the gills of fish and kills by interfering with the respiration of the body cells. Concentrations of 2 ppb will kill sensitive fish species, including most sunfish; higher concentrations (near 15 ppb) kill a wider array of fish, including carp, suckers, and sunfish as well as most game fish species (Berger et al. 1969; Gilderhus et al. 1969). Marketed under the trade name Fintrol, antimycin is somewhat more expensive than rotenone but may be better for some applications (e.g., thinning stunted populations of sunfish).

A few species-specific chemical fish toxicants have been developed for selective chemical control programs.

- The lampricide TFM is used to kill larvae and young adults of the lamprey. At recommended doses, it does not affect trout and other game species, although some species of minnows will show stress.
- Squoxin (1,1'-methylenedi-2-naphthol) is an effective toxicant for squawfish (*Ptychocheilus* spp.), a common rough fish in the western United States. It kills squawfish by acting as a vasoconstrictor, preventing efficient use of oxygen and the proper functioning of the blood vessels. Applied at the recommended dose (about 0.1 ppm), squoxin will not harm salmon and trout, although it may kill some nongame species (e.g., dace and shiners). No effects have been reported on aquatic insects, other fish foods, humans, or other terrestrial animals; however, squoxin has not been approved for use by EPA.

Selective chemical treatments also may be achieved by applying general toxicants such as rotenone only to selected habitats where undesirable fish species are concentrated. Such partial lake treatments may be used to reduce rough fish abundance or decrease the density of overpopulated, stunted populations of fish. For example, in large reservoirs individual bays can be treated to reduce the numbers of stunted panfish, including bluegill or white and black crappie. However, most species have a high reproductive potential, and therefore beneficial effects from such treatments are likely to be short-lived.

Fish poisoning programs are not always successful. Some fish species, such as bullhead, are especially resistant to chemical poisoning and may survive in large numbers. Also, in large lakes with many difficult-to-treat refuge areas — such as lake tributaries and outlets, adjacent marshes and other swampy areas, and large underwater springs — a large portion of the rough fish population may be unaffected. Finally, if reintroductions of rough fish species are likely from interconnected waters either upstream or downstream of the lake, then the effectiveness of the lake reclamation will be short-lived. If any of these situations apply, a fish poisoning program should not be attempted.

State fisheries agencies (see Appendix C) should be contacted for information regarding local regulations, permit requirements, chemicals approved for use in certain types of waters, and suppliers and costs of approved fish poisons.

■ **Extreme water drawdown.** A second drastic approach to rough fish control is extreme water drawdown. Lake levels are dropped to very low levels, leaving little or no standing water and resulting in substantial fish mortality. As for rotenone, water level drawdowns affect all fish in the lake and are used primarily

when fish communities are dominated by rough fish. The specific objective is to eradicate or drastically reduce existing populations and then restock with desirable fish species. Water drawdowns also adversely affect other lake uses and biota and should be used only when such impacts are considered acceptable. Obviously, water drawdowns are a management option only for lakes where water levels can be controlled.

■ **Selective cropping.** Another direct method for reducing the abundance of undesirable fish species is simply to selectively harvest them in large numbers and kill and discard the catch or sell the fish to commercial buyers. Fish can be caught by using any of the sampling techniques described in Appendix B; choose the most effective sampling gear, times, and locations (e.g., spawning habitats) for catching the fish species of concern. Sampling methods that indiscriminately kill all or most of the catch (e.g., overnight gill net sets) should be avoided, however.

[T]he effects of such selective fish cropping are likely to be short-lived. Reproduction will quickly replace the fish lost unless harvesting efforts are repeated regularly and often.

As for partial fish poisoning, the effects of such selective fish cropping are likely to be short-lived. Reproduction will quickly replace the fish lost unless harvesting efforts are repeated regularly and often. Fish harvesting is also labor-intensive; to be cost effective, the program must be operated by volunteers or as a commercial fishery. In addition, the species being removed should be easily caught in large numbers. One approach for encouraging selective cropping is to organize a fishing derby, with prizes for the greatest numbers and biomass of fish removed. Changes in fishing regulations also may be a useful part of a selective cropping program. Fishing regulations and derbies are discussed later in this chapter.

Selective cropping is of little use if the objective is to markedly reduce or eradicate rough fish. It may be a valuable fisheries management tool, however, for dealing with stunted fish populations.

■ **Disruption of spawning behavior and reproduction.** Rather than removing adults through selective cropping, you can reduce the species' reproductive success. Projects to disrupt spawning behavior and reproduction are worth considering, however, only if the fish's spawning activities are reasonably concentrated in time and space, obvious, and easy to disturb. For example, yellow perch lay their eggs in masses loosely attached to vegetation that can be easily seen and removed in large numbers. Sunfish spawn in shallow littoral areas, laying their eggs in nests visible from the shore or by boat. If you use a water pump with sufficient discharge velocity, the eggs can be dislodged and scattered and soon will be eaten by other fish. Alternatively, sunfish spawning beds can be destroyed by dragging logging chains over the area behind a rowboat or simply walking through the nests repeatedly if the water is shallow enough. Sunfish are resilient, however, and often rebuild their nests and lay more eggs if disturbed. Therefore, efforts must continue for several weeks throughout the spawning season to be at all effective.

As for selective cropping, efforts to disrupt spawning and reduce egg survival will generally have only a short-term effect, must be repeated regularly and often, and are labor intensive. Thus, this technique is a useful fisheries management tool only in some circumstances and for some species. Because survival rates of early life stages are naturally quite low and often density-dependent (see Chapter 3), measurable reductions in fish abundance are difficult to achieve.

Water level drawdowns during the spawning season also have been used to reduce the reproductive success of undesirable fish species (see discussion of water level management earlier in this chapter).

■ **Increased predation.** Rather than attempting to decrease reproductive success and increase fish mortality through direct human intervention, increasing natural predation may be more efficient. Increased predation is often the best solu-

Box 8-E.—Predator Introductions to Control Stunted Panfish Populations (Mosher, 1984)

Lyon State Fishing Lake, Kansas, contained an over-abundant, slow-growing population of white crappie. In 1975, fingerling walleye were stocked at a density of 75 fish per acre. Within four years, crappie numbers were reduced, while their total length increased from a maximum of 10 inches to 15 inches. A 12- to 15-inch slot length limit on black bass initiated in 1978 probably also contributed to predation on white crappie. A similar approach was used at Chase State Fishing Lake. However, the white crappie population in Chase State Fishing Lake is extremely dense, and despite repeated introductions, walleye have had limited success in establishing a viable population.

tion for dealing with stunted fish populations. It may be achieved by introducing a new predator, increasing the abundance of an existing predator population, or increasing predator efficiency so that the same number of predators capture larger numbers of prey.

Any species that is an effective predator on the target species can be used for fish control.

Any species that is an effective predator on the target species can be used for fish control (e.g., see Box 8-E). Northern pike are voracious predators, and introductions of pike are frequently considered for controlling stunted panfish populations. As with any fish introduction, however, inadvertent negative side effects on other components of the biological community are of potential concern (see Chapter 9). Increased predator numbers may be achieved through stocking or other fish enhancement programs or by limiting predator losses. Changes in fishing regulations, for example, may be used to decrease fishing mortality and produce more large game fish, which can result in increased predation on small fish in the lake.

Increased predation is often the best solution for dealing with stunted fish populations.

Many game fish are primarily sight-feeders, relying heavily on visual cues to identify and capture their prey. Thus, increases in water clarity may indirectly improve predator efficiency. Problems with high turbidity may result from abundant phytoplankton and algal blooms or from heavy loads of suspended particulates. Algal levels may be reduced by limiting nutrient inputs. Suspended solids may be reduced by controlling watershed disturbances and development. Methods for improving water clarity are discussed in further detail in *The Lake and Reservoir Restoration Guidance Manual* (Olem and Flock, 1990).

Periodic water level drawdowns and reductions in aquatic plants may also increase predator efficiency, as discussed in the subsections on plant and water level management earlier in this chapter.

■ **Fish barriers.** Fish barriers can be constructed on lake inlets and outlets to prevent undesirable fish species from invading lakes in which they do not already occur or from which they have been eliminated by fish poisoning or water drawdowns. The effectiveness of such barriers will vary among fish species; species that are strong swimmers with substantial leaping ability will be more difficult to exclude. In addition, it is more feasible and less expensive to build effective barriers on some types of inlets and outlets than others. Fish barriers are more expensive on larger streams or rivers. They require frequent maintenance or special, more expensive designs on waters with heavy loads of debris that can quickly clog a simple fish screen. If screens become clogged during high flows, the water and fish will simply flow over or around the fish barrier. In streams with erodible stream banks, currents during high flows may soon cut under or around the barrier, making it an ineffective impediment to fish movements. In general, it is easier to prevent fish from moving upstream than downstream. However, in the right circumstances, fish barriers can be built that will significantly delay or prevent the invasion of undesirable fish species, thereby avoiding future fisheries management problems.

One of the simplest barriers is a velocity culvert where outgoing water is channeled to produce high water velocities, preventing poor swimmers such as the common carp from swimming upstream into the waterbody. A velocity culvert is basically a stormwater culvert that is set at a steeper angle than usual. For example, in Thompson Lake near Cosmos, Minnesota, a 3-foot diameter cement culvert was installed with a 4.5-foot drop over a 142 foot length. This 3 percent slope resulted in sufficient water velocities to prevent both carp and bullhead from swimming up the culvert into the lake (McComas, in press). In a similar manner, dams at a lake's outlet with significant head prevent the upstream movement of fish species that have little or no jumping ability.

Simple bar screens or metal grates over a culvert or stream (Fig. 8-8) may be effective in waters with low velocities and where debris is not excessive. These screens are usually made of narrow round iron bars. They should be installed in a manner that will facilitate cleaning, especially during high flows when debris loads are heavier. Often these screens are constructed with removable panels for repair and easy cleaning. Bar screens have been used with some success to divert large adult fish but cannot prevent the movement of small fish.

Other more elaborate types of physical barriers are described in Everhart and Youngs (1981).

Electric screens represent an alternative to physical barriers that can be more cost effective in some situations (Stewart, 1990). An electrode array, used to create an electric field in the water column, is a small and inexpensive structure compared with a dam or fence, does not interfere with water flow, and needs relatively little maintenance. Most electric screens use low intensity fields (1 to 15 Hz) designed to influence fish behavior (e.g., avoidance of the screen) without harming or stunning the fish. The design and efficiency of electric screens depend highly on the species and environmental conditions (e.g., natural patterns of fish behavior at the site). In general, electric fields are more effective (often 70 to 100 percent effective) at preventing upstream fish movements than downstream migrations. Downstream fish movements can be controlled only at low water

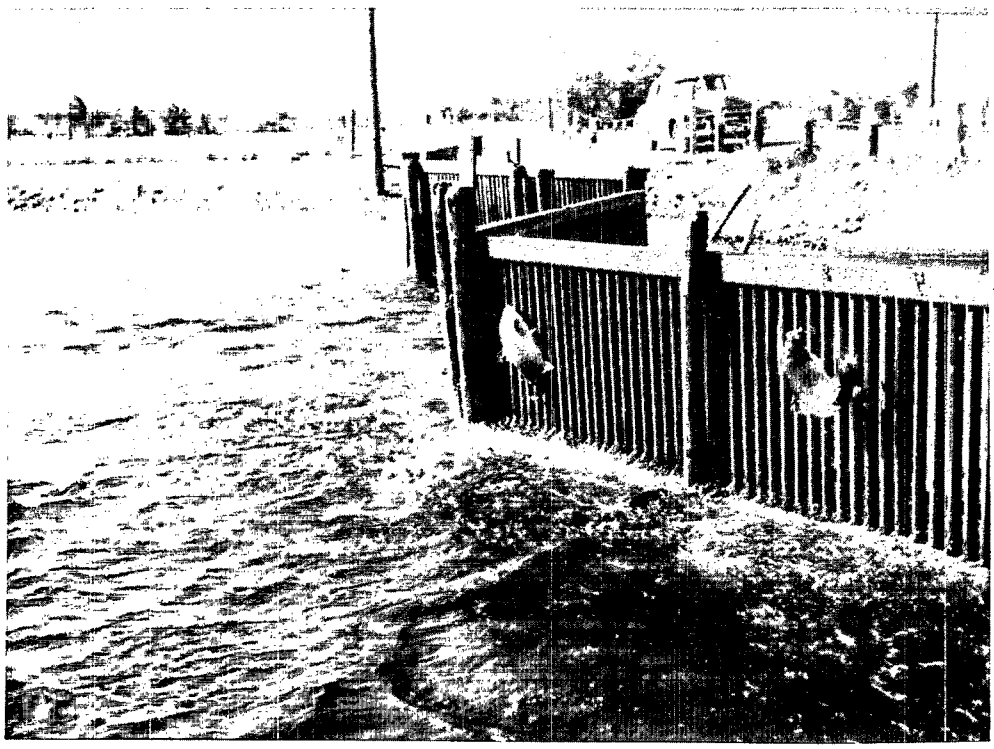

Figure 8-8.—Example of bar screen fish barrier (source: McComas, in press).

velocities (less than about 1 ft/sec, 0.3 m/sec; Stewart, 1990). Screen efficiency can also be increased by providing visual or audible cues so that the fish become aware of the barrier before encountering the electric field.

Electric screens can be a hazard to swimmers, anglers, and boaters and should be clearly marked with warning signs, lights, and/or buoys.

Prey Enhancement

Substantial quantities of readily available prey are required to support large populations of stocked or naturally reproducing game fish. Fish growth rates directly depend on food availability and the energy expended in obtaining sufficient food (see Chapter 3). In addition, most game fish are top predators; that is, they feed high on the trophic pyramid. Many feed primarily on other, smaller fish; they have distinctly higher growth rates if small fish are available than if forced to rely on other types of prey.

Most game fish . . . feed high on the trophic pyramid.

In some lakes, the quantity and/or quality (types) of prey available may be a major factor limiting the numbers and growth of target game fish species. Two methods for improving prey availability are (1) habitat improvements that can lead to increased reproductive success and abundance of important prey species that already occur in the lake and (2) introductions of new prey species to supplement existing food supplies.

Prey introductions can serve to

- increase the total quantity of food available and/or
- increase the efficiency of energy transfers and the proportion of the total lake productivity converted into game fish growth and production.

The latter can be achieved by providing prey that (a) feed themselves lower on the trophic pyramid, thus shortening the length of the food chain to fish, and (b) are more readily caught and digested by game fish, thus increasing growth efficiency —that is, the proportion of food energy consumed that ends up as increased fish growth rather than energy expended on prey capture or sustaining the fish's basic metabolism (see Chapter 3).

■ **Habitat improvements to enhance prey availability.** Most of the habitat management techniques discussed earlier in this chapter would also directly benefit game fish prey as well as game fish populations. Two techniques deserve particular note: (1) efforts to provide sufficient but not excessive areas of fish cover (either physical structures or macrophyte beds) and (2) spawning habitat improvements directed specifically at increasing the reproductive success of important prey species.

Even though prey are abundant, they may not be available to predators if macrophyte beds (or other structural features) cover all or most of the littoral zone and lake bottom. With too many areas to hide, a relatively low fraction of the prey biomass will be caught and converted into game fish biomass. Thus, efforts to control aquatic plants generally benefit game fish growth by increasing prey availability.

Approaches to increasing the reproductive success of prey, at least for forage fish, are the same as for game fish species and may involve habitat protection, improvements (e.g., silt removal), and construction of new spawning sites. Relatively few forage fish species, however, have highly restrictive spawning habitat requirements. Information for selected species is provided in Appendix A.

■ **Prey introductions.** Introducing a new species into a lake ecosystem can cause unexpected negative consequences by disrupting the existing biological community and balances. The same cautionary statements presented earlier in

Prey introductions should proceed only with a high degree of confidence that the effort will result in a significant improvement in fishing quality and little or no negative side effects on other components of the aquatic community or other lake uses.

this section for game fish stocking apply as strongly to prey introductions. All introductions of nonnative species of fish or other taxa will cause some ecological damage, the extent of which can be only poorly predicted (Allendorf, 1991). Therefore, before initiating a prey introduction program, carefully consider the following questions:

- Is prey availability a major factor limiting game fish growth and production? Would similar or better results be obtained through habitat improvements or other means?
- Will the introduction of a new prey species significantly improve the existing prey complex by increasing the total amount of prey biomass available or providing a preferred food source that will increase energy transfer and/or growth efficiency?
- Does the lake provide suitable habitat for the prey species that will be introduced? Is the introduced species likely to survive, reproduce, and sustain a viable population despite heavy predation? (Only species with a high probability of establishing a self-sustaining population should be considered. Populations requiring repeated stockings each year or every several years are generally not cost effective.)
- Will the total abundance of prey be increased, or will the new species simply displace an already existing and desirable prey species?
- Will the introduction of a new prey species result in a significant increase in game fish numbers or growth?
- What proportion of the prey biomass and productivity will be converted into game fish production? Preferably, the prey species should be susceptible to predation throughout all or most of its life cycle. Species that grow quickly and are soon too large to be consumed by target game fish should be avoided because much of the species' production would never be channeled into game fish populations used by anglers. In addition, the prey species should occur in the same habitats and be readily captured by game fish predators.
- Is there a chance that the introduced species will become over-abundant and eventually a nuisance species? Will the new species have indirect, detrimental effects; for example, by competing for food with other desirable species?
- Is there a chance that the introduced species will migrate or be transplanted to other waters in the drainage basin?

Prey introductions should proceed only with a high degree of confidence that the effort will result in a significant improvement in fishing quality and little or no negative side effects on other components of the aquatic community or other lake uses. Li and Moyle (1981) recommended that introductions be considered only for systems that have been so altered by human activity that it is necessary to create a new community to take advantage of the change in environmental conditions (e.g., in reservoirs or eutrophied lakes) and in isolated bodies of water, so that uncontrolled spread of the species is unlikely.

The type of prey best-suited for prey enhancement programs depends on the target game fish species. Prey organisms that are commonly considered for such efforts include the following:

- Threadfin shad and gizzard shad have been successfully introduced to provide forage fish for a diversity of game species, especially in southern reservoirs. Both feed on phytoplankton and zooplankton and thus can efficiently transfer energy to piscivorous fish. Each species also produces large numbers of young and can withstand all but the heaviest

predation. Gizzard shad, however, grow rapidly and may quickly outgrow their usefulness as prey for younger fish and for predators with smaller mouths.

- Silversides and minnow species also feed low on the food chain; however, they generally do not withstand heavy predation and may be most useful as initial ("starter") prey when young predators are first stocked into a lake. These species tend to disappear when predators become larger and better established.
- Rainbow smelt, cisco, and alewife as well as two crustacean species, Mysis relicta and Pontoporeia affinis, have been frequently introduced as prey for lake trout and salmon populations, with varying success (see Box 8-F).
- Bluegill and other sunfish are important prey for largemouth and smallmouth bass; yellow perch are important prey for northern pike. All of these panfish species, however, are susceptible to overpopulating and stunting, can compete with young bass for food, and are predators on bass eggs and larvae. Crayfish also have been introduced as prey for black bass in some lakes.

There are as many or more examples of unsuccessful prey introductions as there are successful programs. In some cases, introductions of new prey species have had no measurable effect on game fish growth or abundance; in others, significant declines or unexpected problems have resulted. Box 8-F provides examples of both successful and unsuccessful prey introduction projects.

Managing Fishing Pressure and Harvest and the Fishing Experience

Anglers and fishing regulations play three important roles in fisheries management. The success of a fisheries management program is determined largely by the degree to which the desires and expectations of the fishing public are fulfilled. Anglers, together with other lake users, define the management goals and specific objectives (see Chapter 5). If angler expectations are unrealistic, even the best management program will fail. An important component of all fisheries management programs, angler education ensures that angler expectations and quality standards are compatible with the natural conditions and uses that the lake (and its watershed) can support most readily. Actively involving anglers and other lake users in the planning process, as discussed in Chapters 5 and 6, also serves to better match expectations with cost-effective and realistic solutions.

The success of a fisheries management program is determined largely by the degree to which the desires and expectations of the fishing public are fulfilled.

Second, fishing mortality can have a major effect on the numbers, size, growth rates, and productivity of fish populations. In combination with the myriad of other factors that influence fish communities, the level, timing, and nature of fishing mortality today will affect the quantity, sizes, and types of fish available in the future — in other words, the quality of subsequent fishing experiences. Fishing regulations, angler education, and controls on lake access are the primary means of controlling fishing mortality and thus are important fisheries management tools. Problems result from both overfishing and underuse.

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Finally, the quality of a fishing experience is determined by more than just the numbers and sizes of fish caught. The surrounding environment, the challenge, the level of effort, and other components of the overall experience all influence the angler's satisfaction. Many fishing regulations and management activities serve primarily social objectives — that is, to improve the quality of the experience rather than alter the fish resource *per se*. Limits on fishing gear (designating "fly-fishing only" waters) are one example of a regulation intended to influence the nature of the fishing experience more than the level of fishing mortality.

Box 8-F.—Examples of Successful and Unsuccessful Prey Introductions to Supplement Food Supplies for Game Fish Species

Havey (1973): Rainbow smelt were introduced in 1965-67 into Schoodic Lake, Maine, as a new forage fish for landlocked Atlantic salmon. Within three years following the initial planting, salmon growth rates had markedly increased. For example, the mean length and weight of 3-year-old salmon increased from 374 mm, 468 g in 1965-67 to 442 mm, 814 g in 1968-70. Condition factors of salmon, ages 3 to 5 years, increased from a mean of 0.76 in 1966 to 1.00 in 1969. One disadvantage of smelt as a forage fish, however, is its extreme population instability. In 1971, as a result of a temporary collapse of the smelt population, salmon growth rates and condition dropped sharply.

Mosher (1984): In 1974 and 1975 Lake Kahola, Kansas, contained an overabundant, slow-growing white crappie population, with few individuals larger than 6 to 7 inches long. In March 1976, the 400-acre lake was stocked with 75 yearling and adult gizzard shad. By 1977, gizzard shad were numerous throughout the lake, and by 1980 anglers were reporting 12-inch crappie. White crappie are still abundant in the lake, with many small crappie, but more larger fish also occur, improving the fishing quality.

DeVries et al. (1991): Threadfin shad were introduced into Clark and Stonelick lakes' shallow turbid reservoirs in southwestern Ohio. In Stonelick Lake, abundant populations of threadfin shad resulted in a marked decline in zooplankton. Survival of young-of-the-year bluegill also declined, perhaps because of the decreased availability of zooplankton. In turn, limited survival of bluegill contributed to reduced growth of young-of-the-year largemouth bass dependent on them for prey. The introduction of threadfin shad, therefore, appears to have negatively affected growth and recruitment of both bluegill and largemouth bass. Similar declines in zooplankton and fish growth and survival did not occur in Clark Lake.

Matuszek et al. (1990): The cisco (*Coregonus artedii*) was successfully introduced in 1948 into Lake Opeongo, a 5,860-ha (14,480-square-mile) oligotrophic lake in south-central Ontario. Data on lake trout growth, abundance, and yields were collected from 1939 to 1979 to assess long-term fisheries trends. Cisco are now the dominant food item in the diet of lake trout in Opeongo Lake. This shift in diet was accompanied by a complex array of changes in lake trout growth, fecundity, maturity, and population abundance. Growth rates of older, piscivorous lake trout (ages 5 to 8) increased initially as cisco abundance increased. Cisco abundance decreased as the density of piscivorous lake trout increased; the size of ciscos eaten declined as a result of heavy predation. Growth rates of younger non-piscivorous lake trout (ages 1 and 2) declined as their abundance increased and the occurrence of their insect prey decreased. As ciscos became the dominant prey for adult lake trout, cannibalism by adults on younger lake trout decreased, resulting in higher survival rates. Overall, the cisco introduction improved the lake trout fishery by raising the maximum sustainable yield from about 0.18 kg/hectare to about 0.48 kg/hectare. However, model simulations suggest that the lake trout population also is now more sensitive to possible overexploitation (see Chapter 12 for further details).

Lasenby et al. (1986): The introduction of the crustacean *Mysis relicta* have been shown to modify benthic, phytoplankton, zooplankton, and fish communities, with varying success relative to fisheries improvements (Table 8-5). *Mysis* were introduced into Lake Tahoe, California-Nevada, from 1963 to 1965, and began appearing in large numbers in lake samples and lake trout stomachs by 1971. The increase in *Mysis* resulted in the loss of several cladoceran zooplankton species (*Daphnia* spp. and *Bosmina longirostris*) on which Mysis feed (Richards et al. 1975) and the eventual collapse of the kokanee salmon population, which relied heavily on these zooplankton for prey. Lake trout length and catch per unit effort also declined. Similar declines in kokanee populations occurred in Idaho and Montana lakes after *Mysis* was introduced (Rieman and Falter, 1981; Rieman and Bowler, 1980).

Continued on next page

Box 8-F.—Continued

Table 8-5.—Fish population responses to introductions of *Mysis relicta* into British Columbia lakes (adapted from Lasenby et al. 1986).

LAKE	YEAR(S) INTRODUCED	VIABLE POPULATION ESTABLISHED	TARGET SPECIES	APPARENT EFFECT ON TARGET SPECIES	
				SIZE	ABUNDANCE
Arrow (upper)	1968, 1974	yes	kokanee	+	–
Arrow (lower)	1974	yes	kokanee	+	–
Canim	1967–68	yes	kokanee	?	–
Christina	1968	yes	kokanee	0	?
Duncan	1975	?	kokanee	0	0
Grave	1979	no	kokanee	0	0
Kalamalka	1965–66	yes	kokanee	0	–
Kootenay	1949–50	yes	rainbow	+	–
			kokanee	+	?
			mt. whitefish	+	?
Lac la Hoche	1975–76	no	kokanee	0	?
Missezula	1975–76	no	kokanee	0	?
Moyle	1970	yes	kokanee	0	–
Okanagon	1966	yes	kokanee	+	–
Otter	1975	?	kokanee	0	?
Pinaus	1965–66	yes	rainbow	+	?
Slocan	1973–74	yes	kokanee	+	?
Whatsam	1974	no	kokanee	?	?
Wood	1966	no	kokanee	+	–

? = not determined; + = positive effect; – = negative effect; and 0 = no effect.

Mysis have also been widely introduced into Swedish lakes. In response, benthic feeding fish, such as brown trout, generally increase in abundance and size while pelagic fish, such as Arctic char, decrease (Fürst et al. 1986). As in North America, *Mysis* results in a decline of cladoceran zooplankton; the pelagic fish that normally feed on these zooplankton are unable to switch to a diet of *Mysis*. Increases in phytoplankton biomass have also been observed in some Swedish lakes as an indirect effect of *Mysis* introductions and the subsequent decline in cladoceran zooplankton (Kinsten and Olsén, 1981; also see Chapter 9). Because of these mixed results, the Mysid Research Group (Morgan, 1982) recommended a moratorium on further introductions of *Mysis relicta* for fisheries management until understanding of ecosystem responses to these introductions improved.

Regulations and Their Effects

Fishing regulations should be as simple and as few as possible.

Fishing regulations should be as simple and as few as possible. None should be implemented unless it will measurably improve the quality of the fishing experience or long-term sustainability of the fisheries resource. Even more so than for other management actions, fishing regulations have a direct impact on and should be closely tied to the pre-established management objectives for the lake.

Some of the regulations widely applied in the past were based on oversimplified assumptions and theories that subsequent research has found to be false or inappropriate for many waters. Examples of these often erroneous assumptions include the following:

- If fewer fish are caught now, more fish will be available for future fishing. However, if natural mortality rates are high and density-dependent (see Chapter 3), this assumption will not necessarily hold.
- A fairly large number of mature fish should be protected to allow for sufficient spawning stock. While true for some species such as salmon, most fish species are extremely prolific. Each individual female fish produces large numbers of eggs, and as a result, sufficient numbers of

eggs can be produced by relatively few fish. For these species, reproductive success is determined more by environmental variables than by the number of spawning fish.

- Fish should be protected from fishing during the spawning season to ensure adequate reproduction. Again as noted above, for most species the number of mature fish that successfully spawn is rarely the dominant factor controlling the number of progeny produced. Closed fishing seasons during spawning are justified only if the numbers of spawning fish are very low or if fish are highly vulnerable to capture at that time.
- Smaller fish should be protected because they will eventually grow into bigger fish. However, many lakes suffer from overpopulation and too many small fish; competition for a limited food supply may result in poor growth rates and stunted fish populations. In these instances, fishing regulations that protect small fish have detrimental effects on fishing quality.

Regulations can be used to reduce the total quantity of fish caught and removed; selectively harvest, or protect, certain portions of the population; influence or control the type of fishing experience; and encourage a more equitable distribution of the catch among anglers.

In some instances, controls on fishing pressure and harvest are needed either to protect and improve the fisheries resource or for social objectives. Regulations can be used to

- reduce the total quantity of fish caught and removed;
- selectively harvest, or protect, certain portions of the population;
- influence or control the type of fishing experience; and
- encourage a more equitable distribution of the catch among anglers.

The types of regulations used in recreational fisheries include the following:

- Creel limits, which prescribe a maximum number or biomass of fish (or maximum number of fish of a certain size range) that can be harvested per angler and per fishing trip. Creel limits may be used to reduce fishing mortality in lakes that are heavily fished and encourage a more equitable distribution of the catch among anglers.
- Quotas, which define the maximum total number or biomass of fish that can be removed from the lake over the entire fishing season or by each individual angler. In both cases, the use of quotas requires some method for tracking and quantifying all fish harvests. In privately owned waters, quotas may be used as a voluntary means of preventing overfishing, especially on small lakes with relatively few large game fish.
- Size limits, where all fish outside of the allowable size range must be returned unharmed to the water. Generally, the primary objective is to increase the mean size of the fish caught and/or allow more fish to grow to reproductive maturity. Minimum, maximum, and slot size limits have been applied, depending on conditions in the lake and the management objectives. The role of size limits in fisheries management is discussed further in Box 8-G.

Minimum, maximum, and slot size limits have been applied, depending on conditions in the lake and the management objectives.

- Catch and release programs, which require all fish caught (or a percentage of the catch) to be returned unharmed to the water; thus, fishing mortality is greatly reduced. Only some of the fish caught will die as a result of the stress caused by hooking, playing, and handling. Catch and release programs may be particularly appropriate for waters that are heavily fished, during fishing tournaments when lakes are subject to heavy fishing pressure, or for protected species or strains (e.g., wild strains or threatened or endangered species) that occur in a mixed fisheries.

Box 8-G.—The Role of Size Limits in Fisheries Management

(adapted from Brousseau and Armstrong, 1987)

Size limits may be used in fisheries regulations for several purposes:

- to maximize yield,
- to prevent overharvest and depletion of stocks,
- to maintain favorable fish population and community structure,
- to maintain favorable fish population dynamics and production (e.g., satisfactory rates of growth, mortality, and reproduction), and
- to sustain the quality of fish and fishing.

These objectives can only be met if size limits are properly applied.

The traditional approach to length-based harvest regulations has been to impose a minimum size limit. It is generally assumed that, by setting a minimum size limit and returning small fish, harvest can be maximized and the mean fish size increased. Generally, the size limit is established so that the majority of fish harvested would have spawned at least once before capture.

Results from minimum size limit regulations have been mixed, however. When small fish are protected, the increase in population density can lead to a significant decrease in fish growth rates. High rates of natural reproduction combined with a slow growth rate can result in large numbers of under-sized fish and relatively few legal-sized fish; thus fisheries yield decline. Minimum size limits should be applied only where

- the fish population has a low natural reproduction potential,
- growth rates are high, especially among younger fish,
- natural mortality rates are low, and
- fishing pressure and fishing mortality rates are high.

Slot size limits protect fish within a specified intermediate size range. Harvests of smaller fish are allowed to "thin out" large year classes at relatively small sizes and reduce intraspecific competition for food, thus improving fish growth rates. As long as reproductive rates are adequate, the younger, smaller fish caught may be able to satisfy those anglers fishing mainly for food. At the same time, by protecting fish of intermediate size, more fish of "trophy" size should eventually be available. In theory, slot limits should sustain angling yields and allow increases in fishing effort without adversely affecting fishing quality in terms of catch rates and the size of fish caught. Slot size limits are most appropriate for fish populations with the following characteristics:

- good natural reproduction,
- slow growth, especially of young fish,
- relatively high natural mortality of young fish, and
- high angling effort.

Maximum size limits may be useful where protecting brood stock is necessary , such as in highly exploited populations with a low density of mature fish, and where recruitment may be low. Maximum size limits are rarely used, however, largely for social rather than biological reasons. For both slot limits and maximum size limits, anglers have resisted regulations that require releasing fish of moderate to large size. Problems with slot size limits can also occur if anglers release a high proportion of the small fish caught (resulting in an overabundance of small fish and reduced growth rates). Both programs, therefore, necessitate an associated user education program to improve angler compliance.

- Restrictions on gear types, either to protect certain sizes or groups of fish or for social objectives. Examples include fly-fishing only areas, minimum hook sizes (to reduce the catch of small fish), and restrictions on the number of hooks per lure. Recreational fisheries are restricted for the most part to hook and line fishing. Netting and most other capture techniques, described in Appendix B, may be used for research and management purposes only.

- Limits on the number or type of fishing units, for example, limiting anglers to a single rod when trolling or to a set number of tip-ups during ice fishing. Motorboats may be prohibited or motor sizes restricted both to limit the total catch and to influence the nature of the fishing experience.

- Fishing closures, which prohibit fishing in particular areas or during some seasons; for example, to protect fish during spawning or while migrating through areas where they may be particularly vulnerable to capture.

For any regulation to work, a high degree of voluntary angler compliance is essential. If anglers are unaware of or do not understand the need for a regulation, high noncompliance rates will render the regulation ineffective. A positive, intensive, and well-conducted public information program is critical, therefore, to the successful use of fishing regulations for fisheries management and especially for innovative approaches or experimental regulations.

For any regulation to work, a high degree of voluntary angler compliance is essential. . . . A positive, intensive, and well-conducted public information program is critical, therefore, to the successful use of fishing regulations for fisheries management. . . .

Fishing Derbies and Tournaments

Fishing derbies and tournaments can be an integral part of a fisheries management program. As noted earlier in this chapter, they are one method for reducing undesirable and stunted fish populations. By offering prizes or other incentives, lake managers can concentrate angler effort on particular fish species or size ranges. Where fisheries resources are underused, a fishing tournament may result in a long-term increase in fishing activity and yields. Finally, fishing derbies can be organized as money-raising events, with the money used to fund other fisheries or lake management projects. Fishing tournaments, however, are illegal in some States (e.g., Oregon), strongly objected to by some anglers and conservation groups, and can interfere with other lake uses. Therefore, these events are appropriate management options only when consistent with the overall, long-term management goals for the lake.

User Conveniences

Fish may be plentiful in a lake but few caught because of low fishing pressure. As part of a fisheries management plan, it may be desirable to build (or remove) various user conveniences that tend to encourage fishing pressure as well as make fishing more convenient and enjoyable. The addition of user conveniences may be particularly appropriate for lakes where the fish resource is currently underused. Three types of user conveniences may be considered:

[I]t may be desirable to build various user conveniences that tend to encourage fishing pressure . . . [in] lakes where the fish resource is currently underused.

- improved lake access, through purchases of rights-of-way, trail construction or maintenance, or road construction and improvements;

- construction or upgrading of boat ramps; and

- construction of fishing piers that allow anglers better access to deeper waters and provide areas for fish cover and concentration, thereby increasing capture efficiency. Earthen piers also effectively increase the length of the lake's shoreline.

Mosher (1984) presents several inexpensive methods for improving and constructing user conveniences.

Conclusions

Many methods are available, therefore, for maintaining and improving fisheries in lakes and reservoirs (Fig. 8-1). The best approach for any given lake and situation will vary depending on the target fish species, nature of the problem, management goals and objectives, and characteristics of the lake. There are no cookbook solutions, although experience has demonstrated that some methods tend to work better in certain situations and for some problems than others (see Fig. 8-9). Appendix A provides a brief discussion of the most commonly used management techniques for selected game fish species, and Chapter 12 describes several case studies of fisheries management programs.

There are no cookbook solutions. . .

Unnecessary management and overmanagement are as undesirable as no management at all. Fish communities and fisheries should be monitored routinely to continually assess the effectiveness of management actions and the management plan altered appropriately. For example, stocking too many fish in a lake may not only lead to an overcrowded fish population but is also a waste of money and resources. The goal should be to select and apply the approach(es) that will achieve the highest quality fishing possible for the lowest cost and effort and also ensure the long-term sustainability of the fish resource and lake ecosystem.

Fish communities and fisheries should be monitored routinely to continually assess the effectiveness of management actions and the management plan altered appropriately.

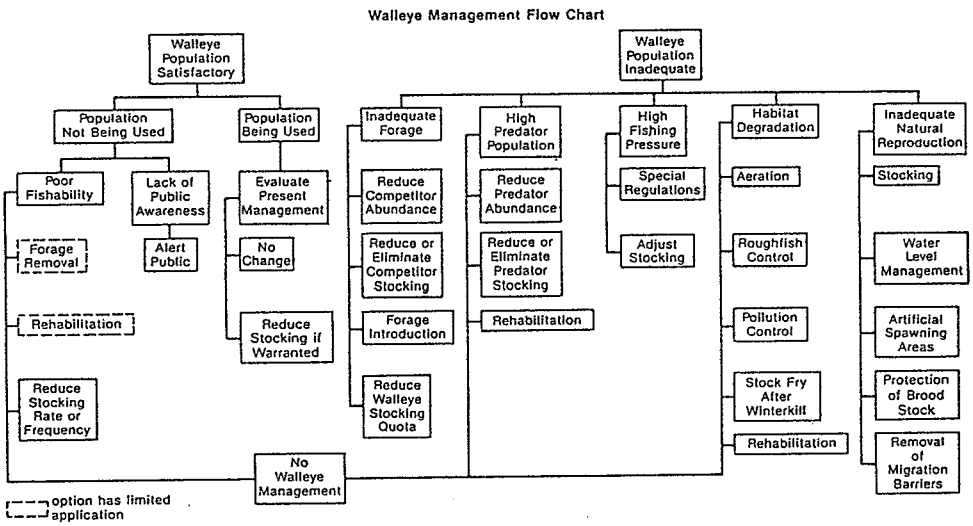

Figure 8-9.—Walleye management flow chart, identifying the major management options available for various walleye management problems (from Minn. Dep. Nat. Resour. 1982).

CHAPTER 9

Methods for Using Fish to Improve Water Quality

Chapter Objective

Changes in the fish community directly and indirectly affect other components of the lake ecosystem, including biological, chemical, and physical lake characteristics (see Chapter 2). Therefore, it may be possible to manipulate the fish community specifically to improve and maintain water quality. This chapter describes the current state-of-the-science regarding biomanipulation — that is, purposely altering the biological community to achieve water quality management objectives: methods that have been proposed and tested; their success, advantages, and limitations; and remaining uncertainties. Only biomanipulation techniques involving fish management are reviewed.

Biomanipulation is just one of a number of approaches to water quality management and often works best when applied in conjunction with other management techniques. Olem and Flock (1990) provide a more comprehensive discussion of methods for water quality restoration and management.

Biomanipulation is just one of a number of approaches to water quality management and often works best when applied in conjunction with other management techniques.

In addition, biomanipulation — using fish to improve water quality — must be viewed as complementary to fisheries management (Chapter 8). Fish can be managed to improve fishing quality (fisheries management) and water quality (biomanipulation). Often the two conflict, however. A management program designed to optimize fishing quality may degrade water quality, and vice versa. Thus, the selection and prioritization of management objectives, as discussed in Chapter 5, are critical to defining the best overall fish management program to achieve the appropriate balance between fisheries and water quality and all lake uses and values.

Background

Biomanipulation, as a distinct field and tool for water quality management, was first suggested by Shapiro et al. (1975). Since that time, a wide range of experiments and applications have been conducted and the fundamental principles and usefulness of biomanipulation have been firmly established. Nevertheless, biomanipulation is still in an early stage of development; it is an active area of research rather than a tried-and-proven management technique (Crowder et al. 1988; Lammens et al. 1990). Ecosystem interactions are complex and only partially understood. As a result, it is difficult to predict *a priori* the full suite of outcomes that will occur in response to a change in the biological community. Surprises are common, and reliable prescriptions for biomanipulation cannot be

The benefits of biomanipulation make efforts to investigate and implement this technique worthwhile, given appropriate controls and caution.

defined. Despite these limitations, the benefits of biomanipulation — its relatively low cost, the absence of machinery and toxic chemicals, and its potential effectiveness — make efforts to investigate and implement this technique worthwhile, given appropriate controls and caution. The high level of interest in the topic is evident from the number of recent symposiums and publications on biomanipulation and related fields (e.g., Carpenter, 1988; Benndorf, 1988; Gulati et al. 1990).

The term "biomanipulation" in this manual is used in a broad context to include any management technique that relies on altering the fish community to improve water quality — to reduce nutrient levels, increase water clarity, reduce growths of algae or macrophytes, or otherwise achieve water quality management objectives. Biomanipulation methods are presented within three groups, based on the types of fish involved and primary lake problem being addressed:

1. introduction of grass carp or other fish species that consume aquatic plants to control excessive macrophyte growths;
2. reduction of populations of bottom-feeding fish, such as common carp, that can be a significant internal nutrient source and can physically disturb the lake bottom, contributing to problems of high lake turbidity and productivity; and
3. top-down management of the pelagic food web by manipulating the occurrence and abundance of predatory or planktivorous fish to help control phytoplankton abundance and improve water clarity.

Grass Carp for Aquatic Plant Control

Excessive macrophyte growth is a common lake problem that adversely affects the value of a lake for swimming, boating, fishing, and other recreational uses and is also aesthetically unpleasing. Chapter 8 presented seven different approaches for controlling plant growth. This section discusses just one of those seven possible methods: the introduction of grass carp.

Grass carp (*Ctenopharyngodon idella*, also called white amur) are an exotic fish, imported originally from Malaysia to the United States in 1962. They are voracious consumers of macrophytes, grow quickly (as much as 6 pounds per year), and if stocked at sufficient rates, can completely eradicate all aquatic plants within several seasons. A genetic derivative, a triploid grass carp (as compared to the normal diploid grass carp) has been developed that is functionally sterile to minimize the potential for the uncontrolled spread of the species. In some areas, it is legal to stock 100 percent triploid grass carp but not diploid grass carp. In many States and provinces, however, both diploid and triploid grass carp are banned (Table 9-1) because of concerns regarding the introduction of exotic species and the invasion of grass carp into nontarget waters. In all cases where grass carp introductions are legal, appropriate permits and environmental approvals must be obtained from the State, provincial, or Federal regulatory authority before importing and/or stocking these fish (see Appendix C).

Grass carp do not consume all types of macrophytes equally. Preferred plant species include elodea, pondweeds (*Potamogeton* spp.), naiads (*Najas* spp.), and hydrilla; carp generally avoid alligatorweed, waterhyacinth, cattails, spatterdock, and waterlilies (Olem and Flock, 1990; Cooke and Kennedy, 1989; Wiley et al. 1987; Van Dyke et al. 1984). Low stocking densities can result, therefore, in selective grazing on preferred plant species, while less palatable macrophyte species increase in abundance (see Box 9-A, Devils Lake case study). Bonar et al. (1990) found that grass carp feeding preferences also depend on the plants' chemical composition, which can vary among lakes.

Table 9-1.—State and provincial regulations on the possession and use of grass carp. In all cases, a permit must be obtained from the appropriate State or provincial regulatory authority.[a]

A. DIPLOID (ABLE TO REPRODUCE) AND TRIPLOID (STERILE) PERMITTED:			
Alabama	Hawaii	Kansas	New Hampshire
Alaska	Idaho	Mississippi	Oklahoma
Arkansas	Iowa	Missouri	Tennessee
B. ONLY 100 PERCENT TRIPLOIDS PERMITTED:			
California	Kentucky	New Mexico	South Dakota
Colorado[b]	Montana	North Carolina	Virginia
Florida	Nebraska	Ohio	Washington
Georgia	New Jersey	South Carolina	West Virginia
Illinois			
C. 100 PERCENT TRIPLOIDS PERMITTED FOR RESEARCH ONLY:			
Alberta	Newfoundland	Nova Scotia	Quebec
British Columbia	New York	Oregon	Saskatchewan
Louisiana	Northwest Territories	Prince Edward Island	Wyoming
New Brunswick			Yukon
D. GRASS CARP PROHIBITED:			
Arizona	Manitoba	Nevada	Texas
Connecticut	Maryland	North Dakota	Utah
Delaware	Massachusetts	Ontario	Vermont
Indiana	Michigan	Pennsylvania	Wisconsin
Maine	Minnesota	Rhode Island	

[a] Reproduced with appropriate updates from *The Lake and Reservoir Restoration Guidance Manual* (Olem and Flock, 1990, pg. 142) and adapted from Allen and Wattendorf (1987).
[b] Written permission required to stock grass carp in western Colorado.

Appropriate stocking rates for grass carp depend on the amount of plant biomass to be consumed, the plant species, the size of the grass carp, the relative length of the growing season for both the fish and plants, and the overall size of the site. Effective stocking rates vary widely from 2 to 200 fish per acre, although rates of 10 to 25 fish per acre are generally used (Allen and Wattendorf, 1987). In most States, specific guidelines or procedures are available for calculating the optimal stocking rate for a given lake (see Box 9-B). Grass carp are most effective at controlling new plant growth, so fish should be stocked preferably in the spring or following other macrophyte control treatments such as herbicides or mechanical harvesting.

Grass carp are most effective at controlling new plant growth, so fish should be stocked preferably in the spring or following other macrophyte control treatments. . . .

In many cases, grass carp provide a feasible and cost-effective alternative to other techniques for managing aquatic weeds (see Box 9-A). They are generally most useful in warmer climates and when the target plant is a preferred food that can be eaten rapidly. However, it is very difficult to control the level of weed control by varying the fish stocking rate. In many instances, this is an "all-or-nothing" control technique. When stocking levels are adequate, carp will greatly reduce or nearly eliminate macrophyte beds, whereas lower stocking rates may have little impact on macrophyte abundance. In larger bodies of water, grass carp may eliminate plants from certain areas, leaving problematic quantities of plants to thrive in others.

Grass carp are not a panacea for plant control. In particular, they may not be the best approach for plant control efforts directed primarily at improving a lake's sport fisheries. The total elimination of macrophytes results in the loss of important nursery areas for small fish and habitat for many invertebrates that are valuable fish prey (see Chapters 3 and 8).

Furthermore, grass carp introductions and the associated disappearance of aquatic macrophytes are accompanied in some cases by an increase in turbidity, nutrient availability, and algal growth (e.g., Leslie et al. 1983; Miller and King, 1984). The cause of this increase is uncertain. Grass carp may convert all or some of the nutrients previously stored as macrophyte biomass into readily available forms in the water column, which can stimulate algal growth. Some portion of

Box 9-A.—Examples of Grass Carp Introductions to Control Macrophytes

Lake Conroe, Texas (Martyn et al. 1986; Olem and Flock, 1990): Diploid grass carp were introduced into Lake Conroe, Texas, a water supply impoundment for Houston. Macrophytes occupied about 44 percent of the 20,000 acres at maximum infestation levels before the introduction. Most plants were hydrilla (*Hydrilla verticillata*), although Eurasian watermilfoil (*Myriophyllum spicatum*) and coontail (*Ceratophyllum demersum*) were also abundant. Between September 1981 and September 1982, 270,000 grass carp 8 inches or longer, were stocked. By October 1983, all submersed plants were gone. Associated with this eradication was an increase in planktonic algae, a decrease in transparency, and an increase in open-water fish species that feed on plankton. Populations of fish species associated with macrophyte beds declined.

Lakes Bell, Clear, and Holden, Florida (Van Dyke et al. 1984; Cooke et al. 1986): Diploid grass carp, each fish weighing 0.5 pounds on average (about 10 lb/acre), were stocked in 1974 into Lakes Bell, Clear, and Holden at a stocking rate of 20 fish per acre (about 10 lb/acre). Lake Bell had about half of its surface covered with hydrilla in November 1974. Between 1974 and 1977, vegetation on transects in the lake decreased by 94 percent, and hydrilla was eliminated. Sawgrass (*Cladium jamaicense*) and fragrant waterlily (*Nymphaea odorata*) were apparently unaffected. Clear Lake was dominated by hydrilla and coontail, which covered one-third of its surface in 1974. By 1976, both species were eliminated, and by 1977 total vegetation cover was reduced by 94 percent. In addition to introduction of grass carp, Holden Lake was treated with herbicide over 13 percent of its area. Hydrilla, which covered more than one-third of the lake in November 1974, was eliminated.

Devils Lake, Oregon (Thomas et al. 1990; CH2M HILL, 1990): Devils Lake (680 acres, mean depth 10 feet) was stocked in September 1986 with 10,000 triploid grass carp and an additional 17,000 fish in March 1987, for a combined stocking rate of 2.7 pounds of fish per ton of vegetation. The specific objective was to reduce but not eliminate macrophytes (from 55 percent cover in 1986 to about 20 percent), thereby avoiding potential adverse effects on the lake's important sport fishery for largemouth bass. The introduction, however, has been only partially successful. In 1986, approximately 55 percent of the lake was covered with macrophytes dominated by Brazilian waterweed (*Elodea densa*; 33 percent by weight), coontail (23 percent), Eurasian watermilfoil (19 percent), and Canadian waterweed (*Elodea canadensis*; 6 percent). Eurasian watermilfoil, which formed large surface mats during summer, particularly interfered with boating, fishing, and swimming on the lake. By 1990, following the introduction of grass carp, macrophyte biomass had increased rather than decreased by about four times relative to levels in 1986.

Despite this increase in macrophyte biomass, the weed problem in Devils Lake is generally considered to have lessened because of the marked reduction in the large mats of Eurasian watermilfoil at the lake surface. The biomass of Brazilian waterweed and coontail have increased, although neither has formed nuisance mats. It is unclear, however, to what degree this shift in macrophyte species was caused by the introduction of grass carp as opposed to a natural succession of plant species. In laboratory feeding studies, triploid grass carp preferred Eurasian watermilfoil and Canadian waterweed over Brazilian waterweed. Also, grass carp have been observed feeding at the lake surface and may have contributed to the decline in surface mats. Finally, macrophyte biomass levels are higher in in-lake enclosures that exclude grass carp than in the lake proper, suggesting that plant biomass in the lake would be even greater in the absence of grass carp. Water quality, as measured by nutrient and chlorophyll *a* concentrations, has not changed appreciably since grass carp were introduced. In addition, no adverse effects are evident on other fish species or the lake's fisheries.

Box 9-B.—Suggested Stocking Rates for Triploid Grass Carp in Illinois (source: Wiley et al. 1987)

Recommended stocking rates for triploid grass carp in Illinois lakes have been developed using the computer model, Illinois Herbivorous Fish Stocking Simulation System. Optimal stocking rates are determined by the following lake characteristics:

- lake area,
- percentage of lake that is less than 8 feet deep,
- percentage of lake that is heavily vegetated when aquatic plant cover is at its peak, typically in July or August,
- the dominant plant species in the lake or the plant targeted for control, and
- the county in which the lake is located (to account for geographic differences in climate and water temperatures).

The result is a site-specific stocking rate that will maximize the cost-effectiveness of using grass carp for aquatic weed control. Examples of recommended stocking rates for a hypothetical lake in northern Illinois are presented in Figure 9-1.

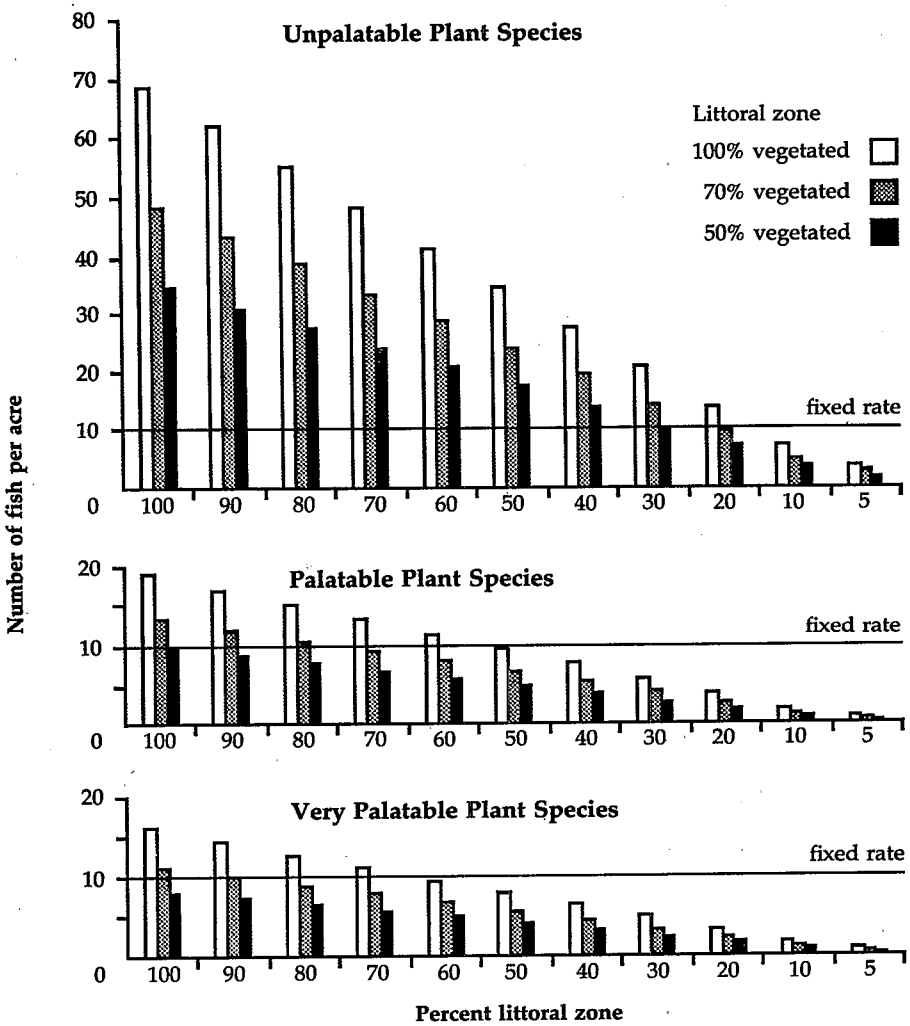

Figure 9-1.—A comparison of fixed-rate (10 fish per acre) recommendations for grass carp stocking versus estimates based on the procedures in Wiley et al. (1987) for three categories of plant palatability. Each comparison shows rates for a lake in northern Illinois when littoral zones are 50, 70, and 100 percent vegetated. Graphs give the recommended stocking rate, in terms of the number of 10-inch grass carp, as a function of the percentage of the lake littoral zone (source: Wiley et al. 1987).

the macrophyte nutrients, however, will be tied up in fish biomass. Relatively few detailed studies have been conducted on the effects of grass carp on nutrient cycling, and the results from the available research are somewhat equivocal (Cooke et al. 1986). In addition, increases in algal growth following macrophyte reductions are not limited to control programs using grass carp. Observed increases may be primarily a response to the loss of a significant competitor (macrophytes) for nutrients rather than a function of the grass carp per se (Richard et al. 1984).

Grass carp can migrate to other lakes and streams where reductions in plant growth are not desired. Even though triploid grass carp are functionally sterile, they can live 10 to 15 years (Allen and Wattendorf, 1987). Bain et al. (1990) observed significant movement (average 20 miles) of individual adult grass carp stocked into an open, mainstream reservoir in Tennessee. Such movements must be anticipated as part of management decisions to introduce this species (Noble et al. 1986). To prevent its uncontrolled spread, grass carp introductions should be limited to isolated lakes with little or no chance of fish migration into other waterbodies.

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All of the available macrophyte control options have disadvantages and advantages (see Chapter 8). The major advantages of grass carp include its relatively low cost and long-term effectiveness. For more information on using grass carp for aquatic plant control, see Chapter 6 of *The Lake and Reservoir Restoration Guidance Manual* (Olem and Flock, 1990), Cooke and Kennedy (1989), Cooke et al. (1986), Allen and Wattendorf (1987), Wiley et al. (1987), and the Illinois Department of Conservation (1988).

Other fish species, particularly *Tilapia zilli* (redbelly tilapia) and *Tilapia aurea* (blue tilapia), have also been considered for control of macrophytes or filamentous algae and applied successfully in a few cases (Cooke et al. 1986; Gophen, 1990); examples include California irrigation canals (Hauser, 1975), a cooling water impoundment in North Carolina (Schmiller, 1984), and an Illinois pond (Childers and Bennett, 1967). Tilapia are intolerant of cooler water temperatures (below 10°C for extended periods of time) and, thus in most areas, need to be restocked annually. In addition, blue tilapia may dominate fish communities of lakes into which they are introduced and compete with native planktivorous fish (Hendricks and Noble, 1979).

Control of Bottom-Feeding Fish to Reduce Internal Nutrient Loads and Water Turbidity

Fish that feed on the organisms and detritus in lake sediments can be a significant internal source of nutrients (Cooke et al. 1986). Nutrients stored in the living and dead organic matter concentrated in the lake sediments are converted into more readily available forms through fish digestive processes and excreted into the water column. Based on experiments in lake enclosures, LaMarra (1975) calculated that common carp at a biomass of 180 lb/acre (200 kg/ha) and temperature of 72°F (22°C) could add about 24 mg of phosphorus to a lake's water column per square foot per day (2.2 mg/m^2/day). Keen and Gagliardi (1981) found similar results in experiments with brown bullhead, while Smeltzer and Shapiro (1982) calculated that the carp and bullhead in Union Lake, Minnesota, contributed 0.8 lb of phosphorus/acre/year (88 mg/m^2/yr), a phosphorus loading rate approximately equivalent to that from external sources (Cooke et al. 1986). Brabrand et al. (1990) estimated that roach (*Rutilus rutilus*) contributed about 30 percent annually of the total phosphorus supply to Lake Gjersjøen, Norway, but about 80 percent of the phosphorus inputs to the lake epilimnion during summer when fish feeding activities were at a maximum and inputs from the watershed were low. Roach and carp feed at the lake bottom and also on zooplankton in the water column. By migrating between the littoral and pelagic zones, they redistribute nutrients bound to the lake sediments into the epilimnion, making them available for phytoplankton uptake and productivity.

Common carp and other bottom-feeding fish also physically disturb the lake sediments, contributing directly to problems of high turbidity as well as nutrient recycling. Carp can reach substantial sizes in eutrophic lakes, 10 to 25 pounds or more per fish. They feed by sucking up large volumes of soft organic bottom sediments and then expelling all but the edible particles into the water column (Scott and Crossman, 1973). In addition especially during the spawning season, carp concentrate in shallow waters and "roll," splashing and thrashing at the lake surface and stirring up the lake bottom. By loosening the top layer of sediment and hindering the development of macrophytes, bottom-feeding fish also make the lake bottom more susceptible to resuspension by winds and waves (Hosper and Jagtman, 1990). Models developed for shallow lakes in the Netherlands suggest that 50 percent of the turbidity in these waters results from sediment resuspension, mainly caused by the activity of bottom-feeding fish (Meijer et al. 1990).

Common carp and other bottom-feeding fish also physically disturb the lake sediments, contributing directly to problems of high turbidity as well as nutrient recycling.

High densities of bottom-feeding fish often accompany eutrophication. Horppila and Kairesalo (1990), Hosper and Jagtman (1990), Brabrand et al. (1990), and others have suggested that large populations of bottom-feeding fish can also substantially delay — or even prevent — lake recovery following reduction of external nutrient loads. Internal nutrient recycling, primarily from the lake sediments, is sufficient to maintain a high level of algal productivity. A reduction in the biomass of bottom-feeding fish can result in decreased water turbidity and nutrient availability and, in some cases, a decrease in phytoplankton abundance. For example, following a reduction in fish biomass in two shallow lakes in the Netherlands, lake transparency increased substantially, the result not only of a decrease in algal biomass but also of a decrease in resuspended sediment and detritus (Meijer et al. 1990). In enclosure experiments in Lake Vesijärvi, Finland, lower levels of roach biomass resulted in lower chlorophyll *a* concentrations (an indicator of phytoplankton abundance) and higher water transparency (Horppila and Kairesalo, 1990; Fig. 9-2).

Methods for reducing and controlling populations of undesirable fish species were described in Chapter 8, and include (1) fish poisoning (e.g., using rotenone); (2) extreme water drawdowns; (3) selective cropping, including establishing commercial fisheries for the species, where possible; (4) disruptions of spawning behavior and reproduction through direct disturbance and water level drawdowns during the spawning season; (5) increased predation; and (6) fish barriers to prevent the migration of undesirable species into lakes where they do not currently occur or following eradication of the fish community. Neither carp nor bullhead spawn in areas where spawning behavior or egg masses can be readily disturbed, nor are they particularly susceptible to increased predation. Carp are also extremely prolific. As a result, both species are difficult to control and only drastic measures, such as rotenone or extreme drawdown, may be effective. Such measures that impact the entire lake, however, may also interfere with other lake uses and values. Where possible, the best approach for carp control is to prevent the species from being introduced or migrating into the lake; for instance, by installing fish barriers.

Where possible, the best approach for carp control is to prevent the species from being introduced or migrating into the lake. . . .

Top-Down Management of the Pelagic Food Web to Reduce Algal Biomass and Improve Water Transparency

The term "biomanipulation" is frequently used to refer specifically to top-down management of the pelagic food web; that is, altering populations of fish predators or planktivores to indirectly control phytoplankton abundance and improve water clarity. The theoretical basis for top-down management was described in Chapter 2 (see Fig. 2-14):

1. a large biomass of piscivorous (fish-eating) fish will consume large numbers of smaller, planktivorous (plankton-eating) fish, resulting in a decline in the abundance of planktivores;
2. lower numbers of planktivores will consume fewer zooplankton, allowing for the development of a large zooplankton biomass, including large-sized zooplankton taxa such as *Daphnia*;

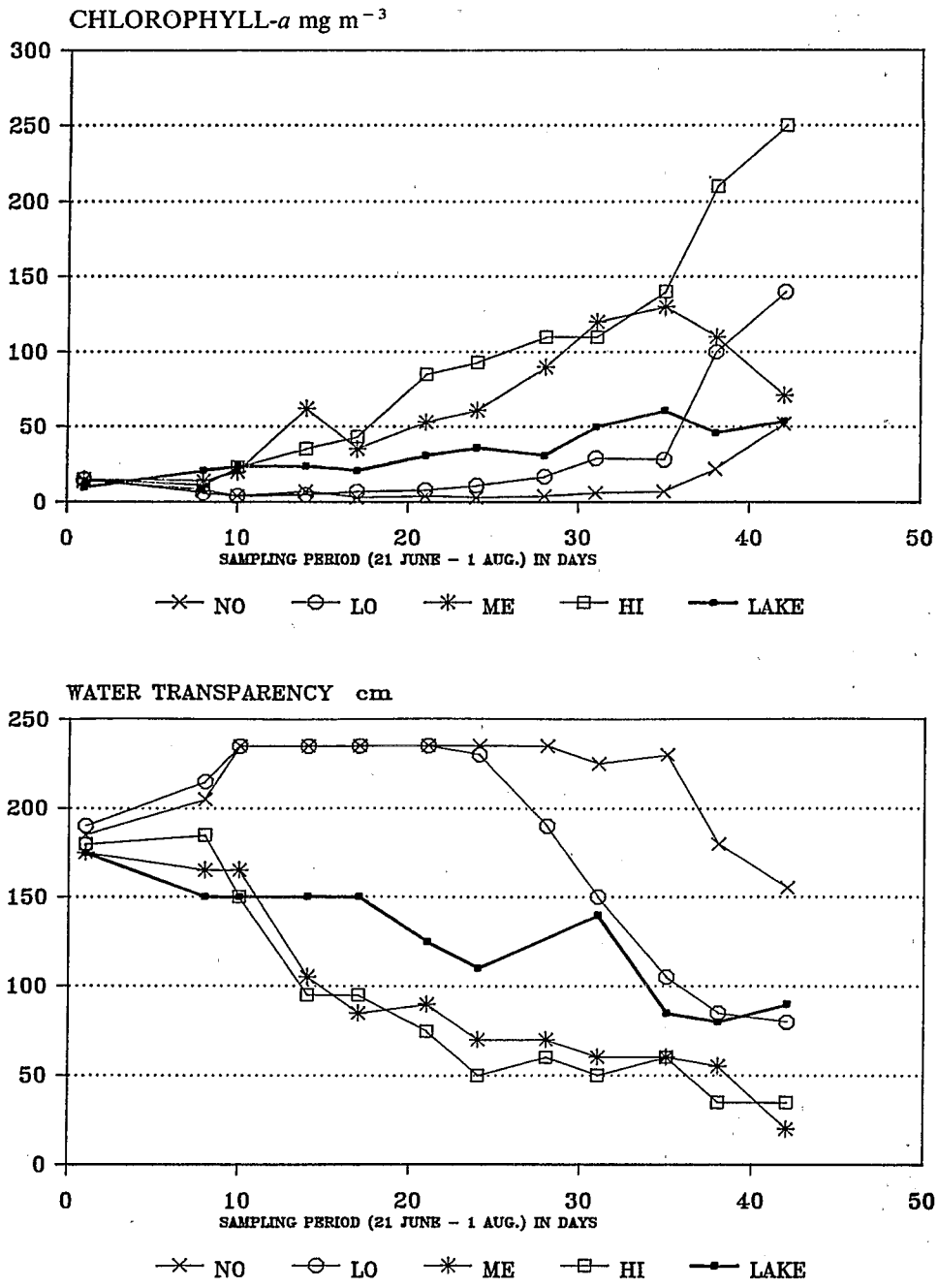

Figure 9-2.—Chlorophyll *a* concentrations and water transparency in enclosure experiments in Lake Vesijärvi, Finland, with no (NO), low (about 25 g/m^2; LO), medium (about 75 g/m^2; ME), or high (150 g/m^2; HI) biomass levels of roach (a bottom-feeding fish species), compared to levels in the lake (with a roach biomass of about 50 g/m^2) (source: Horppila and Kairesalo, 1990).

3. large numbers of zooplankton will consume large numbers of phytoplankton, reducing algal abundance; and
4. lower algal abundance will result in an increase in water transparency and overall improvement in water quality.

Theoretically at least, top-down management of the food web can have the same beneficial effects as a reduction in external nutrient loads (referred to as "bottom-up" management).

Top-down management can be implemented by either increasing piscivore populations or reducing planktivorous fish populations directly. A variety of management techniques can be applied for both approaches, including the following:

- Increase the abundance of piscivores through
  - introduction, by stocking, of new piscivore species,
  - supplemental stocking of existing piscivore populations,
  - fishing regulations to restrict angler harvests of piscivores, and
  - habitat improvements to enhance piscivore survival and/or reproduction.
- Reduce the abundance of planktivorous fish through
  - fish poisoning,
  - extreme water drawdown,
  - selective catches and fish removal,
  - disruption of spawning behavior and reproduction (e.g., water level manipulations), and
  - fish barriers.

Theoretically at least, top-down management of the food web can have the same beneficial effects as a reduction in external nutrient loads.

Additional information on each of these fish management techniques is provided in Chapter 8.

Top-down management can work, as demonstrated by several of the case studies summarized in Box 9-C. However, in most lakes, food webs are more complex than the simple food chain just described, with many interspecies interactions (competition as well as predation) and feedback loops. As a result, lake responses to the application of top-down management are less predictable than desired. In some cases, fish manipulations have resulted in no measurable effect on algal biomass or water transparency; in other instances, the benefits have been short-lived or conditions have actually worsened (see Box 9-C, which also includes examples of unsuccessful projects). Although the basic principles of top-down management are sound, the following subsections review some of the remaining uncertainties and limitations of the approach.

Inedible Phytoplankton

The relative importance of bottom-up (nutrient supply) and top-down (predation) controls varies with position in the food web (McQueen et al. 1986). Nutrient inputs have the greatest effect on phytoplankton; other components of the food web are also affected, but the magnitude of response decreases with each succeeding step up the trophic pyramid. Likewise, responses to a change in fish predation are strongest and most predictable near the top of the food web but weaken and become less predictable with every step down the trophic pyramid. Thus, the weakest component and major source of uncertainty in top-down management is the linkage between zooplankton and phytoplankton (Lampert, 1988; Gulati et al. 1990).

[R]esponses to a change in fish predation are strongest and most predictable near the top of the food web but weaken and become less predictable with every step down the trophic pyramid.

Box 9-C.—Fish Manipulations to Decrease Algal Biomas & Improve Water Transparency: Examples of Successful & Not So Successful Applications of Biomanipulation

Round Lake, Minnesota (Shapiro and Wright, 1984; Shapiro, 1990): Rotenone was applied to Round Lake (31 acres) in fall 1980 to eliminate planktivorous and bottom-feeding fish (primarily bluegill, black crappie, and black bullhead). The lake was subsequently restocked with a high density of piscivores (largemouth bass and walleye) and smaller numbers (relative to pre-treatment) of bluegills and channel catfish. *Daphnia*, which were rare in 1980, subsequently became the dominant zooplankton genus in 1981 and 1982. Even though total zooplankton numbers declined, zooplankton grazing rates on phytoplankton were estimated to have doubled because of the large increase in mean zooplankton size. Chlorophyll *a* concentrations dropped sharply in 1981 and 1982 relative to values in 1980, and Secchi disk transparency increased (Fig. 9-3). Although highly successful for two years, in year three bluegill increased in abundance and large-bodied *Daphnia* decreased, leaving the lake water quality only slightly better than before biomanipulation. Even though large numbers of piscivores were introduced, long-term control of the bluegill population was not achieved. This was likely because larger adult bluegills are not susceptible to predation, and significant numbers of largemouth bass were removed from the lake by anglers.

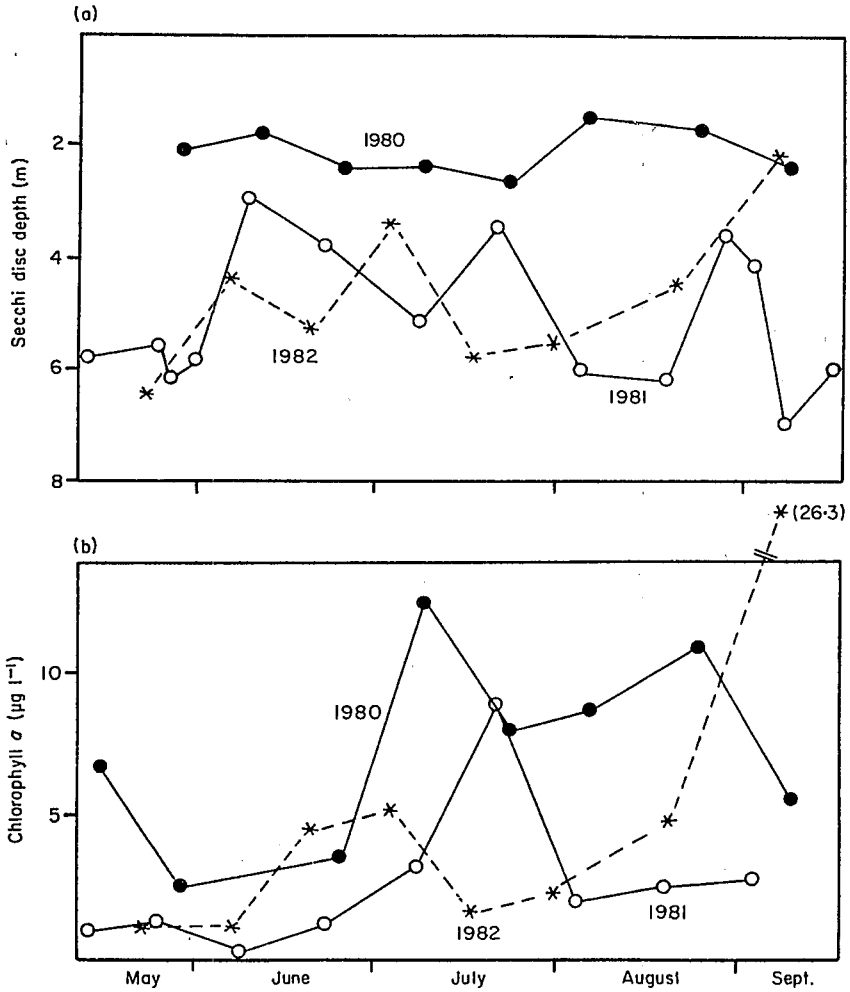

Figure 9-3.—Secchi depth transparency and epilimnetic chlorophyll *a* concentrations in Round Lake, Minnesota, in 1980 before biomanipulation; and in 1981 and 1982 after treatment (source: Shapiro and Wright, 1984).

Continued on next page

Box 9-C.—Continued

Lake Michigan (Scavia et al. 1986, 1988; Kitchell and Carpenter, 1987): During the first half of this century, fisheries exploitation coupled with the invasion of sea lamprey lead to the collapse of the lake trout population, the dominant piscivore in Lake Michigan. In the absence of significant numbers of piscivores, invading populations of planktivorous fish flourished. Alewife, in particular, increased dramatically in abundance during the 1950s and 1960s and was the major component of fish biomass until recently. In response to this alewife expansion, large-bodied copepods and cladocerans virtually disappeared from the lake during the late 1960s and were replaced by smaller zooplankton. The development of an effective lampricide and large-scale lamprey control program in the 1970s allowed for the re-establishment of salmonid populations in the lake. In addition to lake trout, several Pacific salmonid species (including rainbow trout and coho salmon) have been stocked and now provide sport fisheries of substantial economic and social value. Also over the last decade, the dominant zooplankton taxa have shifted from calanoid copepods to *Daphnia*; filamentous cyanobacteria algae, which dominated in the late summer, have been replaced by phytoflagellates; and water transparency has increased. External nutrient loads to the lake have also declined since the mid-1970s and have contributed to the improved water quality. Model analyses, however, suggest that the observed changes in the summer plankton community resulted primarily from the increased abundance of fish piscivores.

Lake Væng, Frederiksborg Castle Lake, and Lake Søbygård, Denmark (Jeppesen et al. 1990b): Lake Væng (37 acres) and Lake Søbygård (99 acres) are quite shallow (mean depth about 3 feet) and have high flushing rates (15 to 25 days). Frederiksborg Castle Lake (52 acres) is stratified in the summer, somewhat deeper (mean depth 10 feet), and has a relatively long hydraulic retention time (4 to 18 years). All three lakes are eutrophic, although to varying degrees and with different phytoplankton composition. Less eutrophic Lake Vænig is dominated by a combination of blue-greens and diatoms. The removal of 50 percent of the planktivorous fish biomass (roach, bream, and rudd, *Scardinus erythrophthalmus*) from Lake Vænig in 1986 and 1987 by selective fishing with various gear types (beach seine, electrofishing, and gill, fyke, and pound nets) resulted in a marked decrease in chlorophyll *a* and increase in water transparency (Fig. 9-4). In contrast, only minor changes occurred in Frederiksborg Castle Lake, a eutrophic lake dominated by blue-greens, after a 78 percent removal of planktivorous fish in 1986 and 1987 (Fig. 9-4). In hypereutrophic Lake Søbygård, dominated by green algae, no fish reproduction occurred from 1983 to 1986, probably because of high pH levels (10 to 11) during the spawning period, and 16 percent of the planktivorous fish biomass was removed by selective fishing from 1986 to 1988. Over the same period, chlorophyll *a* concentrations decreased substantially and water transparency increased. Differences in lake response appeared to be related to phytoplankton community composition — in particular the dominance of bloom-forming blue-greens in Frederiksborg Castle Lake — and perhaps lake depth and flushing rates.

Bautzen Reservoir, Germany (Benndorf et al. 1988; Benndorf, 1990): Bautzen Reservoir (1,317 acres) is a multipurpose reservoir used as a cooling water supply for a power plant, water supply, flood control, and recreation. The major water quality problem is eutrophication. Biomanipulation began in 1977. Each year, zander (*Stizostedion lucioperca*), a piscivore in the same genus as walleye, are stocked as fingerlings. In addition, restrictions on angler harvests of northern pike, the other major piscivore in the lake, have been imposed since 1979. Increased predation by pike and zander reduced the abundance of planktivorous fish in the reservoir (mainly small perch, *Perca fluviatilis*). In recent years, the ratio between piscivores and planktivores plus bottom-feeding fish has stabilized at about 0.3 to 0.5. During the eight years post-manipulation, zooplankton biomass has increased 21 percent relative to pre-manipulation years; the biomass of *Daphnia galeata*, the major large-bodied zooplankton, has increased by 110 percent. The abundance of large predatory invertebrates (*Chaoborus flavicans*, *Leptodora kindtii*) has also increased, but only to moderate levels because of the continued presence of some planktivorous fish. Mean Secchi depth transparency increased by 20 percent, with an extended clear water phase in the early summer. Phytoplankton community composition, however, has shifted to a dominance of inedible cyanobacteria. In most years, maximum phytoplankton biomass levels have been higher following biomanipulation than before. The frequency of occurrence of cynobacterial blooms has also increased. Thus, biomanipulation in Bautzen Reservoir has had both positive and negative effects on water quality.

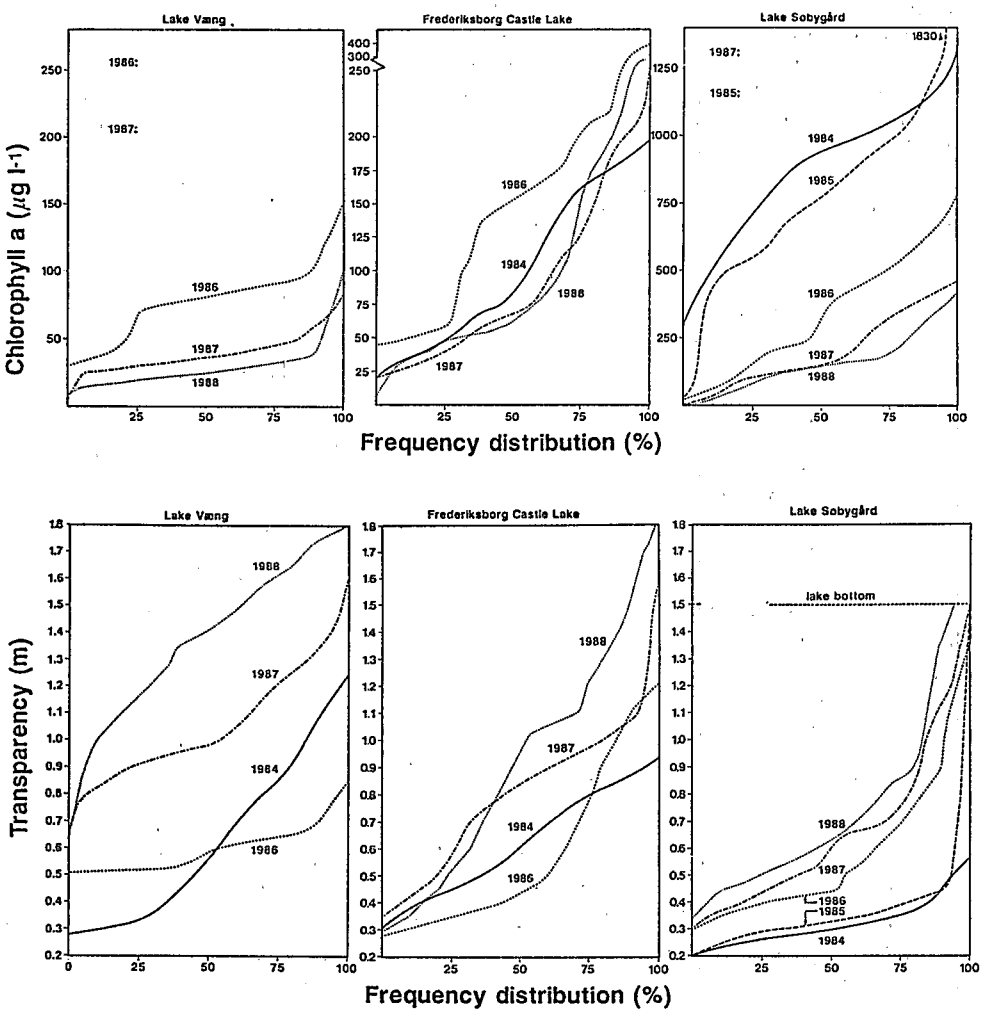

Figure 9-4.—Frequency distribution of chlorophyll *a* and Secchi depth transparency during summer in three Danish lakes in the years before (≤ 1985) and after (≥ 1986) reduction of planktivorous fish biomass (source: Jeppesen et al. 1990b).

Top-down management can fail because not all species of phytoplankton are readily consumed by zooplankton. In a number of lakes and experiments, the primary response to increased zooplankton grazing pressure was a shift in phytoplankton species composition from edible to inedible forms rather than a decrease in total phytoplankton abundance (Stenson et al. 1978; Lynch and Shapiro, 1981; Benndorf et al. 1984, 1988; Bergquist et al. 1985). Two main factors contribute to the suitability of phytoplankton as food for zooplankton:

- **morphology,** the size and shape of the algal cell or colony, and
- **biochemical properties,** in particular the ability of some algae to produce substances toxic to zooplankton (Gliwicz, 1977; Porter and Orcutt, 1980; Lampert, 1981; de Bernardi and Giussani, 1990).

At high densities, large filamentous algae, besides being inedible, can also interfere with the feeding process and decrease the overall feeding efficiency (Webster and Peters, 1978; Infante and Abella, 1985). The probability of a successful top-down management program depends in large part, therefore, on the quality and quantity of phytoplankton in the lake (see Box 9-C).

Table 9-2.—Experiments in lakes (1), reservoirs (2), ponds (3), enclosures (4), and aquaria (5) that support the hypothesis that planktivorous fish reduce the biomass of herbivorous zooplankton (Z), and as a result, increase the biomass of phytoplankton and/or decrease water transparency (Ph/T). Positive results that support the hypothesis are denoted by a plus sign (+), while a zero (0) indicates indifferent results; lack of a sign indicates no information (adapted from Persson et al. 1988).

TYPE	FISH SPECIES/TAXA	Z	Ph/T	REFERENCE
1	Cyprinidae (minnows and carp)	+	+	Hrbácêk et al. 1961
1	Alewife	+	+	Brooks and Dodson, 1965
1	Cyprinidae	+	+	Stenson et al. 1978
1	Cyprinidae	+	+	Henrikson et al. 1980
1	Coregoninae and perch	+	+	Reinertsen and Olsen, 1984
2	Cyprinidae	+	+	Leah et al. 1980
2	Stickleback	+	+	Olrik et al. 1984
3	Cyprinidae	+	0	Grygierek et al. 1966
3	Bluegill	+	0	Hall et al. 1970
3	Mosquitofish	+	+	Hurlbert et al. 1972
3	Cyprinidae	+	+	Losos and Hetesa, 1973
3	Cyprinidae	+	+	Fott et al. 1980
3	Mosquitofish	+	+	Hurlbert and Mulla, 1981
3	*Pimephales* spp. (minnow)	+	+	Spencer and King, 1984
3	Bluegill	+	+	Hambright et al. 1986
4	Cyprinidae	+	+	Andersson et al. 1978
4	Bluegill and *Pimephales* spp.	+	+	Lynch, 1979
4	Bluegill	+		Lynch and Shapiro, 1981
4	*Pimephales* spp.	+	+	Elliot et al. 1983

Most inedible forms of phytoplankton are blue-green algae. Furthermore, inedible blue-greens occur most commonly in eutrophic and hypereutrophic lakes (Davidowicz et al. 1988; di Bernardi and Giussani, 1990; Elser and Goldman, 1991) because large-cell sizes are a disadvantage in nutrient-limited waters. Thus, zooplankton grazing may be a less effective method for reducing phytoplankton abundance in eutrophic and hypereutrophic lakes than in meso- or oligotrophic waters (see the discussion later in this chapter on the influence of trophic status).

Most studies of phytoplankton responses to zooplankton grazing have been relatively short-term, however. It is possible that, over time, zooplankton communities can adapt to and control even relatively inedible phytoplankton species by altering their feeding behavior, grazing on them at susceptible stages of the algal life cycle, or undergoing a shift in zooplankton species composition favoring those species able to handle such food items (Elser and Goldman, 1991). In addition, a longer "clearwater phase" in the spring brought on by increased zooplankton grazing on the edible phytoplankton (primarily diatoms) that predominate at that time may inhibit the proliferation of bloom-forming blue-green algae later in the summer (Spencer and King, 1986; Elser et al. 1990). However, additional research is needed on the long-term response of phytoplankton communities to increased grazing pressure and factors that control the occurrence of inedible, blue-green algae.

Zooplankton Composition and Abundance

The objective of top-down management is to maximize the grazing pressure or "filtration capacity" of herbivorous zooplankton. The best results are achieved not by maximizing total zooplankton abundance but by increasing the abundance of large-sized zooplankton, such as *Daphnia* (Benndorf, 1988). Large zooplankton have higher grazing rates (Peters and Downing, 1984) and can injest a broader variety of algae, including larger algae (Burns, 1968; Carpenter et al.

1985), than do smaller-bodied zooplankton, such as *Diaphanosoma* or *Bosmina*. Smaller zooplankton have relatively restricted diets (e.g., *Diaphanosoma* and *Bosmina* have difficulty consuming items larger than 15 μm) and, as a result, are generally unable to control phytoplankton abundance (Kerfoot, 1987).

The method used to increase the abundance of large-bodied, herbivorous zooplankton is to reduce the biomass of fish that feed on zooplankton — that is, planktivores, such as alewife and rainbow trout (see Table 2-4). A great deal of research has demonstrated the linkage between planktivorous fish and zooplankton community composition and abundance (Table 9-2). In the absence of predation from planktivorous fish, zooplankton communities become dominated by those species with the greatest competitive advantage. Generally, large-bodied zooplankton have a competitive advantage over smaller zooplankton because of their ability to consume a wider array of phytoplankton at faster rates (Kerfoot, 1987).

The method used to increase the abundance of large-bodied, herbivorous zooplankton is to reduce the biomass of fish that feed on zooplankton.

In some studies, however, reductions in planktivorous fish have not resulted in zooplankton communities being dominated by large herbivores. For example, Crisman and Beaver (1990) found that cladoceran assemblages (which include the genus *Daphnia*) in subtropical Florida lakes are smaller than those in temperate lakes. Even though fish reductions result in an increase in total zooplankton abundance, large-bodied zooplankton capable of controlling algal blooms do not occur. Therefore, top-down management through the zooplankton community may not be an effective approach for reducing phytoplankton abundance or improving water transparency in Florida lakes.

Complications may also arise if large predacious zooplankton that feed on other zooplankton occur in a lake (see Fig. 2-14). A reduction in fish predation intended to increase the abundance of herbivorous zooplankton will also automatically reduce fish predation on predacious zooplankton species. Large invertebrate predators — such as *Leptodora, Chaoborus, Mysis* — and some species of Cyclopidae can feed on relatively large zooplankton, including large *Daphnia* (Hall, 1964; Lasenby and Furst, 1981; Barthelmes, 1988; Lunte and Luecke, 1990). Invertebrate predators, in this case, may simply replace the vertebrate (fish) predators with little or no change in zooplankton grazing pressure on phytoplankton.

A reduction in fish predation intended to increase the abundance of herbivorous zooplankton will also automatically reduce fish predation on predacious zooplankton species.

Invertebrate predation, therefore, has the potential to confound the simple food web linkages described at the beginning of this section and must be accounted for in designing a top-down management program. Lunte and Luecke (1990), for example, concluded that the presence of *Leptodora kindtii* in Lake Mendota, Wisconsin, will buffer to some degree lake responses to the ongoing fish management program where piscivorous fish species have been introduced to control algal blooms. Edmondson and Abella (1988) concluded that the marked increase in water transparency observed after 1975 in Lake Washington resulted in large part from the elimination of an invertebrate predator, *Neomysis mercedis*. In previous years, high densities of *Neomysis* had strongly suppressed *Daphnia* populations. In the 1960s, the abundance of fish planktivores increased — in particular, the population of longfin smelt, a fish that feeds selectively on *Neomysis*. The subsequent reduction in *Neomysis* resulted in an increase in *Daphnia*, an eventual decrease in phytoplankton biomass, and an associated increase in water transparency. Changes in Lake Washington are discussed further in Chapter 12 (Case Studies).

Optimal Biomass of Fish Planktivores

What densities of fish planktivores work best? In many biomanipulation studies, fish planktivores have been eliminated entirely by using rotenone or extreme drawdown. Such measures, however, also affect the zooplankton community because rotenone is toxic to zooplankton as well as fish. In addition, Benndorf (1990) suggests that moderate levels of fish planktivores should be maintained to control

invertebrate predators and help stabilize *Daphnia* populations by avoiding overpopulation and subsequent starvation and population declines. Benndorf (1990) defined "minimum fish biomass" as the minimum biomass of zooplanktivorous fish necessary to avoid such negative side effects and "critical fish biomass" as the upper limit that cannot be exceeded if populations of large herbivores are to develop. Minimum and critical biomass levels vary depending on the species and age of fish and lake conditions. For example, critical biomass levels reviewed by Benndorf (1990) ranged from 20 to 1,000 kg/ha. Very efficient fish planktivores (for example, age 0+ yellow perch) had the lowest critical biomass. Lake conditions that decrease fish feeding efficiency, such as refuge areas for zooplankton or high turbidity, increase the critical biomass level. The minimum fish biomass needed to control invertebrate predators can depend on complex interrelationships between the fish, invertebrate predator, and their zooplankton prey. In some cases, the abundance of invertebrate predators may actually be greatest at intermediate fish densities and lower at both high and low fish densities (Kerfoot, 1987; Crowder et al. 1988). In general, optimal biomass levels for fish planktivores cannot be defined with confidence at this time (Benndorf, 1990; Shapiro, 1990).

[M]oderate levels of fish planktivores should be maintained to control invertebrate predators and help stabilize Daphnia populations. . . .

Optimal Biomass and Types of Piscivorous Fish

Benndorf (1990) provides the following guidelines for selecting the optimal biomass and types of piscivores for top-down management programs:

- The proportion of piscivores in the total fish community must be sufficiently high to control populations of planktivorous fish. Generally, piscivores should comprise approximately 30 to 40 percent of the total fish biomass; also, the proportion of piscivores must be relatively stable through time.
- High piscivore diversity increases the stability and reliability of food web manipulations.
- A sufficiently high proportion of the piscivore population(s) must be large enough, with a large enough gape, to exert strong predation pressure on adult planktivores, especially large adult planktivores that have a high reproductive capacity. The occurrence of planktivorous fish, such as gizzard shad and bluegill that tend to grow too large for most predators, may prevent implementation of an effective top-down management program (see Round Lake case study in Box 9-C).
- An adequate number of small piscivore species or age classes must be present that prefer age 0+ fish as prey and can switch to benthic food (but not zooplankton) if age 0+ fish are scarce. A wide range and even distribution of piscivore age classes are important to guarantee high predation on a broad spectrum of planktivorous fish.
- Many piscivores will switch to other food types, including zooplankton, if adequate fish for prey are not available. If the piscivores consume zooplankton when planktivorous fish are in short supply, a top-down management program will likely fail. In addition, some piscivore species feed on zooplankton when young, switching to a diet of fish only when they reach a certain age or size; therefore, the full scope of a fish's feeding habits must be considered.
- The piscivore species must be an effective fish predator given the conditions and planktivores in the lake. For example, piscivores that rely on sight to capture prey and have relatively high light thresholds below which capture efficiency declines (O'Brien, 1987) would be ineffective predators for controlling planktivore populations in a turbid reservoir.

High piscivore diversity increases the stability and reliability of food web manipulations.

Top-down management should not be attempted in lakes where a high proportion of the planktivore population is unavailable to predators.

Many planktivores are prolific, with a high reproductive capacity; thus, establishing adequate control through piscivores or other means can be difficult. If piscivores remove only some age or size classes (e.g., only smaller fish), the end result may be more rather than fewer planktivores because the increased growth and reproductive success of the remaining planktivores can more than compensate for predation losses (see Chapter 3). Top-down management should not be attempted in lakes where a high proportion of the planktivore population is unavailable to predators (because of their large size or abundant refuge areas) and other planktivore control methods would be difficult, expensive, and/or effective for only a short period.

Instability

Two major problems associated with biomanipulation for water quality improvement are (1) making it stable — minimizing year-to-year fluctuations in predator-prey relations and (2) making it last — sustaining these relations and water quality improvements over multiple years or decades.

Populations of planktivorous fish that are reduced by intensive fishing, water level drawdown, or other techniques will generally recover within a relatively short time (one to three years) through fish growth and reproduction — unless fish reduction efforts are continued. Even drastic measures such as fish poisoning with rotenone can be temporary as fish species reinvade the lake from adjacent waters or are accidentally re-introduced. For example, chlorophyll *a* concentrations and water transparency in Round Lake, Minnesota, returned to near pre-manipulation levels within three years after rotenone treatment (Shapiro and Wright, 1984; Shapiro, 1990). Even though large numbers of largemouth bass (a piscivore) were stocked into the lake, bluegill — reintroduced after the rotenone treatment — recovered sufficiently to suppress large-bodied *Daphnia*. Failure of the bass population to adequately control bluegill was attributed to the bluegill's wide-bodied shape, which made a relatively high proportion of the adult population not susceptible to bass predation, and removal of bass by anglers.

In shallow lakes, even relatively short-term improvements in water transparency (e.g., an extended clear water phase during spring) may be sufficient to allow establishment of macrophytes. Extensive macrophyte growths can stabilize the lake bottom, reducing sediment resuspension, and decrease nutrient availability for phytoplankton. Hosper and Jagtman (1990), Jeppesen et al. (1990a), and others have suggested that, once macrophytes are established, this new clear water state can be relatively stable. Biomanipulation may be essential for switching from a turbid, algal-dominated system to a relatively clearwater, macrophyte-dominated system, even with considerable nutrient reduction (Moss, 1990; Hosper and Jagtman, 1990).

In shallow lakes, even relatively short-term improvements in water transparency may be sufficient to allow establishment of macrophytes.

Shapiro (1990) proposed that establishing refuges where prey can escape from predators may be one method for protecting prey populations from excessive predation and helping to sustain food web manipulations. Possibilities for refuges include

- regions of low light intensity (e.g., in the deeper parts of a lake or in turbid lakes);
- areas with low temperature or low dissolved oxygen that the prey (such as herbivorous zooplankton) can inhabit but the predator cannot; and
- macrophyte beds or physical structures where prey can hide.

Relatively few tests have been conducted, however, to evaluate the usefulness of refuges, and those tests have had equivocal results (Gulati et al. 1990).

Year-to-year fluctuations in the effectiveness of predator controls can be substantial. Two main contributing factors are variations in climate and time lags in feedback mechanisms in the food web (Carpenter et al. 1985). Year-class strength

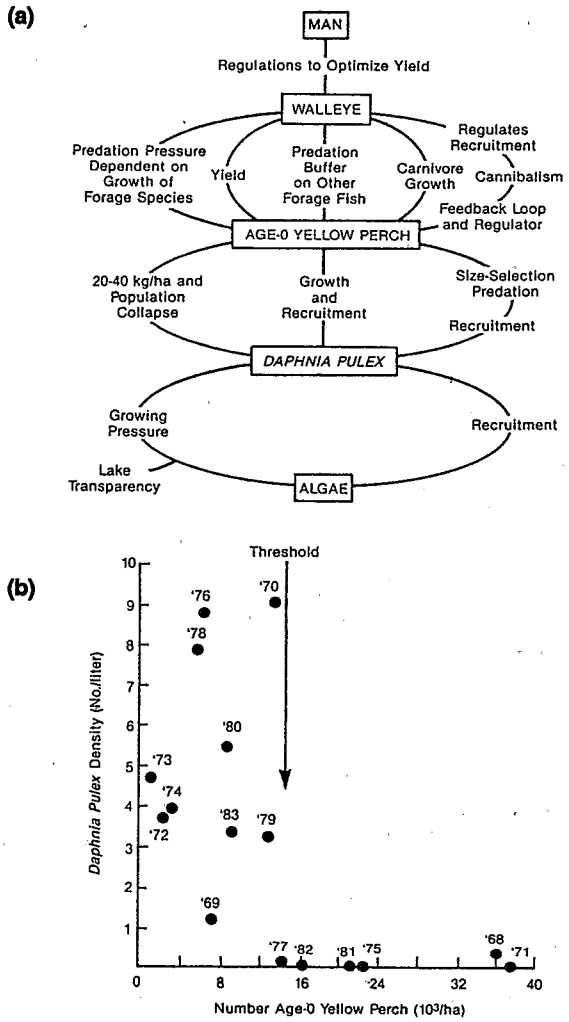

Figure 9-5.—(a) Trophic level interactions in the Oneida Lake food web and (b) the association between the density of *Daphnia pulex* (average value for August to October) and density of age-0 yellow perch in August in the lake (source: Mills et al. 1987).

in fish populations tends to be highly variable (see Chapter 3). Physical factors, such as cold temperatures or wave action, may cause poor embryo survival in some years. Weak year-classes are often followed by strong year-classes, and vice versa, as a result of intra-specific competition for food and cannibalism. The effects of these variations in year-class strength can be transmitted throughout the food web and extend over a long time as each year-class cohort develops and feeding habits change as the fish grow.

Detailed studies over the last 30 years at Oneida Lake, New York, provide insight into the consequences of natural variations in year-class strength and food web interactions (Mills et al. 1987; Mills and Forney, 1988). Walleye is the dominant top predator and young yellow perch are the dominant planktivores (Fig. 9-5a). Walleye feed primarily on young and yearling yellow perch, which prey on *Daphnia pulex* (the major large-bodied herbivore) and other zooplankton. The density of young yellow perch in May is strongly correlated with climatic conditions during egg incubation. Later in the summer (after the perch reach 18 mm), predation by walleye and adult yellow perch is the major factor controlling mortality and young perch abundance. In years when the density of age 0+ yellow perch exceeds 14,000 / ha in August, *Daphnia pulex* disappears (Fig. 9-5b) and smaller zooplankton increase. The loss of *Daphnia pulex* leads to elevated algal

biomass (chlorophyll concentrations nearly two times those in years with low yellow perch density), a shift in phytoplankton composition, and a decrease in water transparency. Seasonal and annual variations in Oneida Lake phytoplankton are determined, therefore, largely by seasonal and annual variations in the intensity of yellow perch grazing on zooplankton.

Human activities also contribute to fluctuations in food web dynamics. For example, Jassby et al. (1990) concluded that year-to-year variations in primary productivity in Castle Lake, California, were caused by the weather, specifically the timing of ice breakup and hydraulic flushing in the spring, and year-to-year differences in angling pressure on rainbow trout, the primary fish planktivore in the lake. Zalewski et al. (1990) found that water levels during May and June in Sulejow Reservoir, Poland, were closely correlated with the reproductive success of the dominant fish in the lake (yellow perch and various minnows). In years with the highest density of fish fry, cladoceran density decreased and phytoplankton abundance increased. Thus, water levels in the spring indirectly influenced water quality in the reservoir later in the summer.

Human activities also contribute to fluctuations in food web dynamics.

Food web interactions are affected, therefore, by a wide array of factors, and some degree of instability is probably inevitable. Major uncertainties remain, however, over the degree to which annual variations can be controlled and whether successful results can be sustained over the long term (Crowder et al. 1988; Shapiro, 1990).

Importance of Behavioral Responses

Most studies of the effects of predators on prey emphasize the direct lethal effects of being eaten. However, just as important in determining the success of a top-down management program can be the sublethal, indirect responses of prey to predators, including changes in prey behavior, habitat use, activity and movement patterns, life history, physiology, or morphology (Sih, 1987). He and Kitchell (1990), for example, found that fish losses resulting from emigration were at least as great as those from direct consumption following the introduction of a fish predator (northern pike) to Bolger Bog, Wisconsin. In Peter Lake, Wisconsin, the minnow population responded behaviorally to even small numbers of largemouth bass by concentrating in the littoral zone to avoid bass predation; as a result, minnow grazing on pelagic zooplankton was minimal (Carpenter and Kitchell, 1988). Some zooplankton also modify their behavior in the presence of fish planktivores, the most common response being diurnal, vertical migrations through the water column (Dini and Carpenter, 1991). All these responses effectively change the nature of food web interactions. Behavioral responses can also occur quite rapidly (within hours or days), more rapidly (in some cases) than predator-caused mortality.

Influence of Trophic Status

A number of investigators have concluded that the importance of top-down effects varies with trophic status. In particular, as noted previously, the zooplankton to phytoplankton linkage tends to be weaker and less consistent in eutrophic and hypereutrophic lakes than in mesotrophic or oligotrophic lakes because of differences in phytoplankton palatability. Based on enclosure experiments and empirical data, McQueen et al. (1986) concluded that fish community alterations would have little to no influence on phytoplankton in eutrophic lakes but could affect phytoplankton in oligotrophic lakes.

A number of investigators have concluded that the importance of top-down effects varies with trophic status.

Elser et al. (1990; also Elser and Goldman, 1991) evaluated phytoplankton responses to variations in zooplankton grazing pressure in three California lakes with different trophic status: Lake Tahoe (ultraoligotrophic), Castle Lake

(mesotrophic), and Clear Lake (hypereutrophic). The effects were greatest in Castle Lake, at an intermediate trophic status, than in either Lake Tahoe or Clear Lake, at the extremes of the trophic status range. Clear Lake is dominated by inedible cynobacteria. Phytoplankton dynamics in Lake Tahoe are controlled primarily by internal nutrient recycling from deepwaters. The introduction of *Mysis relicta* (an invertebrate predator) into Lake Tahoe resulted in the elimination of *Daphnia* (see Box 8-F). But no discernible change occurred in primary productivity, phytoplankton composition or abundance, or water transparency, supporting the conclusion that water quality in ultraoligotrophic lakes may not be sensitive to top-down effects.

Fish manipulations to control pelagic food webs and phytoplankton dynamics may be most successful, therefore, in lakes of moderate productivity or when implemented in conjunction with a reduction in external or internal nutrient loads. Benndorf (1990) concluded that top-down management can be effective only in lakes with phosphorus loading rates below about 0.6 g total P/m^2/year (5.4 lb/acre/year), although the exact loading threshold depends on lake characteristics. Lammens et al. (1990) concluded that the chance of successful biomanipulation is variable in lakes with total phosphorus concentrations between 50 and 200g/L but much less in lakes with higher phosphorus levels. Successful zooplankton control of algal blooms has been observed, however, in some strongly eutrophic systems (Schoenberg and Carlson, 1984; Van Donk et al. 1989).

Fish manipulations to control pelagic food webs and phytoplankton dynamics may be most successful, therefore, in lakes of moderate productivity . . . .

Interactions with Fisheries Management

Fish are an important ecosystem component, and alterations of the fish community directly and indirectly affect many lake physical, chemical, and biological characteristics, referred to collectively as "water quality." Fish are also a valued resource; recreational fishing generates substantial social and economic benefits. The strong linkage between fisheries and water quality management cannot be ignored. Changes in the fish community to improve fishing or as a result of fishing can alter water quality. Changes in water quality also directly affect the quality of habitat for fish and the quality of the fishing experience.

The strong linkage between fisheries and water quality management cannot be ignored. . . . Clearly, interactions can and will occur, although the nature of the final effects – positive, negative, or neutral – will vary depending on the nature of a lake's food web, the ecosystem components and linkages, the target fish species involved in the fishery, and the nature of the fisheries or water quality management.

Many examples abound that demonstrate this linkage, some of which have already been noted in the sections above. The near elimination of macrophytes in Lake Conroe, Texas (Martyn et al. 1986; Box 9-A) resulted in a decline in fish species, such as largemouth bass, for which macrophyte beds are important habitat. Fishing for largemouth bass was suggested as one cause for the inability to sustain water quality improvements following biomanipulation in Round Lake, Minnesota (Shapiro 1990). Anglers depleted the bass population to levels below those required to control bluegill, the dominant planktivore in the lake. Fishing was also cited by Jassby et al. (1990) as a major factor controlling variations in primary production in Castle Lake, California. In this case, however, the target species — rainbow trout — is a planktivore rather than a piscivore. Thus, high levels of fishing pressure decrease the abundance of planktivores and improve water quality.

Historically, fisheries management has involved extensive fish introductions, adding new species to lakes and drainage basins to diversify fishing opportunities or supplement fish prey (see Chapter 8). Such introductions have had both positive and negative effects on water quality. For example, the introduction of coho salmon into Lake Michigan to improve the lake's fisheries has caused a marked decline in the alewife population (a planktivore) and contributed to an overall improvement in water quality (Scavia et al. 1986; Kitchell and Carpenter, 1987; Box 9-C). In contrast, the introduction of rainbow trout into Medical Lake, Washington, resulted in a sharp increase in algal biomass and decline in water

quality (Scholz et al. 1985). Clearly, interactions can and will occur, although the nature of the final effects — positive, negative, or neutral — will vary depending on the nature of a lake's food web, the ecosystem components and linkages, the target fish species involved in the fishery, and the nature of the fisheries or water quality management.

CHAPTER 10

Designing a Field Sampling Program

Chapter Objective

Technical data on the status of a lake's fisheries, fish community, and fish habitat are needed to

- identify existing lake problems and design an effective management approach,
- establish pre-treatment conditions in the lake,
- quantify the system's response to management techniques and adjust the management program accordingly, and
- evaluate the long-term success and effectiveness of the management program (see Figs. 4-1, 6-1, and 8-1).

Chapter 10 contains guidance on developing a field sampling and monitoring plan to address these data needs, including sampling and data quality objectives; deciding when, where, what, and how to sample; quality assurance and quality control; data management; and effective presentation of the sampling results. Specific sampling methods are described in Appendix B. Water quality monitoring is discussed in detail in the companion guidance manual on *Monitoring Lake and Reservoir Restoration* (Wedepohl et al. 1990); therefore, this chapter focuses on monitoring related to fish and fisheries. For additional information on field sampling designs for evaluating fish community status and fisheries problems, see Johnson and Nielsen (1983) and Schreck and Moyle (1990).

Sampling Objectives

The optimal sampling design depends on the sampling objective(s): to assess current conditions, diagnose a lake problem, detect before and after changes in response to a management action, and/or evaluate long-term trends. Therefore, the first step in developing a field sampling plan is to define specific sampling objectives (Fig. 10-1).

- What is it that we really want to know when we're done? What are the key questions to be answered? What lake and fisheries characteristics are of greatest importance?

The first step in developing a field sampling plan is to define specific sampling objectives.

- How confident do we need to be in our answers? What are the consequences of an erroneous conclusion? Are we willing to expend more effort and funds on sampling to increase our confidence in the final conclusions?
- What level of change do we want to be able to detect? How quickly do we need to detect this change?

Decisions about the sampling design rely heavily on the answers to each of these questions. It is impossible to choose among various alternative approaches as to how, when, where, and what to measure without first defining the sampling objectives. In particular, data quality objectives must be established that specify the level of precision and accuracy required to answer important management questions with an acceptable level of confidence.

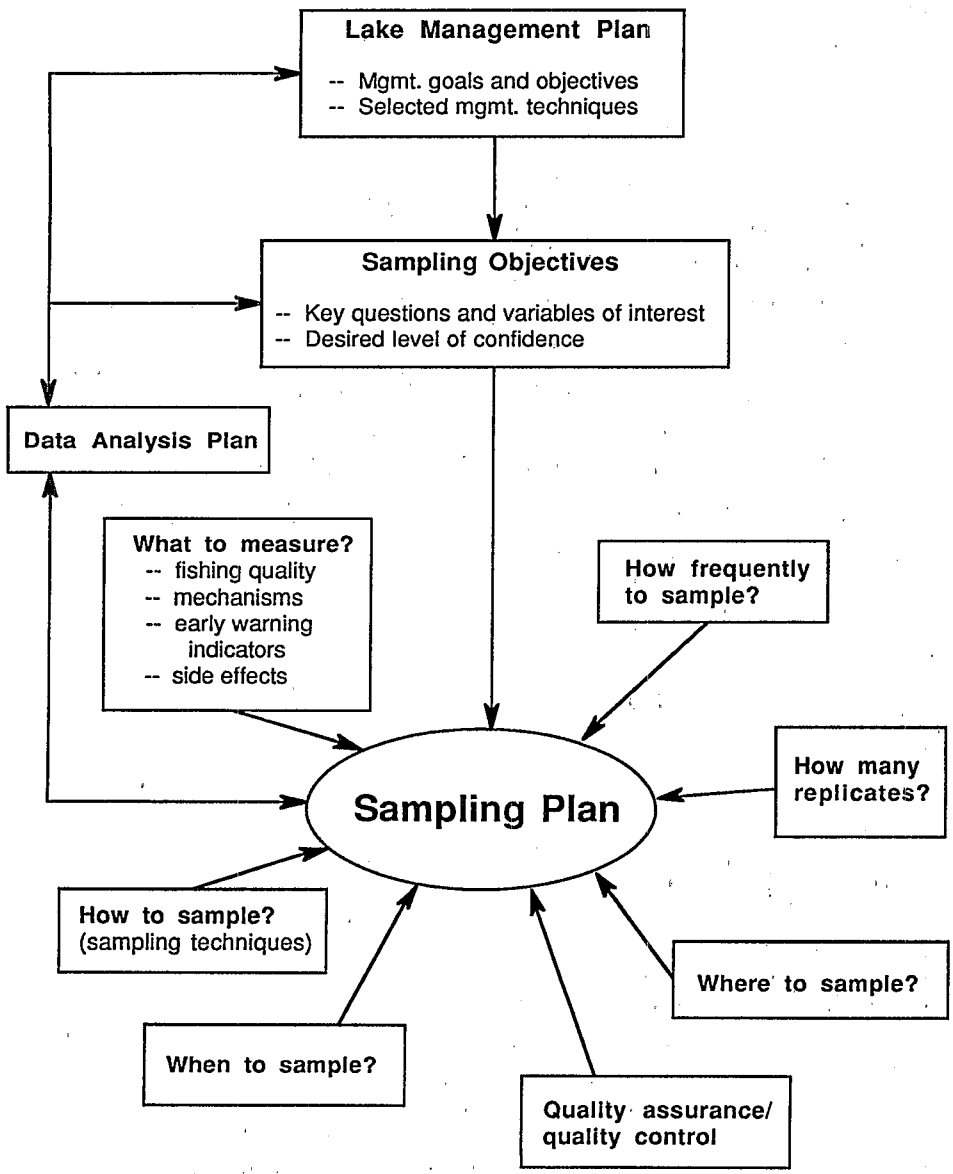

Figure 10-1.—Major components of a field sampling plan.

Developing sampling and data analysis objectives should be a top-down process. Begin with general questions and then move to a more specific delineation of the types of information needed and level of resolution required. Figure 10-2 provides an example of the top-down planning approach for a diagnostic study of Lotsa Luck Lake, a hypothetical lake for which fishing quality for bluegill has reportedly declined in recent years.

Data analysis plans and the sampling design go hand-in-hand. A central part of designing a sampling program is deciding *a priori* how the data will be analyzed and used to address management questions and improve the management program. A data analysis plan should be developed concurrently with the field sampling plan to ensure that the sampling objectives can and will be achieved. The data analysis plan can also assist in designing the most cost-effective sampling and monitoring program. Data needs are better defined, thus avoiding unnecessary expenditures of time and funds to collect information that will not contribute significantly to achieving the sampling objectives.

A data analysis plan should be developed concurrently with the field sampling plan to ensure that the sampling objectives can and will be achieved.

The Sampling and Monitoring Plan

A written sampling and monitoring plan should be prepared and in place before initiating any field activities or management actions. In addition to presenting the specific sampling and data quality objectives, this plan should address each of the major components of a field sampling design (Fig. 10-1):

- What variables (lake and fisheries characteristics) will be measured?
- What sampling and analytical techniques will be employed?
- When will samples be collected (at what times of the year)?
- Where in the lake will the sampling take place?
- How many replicate samples will be collected per visit?
- How often will the lake sampling be repeated and for how long?
- How will the quality of the data be assured?

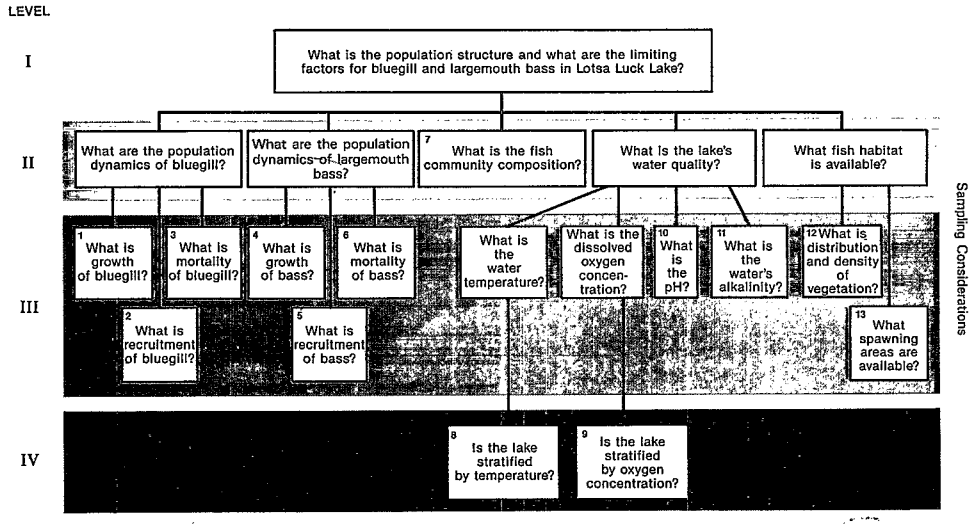

Figure 10-2.—An example of top-down planning for Lotsa Luck Lake. Recent declines in the quality of fishing for bluegill have been reported by local anglers. A hierarchical series of questions is developed to define the sampling objectives for a diagnostic study to determine the cause of the fishing decline. The central question (the uppermost box) can be answered if and *only* if the questions in the second row are answered. The questions in the second row can be answered if and only if the questions in the third row are answered, and so on. The numbered boxes are questions that are answerable with established methods (source: Johnson and Nielsen, 1983).

The sampling program should include all the necessary elements measured at the minimum intensity and frequency required to achieve the sampling objectives.

Designing the field sampling program is not a trivial task. The costs of sampling can be substantial; furthermore, future changes in the sampling program can make trends through time difficult to detect and interpret. Therefore, the field sampling plan should be well conceived and thoroughly reviewed. The sampling program should include all the necessary elements (but no more) measured at the minimum intensity and frequency required to achieve the sampling objectives.

Often, data exist on the lake and fisheries from previous surveys or monitoring efforts. This information should be carefully reviewed for two reasons. First, it can help you design a better sampling plan. The insight and information gained from earlier surveys can guide such decisions as what to measure, where to sample, and how to sample. In addition, in some cases making direct comparisons between previous and current sampling results to evaluate changes over time may be desirable. For such comparisons to be valid, the sampling methods (gear, location, time, and level of effort) must be comparable.

To diagnose lake problems or assess the effectiveness of a management action, sampling may be required not only in the lake but also in inflowing tributaries, the lake outflow, and the watershed as well as other waters in the drainage basin. Chapter 4 of *Monitoring Lake and Reservoir Restoration* (Wedepohl et al. 1990) discusses watershed monitoring. This chapter and Appendix B focus on sampling in aquatic ecosystems.

What to Measure

The information you gather in the field should be a logical outgrouth of the objectives of the sampling program. Diagnostic studies generally focus on indicators of fish or fisheries condition — especially those that may be symptomatic of a particular type of problem — and those factors or conditions most likely to be limiting or adversely affecting the fish community, fisheries, or fish habitat (see Chapter 6 and Fig. 10-2). To detect changes before and after management actions or long-term trends, the lake and fisheries characteristics monitored must be sufficient to assess both the success and effectiveness of the management program. The specific variables will depend on the program's goals and specific objectives as well as the management techniques applied.

At a minimum for fisheries management programs, data must be collected on the key lake and fisheries characteristics that determine the *quality of the fishing experience*. If the management objective is to increase the total harvest or the numbers and size of trophy fish, measures are needed of the numbers, types, and sizes of fish caught by anglers. Frequently, however, a quality fishing experience and the management objectives are more broadly defined, including concepts of ecosystem integrity, a wilderness experience, or other aspects of the quality of the environment in which fishing occurs (see Chapter 5).

In addition to monitoring the program's outcome (i.e., its impact on fishing or water quality), three other measures should be considered:

1. **Information on the underlying mechanism(s) of response.** A better understanding of the mechanism of response and changes in related variables will allow managers to determine why the management program is (or is not) succeeding and better evaluate the program's effectiveness. For example, if insufficient prey was identified as the major problem limiting fishing success, then measures of prey abundance and use should be included in the sampling program. If habitat quality was a problem, these critical habitat features should be routinely monitored. Generally, information on the status of fish populations and the fish community in the lake together with direct measures of fishing success are needed to understand the causes and underlying mechanisms of response.

2. **Early warning indicators of changes or problems.** Generally, the earlier problems or trends can be detected, the easier they can be corrected or appropriately adjusted. Thus, careful consideration should be given to the types of measures and variables most likely to respond and to the reapid detection of this response. Lake and fisheries characteristics with a high natural variability may be quite sensitive but require substantial sampling effort to distinguish between a management-induced change and the background "noise." Such variables should be avoided unless the sampling program can be designed to minimize or account for the effects of this high natural variability.

3. **Potential adverse side effects.** As noted in Chapters 8 and 9, many management techniques can cause undesirable side effects. If such effects occur and are of sufficient magnitude, changes in the management program may be warranted. For example, the eradication of aquatic macrophytes may, in some cases, be accompanied by an undesirable increase in turbidity and/or phytoplankton blooms (see Chapter 9). Thus, the sampling plan also should incorporate measures of the potential side effects of concern for the particular management techniques applied.

[T]he sampling plan also should incorporate measures of the potential side effects of concern for the particular management techniques applied.

In selecting individual lake and fisheries characteristics to monitor, the following questions should be considered:

- How, specifically, will the measurements be used to evaluate the program's success and effectiveness?
- Is the variable likely to change or provide valuable information for assessing the lake's and fisheries' response to the management program?
- What are the incremental costs (time, effort, and dollars) of monitoring the variable? (See Box 10-A.)
- Do these costs compare favorably to the incremental benefit and knowledge gained by including the variable in the sampling program?
- Could alternative lake or fisheries characteristics be monitored that would provide similar information at lower cost?

As a group, the suite of variables selected for monitoring should be comprehensive, balanced, and cover all of the important aspects and questions to be addressed without extensive or unnecessary duplication. Conceptual models, such as Figure 2-14 (Chapter 2), provide a useful check on the completeness of the sampling plan.

How To Sample

Various methods can be used to collect information on the status of fish, the fish community, and fisheries in a lake or reservoir. Some methods work better than others for certain types of fish species, at certain times of the year, and in certain types of environments and areas. In addition, the information provided varies somewhat among the sampling methods.

Direct information on the status of a fishery can be obtained by sampling anglers and evaluating the types, numbers, and sizes of fish caught by anglers actively involved in recreational fishing on the lake. Creel surveys, angler diaries,

Box 10-A.—A Cost-Benefit Hierarchy for Information about Fish Populations and Communities

(source: Johnson and Nielsen, 1983)

The variables measured in a field sampling program should reflect an appropriate balance between the cost of an activity and the new information provided. Table 10-1 lists selected categories of fish sampling information and the relative costs of each. The least expensive, but also least informative, is to simply count the number of fish species present and susceptible to the sampling gear (i.e., number of species caught). At the other end of the scale is sampling that provides food habit information and detailed tracking of the movements of individual fish by using radio or sonar tagging. The metrics included in Table 10-1 are not a comprehensive listing, but an illustration of some common variables monitored and the large variations in the relative costs.

Table 10-1.—Selected metrics of fish population or community status and the relative costs of data collection (source: Johnson and Nielsen, 1983).

ACTIVITY	INFORMATION	RELATIVE COSTS[a]	COMMENTS
Species enumeration	Number of species present	1	Easy to collect but dependent on sampling techniques
Numbers of fish caught of each species	Relative abudance of the species present	X2	Usually the *minimal level of* information needed
Length of fish	Length distributions can give relative year-class strength, growth, and mortality as well as proportional stock densities	X4	A great deal of information added, particularly for fast-growing populations at temperate latitudes
Weight of fish	Length-weight curves, condition factors, and relative weight	X12	Often field scales are not accurate enough, and special shelters should be constructed
Age determination	More accurate than length distributions for calculating year-class strength, age distribution, growth history, and mortality	X120	Requires extra handling of fish and substantial laboratory time for analysis
Radio or sonar tagging	Exact information about fish locations; may be combined with information on water depth, temperature	X1200	Much information gained about movements of relatively few fish. Equipment cost and maintenance can be quite high

[a]Relative costs are expressed by comparison to the first activity listed.

and telephone or mail questionnaires are alternative methods for gathering data on angler catch and use patterns. Such data provide not only insight on the status of fish populations in the lake but also a direct measure of the quality of fishing and the fishing experience. Some methods, such as angler diaries, are also relatively inexpensive. At the same time, however, the numbers and types of fish sampled are limited, focusing on game and large, catchable-sized fish. Little or no information is obtained on nongame species and young age classes. Thus, while angler surveys provide extremely valuable data, they are generally not sufficient for a comprehensive assessment of fish community status and do not provide an early warning indicator of change or potential problems.

Methods for sampling the fish community include gill netting, trap netting, seining, trawling, angling (hook and line fishing), electrofishing, rotenone poisoning, hydroacoustics, and visual observations (e.g., by using SCUBA). Each method

Table 10-2.—Suitable sampling gear for collecting adults and young of the year (YOY) of selected fish species and groups in lakes. The gear listed are intended as examples only; other gear may also be suitable or even better in certain situations or for specific sampling objectives.

		GEAR[a]	
TAXON	FISH LIFE STAGE	STANDARD	SUPPLEMENTAL
Trout, salmon, whitefish, char (except lake trout)	YOY	Electrofishing	Gill nets, trawls, seine
	Adult	Trap nets	Gill nets, electro-fishing (F)
Lake trout	YOY	Electrofishing (F)	Seine (F), trawls
	Adult	Trap nets (F)	
Pike, pickerel, muskellange	YOY	Seine (Su)	
	Adult	Trap nets (S), gill nets (S,F)	
Catfish, bullheads	YOY	Seine	Baited traps
	Adult	Gill nets, trap nets[b]	Slat nets, angling
Bass, sunfish, crappie	YOY	Seine, electrofishing	
	Adult	Electrofishing	Trap nets, angling
Minnows, carp, dace, chub, shiners	YOY	Electrofishing	Seine
	Adult	Electrofishing	Seine
Yellow perch	YOY	Seine (Su), electrofishing	Trawls (S)
	Adult	Gill net, trap net	
Walleye	YOY	Seine (S), electrofishing (F)	Trawls (S)
	Adult	Trap nets (S), gil nets (S,F), electrofishing (S, F)	

[a]Letter codes indicate seasonal restrictions on gear use to the spring (S), summer (Su), or fall (F).
[b]Bullheads only.

has its advantages and limitations, as discussed in Appendix B, and frequently, multiple gear and approaches are employed and compared. The best gear and sampling methods depend on the target fish species and life stage, the types of information desired, and the environment to be sampled. Table 10-2 provides an overview of suitable gear types for sampling selected target fish species and life stages; further information is given in Appendix B.

One overriding guideline for selecting a sampling technique is the need to prevent unnecessary fish mortality and stress. Some gear, such as gill nets (especially if set over-night), can kill all or most of the fish caught. In some cases, however, gill nets may be the most effective approach for collecting fish and the optimal technique despite problems with high fish mortality. Sampling-associated mortality is likely to have a more significant impact in small, low productivity lakes and on fish populations that are less abundant or already heavily stressed by other factors.

One overriding guideline for selecting a sampling technique is the need to prevent unnecessary fish mortality and stress.

Often, sampling results are compared among lakes, among sites, or over time. Because each sampling method has its own biases, these comparisons must be based on a consistent set of sampling methods and effort. To help assure the needed uniformity, written sampling protocols should be prepared that thoroughly describe all aspects of the sampling program. In addition, all information related to the specific sampling visit should be recorded in the field — including gear types employed, the numbers, locations, and times of each sample, and general comments and observations — and the log maintained for future reference.

With the proper guidelines and training, volunteers can provide valuable, high quality monitoring data at minimal costs; therefore, carefully consider using volunteers to expand the sampling program. Volunteer anglers, in particular, can assist in monitoring changes in fisheries status.

When and Where to Sample

In many lakes and regions, the best time to sample fish is during the fall overturn period after thermal stratification breaks down and the lake is completely mixed.

Typically, fish populations are monitored at least annually and often seasonally, two to three times per year in the spring, summer, and/or fall. The best time of year depends on the sampling method, the target fish species, and the type of data to be collected. In many lakes and regions, the best time to sample fish is during the fall overturn period after thermal stratification breaks down and the lake is completely mixed because

- young-of-the-year and age 1+ fish of most target species should be present and vulnerable to most standard collection gear, including seines, trap nets, and electroshockers;
- species that dwell in the hypolimnion during the summer may be more vulnerable to capture during fall overturn; and
- lower water temperatures in the fall can help reduce sampling-related mortalities.

However, one time is most appropriate for all fish species, gear, and sampling objectives. Sampling at other times of the year may be necessary or more effective, particularly for fish species with defined spawning migrations or concentrations of fish during spawning, when they are more easily captured in large numbers. Sampling may also be needed at more frequent intervals or other times of the year to evaluate fish feeding habits or mortality rates relative to special environmental events, such as winterkill or summerkill.

Sampling locations are also species-, life stage-, and gear-dependent. As with sampling methods and time, locations should be selected to maximize capture efficiency for the target species of interest and provide the greatest gain in information for the least amount of sampling effort. In addition, some gear types can be used only in certain types of environments and locales, as discussed in Appendix B. Within the set of acceptable locations, specific sampling sites should be selected using a random, stratified, clustered, systematic, or other suitable sampling design (Fig. 10-3; also see Johnson and Nielsen, 1983; Cochran, 1977; Elliot, 1977).

Measures of habitat quality should be conducted in those areas and during those times most critical to fish population success.

Measures of habitat quality should be conducted in those areas and during those times most critical to fish population success. For example, if winterkill is a major problem, levels of dissolved oxygen should be monitored, at a minimum, during winters with long periods of snow and ice cover. Early life stages of fish are often particularly sensitive to effects from toxicants, acidity, temperature, and low levels of dissolved oxygen. Surface water quality in the times and locations coincident with the occurrence of these sensitive life stages may be a major factor limiting population abundance and productivity and thus an appropriate focal point for the sampling program.

For sampling programs designed to assess the success and effectiveness of management actions, sufficient data must be collected before and after treatment implementation and continue until the lake's response has stabilized. Pre-treatment data must be collected with the same methods and protocols used for post-treatment monitoring. Samples should be collected at consistent time(s) and location(s) year after year to maximize detection of changes and trends. By measuring the variable consistently at the same point on a seasonal or daily cycle, in-lake measurement variability can be reduced and trends through time will be more evident. For many variables, sampling times should be keyed not to a given calendar day but rather to other environmental factors, such as water temperature, degree-days, or day length.

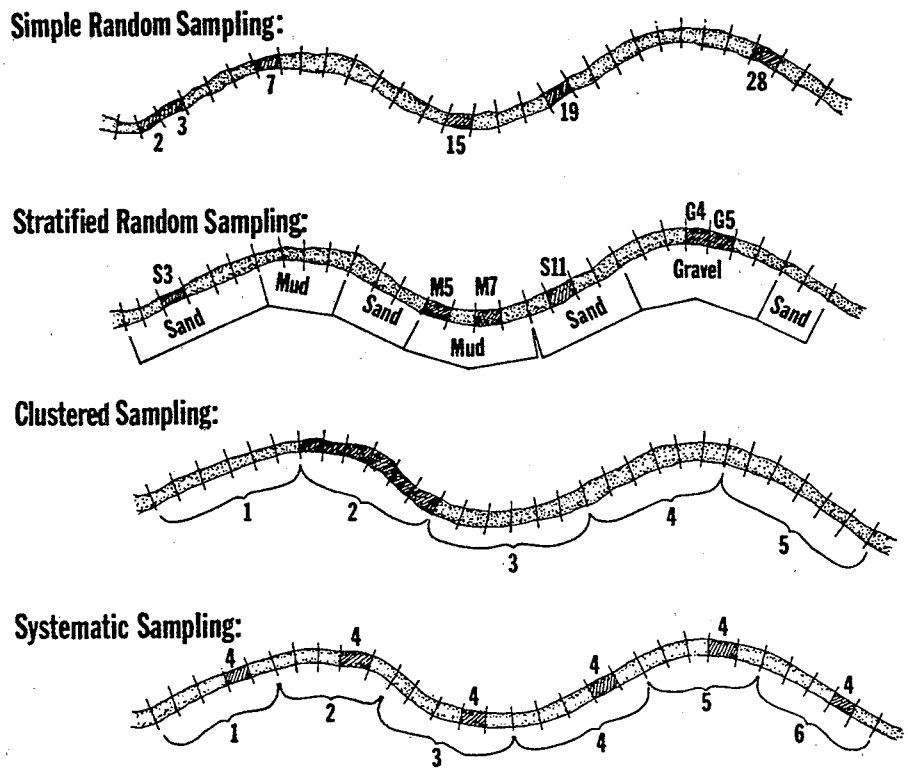

Figure 10-3.—Example of various sampling designs for the selection of six sites for seining along a continuous shoreline. All numbers were chosen from a random number table (source: Johnson and Nielson, 1983).

Number of Replicates and Sampling Frequency

The sampling plan must also specify the number and size of sampling units and the sampling frequency and duration (how often, for how long). The number of replicates required depends on the variability among samples, the questions being addressed, and the desired level of confidence. The more measurements collected, the easier it is to detect differences between sites or changes through time. The more variable the characteristic (i.e., the greater the "background noise"), the more data points are needed to detect a difference or trend of a given magnitude. Large numbers of replicates and frequent sampling are advantageous — but expensive; therefore, an optimal sampling design provides the appropriate balance between costs and the ability to detect statistical differences or trends.

The more measurements collected, the easier it is to detect differences between sites or changes through time.

If the sampling and analytical variability are known or can be estimated, then the numbers of measurements required to detect a statistically significant difference or trend of a given magnitude and with a given level of confidence can be calculated using established statistical procedures. Figure 10-4, for example, provides the results from such calculations for monthly phosphorus measurements collected from the Neuse River, North Carolina. Because of the high natural variation in phosphorus, over 120 monthly samples would be required to detect a 23 percent linear decrease in total phosphorus if an error rate of 10 percent is required. Smaller numbers of samples would be needed for larger changes or for higher acceptable error rates. Many basic statistical texts outline procedures for estimating sample sizes for various types of data analyses (e.g., Snedecor and Cochran, 1980; Cochran, 1977; Green, 1979). In addition, some State agencies have developed standard sampling designs (e.g., Table 10-3) for monitoring long-term trends in fish communities in the types of lakes and reservoirs common within their jurisdiction. Sample sizes of fish required for age, growth, and condition analyses are discussed in Appendix B.

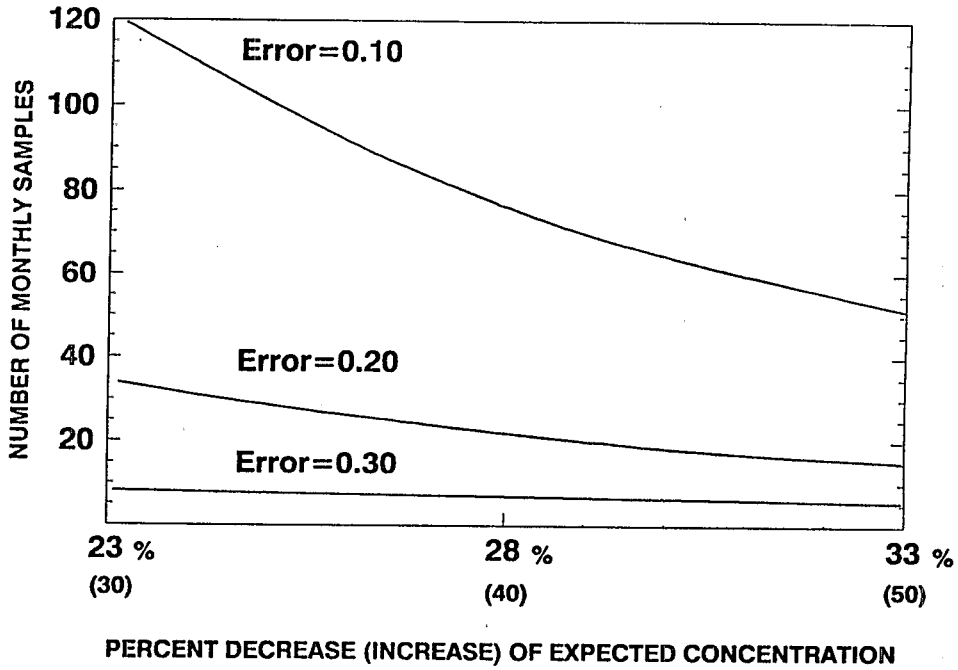

Figure 10-4.—Sample size required to detect a linear trend of the specified magnitude with a given error probability, based on phosphorus monitoring data for the Neuse River, North Carolina (source: Wedepohl et al. 1990).

Table 10-3.—Examples of standard sampling designs developed by the Texas Parks and Wildlife Department for long-term monitoring of fish communities in reservoirs (source: Johnson and Nielsen, 1983).

SAMPLING TECHNIQUE	SIZE OF RESERVOIR (ACRES)	NUMBER OF SAMPLING UNITS	WHERE TO COLLECT	WHEN TO SAMPLE
Cove rotenone poisoning	< 10,000	3 coves, > 1 acre each	Randomly selected	Between June and September, all within 30 days
	≥ 10,000	3 coves, > 5 acres total		
Gill netting	< 100	≤ 5 net nights	Permanently selected in upper, middle, and lower section	May
	101–5,000	5 net nights		
	5,001–10,000	10 net nights		
	> 10,000	15 net nights		
Seining	< 5,000	5 100-ft stations	Permanently selected, various habitats	May, July, and September during daylight
	5,001–10,000	10 100-ft stations		
	> 10,000	15 100-ft stations		
Trap netting	< 100	5 net nights	Permanently selected, various habitats	Once between April and June and once between September and November
	101–5,000	5 net nights		
	5,001–10,000	10 net nights		
	> 10,000	15 net nights		

Quality Assurance/Quality Control

Sampling data must be of known and sufficient quality to achieve the sampling objectives. Thus, the sampling plan should also include a comprehensive quality assurance/quality control program.

Quality control involves procedures and protocols to improve the quality of data collected and decrease the chances of extraneous errors. Examples of quality control activities include the following:

- Preparation of written protocols for all sampling and analytical methods to ensure they are consistently and appropriately applied;

- Sample custody tracking system to minimize problems with the loss or mislabelling of samples;
- Frequent instrument calibrations and internal quality control checks to assure accurate measurements;
- Preventive maintenance procedures and schedules; and
- Database verification and validation procedures to identify outliers and possibly erroneous data points.

Quality assurance involves collecting information to prove that the sampling data are accurate and precise. Examples of quality assurance activities include:

- Field and laboratory audits to confirm that the sampling and analytical method protocols are being followed;
- Replicated, independent measurements to quantify sampling and analytical precision;
- Field blanks and double-blind audit samples to confirm the accuracy of measurements; and
- Routine quality assurance reports summarizing the results of all quality control and quality assurance activities.

Quality control and quality assurance requirements for projects funded by the U.S. Environmental Protection Agency are presented in *Interim Guidelines and Specifications for Implementing Quality Assurance Requirements for EPA Contracts* (EPA QAMS-005/80). State programs may also include written specifications and requirements for quality assurance/quality control.

Data Management

All data collected should be organized and permanently maintained in a form that can be easily accessed and analyzed. The voluminous and diverse nature of the collected data and the variety of persons involved in collecting, recording, and entering data increase the potential for error, which can have serious negative implications for any lake management program. Such problems can be prevented — or at least minimized — however, by setting up a sound and efficient data management system.

All data collected should be organized and permanently maintained in a form that can be easily accessed and analyzed.

When setting up a data management system, several economic, technical, and managerial components must be considered. Economic components include the availability of funds to acquire the necessary computer hardware/software and training to develop and maintain a data management system or to revert to a paper file. If economically feasible, technical components involve selecting appropriate computer equipment and software and designing the database, including data definition, data standardization, and developing a database dictionary. The database dictionary provides a written description, including units and methods of measurement where appropriate, of all variables in the database that can be easily distributed to database users. The managerial components of data management include data entry, data validation and verification, and access procedures for data users.

To assure the integrity of the database, data quality must be controlled and monitored from collection to the time the information is entered into the database. Laboratory and field data sheets or a computerized data entry system may be used to create the initial data record; in either case, care must be taken to avoid transposing numbers, entering information into the wrong location, or other errors. For data recorded on laboratory or field data sheets, subsequent

data entry into a preliminary computerized database file should be made directly from the original data sheets or photocopies to minimize the potential for transcription errors. The database design should include automatic range-checking values for all parameters entered into the computer as an initial screening for errors. Any values outside of the defined ranges should be automatically flagged and checked and corrected as soon as possible. For some parameters, database checks that disallow duplicate numbers may be appropriate (e.g., unique codes for water samples). After a set of values are entered into the preliminary database file, the information should be printed and verified against the original data sheets to eliminate any data entry errors.

Additional validation of the data can include expert review to identify suspect values. To resolve questionable data points, the persons responsible for collecting and entering the original data should be consulted. After all data are verified and validated, they can be merged into the master database for the sampling or monitoring program. To prevent data loss from computer failure, at least one set of duplicate (backup) copies of all database files should be maintained at a separate location. Figure 10-5 diagrams a sample data management process.

Effective Presentation of Results

The monitoring results and outcomes from the fisheries management program should be widely and regularly communicated in an easy-to-understand format to all those involved in the planning process and program implementation. Especially for programs involving volunteers or that rely on voluntary compliance with fishing regulations, the demonstration that the management program has had a positive impact provides important feedback that encourages continued voluntary assistance and compliance. Thus, two types of project reports should be routinely prepared:

1. A technical, detailed analysis of the program results for technical review by professional fisheries biologists; and
2. An interpretive summary written for a more general, broader audience.

The latter should present only key findings and explain the significance of the results with regard to the program's success and future monitoring and management activities. Most results can be presented effectively in summary figures or plots, such as those in Figures 3-1, 3-9, and 3-10. Chambers et al. (1983) and Tufte (1983) discuss graphical methods for data analysis and ideas for visually displaying quantitative information.

This manual cannot provide a discussion of the many statistical techniques used to analyze environmental data and evaluate the results from a field sampling program. Chapter 11 discusses the role of modeling in fisheries management, one method for summarizing and evaluating information. In addition, Chapters 3 and Appendix B mention a number of commonly used analysis routines for fisheries data. However, for more detailed and technical reviews of statistical issues and methods, the reader is referred to Wedepohl et al. 1990 as well as available statistics and fisheries texts, such as Draper and Smith (1966), Ricker (1975), Snedecor and Cochran (1980), Hollander and Wolfe (1973), Zar (1974), Elliot (1977), Green (1979), Conover (1980), Everhart and Youngs (1981), Gilbert (1987), and James and McCulloch (1990).

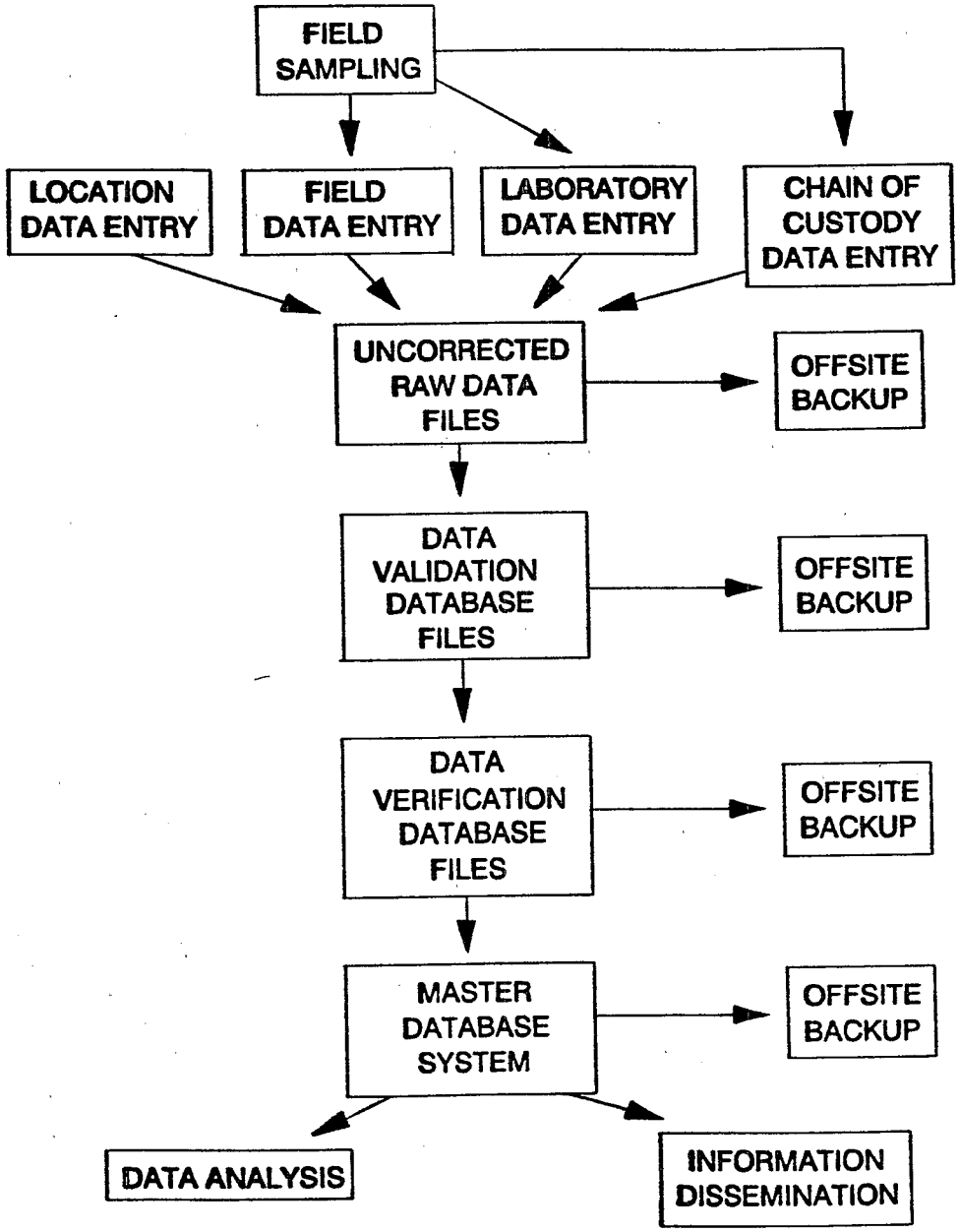

Figure 10-5.—Common steps in the data management process.

CHAPTER 11

Role of Modeling in Fish and Fisheries Management

Chapter Objectives

Chapter 11 provides a brief overview of the role of models in fish and fisheries management, the types of questions models can help address, the types of models and modeling approaches available, and the uses, advantages, disadvantages, and data requirements of each. This chapter does not describe the process of model development nor any specific model used in managing fish or fisheries. Citations are included for details on model formulation and example applications.

Only models relating directly to fish or fisheries management are considered. Water quality models used to predict changes in water chemistry in response to alterations in watershed management or pollutant loadings may also be valuable in addressing some fisheries management concerns. Descriptions and example applications of water quality models are provided in *The Lake and Reservoir Restoration Guidance Manual* (Olem and Flock, 1990).

Definitions

"A model is a simplified representation of a real object, process, concept, or system" (Reckhow and Chapra, 1983; pg. 15). Models can be conceptual or mathematical. "A mathematical model is a mathematical equation or set of equations that translates a conceptual understanding of a system or process into quantitative terms" (Reckhow and Chapra, 1983; pg. 15). Mathematical models are frequently described or categorized by several criteria:

1. **Empirical or mechanistic.** Empirical models are developed primarily from an analysis of data. Mechanistic models, on the other hand, are mathematical descriptions of theoretical principles. Most models have elements of each but can be classified according to which approach dominates.
2. **Static or dynamic.** Dynamic models describe or predict system behavior over time, while static or steady-state models are time-independent.
3. **Deterministic or stochastic.** Deterministic models use expected values for all parameters and yield predictions that are also expected

values—that is, single values with no explicit expression of the uncertainty in the prediction. Stochastic models, on the other hand, incorporate variability and uncertainty directly into the model by expressing model parameters and/or outputs as probability density functions—that is, the distribution of possible values and chance (probability) that each value will occur. Most fish and fisheries models used today are deterministic. Stochastic models are computationally more difficult and time-consuming, although the benefits of explicitly addressing uncertainties can be substantial, especially for models used to aid management decisionmaking.

Reckhow and Chapra (1983) and Chapra and Reckhow (1983) provide additional criteria for model characterization and detailed discussions on model development and testing specifically for lake management. Walters (1986) describes the development and use of models for managing renewable natural resources, such as fisheries.

Why Model?

Models provide a means of synthesizing the available data and understanding of these complex relationships into a more usable form.

Lake ecosystems are complex, with many components, interactions, and indirect effects and substantial spatial and temporal heterogeneity. Models provide a means of synthesizing the available data and understanding of these complex relationships into a more usable form.

Models can be developed to learn, to predict, or to evaluate—or to do all of these functions. Models contribute to the learning process and improved understanding of lake ecosystems in two ways:

1. The process of model building — integrating information together into a representation of the real world — frequently provides new insights, fosters clear thinking, and helps identify gaps in data and understanding.
2. Comparisons of model outputs to expectations and real world data provide important feedback that advances learning. Inconsistencies help to identify misunderstandings, missing components or processes, erroneous assumptions, or other inadequacies that require additional thought or research.

Because a major part of the benefits derived from using models is this contribution to learning and improved understanding, lake managers should be directly involved in model development to the degree possible rather than just as users of model results. Adaptive environmental management is an approach that views management as a continual, adaptive learning process, uses models as the primary means of synthesizing understanding, and actively involves scientists, managers, policy makers, and other appropriate parties in model development (Walters, 1986; also see Chapter 4).

Model outputs can also directly aid management decisions. Models can be applied to predict the outcome of various management options; for example, the effect of a change in the minimum size regulation on fish growth and fisheries yield. Models can assist in evaluating lake problems, such as the effects of toxic substances on fish reproductive success or the relative importance of fishing mortality; identifying fish species for which the lake provides suitable habitat; estimating the maximum sustainable fisheries yield; or assessing the nature and magnitude of user conflicts. All of these model applications can help in selecting the most appropriate and effective management option.

Models are not, however, a substitute for experience, clear and logical thinking, or other types of data analysis. Instead, models should be used as an addition-

al tool that, together with experience, logical thinking, and other analyses, can facilitate and improve lake management decisions. Applying models blindly without understanding their structure, assumptions, and limitations and before confirming their validity is worse than not using models at all.

[A]pplying models blindly without understanding their structure, assumptions, and limitations and before confirming their validity is worse than not using models at all.

Importance of Conceptual Models

Conceptual models are qualitative, usually graphical, representations of important system components, processes, linkages, and interactions, as in Figures 2-14 and 11-1. They serve several important purposes, many of which have been noted in earlier chapters. Development of a conceptual model is an initial step in hypothesis testing and in building mathematical models (Reckhow and Chapra, 1983). Conceptual models, by themselves, can also assist in the following activities:

- Designing field sampling and monitoring programs to ensure that all important system attributes are measured.
- Determining causes of lake problems by delineating system linkages and possible cause-and-effect relationships.
- Identifying potential conflicts among lake users or management objectives.
- Anticipating the full scope of lake responses to management actions, including potential negative side effects.

Conceptual models are relatively easy to develop; therefore, all lake management programs should produce a conceptual model of the lake ecosystem as a framework for all subsequent activities and analyses.

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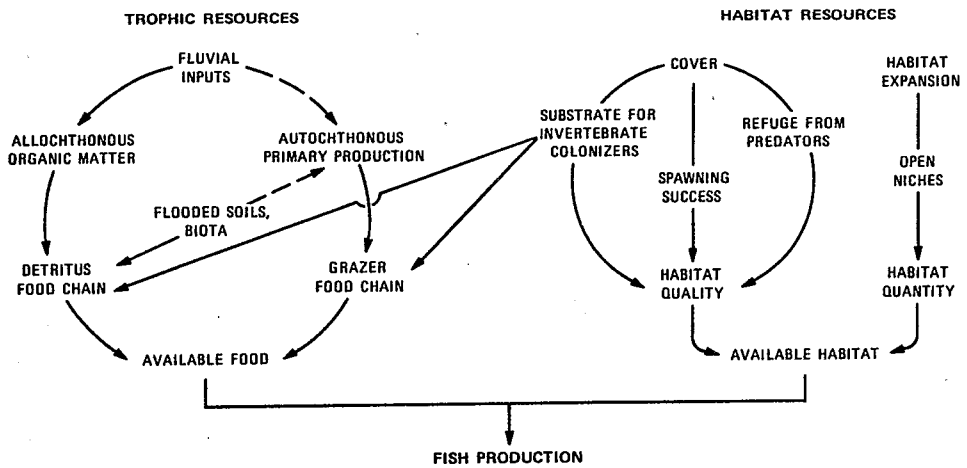

Figure 11-1.—Conceptual model of factors that influence fish production in reservoirs. For trophic resources, solid lines indicate organic matter fluxes and dashed arrows represent nutrient fluxes (source: Kimmel and Groeger, 1986).

Questions that Modeling Can Help Address

The following are examples of the types of management questions and issues that mathematical models can help address, if existing data are available to "model" answers to the questions:

1. How does my lake compare, in terms of fish growth, fish abundance, fisheries yield, or other important attributes, to other similar lakes in the region?

2. Given current conditions in the lake, which fish species are best suited to the lake habitat and most likely to survive and reproduce?
3. What lake characteristics or factors are currently limiting the survival, reproduction, or production of fish species in the lake?
4. In how many years will fish in the lake reach a length and weight suitable for harvesting (e.g., reach the current minimum size limit)?
5. Is fishing a significant contributor to fish mortality? If fishing pressure is increased or decreased, will the numbers and size of fish available for harvest change significantly?
6. How many and what biomass of fish can be harvested annually from the lake or reservoir without adversely affecting the long-term sustainability of the fisheries and fish resource?
7. If the minimum size limit regulation is altered, how will fish growth, reproduction, abundance, and yield change?
8. If a given number, size, and species of fish are stocked into the lake, how fast will they grow and how many will survive to reach harvestable size?
9. If shoreline development destroys five acres of fish spawning habitat, will fish abundance or the quality of fishing decline? If so, by how much?
10. Are current levels of toxic substances in the lake causing a measurable decline in fish survival, growth, abundance, or yield?
11. If nutrient loads to the lake are reduced, how will fish growth and abundance, fisheries yield, and the quality of fishing be affected?
12. Will introducting fish species "X" into the lake adversely affect the survival or growth of other fish species or cause a measurable change in other biotic communities or water quality?
13. If fishing pressure for the top predator in the lake increases, will water quality be adversely affected?

Types of Models Used in Fish and Fisheries Management

Modeling approaches and the best type of model to apply depend on the management questions being addressed. Thus, an important first step in selecting or developing a model is to "bound" the problem: define the appropriate spatial and temporal scale and ecosystem components and processes that must be considered to answer the management questions.

[A]n important first step in selecting or developing a model is to "bound" the problem: define the appropriate spatial and temporal scale and ecosystem components and processes that must be considered to answer the management questions.

- Is it necessary to predict changes over time (a dynamic model) or are predictions of steady-state conditions adequate (static model)?
- If time is important, are we interested in short-term (e.g., daily, seasonal) changes or long-term trends over years?
- Is the problem best addressed on a regional scale (e.g., comparisons among lakes) or by modeling specific processes within an individual lake or watershed?
- Is spatial heterogeneity likely to influence the results, thereby requiring a model with multiple spatial compartments?

- Is modeling a single process (e.g., fish growth or fish mortality) or the dynamics of an individual fish population (species) in isolation sufficient? Or is considering interactions among species (e.g., predator-prey relationships) or the influence of habitat characteristics necessary?

This chapter discusses the following six general types of models, each of which is suitable for addressing one or more of the questions listed previously:

1. Habitat evaluation models
2. Empirical regression models of fisheries yield and other fisheries attributes
3. Fish mortality models
4. Fish growth models
5. Population dynamics models
6. Ecosystem simulation models

Habitat Evaluation Models

Many factors influence the suitability of a lake or reservoir for fish. Models have been used to combine these various factors and variables into simple indices of habitat suitability or quality. The most commonly used habitat evaluation model is the Habitat Suitability Index (HSI), developed using the U.S. Fish and Wildlife Service's Habitat Evaluation Procedures (HEP) (U.S. Fish Wildl. 1980). HSI models are available for 66 species of fish, shellfish, and other aquatic invertebrates (O'Neil and Gray, 1988), including 48 fish species that live at least part of their life cycle in fresh water (Table 11-1).

The most commonly used habitat evaluation model is the Habitat Suitability Index (HSI). . . .

Table 11-1.—Fish species for which Habitat Suitability Indices are available (adapted from O'Neil and Gray, 1988).

alewife	American shad	Arctic grayling
bigmouth buffalo	black bullhead	black crappie
blacknose dace	blueback herring	bluegill
brook trout	brown trout	channel catfish
chinook salmon	chum salmon	coho salmon
common carp	common shiner	creek chub
cutthroat trout	fallfish	flathead catfish
gizzard shad	green sunfish	inland silverside
lake trout	largemouth bass	longnose dace
longnose sucker	muskellunge	northern pike
paddlefish	pink salmon	rainbow trout
redbreast sunfish	redear sunfish	rock bass
shortnose sturgeon	slough darter	smallmouth bass
smallmouth buffalo	spotted bass	striped bass
walleye	warmouth	white bass
white crappie	white sucker	yellow perch

The HSI models are generic and applicable over large geographic areas. They are based largely on literature reviews to identify those habitat characteristics and conditions most important for the survival, growth, and reproduction of a species. For each important environmental variable, the levels and conditions considered suitable for the species are expressed as a suitability index, ranging from 0.0 (unsuitable) to 1.0 (optimal). Measured values for a given lake or reservoir can then be assigned a rating between 0 and 1 for each suitability index. These individual suitability indices are then aggregated, usually as a geometric mean, into a composite index, termed the HSI. An example HSI model for brook trout in lakes is presented in Figure 11-2. Additional guidelines for applying HSI models in lakes and reservoirs are provided by Terrell et al. (1982).

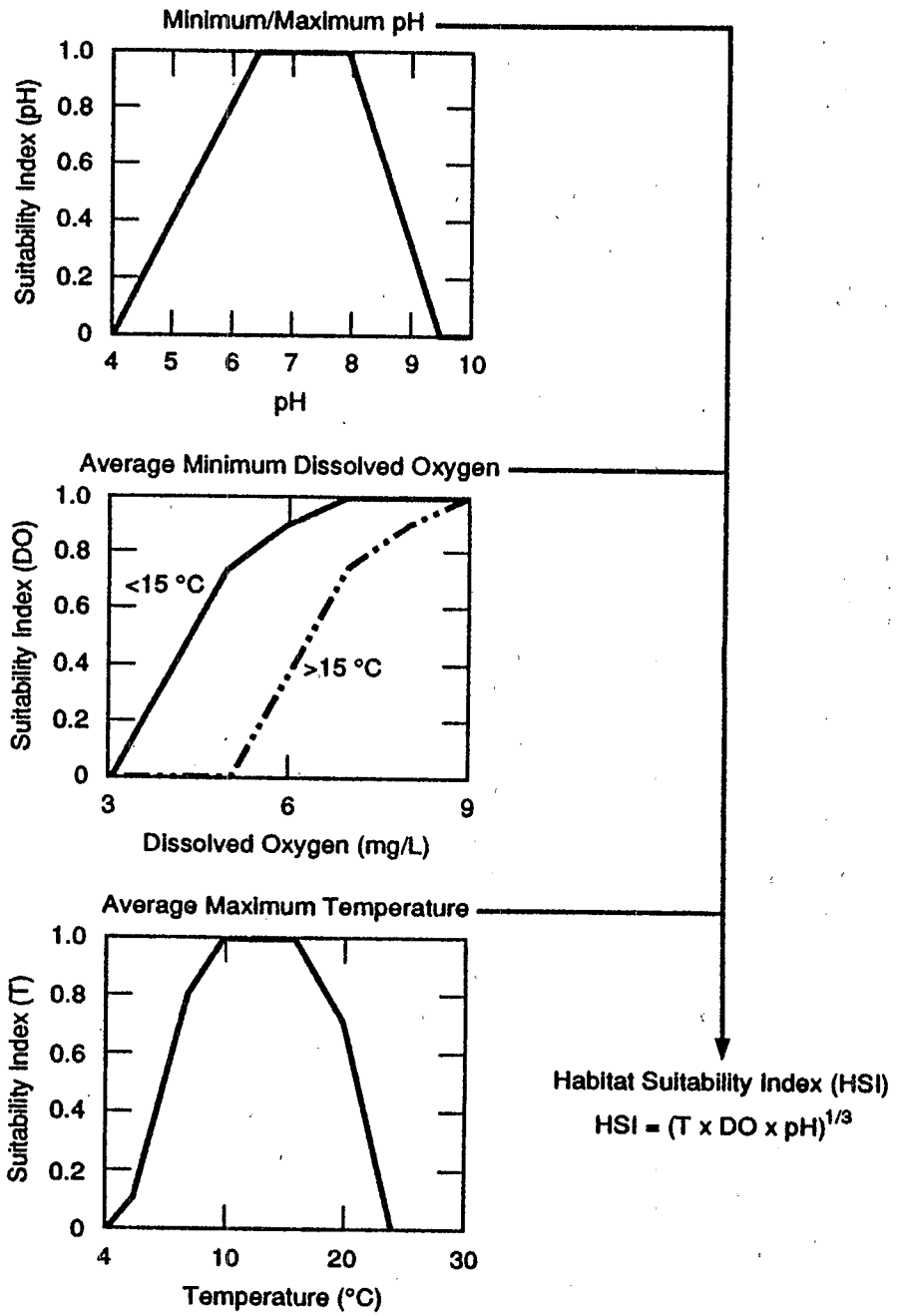

Figure 11-2.—Habitat Suitability Index for brook trout in lakes (modified from Raleigh, 1982).

The major assumption of these models is that the aggregated HSI value is proportional to the carrying capacity or quality of the lake habitat. However, few of the published HSI models have been field validated. Trial et al. (1984), for example, evaluated the performance of HSI models for blacknose dace, common shiner, fallfish, Atlantic salmon, and brook trout in Maine streams. Both brook trout and Atlantic salmon standing crops were significantly correlated with the HSI values. However, Trial et al. (1984) also recommended that the models be significantly revised to address important processes not currently included in the HSI (e.g., the addition of upwelling groundwater and alkalinity to the brook trout

model). Most of the HSI models are also quite data-intensive, requiring fairly detailed assessments of specific habitat features.

Despite these limitations, HSI models provide the best currently available basis for evaluating habitat quality. Applications of HSI models can provide a preliminary assessment of the suitability of a lake or reservoir for a particular fish species (question 2) and insight into major limiting habitat features (question 3). For additional information on the HSI, including a list of available models and documentation, contact the U.S. Fish and Wildlife Service, National Ecology Research Center, 4512 McMurry Avenue, Fort Collins, CO 80525-3400, (303) 226-9311.

Regression Models of Fisheries Yield and Other Fisheries Attributes

How do fish growth rates, fish biomass, or fisheries yield in my lake compare to those in other similar lakes in the region (question 1)? What is the potential fisheries yield? How many and what biomass of fish can be harvested from the lake without adversely affecting the long-term sustainability of the fish resource (question 6)?

These are commonly asked and important questions in fisheries management. One approach to addressing these questions is to quantify the individual processes that contribute to or influence fish population dynamics and yield (e.g., growth rates, fecundity and reproductive success, mortality rates). While it is possible to conduct such a detailed mechanistic analysis, developing and applying it requires a large amount of site-specific information as well as substantial experience and expert knowledge. Mechanistic models of this type certainly have a place in fisheries management and are discussed later in this chapter. However for most management applications, simpler and easier approaches and models, such as empirical, regression-based models, can serve this role.

Regression models rely on the observed association between the fisheries attribute of interest (most often, fisheries yield or fish biomass) and selected lake characteristics measured in a representative sample of lakes or reservoirs within a particular region. Once calibrated, these models can then be applied to other, similar lakes in the area. It is assumed that the observed relationship between the fisheries attribute and lake characteristics in the lakes used to calibrate the model also holds for any additional lakes to which the model is applied. This is a reasonable assumption as long as (a) the lake characteristics included as predictor variables in the model are indeed those factors most important in controling the fisheries attribute or are at least good surrogates for these important factors, and (b) the model is not applied to lakes or reservoirs with characteristics distinctly different from those in the calibration data set. A model calibrated on lakes in a northern temperate region, for example, should not be applied to midwestern or southern waters; a model calibrated for lakes at high elevations is unlikely to provide accurate predictions of yield in lower elevation lakes.

A wide range of lake and reservoir characteristics may serve as useful predictors of fish biomass and fisheries yield, including physical, chemical, and biological variables (Table 11-2). Both single-variable and multiple-variable models have been developed and in some cases can account for up to 90 percent or higher of the variation in yield or biomass among the calibration lakes. Aggregated indices, such as the HSI described in the previous subsection, have also been used as predictors in some models.

A wide range of lake and reservoir characteristics may serve as useful predictors of fish biomass and fisheries yield, including physical, chemical, and biological variables.

One of the most widely used predictors of lake and reservoir fisheries yield is the Morphoedaphic Index (MEI) (Ryder, 1965, 1982; Ryder et al. 1974). The MEI and MEI models were developed originally for northern temperate lakes (see Chapter 3) but have been modified and adapted for lakes and reservoirs in many

Table 11-2.—Summary of percentages of variation explained by single-variable and multivariate models used to predict fish yield and standing crop in lakes and reservoirs from abiotic and biotic variables (source: Carline, 1986).

INDEPENDENT VARIABLES TESTED[a]	MODEL TYPE[b]	% VARIAB. EXPLAINED	SOURCE
FISHERIES YIELD FROM NATURAL LAKES			
Mean depth	S	28-92	Rawson (1952)
Mean depth, MEI	S	54-73	Ryder (1965)
Phytoplankton production	S	57-82	Melack (1976)
Phytoplankton standing crop and production	S	74-84	Oglesby (1977)
Benthic biomass, MEI	S	62-83	Matuszek (1978)
Surface area	S	94	Youngs and Heimbuch (1982)
Length of growing season	S	74	Schlesinger and Regier (1982)
Total P, TDS, MEI, benthic biomass, mean depth	S	54-73	Hanson and Leggett (1982)
Mean depth, MEI	M	63-92	Prepas (1983)
Mean depth, TDS	M	46-76	Ryder (1965)
Mean depth, TDS	M	63-68	Matuszek (1978)
Surface area, mean depth, TDS	M	95-97	Youngs and Heimbuch (1982)
Length of growing season, MEI	M	81-83	Schlesinger and Regier (1982)
Area, mean depth, TDS, total P, benthic biomass	M	40-97	Hanson and Leggett (1982)
FISHERIES YIELD FROM RESERVOIRS			
Chlorophyll *a*, total P	S	52-83	Jones and Hoyer (1982)[c]
Mean depth, MEI	S	8-20	Jenkins (1982)
Length of growing season, area, reservoir age	M	17	Jenkins and Morais (1971)
STANDING CROP IN NATURAL LAKES			
Alkalinity	S	27-41	Carlander (1955)
Benthic biomass/mean depth, depth, biomass	S	20-83	Hanson and Leggett (1982)
Area, mean depth, benthic biomass, biomass/depth	M	35-83	Hanson and Leggett (1982)
Length of growing season, area, Secchi disk depth, macrophyte abundance, panfish index, rough fish index	M	44-56	Schneider (1978)[d]
STANDING CROP IN RESERVOIRS			
Alkalinity	S	69	Carlander (1955)
Retention time	S	72	Jenkins (1976)
Annual outflow volume, retention time, area	S	9-31	Aggus and Lewis (1978)
MEI	S	21-72	Jenkins (1982)
Total P, Secchi disk depth, chlorophyll *a*	S	16-41	G.R. Ploskey, undated
Length of growing season, annual outflow volume, shoreline development index, TDS	M	52	Aggus and Lewis (1978)

[a] Abbreviated variables are P = phosphorus, MEI = Morphoedaphic Index, TDS = total dissolved solids.
[b] S = single-variable model; M = multivariate model. Where more than one single-variable model was tested, the independent variable giving the best predictions is listed.
[c] Some data from lakes were included.
[d] Some data from reservoirs were included.

other regions and climates (Oglesby, 1982). The MEI predicts fish biomass or potential yield as a function of mean depth (z) and the concentration of total dissolved solids (TDS) (Figs. 11-3 and 11-4):

$$MEI = (TDS/z)^{1/2}$$

Jackson et al. (1990) raised concerns, however, about predictive models based on ratio variables, such as the MEI. Rempel and Colby (1991) refute their concerns but support the conclusion that multivariate regression models may be preferable

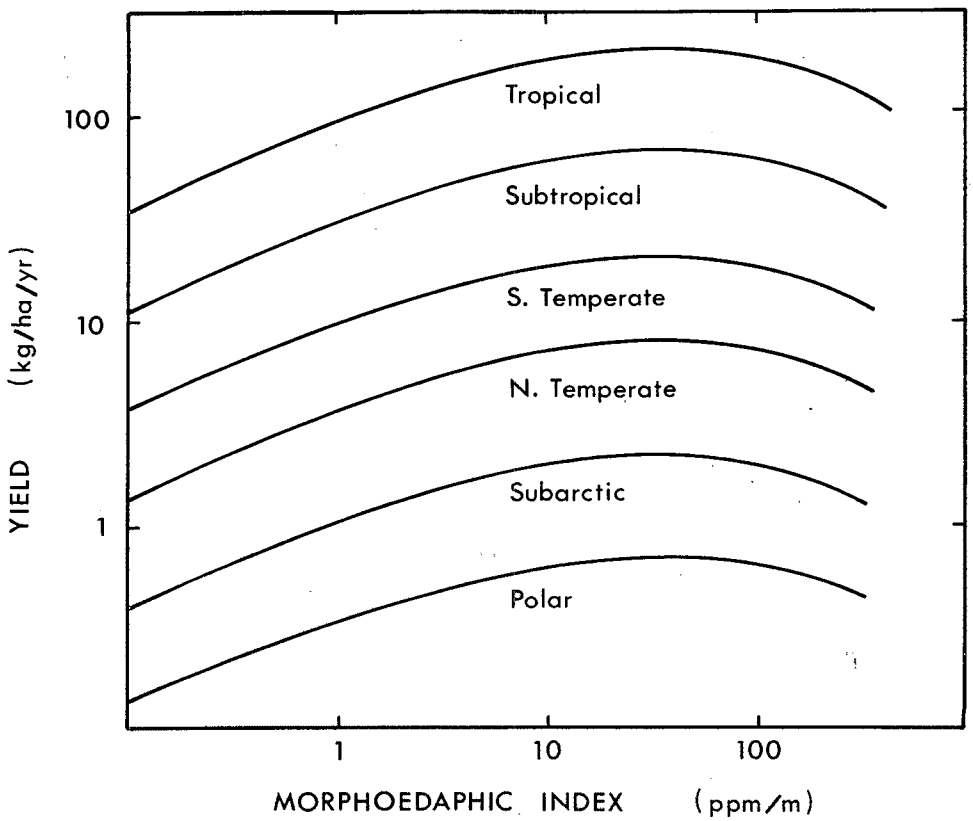

Figure 11-3.—Predicted yield curves as functions of Morphoedaphic Index for six sets of natural lakes representing six of the world's climatic zones (source: Schlesinger and Regier, 1982, adapted from Henderson et al. 1973).

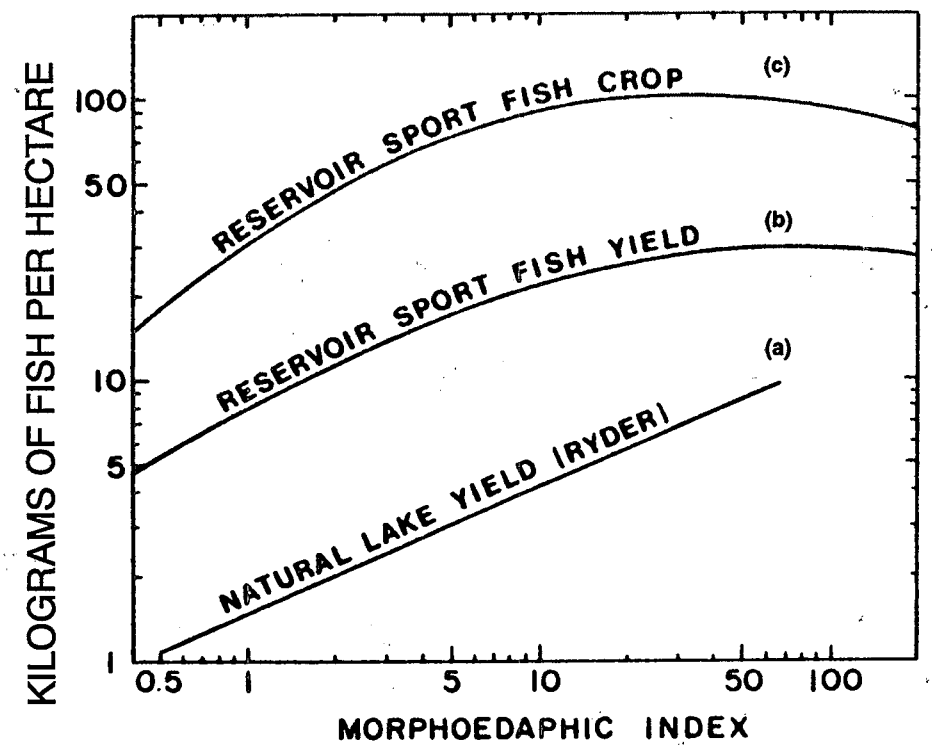

Figure 11-4.—Comparisons of regressions of (a) Ryder's (1965) yield (Y) in a sample of natural lakes, (b) reservoir sportfish harvest (H), and (c) standing crop (C) in kg/hectare on the Morphoedaphic Index (MEI). Regression formulas are (a) log Y = 0.168 + 0.446 log MEI (N=23, r^2=0.73); (b) log H = 0.925 + 0.563 log MEI – log MEI^2 (N=290, r^2=0.08); and (c) log C = 1.498 + 0.677 log MEI – 0.223 log MEI^2 (N=290, r^2=0.21) (source: Jenkins, 1982).

to relying on summary indices. While the MEI and multivariate models produced similar estimates of yield, multivariate models allow for valid, quantitative estimates of model error and confidence limits on model predictions.

Generally, the types of environmental variables significantly correlated with fisheries yield in reservoirs are the same as in natural lakes. The one exception is the mean retention time, which is important in reservoirs but of minor significance in lakes where retention times are often rather long (i.e., several years). The best MEI-based yield models in reservoirs have been derived when reservoirs were subdivided into similar operational or chemical groups, such as hydropower mainstream, hydropower storage, and chemical types of nonhydropower reservoirs (Jenkins, 1982). Retention times are similar within groups; hence, the influence of retention time on productivity is taken into account indirectly by organizing reservoirs into groups with similar retention times.

The predictive function afforded by empirical regression models should be adequate for a number of practical purposes where monetary and labor restraints prevent detailed studies. Quick approximations of yield or fish biomass can be useful to managers who must make management decisions before obtaining comprehensive field data. For the most part, the predictor variables are relatively easy and inexpensive to measure. On the other hand, collecting accurate data on sustainable yields or fish biomass for a sufficient number of lakes for model calibration can be difficult and time-consuming (see Chapter 3 and Appendix B).

Mortality Models

Information on fish mortality rates is essential for many management decisions. If natural mortality rates are high, fish may need to be harvested at relatively young ages to obtain large fisheries yields. The balance between natural and fishing mortality also influences the magnitude of fisheries yields as well as the maximum sustainable fisheries yield. Toxic pollutants, habitat destruction, and many other environmental impacts may affect fish communities primarily by increasing fish mortality. Models of fish mortality (or that include a mortality component) are needed to address questions 5, 6, 7, 8, 9, and 10, at a minimum, and potentially could assist in addressing most of the questions listed earlier.

Most mortality models rely on the same basic equation (Ricker, 1975; Lackey and Hubert, 1978; Everhart and Youngs, 1981):

$$N_t = N_o e^{-zt}$$

where N_t = the number of fish alive at time t,
N_o = the number of fish alive at the start of the time interval, and
z = the instantaneous mortality rate.

The number of fish dying over a given time interval (often, per year) is assumed to be proportional to the number of fish alive at the beginning of the period ($dN/dt = -zN$). If this assumption holds and the mortality rate is constant year to year, then the numbers of fish in a given cohort (year class) will decline exponentially over time (Fig. 11-5a). The mortality rate can be estimated directly from estimates of fish density at each age (Fig. 11-5b) or from changes in catch per unit effort (CPUE), assuming CPUE is a reasonable indicator of relative fish abundance (Fig. 11-5c). A single mortality rate can be applied to all fish (or all adult fish), independent of fish age, or separate mortality rates can be calculated for each age group.

If the numbers of fish harvested each year are known or estimated, then the total mortality rate (z) can be subdivided into fishing mortality (f) and all other sources of fish mortality, generally referred to as "natural mortality" (m):

$$z = f + m$$

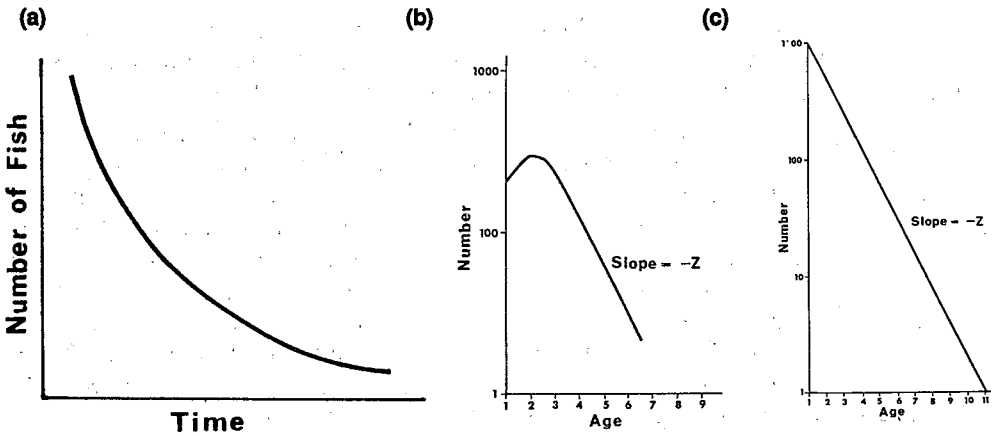

Figure 11-5.—(a) Exponential decline in the number of fish in a cohort over time if the number of fish dying is proportional to the initial number of fish and the mortality rate is constant; (b) on a logarithmic scale, the slope of the line provides an estimate of the instantaneous mortality rate; (c) most sampling methods, however, are less effective at catching small fish. Thus, the mortality rate should be calculated only from that portion of a catch curve where fish are equally susceptible to the sampling gear (source: Everhart and Youngs, 1981).

The fishing mortality rate is a function of fishing pressure and can be controlled, to a large degree, through changes in fishing regulations. In some analyses, the natural mortality rate is assumed to be constant and independent of fishing mortality; alternatively, natural mortality rates can be treated as density dependent, varying as a function of fish density. As discussed in Chapter 3, the degree to which natural mortality is density dependent (and can compensate for changes in fishing or other human-caused mortality) is a major source of uncertainty in assessing and modeling fish population responses to environmental stresses.

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In most management applications, mortality models are used together with models of fish growth and reproduction to assess changes in fish population dynamics (discussed later in this chapter) and fisheries yield. For example, Evans (1989) and Zagar and Orth (1986) examined the influence of a change in the minimum size regulation, and thus age of fish harvest, on fisheries yield and the size of fish harvested. Evans and Willox (1991) included a mortality model as part of their assessment of interactions between native and stocked lake trout, and Muir (1964) analyzed the effect of fishing on muskellunge in Nogies Creek, Ontario.

Growth Models

The von Bertalanffy (1938) growth equation is one of the most widely used models for estimating the length or weight of fish at a future point in time. Length at time t (l_t) is expressed as a function of the maximum length for the population (l_∞), a growth coefficient (K), and the time (t_o) when length would theoretically be zero:

$$l_t = l_\infty[1-e^{-K(t-to)}]$$

Assuming isometric growth, the growth equation stated in terms of weight (w_t) is:

$$W_t = W_\infty[1-e^{-K(t-to)}]^3$$

Values for K and l_∞ (or w_∞) may be obtained by plotting length (or weight) at time t+1 (y axis) against length at time t (x axis) for each successive age (Fig. 11-6); the final parameter, to, can then be back-calculated from the growth equation. Alternatively, computer software is available for estimating all three parameters directly from data on fish size and age (e.g., Saila et al. 1988).

The basic von Bertalanffy equation assumes that fish growth rates are fixed and do not vary as a function of food supply or other environmental factors.

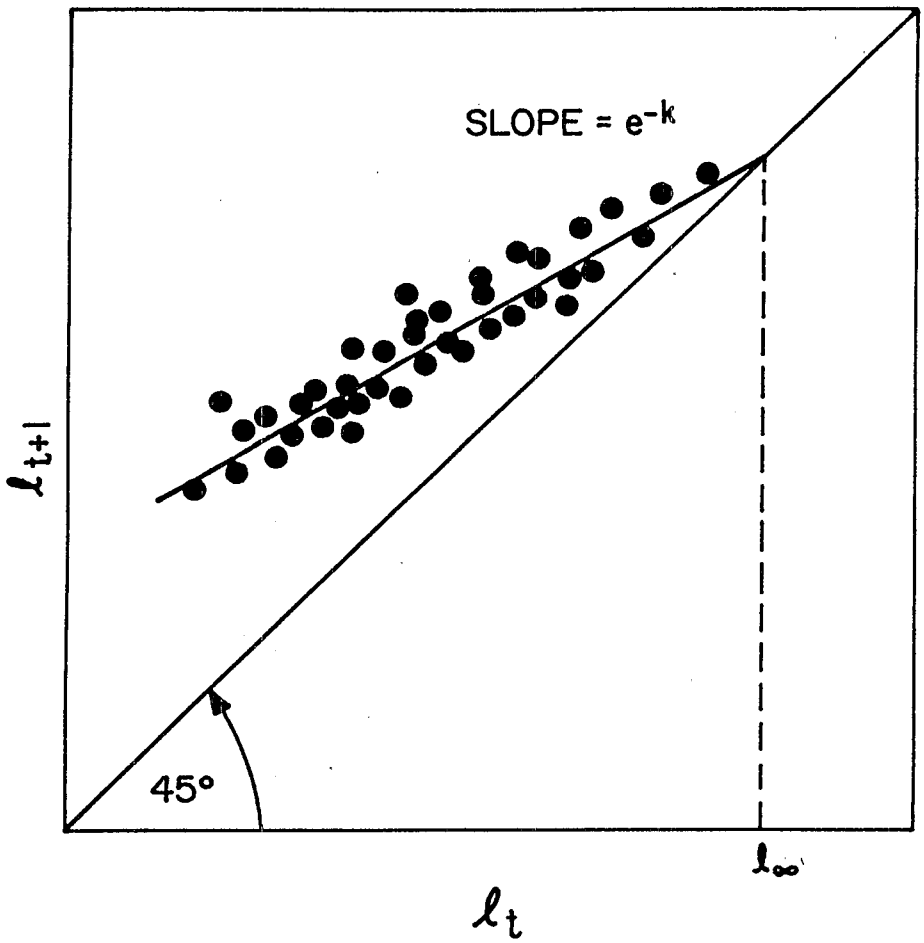

Figure 11-6.—Walford plot (Walford, 1946) of annual increment in fish length. Length at time t plotted against length at time t+1 (l_∞= maximum length attainable) (source: Lackey and Hubert, 1978).

Variations in growth rates can be modeled by applying adjustment factors to the parameters in the von Bertalanffy equation (e.g., Taylor 1981) or by using alternative, more mechanistic models of fish growth. In particular, bioenergetics models have been developed in which fish growth (increase in biomass over time, dB/dt) is predicted by the difference between the energy value of the prey consumed (C) and the sum of the specific energy outputs associated with respiration (R), egestion (F), and excretion (U) (Kitchell et al. 1977):

$$dB/dt = C - (R + F + U)$$

Fish consumption rates are controlled by the availability of suitable prey and temperature. Energy expenditures for reproduction can also be considered.

Bioenergetics models are most commonly used within ecosystem models (discussed later in this chapter) to assess interactive effects among species (e.g., predators and prey). Madenjian et al. (1991), for example, used a bioenergetics model of walleye growth to evaluate walleye stocking strategies as a function of prey (yellow perch) availability and size distributions. Swartzman and Beauchamp (1990) modeled the bioenergetics of rainbow trout growth to assess the effects of trout introduction into Lake Washington on longfin smelt and sockeye salmon parr. Because of the large number of parameters that must be quantified, modeling fish bioenergetics is generally practical only in lakes that have been intensively studied.

Models of fish growth are needed to estimate the number of years required for fish to reach harvestable size (questions 4 and 8) and are a fundamental component of estimates of fish production and potential yield. The von Bertalanffy equation parameters also can be used directly for among-lake comparisons of fish growth (question 1).

Population Dynamics Models

Many fisheries models have their origin in models of commercial fisheries in the ocean or anadromous salmon stocks. Generally, these modeling efforts focused on population-level processes, ignoring species interactions or habitat effects, and on methods for estimating the maximum sustainable fisheries yield. As a result, many diverse models of fish population dynamics have been developed.

Two basic types of population-level models can be distinguished: (1) those that simulate population dynamics by modeling the individual component processes of mortality, growth, and reproduction, and (2) models that treat population processes as a "black box" and focus instead on relationships between integrative indicators, such as changes in fish population abundance and total fish recruitment. Both approaches as well as models have been applied in analyses of recreational fisheries and fish populations in lakes.

The Leslie matrix (Leslie, 1945, 1948) was one of the earliest methods for tracking fish population dynamics as a function of age-specific fish mortality and growth. Computerized models based on similar concepts have since been developed, many of which also incorporate fish fecundity and reproduction, density-dependent growth and mortality, age- and sex-specific exploitation rates, and stochastic components (e.g., random variability in natural mortality rates; the general inland fish simulator GIFSIM program developed by Taylor, 1981).

Advantages of these models include their flexibility, diversity of management questions that can be addressed (e.g. questions 5 through 10), and basis in biological principles. Disadvantages include the large number of model parameters that must be measured or estimated and uncertainties regarding density-dependent mortality. Christensen et al. (1988) calibrated the outputs from a Leslie matrix-type model (expressed as relative reproductive potential) to observed fish population responses in the field in an attempt to adjust for density-dependent mortality and other factors not accounted for in models of fish population responses to acidification in Adirondack lakes. Other applications of this mechanistic approach to modeling fish population dynamics have included environmental assessments of effects from entrainment (Boreman et al. 1982, Cohen et al. 1983) and toxic substances (Barnthouse et al. 1987), fisheries assessments of the effects of harvest regulations on fish size distributions and yield (Zagar and Orth, 1986; Evans, 1989), and analyses of the effects of stocking on native fish strains (Evans and Willox, 1990).

Two examples of black box population models are the stock-recruitment model (Ricker, 1954, 1975; Beverton and Holt, 1957) and surplus yield models (Schaefer, 1957; Gulland, 1961; Fox, 1970; Walter, 1973; Schnute, 1985; Ludwig and Walters, 1989). Both types of models are designed primarily for estimating the maximum sustainable fisheries yield (Question 6). Deriso (1980) and Schnute (1985) (and others) have also developed models that combine aspects of the mechanistic, age-structured models with the concepts of stock-recruitment and surplus production.

Stock-recruitment models, as the name suggests, relate fish recruitment (biomass of new fish entering the fishery or added to the population as a result of fish reproduction) to the biomass of the adult stock. The Ricker (1954, 1975) model assumes that mortality is density dependent; therefore, recruitment is low at both low and high levels of adult stock biomass (Fig. 11-7):

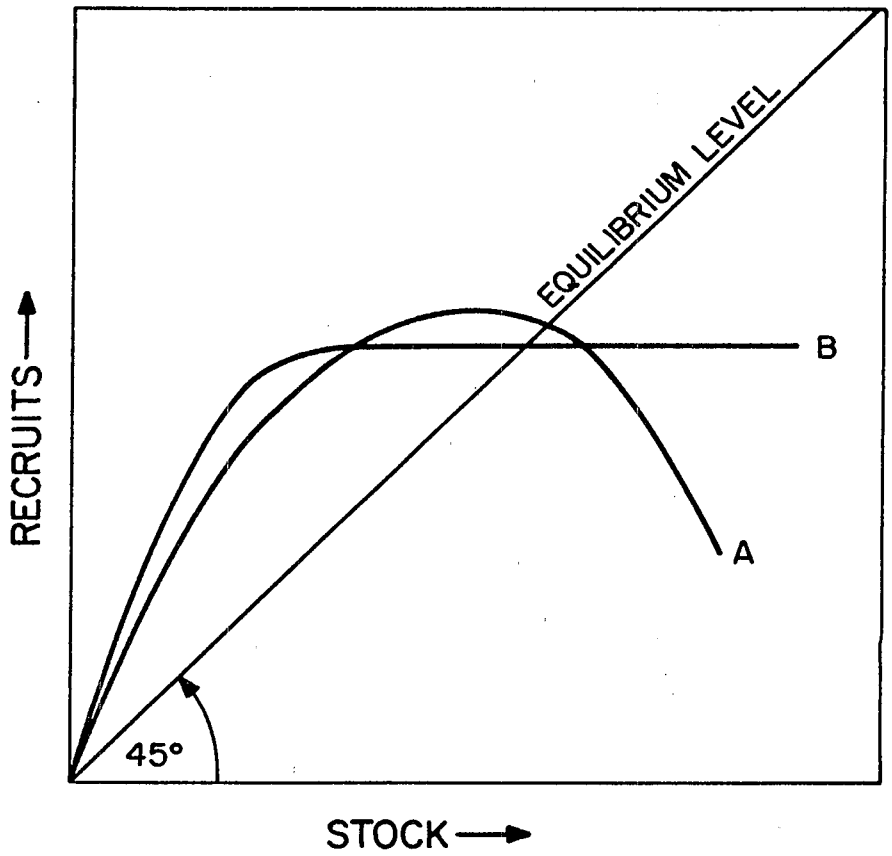

Figure 11-7.—The two classical stock-recruitment curves: (A) the Ricker curve and (B) the Beverton-Holt curve (source: Lackey and Hubert, 1978).

$$R = alpha P^{-betaP}$$

where R = biomass of new recruits,
P = parental stock biomass, and
alpha and beta are positive parameters fit during model calibration.

The Beverton-Holt model (1957) assumes that density-dependent and density-independent mortality factors are important; therefore, recruitment levels off at high adult biomass (Fig. 11-7). In both cases, only the total weight of fish is considered. Observations of adult biomass and recruitment over multiple years are used to calibrate the model for any given population. The maximum sustainable yield is achieved if adult biomass is maintained at a level where the difference (vertical distance) between new recruits and adult biomass is greatest. Software for running these models is available in Saila et al. (1988).

Surplus yield models are also single stock models that require no data on the age structure of either the catch or the stock. The underlying assumption is that fish population production (increase in biomass over time) follows a sigmoidal or logistic curve (Fig. 11-8). The maximum rate of population increase (maximum slope) occurs at the inflection point of the logistic curve, at intermediate levels of fish abundance. If this is true, then the maximum sustainable yield ("excess production") also occurs at an intermediate level of fish abundance (also see Fig. 2-15). In heavily fished populations, fish abundance is controlled largely by the level of fishing effort; moderate levels of effort result in moderate levels of fish biomass. Thus, the maximum sustainable (equilibrium) yield occurs at an intermediate level

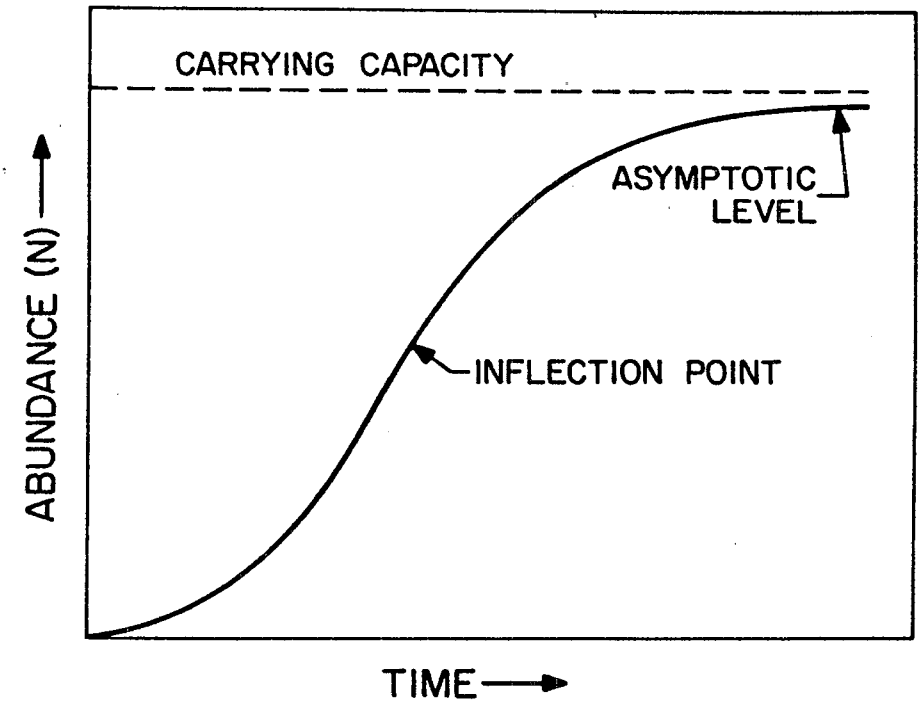

Figure 11-8.—Sigmoid growth curve of abundance (N) versus time, the basis of the surplus yield model (source: Lackey and Hubert, 1978).

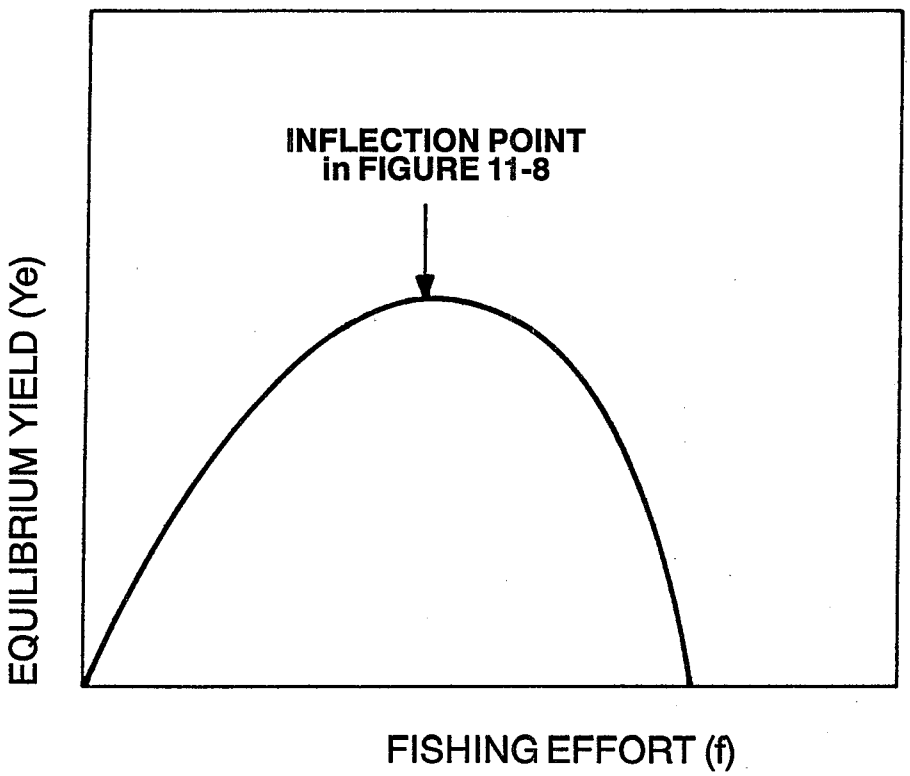

Figure 11-9.—Surplus yield model: equilibrium yield versus fishing effort (source: Lackey and Hubert, 1978).

of fishing effort (Fig. 11-9). A curve, similar to that illustrated in Fig. 11-9, is calibrated from observations of catch and population abundance over multiple years for a given fish population.

Ricker (1975), Lackey and Hubert (1978), Everhart and Youngs (1981), and Walters (1986) explain the underlying mathematics and principles of the surplus yield, stock recruitment, and related models in greater detail. Because of the requirement for long time series of data for model calibration, neither of these modeling approaches has been applied as widely for recreational fisheries analyses as have the mechanistic, age-structured population models described earlier in this section. Most applications have been for commercial fisheries (e.g., Fox, 1970; Welch and Noakes, 1991). In addition, high levels of year-to-year variability and measurement error often obscure the underlying theoretical relationships.

Ecosystem models attempt to integrate interactions between multiple species or trophic levels and habitat features to predict effects on fisheries. . . .

Ecosystem Models

Ecosystem models attempt to integrate interactions between multiple species or trophic levels and habitat features (e.g., nutrient loading or temperature) to predict effects on fisheries (question 11) or the effects of fish on other ecosystem components and water quality (questions 12 and 13). Most ecosystem simulation models are highly mechanistic. Many individual submodels (generally first-order differential equations) are defined representing specific interactions (e.g., zooplankton grazing on phytoplankton) and processes (e.g., fish growth) (see Box 11-A). Each component equation is intended to reflect current understanding of biological systems as closely as possible.

This manual cannot provide an adequate discussion of the diversity of ecosystem models. The components, processes, and modeling approaches vary depend-

Box 11-A.—Ecosystem Models: Example Submodel Equations

Scavia et al. (1988) developed a model of the Lake Michigan ecosystem incorporating the components and pathways presented in Figure 11-11. Model equations for the phytoplankton and zooplankton compartments are listed below to illustrate how differential equations are used to represent biological processes.

Phytoplankton:

$dA/dt = (\mu - s)A - gZ$

A = phytoplankton concentration
μ = growth rate (see below)
s = settling loss = sinking rate/epilimnion depth
g = zooplankton grazing (see below)
Z = zooplankton concentration
$\mu = \mu_m$ * MIN $\{P/(K_P + P), Si/(K_{Si} + Si)\}$

where μ_m = the maximum growth rate
K = half-saturation constants for phosphorus (P) and silicon (Si)

$g = g_m$ * $EFC/(K + EFC)$

where g_m = the maximum weight-specific ingestion rate
K = half-saturation constant
$EFC = \sum (W'_i * X_i)$, where W' is the selectivity coefficient for food source i with concentration X_i

Zooplankton:

$dZ/dT = (g-r)Z - P$

r = respiration (see below)
P = fish predation = specific ration * alewife biomass
$r = r_1 + r_2$ * $EFC/(K + EFC)$

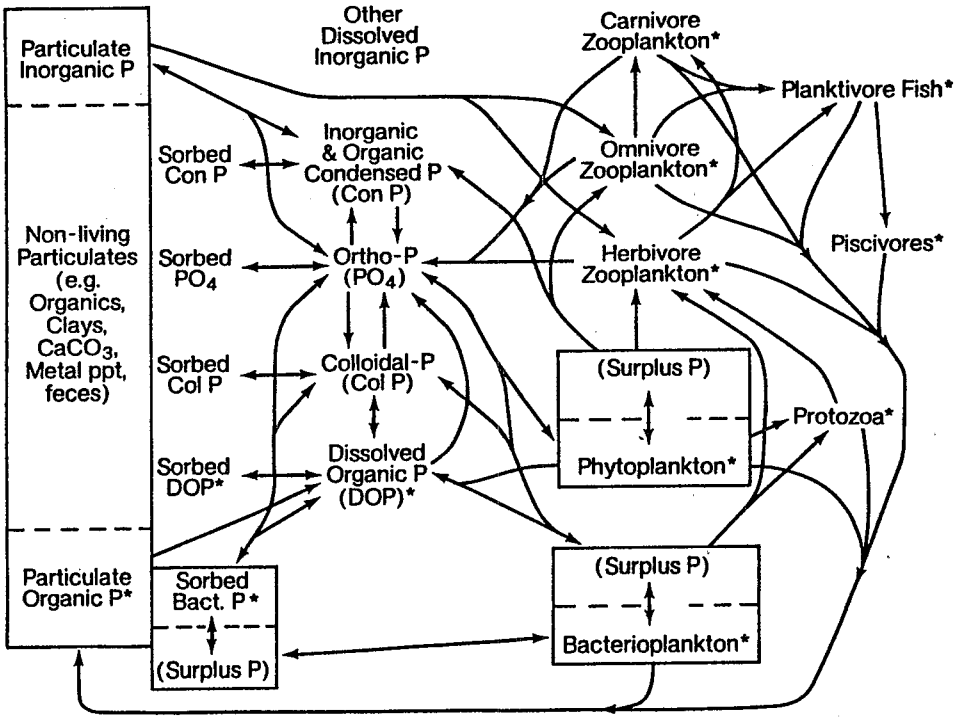

Figure 11-10.—Conceptual model of phosphorus dynamics indicating major components and pathways within the water column. Asterisks indicate several functional groups or life stages within each component (source: Chapra and Reckhow, 1983; reprinted from Scavia, 1981).

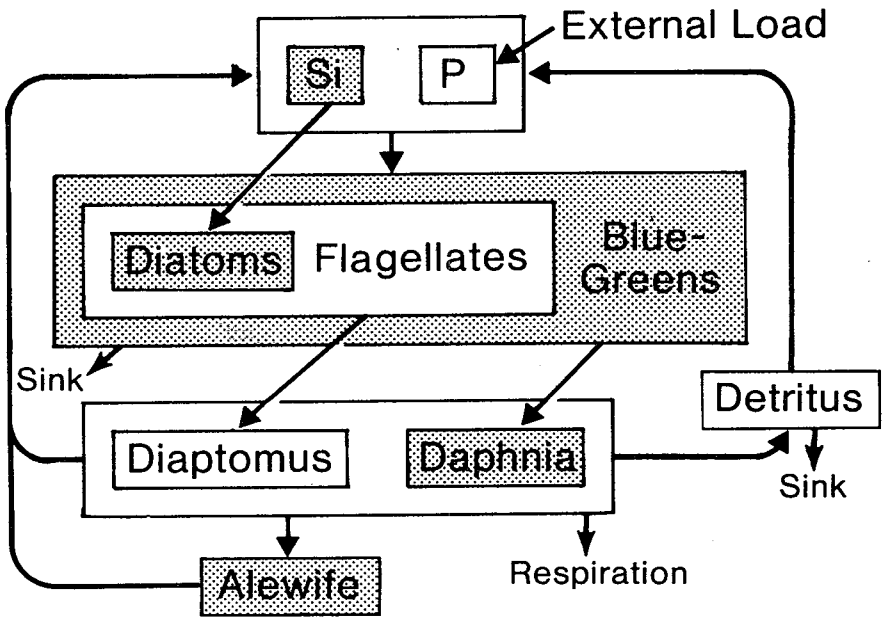

Figure 11-11.—Schematic of major pathways in model designed to simulate nutrient cycles and biomass flow among competing phytoplankton and zooplankton groups. Arrows represent major pathways; some are omitted for clarity. Nested boxes are used to show selective grazing pathways. For example, all algal groups are consumed by *Daphnia,* whereas only flagellates and diatoms are consumed by *Diaptomus* (source: Scavia et al. 1988).

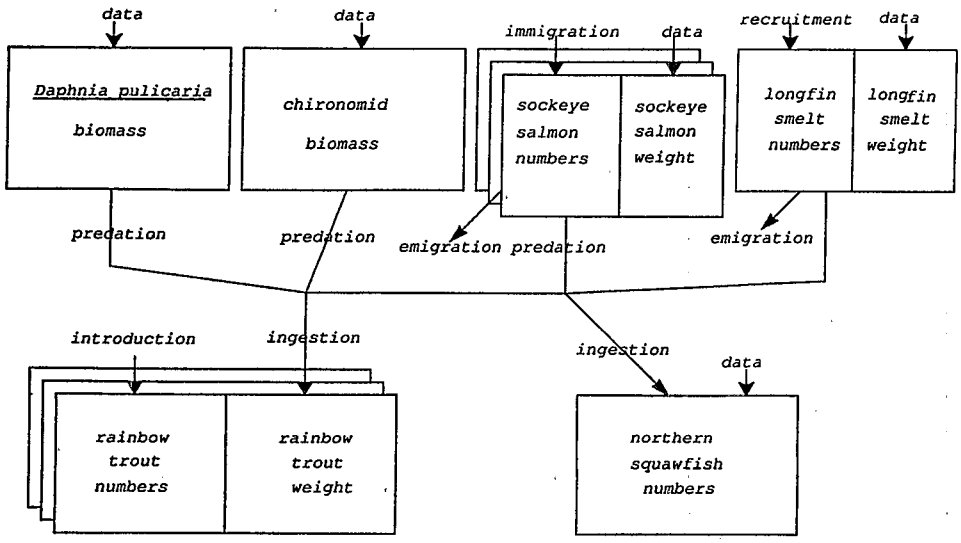

Figure 11-12.—Flow diagram for the LKWASH model of fish interactions in Lake Washington (Seattle, Washington). Major model variables are contained in boxes. Arrows denote flows between compartments and are labeled according to the relevant process. Multiple cohorts of the same variable are denoted by a stack of boxes. Driving variable inputs to model variables are denoted by arrows labeled data (source: Swartzman and Beauchamp, 1990).

ing on the modeling objectives. Models may be highly complex (e.g., Fig. 11-10) or model components may be lumped or aggregated by functional group or other relevant category (e.g., Fig. 11-11). Example applications include (a) modeling of interspecific interactions in the fish community in Lake Washington to evaluate effects from the introduction of rainbow trout on other fish species in the lake (Swartzman and Beauchamp, 1990; Fig. 11-12) and (b) a model-based assessment of the relative importance of changes in nutrient loading and top-down (fish) predation on phytoplankton and zooplankton communities in Lake Michigan (Scavia et al. 1988; Fig. 11-11). Chapra and Reckhow (1983) describe the basic concepts and approaches to mechanistic modeling of food webs and ecosystems.

Johnson et al. (1991) present an alternative approach to ecosystem modeling in which empirical regression analysis and mechanistic understanding of ecosystem processes play an equally important role. Conceptual relationships among important ecosystem components are defined based on ecosystem theory (Fig. 11-13a) and then quantified using path analysis (Fig. 11-13b). Traditional path analysis (Wright, 1968) uses a hierarchical series of linear regression analyses (single or multiple) to establish the relationships among variables. The path coefficients are the standard regression coefficients. LISREL (Hayduk, 1987), recommended by Johnson et al. (1991), however, uses maximum likelihood estimation techniques to estimate path coefficients rather than least-squares regression. LISREL also incorporates measurement error into the modeling process by separating theoretical concepts (the boxes in Fig. 11-13) from their measured environmental indicator variables (the ovals in Fig. 11-13). The outputs from LISREL provide a determination of the total, direct, and indirect effects of the variables in the model on each other. Ecosystem modeling with LISREL may be particularly useful, therefore, for identifying the relative importance (strength of relationships) of alternative causes of lake problems.

To date, ecosystem models have been used primarily for research; management applications have been limited. Because of their complexity and the number of components and processes incorporated, most models are very data-intensive. Their primary benefit has been improved understanding, although "game playing" (evaluating model responses to perturbations or management actions) can

provide new insight on emergent ecosystem properties. As for all models, ecosystem models are a tool that should be used in conjunction with other information (logical thinking, direct experience, and other data analyses) to aid in management decisionmaking.

ECOSYSTEM MODELING WITH LISREL

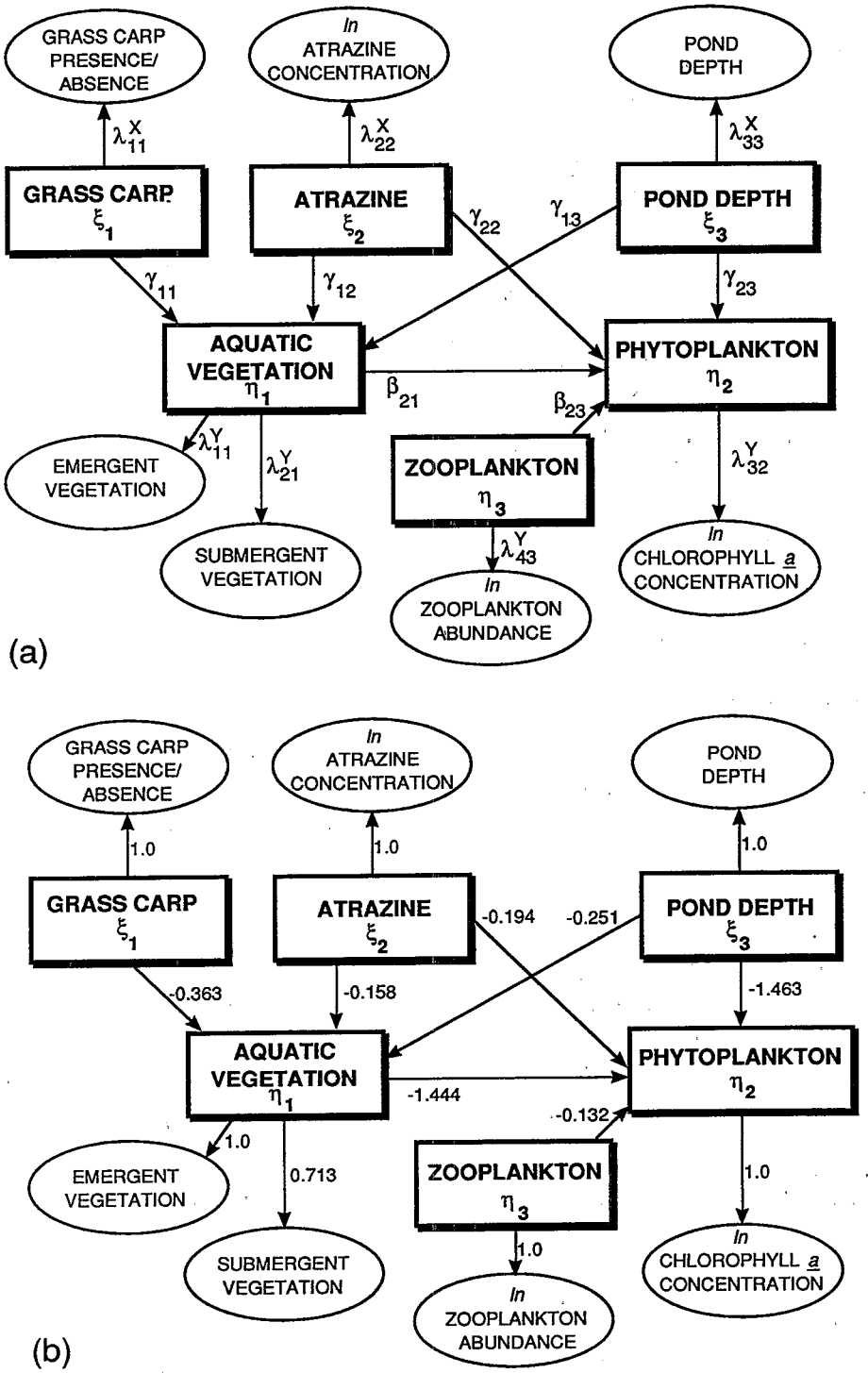

Figure 11-13.—Simple pond ecosystem modeled with LISREL. The ecosystem is placed into a framework of concepts (boxes) and indicator variables (ovals). Causal pathways proposed among variables are presented in part (a); standard coefficients from LISREL analysis of data from the Kansas Aquatic Mesocosm Program, indicating the relative effects of variables, are presented in part (b) (source: Johnson et al. 1991).

CHAPTER 12

Case Study Examples

Chapter Objective

This chapter presents summaries for seven lake management and restoration projects that illustrate many of the concepts and techniques discussed in this manual. These seven projects were selected to represent a diverse array of regions, different lake types and reservoir systems, a broad sample of problems and objectives, and a wide range of management approaches and techniques (Table 12-1).

Table 12-1.—Summary of case study lakes.

LAKE NAME	LOCATION/ SIZE	MANAGEMENT GOALS (TARGET FISH)	MANAGEMENT APPROACHES	INFORMATION SOURCE
Lake Chicot	SE Arkansas 3,500 acres	Restore balanced fish community and fisheries (largemouth bass)	— Siltation reduction — Water level mgmt. — Reclamation — Stocking — Fish cover — Seeding	Arkansas Game and Fish Commission (Filipek et al. 1989)
Cold Springs Lake	Iowa 16 acres	Increase fish growth rates and size (largemouth bass, bluegill, channel catfish, crappie)	— Aeration/ destratification	Iowa Conservation Commission (Hill, 1987)
Bear Lake	N. Wisconsin 300 acres	Increase fish growth rates and size (walleye, largemouth bass, bluegill)	— Selective cropping — Spawning disruption — Catch and release — Game fish stocking	McComas (1988, 1989)
Lake Opeongo	South Central Ontario, Canada 14,464 acres	Increase lake trout growth and yields (lake trout)	— Prey enhancements — Fishing regulations	Matuszek et al. (1990)
Flaming Gorge Reservoir	NE Utah and SW Wyoming 42,000 acres	Provide a diverse, high quality, sustainable fisheries (rainbow trout, lake trout, cutthroat trout, kokanee salmon)	— Game fish stocking — Fishing regulations	Wyoming Game and Fish Department (Wiley et al. 1976; Wengert and Wiley, 1987)
Flathead Lake	NW Montana 20,636 acres	Protect native fish assemblages (bull trout, cutthroat trout, mountain whitefish); protect aquatic habitat and prevent eutrophication; maintain a diverse, high quality recreational fisheries (kokanee salmon, rainbow trout, lake trout, yellow perch)	— Reduce nutrient loading — Habitat protection — Water level mgmt. — Fish stocking — Fishing regulations	Flathead Basin Commission (1990), Montana Dept. Fish, Wildlife and Parks, and Confederated Salish and Kootenai Tribes (1989, 1991)
Lake Washington	Washington 21,500 acres	Improve water quality; maitain fisheries yields (sockeye salmon, rainbow trout)	— Sewage diversion — Physical habitat improvement — Food web manipulation	Edmonson and Lehman (1981); Edmonson and Abella (1988)

Lake Chicot, Arkansas

Background

Lake Chicot is a 3,500-acre natural oxbow lake that was originally created 400 years ago when the meandering Mississippi River changed its course. It has a maximum depth of 30 feet and a mean depth of 13.8 feet. The lake had an early history of being prized as scenic and pristine. It served as an untreated water source for a nearby community and provided an outstanding largemouth bass fishery.

A series of hydrologic modification projects implemented in 1926 connected Lake Chicot to a nearby lake. These projects (and a subsequent failure of associated levees) expanded the watershed draining into Lake Chicot and lowered its lake level below that originally intended. Following World War II, agricultural uses expanded from 10 to 80 percent of the watershed, increasing lake turbidity and pesticide and nutrient concentrations. In addition, irregular fluctuations in lake levels caused by inadequate flow control caused severe turbidity problems and habitat destruction. Consequently, both water quality and the lake's fisheries deteriorated substantially.

In 1948, the Arkansas Game and Fish Commission constructed a dam that blocked the channel connecting Lake Chicot to the lake to the north. Water quality and fisheries in the upper fourth of the lake then returned to near its earlier condition. The remainder of the lake, however, continued to have severe turbidity problems, along with uncontrolled water level fluctuations.

The Lake Chicot Project was authorized as part of the Flood Control Act of 1968, which committed the U.S. Army Corps of Engineers (COE) to assist Arkansas in restoring the lake. The Chicot County Improvement District, COE, and Arkansas Game and Fish Commission contributed funds and resources to the project. The following information on restoration methods and results is summarized from Filipek et al. (1989).

Restoration Activities

[T]he lake was reclaimed to eliminate or reduce existing fish populations. . . . About 3,000 citizens assisted with the removal of 155,000 pounds of fish.

[T]he bottom of the lake was seeded with sorghum sudan and winter wheat. Also, 36 fish shelters constructed of PVC pipe were installed and marked by buoys.

Restoration plans called for reestablishing Lake Chicot's original hydrologic regime and eliminating the heavy loads of suspended sediments entering the lake. New outlet structures were constructed that minimized lake-level fluctuations and restored the lake's original water level. A pumping plant and diversion structures were constructed to redirect agricultural runoff from areas outside of Lake Chicot's original pre-1926 watershed. Following these improvements, fisheries restoration activities were begun.

Several management actions aimed at restoring a balanced fish community and fisheries were coordinated by the Arkansas Game and Fish Commission and COE. First, the lake was reclaimed to eliminate or reduce existing fish populations. The lake was drawn down to the lowest possible level and fish were further concentrated by baiting; these concentrated fish were then killed using rotenone. About 3,000 citizens assisted with the removal of 155,000 pounds of fish (about 300 pounds per acre). Interestingly, only one largemouth bass was observed in the fish removed. Subsequently, a comprehensive stocking program was initiated by the Arkansas Game and Fish Commission to repopulate the reservoir (Table 12-2).

To enhance the quality of the lake's habitat, during the drawdown the bottom of the lake was seeded with sorghum sudan and winter wheat. Also, 36 fish shelters constructed of PVC pipe were installed and marked by buoys. Hydroacoustic surveys conducted after stocking and restoration of the lake level revealed that stocked fish congregated around these shelters almost immediately.

Table 12-2.—Corrective fish stockings following restoration of Lake Chicot, Arkansas (source: Filipek et al. 1989).

YEAR	SPECIES	NUMBER STOCKED
1985	Redear sunfish fingerlings	65,000
	Florida largemouth bass yearlings	30,810
	Blue catfish catchables	19,000
	Channel catfish catchables	10,475
	Crappie yearlings	10,000
1986	Bluegill adults	100
	Bluegill yearlings	25,000
	Florida largemouth bass fingerlings	43,125
	Channel catfish catchables	5,000
	Channel catfish yearlings	10,200
1987	Largemouth bass fingerlings	10,200
1988	Largemouth bass fingerlings	18,000

Table 12-3.—Mean values for eight water quality variables at two stations in Lake Chicot, Arkansas, before and after lake restoration (source: Filipek et al. 1989).

	STATIONS			
VARIABLE	7 PRE-RESTORATION	7 POST-RESTORATION	9 PRE-RESTORATION	9 POST-RESTORATION
Turbidity	182	12	152	25
Secchi depth	0.25	0.65	0.20	0.45
Total solids	347	189	280	189
Suspended solids	142	17.2	131	26.1
Nitrate	0.534	0.044	0.430	0.124
Chorophyll *a*	11.6	35.7	8.9	30.4
Total phosphorus	0.355	0.083	0.430	0.102
Orthophosphorus	0.082	0.059	0.091	0.052

To aid in evaluating the effectiveness of the lake restoration, eight water quality variables were sampled at two stations several years before the renovation of Lake Chicot. Table 12-3 presents mean values from pre-restoration and post-restoration sampling for turbidity, Secchi depth, total solids, suspended solids, nitrate, chlorophyll *a*, total phosphorous, and orthophosphorus. For each of these water quality variables, postrestoration concentrations were significantly different ($p \leq 0.05$) from prerestoration samples. Concentrations of chlorophyll *a* increased despite the reduction in nutrient concentrations because as turbidity decreased light penetration increased and, consequently, algal productivity increased.

Fisheries responded positively to the restoration effort. Comparisons of pre-restoration (1973, 1981, 1984) and post-restoration (1986, 1987, 1988) surveys indicated major differences in fish species composition, numbers, weights, and relative abundances (Table 12-4). Largemouth bass, virtually nonexistent before lake renovation, became a significant component of the fish community. Distributions of numbers and biomass among fish species indicated a better balanced community following renovation. For example, despite increased predation as a result of the reintroduction of largemouth bass, bluegill increased 10-fold in numbers and weight following restoration.

Fisheries responded positively to the restoration effort. . . . Several components combined to make the Lake Chicot project a success.

Several components combined to make the Lake Chicot project a success. The extensive drawdown exposed much of the lake bottom to the air; thus, nutrients in the bottom sediments were tied up by oxidation. Drawdown also compacted the bottom sediments and allowed seeding of much of the lake bottom to help regulate post-flooding losses of nutrients and sediments to the water column.

Table 12-4.—Numbers and biomass of fish in Lake Chicot, Arkansas, before and after lake restoration; differences before and after restoration were evaluated using a t-test (source: Filipek et al. 1989).

SPECIES	BEFORE MEAN NO./ACRE	AFTER MEAN NO./ACRE	PROB. > T[1]	BEFORE MEAN LB/ACRE	AFTER MEAN LB/ACRE	PROB. > T[1]
Largemouth bass	0	103	0.17	0	26	0.02
Bluegill	386	5,108	0.13	10	97	0.13
Gizzard shad	2,547	2,414	0.86	92	309	0.04
Channel catfish	304	98	0.16	88	83	0.17
Total all species	6,962	11,055	0.27	336	656	0.11

[1]Probability value from the t-test; probability values less than 0.05 are usually considered indicative of a statistically significant difference — in this case, between before and after lake restoration.

The low water level during drawdown concentrated fish, permitting efficient rotenone treatment to thin the overabundant populations of stunted crappie, shad, sunfish, and catfish. Finally, construction and operation of the pumping plant diverted much of the turbid and polluted water inputs away from the lake. Rejuvenation of the largemouth bass population can be attributed to the improved water quality (especially the increased water clarity needed by these sight-feeding predators), increased availability of forage fish, and corrective stocking. Changes in the population structure for most other fish species following restoration can be partially attributed to increased predation by largemouth bass.

Cold Springs Lake, Iowa

Surveys by the Iowa Conservation Commission (ICC) indicate that the size and growth of panfish (sunfish and crappie) are unsatisfactory in many small Iowa lakes and are a function of fish density and the available food supply. Generally, bluegill in Iowa lakes grow rapidly during the spring and slowly during the summer. Previous studies by the ICC suggest that this decrease in growth during summer is caused by increased bluegill densities above the hypolimnion in stratified lakes. Because of anoxic conditions in the hypolimnion, few fish are found below the thermocline. Thus, a substantial portion of the lake bottom is inaccessible for fish feeding on benthic organisms. Furthermore, reduced oxygen levels in deeper waters can alter the numbers and types of benthos. *Hexagenia* nymphs, a preferred prey for bluegill, are intolerant of low oxygen levels, while oligochaetes and chironomids, which are commonly found in waters with low oxygen, are less desirable prey.

In 1980, the ICC initiated a program of lake destratification to evaluate its potential for improving benthic biomass and production and its effects on the growth, size structure, and biomass of largemouth bass, bluegill, crappie, and channel catfish in small stratified lakes.

In 1980, the ICC initiated a program of lake destratification to evaluate its potential for improving benthic biomass and production and its effects on the growth, size structure, and biomass of largemouth bass, bluegill, crappie, and channel catfish in small stratified lakes. Years of thermal destratification were alternated with years of stratification in an attempt to control the survival of small panfish and prevent overcrowding and stunting. The following paragraphs extracted from Hill (1987) summarize results from this restoration program for Cold Springs Lake.

Cold Springs Lake was selected for an initial evaluation of mechanical summer aeration because of its history of slow-growing panfish and its small size and close proximity to an ICC research station. Cold Springs Lake, a 16-acre public recreation lake was reconstructed in 1949 by the ICC specifically for fishing and swimming. The maximum depth is 14 feet with a mean depth of 5.5 feet. Thermal stratification occurs at 6.5 feet; during stratification, 50 percent of the lake bottom is located beneath the hypolimnion and anoxic conditions occur. This severe thermal stratification persists from June through August.

Several management techniques had already been employed at Cold Springs Lake with some success, including (1) chemical reclamations to reduce bluegill density, (2) grass carp introductions to reduce nuisance aquatic vegetation, and (3) a minimum length limit to reduce the harvest of smaller largemouth bass. As a result of these management efforts, fishing improved and fishing pressure increased. Currently, Cold Springs Lake receives more fishing pressure per unit area than most Iowa lakes.

An axial flow water pump was used to destratify Cold Springs Lake from June 1 to September 15 in 1981, 1982, 1983, and 1986. The pump was placed in the deepest portion of the lake and operated to create a downward flow of water. The pump's effectiveness in destratifying the lake is illustrated in Figure 12-1 by the absence of a thermocline during the years when the pump was in operation, as opposed to the sharp temperature gradient with depth for the months of June, July, and August during the years when the pump was not in operation.

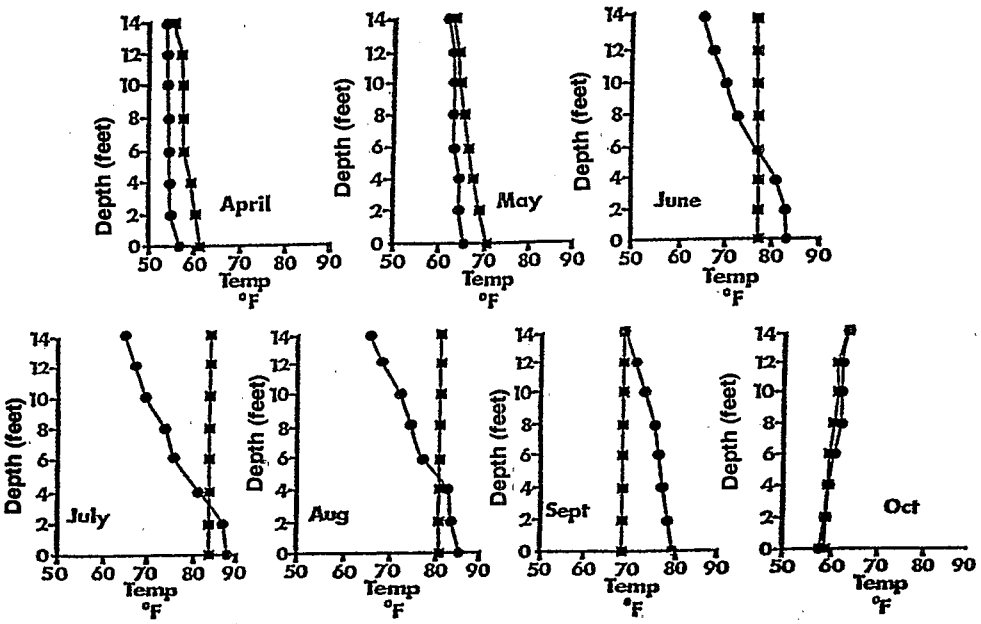

Figure 12-1.—Average mid-month temperature profiles in Cold Springs Lake, 1980-86 (source: Hill, 1987).

The biomass and production of benthic invertebrates was significantly greater ($p \leq 0.05$) during the years of destratification (1981, 1982, 1983, and 1986) than in the years of stratification (1980, 1984, 1985) at both deep and shallow stations (Table 12-5). No significant difference in biomass or production occurred in years when the lake was allowed to stratify.

The biomass and production of benthic invertebrates was significantly greater during the years of destratification than in the years of stratification [and] fish reproductive success increased.

A variety of changes also occurred in the fish community in Cold Springs Lake in response to the destratification/stratification program:

- Fish reproductive success increased. During three of the four years of destratification (aeration), the numbers of age 0+ bluegill were three times higher than during years of stratification. Numbers of age 0+ largemouth bass also were higher during years of destratification than when the lake stratified.

Table 12-5.—Estimate of benthos biomass and benthos production at deep and shallow water sampling stations in Cold Springs Lake, 1980-86 (source: Hill, 1987).

	BIOMASS LB/ACRE (WET WT.)		PRODUCTION LB/ACRE (WET WT.)	
YEAR[1]	SHALLOW	DEEP	SHALLOW	DEEP
1980 (S)	351	436	7,581	7,255
1981 (D)	550*	742*	11,404*	15,173*
1982 (D)	1,013*	696	20,426*	14,034
1983 (D)	1,073	681	21,575	13,731
1984 (S)	475*	393*	10,127*	6,158*
1985 (S)	368	286	7,948	4,684
1986 (D)	590*	715*	12,236*	14,829*

[1] (S) = Stratified (D) = Destratified
* Denotes statistically significant difference with previous year (by station) using a t-test ($p \leq 0.05$)

- Destratification, in general, also increased fish survival rates. The mortality of age 0+ bluegill and largemouth bass decreased in years when the lake was destratified and, conversely, nearly doubled in the following period when the lake was allowed to stratify. In three out of the four years of destratification, bluegill year-classes experienced significantly lower mortality than in stratified years. Age 2+ largemouth bass in all years except for the 1981 year-class also experienced higher mortality during periods of stratification than during years of destratification.

Both bluegill and largemouth bass grew significantly faster during the four years of lake destratification compared to years when the lake stratified.

- Both bluegill and largemouth bass grew significantly faster ($p \leq 0.05$) during the four years of lake destratification compared to years when the lake stratified. Panfish growth rates declined, however, during later years of the aeration program as a result of their increased reproductive success and subsequent increase in panfish density. Bass growth improved in all years of destratification.
- The overall numbers of fish for all species and most age categories were substantially higher after initiation of the aeration program at Cold Springs Lake.
- The expanded environment and increased food supply created by summer destratification in the first two years (1981, 1982) resulted in a significant increase ($p \leq 0.05$) in bluegill biomass relative to 1980 (stratified conditions). Bluegill biomass fluctuated in the remaining years of the study. The fluctuations probably resulted from a combination of (a) increased competition for food with channel catfish, which were stocked at higher rates during this period; (b) stunted growth for some year-classes and years as a result of increased recruitment and crowding; and (c) increased predation by the largemouth bass population.
- Largemouth bass biomass peaked after two years of destratification. Trends in the biomass and growth of largemouth bass and other fish are complicated by the coincident increase in fishing pressure and harvest.

Overall, the aeration/destratification program at Cold Springs Lake resulted in a significant improvement in the fisheries at moderate cost.

The axial pump and installation cost the ICC $1,300 in 1980. The electrical cost for running the pump for one season averaged $150. One unintended impact was a moderate to high plankton bloom continuously from June to September during destratification years. Before destratification, occasional intense algal blooms were followed by a few weeks of clear water.

Overall, the aeration/destratification program at Cold Springs Lake resulted in a significant improvement in the fisheries at moderate cost. Problems with panfish stunting might be better controlled through further refinement of the alternate year stratification/destratification design. During years of stratification, fish are concentrated within the epilimnion, increasing predation and decreasing the sur-

vival rates of small panfish. Thus, the benefits of alternating stratification and destratification are similar to those of periodic water level drawdown (see Chapter 8) without the adverse effects on other lake uses, such as boating and swimming.

Bear Lake, Wisconsin

Problems associated with too many rough fish, stunted panfish, and too few game fish may become self-sustaining as anglers continue to harvest scarce game fish while leaving the abundant, less desirable species to reproduce in excess. The Bear Lake District in northern Wisconsin instituted a fisheries management program to deal with such a problem involving stunted sunfish (pumpkinseed sunfish and bluegills) and the decline of walleye from the 300-acre mesotrophic Bear Lake. In theory, if sunfish densities could be reduced, competition for food in the shallow nearshore areas would decrease and young walleye inhabiting these areas would benefit from improved conditions for feeding and survival. Similarly, the sunfish remaining would have more food available, resulting in faster growth rates and larger sizes. The following overview of the Bear Lake project is summarized from McComas (1988, 1989).

The Bear Lake District in northern Wisconsin instituted a fisheries management program to deal with such a problem involving stunted sunfish (pumpkinseed sunfish and bluegills) and the decline of walleye from the 300-acre mesotrophic Bear Lake.

The Bear Lake project demonstrates how fisheries restoration programs can be promoted and conducted by small groups with a limited budget. A combination of several small-scale projects were implemented: (a) removal of sunfish and bullheads using fyke nets and shoreline seining during spawning time; (b) a volunteer catch and release program for walleye; and (c) continuation of the Wisconsin Department of Natural Resources (DNR) walleye stocking program.

The collection and removal of stunted sunfish and bullheads using fyke nets required the greatest amount of effort. The goal was to remove 8 to 12 pounds of fish per acre of lake surface area each year for three to four years. In support of this project, the Wisconsin DNR granted permits for fish removal and annually loaned 10 fyke nets to the Bear Lake District. Volunteer members from the district ran the nets and counted, measured, and weighed the sunfish and bullheads collected. The sunfish were then transported either to nearby muskie ponds where sunfish provide forage for muskellunges or to nearby Big Bearskin Lake, which had low sunfish numbers (a permit was required), or to a landfill for disposal.

During the first year of netting (1985), the district learned that pumpkinseed spawn first, followed by bluegills. The one week of netting resulted in a catch dominated by pumpkinseed sunfish with only a few bluegills. Consequently, for the remaining years of the program, the netting period was increased to two weeks in June encompassing the end of the pumpkinseed spawning period during the first week and the beginning of the bluegill spawning period in the second week. The first two weeks of June is the period in northern Wisconsin when bluegill and pumpkinseed spawning typically peak.

Fish removal efforts lasted for four years, ending in June 1988. Maintenance removal continued in 1989 and 1991. During that time, over 12,000 pounds of sunfish and bullheads (about 40 lbs/lake surface acre) and over 117,000 fish were removed.

Removing panfish for fisheries improvement is not a new idea. Buchanan et al. (1974) reported, however, that only about 40 percent of the fish removal projects conducted have been successful. The Bear Lake project has many of the characteristics associated with the successful projects described by Buchanan et al. (1974), as follows:

- lake area 300 acres or less,
- lakes with no permanent surface inflow or outflow,
- low fish species diversity,
- few areas of dense macrophyte growth,

- fish removal conducted over multiple years, and
- sunfish removed during their spawning period to disrupt spawning success.

In addition to the fish removal effort, anglers at Bear Lake initiated a catch-and-release program for walleye and every other year, the Wisconsin DNR stocks 15,000 walleye fry or fingerlings. The Wisconsin DNR has also initiated more intensive sampling of the walleye population.

As of early 1993, the response of the fish community and fisheries to these management efforts appears to still be changing, and monitoring to assess the program's success is continuing. Several preliminary observations are encouraging, however.

Data on the length-frequency distributions of bluegill and pumpkinseed sunfish for 1985 to 1988 indicate no dramatic shifts in size. However, anglers on the lake report keeping and eating more sunfish, suggesting an increase in the harvest of larger fish. Walleye have been observed on their old spawning beds. Although this is not necessarily indicative of successful reproduction, walleye had not been observed on these beds since the early 1960s (Table 12.6).

Table 12-6.—Number of gamefish and panfish caught for every fyke net set in Bear Lake.

DATE	WALLEYE	NORTHERN PIKE	LARGEMOUTH BASS	YELLOW PERCH	BLUEGILL	PUMPKIN-SEED	BULL-HEAD
1985*	0.3	0.2	1.9	3.4	131	187	—
1986	0.3	0.4	2.1	1.2	246	145	19
1987	0.5	0.6	0.9	1.0	240	116	17
1988	0.1	0.5	1.7	0.4	188	91	40
1989*	0.2	0.6	4.0	0.4	169	110	35
1991	0.2	1.4	3.5	0.4	343	81	28

* Netting conducted for one week period. Other years netting was conducted for 2 weeks.

The occurance of largemouth bass in test nets has nearly doubled since 1985, the year the sunfish removal began. Walleye were overfished in the 1960s (leading to collapse of the walleye fishery), and largemouth bass appear to have partly filled their niche. Competition by bass, crappie, and other larval fish with walleye for prey and the predation on stocked walleye may contribute to the relatively poor stocking success for walleye in Bear Lake (Fig. 12-2). Because of the increasing dominance by

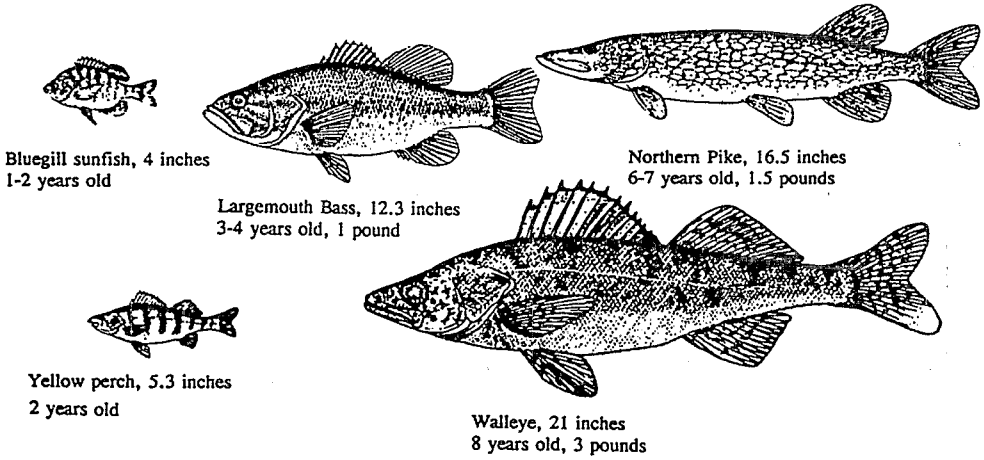

Figure 12-2.—Relationship (to scale) of predator fish and prey fish in Bear Lake. For gamefish to control stunted sunfish (4 inches), a bass must be 12.3 inches; a pike, 16.5 inches; and a walley, 21 inches. This is based on the predator mouth width to prey body depth relationship. A 5.3 inch perch is equivalent to a 4 inch bluegill in regard to what can be swallowed by a gamefish.

largemouth bass, the Bear Lake District members are considering asking the WDNR to shift the fisheries management emphasis from walleye to largemouth bass as the target species. Additional data on the possible recovery of the walleye population will help in this decision.

Water clarity also increased in Bear Lake. In 1977 and 1985, the average summer Secchi depth transparency in Bear Lake was 9.5 feet. By 1986, Secchi depth transparency had increased to 10.3 feet and to over 11 feet in 1987, 1988, 1991, and 1992. Manipulation of the fish community may have contributed to this improvement in water clarity. As noted in Chapters 2 and 9, a decrease in the panfish population would be expected to increase the abundance of large zooplankton, which would in turn decrease the abundance of phytoplankton and increase water clarity. However, while sunfish removal may have helped improve water transparency, the lower than normal precipitation levels in 1987 and 1988 also may be a factor and seem to have improved water transparency in many Wisconsin lakes.

Lake Opeongo, Ontario

Lake Opeongo, with a surface area of 22.6 square miles (about 14,500 acres), is located in southcentral Ontario, Canada. The lake, which rests on Precambrian bedrock, is oligotrophic. Annual surveys of lake trout and smallmouth bass angling catches on Lake Opeongo began in 1936 and have operated continuously. The Lake Opeongo creel survey stands as one of the longest and most complete sources of information on the dynamics of freshwater fish populations in the world. This database was used to examine changes in the annual age-specific growth rates of lake trout 0-8 years old after the 1948 introduction of cisco (Shuter et al. 1987; Matuszek et al. 1990).

In 1939, the introduction of cisco was first suggested as a management technique for Lake Opeongo (Fry, 1939) to improve the food supply of the resident population of lake trout, thus improving the lake trout fishery. Researchers evaluating the lake's survey data were concerned with an apparent slowing of growth when lake trout switched their diet from small yellow perch and lake whitefish to larger prey (Fry, 1949). These surveys also found a high percentage of infertile mature lake trout at the lengths associated with this transition stage (Fry and Kennedy, 1937). The researchers determined that if a deficiency in the lake trout diet was responsible, the introduction of cisco might remedy the situation.

In 1939 the introduction of cisco was first suggested as a management technique for Lake Opeongo to improve the food supply of the resident population of lake trout, thus improving the lake trout fishery.

It took a few years for cisco populations to increase in abundance and become a significant component of the lake trout diet. From 1948 through 1951, cisco were rarely seen in lake trout stomachs. They first appeared in significant numbers in 1952 and rapidly increased until, by 1960, they had become the primary fish food resource for Opeongo lake trout (Fig. 12-3a). Three distinct periods can be identified in the time series trends illustrated in Figure 12-3: 1936-50, the pre-cisco period; 1951-59, the transition period, when cisco increased from a minor component of the lake trout diet to the primary food source for the piscivorous segment of the population; and 1960-79, the period of cisco dominance. As the importance of cisco increased, the frequency of occurrence of yellow perch and lake whitefish, which had previously been major components of the piscivorous lake trout diet, declined. Likewise, the incidence of insects in the stomachs of lake trout during spring also declined (Fig. 12-3b).

It took a few years for cisco populations to increase in abundance and become a significant component of the lake trout diet.

The transition to cisco as the dominant prey resulted in complex changes in lake trout growth patterns (Fig. 12-4). Growth rates for older lake trout aged 6 to 8 years increased rapidly and substantially during the transition period but began to decline gradually after 1960 before leveling off in more recent years. Shifts in the growth rate of lake trout ages 3 to 5 years have been more erratic, with an eventual decline below pre-cisco levels. Growth rates of lake trout ages 1 and 2 decreased continually throughout the transition period years and on into the late 1960s.

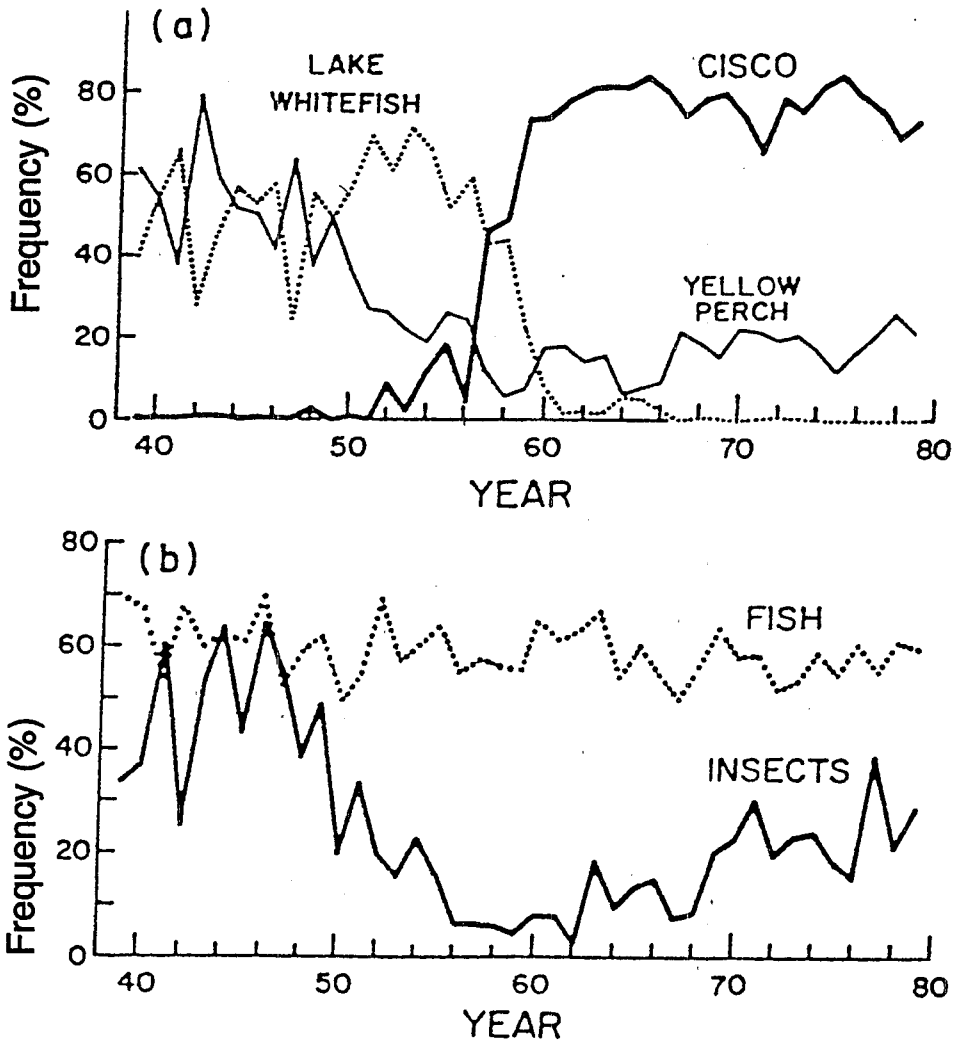

Figure 12-3.—Annual frequency of occurrence of prey types in the stomachs of (a) piscivorous lake trout and (b) all lake trout caught in the Lake Opeongo fishery (source: Matuszek et al. 1990).

The transition to cisco as the dominant prey resulted in complex changes in lake trout growth patterns.

The generally slower growth for all age classes after 1960 is coincident with an increase in the numbers of lake trout in Lake Opeongo. The introduction of cisco resulted in a marked improvement in lake trout reproductive success. Fertility, fecundity, and the abundance of young age classes all increased. As a result of this increased fish abundance, competition for the available food resource, especially among young fish, also increased, resulting in a decline in the growth rate of lake trout ages 1 and 2 and the somewhat erratic patterns for lake trout ages 3 to 5. Older lake trout that feed primarily on fish, however, experienced a net increase in growth. Even though growth rates declined slightly in the 1960s, lake trout ages 6 to 8 in Lake Opeongo still have significantly greater annual growth increments now than prior to the cisco introduction.

The increase in lake trout abundance occurred despite a simultaneous increase in fishing pressure and fish harvest from the lake. The primary benefit of the cisco introduction and lake trout population response was a large increase in the sustainable lake trout yield. The estimated annual maximum sustainable yield increased by about 170 percent, from 0.16 to 0.43 lb/acre (0.18 to 0.48 kg/ha).

The effectiveness of the cisco introduction at increasing lake trout abundance and yield results from several key aspects of the lake trout-cisco, predator-prey interaction as follows:

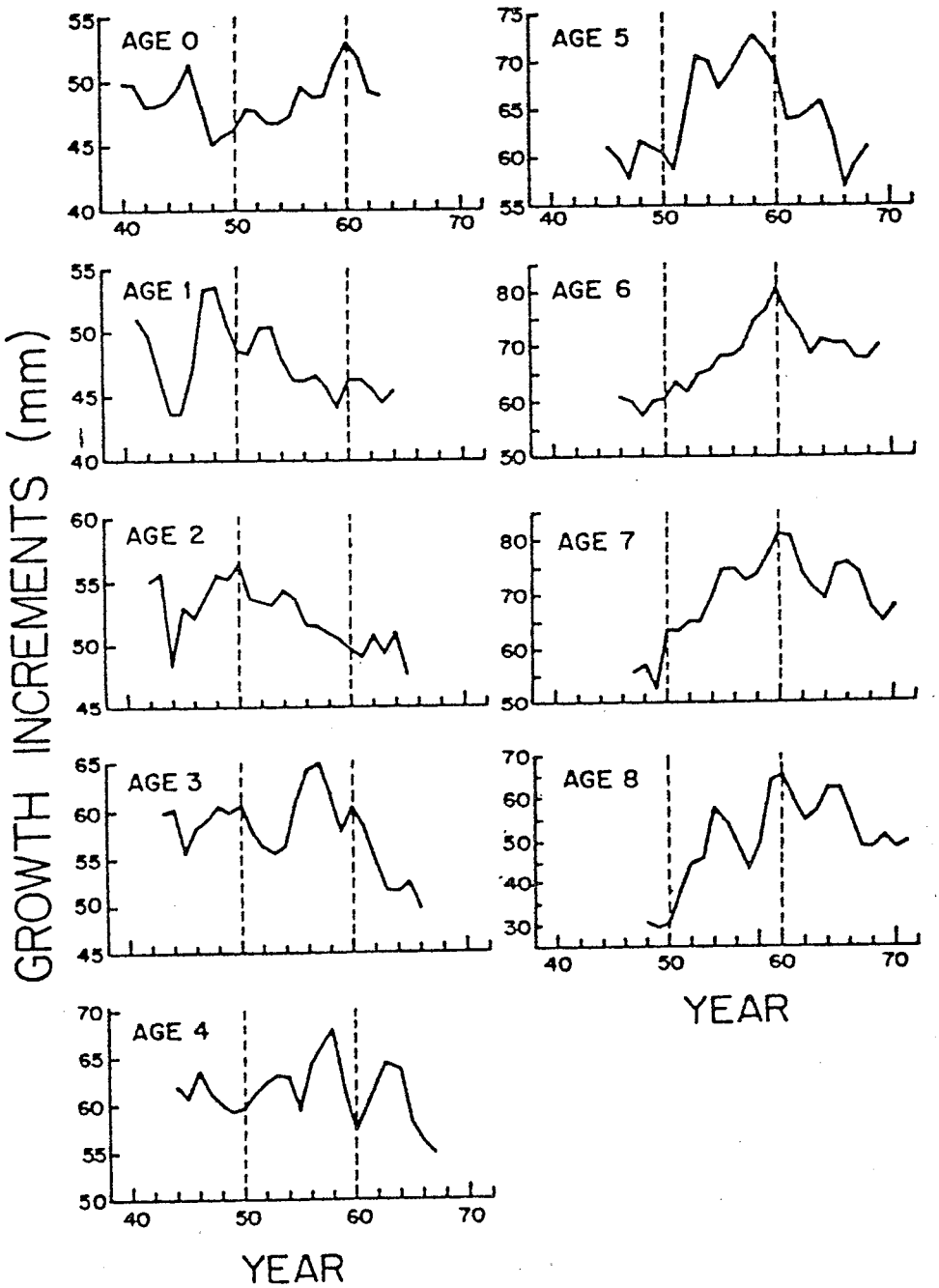

Figure 12-4.—Annual growth increments of lake trout in Lake Opeongo by age class (source: Matuszek et al. 1990).

- Within a lake trout size-class, the ciscoes consumed tend to be larger than the yellow perch that were eaten before the cisco introduction, resulting in a decrease in lake trout foraging costs (the net energy expended searching for and capturing prey) and an increase in growth efficiency (see Chapter 3).
- Lake trout and cisco inhabit the same region of the lake during thermal stratification, while yellow perch do not. Therefore, lake trout encounter ciscoes more frequently during critical growth periods.

The primary benefit of the cisco introduction and lake trout population response was a large increase in the sustainable lake trout yield.

- The introduction of planktivorous ciscoes resulted in an increased transfer of energy from underused zooplankton populations to a fish population (cisco) that could then be efficiently and directly used by the lake trout population.

Although the introduction of cisco into Lake Opeongo had a net positive benefit, one cautionary note deserves mention. In addition to the changes in lake trout population dynamics noted above, the age at which lake trout become sexually mature has increased, while the age at which they are first vulnerable to angler harvest has declined. These combined characteristics create a situation in which significant fishing mortality occurs before sexual maturity is attained. As a result, the population is more sensitive to high fishing pressure and potential overexploitation (Fig. 12-5).

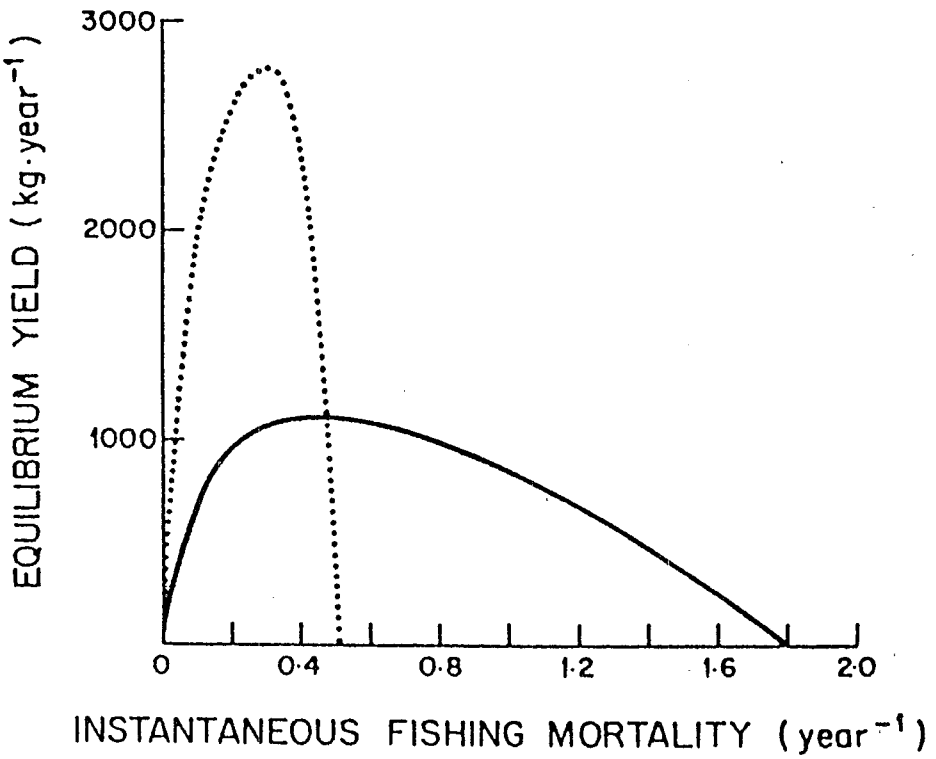

Figure 12-5.—Relationship between simulated equilibrium yield and fishing mortality in Lake Opeongo during the pre-cisco period (solid line) and the period of cisco dominance (dotted line) (source: Matuszek et al. 1990).

Flaming Gorge Reservoir, Utah and Wyoming

Data from Flaming Gorge Reservoir on the Green River in Wyoming and Utah provide an opportunity to review three decades of fisheries management.

Data from Flaming Gorge Reservoir on the Green River in Wyoming and Utah provide an opportunity to review three decades of fisheries management. Flaming Gorge is an especially interesting example because management of the fisheries evolved over time in response to changing conditions in the reservoir as the reservoir aged. Flaming Gorge was originally intended as a rainbow trout fishery and for the first decade provided a productive and successful fishery. However, as this case study documents, fish and creel surveys indicated that changing conditions required a reassessment of management policies. The following paragraphs summarize, by decade, the condition of the fisheries, fishing success, assumptions regarding the reason for fisheries conditions and problems, management actions, and the results stemming from these management actions based on Varley et al. (1971), Wiley et al. (1976), Wengert and Wiley (1990), and Wiley (1991).

Flaming Gorge Reservoir is 91 miles long, stores over 3.7 million acre-feet of water, has a surface area of 42,000 acres, and is characterized by three areas — the Canyon (lower third), Open (middle third), and Inflow (upper third) areas — which have unique topographic, limnological, and fisheries characteristics. Water storage began in 1962, and rainbow trout were introduced almost immediately thereafter. Several thousand catchable rainbow trout were introduced in the fall of 1962. This initial introduction was followed by annual stockings of up to four million (95 per acre) fingerling (3-inch) rainbow trout. Salmonid growth has been best in the Inflow, Open, and Canyon areas, in that order, and each of the areas supports a distinct salmonid stock with different growth and forage qualities.

The 1960s

In the 1960s, the primary emphasis was on a family-type fishery for rainbow trout, which could be caught reasonably easily at a rate of about 0.50 to 0.75 fish per hour. Fish averaged 0.50 to 0.75 pounds each. Approximately three million hatchery-reared fingerlings were stocked annually. Competing nongame fishes appeared in the reservoir during this time, the most numerous being the Utah chub (*Gila atraria*).

The condition of rainbow trout (see Chapter 3 for a discussion of condition factors) declined significantly in 1965, and several hundred dead rainbow trout were discovered in the southern-most half of the reservoir. The cause of the die-off was never completely identified but appeared to be a combination of effects from overstocking and an enormous bloom of the toxic blue-green algae, *Aphanizomenon flos aquae*. Subsequently, stocking rates were reduced by a half to two-thirds, resulting in better fish growth and condition.

Fisheries yields during this decade were calculated at about 20 pounds per acre, remarkable for an inland trout fishery. However, stocks of rainbow trout, measured by gillnetting, appeared to be declining as populations of nongame fish increased.

The condition of rainbow trout declined significantly in 1965, and several hundred dead rainbow trout were discovered in the southern-most half of the reservoir.

Several additional game fish were introduced to the lake during the 1960s. Kokanee salmon were stocked in the early 1960s to provide a pelagic fishery and make use of the extensive zooplankton resource. Kokanee provided only incidental catches during the decade, however. Toward the close of the decade, brown trout were stocked as a piscivorous species that could make use of the burgeoning populations of Utah chubs in the upper quarter of the reservoir and offer a trophy fishery. Smallmouth bass were introduced to provide additional sport fishing diversity but primarily to prey upon expanding populations of Utah chub. Although the successful introduction of smallmouth bass provided a popular but localized fishery, bass growth rates were slow.

The 1970s

During the 1970s, populations of nongame fish continued to expand and flourish, primarily Utah chub and white sucker. Rainbow trout populations and sport fishery returns continued to decline. A shift to stocking larger (5-inch) trout was initiated to improve fish survival and return rates (i.e., the percentage eventually harvested by anglers). The program was only partly successful, however, and gillnet catches of rainbow trout continued to decline.

Brown trout introduced in the late 1960s were very successful; Flaming Gorge became known across the Nation as an excellent fishery for very large brown trout. The North American record was harvested from the reservoir.

Lake trout first appeared in the reservoir during the 1970s, apparently through drift from upstream lakes in Wyoming. Lake trout were harvested infrequently during the decade, as were kokanee salmon.

Threadfin shad from Lake Powell were stocked at the beginning of the decade. The objective was for the shad to compete with the Utah chub for food, depress the size of chubs (because of decreased growth), and provide additional forage fish for rainbow and brown trout. The experiment failed, however, because shad could not survive in the relatively cold water of the reservoir.

The 1980s

Rainbow trout populations continued to decline while Utah chub stocks increased and white sucker stocks remained about the same. Creel rates for rainbow trout declined to less than 0.3 fish per hour, especially in the northern half of the reservoir. Lake trout were caught more frequently and began to replace brown trout as a trophy fish.

The size of rainbow trout stocked was increased to about 8 inches during the decade and has continued into the 1990s. Return rates have increased from 3 percent of the number planted to about 23 percent, about the same level as in the 1960s. However, harvested rainbow trout still did not meet management objectives for the desired size and weight of the angler harvest.

A study of the zooplankton resource was completed during the 1980s. Sites sampled originally in the 1960s were sampled again in the 1980s. Results from these surveys indicated a drastic decline in the abundance of the types and sizes of zooplankton that serve as preferred food for rainbow trout. Zooplankton densities were up to 10 times less than those measured in the 1960s. It was concluded that this reduced abundance of preferred prey had resulted in the poor survival, decreased growth, and low angler returns for rainbow trout observed over the 20-year period from the 1960s to 1980s. Rainbow trout stocked at 8 inches continued to be well represented in the harvest, but were caught by anglers shortly after planting.

Angler interest in trophy lake trout increased through the 1980s. Age-growth analysis showed that lake trout in Flaming Gorge Reservoir reached trophy size more rapidly than in other less temperate, less productive lakes.

Kokanee salmon populations increased gradually during the decade. Spawning populations were documented in several tributaries to the reservoir, the largest in the Green River upstream. Also, some kokanee stocks spawned along the reservoir shore. Gill net and purse seine data suggest that populations of Utah chub and white suckers were at least static and possibly declining.

A study of the zooplankton resource indicated a drastic decline in the abundance of the types and sizes of zooplankton that serve as preferred food for rainbow trout. [T]his reduced abundance of preferred prey had resulted in the poor survival, decreased growth, and low angler returns for rainbow trout observed over the 20-year period from the 1960s to 1980s.

The 1990s

The primary sport fishes of interest have become the lake trout and kokanee salmon, both largely self-sustaining. Rainbow trout continue to be stocked and harvested, but conditions for long-term survival remain difficult because of depressed zooplankton abundance and competing predatory trout and nongame fishes.

The long-term management objectives for Flaming Gorge Reservoir are as follows:

- to discontinue stocking rainbow trout when harvest of kokanee salmon equals or exceeds that of stocked rainbow trout,
- to manage lake trout as a trophy fishery, and
- to manage kokanee salmon as a self-sustaining sport fishery and as alternative (to Utah chub) forage for lake trout.

A primary management tool being used to meet these objectives is regulation of the numbers of trophy lake trout harvested through the use of a "slot" limit: only two lake trout may be taken per day, all lake trout 26 to 36 inches must be released, and only one may exceed 36 inches.

Flathead Lake, Montana

Background

The Flathead Lake restoration program is somewhat unique because of its geographic scale, the comprehensive scope of the management activities, and the number of agencies and people involved. Activities include land use (forestry and agriculture) management, wastewater treatment, water level control, and direct management of the fisheries in the Upper Flathead Basin, including Flathead Lake, its tributaries, and associated watersheds. An ecosystem, whole-basin approach to resource planning and management is being developed for the drainage basin and its fisheries. In fact, one very important consideration in development of the overall management plan for Flathead Lake Basin is the diversity of fish species that reside in the lake and its surrounding tributaries and migrate between the two to spawn. Information on the management plan and program results were summarized from Cross (1987); Flathead Basin Commission (1990); Montana Department of Fish, Wildlife, and Parks and Confederated Salish and Kootenai tribes (1989, 1991); and Montana Power Company (1990).

The Flathead River basin covers 30,880 square miles and comprises the northeasternmost basin of the Columbia River drainage, located primarily in northwestern Montana (Fig. 12-6). The lake is 28 miles long, has a surface area of 20,636 acres, maximum depth of 371 feet, and an average depth of 107 feet, with the upper 10 feet regulated by Kerr Dam. The steep-sided main basin of the lake was formed by glacial scouring of underlying soft sedimentary rock, glacial deposits define the lake's southern boundary, and sediments deposited by the Flathead River modify its northern shoreline.

An ecosystem, whole-basin approach to resource planning and management is being developed for the drainage basin and its fisheries.

Flathead Lake is a relatively cold and unproductive (oligotrophic) lake. Recent water quality studies suggest, however, that potential problems may be developing because of increasing phosphate loads from point sources (primary waste-water treatment plants) plus additional nutrient inputs from nonpoint source runoff from urban, agricultural, and timber harvest areas. Native vegetation and land forms within the watershed have been altered by livestock grazing, agriculture, water diversion and impoundment, logging, mining, and settlement activities. Periodic blooms of blue-green algae (e.g., *Anabaena flos aquae*) also indicate possibly declining water quality and accelerated eutrophication of Flathead Lake.

Additional concerns for management of the lake's fisheries are changes in the hydrologic regime and introductions of nonnative fish species. The annual hydrographic regime of the Flathead system has been modified by the construction and operation of hydroelectric and irrigation dams with significant impacts on kokanee salmon and several species of trout. Native fish assemblages have been altered by the introduction of nonnative fish species, which now dominate parts of the ecosystem and are the management focus for some agencies.

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In 1980, Congress enacted the Pacific Northwest Electric Power Planning and Conservation Act (Public Law 96-501). This act mandated the Northwest Power Planning Council, composed of representatives from Idaho, Montana, Oregon, and Washington, to develop a regional energy plan and a fish and wildlife program for the entire Columbia River basin. In June 1981, the Council asked the American Indian tribes and State and Federal agencies located within the basin to submit recommendations for the fish and wildlife program. In 1983, the Montana legislature enacted the Flathead Basin Commission Act, which established a commission to coordinate agency activities, monitor existing environmental conditions, and provide a common forum for activities associated with the watershed. The Commission includes the 11 State and Federal agencies, the Montana Power Company, the Confederated Salish and Kootenai tribes, and agricultural and other interests.

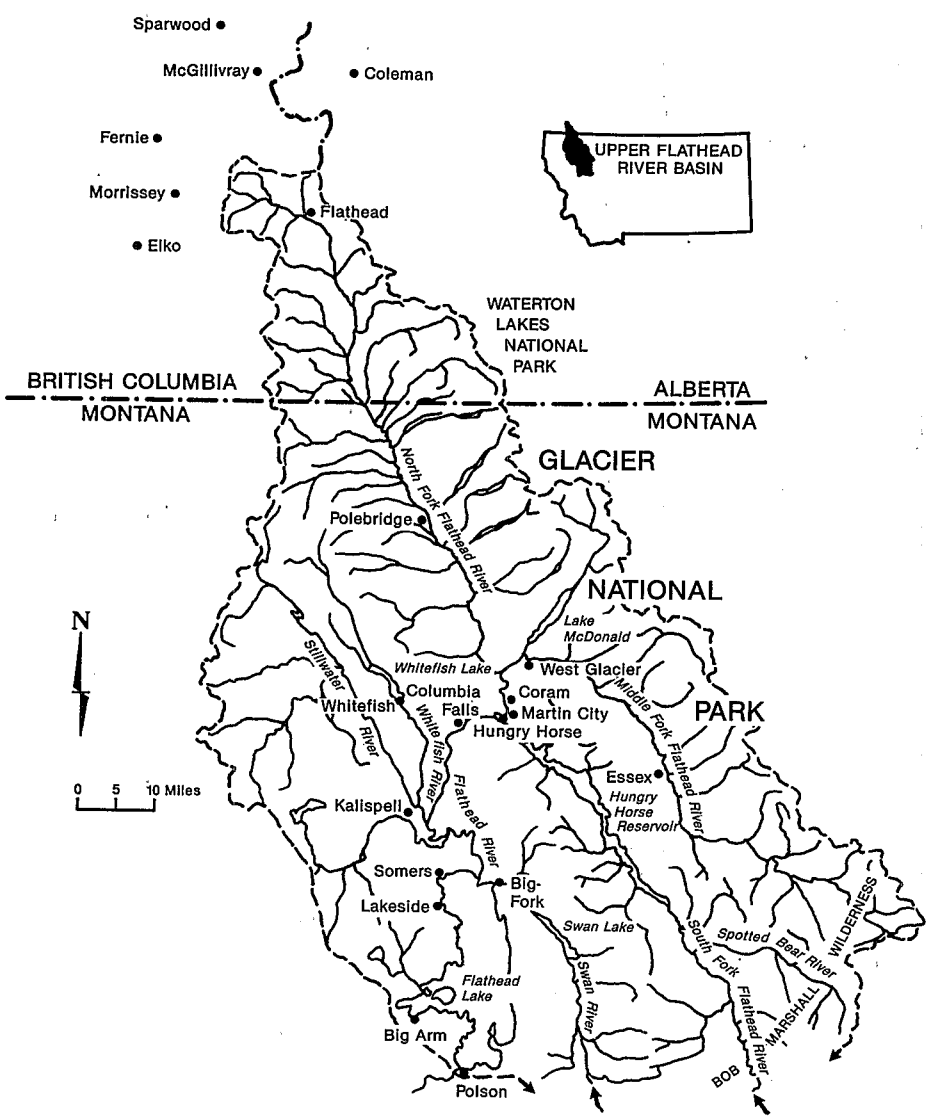

Figure 12-6.—Flathead River Basin above Flathead Lake (source: Montana Dep. Fish, Wildlife, and Parks and Confederated Salish and Kootenai tribes, 1989).

The Fisheries

Twelve game fish species inhabit the Flathead system. Three of these species are native (cutthroat trout, bull trout, and mountain whitefish), while nine are introduced species (lake trout, rainbow trout, lake whitefish, Yellowstone cutthroat trout, brook trout, northern pike, grayling, largemouth bass, and kokanee salmon). With the exception of yellow perch, all of the common nongame fish are native species.

Average fisheries harvest from Flathead Lake consists of 92 percent kokanee salmon, 4 percent yellow perch, 2 percent lake trout and bull trout, and 1 percent cutthroat trout. The average harvest from the mainstem of the Flathead River includes 86 percent kokanee salmon, 10 percent cutthroat, 2 percent bull trout, 2 percent whitefish, and 0.5 percent rainbow trout. Local anglers comprise 73 percent of the total angling population on the lake and 88 percent of the anglers on the river.

In 1987, the kokanee salmon fishery collapsed in the lake. Major factors contributing to this appear to be overharvest, hydroelectric operations, and natural

predation plus the appearance and increasing abundance of opossum shrimp (*Mysis relicta*) in Flathead Lake. *Mysis* prey mainly on crustacean zooplankton, including *Daphnia*, which also are the primary prey for kokanee salmon. The presence of *Mysis* in this system now complicates efforts to manage kokanee and is likely to increase management costs for the species.

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Water Quality

The average annual primary production of phytoplankton in Flathead Lake has increased significantly since 1977 (Fig. 12-7), suggesting that nutrient concentrations (phosphorus and nitrogen) in the Flathead Lake drainage are becoming elevated above natural baseline levels. This trend of increased algal productivity, however, may also relate to changes in the food web resulting from increasing populations of Mysis. Additional monitoring data and analyses are needed to better clarify the relative importance of these factors in causing productivity changes.

The average annual primary production of phytoplankton in Flathead Lake has increased significantly since 1977 . . . . .

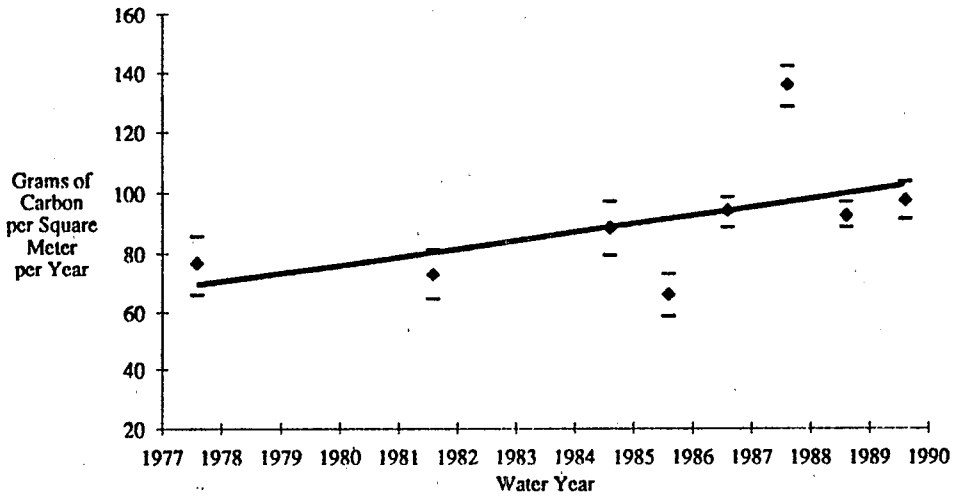

Figure 12-7.—Annual primary production in the water column of Flathead Lake, 1977 to 1990 water years (source: Flathead Basin Commission, 1990).

Wastewaters are believed to be major sources of phosphorus entering Flathead Lake. Primary wastewater sources to the lake include discharges from municipal treatment facilities in Kalispell, Whitefish, Columbia Falls, and Big Fork upstream from Flathead Lake. Also, other unincorporated areas and many individual homes have not been included in any of the combined collection and treatment systems. In attempts to reduce contributions from these latter sources, the Flathead Basin Commission has promoted improved public understanding of the present and potential water pollution problems related to continued use of home septic tank systems. Also, it continues to encourage and support improvements in municipal waste treatment systems throughout the basin. Permit limits for phosphorus at the wastewater treatment facilities and other point sources have been restricted to 1.0 mg/L. Additionally, a phosphate detergent ban has been implemented for the Flathead Basin. However, although these nutrient reduction programs appear to be working, they have not been operating long enough for effects to be documented.

[T]he Flathead Basin Commission has promoted improved public understanding of the present and potential water pollution problems related to continued use of home septic tank systems.

In addition to these point sources, an estimated 75 percent of the total phosphorus entering Flathead Lake originates from nonpoint sources and activities in the watershed that increase the runoff of sediments into the lake. Activities of

special concern include road building, poor logging or agricultural practices, resource extraction, and other land developments that can increase surface runoff volumes and sediment movement.

Timber harvest is a major activity in the Upper Flathead Basin. While modern forest practices can help reduce stream damages, cumulative effects of timber removal have increased water and sediment yields to excessively high levels in some drainages, particularly in watersheds where there is mixed public and private ownership and little coordination of management activities. Road construction accompanying logging activities can also physically alter streams at crossing points, causing erosion and fish migration barriers if crossings are improperly completed. Timber harvest is of particular concern because it often occurs in the upper reaches of watersheds that provide critical spawning and rearing habitat for cutthroat and bull trout.

Several efforts are underway to mitigate the effects of logging on fisheries in the Upper Flathead Basin. The Flathead National Forest has adopted a forest plan that sets objectives for maintaining fish populations, water quality, and physical habitat. Several field research and modeling efforts are underway to determine whether these and related objectives are not only appropriate but also being achieved. In addition, timber sales in critical areas for fish populations are reviewed by the Montana Department of Fish, Wildlife, and Parks, the Confederated Salish and Kootenai tribes, and the Flathead National Forest.

In addition to promoting forestry and agriculture best management practices, both State and Federal agencies are continuing to annually review 250 to 300 land use projects within their jurisdiction that could physically alter stream or lake habitats. These reviews attempt to eliminate projects or mitigate damage to aquatic habitat.

In addition to promoting forestry and agriculture best management practices, both State and Federal agencies are continuing to annually review 250 to 300 land use projects within their jurisdiction that could physically alter stream or lake habitats.

Hydroelectric Developments

Development and operation of three hydroelectric dams have had a profound effect on the Flathead fisheries. Hungry Horse Dam blocks access to 42 percent of the traditional cutthroat and bull trout spawning grounds in the South Fork of the Flathead, while Bigfork Dam has eliminated or restricted access to an additional 18 percent of the spawning areas in the Swan drainage. Erratic flow releases from Hungry Horse Dam have nearly eliminated kokanee salmon spawning in the main Flathead River. Kerr Dam, which controls the upper 10 feet of Flathead Lake, adversely affects food production and fish spawning around the lakeshore and has essentially eliminated most kokanee shoreline spawning from Flathead Lake. In addition, water level fluctuations have increased erosion of not only the lakeshore but also streambanks of the Flathead River for 22 miles above the lake.

The Northwest Power Planning Act passed in 1980 directed the Bonneville Power Administration and associated electric utilities to document and mitigate impacts to fish and wildlife from the construction and operation of hydroelectric projects in the Columbia River drainage. Studies in the Flathead system have focused on impacts to cutthroat and bull trout, kokanee salmon, and yellow perch. A mitigation plan for Kerr Dam has been developed by the Montana Power Company under a relicensing provision by the Federal Energy Regulatory Commission. Fisheries mitigation plans to compensate for losses attributed to the construction and operation of Hungry Horse Dam have been completed by the Montana Department of Fish, Wildlife, and Parks and the Confederated Salish and Kootenai tribes. Operational changes, including minimum releases from Kerr and Hungry Horse dams, have been recommended. However, because optimal flow for fisheries is not possible given the demands placed by hydroelectric generation and because of fisheries losses unrelated to current operations regimes, other mitigation measures are required, including

- improving fish access to spawning grounds,
- additional stocking of hatchery fish,

- construction and operation of a small-scale hatchery,
- acquisition and enhancement of off-site habitat, and
- construction of a gravel beach dike to control shoreline erosion on the north shore of Flathead Lake caused by wave action during periods of full lake levels.

In addition, Pacific Power and Light will evaluate the feasibility of changing the design and operation of a fish ladder on Bigfork Dam to facilitate fish migration to Swan River. Unfortunately, the degree of regulation possible for dam discharges at Kerr Reservoir will be inadequate to totally eliminate impacts on the fisheries in Flathead Lake.

Many small hydroelectric projects were proposed in the Upper Flathead System in the early 1980s. Because of changes in hydroelectric rates and present policies, most of these proposals have been dropped; nevertheless, a number of other small dams constructed for irrigation continue to have localized but cumulative effects on fisheries. The Northwest Power Planning Council has adopted a Protected Areas Program that effectively bans new hydroelectric development on critical stream reaches used for spawning or as nursery areas for young fish. This program should significantly reduce the potential for new impacts on western Montana fisheries from hydroelectric developments.

Water Quantity

Maintenance of the Flathead drainage fisheries depends on maintaining adequate amounts of water in the streams and reservoirs to allow for spawning, rearing, and feeding. In addition to the considerations discussed previously for securing flows from existing hydroelectric reservoirs, management strategies planned to maintain appropriate water flow include

- negotiation and purchase to secure water rights to supplement flows for the best trout streams,
- purchases of additional water stored in area lakes from local irrigation districts to maintain fish and wildlife habitat and dilute wastewater treatment waters from Kalispell treatment plant, and
- maintenance of in-stream flows in the drainage by reviewing water right applications and other water development projects.

Fisheries Management

Past management of fisheries in Flathead Lake and the upper river system has centered around the maintenance of wild, self-sustaining fish populations. Much effort has also focused on protecting and expanding the critical habitat for native cutthroat and bull trout, two species of special management concern in Montana. In addition, the public has exerted considerable pressure to restore the kokanee salmon fishery or develop some comparable replacement fishery.

Three primary fisheries goals established by the Montana Department of Fish, Wildlife, and Parks and the Confederated Salish and Kootenai tribes guide fisheries management in the Flathead Basin, with the lake, river, and tributaries now managed as a single, interconnected system.

1. Populations of native fish species living in the basin will be preserved, protected, and enhanced. Species of special concern, such as bull trout and westslope cutthroat trout, shall receive top priority for protection activities.

Populations of native fish species living in the basin will be preserved, protected, and enhanced.

2. A diverse recreational fisheries will be maintained in the Flathead Basin to provide a variety of opportunities for fishing during all seasons of the year for a variety of fish species and sizes, with trophy, sport, and harvest-oriented fishing available to the angler.

3. The existing water quality and aquatic habitat will be maintained or enhanced.

Individual species management plans have been developed for 10 species of game fish, including bull trout, westslope cutthroat trout, kokanee salmon, lake trout, yellow perch, lake whitefish, mountain whitefish, rainbow trout, northern pike, and largemouth bass. These management plans emphasize development of naturally reproducing wild stocks of a diverse array of species. The highest priority in the management plan is to ensure the survival and genetic integrity of native bull and westslope cutthroat trout populations. Table 12-7 summarizes the individual fishery management issues, goals, and strategies for 8 of the 10 target species. (Northern pike and largemouth bass were excluded because of their relative unimportance in the overall fisheries plan for the Upper Flathead Basin.)

With the collapse of the kokanee salmon fishery, other fisheries will receive increased angler interest and will have to provide a larger share of the annual harvest. Therefore, several game fish species will receive supplemental stocking until natural populations are sufficiently abundant and natural reproduction can sustain the increased harvest pressure.

The fisheries management program is integrally tied to the water quality and habitat improvement programs; thus, population increases may occur for a number of formerly less abundant fish species. To date, only preliminary data are available to assess the benefits of these restoration efforts, but this information is encouraging. Substantive data to evaluate the success of these efforts will probably not be available until 1994—the last year of this management cycle.

Lake Washington, Washington

Lake Washington is one of the best known examples of recovery from cultural eutrophication.

Lake Washington is one of the best known examples of recovery from cultural eutrophication. Over the last 30 years, it has reverted from a eutrophic lake to its more natural mesotrophic-oligotrophic condition. Located adjacent to Seattle (Fig. 12-8), Lake Washington (area, 33.6 square miles; maximum depth, 213 feet) provides a diversity of fishing and other recreational opportunities. The following paragraphs provide a brief summary of eutrophication control efforts and the role of fish in lake improvements as compiled from Eggers et al. (1978), Edmondson (1979), Edmondson and Lehman (1981), Edmondson and Litt (1982), Edmondson and Abella (1988), Swartzman and Beauchamp (1990), and the National Research Council (1991).

Lake Washington was first affected by raw and treated sewage from Seattle in the early 1900s; however, diversion of Seattle's effluent from the lake to Puget Sound in the mid-1930s ended this initial period of pollution. Water pollution problems in the lake again became apparent in the 1940s, when suburban growth from Seattle spread along the lakeshore north and south of the city. By 1955, the first bloom of the blue-green alga, *Oscillatoria rubescens*, was observed. By 1963, effluents from 11 sewage treatment plants were being discharged into the lake or its tributaries, contributing 63 percent of its total phosphorus load.

Diversion of this sewage effluent away from Lake Washington began in 1963; by March 1967, 99 percent of the sewage effluent had been diverted. Phosphorus inputs dropped from a high of about 450,000 lb/yr (204,000 kg/yr) in 1964 to a low of 95 lb/year (43 kg/yr) in 1973 and 1976. The lake promptly responded with decreases in nutrient concentrations, phytoplankton abundance, and the proportion of blue-green algae in the phytoplankton community (Fig. 12-9). Secchi disk

Table 12-7.—Individual species management concerns, objectives, and strategies for the Flathead Basin (compiled from Montana Dep. Fish, Wildlife, and Parks and Confederated Salish and Kotenai tribes, 1989).

SPECIES	MANAGEMENT ISSUES	MANAGEMENT OBJECTIVES	MANAGEMENT STRATEGIES
Bull trout	• International coordination required; some fish spawn in British Columbia • Very sensitive to streambed habitat degradation and angling pressure • Predatory fish that may compete with lake trout and may also eat cutthroat trout • Hatchery production is experimental; return rate to creel is unknown • Genetic integrity of native population high priority	• Increase use and harvest by 20 to 25 percent • Increase levels of spawning fish beyond existing counts in most productive tributaries	• Increase enforcement activities in spawning areas and at the river mouth fishery • Increase agency coordination and habitat monitoring; increase available spawning and rearing habitat by opening blocked areas • Plant 260,000, 8" bull trout directly into Flathead Lake through an experimental hatchery program • If hatchery program is successful in increasing population, daily bag limit may be increased. If population doesn't respond, shorten angling season for river or close additional spawning streams from fishing • Encourage voluntary catch and release through public education campaign
Westslope cutthroat trout	• Maintenance of genetic purity and diversity of stocks • Spawning and rearing habitat threatened • Very vulnerable to anglers in rivers; requires suitable catch restrictions • Difficult to monitor populations in lake and river • Substantial fishing pressure increase possible with loss of kokanee salmon fishery	• Increase harvest and use of cutthroat by 20 percent • Increase populations substantially to buffer impact of increased harvest	• Improve fish passage in blocked areas. Increase agency coordination, habitat protection, and monitoring • Increase enforcement to ensure compliance with fishing regulations • Stock Flathead Lake with 1 million 4- to 6-inch fish annually • Initially set lakewide daily limit of 2 to standardize limit and prevent over harvest until hatchery fish enter fishery. Limits increased if plants successful. Tailor other restrictions for other sections of watershed • Encourage voluntary catch and release with education program
Kokanee salmon	• Impact of *Mysis* shrimp on survival of kokanee • Spawning areas greatly reduced because of hydroelectric operations • Hatchery facilities inadequate to producenecessary egg supplies; costly and time-consuming to remedy • Plants of fingerlings experimental; success unknown • Lake trout predation may limit kokanee recovery	• Restore kokanee population to levels required to sustain a harvest of 60,000 fish/15,000 angler days (small fraction of pre-crash harvest)	• Continue annual experimental stocking of 3-5 million fish, which may produce 60,000 adults • Continue current management efforts to protect kokanee in lake and river system (size, catch, and season limits)

continued on next page

Table 12-7—Continued

SPECIES	MANAGEMENT ISSUES	MANAGEMENT OBJECTIVES	MANAGEMENT STRATEGY
Lake trout	• Maintain trophy segment of population in spite of loss of kokanee food base • Limit overharvest of fish that take 15 years to reach trophy size • Potential for increased predation on kokanee if lake trout population increases • Competition with other large predators (bull trout) if favored prey (kokanee) decreases	• Maintain trophy fishery • Reduce overall lake trout biomass by increasing harvest of small fish • Increase angler use to 15,000 angler days/year; harvest to 8,000 fish/year	• Public education program on methods to catch smaller (3-8 lb) lake trout • Survey public; modify regulations. Options include increase in size limit, a slot limit, increase in daily bag limit, or some combination.
Yellow perch	• Receives little management attention despite occupying portion of lake underused by other game fish and anglers • Not classified as game fish; no harvest restrictions • Yellow perch populations expanding in warmer, shallower portion of lake	• Increase harvest to 100,000 fish annually; maintain catch rate and average length	• Provide better public access for anglers to portion of lake occupied by yellow perch • Increase public awareness of fishing opportunities for yellow perch • Develop fishing guide describing fishing techniques, seasons, and locations • Introduce artificial structural enhancement to provide structural diversity at low pool to improve recruitment and minimize overwinter predation
Lake whitefish	• Lake whitefish may compete with other species for zooplankton forage (i.e., kokanee and westslope cutthroat) • Underused by anglers despite good fishing experience and taste qualities	• Increase use to 10,000 angler days/year and harvest to 20,000 fish/year	• Publicize fishing quality, fishing techniques, locations, and seasons in the lake through brochures and the media
Mountain whitefish	• Greatly underused relative to abundance; small average size discourages more harvest • May compete for food and space with other game fish that are more popular with anglers	• Increase use and harvest to 10,000 fish/year	• Publicize fishing techniques, seasons, locations, and cooking tips through brochures and the media
Rainbow trout	• May compete for food and space with native cutthroat trout • May hybridize with westslope cutthroat trout, reducing genetic integrity of native stocks • Returns from past plants have been poor	• Increase use and harvest to 1,000 fish/year	• Publicize identification of rainbow and cutthroat trout, encourage angler harvest of rainbow and voluntary catch and release of cutthroat

transparency increased from about 3 to 13 feet (1 to 4 meters), total phosphorus decreased from 70 to 16 μg/L, and epilimnetic chlorophyll decreased from 35 to 4 μg/L. By 1975, the lake was considered to have largely recovered from eutrophication.

Lake Washington supports about 30 species of fish, many of them introduced. Fisheries management concerns focus on interactions among four species:

1. **Rainbow trout.** Introduced into the lake in 1981, this species is stocked annually (average 250,000 young fish stocked per year).
2. **Juvenile sockeye salmon.** This species resides in the lake for about 15 months before migrating to sea.
3. **Northern squawfish (*Ptychocheilus oregonensis*).** Native to Lake Washington, these voracious piscivores feed heavily on juvenile sockeye salmon but are not an important game or sport fish.
4. **Longfin smelt (*Spirinchus thaleichthys*).** This species currently dominates the pelagic zone of the lake along with juvenile sockeye salmon.

Rainbow trout support a put, grow, and take fishery that averages 20,000 angler-caught fish per year. In addition, Lake Washington has the largest sockeye salmon run in the State of Washington, supporting a commercial and sport fishery that averaged about 80,000 adults per year from 1971 to 1984.

Changes in Lake Washington's water quality have continued to occur since 1975 and are attributed largely to changes in the fish and zooplankton communities in combination with reduced nutrient loads. In 1976, *Daphnia* (which had occurred in the lake only sporadically and in modest numbers) suddenly became the dominant zooplankton (Fig. 12-10). Coincidently, the mean summer transparency doubled (Fig. 12-11). Secchi disk transparency had increased from about 3 to 13 feet (1 to 4 meters) in response to nutrient diversions in the 1960s but increased even further to approximately 23 feet (7 meters) in the late 1970s in response to the explosion in the *Daphnia* population. The effects of *Daphnia* on phytoplankton abundance and composition and indirectly on water transparency are well documented (see Chapter 9).

Two factors contributed to the increased abundance of *Daphnia*: a sharp decrease in the abundance of the predatory zooplankton *Neomysis mercedis* in the mid-1960s and a decrease in the abundance of *Oscillatoria*, a filamentous blue-green algae, in 1975. The reduction in *Neomysis* was caused, most likely, by an increase in the abundance of longfin smelt, a planktivore that feeds selectively on this zooplankton. (During 1962-64, *Neomysis* accounted for 85 percent of smelt gut contents.) Although native to the system, before 1960 longfin smelt were quite rare. Increases during the 1960s were attributed primarily to the following physical improvements in smelt spawning habitat in Cedar River, the major tributary to Lake Washington: cessation of the annual stream dredging program, installation of shoreline stabilization structures (banks of large stones), and initiation of low flow regulations.

Although the *Neomysis* population declined in the mid-1960s, increases in *Daphnia* did not occur until 1975. Thus, the decrease in *Neomysis*, although essential, was not sufficient in itself to permit *Daphnia* to flourish. As long as *Oscillatoria* were abundant, *Daphnia* remained scarce. The mechanical interference of *Oscillatoria* with *Daphnia* feeding is considered the most likely cause for the delayed success of *Daphnia*. As noted above, the decline in *Oscillatoria* and other blue-greens (see Fig. 12-9) was a direct result of sewage diversions and reduced nutrient inputs.

The introduction of rainbow trout into Lake Washington in 1981 raised concerns about adverse effects on both *Daphnia* and sockeye salmon. Rainbow trout have elastic feeding habits that range from planktivory and benthic feeding to

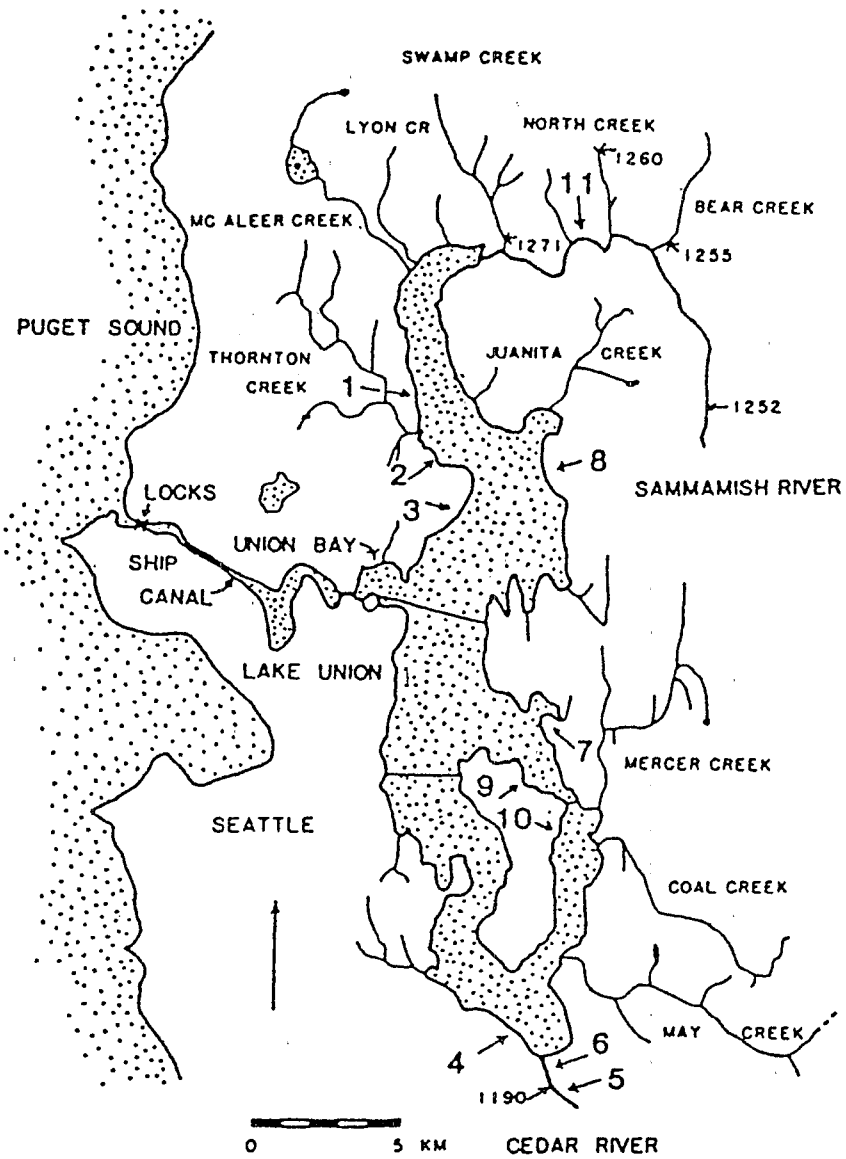

Figure 12-8.—Lake Washington and its tributaries. Arrows numbered 1–11 show sewage treatment plants. Four-digit numbers are U.S. Geological Survey gauging stations (source: Edmondson and Lehman, 1991).

piscivory; their diet depends primarily on prey availability. Bioenergetics models were developed to evaluate the interactions among rainbow trout, sockeye salmon, longfin smelt, *Daphnia*, and other species (see Fig. 11-12 in Chapter 11). Model results suggest that an increase in rainbow trout abundance as a result of either increased stocking (by 10-fold) or decreased fishing pressure (by 50 percent), could decrease (by 50 percent or more) the abundance of both sockeye salmon and longfin smelt. Although not explicitly modeled, increases in rainbow trout could also depress populations of *Daphnia*, an important prey for young trout, and potentially reverse recent improvements in water transparency.

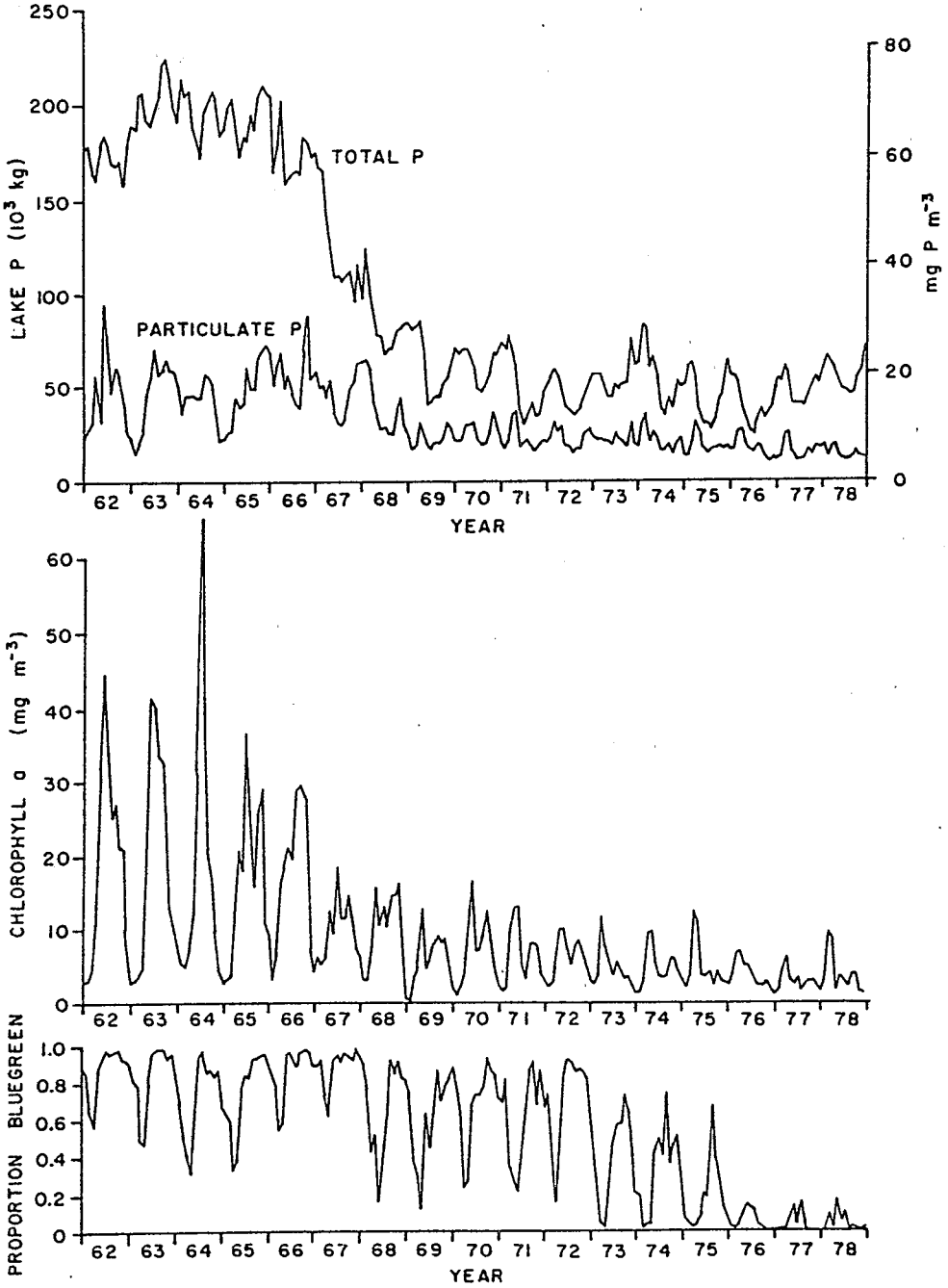

Figure 12-9.—Total mass of phosphorus (P) and of particulate P in Lake Washington plotted by months, concentrations of chlorophyll *a* in surface samples, and proportion of total phytoplankton biomass represented by filamentous blue-green algae in surface samples (source: Edmonson and Lehman, 1981).

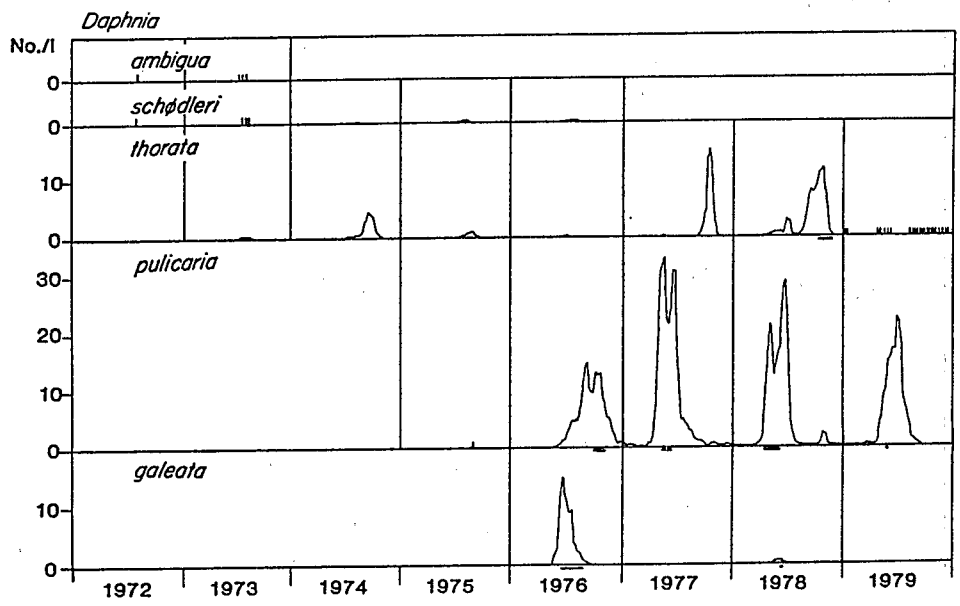

Figure 12-10.—Abundance of various species of *Daphnia* in the top 10 meters of Lake Washington from 1972-79. Bars above baseline indicate presence of males, ephippia (egg cases), or both (source: Edmondson and Litt, 1982).

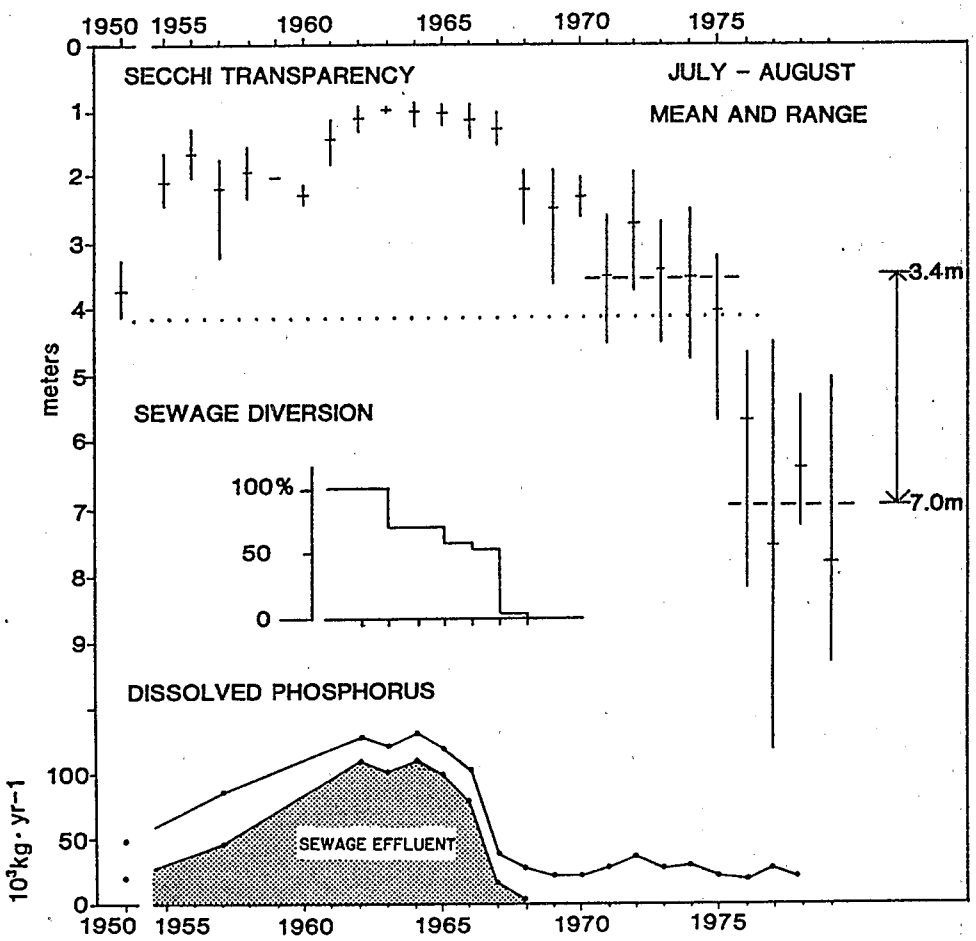

Figure 12-11.—Mean and range of summer Secchi disk transparency for each year (mean values for 1971-75 and 1976-79 shown to the right); schedule for diversion of sewage effluent; and total loading rate of dissolved phosphorus and loading rate contained in sewage effluent (source: Edmondson and Litt, 1982).

APPENDIX A

Background Information on Selected Fish Species

Appendix Objective

This appendix contains brief descriptions of the habitat requirements and management concerns for selected fish species widely distributed in lakes and reservoirs in the United States and Canada. Its objective is to provide introductory information that can assist managers in selecting target species, evaluating lake problems, and designing a fish or fisheries management program. A number of good reference books are available for further details as well as information on species not covered in this appendix. General reference books include Scott and Crossman (1973), Carlander (1969, 1977), Kendall (1978), Nelson (1984), and Hocutt and Wiley (1986). Region-specific fish guides have also been prepared for many States and geographic areas (e.g., Becker, 1983; Manooch, 1984; Miller et al. 1982; Robinson and Buchanan, 1988; Sigler and Sigler, 1987; Smith, 1985; Sublette et al. 1990; Tomelleri and Eberle, 1990; Trautman, 1981; and Wydoski and Whitney, 1979). In addition, many State agencies prepare species-specific management plans that include basic information on fish biology and habitat needs (e.g., Minn. Dep. Nat. Resour. 1982; La. Dep. Wildl. Fish. 1990; Me. Dep. Inland Fish. Wildl. 1986). The information summarized here is extracted from Scott and Crossman (1973) and Carlander (1969, 1977) as well as the other references noted for each species or fish group.

Threatened and Endangered Species

Special care and management approaches are needed for fish species or strains classified as threatened or endangered. Most States and provinces regularly publish and update lists of threatened and endangered species as well as species or strains of special concern. Williams et al. (1988, 1989), Johnson (1987), and Ono et al. (1983) review threatened and endangered fish species in broader geographic areas. The occurrence — or potential occurrence — of protected or rare species must be carefully assessed before any lake management activities are initiated.

Special care and management approaches are needed for fish species or strains classified as threatened or endangered.

Largemouth Bass, Smallmouth Bass, and Spotted Bass

Largemouth bass (*Micropterus salmoides*), smallmouth bass (*M. dolomieu*), and spotted bass (*M. punctulatus*) are all important game fish. Largemouth bass, in particular, are widely distributed throughout much of the United States and Canada, the primary game fish managed in many warmwater lakes and reservoirs, and often the focus of fishing tournaments. Two subspecies are recognized: the northern largemouth bass, *M. salmoides salmoides*, and the Florida largemouth bass, *M. salmoides floridanus*. Spotted bass are native to the southcentral United States, but have been introduced into California, Nebraska, South Carolina, and several other States. Smallmouth bass occurred originally from southern Canada as far south as Oklahoma and Alabama, although they have also been widely introduced in other areas. All three black bass species have a number of common habitat needs and management concerns.

Largemouth bass . . . occur most often in the upper levels (warmer waters) of small, shallow lakes or shallow bays of larger lakes, in association with soft bottoms, stumps, and extensive growths of emergent and submergent aquatic vegetation.

Habitats

Largemouth bass are highly adaptable to a wide range of environmental conditions and inhabit a variety of aquatic habitats. They occur most often in the upper levels (warmer waters) of small, shallow lakes or shallow bays of larger lakes, in association with soft bottoms, stumps, and extensive growths of emergent and submergent aquatic vegetation. They can tolerate moderate turbidity and warm water temperatures (up to 97°F if fish are acclimated to warmer water). Preferred summer temperatures are in the upper 70s(°F), while feeding is restricted below 50°F. Florida largemouth bass and spotted bass are less tolerant of low temperatures than are northern largemouth, while smallmouth bass prefer slightly cooler waters (preferred temperature range in the low 70s(°F) during summer). Both smallmouth and spotted bass are also less tolerant of high turbidity and prefer waters with firmer substrate (e.g., rocky or gravel substrate) than largemouth bass.

Reproduction

All three species spawn in the late spring, early summer. Spawning is keyed primarily to water temperature, rather than a specific date, and therefore generally progresses from south to north following the seasonal warming trend. Spawning begins as temperatures reach around 55° to 60°F, and activity peaks at 65° to 70°F for largemouth and spotted bass and 61° to 65°F for smallmouth bass.

The male develops the nest site and guards the eggs and schools of fry for several weeks after emergence. In lakes and reservoirs, nests are usually constructed at water depths of 1 to 4 feet but can occur as deep as 15 feet. The depth selected in any given lake can vary directly with water clarity. Largemouth bass reproduce successfully on almost any type of bottom as long as a firm, silt-free nest bed can be created; sites with rocky or gravelly substrate and adequate cover, in the form of logs, stumps, or vegetation, are preferred. Smallmouth bass and spotted bass, on the other hand, reproduce successfully only in waters with suitable areas of shoreline gravel or rocky substrate for nest construction. For all three species, reproductive success may be reduced by sudden drops in temperature or water level, high winds and wave action, heavy predation on eggs and fry by other fish (e.g., sunfish), or silt deposits on the eggs after a heavy rainfall.

Adult bass feed primarily on forage fishes, such as sunfish and shad, and are top predators in most waters.

Food Habits

Adult bass feed primarily on forage fishes, such as sunfish and shad, and are top predators in most waters. Crayfish are also often an important component of adult diets. Fry feed primarily on zooplankton, while fingerlings feed on aquatic insects and other small organisms. All three species become piscivorous at a fairly young age and small size (when individuals reach about four inches in length).

Management Concerns

Black bass are "net shy" and difficult to sample quantitatively with gill nets, trap nets, or other nets commonly employed to sample fish in lakes. Better information can be obtained using one or more of the following:

- night electrofishing,
- seining, especially for adult bass in the spring or young-of-the-year bass later in the year,
- angler reports and creel censuses, and
- visual observations of male bass on spawning beds in the spring.

Common problems encountered in largemouth bass management include the following:

- **Inadequate forage.** Other predators, such as walleye and northern pike, may compete with bass for forage fish. If forage is scarce and bass are considered the primary target fish of interest, stocking of other predators should be reduced or discontinued and other control measures considered. Stocking of forage fish is unlikely to be effective.

- **High predator population.** Northern pike may, in some cases, consume excessive numbers of young, small bass. Methods for controlling or eliminating northern pike may be worth considering in these instances.

- **Habitat degradation.** The shallow, fairly productive lakes generally inhabited by largemouth bass may be subject to periodic oxygen depletion (e.g., winterkill) and eutrophication. Methods for countering these problems were discussed in Chapter 8. If the entire population of bass is lost from winterkill, for example, the easiest methods for reintroducing the species are (a) transplants of sexually mature fish from other nearby waters or (b) stocking of fry, collected at the time of swim-up. Aquatic vegetation provides essential cover for young bass; watershed or lake disturbances that markedly reduce the extent of macrophyte beds can also be detrimental to largemouth bass populations.

- **Inadequate natural reproduction.** Largemouth bass have a high reproductive potential and insufficient natural reproduction is seldom a problem. If maintenance stocking is necessary to provide a bass fishery, managing the lake for bass is probably not cost effective nor appropriate. Poor year classes can occur, however, because of sudden changes in water temperature during spawning, excessive wind and wave action, or limited availability of food for newly rising fry. Heavy cannibalism of older bass on young-of-the-year bass can also occur in waters with high fish density.

- **Fishing pressure.** High fishing pressure generally does not significantly reduce bass reproduction and recruitment but can result in a decline in fishing quality. Large harvests of fish greater than some minimum size limit (e.g., longer than 12 inches) also can adversely affect the predator/prey balance by decreasing bass predation on other smaller fish, increasing the possibility of a stunted panfish population. Slot length limits may be one possible solution to excessive harvests of larger fish.

Management concerns for smallmouth and spotted bass are generally similar. However, spotted bass tend to grow slower and to have shorter life spans (often, few fish live longer than three years) than largemouth bass, requiring quite different length limits and other fishing regulations for optimal fisheries management.

Aquatic vegetation provides essential cover for young bass; watershed or lake disturbances that markedly reduce the extent of macrophyte beds can also be detrimental to largemouth bass populations.

If maintenance stocking is necessary to provide a bass fishery, managing the lake for bass is probably not cost effective nor appropriate.

References

In addition to Scott and Crossman (1973) and Carlander (1977), the following references provide useful information on black basses: Minnesota Department of Natural Resources (1982), Louisiana Department of Wildlife and Fisheries (1990), Morrison and Tilyou (1991), and Boyle (1980).

Sunfish and Crappie

Like black bass, sunfish and crappies are members of the sunfish family, Centrarchidae. Common sunfish species include bluegill (*Lepomis macrochirus*), pumpkinseed (*L. gibbosus*), and redear (*L. microlophus*). Two species of crappie occur in North America: the white crappie (*Pomoxis annularis*) and black crappie (*P. nigromaculatus*). Collectively, sunfish and crappie are often referred to as panfish; that is, smaller fish caught primarily for their food value rather than for fishing sport. They can occur in large numbers and represent a valued fisheries component in many waters. Both groups, however, have a tendency to overpopulate and stunt if the numbers of small fish are not adequately controlled by predators or other means.

[S]unfish and crappie . . . can occur in large numbers and represent a valued fisheries component in many waters. Both groups, however, have a tendency to overpopulate and stunt if the numbers of small fish are not adequately controlled by predators or other means.

Habitat

Sunfish and crappie are generally classified as warmwater fish. They are usually found in quiet warm waters of small lakes and bays and shallower areas of larger lakes and reservoirs. Most sunfish species prefer well-vegetated habitats, which provide protection from predators. Maximum growth rates for bluegill occur at summer temperatures in the low 70s (°F), although fish still actively feed and grow at higher temperatures (up to about 80°F); pumpkinseed prefer somewhat cooler waters, while redear sunfish grow better in warmer waters. The black crappie prefers clearer, deeper, and cooler lakes than the white crappie, and its range extends further north. Abundant cover, such as inundated timber or submerged vegetation, and clear water are the black crappie's primary habitat requirements. The white crappie is quite tolerant of turbidity and siltation and often occurs in lakes where aquatic vegetation is lacking.

Most sunfish species prefer well-vegetated habitats, which provide protection from predators.

Reproduction

As for black bass, sunfish and crappie spawn in relatively shallow waters (generally 1 to 5 feet) in quiet areas and bays. Males develop the nest sites and guard the eggs during incubation and schools of fry for a period of time after emergence. Most sunfish and crappie will spawn in a variety of substrates including mud, gravel, or sand, although nests are usually located near some type of cover, such as macrophytes, stumps, or brushpiles. Depending on the location, crappie spawning occurs from mid-March to early summer (June to mid-July), when water temperatures rise above about 60°F. Most sunfish species spawn for extended periods, often from late spring through mid- to late-summer, and in some cases in early fall.

Food Habits

Primary food items include aquatic insects, crustaceans, and snails. Adult bluegills and crappie also feed in some lakes on small forage fish. Young fish feed almost solely on small zooplankton during their first year.

Management Concerns

Information on the relative abundance and population characteristics of sunfish and crappie can be obtained most readily by trapnetting during the spawning season, observing spawning sites, and conducting creel censuses in early or late winter or early spring.

Major management problems include the following:

■ **Stunting.** Overcrowded and therefore stunted fish is the most common management problem. To improve fish growth rates, the numbers of small fish must be reduced substantially. Management approaches for stunted populations were discussed in Chapter 8 and include water level management, aquatic vegetation control, introductions of predators or increased predator efficiency, and selective cropping and reclamation.

Overcrowded and therefore stunted fish is the most common management problem.

■ **Habitat degradation.** Crappies are relatively tolerant of low levels of dissolved oxygen, and are among the most winterkill-resistant species. Yet, a variety of habitat problems may limit crappie survival and production, including excessive eutrophication or pollution. Bluegills and other sunfish may also be adversely affected by eutrophication, toxic contaminants, increased turbidity, and low levels of dissolved oxygen. Maintaining appropriate covers of aquatic vegetation is an important component of habitat management for sunfish.

Maintaining appropriate covers of aquatic vegetation is an important component of habitat management for sunfish.

■ **Inadequate natural reproduction.** Crappie and sunfish have a high reproductive potential; inadequate natural reproduction is seldom a problem. However, low levels of recruitment may occur in the absence of emergent and submerged vegetation to provide protective cover and feeding areas for young fish.

■ **Poor fishing.** If the lake lacks adequate structures to provide cover and concentrate fish, crappies may distribute themselves throughout the midwater pelagic zone and be difficult to locate. Thus, crappie may be abundant in a lake, yet few caught by anglers. Additions of artificial reefs or other structural features may improve fishing success.

References

Useful references include Arnoldi et al. (1991) and Minnesota Department of Natural Resources (1982) as well as the many general and region-specific references listed at the beginning of this appendix.

Striped Bass and White Bass

Striped bass (*Morone saxatilis*) and white bass (*M. chrysops*) are members of the temperate bass family in the order Perciformes.

[S]triped bass as well as striped bass/white bass hybrids have been widely introduced into large reservoirs, particularly in the southern United States.

Habitat

In their natural habitat, striped bass are anadromous, moving from the ocean up rivers into fresh water to spawn. In recent years, however, striped bass as well as striped bass/white bass hybrids have been widely introduced into large reservoirs, particularly in the southern United States. White bass inhabit coolwater lakes and reservoirs from Canada to the Gulf of Mexico. Both species occur primarily in pelagic regions and can be an important component of open-water fisheries in lakes and reservoirs.

Reproduction

Sexually mature white bass form schools and move onto shoals for spawning in the spring. Spawning commences in April in the southern United States and late May/early June in northern areas, at a water temperature of 50° to 65°F. A given population may spawn over a period of 5 to 10 days. Eggs and sperm are released simultaneously into the water, near the lake surface, or in mid-water.

The eggs sink and become attached to gravel, boulders, or vegetation on the bottom. Egg survival depends on the availability of silt-free surfaces. Eggs hatch in a relatively short period of time (generally two to three days); adults provide no parental care to either the eggs or fry.

Striped bass also spawn in the spring, when water temperatures reach 60° to 70°F. Like white bass, the eggs and sperm are released simultaneously into the water column. However, striped bass eggs are semibuoyant. Unless suspended by water currents, they will settle to the bottom and perish. Thus, striped bass spawn in rivers; sexually mature fish can migrate long distances upriver to spawn.

Food Habits

Both white and striped bass are piscivores; important forage fish include threadfin and gizzard shad, alewifes, silversides, blueback herring, and yellow perch. Adults also consume insects and crayfish. Younger fish feed on insect larvae and zooplankton.

Management Concerns

The most frequently cited management problem for reservoir populations of striped bass is summerkill caused by high temperatures and low levels of dissolved oxygen (see Box 3-E). Eleven of the 30 State agencies that manage one or more striped bass populations reported having problems with high-temperature, low-oxygen stress (Axon and Whitehurst, 1985). Likewise, 27 of the 80 reservoirs (34 percent) reviewed had some summer mortality of striped bass (Matthews, 1985). For populations in more northern waters (e.g., Minnesota and Oregon) low-temperature stress during long winters may also be a problem. Although of concern, periods of high mortality (summerkill or winterkill) do not usually prevent the establishment of a quality fishery for striped bass or striped bass/white bass hybrids.

The most frequently cited management problem for reservoir populations of striped bass is summerkill caused by high temperatures and low levels of dissolved oxygen .

The second most commonly cited problem is an inadequate forage base. Gizzard or threadfin shad are often stocked coincidently with striped or white bass introductions into reservoirs. However, heavy predation by adult bass may deplete the supply of available forage, aggravated by problems with high mortality (winterkill) of gizzard or threadfin shad. Food supplies may be inadequate, even in some waters with a high biomass of forage fish, if a substantial fraction of the fish are too large to be readily eaten.

The second most commonly cited problem is an inadequate forage base.

Concerns have been raised regarding potential adverse effects of striped bass/white bass introductions on other game fish populations. Several States have reported problems with striped bass predation on rainbow trout in reservoirs with a "two-story" trout fishery (Axon and Whitehurst, 1985). Studies of striped bass-largemouth bass interactions, however, have found no significant negative effects on largemouth bass growth rates or population structure (Turner, 1986; Harper and Namminga, 1986).

Finally, losses of striped bass through emigration can be an important problem in some systems. Spillway escapement, high discharge rates, or extreme water-level fluctuations were reported to cause emigration of striped bass from reservoirs in eight States (Axon and Whitehurst, 1985).

References

Publications with useful information on striped bass, white bass, and hybrid populations in freshwaters include Scott and Crossman (1973), Manooch (1984), Axon and Whitehurst (1985), Matthews (1985), and Coutant (1985).

Bullheads and Catfish

In the family Ictaluridae, a number of bullhead and catfish species can be important components of fish or fisheries management programs. Channel catfish (*Ictalurus punctatus*) grow to large sizes (up to 25 to 30 pounds) and provide highly valued commercial as well as recreational fisheries, particularly in the southern United States. Blue catfish (*I. furcatus*) and flathead catfish (*Pylodictis olivaris*) occur primarily in large rivers, although they have also been stocked into a few reservoirs with varying success. Several bullhead species are widely distributed in central and eastern North America: brown bullhead (*Ameiurus nebulosus*), black bullhead (*A. melas*), and yellow bullhead (*A. natalis*). Bullheads are generally smaller than catfish. Depending on angler preferences, the region, and size distribution of the population, bullheads may be viewed as a nuisance species or a prized game fish.

Habitats

As a group, catfish and bullhead are highly adaptable, occur in almost all types of habitats from southern Canada to Florida and Texas, and are quite tolerant of environmental stresses, including low levels of dissolved oxygen, high temperatures, and toxic pollutants. Brown bullhead prefer cooler, northern lakes, and are one of the most common fish in high elevation lakes in the Adirondack Mountains of New York and widely distributed across northern Michigan, Wisconsin, and Minnesota. Black and yellow bullhead occur predominantly in warmwater lakes and reservoirs; black bullhead in particular are common in warm, turbid, eutrophic waters. Channel catfish occur as far north as southern Canada but are of greater importance in southern warmwater lakes and reservoirs.

As a group, catfish and bullhead are highly adaptable, occur in almost all types of habitats from southern Canada to Florida and Texas, and are quite tolerant of environmental stresses. . . .

Reproduction

Spawning occurs in late spring and early summer as water temperatures warm to 70° to 80°F. The male — or for brown bullhead, the male and female — fish select a nest site in shallow waters, generally in a secluded area under logs, brush, or banks or in patches of vegetation. Less often, nests may be constructed in the open as a shallow depression in a sand or mud bottom. Eggs are laid in large adhesive, gelatinous masses that the male guards through incubation and, in some species, for a short period after fry emergence.

Feeding Habits

Bullhead and catfish are primarily bottom feeders, feeding on insects, crayfish, amphipods, mollusks, algae, fish eggs, and to a lesser degree, other fish.

Management Concerns

Because of their adaptability and tolerance of a wide range of environmental conditions, bullhead and catfish populations often need little direct management or manipulation. Natural reproduction is generally adequate. However, in waters with few predators, populations can overcrowd and stunt. In many regions, bullhead populations are underused by anglers. In eutrophic waters, bullheads and catfish may contribute to internal nutrient recycling and high algal productivity (see Chapter 9). In such cases, a fish control program, as discussed in Chapter 8 (reducing undesirable fish populations), may be warranted.

In many regions, bullhead populations are underused by anglers.

References

This information was summarized from Scott and Crossman (1973), Carlander (1969), and Manooch (1984).

Walleye and Yellow Perch

Walleye are an important coolwater game fish . . . .

Walleye (*Stizostedion vitreum*) and yellow perch (*Perca flavescens*) are members of the family Percidae. Walleye are an important coolwater game fish, particularly in northern areas. Scott and Crossman (1973) describe walleye as probably the most economically valuable species in Canada's inland waters. Yellow perch are harvested by anglers in some waters and serve as important prey for many valued sport fish species, including walleye. High quality walleye fishing is frequently associated with fairly large populations of perch.

Habitat

They . . . are most abundant in large, shallow lakes that are moderately turbid but also frequently occur in large, deep, clearwater lakes with rocky bottoms.

Walleye can survive at extreme temperatures (32° to 90°F), but prefer waters with a maximum temperature of 77°F (coolwater). They occur primarily in medium to large lakes (greater than about 1,000 acres), are most abundant in large, shallow lakes that are moderately turbid (Secchi depth 3 to 6 feet) but also frequently occur in large, deep clearwater lakes with rocky bottoms.

Yellow perch can adapt to a wide range of lake habitats and occur in a greater diversity of environments than walleye, including both small and large lakes and warm and cool waters. They tend to be most abundant in the upper pelagic region at a temperature of 66° to 70°F in lakes with moderate vegetation, clear water, and bottoms of muck, sand, or gravel.

Reproduction

Both walleye and yellow perch spawn in early spring. Normally, walleye spawning begins shortly after the ice breaks up, at a water temperature of 42° to 48°F. Spawning occurs in rocky areas in the white waters below impassible falls or dams or along boulder to coarse gravel shoals in lakes. Eggs are dispersed in shallow waters along the shoreline, falling into crevices in the rocky/gravel substrate.

Yellow perch spawn slightly later, when water temperatures range between 45° and 55°F. Adults migrate shoreward into the shallows of lakes and sometimes tributary streams. Spawning usually takes place near rooted vegetation, submerged brush, or fallen trees. Eggs are laid in a long, semibuoyant gelatinous strand that adheres to submerged surfaces or the lake bottom. Neither walleye nor yellow perch develop nests or provide any parental care of eggs or fry.

Feeding Habits

Walleye are piscivores, feeding predominantly on other fish after reaching about three inches in length. Walleye populations can also be highly cannibalistic if other small fish are not available. Young walleye feed on small, planktonic crustaceans and insects. Yellow perch diets are more diverse and include benthic insect larvae, leeches, amphipods, crayfish, and small fish. In some lakes, yellow perch mainly prey on fish eggs of yellow perch as well as other fish species.

Management Concerns

Figure 8-9 in Chapter 8 presents a flow chart for managing walleye in Minnesota lakes, identifying major problems as well as potential management approaches for resolving these problems. Factors that frequently limit walleye success or productivity include the following:

- **Inadequate forage.** Poor growth rates and low condition factors may indicate that food supplies are inadequate as a result of low prey abundance, excessive competition from other top predators (e.g., northern pike or largemouth bass) or

rough fish (e.g., white sucker), or excessive numbers of walleye. Possible management methods for improving growth include reducing the abundance of competitors, introductions or enhancement of prey (effective in some circumstances only), or reduced stocking of walleye to decrease intraspecific competition.

- **Large predator population.** Young walleye are highly susceptible to predation, and almost any fish-eating fish can become a significant walleye predator. Predation is a common cause of unsuccessful walleye stocking or reproduction in waters with existing, abundant populations of piscivores. Management approaches for reducing predatory losses include cessation of predator stocking, netting programs to reduce predator abundance, and in small lakes, chemical reclamation with rotenone. Northern pike, in particular, frequently co-occur with walleye and can be important predators as well as competitors.

Predation is a common cause of unsuccessful walleye stocking or reproduction in waters with existing, abundant populations of piscivores.

- **High fishing pressure.** Indicators of excessive harvests of walleye include a reduction in catch rates over time, decrease in average size, and decrease in the number of walleye year-classes represented in the fishery. Management alternatives include fishing regulations (e.g., size limits or closed seasons or areas to protect spawning fish), increased walleye stocking, or adjustments in other fish populations that may enhance walleye productivity (e.g., increase in abundance of yellow perch or other forage fish). Brousseau and Armstrong (1987) discuss the role of size limits in walleye management.

- **Habitat degradation.** Winterkill is a problem in some walleye lakes. In addition, walleye can be adversely affected by eutrophication or increased levels of toxic contaminants.

- **Inadequate natural reproduction.** Poor reproductive success may be countered by means of supplemental stocking, water level management to ensure stable or rising water levels during egg incubation, development of artificial or enhanced spawning areas, fishing regulations to protect spawning adults, or removal of barriers to spawning migrations into tributary streams and rivers.

Yellow perch are highly prolific, with a high reproductive potential and voracious appetites. Thus, problems with yellow perch generally relate to overcrowding. High fish densities resulting in poor growth rates and stunted populations make them of little interest to anglers. In addition, large numbers of perch can lead to detrimental effects on other more valued fish species, such as bass or trout, as a result of competition or perch predation on fish eggs.

[P]roblems with yellow perch generally relate to overcrowding.

References

The information above was summarized from Minnesota Department of Natural Resources (1982), Scott and Crossman (1973), Manooch (1984), and Bennett and McArthur (1990). Ebbers et al. (1988) compiled a bibliography of references on walleye and sauger (*Stizostedion canadense*). Craig (1987) discusses the biology of perch and related fish.

Pike, Pickerel, and Muskellunge

Members of the family Esocidae in North America include muskellunge (*Esox masquinongy*), northern pike (*E. lucius*), chain pickerel (*E. niger*), redfin pickerel (*E. americanus americanus*), and grass pickerel (*E. americanus vermiculatus*). Redfin and grass pickerel occur primarily in slow moving streams and rivers, rather than lakes, and are not discussed further. Muskellunge are the largest of the esocids, growing commonly to 28 to 48 inches and 5 to 36 pounds, and provide prized trophy fishing. Northern pike and chain pickerel are viewed as valued game fish in some waters but rough fish in others. All esocids are highly efficient predators that can compete with and/or prey upon other fish species in a lake or

reservoir. Muskellunge and northern pike occur only in Canada and the northern United States. Tiger muskie, a cross between northern pike and muskellunge, are also stocked in some areas. Chain pickerel are widely distributed throughout the eastern edge of North America.

Habitats

Esocids tolerate a broad spectrum of water quality and habitats but are most common and abundant in relatively shallow, warm bodies of water or coves in larger lakes with extensive growths of aquatic vegetation. For muskellunge, maximum water temperatures of 78°F are optimal, although the species can withstand temperatures as high as 90°F. Chain pickerel prefer waters with summer temperatures of 70° to 86°F. Esocids, in general, are relatively tolerant of low levels of dissolved oxygen. However, because they are sight feeders, feeding efficiency as well as fishing are adversely affected by high turbidity.

Esocids . . . are most common and abundant in relatively shallow, warm bodies of water or coves in larger lakes with extensive growths of aquatic vegetation.

Reproduction

Spawning occurs in the early spring, immediately after ice out for northern pike (at water temperatures of 40° to 52°F) and shortly thereafter for chain pickerel and muskellunge (at temperatures of 47° to 52°F and 49° to 59°F, respectively). Northern pike and muskellunge spawn in shallow (15 to 20 inches) weedy bays, adjacent marshes connected by small tributary streams or in heavily vegetated floodplains of rivers; chain pickerel generally spawn in somewhat deeper water (usually 3 to 10 feet) over flooded vegetation. Eggs are scattered at random, are slightly to very adhesive, and remain attached to the vegetation in the spawning area. No parental protection or care is provided.

Food Habits

Pike, muskellunge, and pickerel are all highly efficient predators and strongly piscivorous (after reaching about 1.5 inches in length). Adult esocids will consume most any living vertebrate within the size range that they can engulf, including frogs, muskrats, mice, and ducklings.

In some lakes and regions, pike and pickerel are considered undesirable fish species because of their predation on or competition with other, more valued game fish . . . .

Management Concerns

In some lakes and regions, pike and pickerel are considered undesirable fish species because of their predation on or competition with other, more valued game fish, such as trout or walleye. In such cases, populations may be reduced or eliminated by netting and fish removal, building barriers (where feasible) to block migrations into spawning areas, or applying fish poisons, such as rotenone, as part of a chemical reclamation project. It may also be desirable to increase angler exploitation of pike and pickerel resources through angler education and communication programs.

Common factors limiting muskellunge production and fisheries yield include the following:

- **Inadequate forage.** Muskellunge growth rates are low in lakes with inadequate numbers of suitable-sized (including larger) prey, in particular yellow perch and minnows. Possible management methods for improving growth include reducing the abundance of northern pike (which compete with muskellunge) by netting and removal or interfering with pike reproduction; when appropriate, introducing new forage fish; or in infertile waters where populations are supported or supplemented by stocking, reducing the rate or frequency of muskellunge stocking.

■ **High predator population.** Northern pike is the most common and serious predator on muskellunge. Control methods for northern pike were previously noted.

■ **High fishing pressure.** Waters with a relatively small number of large, old muskellunge may suffer from overfishing. Fishing pressure can be reduced by increasing the minimum size limit or closing the fishery until the population recovers.

Waters with a relatively small number of large, old muskellunge may suffer from overfishing.

■ **Habitat degradation.** Problems with periodic winterkill can be alleviated through aeration or other techniques for increasing winter oxygen levels (see Chapter 8) or restocking in the spring. Esocid populations can also be adversely affected by decreased water clarity and by draining adjacent marshes and floodplains that provide important spawning and nursery areas.

■ **Inadequate natural reproduction.** Reproductive success can be enhanced by removing barriers (e.g., beaver dams, log jams, or silted channels) to fish migration into suitable spawning areas; improving the spawning habitat by removing brush, trees, and silt to encourage growths of desirable vegetation; and managing water levels, increasing areas of flooded vegetation during spawning, and maintaining stable water levels through egg incubation, fry emergence, and early feeding. Supplemental stocking may also be effective in some instances.

Similar management concerns apply to northern pike and chain pickerel, where populations are managed as a fisheries resource. Common problems include inadequate forage, inadequate natural reproduction, and habitat degradation. Anglers often have difficulty distinguishing among muskellunge, northern pike, and hybrids where they co-occur (Casselman et al. 1986). Thus, implementing distinct fishing regulations for each species will be ineffective without an accompanying angler education program.

References

Information on pike, pickerel, and muskellunge was compiled from the Minnesota Department of Natural Resources (1982), Maine Department of Inland Fisheries and Wildlife (1986), and Scott and Crossman (1973). Hall (1986) also discusses the management of muskellunge.

Trout and Salmon

Many members of the family Salmonidae are highly valued game and sport fish, supporting important fisheries in coldwater lakes. Only six are reviewed briefly here, however: brook trout (*Salvelinus fontinalis*), rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*), cutthroat trout (*O. clarki*), lake trout (*Salvelinus namaycush*), and kokanee salmon (*O. nerka*).

Many members of the family Salmonidae are highly valued game and sport fish, supporting important fisheries in coldwater lakes.

The wide distribution of these species reflects, in part, the historical popularity of salmonid transplants and stocking. Brook trout are native to northeastern North America, from Canada to the southern Appalachians in Georgia and west to Minnesota. They have been introduced, however, into many coldwater lakes in western regions, especially high elevation lakes in the Rocky Mountains. Rainbow and cutthroat trout are native to western North America, although rainbow trout, in particular, have been widely stocked throughout northcentral and northeastern North America. Brown trout are native to Europe and western Asia but were transplanted to the United States initially in 1883 and now occur in coldwater lakes scattered throughout Canada and the northern United States. Lake trout also occur throughout northern North America. Kokanee, the landlocked form of the anadromous sockeye salmon, are native to the northwest, but like most salmonids, have been introduced into a diversity of coldwater habitats and regions.

Habitat

All salmonids require or prefer clear, cool, well-oxygenated (> 5-6 mg/L dissolved oxygen) lakes and streams. Brook and cutthroat trout occur most commonly in small headwater lakes, often at high elevations (above 8,000 feet). Both species are able to survive and grow in very cold lakes with short growing seasons and are relatively intolerant of warm water, seeking out temperatures below 68°F (in the hypolimnion) when surface waters warm up during summer. Rainbow trout are usually found in moderately deep to deep cool lakes with adequate shallows and vegetation to support good food production. They are most successful in habitats with temperatures of 70°F or slightly lower available, but they grow slowly in cold alpine lakes. The optimum temperature range for brown trout is 65° to 75°F. Brown trout remain active and can thrive at slightly higher temperatures than brook trout, but otherwise they have very similar habitat requirements. Kokanee salmon and lake trout prefer even colder waters (50° to 59°F and 50°F, respectively), moving into deep hypolimnetic waters during summer stratification. Both species occur, therefore, primarily in large, deep lakes; typical lake trout habitat consists of a large, deep coldwater lake with irregular bottom contours and shorelines covered with rock and gravel. In cold climates (e.g., Canadian Northwest Territories), however, lake trout can also persist in shallow lakes.

All salmonids require or prefer clear, cool, well-oxygenated lakes and streams.

Reproduction

For lakes to support self-sustaining salmonid populations, habitat suitable for spawning and survival of eggs and fry must be available. Brook, rainbow, brown, and cutthroat trout and kokanee salmon all spawn over gravel beds in small streams. Mature fish may travel many miles upstream to reach suitable spawning areas. Brook trout, brown trout, and kokanee salmon can also spawn on gravelly shallows in lakes, although brook trout require groundwater upwelling and a moderate current for successful reproduction. Lake trout spawning occurs most often in lakes over a large boulder or rubble bottom at depths of less than 40 feet and sometimes as shallow as 1 foot.

Mature fish may travel many miles upstream to reach suitable spawning areas.

Brook, brown, and lake trout and kokanee salmon are fall spawners. Brook trout eggs are deposited in late summer (August) in northern regions and as late as December in the southern portion of the range. Brown trout spawn in late autumn to early winter, at a temperature of 44° to 48°F; kokanee generally spawn between September and December at 41° to 51°F. Lake trout spawn in the fall, but the exact date varies from lake to lake and depends on latitude, weather, and the size and topography of the lake as well as water temperature. For all four species, eggs hatch in midwinter and swim-up fry emerge from the gravel in very early spring, just before ice breakup.

Rainbow trout and cutthroat trout are primarily spring spawners. Cutthroat trout spawn about three to five weeks after ice breakup at a water temperature of about 50°F. Rainbow trout spawn between mid-April and late June in most areas at temperatures between 50° and 60°F. Eggs incubate for four to seven weeks before hatching, and fry emerge from the gravel after another five days to two weeks.

All six species spawn in nests, referred to as "redds," prepared primarily by the female. Lake trout clean the spawning area by brushing the rocks with their body or tail or rubbing them with their snout. The fertilized eggs fall into the crevices between the large rocks. The remaining species clear away debris and silt from the redd by turning sideways and beating the bottom substrate using a series of rapid fanning movements of the caudal fin. When the spawning process is completed, the female covers the redd with loose gravel using a similar motion. No further parental care or protection is provided.

Kokanee salmon (like most Pacific salmon) generally die a few days to several weeks after spawning. Kokanee mature, spawn, and die at about four years (range: two to eight years). Atlantic salmon and trout, on the other hand, do not die after spawning and generally spawn in multiple years.

Food Habits

Brook, rainbow, brown, and cutthroat trout are carnivorous and feed on a wide range of organisms, including aquatic and terrestrial insects, crayfish, leeches, large zooplankton, mollusks, frogs, and small fish. In general, fish play a less important role in the diet of these species than for most other important game fish, such as largemouth bass, walleye, and muskellunge. Brown trout and rainbow trout tend to reach larger sizes than either brook or cutthroat trout. Fish and crayfish figure more prominently in the diet of very large brown and rainbow trout.

Lake trout also feed on a broad range of organisms, including freshwater sponges, crustaceans, aquatic and terrestrial insects, many species of fish, as well as small mammals. The food consumed depends on availability and lake trout size. Like brown and rainbow trout, lake trout can grow to large sizes. Lake trout commonly live to be 15 to 25 years old and can grow to be 30 to 40 inches and 10 to 25 pounds or more. The importance of fish in the lake trout diet tends to increase with increasing size. In lakes without suitable forage fish, lake trout grow slowly and do not live as long as trout feeding primarily on other fish.

Kokanee salmon feed mainly on zooplankton, although bottom organisms can represent a significant diet component in some lakes. They are not known to prey on other fish.

Management Concerns

In general, trout and salmon fisheries require more intensive management than do many warmwater or coolwater fisheries. Management problems and concerns frequently encountered include the following:

In general, trout and salmon fisheries require more intensive management than do many warmwater or coolwater fisheries.

- **Habitat degradation.** Poor forestry or other land use practices can lead to siltation of spawning areas. Salmonids can reproduce successfully only in *clean* gravel substrate; egg and fry survival can be decreased dramatically by even small to moderate silt loads. Land clearing can also increase water temperatures. Eutrophication can deplete oxygen levels in the hypolimnion, eliminating suitable habitat for trout and salmon during summer. Brook, cutthroat, and to a lesser degree, rainbow trout also occur in habitats susceptible to winterkill (small lakes in cold climates with long winters and heavy snow cover).

Poor forestry or other land use practices can lead to siltation of spawning areas.

- **Inadequate natural reproduction.** Because of their fairly specific spawning habitat requirements, salmonid populations are generally limited by inadequate natural reproduction. Suitable spawning areas may be unavailable or migrations into spawning streams may be blocked by beaver dams, log jams, or construction of dams or roads. Lake trout can experience high egg and fry mortality if spawning occurs in shallow waters and water levels drop during egg incubation overwinter. Reproductive success may also be low as a result of fish predation on salmonid eggs, fry, and juveniles. Often, populations with inadequate reproduction are supplemented or supported by stocking. As discussed in Chapter 8, however, stocking should occur only if it is cost effective and if native strains of the species are not endangered.

[S]almonid populations are generally limited by inadequate natural reproduction.

- **Excessive predators or competitors.** Young trout and salmon are highly susceptible to predators, such as chain pickerel, northern pike, walleye, or fish-eating waterfowl. Yellow perch may compete with juvenile salmonids and also,

potentially, feed on salmonid eggs. Historically, the common solution to problems with predators or competitors was chemical reclamation, poisoning all fish in the lake and re-stocking with only salmonids.

■ **Slow growth.** Slow growth rates may occur naturally in highly oligotrophic lakes. However, in some cases growth rates can be increased by eliminating or reducing populations of competitors, reducing salmonid stocking rates, increasing forage fish availability (for lake, rainbow, and brown trout), or eliminating stressful environmental conditions (e.g., water temperatures above optimal levels during part of the growing season). As noted in Chapter 8, forage introductions are often unsuccessful, with negative side effects, and should be considered only in limited circumstances. Chapter 12, however, presents a successful case study of introducing cisco as a forage fish to increase lake trout growth rates and fishery yields in Lake Opeongo, Ontario.

■ **Overfishing.** Trout, in general, are highly catchable and susceptible to overfishing during some seasons of the year. In addition, brook and cutthroat trout, in particular, tend to occur in small unproductive lakes that support relatively few fish; therefore, populations can be easily depleted. Possible remedies for overfishing include fishing regulations and stocking. Lake trout typically mature at 6 or 7 years old, but may mature as late as 13 years old in some lakes. Slow-growing, late-maturing populations may require relatively long minimum size regulations to sustain adequate numbers of sexually mature, reproducing fish.

■ **Loss of wild, native strains and genetic diversity.** Extensive stocking of hatchery strains of trout and salmon in previous years has resulted in the loss of many native strains and decreased genetic diversity (see Chapter 3). In many States, wild strains and naturally reproducing populations are legally protected. Stocking these waters is prohibited and fishing pressure may be limited by special regulations.

References

Information on trout and salmon management was compiled from Scott and Crossman (1973), Carlander (1969), Minnesota Department of Natural Resources (1982), Maine Department of Inland Fisheries and Wildlife (1986), and Nelson (1988). Olver and Martin (1984) compiled a bibliography of publications and reports on lake trout. Other references of potential interest include Willers (1981), Trotter (1987), Gresswell (1988), and Mills (1989).

Threadfin Shad, Gizzard Shad, and Alewife

The alewife (*Alosa pseudoharengus*), gizzard shad (*Dorosoma cepedianum*), and threadfin shad (*D. petenense*) are members of the herring family, Clupeidae. None of these species is of any major recreational or commercial importance in freshwaters, although they all can be important forage fish for game species.

The alewife, gizzard shad, and threadfin shad . . . can be important forage fish for game species.

Habitats

The alewife is primarily an anadromous fish on the Atlantic coast of North America from the St. Lawrence River to North Carolina, but it has also been stocked into a number of lakes and reservoirs. The gizzard and threadfin shad occur primarily in southern regions, the northern extent of their range being the Great Lakes for gizzard shad and Oklahoma/Tennessee for threadfin shad. Threadfin shad cannot tolerate temperatures below about 7°F.

Reproduction

Landlocked alewife inhabit the open waters of lakes during most of the year but move onto shallow beaches and into ponds to spawn in late spring and early summer. The eggs, which are essentially nonadhesive, are broadcast at random over sandy or gravelly bottoms.

Gizzard shad also spawn in spring to early summer (mid-March to mid-August) generally at water temperatures of 63° to 73°F. The eggs are highly adhesive. After being released near the lake surface, they sink slowly to the bottom or are carried with the current until attaching to any object with which they come in contact.

Threadfin shad generally spawn in the spring and early summer (April to early July, temperatures 57° to 70°F), but some populations have two spawning peaks in spring and fall. They spawn in schools in open water or under brush and floating logs, where the eggs adhere through incubation and hatching.

Food Habits

All three species feed primarily on plankton, both as young and as adults. Gizzard and threadfin shad consume both phytoplankton and zooplankton, while alewifes are basically zooplankton feeders.

Management Concerns

Shad and alewife are eaten by a wide range of fish predators and can provide important forage to sustain good fish growth rates and high fisheries yields. Game fish that consume these fish when available include lake trout, rainbow trout, northern pike, muskellunge, smallmouth and largemouth bass, and walleye. Gizzard shad, however, grow rapidly and are too large for most piscivorous fish by two years of age. Thus, a substantial portion of gizzard shad production may be unavailable for conversion into harvestable fisheries biomass.

All three species are subject to periodic die-offs, generally caused by sudden temperature changes. Large fish die-offs can be a serious nuisance, causing heath concerns and problems with odors and aesthetics. Each of these species is highly prolific, can increase to nuisance densities, and is difficult to eradicate once established. Therefore, new introductions should be attempted only after careful study and review of the potential negative consequences (see Chapter 8).

All three species are subject to periodic die-offs, generally caused by sudden temperature changes.

References

This information was compiled from Scott and Crossman (1973) and Carlander (1969).

APPENDIX B

Methods for Assessing Fisheries Status

Appendix Objectives

This appendix describes specific sampling and analytical techniques that can be applied as part of a field sampling program to collect information on the status of a lake's fisheries and related variables. It supplements the information in Chapter 10 on the overall design of a field sampling plan. The sections that follow review techniques for surveying anglers and fish communities, methods for measuring fish characteristics (such as length, age, and fecundity), and methods for assessing the food base, water quality, and physical habitat. Much of the material presented is summarized from *Fisheries Techniques* (Nielsen and Johnson, 1983), published by the American Fisheries Society.

[M]any good reference materials are available on fish and fisheries sampling techniques . . . .

This appendix provides only an introductory summary of the principles, advantages, and limitations of each sampling technique. However, many good reference materials are available on fish and fisheries sampling techniques, including books edited or written by Nielsen and Johnson (1983), Schreck and Moyle (1990), and Everhart and Youngs (1981) as well as sampling manuals prepared by most State and provincial fisheries agencies (e.g., Ontario Ministry of Natural Resources, 1989; Minnesota Department of Natural Resources, 1970, 1978, 1985; Texas Parks and Wildlife Department, 1991).

As noted in Chapter 10, a field sampling program for managing fish or fisheries in lakes and reservoirs may involve sampling in not only the lake but also adjacent streams, other lakes in the drainage basin, and the watershed. Watershed monitoring techniques and methods for measuring lake physical and chemical characteristics are discussed in other supplements in this series: Wedepohl et al. (1990), and Olem and Flock (1990). This appendix focuses, therefore, on sampling fisheries, fish, fish prey, and fish habitat in lakes and, to a lesser degree, streams.

[A] field sampling program for managing fish or fisheries in lakes and reservoirs may involve sampling in not only the lake but also adjacent streams, other lakes in the drainage basin, and the watershed.

Techniques for Surveying Anglers

Creel Surveys

One common complaint from anglers is that fish catch rates or sizes have declined in recent years or are less than expected, based on catches in other similar waters in the area. Creel surveys are one approach for verifying or evaluating trends in angling success.

Creel surveys are one approach for verifying or evaluating trends in angling success.

Basically, creel surveys entail direct contacts with anglers by creel "clerks" on the lake or reservoir of interest. Each angler is asked the number of anglers in the party, the total number of hours and times fished during the visit, angling methods (e.g., shore, boat still-fishing, trolling, casting, ice), and the total numbers of fish caught (including those released) and harvested by species and fish size (numbers of legal-sized versus undersized fish caught). The creel clerk may also measure fish in the angler's creel for length and weight and collect a scale sample for aging. Additional information on angler expenditures or other characteristics may also be useful. A sample creel survey form is presented in Figure B-1.

SPECIES CAUGHT	LEGAL SIZE (NUMBER)	UNDER-SIZE (NUMBER)	FISH KEPT (NUMBER)	FISH RELEASED (NUMBER)	FREQUENCY OF FISHING	HOURS FISHED	METHOD USED	NUMBER IN PARTY
Brook Trout								
Rainbow Trout								
Brown Trout								
Large-mouth Bass								
Small-mouth Bass								
Bluegills								
Sunfish								
Yellow Perch								
Pike Perch (Walleye)								
Northern (Grass) Pike								
Rock Bass								
Crappies (Speckled Bass)								
Carp								
Catfish								
Bullheads								

Figure B-1.—Example form used in creel surveys.

Creel clerks should interview all anglers fishing the lake during the sampling interval or, alternatively, should count or otherwise estimate (e.g., by counts from aircraft) the total number of active anglers and then collect creel survey data from a representative subset. Sampling intervals should be conducted on weekdays, weekends, and holidays, both morning and evening. Clerks can contact all or a defined frequency of the anglers fishing along shorelines or in boats (roving

method), contact anglers as they return to boat launch areas or along access routes (point of access method), or employ a combination of roving and point of access methods.

Creel surveys can be designed to sample anglers at random or during regular sampling intervals (days or parts of days) over specific period(s) of interest (a month, season, or year). It is generally best to include three or more sampling intervals in each period of interest. Larger sample sizes are needed when the period of interest is longer. Larger sample sizes also tend to reduce error and uncertainty associated with using samples to estimate population parameters.

Sampling intervals and survey times must be standardized. Because fishing pressure tends to be heavier during weekends than weekdays, the sampling effort can be stratified (split) to provide comparable information for weekday and weekend anglers. Sampling could also be stratified among morning, mid-day, and evening hours to provide a better estimate of total angling effort and success.

Based on the creel data collected for anglers interviewed during each sampling interval, estimates of the total angling effort can be derived for the period of interest, total numbers of fish caught and harvested by species or angling method, and numbers of fish caught per hour fished or other unit of effort. Fish population status can also be inferred from information on relative catch rates (catch per unit effort) as well as fish size and age distributions.

Further details on the design and implementation of creel surveys and the analysis of creel survey results can be found in Malvestuto (1983), Van Den Avyle (1986), and Guthrie et al. (1991).

Angler Diaries

Information on fishing success also can be obtained by asking individual anglers who frequent the lake or reservoir to maintain a diary or written log of fishing effort and fish caught. Generally, the cooperating anglers are volunteers. Angler diaries, therefore, can be an inexpensive way to collect data on fisheries and the fish community. Drawbacks, however, include (a) less control over the quality and completeness of data recorded and (b) lack of data or estimates for all anglers and inability, therefore, to quantify total angling effort and harvest. Anglers' fishing effort and skills vary greatly, and these factors are difficult to account for when analyzing and interpretating angler diaries. Furthermore, success rates may improve over time as the angler learns more about where, when, and how to fish in a given lake. Nevertheless, because of the ease of data collection, angler diaries should be seriously considered as at least a supplemental data collection technique.

Information on fishing success also can be obtained by asking individual anglers who frequent the lake or reservoir to maintain a diary or written log of fishing effort and fish caught.

Typically, anglers are given individual copy(ies) of the diary (often a pocket-sized booklet) to be used for the survey. Anglers can be instructed to maintain separate diaries for different fish species or groups of fish. Figure B-2 shows sample record pages from an angler diary for largemouth bass. All information requested about each fishing trip is entered by the angler keeping the diary.

The opening pages of an angler's diary should include a place for the angler's name and address, an address and person to whom the completed diary should be returned, the starting and ending dates for diary entries, a contact (and telephone number) for additional information, and a brief introduction on how the information will be used. Instructions for making diary entries must also be provided. The following should be noted:

- The diary should be taken on all fishing trips so information can be recorded accurately as it is obtained.
- Information for each fishing trip should be recorded on a separate page whether or not fish are caught.

Name: _____ Weather: _____

Address: _____ Time: _____

_____ Date: _____

Record Individual Lengths

HARVESTED			CATCH/RELEASE ONLY		
LENGTH (INCHES)	FIN CLIP CODE	TAG NUMBER	LENGTH (INCHES)	FIN CLIP CODE	TAG NUMBER

Remarks:

Figure B-2.—Example form used in angler diaries (adapted from the Illinois Department of Conservation).

- Information for each fish caught should be recorded as required on the form. When information on fish length is requested, the diary should include a diagram illustrating the specific points on a fish that define the desired length measurement. Diaries can also include drawings or photographs of important fish species to help anglers identify species accurately.

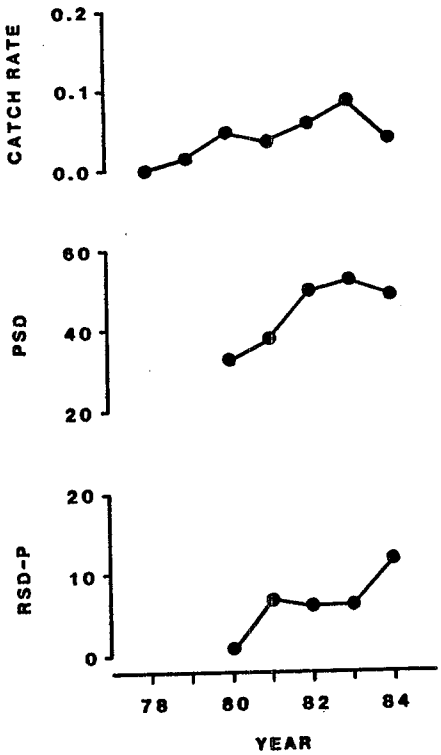

Figure B-3.—Changes in catch rate (20-cm and longer fish per angler hour), proportional stock density (PSD), and relative stock density (RSD) for smallmouth bass caught by tournament anglers at Wilson Reservoir, Kansas, 1978-84. Smallmouth bass were stocked into Wilson Reservoir from 1978 to 1981 (source: Willis and Hartmann, 1986).

- Any markings (e.g., clipped fins, tags) on the fish should be recorded. The types and locations of management markings used in the lake should be explained and illustrated. If requested, fish tags may be returned with the diary.
- The importance of maintaining accurate and complete records should be emphasized.

Organized tournaments on a lake or reservoir provide a special opportunity to compile a large database on angler catch rates and success. While tournament anglers, on average, have higher success rates than do nontournament anglers, the biases in catch rates and length distributions are consistent. Therefore, long-term trends in fishery characteristics can be assessed (see Figure B-3). By involving local fishing clubs and tournaments, the numbers of cooperating anglers can be increased substantially. Angler diaries, in general, provide data for more fish and anglers at lower cost than can be obtained using creel surveys. Sztramko et al. (1991) present an example application of angler diaries to monitor fisheries trends and use in Lake Erie from 1984 to 1989.

Organized tournaments on a lake or reservoir provide a special opportunity to compile a large database on angler catch rates and success.

Questionnaires to Obtain Angler Use or Opinion Data

Questionnaires are particularly useful for obtaining general information on lake use patterns, angler expectations and preferences, and fishing success because data can be compiled from a large number of lake users at relatively low cost. These surveys do not, however, provide reliable, quantitative information on specific fishery characteristics, such as catch rates or fish sizes.

Methods for questionnaires include volunteer response surveys (e.g, box-on-post surveys), personal contact interviews, telephone interviews, and mail surveys. To acquire accurate information requires considerable planning and a

Questionnaires are particularly useful for obtaining general information on lake use patterns, angler expectations and preferences, and fishing success . . . .

To acquire accurate information requires considerable planning and a comprehensive survey design.

comprehensive survey design. Babbie (1973) provides a good general introduction to survey methods. Dillman (1978) presents "The Total Design Method" for mail and telephone surveys, which is followed by many of the most successful surveys now conducted. Important considerations from these texts are highlighted in the paragraphs that follow.

When designing a questionnaire survey, the first step is to carefully define the information needed, the population(s) from whom this information is needed, and any subpopulations (subsets) of interest. Then develop the questions, the questionnaire, introductory materials for the survey, and the sampling design. Questionnaires must be succinct, the layout should be eye-appealing, and the format and questions should be simple and clear. A short explanation should be provided on why the information is needed, how to complete the questionnaire, and where to submit the completed form and request additional information. For mail surveys, special consideration must also be given to writing and designing the cover letter(s), supplemental materials to accompany each package, and any pre-notification or post-mailing follow-up to the survey mailings.

The least demanding approach to collecting survey information is a volunteer response survey. Boxes containing copies of questionnaires can be placed at access locations (e.g., boat launches, picnic areas, or trail heads) with a sign requesting users to complete the form and noting briefly why the information is needed. User response rates can sometimes be increased by providing a space on the questionnaire form for respondents to (a) contribute any additional information and/or (b) enter his or her name and address to request copies of summary information or reports resulting from the survey.

Personal or telephone interviews allow more rigorous control on the quality of data collected and can provide a more accurate and statistically defensible data set. Personal interviews can be conducted door-to-door with lakeshore residents or anglers entering or leaving fishing access trails or boat sites. Phone interviews can be used to contact somewhat larger numbers of respondents more economically. In either case, to obtain high quality information, procedures for introducing the survey, interview techniques, and questionnaire forms must be standardized. The most successful phone surveys are those that can be completed in 10 minutes or less.

While telephone interviews can be used to survey more dispersed groups or large populations of interest, mail surveys are more commonly used for this purpose. For example, estimates of the total fishing pressure or of angler attitudes within a region or across a State are generally obtained through mail surveys.

For surveys of large populations of interest, whether by telephone or mail, contacting all members of the group is often impossible . Statistical procedures are then applied to select one or more representative samples or subsets of the group to be surveyed. A sample for a fishing pressure mail survey, for example, could be drawn from the fishing license receipts issued within the area where the information is desired.

Intuitively, one might assume that the larger the population of interest, the larger the sample size needed to accurately estimate population characteristics. This is not always the case, however, especially for very large populations. Generally, a sample size of 400 randomly selected persons is sufficient to estimate population parameters with reasonable accuracy and precision no matter how large the population. Where separate estimates are required for two or more similar groups (such as anglers in the northern and southern halves of a State), a sample of up to 400 people must be surveyed from each subpopulation. For smaller populations, sample sizes can be smaller. In general, less than 10 percent of any population must be randomly sampled to obtain accurate population estimates. Most introductory statistical texts present procedures for determining appropriate sample sizes and for selecting random samples (e.g., Cochran, 1977; Snedecor and Cochran, 1980).

To obtain data from 400 respondents, more than 400 questionnaires must be distributed. Questionnaire response rates will determine the number of questionnaires that are needed. If, for example, the expected response rate is 65 percent, at least 923 (400/0.65) questionnaires must be mailed to ensure that 400 completed questionnaires are returned.

Response rates can vary from 10 percent to 90 percent. However, using Dillman's (1978) procedures for the Total Design Method, response rates are commonly greater that 65 percent and frequently greater than 85 percent. In addition to paying careful attention to the survey and mail-out package design, Dillman's approach includes substantial follow-up efforts to increase response rates. One week after the surveys are mailed, a postcard reminder/thank-you is sent to the entire survey sample. Three weeks later, a letter of encouragement/thank-you is sent to all non-respondents, and a final letter and replacement questionnaire is sent to all non-respondents seven weeks after the first mailing. Thus, to be successful and provide accurate results, mail surveys require a substantial commitment of money and personnel. Meiers et al. (1992) present an example application of this method to estimate fishing pressure in Wyoming waters.

Techniques for Surveying Fish Populations and the Fish Community

Firsthand information on the status of the fish community is often required to evaluate fisheries problems and the effectiveness of management programs. Direct sampling can be used to determine, for example, fish growth rates, the frequency of reproductive failures, fish feeding habits, and fish mortality rates. A variety of methods are available to directly sample fish populations. These can be loosely classified into passive capture methods, active capture methods, fish toxicants, and observational methods. This section briefly describes some of these methods and the factors important in selecting the most appropriate gear or method for sampling a specific fish population or community. Further details on fish sampling techniques can be found in Nielsen and Johnson (1983) as well as most introductory fisheries texts (e.g., Lagler, 1956; Everhart and Youngs, 1981).

Direct sampling can be used to determine, for example, fish growth rates, the frequency of reproductive failures, fish feeding habits, and fish mortality rates.

Passive Capture Methods

Passive capture techniques include both entanglement (gill and trammel nets) and entrapment methods (hoop nets, fyke nets, trap nets, pound nets, minnow traps, and weirs) (Hubert, 1983). All of these sampling methods use equipment with relatively simple designs and construction that requires little training to use. Each technique, when deployed correctly, can capture large numbers of fish and provide reasonably precise data on relative fish abundances.

Passive capture methods are not without limitations, however. Most are size- and species-selective; that is, they catch some sizes and types of fish more effectively than others. Catches are also biased toward fish with greater daily movements, and numbers of fish caught depend on the duration of the set (length of time the net is left in the lake), times of day they are fished, season, water temperature, light, turbidity, and sometimes unpredictable changes in fish behavior. To help reduce the influence of some of these factors, the fishing effort should be standardized, especially if results will be compared among different periods. In general, passive capture techniques tend to be most efficient when the nets are set overnight and emptied each day.

Entanglement methods

- **Gill nets,** the most common fishing gear that depends on fish entanglement, are generally fished as a single layer web wall (Fig. B-4). Often, experimental gill

nets are made up of multiple panels, with each panel comprised of a different size of mesh. Plastic or wooden floats are used to support the net on the top, with lead weights attached on the bottom to maintain the net in a vertical orientation. Gill nets are relatively light and easy to transport and deploy.

Commonly, gill nets are set to be stationary on the bottom, but they also can be floated on or near the surface or hung vertically through the water column with anchor ropes extending to the bottom or the shore. Depending on how they are deployed, gill nets can sample littoral or pelagic areas at a variety of depths. Nets are generally set while traveling or drifting downwind to keep them from tangling. In turn, net retrieval is usually done while traveling into the wind and fish are removed as the nets are pulled out of the water. Gill nets are commonly fished in lakes and reservoirs with minimal currents and bottoms free of snags.

Mesh sizes should be appropriate for the size of fish sought. Too large a mesh opening allows small fish to swim through, while small mesh sizes do not capture large fish effectively. Gill nets capture fish whose girth is about 1.25 times the size of the mesh perimeter most efficiently. Experimental gill nets (with multiple panels of varying mesh size) are useful for collecting a wide variety of species and fish size classes. Independent of the mesh sizes used, however, gill nets are less efficient at collecting small fish, which do not have the power to swim far enough into the mesh to become entangled.

Gill nets have one major disadvantage. Unless tended at frequent intervals, they generally result in the death of all or most of the fish caught.

Gill nets have one major disadvantage. Unless tended at frequent intervals, they generally result in the death of all or most of the fish caught. Frequent tending (e.g., every one to two hours) to release fish caught in the net can reduce but not eliminate fish mortality. Thus, these nets must be used with caution in most lakes and may not be suitable in some. Shorter set durations, careful removal of the entangled fish, and cooler water temperatures can all help reduce mortality rates.

■ **Trammel nets** are made from three panels of nets: two larger mesh nets on the outside and a single, finer-mesh, looser-hanging net on the inside. While this type of net can be fished in many of the same ways as gill nets, a particularly effective approach is to surround concentrations of fish, such as can occur in weed beds, and then scare the fish into the nets. Fish swimming into the net pass through the first outer netting and then push the inner netting through the second outer netting, trapping themselves in pouches of the protruding inner netting (Fig. B-4).

Trammel nets are best for fish that have external spines or rough surfaces ....

Trammel nets are best for fish that have external spines or rough surfaces, such as catfish, sturgeon, yellow perch, and largemouth and smallmouth bass. Trammel nets have two advantages over gill nets: they tend to leave the fish in better shape following removal from the net, and they are less size-selective. Otherwise, trammel nets have many of the same uses and biases as gill nets.

Entrapment methods

A variety of common entrapment methods are available for sampling, including hoop nets, fyke nets, trap nets, and minnow traps (Hubert, 1983). An important advantage of entrapment sampling techniques is that most of the fish caught are not harmed.

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■ **Hoop nets** consist of circular hoops ranging from 0.5 to over 3 meters (1 1/2 to 10 feet) in diameter that are connected by netting to form a long cylinder (Fig. B-5). The netting mesh size is small enough to prevent all but the smallest fish from passing through (10- to 100-mm mesh; 1/3- to 4-inch). Additional netting in the mouth of these nets forms a funnel-like throat opening into the first hoop. The fish enters the net at the larger end of this funnel opening, while the small diameter of the funnel inside the net prevents captured fish from escaping. Often, the interior of the net includes one or more additional funnel throats that can help concentrate captured fish in the closed "cod end" or "pot" of the net (see Fig. B-5). When the

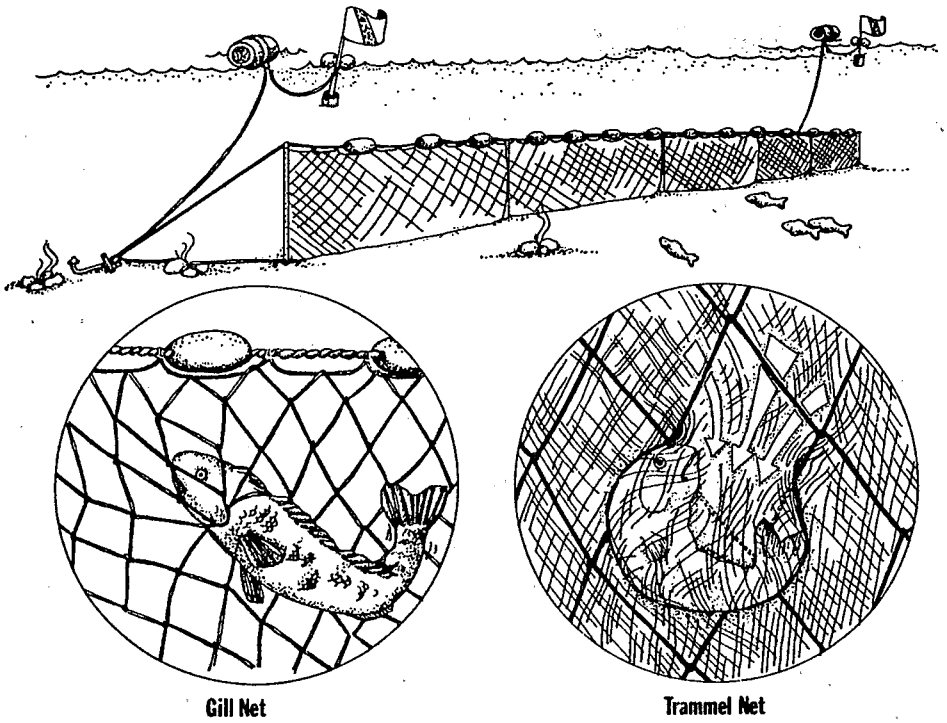

Figure B-4.—Examples of entanglement nets — gill and trammel (source: Hubert, 1983).

first one to three circular hoops at the mouth end are replaced with rectangular frames, the net is called a frame net. Frame nets are less inclined to roll on sloping bottoms or in currents than hoop nets.

While hoop nets are commonly used in rivers and can be fished in fairly strong currents without damage, they can also be fished along lakeshores. They may be especially effective near weed beds to capture the fish attracted to this cover. When setting hoop nets, the cod ends are often anchored to posts driven into the lake bottom. Generally, the nets are baited with cheese or pressed soybean cakes and fished overnight or for 24 hours. When retrieving the nets, the cod ends are retrieved first, the drawstrings closing the net are untied, and the fish are removed and sorted.

Hoop nets share the common biases of the other passive sampling methods discussed previously. As with other entrapment methods, some fish species are better able to escape from the net than others and capture efficiency can depend largely on net size.

■ **Fyke nets** are essentially hoop nets (or frame nets) with a "leader" and/or "wing" net(s) attached to the hoop at the mouth. The leader net extends perpendicularly from the mouth generally toward the shore, while the two wing nets extend out from the mouth at 45° angles (Fig. B-5). Because of their design, fyke nets are most commonly fished in lakes and reservoirs near weedy cover to capture highly mobile, cover-seeking fish species, including sunfish, crappie, bass, and pike. They can also be used to successfully capture trout and salmon species in more open areas of lakes and reservoirs during the spawning season. As fish travel along the shore in search of prey or spawning sites, the leader net deflects their path of travel outward and the wing nets help funnel the fish into the mouth of the net for capture.

[F]yke nets are most commonly fished in lakes and reservoirs near weedy cover to capture highly mobile, cover-seeking fish species . . . .

■ **Trap nets** are very similar to fyke nets in design and use. Both net designs include a leader and/or wing nets (Fig. B-5). The principal difference is that, instead of using hoops to maintain the inner circular integrity of the net from the mouth to the cod end, the rectangular interior of a trap net is maintained by means of spreader rods, floats, and anchors. As a result, trap nets are less bulky

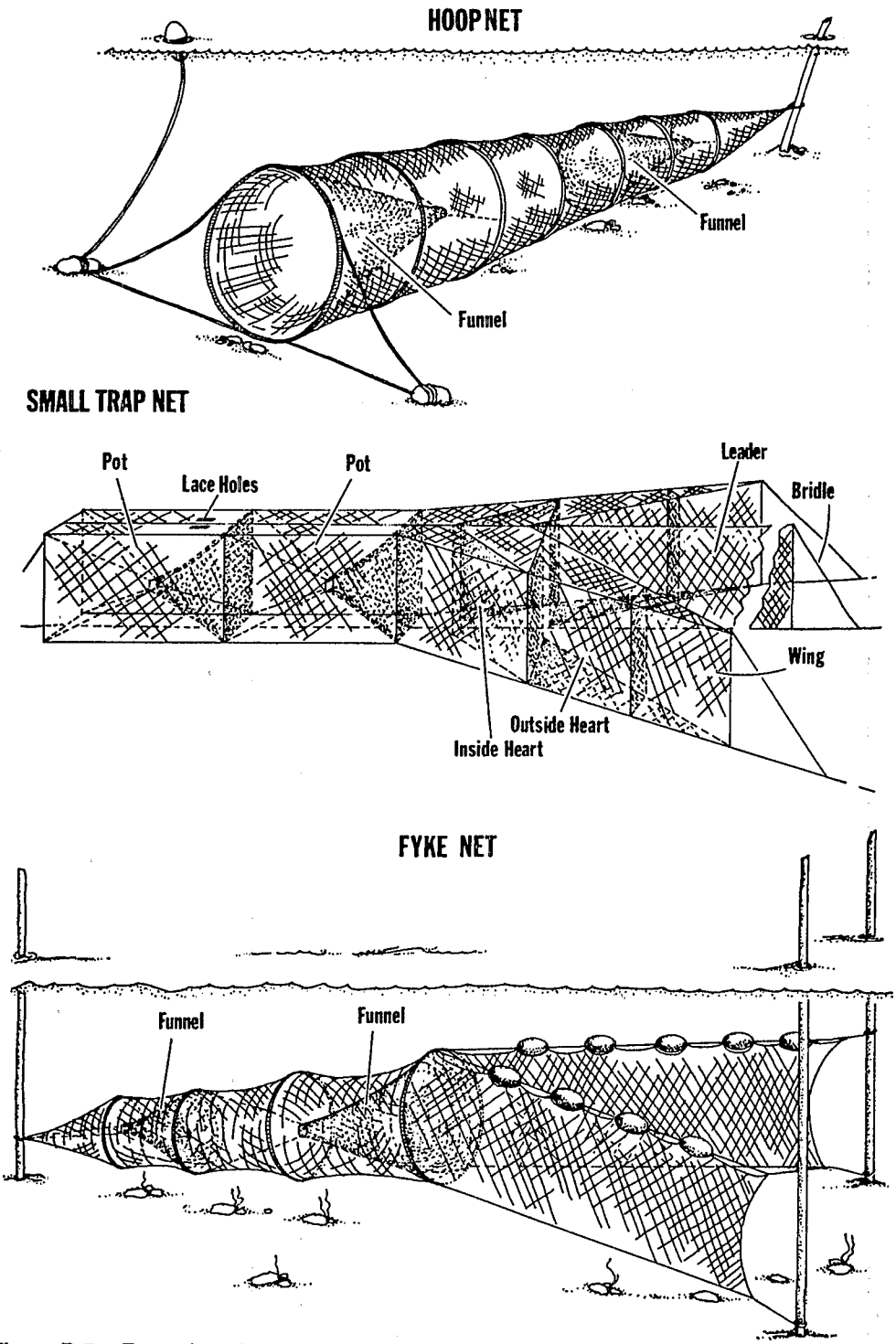

Figure B-5.—Examples of entrapment nets — hoop, trap, and fyke (source: Hubert, 1983).

and easier to transport than other styles of entrapment nets. Thus, trap nets may be especially appropriate in waters with more difficult access (for example, remote lakes with no road access).

■ **Minnow traps** are one example of "pot gear," which also includes lobster, eel, and slat traps used to capture a variety of small fish and shellfish (Fig. B-6). Like hoop nets, which they resemble in general appearance, pot gear is generally baited with dried bread crumbs, cheese, or pressed soybean meal. Wire or plastic minnow traps can be very useful for assessing the presence of small fish in lakes, reser-

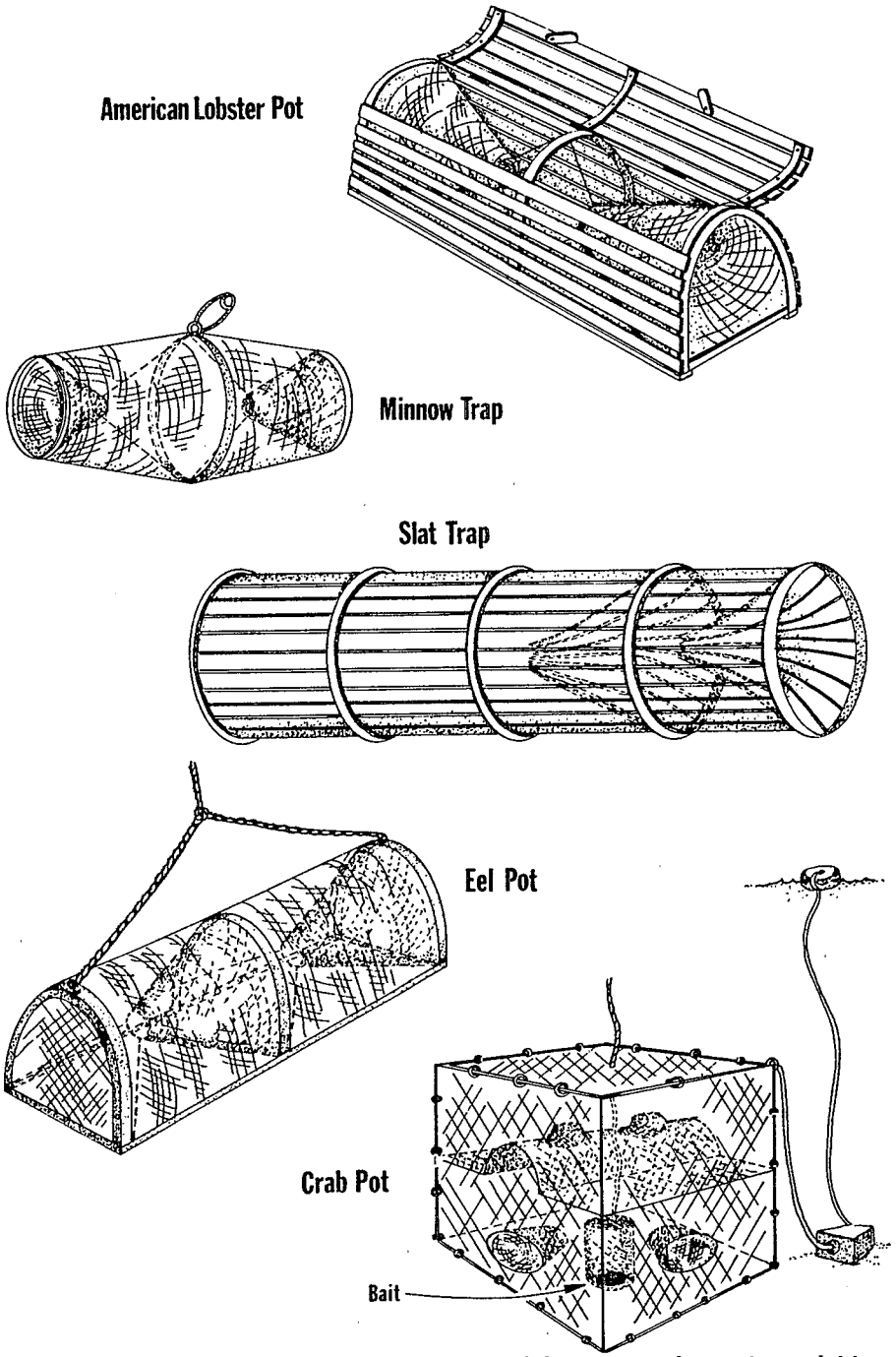

Figure B-6.—Examples of pot gears — American lobster pot, minnow trap, slat trap, eel pot, and crab pot (source: Hubert, 1983).

voirs, and quiet areas of streams. Fish captured in these traps can provide valuable information on the age structure and condition of small-sized fish species as well as supplemental information on the reproductive success of populations of larger species. The capture efficiency of most pot gears is highly variable. As a result, these gear types are relatively poor indicators of fish abundance or fishing catch rates.

Because most of the fish captured can be returned to the water alive, entrapment methods may serve as the primary sampling gear (rather than gill or trammel nets) in waterbodies where it is important to minimize fish mortality—for example, in very small lakes or lakes with small numbers of fish or threatened or endangered fish species.

Active Capture Techniques

Active capture methods include angling, various kinds of seines and trawls that sieve fish from the water, and electrofishing techniques (Hayes, 1983).

Angling is the simplest, at times the most effective, and potentially the most fun collection technique . . . .

■ **Angling** is the simplest, at times the most effective, and potentially the most fun collection technique, but it is often overlooked as an appropriate approach for collecting technical information on fish community status. Angling can be one of the best methods for collecting some fish species and sizes (e.g., adult bass and catfish) that are less vulnerable to many of the other sampling techniques. To provide comparable information among samplers and sampling periods, the angling techniques employed (i.e., gears, effort, times) must be standardized. In the absence of sufficient anglers for a creel survey, standardized angling can also be used to generate data on the recreational fishing potential.

■ **Beach or haul seines** are one of the most commonly used active capture techniques in lakes and reservoirs. Seines are constructed of mesh panels and some include a bag in the middle portion, which can increase catch rates in long seines and facilitate fish removal (Fig. B-7). Generally, floats support the top of the seine at the water surface, while lead weights help hold the seine on the lake bottom. Sticks or poles attached at each end of the seine are used to haul the net through the water. Beach or haul seines may range from a few feet to 90 feet (or more) long.

Seines are generally fished by one or more persons holding each end of the seine and wading through the water. Often one end of the seine is held stationary on or near the shore while the other end is swept out from and then back to the

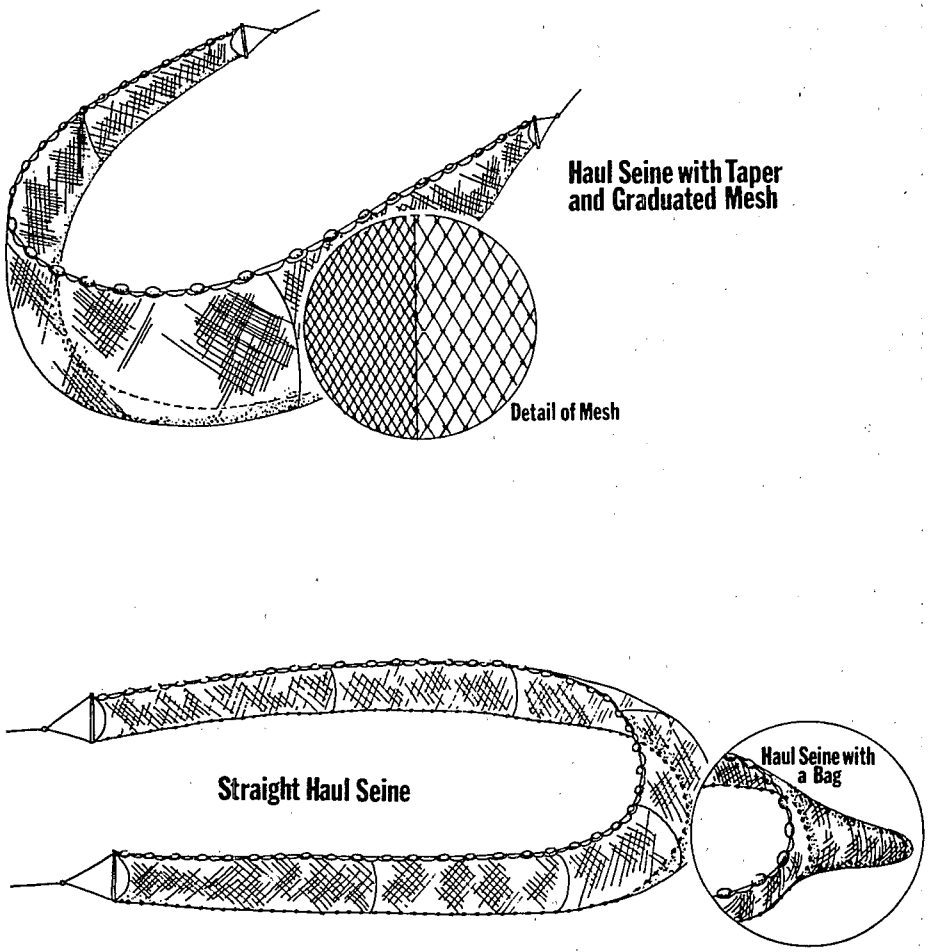

Figure B-7.—Two examples of seines (source: Hayes, 1983).

shore in a wide closing arc. Sometimes, the shore end of the seine is moved parallel to the shore to increase the area of the arc sieved. In deeper waters, a small boat may be used to help drag the outer end of the seine, after anchoring the other end on shore. The boat end of the seine must be attached to a paddle or stick to keep it submerged. In all cases, the depth of the water should be less than the height of the seine. In addition, the area seined should have a relatively smooth bottom, free of any extensive weed cover, so that the lead line glides smoothly over the bottom without riding up on obstructions that would permit fish to escape beneath the seine.

Beach seines are most effective for capturing near-shore spawners and small, slow moving or schooling fish that live in shallow waters in both lakes and streams. Field experience indicates that long (90-foot) seines cause less disturbance and provide better estimates of the numbers and types of fish within the sampled area than do shorter seines. Small mesh sizes (i.e., 6.4-mm or 1/4-inch mesh) allow capture of small fish, which may provide an indication of fish reproductive success or the available forage base. The number of fish caught relative to the area of the lake bottom included within the arc circumscribed by the seine haul provides a quantitative estimate of fish abundance in the littoral habitat or stream.

Beach seines are most effective for capturing near-shore spawners and small, slow moving or schooling fish that live in shallow waters in both lakes and streams.

■ **Trawls** are bag nets that are generally towed behind one or two boats to sieve fish from the bottom, midwater, or surface layers of the water column (Fig. B-8). Catches from trawls can be quantified based on the volume or surface area of water sieved during the time of the haul. Large trawls for capturing adult fish are used primarily in marine environments or larger lakes, reservoirs, or slow-moving rivers. One of the most common applications of trawls for freshwater fisheries assessments, however, is to sample larval and juvenile fish in the pelagic region with a small-mesh trawl to estimate year-class strength and young-of-the-year survival.

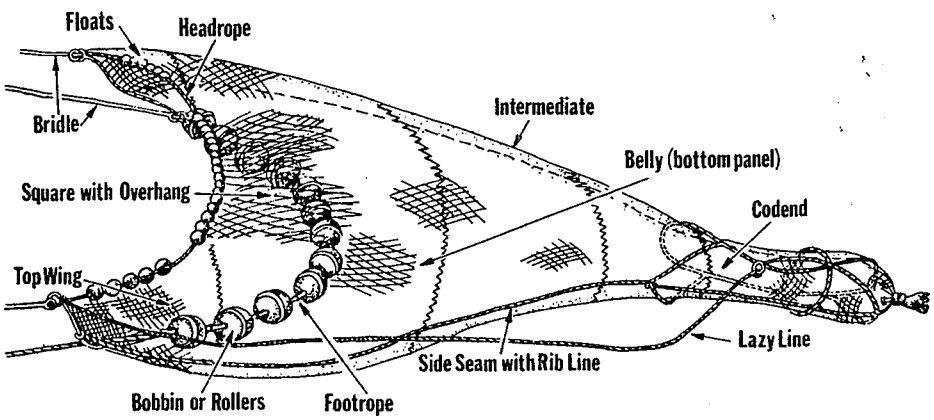

Figure B-8.—Example of trawl net (source: Hayes, 1983).

■ **Electrofishing** involves the use of electricity to immobilize fish, which are then captured by dip nets. Subsequently, fish are usually returned to the water unharmed. Electricity can also be used to guide or block fish movements or to anesthetize or quickly kill fish for eradication or human consumption. Three types of electrofishing units are commonly used to capture fish: (1) boat-mounted units that are usually generator powered, (2) backpack-mounted units powered by a generator onshore, and (3) backpack-mounted units powered by either 12V batteries or small generators mounted on the backpack frame. Reynolds (1983) and Cowx and Lamarque (1990) provide detailed discussions on the use of electricity for fish sampling. Information from these documents is summarized in the next paragraphs.

Electrofishing involves the use of electricity to immobilize fish, which are then captured by dip nets.

Fish react to electric fields in several ways, depending on the type of current and voltage gradient they encounter. Current densities are highest near the electrode and decrease rapidly with increasing distance away from the electrode. The higher the current density, the higher the voltage gradient and the greater the effect. High current densities kill fish, moderate densities stun them, and low densities produce a "fright" reaction, allowing the fish to escape.

Current types include unmodified direct current (DC), unmodified alternating current (AC), and a number of modifications of DC and AC, including pulsed DC (with different pulse shapes, durations, and frequency), quarter-wave rectified AC, fully rectified AC. Each current type produces a somewhat different fish response. Fish exposed to DC in the "stun" field are attracted to the anode (positive electrode); fish swim toward the anode, where they roll over and are easily captured. In an alternating current (AC) field, by contrast, fish tend to orient perpendicularly to the electric field, show no directed movement toward the anode, and tetanus (state of muscle rigidity) occurs at a greater distance from the electrode than with DC. Unmodified AC also causes the greatest damage to fish and can result in hemorrhaged tissue, ruptured swim bladders, and fractured vertebrae. Fish responses to pulsed DC and modified AC are generally intermediate between those for unmodified DC and AC. The art of effective electrofishing is selecting the best current type (usually pulsed DC) that will capture the greatest number of fish with the least injury or mortality, given the specific environmental conditions in the field.

The art of effective electrofishing is selecting the best current type (usually pulsed DC) that will capture the greatest number of fish with the least injury or mortality, given the specific environmental conditions in the field.

Water conductivity (i.e., its ability to conduct an electric current) can have a substantial effect on electrofishing efficiency. At high conductivities (> 500 μmhos/cm) water is less resistant than fish and electric currents tend to flow around rather than through the fish, producing little to no electroshock. For this reason, electrofishing is not widely used in brackish or salt waters. In waters with very low conductivity (< 100 μmhos/cm), the electric field is limited to the immediate area of the electrodes. Higher voltage gradients can be produced by increasing the circuit voltage or, within limits, the electrode size. Increasing the voltage, however, requires a larger generator, which may be expensive and unwieldy. In small streams, salt blocks added upstream can be used to increase water conductivity but may be illegal in some areas.

Electrofishing efficiency is also affected by other environmental conditions as well as operating conditions and the target fish species. Because of the physical limitations of the electrical field, electrofishing is effective only in relatively shallow water (less than about 10 to 12 feet). At night, large predatory fish can often be found inshore feeding. Fish are attracted by the lights used during sampling and seem less apt to avoid capture. Thus, night electrofishing generally catches more fish, more species, and larger fish than electrofishing during the day. High turbidity and dense macrophyte beds can make it more difficult to see and collect fish that have been stunned. High water transparency, on the other hand, can shift fish distributions into deeper waters, where they are less susceptible to capture. At a given voltage gradient, larger fish receive a greater electroshock than smaller fish. Large fish are also more visible and may be inadvertently selected during fish collections. Finally, fish species that inhabit littoral areas in lakes are more vulnerable to capture than are pelagic or benthic species.

Working with electricity near water can be hazardous. However, with appropriate precautions, electrofishing can be conducted safely.

Working with electricity near water can be hazardous. However, with appropriate precautions, electrofishing can be conducted safely. Goodchild (1990, 1991) and Reynolds (1983) discuss guidelines for equipment construction, maintenance, and safe operations. In addition, many States and provinces conduct training and certification courses to ensure that electrofishing is used safely and reliably.

Fish Toxicants

The use of rotenone and other fish poisons to remove populations of undesirable fish species was discussed in Chapter 8. The same principles and methods can be applied to fish sampling. Small areas of a lake, reservoir, or stream (e.g., coves or stream reaches) are blocked off with nets and treated with rotenone. Fish killed by the rotenone treatment are then collected over the next several days using hand-held or boat-mounted scoop nets. It is essential, especially in standing waters, that rotenone be applied over the entire sample area. Generally, the rotenone is applied as an emulsifiable liquid. A weighted hose can be used to ensure complete mixing throughout the water column. Potassium permanganate or another detoxifying agent (e.g., chlorinated lime) can be applied outside the boundary of the blocking nets to reverse the action of the rotenone.

The toxicity of rotenone varies with fish species and size, water temperature, pH, and concentrations of dissolved oxygen and suspended matter. At water temperatures of 50 to 75°F, 1.0 to 2.0 mg/L (ppm) of rotenone are usually applied to assure a complete kill of all fish species. Treatments in streams tend toward the lower limit of this range, while the upper limits are more common in larger, warmer, turbid lakes and reservoirs. These concentrations are also lethal to zooplankton and many other aquatic invertebrates.

Toxicants are particularly efficient for obtaining a nearly complete sample of the fish within a particular area for detailed information on population biomass and age structure. Potential problems can arise, however, where high densities of macrophytes occur. Such growths can trap affected fish and prevent their retrieval. Recovery percentages of marked fish introduced before treatment or underwater SCUBA surveys can be used to evaluate collection efficiencies and develop correction factors to account for the proportion of fish not retrieved. Davies and Shelton (1983) provide additional details on fish sampling with rotenone and other toxicants; Booth and Holtz (1988) review the available literature on rotenone effects.

Toxicants are particularly efficient for obtaining a nearly complete sample of the fish within a particular area for detailed information on population biomass and age structure.

Note: Since both rotenone and potassium permanganate are hazardous substances, their use requires care in handling to avoid contact with the skin and especially with the eyes, nose, and throat. All individuals applying pesticides, including rotenone, must be certified.

Observational Techniques

Two common observational techniques can be used to aid in detecting fish and quantifying fish abundance in lakes: hydroacoustics (sonar) and visual underwater surveys conducted by swimmers using snorkeling or SCUBA.

■ **Hydroacoustical methods** have advanced greatly in the past decade. "Fish finders" are now commonly used by anglers. More sophisticated devices that can accurately estimate fish density and biomass and monitor fish behavior have been successfully applied in both small and large lakes (Thorne, 1983; Brandt and Unger, 1986). Two advantages of hydroacoustics are (1) the measurements are not affected by most environmental conditions and (2) data on fish communities can be collected without disrupting fish behavior or requiring their removal. Disadvantages include poor discrimination among fish species, poor ability to detect fish on or very near either the lake bottom or surface, and the lack of fish samples for determining length, weight, and age distributions. In addition, sophisticated hydroacoustic equipment can be expensive and requires specialized training and expertise. Once the equipment is purchased and training completed, however, the costs of data collection per sampling trip are relatively low compared to many other fish sampling techniques. Sonar may be especially useful for evaluating capture efficiencies associated with other gear; for example, by estimating fish abundance just before trawl passage.

Two advantages of hydroacoustics are (1) the measurements are not affected by most environmental conditions and (2) data on fish communities can be collected without disrupting fish behavior or requiring their removal.

■ **Underwater survey** is the second common observational technique of fish in lakes or streams using snorkel- or SCUBA-equipped divers (Helfman, 1983). Snorkeling has the advantages of requiring less equipment, limited training, and consequentially, lower costs. SCUBA, on the other hand, allows for longer continuous underwater sessions. The efficiency of both methods can be limited by poor visibility. Diving at night, in areas with strong currents, or under ice is potentially dangerous and should be avoided.

The numbers, species, length, behavior, and locations of fish observed can be used to estimate fish species composition, approximate size distributions, and relative abundance as well as fish distribution and behavior patterns. Actual population estimates can be made using transect methods, where divers count fish while swimming or being pulled behind a boat, or grid count techniques, where divers swim to set locations or for set distances before stopping to count fish. Data can be recorded underwater on special underwater paper and scrolls, erasable slates, or writing cuffs made from roughened plastic pipes.

When there are particular concerns about populations of genetically unique fish species within a lake or reservoir, the nondisruptive and nondestructive aspects of these observational techniques are particularly important attributes.

When there are particular concerns about populations of genetically unique fish species (e.g., fish species listed as threatened or endangered) within a lake or reservoir, the nondisruptive and nondestructive aspects of these observational techniques are particularly important attributes. Other fish observation methods include underwater cameras and glass- or plexiglass-bottom boats and lookboxes.

Marking Fish for Identification

Fish tags and other marks are used to uniquely identify individual fish or groups of fish. Data on marked fish collected using one or more of the above sampling techniques can then be used to

- study the movement and locations of individual fish in their natural environment over extended periods,
- identify individual stocks of fish of special interest,
- assess the success of fish stocking programs,
- estimate fish population abundance, mortality, or angler harvests, and
- validate fish age and growth assessments.

Wydoski and Emery (1983) provide a comprehensive review of the methods, uses, and advantages and limitations of alternative techniques for marking fish.

Fish marks can be biological, chemical, or physical.

Fish marks can be biological, chemical, or physical. Biological marks have natural origins, including marks caused by parasites, morphological differences, and genetic differences among individual fish or groups of fish. Chemical marks can be applied by immersion, injection, tattooing, or feeding fish foods containing dyes. Physical marks include various fin clips, internal and external tags, cold branding, and spray (dye) marking. Table B-1 presents general criteria for selecting appropriate fish marks.

Fin clipping and external body tags are the most common methods for marking fish.

Fin clipping and external body tags are the most common methods for marking fish. Fin clipping can be used to identify specific fish stocks or groups of fish. However, the number of marking combinations is limited by the number of fins. Thus, fin clips are inappropriate for tracking individual fish. Partial fin clips or punches may be used when fish need only be recognized over a short time, as with mark-recapture studies conducted over a few days (discussed further later in this chapter). Otherwise, the entire fin is removed by clipping close to the body. Even these fins can regenerate, however, although the regenerated fins are often deformed (Fig. B-9). Permanent records should be maintained of all fin clip combinations used in a given water.

Some special studies may require tagging of individual fish. Many kinds of external and internal body tags are available from a variety of sources (Fig. B-10,

Table B-1.—General criteria for selecting a marking technique (modified from Wydoski and Emery, 1983).

CHARACTERISTICS	BIOLOGICAL (NATURAL)	CHEMICAL			PHYSICAL	
		IMMERSION	INJECTING AND TATTOOING	FEEDING	MUTILATION	TAGS
Duration of Mark						
Days		X	X		X	X
Weeks		X	X	X	X	X
Months	X		X	X	X	X
Years	X		X	X	X	X
Individuality of Mark						
Very Low		X	X	X		
Low	X				X	
High						X
Size of Organism at Marking						
Very Large	X		X	X	X	X
Large	X		X	X	X	X
Medium	X		X	X	X	X
Small	X	X	X	X?	X	X
Very Small	X	X	X	X		X
Numbers to be Marked						
Low (<59)			X	X	X	X
Medium (>50—<200)		X	X	X	X	X
High (>200—<1,000)		X	X	X	X	X
Very High (>1,000)	X	X	X	X	X	X
Recovery Method						
Visual	X[a]	X	X[c]	X[a]	X	X
Nonvisual						X[a]
Cost						
Low		X		X		
Medium			X		X	X
High	X[b]					

[a]May be necessary to use a microscope or other equipment to detect mark
[b]Personnel must have specialized skill to identify mark and look at large numbers of fish
[c]Ultraviolet light (black light) necessary to detect flourescent pigments

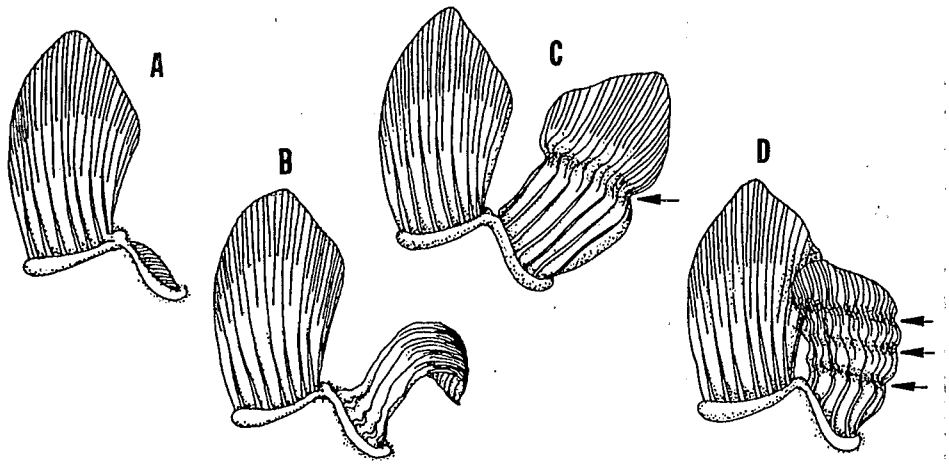

Figure B-9.—Appearance of generated fins — (A) fins clipped close to body usually have little generation; (B) fins clipped away from body often regenerate with deformed rays; (C) fins clipped further from the body often regenerate to normal size with irregularities where clip occurred; (D) fins with multiple clips often will show multiple irregularities (source: Wydoski and Emery, 1983).

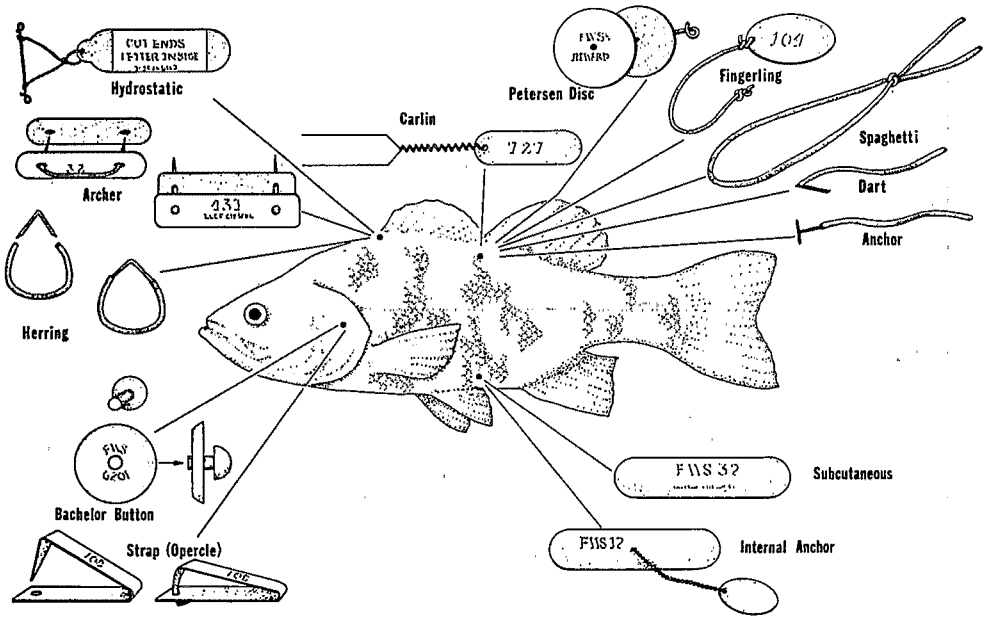

Figure B-10.—Example of the various tags and body locations on or in fish used for marking fish (source: Wydoski and Emery, 1983).

Table B-2). Individually coded tags can be used to identify individual fish and most tags are highly visible. However, fish tags cost substantially more than fin clips and may work lose and be lost over time. Before purchasing physical body tags, the manufacturer or distributor should be requested to supply information on the long-term persistence of their tags on or in fish. Tag loss rates reported range from a low of 13 percent over 12 months (Keefer, 1988) to a high of 79 to 90 percent over 9 months (Prichard et al. 1974; reviewed by Evans, 1989) and vary with tag design, quality control during manufacture, quality of attachment, and other factors. Fish handling and tagging, if not conducted with care, can also cause substantial fish mortality after release.

Radio and sonar tags are used to monitor remotely the location, behavior, and/or physiology of individual fish in their natural environment.

Radio and sonar tags are used to monitor remotely the location, behavior, and/or physiology of individual fish in their natural environment. Generally, radio tags work better than sonar tags for tracking fish in waters that are shallow, thermally stratified, low conductivity, or turbulent, and where large areas need to be searched to track highly mobile species. Tags can be attached externally, surgi-

Table B-2.—Manufacturers and distributors of fish marking materials, equipment, and related supplies (modified from Wydoski and Emery, 1983).

Carolina Biological Supply Company
2700 York Road
Burlington, NC 27215
919-584-0381
FAX 919-584-3399
Biological stains and chemicals

Fisher Scientific Company
1600 W. Glenlake Avenue
Itasca, IL 60143
708-773-3050
FAX 708-773-5916
Biological stains and dyes

Floy Tag & Manufacturing, Inc.
4616 Union Bay Place, NE
Seattle, WA 98105
206-524-2700
FAX 206-524-8260
Dart tags, spaghetti tags (tying or locking), anchor tags, stream tags, Petersen tags, applicators

National Band and Tag Co.
721 York Street
P.O. Box 430
Newport, KY 41072
606-261-2035
FAX 606-261-8247
Monel strap tags, magnetic internal tags, vinyl subcutaneous tags

Northwest Marine Technology
Shaw Island, WA 98286
206-468-2340
FAX 206-468-3844
Coded wire tags and related equipment

Philips Process Co., Inc.
20 Magnolia Street
Rochester, NY 14608
716-436-2310
No FAX
Industrial inks for all purposes

Pilgrim Plastic Products Co.
278 Babcock Street
Boston, MA 02215
617-782-9300
FAX 617-782-4740
Internal tags, messages printed on white plastic for capsule tags

Salt Lake Stamp Co.
380 West Second South, Box 2399
Salt Lake City, UT 84101
801-364-3200 or 800-677-6809
FAX 801-364-6809
Circular strap tags

Scientific Marking Materials
Box 24122
Seattle, WA 98121
206-524-2695
No FAX
Fluorescent pigments and equipment to apply to fish

Sigma Chemical Company
P.O. Box 14508
St. Louis, MO 63178
314-771-5765
FAX 800-325-5052
Biological stains and dyes

Wildlife Supply Company
301 Cass Street
Saginaw, MI 48602
517-799-8100
FAX 517-799-8115
Aquatic sampling equipment

cally implanted, or inserted into the fish's stomach. After a suitable period of recovery and tag testing, the fish is released into the environment. Information is then relayed from the tag through ultrasonic or radio signals to a remote receiving system. Tags may be set to unique signal frequencies to identify individual fish. Sensor tags are also available commercially that monitor temperature or water depth, although sensor tags and the associated recording equipment are expensive. Winter (1983) reviews telemetry systems, equipment needs, methods for tag attachment, fish tracking, and data collection and analysis.

Fish Measurements

Fish collected using the sampling techniques described previously can be measured for length and weight; aged; examined to determine their sex, sexual maturity, and fecundity; and used to estimate the density and biomass of the fish population in the lake, reservoir, or stream. Methods for each of these tasks are described in the following subsections, compiled from information presented in Living Lakes, Inc. (1989), Lagler (1956), Everhart and Youngs (1981), Anderson and Gutreuter (1983), and Jearld (1983).

Assessing Fish Size, Age, Growth, and Condition

Processing fish in the field

Generally, all fish caught in the field should be counted, by species. Data on fish length, weight, and age can be collected for all fish caught or for a representative subset of the total samples.

Generally, all fish caught in the field should be counted, by species. Data on fish length, weight, and age can be collected for all fish caught or for a representative subset of the total samples.

Total length is the distance from the anterior-most part of the fish to the end of the longest caudal fin ray when the fin is compressed for maximum extension (Fig. B-11). Length measurements should be to the nearest millimeter or 1/8 inch. Length measurements should be obtained for all target game fish caught or a large (> 100) representative sample of the fish caught for length-frequency analyses.

Individual fish should be weighed on the most sensitive scale available. When a large number of fish are captured at a single location, only a subsample (30 to 100 fish per species) must be weighed individually. The fish weighed should be selected to cover the full range of fish length. As a general rule of thumb, up to five fish should be measured in each one-inch length class. This results in approximately 30 individual fish weights for small species, such as bluegill, and about 100 for large species (with more length classes), such as largemouth bass. The remaining fish may be weighed as a group, sorted by species.

To assess the general health of the collected fish, examine each fish for signs of physical deformity, wounds, injuries, and external parasites. The presence of marks (e.g., fin clips or tags) should also be noted. Additionally if appropriate, fish

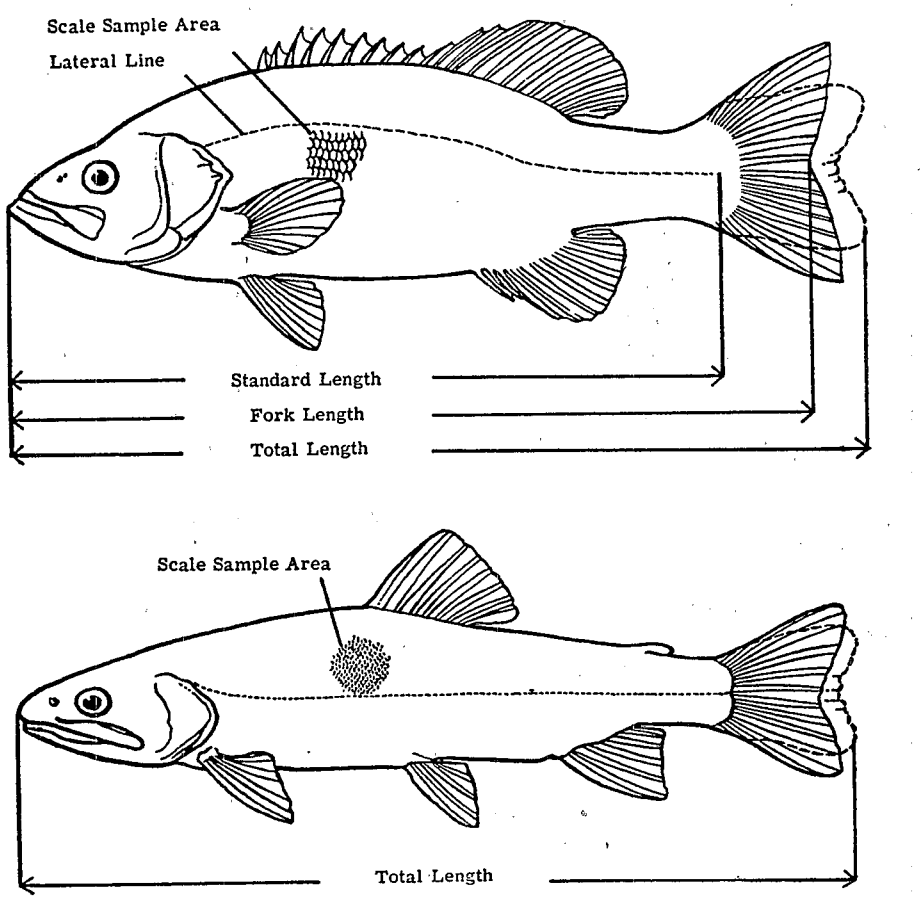

Figure B-11.—Locations included in various length measurements used for fish and locations used for sampling scales described in text (source: Lagler, 1956). Top: spiny-rayed fish (perch, sunfish, bass); bottom: soft-rayed fish (trout, salmon, pike).

sex and sexual maturity can be determined by examining adult fish during the spawning period (discussed in the next subsection). All information should be recorded on field sheets.

If fish are to be aged, calcified structures for age estimation should also be collected from a representative sample of fish. As for fish weights, preferably about five fish per one-inch length class should be aged, for a total of 30 to 100 fish per species. Lagler (1956), Bagenal and Tesch (1978), Jearld (1983), and Casselman (1987) provide detailed discussions of methods for determining fish age.

If fish are to be aged, calcified structures for age estimation should also be collected from a representative sample of fish.

Fish scales are the most commonly used structure for fish aging. For soft-rayed fish species (e.g., trout, salmon, and pike), scale samples should be collected from the left side below the forward-most portion of the dorsal fin and above the lateral line (Fig. B-11). For spiny-rayed fish (e.g., perch, sunfish, and bass), scales should be obtained from the left side of the fish in the region below the lateral line and behind the pectoral fin, with the pectoral fin pressed against the body. Areas of obvious scale regeneration should be avoided. If necessary, the scale sample can be collected from the right side of the fish; it may be necessary to skip scale sampling if excess scarring is present on both sides.

Fish scales are the most commonly used structure for fish aging.

Remove dirt and mucus in the area where the scales are to be sampled by gently scraping in the direction of the tail with a knife. The scales can then be removed by placing the blade of the knife on the scales in the cleaned area and carefully moving the blade with downward pressure toward the tail of the fish. When several scales are obtained, they should be placed within a small folded piece of paper and the paper inserted into a labeled scale envelope. The scale removal instrument should be cleaned after each sample is taken. Scale envelopes should be labeled with the name of the waterbody, location, date, collection method, fish species, number, length, weight, and collector information. These samples and accompanying field sheets are then returned to the laboratory for analysis.

All other calcified structures used for age determination require that the fish be sacrificed. Often, however, these structures provide more reliable age estimates than scales for certain species, age classes, or environmental conditions. Otoliths (earstones) can be used to determine fish age in days for juvenile fish or improved age estimates for adult fish from waters where the annual marks on fish scales are poorly defined. Otoliths are removed by cutting open the top of the fish skull, from slightly behind the eyes back to the upper edge of the gill cover. The head is then opened by pressing down quickly on the nose, and the large sacculus otoliths should be visible behind the brain. After removal, otoliths can be stored dry in an envelope or in alcohol or glycerin. Storing otoliths in a medium of 2:3 glycerine to alcohol helps to clear thicker otoliths and facilitate fish aging at a later date.

For catfish (Ictaluridae), spines from the left pectoral fin should be obtained by grasping the spine with a forceps or pliers, and pulling and twisting the spine outward to remove it at the point it enters the body (articulation). The spine should then be placed in a labeled scale envelope. Similarly for suckers (Catostomidae), fin rays may be better for age determinations than scales. Fin rays can be severed at or below their articulation using cartilage scissors or cutting pliers. Finally, the cleithrum bone is frequently used for more accurate aging of esocids (pike, pickerel, and muskellunge).

Laboratory procedures for aging fish using anatomical structures

After being removed from the scale envelopes, scales are soaked in water to separate them and remove debris. A small, fine-bristle brush or ultrasonic cleaner can facilitate this process. Six to eight scales are mounted on a single cellulose acetate slide and rolled through a scale press. These acetate impressions are then

examined to estimate the fish's age. A diamond pencil or other suitable implement should be used to etch a code to identify the scale mounts from each individual fish into the upper right-hand corner of each acetate slide.

With trout and small fish, acetate impressions can be difficult to interpret. In these cases, scales should be mounted between two glass slides. The slides are taped at each end and labeled in the same manner used to identify the acetate impressions. All mounts and acetate impressions should be stored in their respective envelopes with their original scales.

Pectoral spines, fin rays, and cleithra should be sectioned perpendicular to the longitudinal axis just above the basal recess or groove for spines and fin rays. It may be necessary to dry some spines and rays in an oven before sectioning. Sections 0.4-0.6 mm thick generally are cut using a fine (70 teeth per inch) jewelers' saw. Cut sections can then be polished, if necessary, with an extra fine (#180 or finer) grit silicone carbide paper. A clear mounting cement can be used to mount sections onto glass or plastic slides. Typically, two or three sections from a single fish should be mounted onto a single slide, with each slide labeled as noted above.

Otoliths may be examined directly in glycerin or alcohol; larger otoliths may require thin sectioning using a jeweler's saw.

After the scales, otoliths, spines, fin rays, or cleithra from a sampling trip have been processed, the samples should be sorted by species and size. Examinations to estimate fish ages should proceed one species at a time, beginning with the smallest (i.e., youngest) fish. Since members of a species from the same lake should exhibit similar growth patterns, working from the smallest to the largest can help to avoid overlooking annuli and reduce errors in fish aging.

The impressions or mounts of the scales or other structure are examined using a microprojector or microscope. These structures each show growth patterns similar to tree growth rings. During cold weather, growth slows and the ringed patterns grow close together, at times appearing as a single dark ring. Generally, the interval between dark rings represents the growth between one winter and the next (Fig. B-12). However, factors other than winter can cause growth to slow and dark "false annuli" to form. These factors can include unseasonably cold weather, chemical stress, disease, or spawning, factors not uncommonly encountered in natural populations. Therefore, when estimating fish ages, it is critical to watch for such problems and to obtain expert assistance. Lagler (1956), Bagenel and Tesch (1978), Jearld (1983), Casselman (1987), or other fisheries management texts should be consulted for more information on fish aging.

Back calculation of length at age

[I]t is also assumed that the distance between each scale annuli is proportionally equal to the increase in the fish's total length for that year.

While a variety of formulae and techniques are available for assessing fish growth, only one approach—using a modified direct-proportionality formula—is discussed here. It is assumed that there is a direct linear relationship between the total length of a fish and its total scale, otolith, spine, or fin ray radius. Furthermore, it is also assumed that the distance between each scale annuli is proportionally equal to the increase in the fish's total length for that year. Using these relationships, a graph of body length against scale radius can be produced for each group of fish (Fig. B-13). Male and female fish often have distinctly different growth rates and thus require separate scale-body length relationships.

Frequently, rather than a strict 1:1 relationship between scale radius and fish length that passes through the origin (as in line A in Fig. B-13), body growth begins before scale formation, as in line C, or the relationship between scale and body length may best match line B. If the y-axis is crossed at some positive or negative length, then a correction factor is needed, requiring use of a modified direct-proportionality formula:

$$L' = C + \frac{S'(L - C)}{S}$$

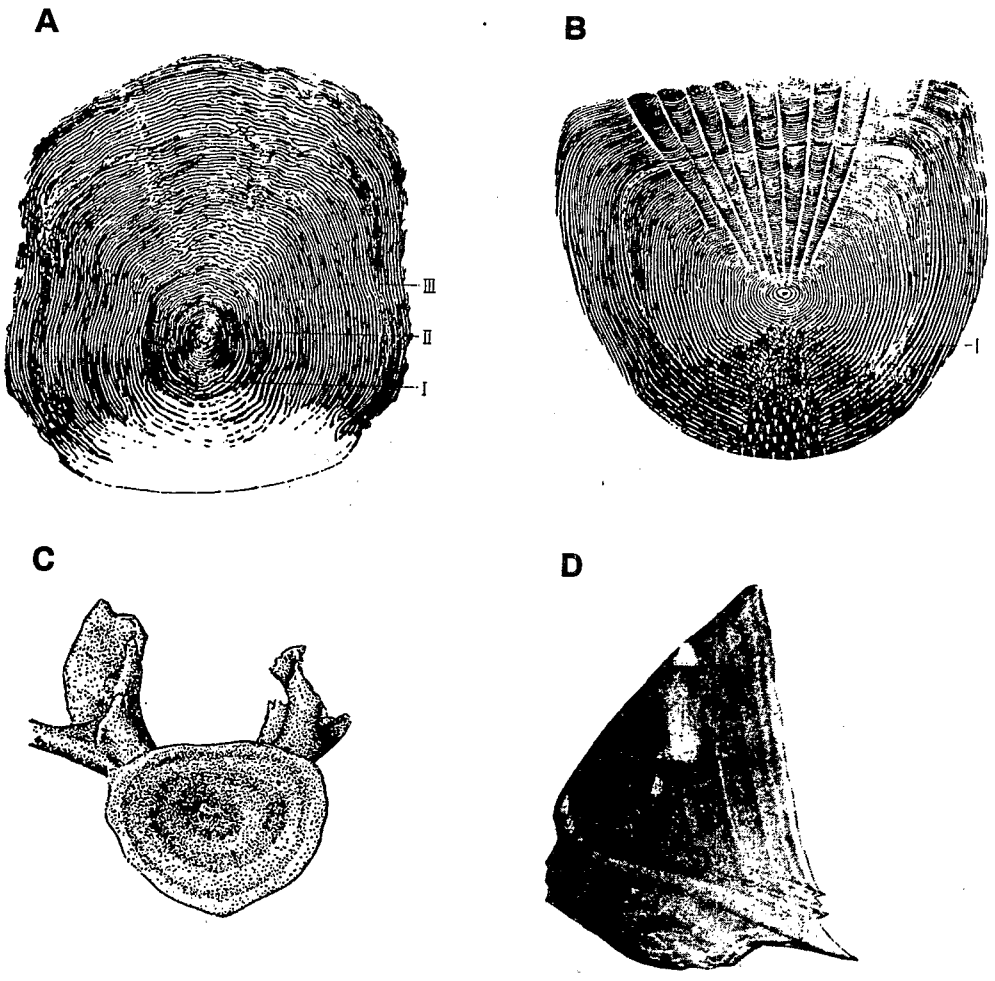

Figure B-12. — Typical enlarged appearances of structures used to age fish: (A) trout scale showing three annuli; (B) sunfish scale showing one annuli; (C) madtom catfish vertebra showing two annuli; (D) yellow perch opercle showing five annual marks (source: Lagler, 1956).

where: L′ = length of fish when annulus "n" was formed,
S′ = radius of annulus "n" (at length L),
S = total scale radius,
L = length of fish at time scale sample was obtained, and
C = intercept of the line on the y-axis.

Standard intercept values are available in the literature for many species (Carlander, 1982) and may be preferable to use when sample sizes are small rather than calculating the y-intercept by regression analysis. Digitized pads and computer programs are also available that can facilitate fish scale measurements and back-calculation of fish lengths (Frie, 1982).

Length-frequency analysis

Length-frequency analyses often can aid in the assessment of fish ages, as long as each age group has a unimodal size distribution and there is little overlap in fish lengths among age classes. Plots are prepared showing the numbers of fish caught in each length interval (see Fig. 3-9, Chapter 3). Various graphical and computer-assisted statistical methods can be applied to compile individual lengths for a large number of fish from a population. Accurate estimates of fish age based on length measurements are generally pos-

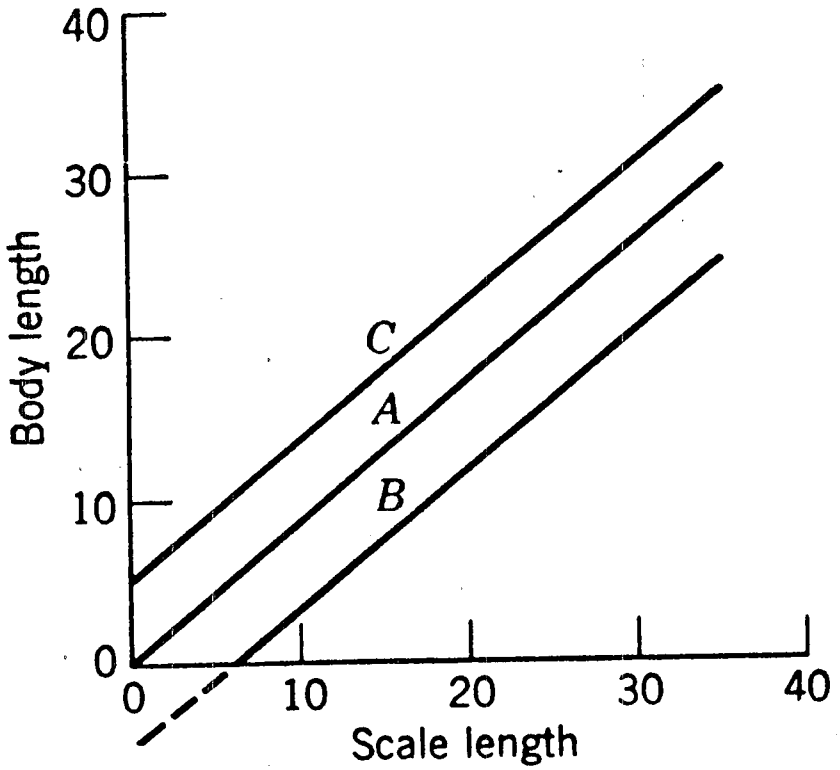

Figure B-13.—Example relationships showing relation of body length and scale radius (source: Everhart and Youngs, 1981). Explanation of lines A, B, and C appears in text.

sible, however, only for younger age classes or for fish species with relatively short life spans (less than five years). In addition as noted above, male and female fish often have distinctly different growth rates and may require separate length-frequency analyses.

Condition factors and relative weight

Fish length and weight measurements can be used as the basis for a number of indices of fish well-being....

Fish length and weight measurements can be used as the basis for a number of indices of fish well-being, including Fulton's condition factor (C or K), the relative condition factor (Kn), and relative weight (Wr). Calculation methods for each of these indices are presented in Chapter 3.

Sex, Maturation Rate, and Fecundity

Rarely for lake management programs is the need for information on fish sex sufficient to justify destroying large numbers of fish.

The eggs of most fish species are fertilized outside of the body, and because of this, most fish do not have specialized external reproductive structures. Without such morphological characteristics, it is impossible to distinguish between males and females during most of the year without dissecting the fish and examining the reproductive organs. Rarely for lake management programs is the need for information on fish sex sufficient to justify destroying large numbers of fish.

For a period before, during, and following spawning, however, some species develop sexually dimorphic characteristics. For example, some male trout and salmon develop hooked jaws and humped backs. Tubercles form on the heads of the males of some suckers, chubs, and minnows. Some fins of certain fish species elongate, and in a number of species, males and occasionally females become more colorful. Female fish may also have visibly distended body cavities when they are filled with eggs. General references on fish taxonomy (Eddy, 1957) and regional guides to fishes (Baxter and Simon, 1970; Phillips et al. 1982) provide descriptions

of these species-specific morphological differences between the sexes during spawning times. In addition in some species, males and females can be distinguished during spawning by applying gentle front-to-rear pressure on the abdomen to extrude gametes (eggs or sperm).

Lake problems that result in poor reproductive success may cause missing year classes and fish population declines, as discussed in Chapter 3. The population sampling and assessment procedures discussed in earlier sections of this chapter can reveal missing age classes. In particular, the absence of small, young fish in samples collected using beach seines or minnow traps can provide an early warning of year-class failures. Such observations may trigger the need for more comprehensive evaluations of specific reproductive functions, such as sexual maturation and fecundity (number of eggs per female).

Lake problems that result in poor reproductive success may cause missing year classes and fish population declines . . . .

Sexually mature fish can be identified using the sexual characteristics described above or by dissecting the fish and examining the condition of the reproductive organs. In combination with age estimates, the average age at which fish reach sexual maturity can be determined. The gonadosomatic index (GSI) — the weight of the gonads expressed as a percentage of body weight— may also be monitored as an indicator of gonad development and maturity.

Fecundity is determined by counting, weighing, or measuring the volume of eggs per fish in a representative sample of females from the lake. Larger fish generally have more eggs. Thus, analyses of fish fecundity must account for differences related to fish size. Synder (1983) provides additional information on methods for studying fish fecundity.

If the ages at which fish sexually mature or levels of fish fecundity are significantly higher or lower than expected based on data from similar lakes in the region, then further study of fish population dynamics in the lake may be warranted.

Estimating Fish Population Size

Commonly used approaches for estimating fish density or biomass in a lake or stream include catch per unit effort, mark-recapture, and depletion methods. Estimates of absolute fish abundance can require considerable technical expertise and resources, especially in large lakes and reservoirs. As a result, absolute population estimates may be practical only in streams and small-to-moderate sized lakes. Furthermore, for many management purposes, information on relative fish abundance is sufficient and more cost effective.

Estimates of absolute fish abundance can require considerable technical expertise and resources, especially in large lakes and reservoirs. . . . [F]or many management purposes, information on relative fish abundance is sufficient and more cost effective.

Catch per unit effort (CPUE) is the most commonly used index of relative abundance. The basic assumption is that CPUE is related directly to population size:

$$C = q\,f\,P$$
or
$$C/f = q\,P$$

where: C = the numbers (or biomass) of fish caught,
f = the fishing effort applied, for example, the number of hours fished,
C/f = the catch per unit of sampling effort (CPUE),
q = the catchability coefficient, which is species- and gear-specific, and
P = the population density or biomass.

For CPUE to be proportionally related to population abundance, the catchability coefficient must be constant, at least for a given fish species, gear type, and sampling protocol. Because of uncontrolled variations in catchability, CPUE is only an approximate index of relative fish abundance. Despite this, trends in angling success (e.g., the catch rates in Figure B-3) or catches obtained from routine sampling programs may provide important information at relatively low cost on the year-to-year status of a fishery and fish population.

If absolute estimates of fish abundance are required, one of the simplest approaches is the Petersen mark-recapture method.

If absolute estimates of fish abundance are required, one of the simplest approaches is the Petersen mark-recapture method. In the Petersen method, a sample of fish is collected, marked, and released. Then, at a later time (commonly, later in the same day or the next day), a second sample is collected that includes both marked and unmarked fish. It is assumed that the proportion of fish that are marked in the recapture sample is the same as the proportion marked in the total population. Therefore, since the number of marked fish is known, the total population size can be estimated as follows:

$$N = MC/R$$

where: N = the estimate of the population size,
M = the total number of marked fish,
C = the number of fish in the second sample, and
R = the number of marked fish in the second sample.

The validity of the Petersen method depends on the following assumptions:

- marked fish have the same mortality and behavior as unmarked fish,
- marks are not lost,
- marked fish are caught at the same rate as unmarked fish,
- marked fish are randomly distributed, and
- the population size is constant over the sampling period.

Many refinements and improvements on the basic Petersen mark-recapture technique have been developed (e.g., adjustments for tag loss rates, when known) and are described in Ricker (1975), Everhart and Youngs (1981), and other fisheries texts. Mark-recapture studies can also be used to estimate fish mortality and exploitation rates (e.g., Robson, 1963; Seber, 1972; Ricker, 1975).

For depletion methods of population estimation, the population is sampled repeatedly. The fish caught are removed, at least temporarily, from the population. As developed originally (Leslie and Davis, 1939; DeLury, 1947), CPUE is plotted against the cumulative catch. The number of fish in the original population is estimated by extrapolating this regression line to the point at which it would intersect with the x-axis (cumulative catch) (Fig. B-14). Presumably, when CPUE equals 0, all fish would have been captured and the cumulative catch would equal the original population size. To work, the sampling effort must be sufficiently intense to measurably reduce the population size, an impossible task in most large lakes and reservoirs but possible in some smaller lakes and also streams. The relationship between CPUE and cumulative catch is assumed to be linear; that is, it is assumed that fish catchability remains constant. Additional assumptions include:

- the population is totally available to the sampling effort,
- no natural mortality or recruitment occurs during the sampling period, and
- the method is constant in its effectiveness.

More sophisticated adaptations of the Leslie and DeLury method have also been developed. The Zippen maximum likelihood model (Zippen, 1958) is one of the most satisfactory and easy-to-use estimation techniques when the proportion of the population taken in consecutive catches remains constant throughout the sampling. When this is not the case, the more robust maximum weighted likelihood model developed by Carle and Strub (1978) produces more statistically reliable estimates. Further information on depletion methods can be found in Ricker (1975) and Cowx (1983).

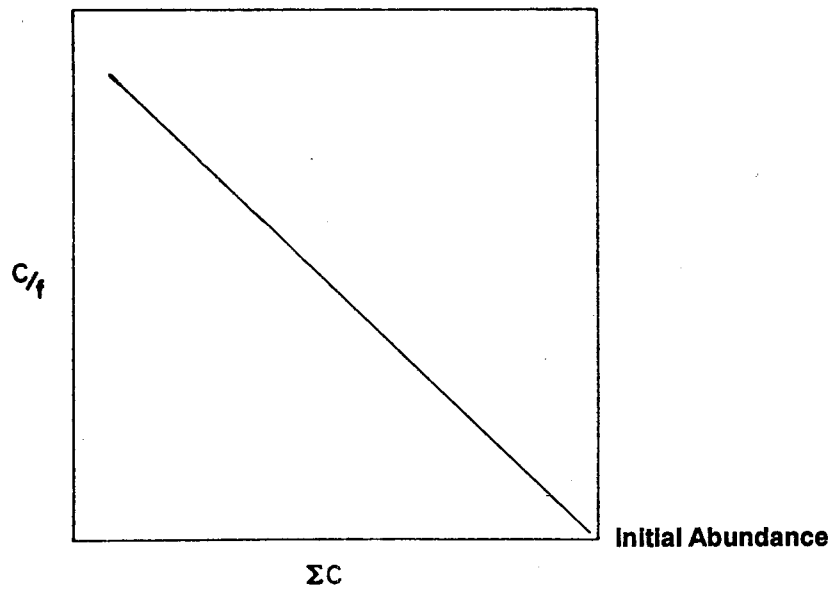

Figure B-14.—Example regression line calculated for the relationship between catch per unit effort (C/f) and cumulative catch (sum C); the x-axis intercept gives an estimate of the initial fish abundance (source: Lackey and Hubert, 1978).

Computerized programs are available for a number of population estimation routines, both depletion and mark-recapture, and for estimating fish mortality rates from mark-recapture data (e.g., Brownie et al. 1985; Saila et al. 1988).

Fish Genetics

For some management objectives, it is necessary to distinguish genetically divergent populations, strains, or stocks within the same species (see Chapters 3 and 5). Historically, fisheries biologists relied on morphological and meristic differences; that is, variations in body shape, the number or geometric relation of body parts, or other visible external characteristics. Such an approach, however, has poor discriminatory power at the subspecies level, is subject to environmental influences, and does not directly assess the degree of genetic divergence between individuals or groups of fish.

For some management objectives, it is necessary to distinguish genetically divergent populations, strains, or stocks within the same species.

A second approach, which is now fairly widely employed, relies on electrophoresis, a process in which the genetically controlled structure of proteins is displayed. Fish tissues, frequently from the liver or muscle, are homogenized; an electric field is then applied during electrophoresis to separate the proteins in the tissue based primarily on their charge. Differences in protein patterns provide the basis for distinguishing among fish stocks. Methods for electrophoresis are described in Utter et al. (1974), Harris and Hopkinson (1976), and Aebersold et al. (1987); example applications include Clayton et al. (1974), Philipp et al. (1983), Leary et al. (1987), Ihssen et al. (1988), and White and Shaklee (1991).

In recent years, techniques have been developed that examine the structure of DNA directly. Analyses of differences in DNA among fish stocks are highly sensitive. While protein separation techniques are limited in terms of the number of genetically distinct stocks that can be detected, the number of DNA-level markers is almost infinite. Disadvantages of DNA analyses, however, are the expense and high level of technical expertise required. Hallerman and Beckmann (1988) review the advantages and disadvantages and different methods for examining DNA variations. Billington and Hebert (1991) review the results of studies of mitochondrial DNA for over 40 fish species. Ryman and Utter (1987) provide an overview of fisheries management and population genetics, including methods for studying fish genetics.

Assessing the Food Base

Evaluating the quantity and quality of food available for target fish species is an important aspect of assessing fisheries status and potential fisheries problems.

Evaluating the quantity and quality of food available for target fish species is an important aspect of assessing fisheries status and potential fisheries problems. Quantitative information is needed on both the composition of the fish's diet (food consumed) and the availability of alternative prey items in the fish's environment. Very brief discussions are presented for both activities. Additional information on techniques for evaluating fish diets can be found in Bowen (1983). Prey organisms may include algae, zooplankton, littoral and benthic macroinvertebrates, and fish. Methods for sampling fish populations, including forage fish species, were described earlier in this chapter. Detailed sampling methods for other aquatic organisms are presented by Standard Methods (1989), American Society for Testing and Materials (1991), Lind (1985), and Wetzel and Likens (1979).

Quantitative Description of Diet

To quantitatively describe the diet of a fish population requires

- collecting a representative sample of fish,
- removing, fixing, and preserving the gut contents,
- identifying the food items in the gut, and
- quantifying the absolute or relative amount of each food type in the diet (Bowen, 1983).

Techniques for collecting representative samples of fish were described elsewhere in this chapter. Sampling should consider the daily and seasonal variations in fish feeding and the effects of fish size, territoriality, and differential digestion rates on the types of food organisms consumed and identifiable in the gut.

Gut contents can be removed from live fish using stomach pumps or, if the fish is sacrificed, by dissection. Ten percent formalin is generally used to fix the sample. After removal of the formalin by washing, the samples can be preserved in 70 percent ethanol.

Any differences in prey digestibility or recognizability must be accounted for in interpreting the results from fish stomach analyses.

Because of digestion, many of the items in the fish's stomach may be difficult or impossible to identify. Furthermore, some types of prey, such as those with hard-to-digest body parts (e.g., shells or spines), may be more readily identifiable than others. Any differences in prey digestibility or recognizability must be accounted for in interpreting the results from fish stomach analyses. Prey should be identified to the lowest taxonomic unit practical, although generally identifications to order or family are adequate.

The results from stomach analyses may be expressed in terms of the frequency of occurrence of different food items, percent composition by number, and/or percent composition by weight or volume. Frequency of occurrence is the fastest approach to quantitatively describe the diet. A list is made of all likely food types and the presence or absence of each food type in each specimen is recorded. The frequency of occurrence is the proportion of the fish examined that contained one or more representatives of a given food type. The percent composition by number is the number of items of a given food type divided by the total number of food items counted in a given stomach, multiplied by 100. Percent composition by weight or volume is the weight or volume of items of each food type expressed as a percentage of the total weight or volume of ingested food for an individual fish.

Diet Indices

The electivity index developed by Ivlev (1961) is used to compare the composition of food items observed in the fish's stomach to the relative abundance of prey available in the fish's environment. The index value indicates the extent to which the observed diet differs from a diet selected at random. A number of indices have

also been proposed that quantify diet overlap between fish species (Schoener, 1970; Wallace, 1981; Bowen, 1983; Crowder, 1990), although opinions vary regarding which, if any, index is most biologically relevant and statistically reliable. Other types of diet indices are described by Bowen (1983) and Crowder (1990).

Phytoplankton

Phytoplankton (free-floating, microscopic algae) are eaten by the early life stages of many fish species and by adults of a few species. Phytoplankton composition and abundance are also useful indicators of specific water quality conditions.

Phytoplankton composition and abundance are also useful indicators of specific water quality conditions.

Because phytoplankton distributions can be patchy, several water samples should be collected at discrete depth intervals in the epilimnion and then composited or an integrated water sample drawn from throughout the epilimnetic water column. Samples can be collected with a pump or sampling bottle similar to that illustrated in Figure B-15. Samples should be collected at several times during the growing season because plankton communities change seasonally and often rapidly.

Typically, 250 to 1,000 mL of water are preserved per sample. By examining samples under the microscope and weighing a filtered subsample, data can be generated on the total phytoplankton biomass per unit volume of water, the numerical density (number of organisms per unit volume) of each phytoplankton taxon identified, relative abundance by numbers or biomass of each taxon, and the presence and abundance of indicator species.

Chlorophyll *a* is the pigment that gives primary producers their green color. Chlorophyll concentrations in water, therefore, provide an indirect measure of phytoplankton abundance. Water for chlorophyll analysis can be subsampled

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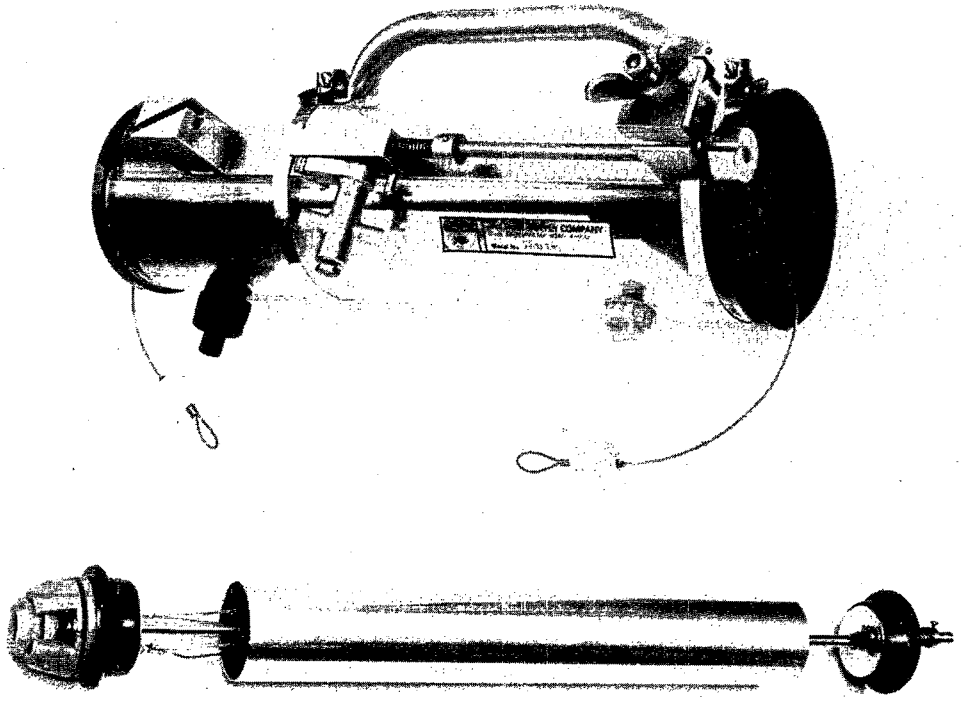

Figure B-15.—Two common water sample bottles — horizontal plexiglass Van Dorn (top) and a brass Kemmerer (bottom) (source: Wildlife Supply Co.).

from the samples described above for phytoplankton community analysis. Each chlorophyll sample must be filtered through a separate glass fiber filter. The filters are then placed on ice or frozen in the dark immediately following filtration to minimize sample degradation. Typically, the samples are extracted in the laboratory using 90 percent acetone. Frequently, to aid in extraction, the filter containing the sample is ground using a tissue grinder to disrupt the algal cells on the filter. After clarification, the samples are analyzed using a spectrophotometer or fluorometer.

Methods for assessing algal biomass and phytoplankton community composition are discussed further in Olem and Flock (1990), Standard Methods (1989), and Wetzel and Likens (1979).

Zooplankton

Zoolankton provide a critical food resource for most young fish and are important prey for the adults of many fish species.

Zooplankton are microscopic animals that live suspended in the water column. They provide a critical food resource for most young fish and are important prey for the adults of many fish species. Zooplankton communities, like phytoplankton, can change rapidly and must be sampled multiple times during the year.

One simple method to collect zooplankton is to tow a Wisconsin plankton net (Fig. B-16) though a known volume of water. This volume can be measured using a flowmeter set into the mouth of the towed net or estimated using the measured diameter of the net mouth times the measured or estimated distance that the net is towed vertically through the water column or horizontally behind a boat. After the net is retrieved, the sides should be washed from the outside, using lake water, to concentrate the plankton into the removable collection bucket at the bottom of the net. This concentrate is then rinsed from the collection bucket into an appropriate sized (often 125 mL) sample bottle, where preservatives are added (see Wetzel and Likens, 1979; Standard Methods, 1989).

Individual zooplankton can be identified and measured in the laboratory under a microscope. As for phytoplankton, the results from these analyses can be expressed as

- the total zooplankton biomass per unit volume of water,
- the numerical density of each zooplankton taxon identified,
- relative abundance of each taxon by numbers or biomass, and
- the presence and abundance of specific indicator species.

Benthic and Littoral Macroinvertebrates

Populations of benthic and littoral macroinvertebrates, particularly aquatic insects and crustaceans, are important food sources for fish and widely recognized as useful indicators in aquatic monitoring programs.

Populations of benthic and littoral macroinvertebrates, particularly aquatic insects and crustaceans, are important food sources for fish and widely recognized as useful indicators in aquatic monitoring programs. In lakes, the benthic macroinvertebrate community is generally sampled using the dredges shown in Figure B-17. Samples are brought to the surface and either preserved in their entirety in polyethylene bags or other suitable containers or washed using a fine sieve (e.g., with 500-µm screening) and then preserved in a suitable container. Samples are analyzed to determine the total benthic invertebrate biomass, the biomass and/or numerical density (numbers per substrate area) of each taxon identified, relative abundances for each taxon by numbers or biomass, and/or the abundance of indicator species and taxa.

Littoral invertebrate communities in lakes can be sampled with D-frame dip nets, sweeping the lake bottom, water column and water surface, and macrophyte beds in as many different habitats as possible (e.g., shallow weedy coves, tributary

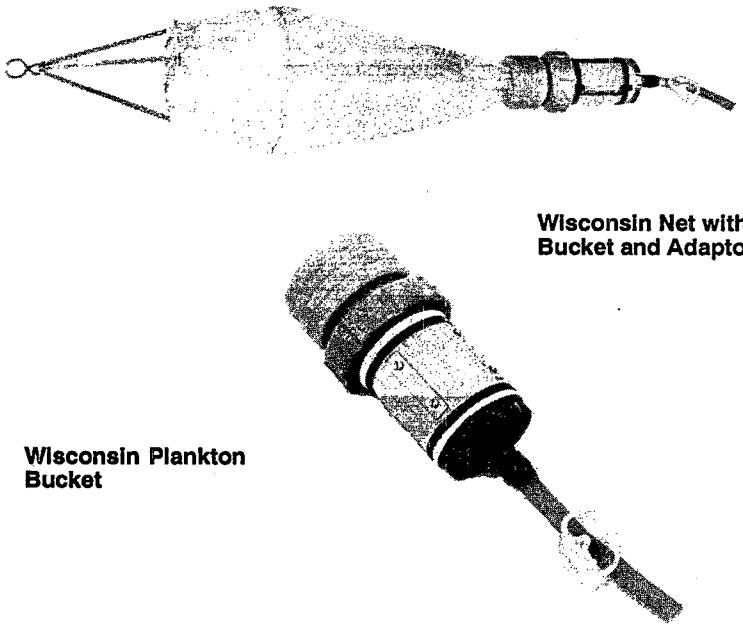

Figure B-16.—Wisconsin-style plankton net, which can be used as a horizontal, vertical, or diagonal tow net or as a filter net through which water is poured (source: Wildlife Supply Co.).

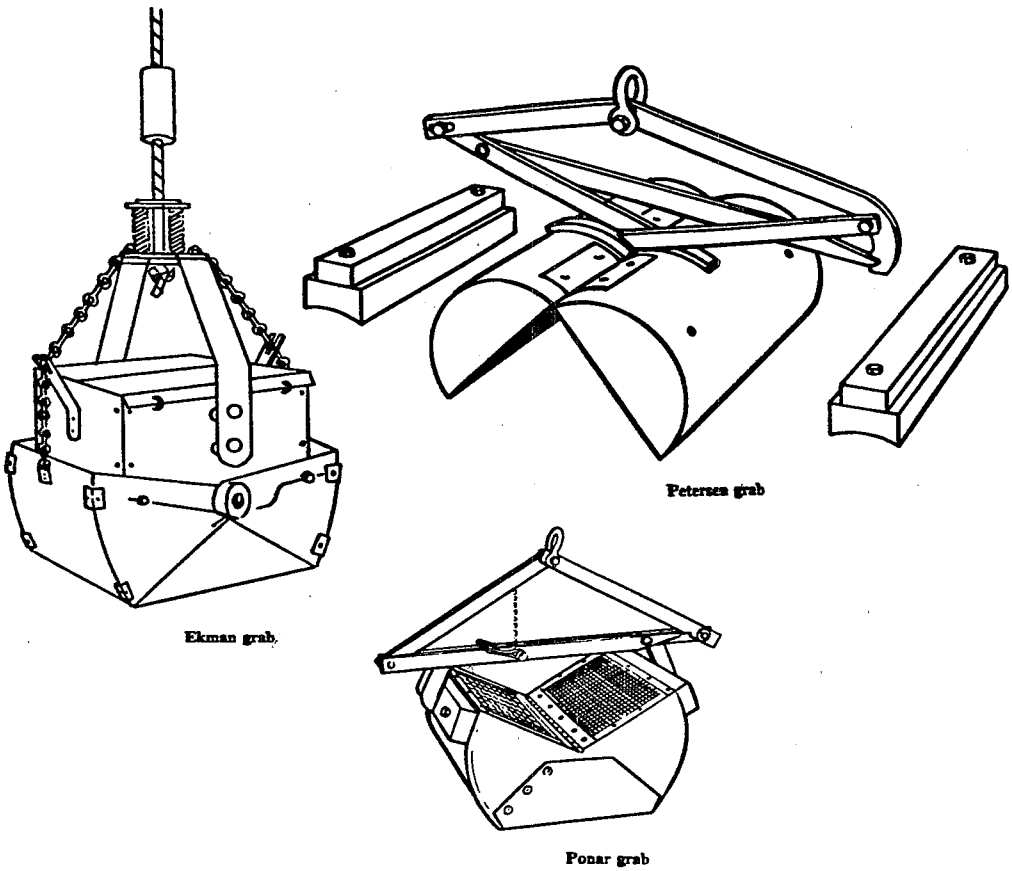

Figure B-17.—Three common styles of dredges used to collect bottom sediment and benthic invertebrates (source: Standard Methods, 1989).

mouths). Sampling times (total minutes spent searching and sweeping) per lake or unit lake area should be standardized. Clams, snails, and leeches can be preserved in 10 percent formalin; insects, crayfish, and sponges should be preserved in 70 percent ethyl alcohol. Hard-bodied forms can be dropped directly into the preservative. If time permits, soft-bodied insects, such as mayflies, should be dropped live into hot (not boiling) water for 30 seconds and then transferred into the preservative. The numbers of organisms collected per unit sampling effort provide a qualitative index of relative macroinvertebrate abundance by taxon.

In streams, benthic macroinvertebrates can be sampled qualitatively, using kick samples, or quantitatively with a Surber sampler, to collect organisms from a standard known area of the stream bottom. The open frame of the Surber sampler is placed on a suitable area of stream substrate with the mouth of the net facing upstream. Substrate within the frame is then thoroughly disturbed, rocks are removed from the bottom, and the associated animals and debris are carefully washed into the mouth of the net. The collected sample may be sorted to separate macroinvertebrates from the debris, either in the field or laboratory. Most samples can be preserved in 10 percent formalin, although samples with large amounts of organic debris require 15 to 20 percent formalin. Alternatively, samples can be preserved in the field with 80 percent ethanol but must be sorted within two days or drained and fresh 80 percent ethanol added to the sample within 24 hours of collection.

As for lake benthic invertebrates, results from Surber samplers can be used to estimate the total benthic invertebrate biomass, the biomass and/or numerical density (numbers per substrate area) of each taxon identified, relative abundances for each taxon by numbers or biomass, and/or the abundance of indicator species and taxa. Standard protocols and indices have also been developed for stream invertebrates that form the basis for EPA and State biocriteria. Rapid bioassessment protocols for use in streams and rivers are described in Plafkin et al. (1989), and Barbour et al. (1992) provide a review of EPA's benthic metrics based on these rapid bioassessment protocols.

Assessing Water Quality

Methods for assessing water quality are discussed in detail in *The Lake and Reservoir Restoration Guidance Manual* (Olem and Flock, 1990) and the technical supplement on *Monitoring Lake and Reservoir Restoration* (Wedepohl et al. 1990). Only methods for those variables that may directly impact fish are briefly reviewed here: toxic chemicals, dissolved oxygen, temperature, pH, salinity (total dissolved solids), and suspended solids.

Toxic Chemicals

Problems caused by toxic chemicals can be identified by several means:

- Routine monitoring of toxic chemicals in water, fish, and/or sediments may indicate concentrations elevated above background levels.
- The presence of a source of toxic chemicals in the watershed (e.g., pesticide spraying) may alert lake managers and users to a potential problem.
- An impairment of lake uses may occur (e.g., decline in fishing success or increase in the incidence of tumors on fish) that may be related to toxic chemicals.
- Routine biological monitoring may identify a pattern or trend (e.g., reduced fish abundance) potentially attributable to toxic chemicals.

Because a large number and diversity of toxic chemicals may adversely affect fish communities and fisheries, comprehensive chemical-specific monitoring can be expensive.

Once a potential problem is identified, the identity and source of the chemical or chemicals causing the problem must be determined, and the linkage between the chemical source and problem must be established. Three approaches are available for identifying causes and sources of toxic effects in lake ecosystems: chemistry-based, biology-based, and toxicity-based approaches. The chemistry-based approach relies on analytical chemistry to detect specific toxic chemicals; the biological approach relies on measurements of population or community level parameters and effects; and the toxicity approach relies on *in situ* and laboratory toxicity tests. Details of these approaches will be presented in the EPA Clean Lakes Program technical supplement, *Toxic Substances in Lakes and Reservoirs*, in preparation. Often, toxic contaminants are concentrated in lake sediments. Forstner (1989) and Baudo et al. (1990) discuss methods for assessing the chemistry and toxicity of pollutants in sediments.

Three approaches are available for identifying causes and sources of toxic effects in lake ecosystems: chemistry-based, biology-based, and toxicity-based approaches.

Dissolved Oxygen

Dissolved oxygen can be measured using chemical methods (U.S. Environ. Prot. Agency, 1983 [EPA Method 360.2]) or with a dissolved oxygen electrode and meter (U.S. Environ. Prot. Agency, 1983 [EPA Method 360.1]). Dissolved oxygen meters are generally used when numerous determinations are necessary. The meter must be regularly calibrated by comparison to chemical measurements, however, because some meters have a tendency to drift. Lethal limits of dissolved oxygen for fish are discussed in Chapter 3, Box 3-C.

Temperature

Temperature can be measured with simple, liquid-filled, or electronic thermometers. Multiple readings at various depths through the water column are used to determine the degree and extent of thermal stratification. Lethal temperature limits and preferred temperatures for fish are discussed in Box 3-D, Chapter 3.

pH

Water pH can be determined in the field using a field pH meter and probe, or a water sample can be collected and returned to the laboratory. For the most accurate measurement of *in situ* pH, which can be affected by changes in aqueous CO_2 following contact with the atmosphere, water samples can be collected at the lake or stream station in syringes and sealed. In the laboratory, the syringe contents are injected into a closed chamber surrounding a highly sensitive pH probe. For most fisheries management projects, however, field pH meters, accurate to 0.1 to 0.2 pH units, are adequate. Details on pH measurements in the field and laboratory are provided in handbooks from the U.S. Environmental Protection Agency (1987, 1989). Critical pH levels for effects on fish were summarized in Figure 3-5.

Salinity

Most freshwater fish can tolerate waters with salinities up to 1,000-2,000 mg/L total dissolved solids. Some fish, including some salmonid species, can tolerate and thrive in waters with even higher salinity, up to and including seawater.

Total dissolved solids are measured by filtering a water sample through a 0.45 μm filter, evaporating the filtrate (water that passes through the filter), and

then weighing the residue. An indirect measure of total dissolved solids in fresh waters is conductivity, which can be easily measured with a conductivity meter. Conductivity and total dissolved solids are positively correlated. Based on published empirical relationships between conductivity and total dissolved solids for specific types of waters, conductivity can be used to quantitatively estimate total dissolved solids. Further information on measuring conductivity and total dissolved solids is provided in Standard Methods (1989).

Suspended Solids

Although suspended solids rarely attain lethal levels in lakes and reservoirs, they can smother eggs and fry and depress lake productivity by inhibiting photosynthesis.

High levels of suspended solids sometimes occur in lakes and more often in reservoirs. Although suspended solids rarely attain lethal levels in lakes and reservoirs, they can smother eggs and fry and depress lake productivity by inhibiting photosynthesis. Suspended solids are measured by filtering a water sample through a 0.45 μm filter (pre-weighed), drying, and then weighing the filter and associated residue. The original filter weight is then subtracted from the combined weight to determine the weight of the solid residue. Methods for sampling and monitoring suspended solids are provided in Standard Methods (1989).

Assessing the Physical Habitat

Important components of lake and reservoir habitat for fish include lake area, depth, morphometry, shoreline contours, flushing rate, water level, cover, structures, substrate, and vegetation (Orth, 1983). Habitat Suitability Indices (HSI) developed by the U.S. Fish and Wildlife Service provide one means for using these physical measurements to assess habitat quality for particular fish species (see Chapter 11). Hamilton and Bergerson (1984) describe procedures for measuring the specific habitat features used to define each HSI. Additional information on appropriate methods for assessing physical habitats are contained in EPA's *The Lake and Restoration Guidance Manual* (Olem and Flock 1990) and *Monitoring Lake and Reservoir Restoration* (Wedepohl et al. 1990), Lind (1985), and the lake inventory manuals developed by many State and provincial fisheries agencies (e.g., Ontario Ministry of Natural Resources, 1989; Minnesota Department of Natural Resources, 1970, 1978, 1985; Texas Parks and Wildlife Department, 1991).

Morphometric Measurements

Common morphometric habitat measurements include lake area, depth, volume, and shoreline development. Lake area can be determined using a polar planimeter, tracing the boundaries of the lake from a topographical map or aerial photograph of known scale. Depth is most easily measured with an electronic echosounder or fish finder. A continuous record of depth along transects can be obtained using a depth sounder moved across the lake at a constant speed. Contour maps can be made by interpolating the spatial data to connect lines of equal depth. Computer software is available for digitizing map depth data to produce contour maps.

Lake volume can be approximated by multiplying the mean depth times the surface area. More precise estimates of volume require a good contour map. First, determine the surface area at each contour, then, estimate the volume of water in the stratum between contour lines (V_s) as

$$V_s = \frac{h}{3}(A_1 + A_2 + \sqrt{A_1 A_2})$$

where: h = the height of each stratum,
A1 = the area of the upper surface of the stratum, and
A_2 = the area of the lower stratum.

The total volume is the sum of the volumes for each stratum. Mean depth is estimated simply by dividing the volume by the surface area.

The shoreline development index (SDI) is an indicator of the potential amount of littoral zone development and is the ratio of the shoreline length (L) to the circumference of a circle of the same area as the lake:

$$SDI = \frac{L}{2\sqrt{A * \Pi}}$$

Shoreline length and area must be expressed in comparable units (e.g., miles and square miles). A circular lake will have a SDI of 1, and the greater the irregularity of the shoreline, the greater the SDI.

The shoreline development index (SDI) is an indicator of the potential amount of littoral zone development . . . .

Flushing Rate and Water Levels

The flushing rate is equal to the proportion of the lake or reservoir volume discharged per unit time and is calculated as the discharge divided by the volume (see Chapter 2). Staff gauges or continuous recorders can be installed for measuring fluctuations in water level, which in streams can be related to stream discharge.

Cover

In shallow and clear lakes and reservoirs, cover — such as logs, boulders, brush piles, and vegetation — can be quantitatively mapped using grids, transacts, or point sampling methods. In deep waters, cover can be detected using echosounders to map locations and extent of cover. Transect sampling is recommended (Platts et al. 1983).

Substrate

Substrate type can be classified using the modified Wentworth scale (see Table 2-1, Chapter 2) and spatial distribution can be determined using a point sampling method. Substrate samples can be collected using the same methods described for benthic macroinvertebrates, as discussed earlier in this chapter. Subsurface analysis of the substrate can be completed on samples collected using a McNeil or freeze-core sampler (Platts et al. 1983).

Vegetation

In shallow waters, aerial photography or shoreline surveys with boats can be used to map the distribution of aquatic macrophytes. Macrophytes are usually surveyed once or twice during the growing season. Information collected should include species, area covered, relative abundance (e.g., abundant, common, or sparse) or density (stems per unit area), and depth.

APPENDIX C

Addresses and Telephone Numbers

State Agencies

Alabama

Division of Game and Fish
Department of Conservation and Natural Resources
64 N. Union Street
Montgomery, Alabama 36130
205/242-3465
FAX 205/242-3032

Alabama Department of Environmental Management
1751 Congressman W.L. Dickinson Drive
Montgomery, Alabama 36109
205/271-7700
FAX 205/270-5612

Alaska

Department of Fish and Game
P.O. Box 25526
Juneau, Alaska 99802-5526
907/465-4100
FAX 907/465-2332

Department of Environmental Conservation
410 Willoughby Ave., Suite 105
Juneau, Alaska 99801-1795
907/465-5000
FAX 907/465-5097

Arizona

Arizona Game and Fish Department
2221 W. Greenway Road
Phoenix, Arizona 85023-4312
602/942-3000
FAX 602/789-3920

Department of Environmental Quality
3033 North Central Ave.
Phoenix, Arizona 85012
602/207-2300
FAX 602/207-2218

Arkansas

Game and Fish Commission
#2 Natural Resources Drive
Little Rock, Arkansas 72205
501/223-6300
FAX 501/223-6425

Department of Pollution Control and Ecology
8001 National Drive
P.O. Box 8913
Little Rock, Arkansas 72219
501/562-7444
FAX 501/562-4632

California

Department of Fish and Game
1416 Ninth Street
Sacramento, California 95814
916/653-7664
FAX 916/653-1856

Water Resources Control Board
901 P Street
P.O. Box 100
Sacramento, California 95801-0100
916/657-1155
FAX 916/657-1747

Colorado

Division of Wildlife
Department of Natural Resources
6060 Broadway
Denver, Colorado 80216
303/297-1192
FAX 303/294-0874

Division of Water Resources
Department of Natural Resources
1313 Sherman, Room 818
Denver, Colorado 80203
303/866-3581
FAX 303/866-3589

Connecticut

Wildlife Division
Department of Environmental Protection
State Office Building
165 Capitol Avenue, Room 254
Hartford, Connecticut 06106
203/566-4683
FAX 203/566-6024

Bureau of Water Management
Department of Environmental Protection
165 Capitol Avenue
Hartford, Connecticut 06106
203/566-3245
FAX 203/566-8650

Delaware

Division of Fish and Wildlife
Department of Natural Resources and Environmental Control
89 Kings Highway
P.O. Box 1401
Dover, Delaware 19903
302/739-5295
FAX 302/739-6157

Division of Water Resources
Department of Natural Resources and Environmental Control
89 Kings Highway
P.O. Box 1401
Dover, Delaware 19903
302/739-4860
FAX 302/739-3491

Florida

Game and Fresh Water Fish Commission
620 S. Meridian Street
Tallahassee, Florida 32399-1600
904/488-1960
FAX 904/488-6988

Department of Environmental Regulation
Division of Water Management
2600 Blair Stone Road
Tallahassee, Florida 32399-2400
904/488-4805
FAX 904/488-6579

Georgia

Game and Fish Division
Department of Natural Resources
2070 U.S. Hwy 278 S.E.
Social Circle, Georgia 30279
404/918-6400
FAX 404/656-2285

Environmental Protection Division
Department of Natural Resources
Floyd Towers East
205 Butler Street
Atlanta, Georgia 30334
404/656-4713
FAX 404/656-2285

Hawaii

Division of Aquatic Resources
Department of Land and Natural Resources
1151 Punchbowl Street, Room 330
Honolulu, Hawaii 96813
808/587-0100
FAX 808/587-0115

Division of Water and Land Development
Department of Land and Natural Resources
P.O. Box 373
Honolulu, Hawaii 96809
808/587-0230
FAX 808/587-0219

Commission on Water Resource Management
Department of Land and Natural Resources
P.O. Box 621
Honolulu, Hawaii 96809
808/587-0214
FAX 808/587-0219

Idaho

Idaho Department of Fish and Game
600 S. Walnut
P.O. Box 25
Boise, Idaho 83707
208/334-3700
FAX 208/334-2114

Community Program Division of Environmental Quality
IDHW
1410 N. Hilton
Boise, Idaho 83706
208/334-5860
FAX 208/334-0576

Illinois

Fisheries Division
Illinois Department of Conservation
600 N. Grand Ave. West
Springfield, Illinois 62706
217/782-6424
FAX 217/785-8262

Illinois Environmental Protection Agency
2200 Churchill Road
Springfield, Illinois 62706
217/782-3397
FAX 217/782-9891

Indiana

Division of Fish and Wildlife
Department of Natural Resources
402 W. Washington St.
Room W 273
Indianapolis, Indiana 46204
317/232-4080
FAX 317/232-8150

Indiana Department of Environmental Management
105 S. Meridian Street
P.O. Box 6015
Indianapolis, Indiana 46206-6015
317/232-8603
FAX 317/233-3257

Iowa

Fish and Wildlife Division
Department of Natural Resources
E. Ninth and Grand Avenue
Wallace State Office Bldg.
Des Moines, Iowa 50319-0034
515/281-5145
FAX 515/281-6794

Environmental Protection Division
Department of Natural Resources
E. Ninth and Grand Avenue
Wallace State Office Bldg.
Des Moines, Iowa 50319-0034
515/281-5145
FAX 515/281-8895

Kansas

Kansas Department of Wildlife and Parks
900 Jackson Street, Suite 502
Topeka, Kansas 66612-1233
913/296-2281
FAX 913/296-6953

State Department of Health and Environment
Landon State Office Bldg., Room 901
Topeka, Kansas 66612-1290
913/296-1522
FAX 913/296-7119

Kansas State Water Office
109 SW Ninth Street, Suite 300
Topeka, Kansas 66612-1249
913/296-3185
FAX 913/296-0878

Kentucky

Department of Fish and Wildlife Resources
#1 Game Farm Road
Frankfort, Kentucky 40601
502/564-3400
FAX 502/564-6508

Natural Resources and Environmental Protection Cabinet
Department for Environmental Protection
14 Reilly Road
Frankfort, Kentucky 40601
502/564-2150
FAX 502/564-4245

Maine

Department of Inland Fisheries and Wildlife
284 State Street, Station #41
Augusta, Maine 04333
207/289-2766
FAX 207/287-6395

Department of Environmental Protection
State House, Station #17
Augusta, Maine 04333
207/289-2811
FAX 207/287-7826

Maryland

Department of Natural Resources
Tawes State Office Bldg.
Annapolis, Maryland 21401
410/974-3041
FAX 410/974-5206

Department of the Environment
2500 Broening Highway
Baltimore, Maryland 21224
410/631-3000

Massachusetts

Department of Fisheries, Wildlife, and Environmental Law Enforcement
100 Cambridge Street
Boston, Massachusetts 02202
617/727-3194
FAX 617/727-7988

Department of Environmental Management
100 Cambridge Street, Room 1905
Boston, Massachusetts 02202
617/727-3163
FAX 617/727-9402

Michigan

Fisheries Division
Department of Natural Resources
Box 30028
Lansing, Michigan 48909
517/373-1280
FAX 517/373-0381

Surface Water Quality Division
Department of Natural Resources
Box 30028
Lansing, Michigan 48909
517/373-1949
FAX 517/373-9958

Minnesota

Department of Natural Resources
Division of Fisheries
500 Lafayette Road
St. Paul, Minnesota 55155-4012
612/296-6157
FAX 612/297-4916

Minnesota Pollution Control Agency
Water Quality Division
520 Lafayette Road
St. Paul, Minnesota 55155
612/296-6300
FAX 612/297-8683

Mississippi

Department of Wildlife, Fisheries, and Parks
2906 State Street
P.O. Box 451
Jackson, Mississippi 39205
601/362-9212
FAX 601/364-2125

Bureau of Pollution Control
Department of Environmental Quality
P.O. Box 10385
Jackson, Mississippi 39289-0385
601/961-5171
FAX 601/354-6612

Missouri

Fisheries Division
Department of Conservation
P.O. Box 180
Jefferson City, Missouri 65102-0180
314/751-4115
FAX 314/893-6079

Division of Environmental Quality
Department of Natural Resources
P.O. Box 176
Jefferson City, Missouri 65102
314/751-4810
FAX 314/751-9277

Montana

Department of Fish, Wildlife, and Parks
1420 East Sixth Avenue
Helena, Montana 59620
406/444-2535
FAX 406/444-4952

State Department of Health and Environmental Sciences
Cogswell Bldg.
Helena, Montana 59620
406/444-2544
FAX 406/444-1804

Nebraska

Game and Parks Commission
2200 N. 33rd Street
P.O. Box 30370
Lincoln, Nebraska 68503
402/471-5515
FAX 402/471-5528

Department of Environmental Quality
1200 N Street, Suite 400
P.O. Box 98922
Lincoln, Nebraska 68509-8922
402/471-2186
FAX 402/471-2909

Department of Water Resources
Box 94676
Lincoln, Nebraska 68509-4676
402/471-2363
FAX 402/471-2900

Nevada

Department of Wildlife
Box 10678
Reno, Nevada 89520
702/688-1500
FAX 702/688-1595

Department of Conservation and Natural Resources
Division of Environmental Protection
Capitol Complex
333 W. Nye Lane
Carson City, Nevada 89710
702/687-4670
FAX 702/687-5856

New Hampshire

Fish and Game Department
2 Hazen Drive
Concord, New Hampshire 03301
603/271-3421
FAX 603/271-1438

Department of Environmental Services
Water Supply and Pollution Control Division
6 Hazen Drive
P.O. Box 95
Concord, New Hampshire 03302-0095
603/271-3503
FAX 603/271-2867

New Jersey

Division of Fish, Game, and Wildlife
Department of Environmental Protection
501 E. State Street, CN 400
Trenton, New Jersey 08625-0400
609/292-2965
FAX 609/984-1414

Division of Water Resources
Department of Environmental Protection
401 E. State Street
Trenton, New Jersey 08625-0402
609/292-1637

New Mexico

New Mexico Game and Fish Department
P.O. Box 25112
Santa Fe, New Mexico 87504
505/827-7899
FAX 505/827-7915

New Mexico Environment Department
Surface Water Quality Bureau
1190 St. Francis Drive
P.O. Box 26110
Santa Fe, New Mexico 87502
505/827-2792
FAX 505/827-0160

New York

Division of Fish and Wildlife
Department of Environmental Conservation
50 Wolf Road, Room 518
Albany, New York 12233-4753
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FAX 518/485-5827

Division of Water
Department of Environmental Conservation
50 Wolf Road, Room 306
Albany, New York 12233-3500
518/457-6674
FAX 518/485-8991

North Carolina

Division of Boating and Inland Fisheries
Wildlife Resources Commission
Archdale Building
512 N. Salisbury Street
Raleigh, North Carolina 27604-1188
919/733-3633
FAX 919/733-7083

Division of Water Resources
Department of Environment, Health, and Natural Resources
P.O. Box 27687
Raleigh, North Carolina 27611
919/733-4064
FAX 919/733-3558

North Dakota

State Game and Fish Department
100 North Bismarck Expressway
Bismarck, North Dakota 58501
701/221-6300
FAX 701/221-6352

State Department of Health and Consolidated Laboratories
Department of Health
1200 Missouri Avenue
Bismarck, North Dakota 58502-5520
701/221-5210
FAX 701/221-5200

Ohio

Division of Wildlife
Department of Natural Resources
1840 Belcher Drive
Columbus, Ohio 43224
614/265-6300
FAX 614/262-1143

Environmental Protection Agency
1800 Watermark Drive
Columbus, Ohio 43215
614/644-3020
FAX 614/644-2329

Oklahoma

Fisheries Division
Department of Wildlife Conservation
1801 N. Lincoln
P.O. Box 53465
Oklahoma City, Oklahoma 73152
405/521-3721
FAX 405/521-6535

State Department of Health
1000 Northeast Tenth
Oklahoma City, Oklahoma 73117-1299
405/271-5601
FAX 405/271-2865

Oregon

Oregon Department of Fish and Wildlife
P.O. Box 59
Portland, Oregon 97207-0059
503/229-5400
FAX 503/229-5602

Department of Environmental Quality
811 SW Sixth Avenue
Portland, Oregon 97204
503/229-5630
FAX 503/229-6124

Pennsylvania

Fish and Boat Commission
P.O. Box 6700
Harrisburg, Pennsylvania 17106-7000
717/657-4518
FAX 717/657-4549

Department of Environmental Resources
Public Liaison Office
P.O. Box 2063
Harrisburg, Pennsylvania 17105-2063
717/783-8303
FAX 717/783-8926

Puerto Rico

Department of Natural Resources
P.O. Box 5887
Puerta de Tierra Station
San Juan, Puerto Rico 00906
809/724-8774
FAX 809/722-2785

Rhode Island

Division of Fish, Wildlife, and Estuarine Resources
Department of Environmental Management
Stedman Government Center
4808 Tower Hill Road
Wakefield, Rhode Island 02879
401/789-3094
FAX 401/783-4660

Division of Water Resources
Department of Environmental Management
291 Promenade Street
Providence, Rhode Island 02908
401/277-3961
FAX 401/521-4230

South Carolina

Wildlife and Marine Resources Department
Division of Game and Fresh Water Fisheries
Rembert C. Dennis Bldg.
P.O. Box 167
Columbia, South Carolina 29202
803/734-3889
FAX 803/734-3951

Water Resources Commission
1201 Main Street, Suite 1100
Columbia, South Carolina 29201
803/737-0800
FAX 803/765-9080

South Dakota

Game, Fish and Parks Department
523 East Capitol
Pierre, South Dakota 57501-3182
605/773-3381
FAX 605/773-6245

Environment and Natural Resources
Joe Foss Office Bldg.
523 East Capitol
Pierre, South Dakota 57501-3181
605/773-3151
FAX 605/773-6035

Tennessee

Wildlife Resources Agency
Fish Management Division
P.O. Box 40747
Ellington Agricultural Center
Nashville, Tennessee 37204
615/781-6500
FAX 615/741-4606

Division of Water Pollution Control
Department of Environment and Conservation
401 Church Street
6th Floor L & C Annex
Nashville, Tennessee 37243-1534
615/532-0625
FAX 615/532-0614

Texas

Parks and Wildlife Department
Fisheries
4200 Smith School Road
Austin, Texas 78744
512/389-4800
FAX 512/389-4894

Guadalupe-Blanco River Authority
P.O. Box 271
Sequin, Texas 78156-0271
210/379-5822
FAX 210/379-9918

Texas Water Development Board
1700 N. Congress Avenue
P.O. Box 13231
Austin, Texas 78711
512/463-7847
FAX 512/475-2053

Utah

Division of Wildlife Resources, Fisheries Management
State Department of Natural Resources
1596 W. North Temple
Salt Lake City, Utah 84116-3154
801/538-4700
FAX 801/538-4709

Division of Water Resources
State Department of Natural Resources
1636 W. North Temple
Salt Lake City, Utah 84116-3156
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FAX 801/538-7315

Vermont

Department of Fish and Wildlife
Agency of Natural Resources
103 South Main, 10 South
Waterbury, Vermont 05671-0501
802/244-7331
FAX 802/241-3295

Agency of Natural Resources
Department of Environmental Conservation
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103 South Main Street
Waterbury, Vermont 05671
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FAX 802/244-5141

Virgin Islands

Department of Planning and Natural Resources
Suite 231, Nisky Center
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FAX 809/775-5706

Virginia

Department of Game and Inland Fisheries
4010 W. Broad Street
Box 11104
Richmond, Virginia 23230
804/367-1000
FAX 804/367-9147

Department of Conservation and Recreation
Division of Soil and Water Conservation
203 Governor Street
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Richmond, Virginia 23219
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FAX 804/786-1798

Washington

Department of Wildlife
Fisheries Management Division
600 Capitol Way North
Olympia, Washington 98501-1091
206/753-5700
FAX 206/586-0248

Department of Ecology
P.O. Box 47600
Olympia, Washington 98504-7600
206/459-6000
FAX 206/459-6077

West Virginia

Warmwater Fisheries
Department of Natural Resources
1900 Kanawha Blvd., East
Charleston, West Virginia 25305
304/558-2771
FAX 304/558-3147

Coldwater Fisheries
Department of Natural Resources
P.O. Box 67
Elkins, West Virginia 26241
304/637-0245
FAX 304/637-0250

Water Resources
Department of Natural Resources
1201 Greenbrier Street
Charleston, West Virginia 25311
304/558-2107
FAX 304/558-5905

Wisconsin

Bureau of Water Resources Management
Department of Natural Resources
Box 7921
Madison, Wisconsin 53707
608/267-7610
FAX 608/267-2800

Bureau of Fisheries Management
Department of Natural Resources
Box 7921
Madison, Wisconsin 53707
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Wyoming

Game and Fish Department
5400 Bishop Blvd.
Cheyenne, Wyoming 82002
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FAX 307/777-4610

Environmental Quality Department
122 W. 25th Street
4th Floor West, Herschler Bldg.
Cheyenne, Wyoming 82002
307/777-7937
FAX 307/777-7682

Provincial Agencies

Alberta

Fish and Wildlife Division
Fisheries Management
Department of Environmental Protection
5th Floor, Bramalea Bldg.
9920 108 Street
Edmonton, Alberta T5K 2M4
403/427-6730
FAX 403/422-9559

British Columbia

Fisheries Branch
Ministry of Environment, Lands, and Parks
780 Blanchard Street, 2nd Floor
Victoria, British Columbia V8V 1X4
604/387-9711
FAX 604/387-9750

Water Management Division
Ministry of Environment
765 Broughton Street, 6th Floor
Victoria, British Columbia V8V 1X4
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FAX 604/954-3603

Manitoba

Department of Natural Resources
Legislative Bldg., Room 314
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FAX 204/945-3586

New Brunswick

Fish and Wildlife Branch
Department of Natural Resources, and Energy
P.O. Box 6000
Fredericton, New Brunswick E3B 5H1
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Newfoundland

Department of Environment and Lands
P.O. Box 8700
St. John's, Newfoundland A1C 4J6
709/729-2574
FAX 709/729-0112

Northwest Territories

Department of Renewable Resources
Government of the Northwest Territories
P.O. Box 1320
Yellowknife, Northwest Territories
X1A 2L9
403/873-7128
FAX 403/873-0110

Nova Scotia

Department of Fisheries
Scotia Fundy Region
P.O. Box 550
Halifax, Nova Scotia B3J 2S7
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FAX 902/426-3479

Ontario

Ministry of Natural Resources
Whitney Block
99 Wellesley St. West, Room 6301
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Prince Edward Island

Department of the Environment
P.O. Box 2000
Charlottetown, Prince Edward Island
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902/368-4689
FAX 902/368-5830

Quebec

Department of Recreation, Fish, and Game
Place de la Capitale
150 Rene-Leuesque E. Blvd., 17th Floor
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FAX 418/643-9588

Saskatchewan

Saskatchewan Natural Resources
Fisheries Branch
3211 Albert Street, Room 338
Reginia, Saskatchewan S4S 5W6
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FAX 306/787-0737

Yukon Territory

Department of Renewable Resources
Fisheries Section
Box 2703
Whitehorse, Yukon Territory Y1A 2C6
403/667-5110
FAX 403/668-4263

Professional Societies

American Fisheries Society
5410 Grosvenor Lane
Suite 110
Bethesda, Maryland 20814
301/897-8616
FAX 301/897-8096

American Society of Limnology and Oceanography
Biological Oceanography Division
Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia B2Y 4A2
902/426-3793
FAX 902/426-9388

American Water Resources Association
5410 Grosvenor Lane, Suite 220
Bethesda, Maryland 20814
301/493-8600
FAX 301/493-5844

North American Benthological Society
Business Office
P.O. Box 1897
Lawrence, Kansas 66044
913/843-1221
FAX 913/843-1274

North American Lake Management Society
1 Progress Blvd., Box 27
Alachua, Florida 32615-9536
904/462-2554
FAX 904/462-2568

Society of Environmental Toxicology and Chemistry
1010 North 12th Avenue
Pensacola, Florida 32501-3307
904/469-1500
FAX 904/469-9778

Private Organizations

American Bass Association, Inc.
2810 Trotters Trail
Wetumpka, Alabama 36092
205/567-6035
FAX 205/567-8632

BASS, Inc.
Anglers for Clean Water, Inc.
P.O. Box 17900
Montgomery, Alabama 36141
205/272-9530
FAX 205/279-7148

Bass Anglers Sportsman Society
5845 Carmichael Road
Montgomery, Alabama 36117
205/272-9530
FAX 205/279-7148

Clean Water Action
1320 18th Street, NW, Suite 300
Washington, DC 20036
202/457-1286
FAX 202/457-0287

Environmental Defense Fund, Inc.
257 Park Avenue South
New York, New York 10010
212/505-2100
FAX 212/505-2375

Federation of Fly Fishers
P.O. Box 1088
West Yellowstone, Montana 59758
406/646-9541
FAX 406/646-9728

Freshwater Foundation
725 County Road Six
Wayzata, Minnesota 55391
612/449-0092
FAX 612/449-0592

Izaak Walton League of America, Inc.
1401 Wilson Blvd., Level B
Arlington, Virginia 22209-2318
703/528-1818
FAX 703/528-1836

Muskies, Inc.
2301 7th Street, North
Fargo, North Dakota 58102
701/239-9540
FAX 701/239-9540

National Audubon Society
700 Broadway
New York, New York 10003-9501
212/979-3000
FAX 212/979-3188

National Wildlife Federation
1400 Sixteenth Street, NW
Washington, DC 20036-2266
202/797-6800
FAX 202/797-6646

Natural Resources Defense Council, Inc.
40 West 20th Street
New York, New York 10011
212/727-2700
FAX 212/727-1773

North American Native Fishes Association
123 West Mt. Airy Avenue
Philadelphia, Pennsylvania 19119

Sierra Club
730 Polk Street
San Francisco, California 94109
415/776-2211
FAX 415/776-0350

Soil and Water Conservation Society
7515 NE Ankeny Road
Ankeny, Iowa 50021-9764
515/289-2331
FAX 515/289-1227

Sport Fishing Institute
Suite 320
1010 Massachusetts Avenue, NW
Washington, DC 20001
202/898-0770
FAX 202/371-2085

Trout Unlimited
800 Follin Lane, Suite 250
Vienna, Virginia 22180
703/281-1100
FAX 703/281-1825

Water Environment Federation
601 Wythe Street
Alexandria, Virginia 22314-1994
703/684-2400
FAX 703/684-2492

GLOSSARY

Adaptive management. The process whereby information is gained and management strategies are improved through direct experience with applying management techniques.

Aerobic. Describes life or processes that require the presence of molecular oxygen.

Algae. Small aquatic plants that occur as single cells, colonies, or filaments.

Allochthonous. Materials (e.g., organic matter and sediment) that enter a lake from the atmosphere or a drainage basin (see autochthonous).

Anaerobic. Describes processes that occur in the absence of molecular oxygen.

Anoxia. A condition of no oxygen in the water. Often occurs near the bottom of fertile stratified lakes in the summer and under ice in late winter.

Autochthonous. Materials produced within a lake (e.g., autochthonous organic matter from plankton versus allochthonous organic matter from terrestrial vegetation).

Bathymetric map. A map showing the bottom contours and depth of a lake; can be used to calculate lake volume.

Benthos. Macroscopic (seen without aid of a microscope) organisms living in and on the bottom sediments of lakes and streams. Originally, the term meant the lake bottom, but it is now applied almost uniformly to the animals associated with the substrate.

Biochemical oxygen demand (BOD). The rate of oxygen consumption by organisms during the decomposition (respiration) of organic matter, expressed as grams oxygen per cubic meter of water per hour.

Biological criteria. Indicators of biological or ecological integrity compared to some least-disturbed reference site.

Biomanipulation. Any management technique that relies on altering the fish community to improve water quality.

Biomass. The weight of biological matter. Standing crop is the amount of biomass (e.g., fish or algae) in a body of water at a given time. Often measured in terms of grams per square meter of surface.

Biota. All plant and animal species occurring in a specified area.

Catch per unit effort and harvest per unit effort. The number or biomass of fish caught and harvested, respectively, per unit of angling effort.

Chemical oxygen demand (COD). Nonbiological uptake of molecular oxygen by organic and inorganic compounds in water.

Chlorophyll. A green pigment in algae and other green plants essential for the conversion of sunlight, carbon dioxide, and water to sugar (i.e., photosynthesis). Sugar is then converted to starch, proteins, fats, and other organic molecules.

Chlorophyll *a*. A type of chlorophyll present in all types of algae, sometimes in direct proportion to the biomass of algae.

Decomposition. The transformation of organic molecules (e.g., sugar) to inorganic molecules (e.g., carbon dioxide and water) through biological and nonbiological processes.

Detritus. Nonliving dissolved and particulate organic material from the metabolic activities and deaths of terrestrial and aquatic organisms.

Ecosystem. A system of interrelated organisms and their physical–chemical environment. In this manual, an ecosystem includes the lake and surrounding land as well as streams that drain into the lake.

Epilimnion. Uppermost, warmest, well-mixed layer of a lake during summertime thermal stratification. The epilimnion extends from the surface to the thermocline.

Eutrophic. From Greek for "well-nourished," describes a lake of high photosynthetic activity and low transparency.

Eutrophication. The process of physical, chemical, and biological changes associated with nutrient, organic matter, and silt enrichment and sedimentation of a lake or reservoir. If the process is accelerated by human influences, it is termed "cultural eutrophication."

Evaporation. The direct conversion of liquid water into water vapor by the addition of heat.

Evapotranspiration. The combined conversion of water to water vapor, and loss resulting from both evaporation and transpiration.

Fall overturn. The autumn mixing, top to bottom, of lake water caused by cooling and wind-derived energy.

Fecundity. The number of eggs produced by a single female fish.

Fish abundance. The density and/or biomass of fish present per unit area or volume, by species.

Fish community. The collection of all fish populations (i.e., all fish species).

Fish population. A group of fish of the same species that occurs within a given lake or reservoir.

Fisheries yield. The total number or biomass of fish removed from the lake through angling (per unit area or volume and period of time), estimated from the measures of fishing pressure and harvest per unit effort.

Fishery. The act or occupation of fishing — the harvesting of fish from waterbodies for either commercial or recreational purposes.

Fishing pressure. The total number of hours (or other suitable unit) of angling effort.

Flushing rate. The rate at which water enters and leaves a lake relative to lake volume, usually expressed as time needed to replace the lake volume with inflowing water.

Food chain. The general progression of feeding levels from primary producers, to herbivores, to planktivores, to the larger predators.

Food web. The complex of feeding interactions existing among the lake's organisms.

Forage fish. Fish, including a variety of panfish and minnows, that are prey for game fish.

Groundwater. Water that infiltrates into the soil and underlying rock layers. Groundwaters eventually flow into lakes and other surface waters through seeps and springs, although some deep groundwaters can remain underground for hundreds of years.

Habitat. The place or type of area where a plant or animal normally lives and grows.

Hybrids. The offspring of parents of different species; for example, a cross between bluegill and green sunfish.

Hydraulic residence time. The average time required to completely renew a lake's water volume.

Hypereutrophic. Describes a lake that often experiences pea-soup conditions because of high concentrations of algae and/or excessive densities of rooted aquatic plants.

Hypolimnion. Lower, cooler layer of a lake during summertime thermal stratification.

Internal nutrient cycling. Transformation of nutrients such as nitrogen or phosphorus from biological to inorganic forms through decomposition, occurring within the lake itself.

Internal nutrient load. Nutrients that reenter the water column from sediments.

Lake. A considerable inland body of standing water, either naturally formed or human-made.

Lake management. A comprehensive program that incorporates both protection and restoration activities to effectively improve and maintain the quality of the lake ecosystem.

Lake morphometry. The physical configuration and shape of the lake basin.

Lake reclamation or rehabilitation. An extreme approach to rough fish control whereby all or most fish in the lake are poisoned and desirable fish species are reintroduced.

Limnology. The scientific study of the physical, chemical, geological, and biological factors that affect aquatic productivity and water quality in freshwater ecosystems — lakes, reservoirs, rivers, and streams. Also termed freshwater ecology.

Littoral zone. That portion of a waterbody extending from the shoreline lakeward to the greatest depth occupied by rooted plants.

Loading. The total amount of material (e.g., sediment, nutrients, oxygen-demanding material) brought into the lake by inflowing streams, runoff, direct discharge through pipes, groundwater, the air, and other sources over a specific period of time, often annually.

Macroinvertebrates. Aquatic insects, worms, clams, snails, and other animals visible without aid of a microscope that may be associated with or live on substrates such as sediments and macrophytes. They supply a major portion of fish diets and consume detritus and algae.

Macrophytes. Rooted and floating aquatic plants, commonly referred to as waterweeds. These plants may flower and bear seed. Some forms, such as duckweed and coontail (*Ceratophyllum*), are free-floating forms without roots in the sediment.

Maximum sustainable yield. The maximum quantity of biomass that could be harvested from a population each year without causing a long-term population decline.

Meromictic lakes. Lakes that are permanently stratified as a result of differences in total dissolved solids.

Mesotrophic. Describes a lake that has intermediate nutrient availability and biological productivity.

Metalimnion. Layer of rapid temperature and density change in a thermally stratified lake. Resistance to mixing is high in the region.

Microbes. Term used to refer collectively to bacteria, fungi, and other microscopic organisms involved in organic matter decomposition.

Morphometry. Relating to a lake's physical structure (e.g., depth, shoreline length).

Oligotrophic. From Greek for "poorly nourished," describes a lake of low plant productivity and high transparency.

Ooze. Lake bottom accumulation of inorganic sediments and the partially decomposed remains of algae, weeds, fish, and aquatic insects. Sometimes called muck; see sediment.

Optimum sustainable yield. The quantity of fish harvested and the level of effort and expense required to collect these fish and, in recreational fisheries, a wide range of other characteristics relating to angler values and the overall quality of the fishing experience.

Pelagic zone. This is the open-water area of a lake, from the edge of the littoral zone to the center of the lake, not directly influenced by the shore or the bottom.

Periphyton. Organisms associated with submerged substrates, such as bottom sediments, aquatic vegetation, docks, and other surfaces.

Photic zone. The lighted region of a lake where photosynthesis takes place. Extends down to a depth where plant growth and respiration are balanced by the amount of light available.

Photosynthesis. The biological process by which light energy is converted into chemical energy and stored as organic compounds, which can then be used to support biological growth and production.

Phytoplankton. Microscopic algae and microbes that float freely in the open water of lakes and oceans.

Piscivores. Fish that feed primarily on other fish, often referred to as forage fish.

Planktivores. Plankton-eating fish.

Plankton. Planktonic algae float freely in the open water. Filamentous algae form long threads and are often seen as mats on the surface in shallow areas of the lake.

Primary productivity. The rate at which algae and macrophytes fix or convert light, water, and carbon dioxide to sugar in plant cells. Commonly measured as milligrams of carbon per square meter per hour.

Profundal zone. Mass of lake water and sediment occurring on the lake bottom below the depth of light penetration.

Reservoir. A human-made lake where water is collected and kept in quantity for a variety of uses, including flood control, water supply, recreation, and hydroelectric power.

Respiration. Process by which organic matter is oxidized by organisms, including plants, animals, and bacteria. The process releases energy, carbon dioxide, and water.

Rough fish. Undesirable fish species that interfere with the survival and growth of desirable fish species or with other lake uses.

Sediment. Bottom material in a lake that has been deposited after the formation of a lake basin. It originates from remains of aquatic organisms, chemical precipitation of dissolved minerals, and erosion of surrounding lands (see ooze).

Stratification. Layering of water caused by differences in water density. Thermal stratification is typical of most deep lakes during summer. Chemical stratification can also occur.

Surface runoff. Excess precipitation or snowmelt that does not infiltrate into the soil but flows over the land surface before reaching a defined stream channel or other surface water. Large quantities of surface runoff are most common in arid regions and in humid regions where the natural vegetation and soils have been disturbed.

Surface water. Standing or flowing water on top of the land surface, such as streams, rivers, lakes, and oceans.

Transpiration. The conversion of water to water vapor by plants and loss of the water vapor from plant surfaces.

Trophic level. A step or level within the trophic pyramid, that is, a hierarchical classification of organisms based on the types of organisms that they eat and that eat them. Plants are eaten by herbivores, which are eaten in turn by predators, which may be consumed by other predators. Each of these groups represents a level on the trophic pyramid.

Trophic state. The degree of eutrophication of a lake. Transparency, chlorophyll levels (as an indicator of algal abundance), phosphorus concentrations, amount of rooted aquatic vegetation, and quantity of dissolved oxygen in the hypolimnion can be used to assess a lake's trophic state.

Watershed. A drainage area or basin in which all land and water areas drain or flow toward a central collector such as a stream, river, or lake at a lower elevation.

Yield. That portion of a fish population, in terms of numbers or weight, harvested by humans through recreational or commercial fisheries over some specified period of time and per unit area or volume.

Zooplankton. Microscopic animals that float freely in lake water, graze on detritus particles, bacteria, and algae, and may be consumed by fish.

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