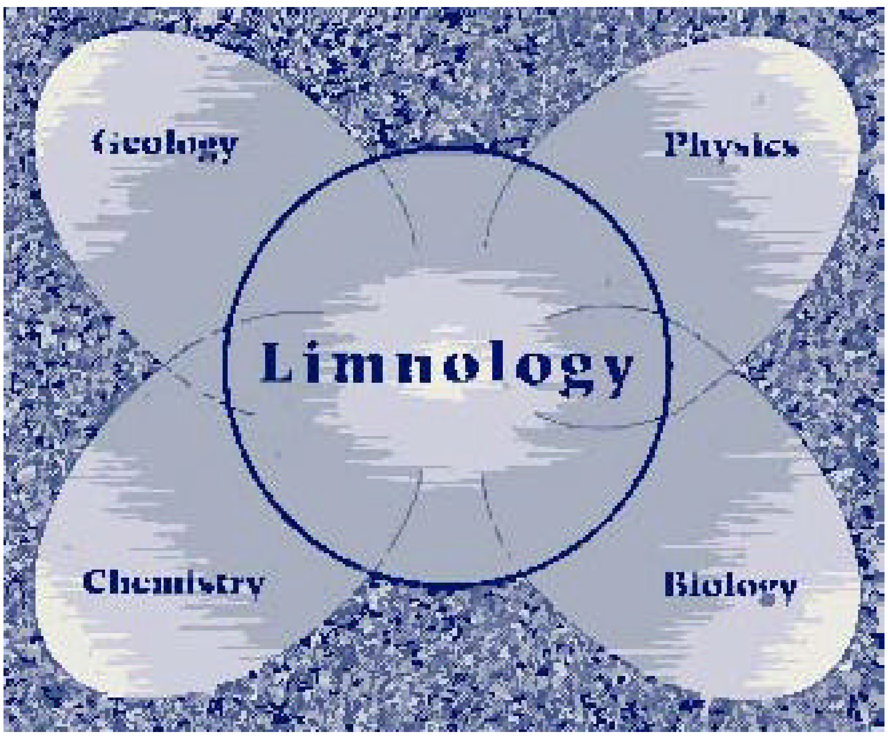
Challenges for Limnology in the United States and Canada:

An Assessment of the Discipline in the 1990's

Report of the
American Society of Limnology and Oceanography
Challenges for Limnology Committee



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The figure on the front cover is a depiction of the multidisciplinary nature of limnology.

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Preface

The ASLO Board of Directors has often discussed the status or welfare of limnology in North America and the responsibility of ASLO to promote beneficial change in limnology. Although extending back many years, and probably even to the beginning of the society, these discussions became especially pointed during 1990 at a time when published commentaries on the state of limnology began to appear in the Society's journal, *Limnology and Oceanography*, in the *ASLO Bulletin*, and elsewhere. There seemed to be a general sense that limnology might be facing a decline of some sort, although individual commentators diagnosed the situation in a variety of ways. The Board, acting through the President, responded to this building concern by creating a committee, which came to be known as the Challenges for Limnology Committee, that was charged with assessing the state of limnology in the U.S. and Canada and with making recommendations that might be beneficial to the development of limnology.

The Committee consisted of 9 members drawn from various branches of the society. Following a meeting at the Institute of Ecosystem Studies at Millbrook, NY, the Committee drafted a report including an analysis of current trends in limnology, or opportunities that seem to be undeveloped or underdeveloped by limnologists, and of support and strategies for research and education in limnology. The Committee also expressed its opinions on the causes of trends in limnology, and offered a set of recommendations to be considered by limnologists for the future. After the development of consensus within the Committee, which was no easy task, the report, which is presented here, was sent to reviewers and then finalized. The Committee has hoped from the beginning to stimulate debate and action among the limnologists of ASLO and limnologists generally.

William M. Lewis, Jr., Chair
Challenges for Limnology Committee

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Summary

Within the last 20 years, the United States and Canada have committed vast new resources to the protection of inland waters. The U.S. Environmental Protection Agency (USEPA) estimates that, in the United States alone, the present annual cost of water pollution control, which is primarily for inland waters, totals approximately 50 billion dollars per year and is escalating rapidly. Additional large amounts are committed to management and restoration of aquatic ecosystems. These financial commitments are a societal acknowledgement of the incalculable value of inland waters — including streams, rivers, reservoirs, natural lakes, wetlands, and groundwaters — to human welfare.

Protection and management of inland waters require a comprehensive understanding of physical, chemical, geological, and biological processes, and are thus dependent on limnology, which is the integrative study of inland waters. Limnology has repeatedly proven the effectiveness of its multidisciplinary approach in analyzing aquatic environments. For example, limnologists identified, diagnosed, and prescribed effective solutions for eutrophication caused by detergents, organic wastes, urban development, and agriculture. Limnologists also identified and described acidification of waters associated with fossil fuel combustion. Limnology has produced information, theory, and principles encompassing biological productivity, biogeochemistry, land-water interactions, optics and physical dynamics of natural waters, biotic community composition, adaptations of aquatic organisms, and numerous other subjects that provide the foundation for sustained quality, biodiversity, and yield of renewable resources in inland waters.

Limnological study in the U.S. and Canada presently shows signs of inability to keep pace with the need for limnological knowledge and expertise. Universities have been slow to develop educational programs that are well suited for the production of limnologists who will be employed by government agencies and the private sector. University limnology programs tend to be specialized, and have not shown sufficient emphasis on the ecosystem perspective that unifies the field. The connection between university limnologists and the application of limnological knowledge is insufficiently developed and without structure. In addition, the essential multidisciplinary mix supporting the field has become imbalanced, particularly through the atrophy of physical and chemical limnology. Also, in contrast with Europe, the U.S. and Canada show weak recognition of limnology. This situation is paradoxical given the practical significance of limnology, and the increasing investments in protection, management, and restoration of inland waters.

The full potential of limnology can be realized only through changes internal and external to the discipline. Limnologists should supplement the production of Ph.D. students for university employment with programs more closely matched to other markets, and at the graduate level should increase emphasis on the ecosystem perspective. Limnologists should also propose geographically broad, cooperative programs that focus on issues of acknowledged importance such as the linkage between water quality and riparian zones, or responses of aquatic communities to anthropogenic stress. Limnology also needs a strong, unified voice capable of articulating externally the strengths and opportunities of the discipline. The American Society of Limnology and Oceanography has focused almost exclusively on scientific communication rather than policy or education.

Other societies (North American Benthological Society, Society for Wetland Science, North American Lake Management Society, Ecological Society of America) have been more active in policy matters, but represent only a portion of the limnological spectrum. The societies that serve limnologists should cooperate in efforts that extend beyond science to education, policy, and strategic development of research in limnology.

In neither the U.S. nor Canada does limnology receive support for research under its own name. Governmental anonymity of limnology has caused a decline in its recognition by other disciplines, which in turn has weakened the connection between academic and applied limnology. In addition, the multidisciplinary nature of limnology is often not well served by the present support system; the organization of government programs has restricted severely the amount of support that is available to physical and chemical limnology. In general, support is too meager to maintain robust programs that are also of broad scope. Restrictive support has encouraged limnologists to focus on studies that can be designed around small, discontinuous budgets. Broader programs supplementing or encompassing these more focused programs would serve national needs, but would require more support.

The U.S. National Science Foundation should consider establishing a named program in limnology, as should the Natural Sciences and Engineering Research Council of Canada. The U.S. and Canadian governments should also develop interagency plans for expansion of research in limnology; extramural research should be expanded several-fold and should be maintained by budget formulas that reflect societal investments in protection and management of inland waters.

As a means of establishing critical logistical support for projects of broad, interdisciplinary character, of fostering graduate education, and of analyzing regional features of inland waters, the U.S. and Canadian governments should greatly expand support for selected limnological field stations of high quality and should support the addition of stations in regions where there are none. Professional societies, including the American Society of Limnology and Oceanography, should cooperatively initiate discussions of the status of limnology, should assume responsibility for stimulating improvements in the discipline, and should provide leadership for the development of opportunities in limnology. Specific goals for limnology over the short term should include: (1) educational reform, (2) development of broad cooperative studies, (3) designated support of basic research in limnology, (4) development of a coordinated interagency support plan for research extending beyond the National Science Foundation, (5) increased support of selected limnological field stations, and (6) expanded involvement of limnologists in policy matters related to inland waters.

Introduction

Inland waters, which include streams, rivers, wetlands, natural lakes, reservoirs, and groundwaters, are affected in many ways by industrial societies. Agriculture, waste disposal, and disturbance of soil and terrestrial vegetative cover often change water quality, physical conditions, and composition of aquatic communities. Oxides of sulfur and nitrogen that are released as by-products of energy production change both the acidity and nutrient content of water and alter terrestrial biogeochemical processes that influence the chemistry of surface waters. Harvesting, stocking, and accidental introductions of species directly affect aquatic communities through predation, competition, and other biotic interactions. Physical disruption and manipulation involving the installation of dams, diversion and regulation of flow, or redefinition of shorelines and channels perturb the functional characteristics of aquatic environments. Such influences frequently cause aquatic ecosystems and their resident communities of organisms to deviate radically from their natural states; degradation of the commercial and aesthetic value of inland waters is a common result.

The United States and Canada, as well as a number of other nations, have foreseen the necessity of moderating the human alteration of aquatic environments, and have taken the first steps toward protection and restoration of inland waters. The U.S. EPA (1991) estimates that the United States now expends approximately 50 billion dollars per year for control of water pollution, and that future costs will increase steeply. Management and restoration of inland waters are also large and growing commitments in the U.S. (NAS 1992). The commitments of Canada to inland waters are proportionate in scope to those of the U.S. (National Science Council of Canada 1988).

The protection of inland waters, which is motivated partly by a desire to preserve their value to society and partly by an increasingly powerful environmental ethic that opposes environmental despoliation, requires a comprehensive scientific understanding of inland waters as ecosystems. Traditional methods of using and protecting inland waters typically have involved manipulation or control of one or at most a few environmental factors. As the priorities for protection of aquatic resources increase simultaneously with increasing demands, which are now reaching critical levels in the U.S. (Francko and Wetzel 1983), integrated systems of protection and management will replace historically simpler approaches. Integrated management systems will require far greater understanding of inland waters, will draw more heavily on scientific and technical expertise, and in many cases will create a strong need for advances in the state of the art for management and protection. Restoration, which is rapidly becoming a priority (NAS 1992), will require unprecedented sophistication in the understanding of aquatic ecosystems.

Limnology is the integrative study of inland waters. It encompasses biological, chemical, geological, and physical phenomena, as well as all levels of organization extending from individual chemical reactions or adaptations of individual organisms to the analysis of entire ecosystems. Limnology lends itself both to comparative and to experimental analysis of inland waters. The effectiveness and cost efficiency of protection and management systems for inland waters will be dictated to a large extent by concepts and principles from the field of limnology.

Over its century of existence as an organized discipline, limnology has repeatedly proven to be a scientific resource of direct importance to industrial societies in anticipating, limiting, and repairing environmental damage to inland waters (Cooke et al. 1993). Limnologists first diagnosed the problem of eutrophication, analyzed its underlying mechanisms, and successfully prescribed solutions such as control of phosphorus sources associated with land use, detergents, and waste disposal (Vollenweider 1968, Likens 1972, Schindler 1974, Edmondson 1991). The result has been improved water quality in many parts of North America. Similarly, the threat of acid rain to inland waters was first anticipated and described by limnologists, who showed how airborne acidity could degrade water quality and damage biotic communities (Gorham 1955, 1976, Likens et al. 1972, Likens and Bormann 1974). As a result, acidification became a matter of public concern leading to legislative action that has set the stage for reduction in the release of acid precursors to the atmosphere (U.S. EPA 1991). Recently, limnologists have identified mercury accumulation in aquatic food webs as a serious environmental problem in lakes that were previously considered free of toxic substances (Bodaly et al. 1984, Fitzgerald and Watras 1989, Cabana et al. 1993). Limnologists are also presently analyzing the potential effects of climate change on inland waters, the effects of exotic species such as the zebra mussel on aquatic ecosystems, and strategies for sustaining biodiversity in inland waters.

Despite its past success, limnology in the 1990's has much unrealized potential in the U.S. and Canada. The physical and chemical subdivisions of limnology, which are critical to its multidisciplinary foundation, are not sufficiently developed in the scientific repertoire of North America. Studies that cover large geographic regions or that deal comprehensively with aquatic ecosystems are rare, even though these two lines of inquiry are most directly connected to the development of integrated systems for management and protection of inland waters. A stronger liaison is needed between basic and applied limnology, and the education of limnologists must be better matched to the growing task of understanding and managing inland waters as multidimensional ecological systems. At a time when society could benefit immediately from growth and consolidation of this field, limnology shows signs of fragmentation and loss of identity, which will reduce its potential to solve problems that arise from the escalating human demands on inland waters. Limnologists have begun to cooperate on remedies to these problems, as shown by their participation in the recent Freshwater Initiative (Firth and Wyngaard 1993) and their call for an assessment of inland water sciences by the National Research Council, but much remains to be done.

The purpose of this report is to assess the present status of limnology in the U.S. and Canada and to show how new opportunities to develop and apply limnological knowledge could benefit society. The report is motivated by a concern that the discipline of limnology must change to meet an unprecedented demand for limnological knowledge.

Limnology Described

Limnology has as its objective a comprehensive, integrated understanding of inland waters. The thread that unifies the field is water itself, rather than any specific scale of space or time, or any particular commitment to physics, chemistry, geology, or biology (Figure 1). The physical branch of the discipline concerns itself with such phenomena as the optical properties of natural waters, water movement, and sedimentation of solids in water. Chemical limnology deals with nutrients, dissolved gases, transformations of organic and inorganic substances in water, their derivation from soil, rock, atmosphere, and organisms, chemical interactions between sediment and water, and other related subjects. Geological limnology deals with drainage patterns, runoff, morphometry of basins, and development of aquatic components of landscapes through time. Biological limnology encompasses the distribution and adaptation of organisms that inhabit inland waters, their functions and behaviors, their interactions such as competition and predation, and their individual and collective metabolism. Although branches or subdisciplines can be identified, limnology is synthetic across subdisciplines. The full integration of chemical, physical, geological, and biological limnology is achieved at the level of the ecosystem, which is treated by limnology as a unit of nature requiring integrated, multidisciplinary study.

Limnology originally developed as the study of natural lakes, partly because of the ease with which lakes can be understood as discrete ecological systems (Likens 1984). Since that time, limnology has grown to encompass all inland waters, including rivers, streams, wetlands, and reservoirs, as well as natural lakes.

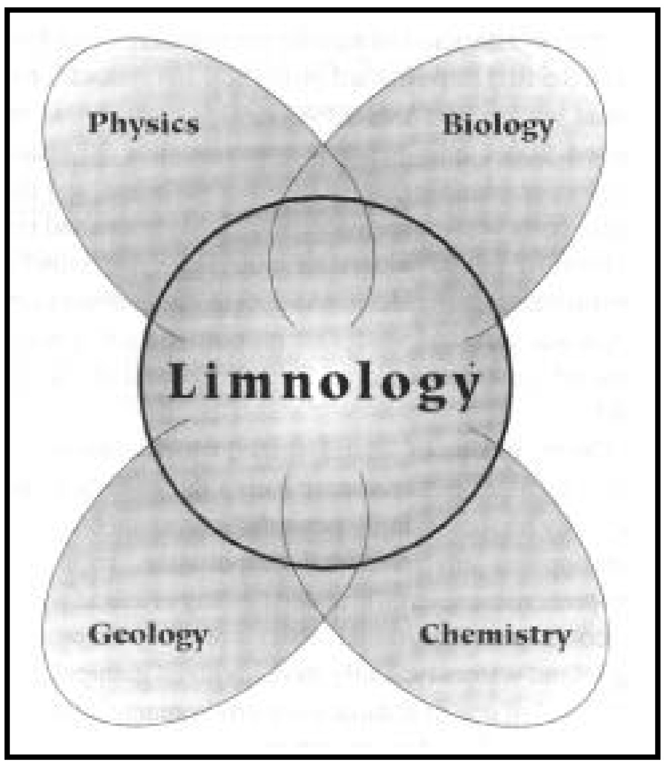

Figure 1. A depiction of the multidisciplinary nature of limnology.

A Selection of Unifying Concepts in Limnology

Limnology has produced numerous unifying concepts and research themes that bear directly upon the protection and management of aquatic resources. A selection of these demonstrates the breadth of modern limnology.

Principles Governing Aquatic Food Webs. The role of consumers in determining the biomass, species composition, and production of prey is a centerpiece of biological limnology (Hrbáček 1962, Brooks and Dodson 1965, Reynolds 1984). In fact, size-selective predation by fish on zooplankton is one of the most predictable community phenomena in all of ecology (O'Brien 1979). Numerous other direct and indirect effects of consumers on lower trophic levels have also been documented. Control of primary producer biomass and productivity by higher trophic levels, now referred to as a "trophic cascade" (Carpenter 1988), has been a reappearing theme in limnological thinking over several decades for lakes (e.g., Hrbáček et al. 1961, Shapiro et al. 1975, Lewis 1979, McQueen et al. 1986), and more recently for running waters as well (e.g., Bowlby and Roff 1986, Power 1990). Such studies demonstrate the ability of limnology to produce integrative theory that unifies research as diverse as fisheries management practices, the adaptations of organisms to predation, and the controls of primary production, and to apply them to lake management practices such as biomanipulation (Hulbert et al. 1972, Shapiro and Wright 1984) and physicochemical control of organisms or environmental conditions (Cooke et al. 1993).

Explanation of the Role of Organic Matter in Natural Waters. Limnologists have made substantial progress toward a mechanistic understanding of the role of organic matter in determining the optical properties of water, the binding of metals, and the influence of soil on the inventory of organic compounds in natural waters. In addition, quantitative analysis of organic carbon flux has yielded a comprehensive view of the way in which organic matter affects the metabolism in aquatic ecosystems (Wetzel 1992). Analysis of the fate of organic matter has been greatly facilitated by new methods for quantifying the abundances and metabolic rates of microbes in surface waters (Hobbie 1992).

Advances in the Understanding of Water Movement. Analysis of physical processes in lakes and running waters has developed rapidly in the last decade in conjunction with the introduction of new instruments and the application of basic concepts of fluid mechanics to inland waters. For lakes, the combination of better instruments and better theory has much improved the understanding of turbulence and of the relationship of flow to density gradients, and has established a better basis for modeling thermal structure and advection (Imberger and Patterson 1990, Schwab 1992). Better predictions are now also possible for spatial variability of dissolved and particulate materials and physical constraints on small organisms (e.g., MacIntyre 1993). For running waters, the application of fluid mechanics to flow at the substrate boundary has helped to define the conditions for growth of attached organisms (Ward and Stanford 1991).

Biogeochemistry of Aquatic Ecosystems. Analysis of the transfer of elements into and out of ecosystems, and of their cycles within ecosystems, reveal ecosystem functions and support predictions of response to disturbance (Gorbas and McCorquondale 1992). The biogeochemistry of carbon, nitrogen, and phosphorus is especially important. Carbon is the feedstock of photosynthesis; its rate of passage through the biota is the key index of metabolism for individual organisms, populations, and entire ecosystems. Phosphorus and nitrogen are the two elements most likely to regulate biological productivity in aquatic ecosystems; their rates of supply, storage, and mobilization in aquatic ecosystems are related directly to the productivity and biotic composition of aquatic environments. For example, studies of the response of lakes to phosphorus enrichment has been the basis for extensive regulation of phosphorus, which in turn has improved water quality in the U.S. and elsewhere (Edmondson 1991).

Energetics of Aquatic Ecosystems. The use of energy as an ecological currency simplifies the analysis of ecosystems and allows comparison of ecosystems. Studies of ecological energetics were pioneered in aquatic ecosystems (Lindeman 1942), which continue to provide an excellent basis for understanding food web efficiency, chemical and physical constraint of biological production, relationships between production and decomposition, and other phenomena basic to all ecological systems. The practical significance of ecological energetics lies in its relevance to biological productivity, including yield of either desirable or nuisance organisms in aquatic environments. Enhancement of fish production or manipulation of plant growth by grazing, for example, can be approached through the principles of ecological energetics.

Land-Water and Atmosphere-Water Interactions. Differences among aquatic ecosystems can often be understood through study of their linkages to land and atmosphere (Likens 1984, Wetzel 1990). Similarly, aquatic ecosystems often respond to changes in the terrestrial or atmospheric environments to which they are connected. Examples include the response of aquatic ecosystems to changes in land use (siltation, eutrophication) or to increased amounts of atmospheric combustion products (acidification, toxification with metals). Aquatic ecosystems may also have reciprocal effects on other components of the environment. Examples include the release of decomposition products (methane, CO_2, and others) from wetlands and lakes to the atmosphere, and effects of lakes on regional weather patterns. Understanding of these processes is critical to an evaluation of regional environmental change through global warming or changes in land use.

Supporting Disciplines

The physical, geological, chemical, and biological branches of limnology are closely connected to other disciplines. Physical limnology is joined to meteorology and climatology through studies of the heat content, solar irradiance, and water balance of inland waters, and to fluid mechanics, from which limnologists draw information on water movement, sediment dynamics, and mixing. Hydrology, which deals with the water cycle globally, regionally, or in specific environments, is an essential underpinning of biogeochemical studies. Geology explains the formation and aging of drainage networks and lake basins, as well as chemical weathering and erosion leading to sediment transport. Discoveries in chemistry and geochemistry have improved the modelling of geochemical equilibria in aqueous mixtures and the analysis of organic matter.

Biological limnology is connected to zoology, botany, and microbiology, and to population and community ecology. Fisheries science developed almost independently, but the strong overlap of interests between limnology and fisheries science is becoming increasingly apparent (Magnuson 1991).

Oceanography has a special relationship to limnology, to which it is similar in many of its principles and methods, and in its combination of physical, chemical, geological, and biological sciences. In fact Forel (1892), one of the founders of limnology, described limnology as "the oceanography of lakes." Similarity in limnology and oceanography was the justification for their unification in the American Society of Limnology and Oceanography; the two disciplines have often supported each other conceptually and methodologically (Mills 1989). Even so, limnology and oceanography have evolved separate infrastructures. Oceanography is usually taught separately from limnology in university curricula, and graduate programs are typically separate.

Environmental engineering, which deals with such issues as water treatment, waste disposal, impoundment, and routing of waters, has a close interface with limnology insofar as it defines many of the manipulations whose effects are analyzed through limnology. In addition, limnology shares boundaries with water law, environmental regulation, and public and private policies for the use of surface waters.

Limnology's Distinguishing Features

The difference between limnology and the disciplines that contribute to it is one of motivation and integration rather than content. An invertebrate zoologist can measure respiration in aquatic crustaceans, a chemist can quantify the speciation of metals, and a physicist can produce new equations for fluid motion. Such information is not limnological unless it is cast in a form that sheds light on the functioning of aquatic ecosystems. Limnologists may explain how eddies move dissolved substances vertically in lakes, how calcium can remove phosphorus from natural waters in the presence of organic matter, or how the ingestion rate of a filter feeding organism in a stream or lake is suppressed by an undesirable food item. Physicists, chemists, or biologists in general would have no specific motivation to study such phenomena, but the limnologist studies them because they are part of the functional scheme of an aquatic environment. The unique practical strength of limnology is its direct applicability to society's concern for the preservation and wise exploitation of aquatic resources.

The Importance of Limnology to Society

The value of water for irrigation, domestic and industrial consumption, hydropower production, waste disposal, recreation, and support of aquatic life, including commercial and sport fisheries, has created tension between protection and use of aquatic resources. Technical evaluation of this conflict requires detailed and sometimes profound understanding of aquatic ecosystems, which are studied largely through limnology.

Protection of Aquatic Ecosystems

The United States has committed itself to the most ambitious conceivable program of water quality protection, i.e., elimination of all effects of pollution from waters of the United States. This commitment, was consolidated in the 1972 Clean Water Act and its amendments, has been pressed forward steadily from law to regulation, and has dictated the expenditure of many billions of dollars to protect aquatic environments (cumulatively about 600 billion dollars since 1972: U.S. EPA 1991). Ambitious systems of physical protection are also beginning to evolve, particularly for wetlands (NAS 1995). Through its Fisheries Act, Canada has adopted similarly rigorous policies for protection of aquatic environments.

Society can maximize the effectiveness of its rapidly increasing expenditures on protection only through accelerated acquisition of knowledge about the functioning of aquatic environments. Regulatory systems must employ a general understanding of the relative vulnerabilities of aquatic environments to different kinds of stresses, as well as specific knowledge of the variations in response to stress under contrasting geologic or climatic conditions. Knowledge of restoration and rebound from stress must also be used in guiding the investment of public money.

Environmental legislation and the public call for correction of specific environmental problems such as acidification of surface waters, pollution of waters with metals and organic wastes, and physical alteration and impairment of aquatic environments, should have justified a substantial increase in the study of aquatic ecosystems. However, the great increase in expenditure of public money to protect aquatic environments has had surprisingly little effect on the rate of limnological research. Governments have made typically small concessions to research, often through quick and superficial applied studies or syntheses of the existing literature on subjects critical to the formation of new regulations. Thus new regulations, and the expenditures associated with them, have been made with the implicit but unrealistic assumption that the field of limnology will continue to provide, with minimal new resources, a steady stream of fundamental information. If protection systems continue to evolve in the absence of a robust connection to research, they run an increasing risk of deviating from their primary goals, and of wasting public money.

What Limnology Has to Offer

The potential of limnology is well demonstrated by two of the largest limnological projects of the last two decades. At the Experimental Lakes Area in Canada, the challenge of understanding aquatic ecosystem function was taken to one of its logical conclusions through an aggressive, experimentally oriented program involving the manipulation of numerous lakes in a region where manipulated lakes could be compared with unmanipulated ones in the spirit of experimental science (Schindler 1974, Schindler et al. 1992). A similarly impressive display of the potential of limnology comes from the Hubbard Brook Experimental Forest, where dozens of implicit questions about the management of watersheds were answered clearly and quickly through experimental manipulation of small watersheds (e.g., Likens et al. 1977, Likens 1985). Both of these large projects illustrate the strength and flexibility of the comparative and experimental approaches that are characteristic of ecosystem analysis in limnology.

The Present Context for Assessment of Limnology

Motivations for the assessment of limnology at present include potential changes in governmental strategies for supporting environmental science, internal assessments in related disciplines that may influence limnology, decline of field stations, and, most importantly, an emerging consensus among limnologists and others that education, research, and applications in limnology must be improved.

Potential Changes in the Support of Environmental Sciences

A group of professional ecologists has asked the U.S. Federal Government to consider the creation of a National Institute of the Environment (NIE) that would be organized similarly to the U.S. National Institutes of Health. The future of the NIE proposal is unclear. It may fail or, if adopted, it may be greatly modified. Even if it fails, however, the NIE proposal demonstrates the necessity for limnologists to clarify their niche so that new systems for federal support of environmental science will strengthen limnology and magnify the benefits of limnology to society.

Another indicator of possible change in the U.S. is the Freshwater Initiative (now called the Freshwater Imperative), which is an attempt by a group of federal agencies that deal with water resources to reorganize and coordinate their support of freshwater studies (Threlkeld 1991, Firth and Wyngaard 1993). Most of these agencies have responsibilities for management or development and many have been dominated historically by an engineering perspective. As a result of trends in environmental regulation, however, most of them now also have extensive environmental responsibilities directly related to limnology. For this reason, limnologists should clarify the potential contributions of their discipline to the management and regulatory missions of government agencies.

Internal Assessments in Related Disciplines

Hydrologists have recently completed an important assessment of their field and have produced recommendations for change in the form of a report describing many concerns that are also felt by limnologists (NAS 1991). Hydrology, which is an integrative discipline drawing strength from physics, chemistry, climatology, and other fields, has been viewed in the U.S. primarily as a branch of engineering. Hydrologists emphasize that hydrology is a geoscience, and should not be treated exclusively as a branch of engineering. Hydrology has suffered decline and lack of integration because its geoscience foundations have not been recognized by federal agencies. The complementary but distinctive roles of limnology and hydrology should be explained to governmental agencies that support work on inland waters.

Fisheries scientists also show a desire to redefine boundaries and, like hydrologists, they see the need for a more integrative view of aquatic environments (Magnuson 1991). Closer connection of fisheries science to limnology would strengthen both fields, given that fish cannot be functionally separated from aquatic ecosystems (Carpenter and Kitchell 1988).

Field Stations

Historically, many pioneering limnologists have worked at field stations, which serve limnology in much the same way that research vessels and marine stations serve oceanography and marine biology. Field stations provide the logistical base necessary for the support of multidisciplinary programs. Extensive equipment inventories, analytical facilities, and the raw space necessary to conduct experiments and stage field programs are often not available on university campuses where many limnologists are employed. The availability of these facilities in close proximity to field sites greatly increases the feasibility of sustained field programs. Beyond their logistical functions, field stations are a unique environment for the instruction of graduate students and for interdisciplinary collaboration. Group field experience supplements the more formal and segregated environment of university campuses and governmental laboratories. Daily work in the field and processing of samples and data in an interdisciplinary atmosphere encourages collaboration and produces insight that may not be forthcoming from other sources. Finally, field stations provide the basis for sustained data collection and analysis of specific environments through comparative regional studies that are essential for the junction of basic limnology with applied limnology and regional problem solving. The philosophy of the National Science Foundation's Long Term Ecological Research Program, which incorporates a number of aquatic sites, applies well to field stations: some important kinds of limnological information simply cannot be obtained by any means other than long-term commitments to field studies in a variety of physiographic regions.

The effectiveness of limnological research can be greatly enhanced through greater, though highly selective, support of field stations. Also, addition or development of a few major new stations would be desirable in regions that lack them. Either new or existing stations must be supported well to be an asset to the discipline: poorly managed or weakly budgeted stations may actually be detrimental by setting low standards for education and research. Except under unusual circumstances, field stations should be operated by universities or consortia involving universities, given that universities provide direct linkage to graduate education and are typically more flexible than government agencies. The most successful stations typically have a resident faculty, and are reasonably close to universities.

The Present Needs of Limnology

Prominent limnologists and others in related disciplines have recently offered opinions on the status of limnology (Banse 1990, Jumars 1990, Wetzel 1991a,b, Hairston 1990, Hrbǎcek 1991, Kalff 1991). Although the individual commentaries deal with issues ranging from inadequacy of education in limnology to poor governmental support of limnological research, the collective tone is one of concern and even alarm over the present status of limnology in North America.

Observers of limnology have identified several ways in which limnology should be improved: (1) creation of more effective educational programs, (2) reinforcement of the ecosystem perspective, (3) better balance in the development of critical subdisciplines, (4) improved interaction of limnology with other disciplines, (5) improved connection to applications, and (6) a stronger base of research support.

Educational Programs

Limnologists should reform the educational programs of universities, and should seek significant university-government partnerships centering on the practical need for broadly educated limnologists in government and private work forces. The education of limnologists presently emphasizes the production of Ph.D.s for academic positions. While some graduates pass into government agencies or the private sector, the clear emphasis of the leading institutions is to produce individuals who will take tenure-track positions at institutions of higher learning. This tradition ignores the recent growth in demand for limnological knowledge outside universities. Much of the demand for limnological expertise in government and private labor pools is at the level of the master's degree rather than the Ph.D. By focusing on the production of academically oriented Ph.D.s, limnologists may have facilitated a decline in recognition and utility of their discipline.

Connections between academic programs and applications could be improved by academic certification involving conventions for education that assure a certain degree of breadth and uniformity in the capability of graduates. Such systems exist in some other disciplines, but have not yet evolved in limnology.

Partly because of their orientation on the Ph.D. degree and the academic job market, limnologists often lack breadth that is consistent with the scope of the discipline. Whereas limnologists should possess some universal competence in physical, chemical, geological, biological, and system-level integration of limnological knowledge, the programs within which they are educated often focus almost exclusively on a particular subdiscipline or problem. Increase in the breadth of limnological graduate programs would facilitate connections with environmental engineering and management. Oceanography, which typically provides a broader base for its graduate programs, might serve as a useful model for educational reforms in limnology.

The Ecosystem Perspective

In an era of increasing specialization, many limnologists have drifted away from the roots of limnology, which emphasized the multidisciplinary analysis of aquatic ecosystems. As a result, limnology has become more specialized and increasingly fragmented into a set of subdisciplines that focus on specific components of ecosystems (Peters 1990). Studies of system components are an essential part of the framework of limnology, but their utility is greatly weakened without integration at the system level. Specialization may be quite a successful strategy for individual scientists who are able to make a series of discoveries that open up new perspectives on some particular adaptation or chemical transformation in aquatic environments, but the cumulative effect of increasing specialization may be to reduce the strength of the discipline in analyzing systems.

Balance Among Subdisciplines

Because limnology is a blend of topics that are biological, physical, geological, and chemical, each of these areas of inquiry must be under development at a sufficient pace to support advances in other areas. Similarly, aquatic biotas are not exclusively zoological, botanical, or microbial; they are a composite that must be reflected in the research programs of limnologists. Even so, limnology has developed a serious imbalance of components (Wetzel 1991b). At present, physical limnology is especially weak in North America, and chemical limnology is underemphasized. Zoological studies have traditionally outnumbered botanical or microbial ones, despite the pivotal importance of photosynthesis and decomposition. Uneven development of components is especially perilous to a science that draws much of its significance from the integrated understanding of ecological systems.

Extradisciplinary Connections

Limnology is not well connected to some of the disciplines whose specialists should best be able to work with limnologists. Even though much of the foundation of population and community ecology and ecosystem science arose directly from limnology, at least some ecologists have come to view limnology as irrelevant to their interests (Hairston 1990). Similarly, in reviewing and making recommendations for the expansion and rejuvenation of hydrology, a distinguished NRC committee including numerous hydrologists made scarcely any mention of the contributions or scope of limnology (NAS 1991).

Although the poor connection of limnology to related disciplines is disturbingly commonplace, it is not universal. Oceanographers, who occupy a discrete niche in government research support, university programs, and job markets, show substantial interaction with limnologists, and have expressed concern about the apparent decline of limnology (Jumars 1990, Banse 1990).

Connections to Applications

Especially in the U.S., limnology is not well connected to applications (Kalff 1991). Assessments of aquatic ecosystems are often conducted without the participation of limnologists, even though aquatic resources must be analyzed, managed, and protected as systems rather than as aggregations of separate physical and biological resources. When limnologists are involved in such projects, they may take a supporting role as counters of organisms or assayers of nutrient concentrations, rather than as analysts of aquatic systems. In addition, general strategies for management and protection of aquatic environments are often formulated in the absence of limnological expertise, even though the utility of limnology is well illustrated by the past role of limnologists in identifying and diagnosing the causes of major environmental problems such as acidification or eutrophication of waters. These poor connections are in part the legacy of past societal attitudes that emphasized extraction and exploitation, with little concern for sustainability and multivariate management. This attitude has changed, and is being reflected in federal agencies by the concept of ecosystem management (Lewis 1994, Keiler 1994). Limnology is preadapted for this change in environmental management, but must make itself known if it is to participate fully.

Support of Research

Most scientific disciplines can justify additional support, as can limnology. Even in the context of limited resources, however, support for research in limnology is inadequate when taken in appropriate context with the societal need for limnological knowledge. Limnologists with demonstrated ability to advance the discipline commonly find support so difficult to obtain that they either do without it much of the time or budget large percentages of effort to obtaining it. In the U.S., opportunities for post-doctoral training are few. There are no designated training grants, except for the limnology of the Great Lakes, nor are any federal programs specifically designed to strengthen limnology. Limnologists in many universities cannot support the scientific infrastructure that may be essential in some branches of limnology for credible analytical work. University research programs have in many areas not been able to keep pace with government research laboratories that deal with aquatic sciences; this handicaps not only the national research effort, but also the education of graduate students.

Factors Presently Affecting Limnology

Present Investments in Limnological Research

It is difficult to quantify support for research in any field of science. This is particularly true for limnology and other multidisciplinary fields that may receive support from a variety of disciplinary sources. However, an overview is possible for the United States on the basis of current federal statistics as interpreted by the American Association for the Advancement of Science (AAAS 1994).

The context for support of research and development in the United States is given by Table 1. The total national R&D for 1995 is estimated at approximately

Table 1. Support of research and development in the U.S. for 1995 (expected or proposed) as summarized by AAAS (1994).

Budget Items	**Billions of Dollars**	
Overview of R&D		
Total Federal Budget for R&D	73.4	
Private R&D	85.0	
Total National R&D	**158.4**	
Major Components of Federal R&D		
Applied Research	59.2	(81%)
Basic Research	14.2	(19%)
Total Federal R&D	**73.4**	
Support of R&D at Colleges and Universities		
National Institutes of Health	6.4	
National Science Foundation	1.8	
Department of Defense	1.5	
National Aeronautics and Space Administration	0.7	
Environmental Protection Agency	0.2	
Other	1.6	
Total	**12.2**	
Components of the Total National R&D Investment (for Perspective)		
Leisure Time Products	2.0	
Health Care	11.2	
Office Equipment and Computers	17.2	
Federal R&D by Agency, Total (Basic)		
Department of Defense	37.0	
National Institutes of Health	11.0	
National Aeronautics and Space Administration	9.4	
Department of Energy	6.9	
National Science Foundation	2.4	
U.S. Department of Agriculture	1.5	
National Institute of Standards and Technology	0.8	
Other Health and Human Services (non-NIH)	0.6	
Environmental Protection Agency	0.6	
National Oceanic and Atmospheric Administration	0.5	
U.S. Geological Survey	0.4	
Department of Education	0.2	
National Biological Survey	0.2	
Other	1.9	
Total	**73.3**	

160 billion dollars, of which slightly less than half flows through the federal budget. The ratio of basic to applied research overall is approximately one to four. Support of research and development at colleges and universities, which conduct a large portion (86%) of federally funded basic research, totals just over 12 billion dollars annually. More than half of this is accounted for by research related to human health, which leaves approximately 5 billion dollars to be distributed among all other branches of science and engineering that conduct basic research in universities.

Of the total federal R&D, approximately half flows through the Department of Defense, and about half of the remainder through NIH and NASA. The National Science Foundation receives approximately 3% of the federal investment in R&D.

Table 2 provides information related to federal support of environmental R&D as well as an itemization of R&D related to inland water resources and an estimate of the support of limnological research through the federal government. Federal environmental R&D totals approximately 3.9 billion dollars, of which approximately 1 billion dollars can be attributed to oceans, 1 billion dollars to inland waters, and the remainder to other categories. Federal definitions of research and development are very generalized, however. A substantial portion of the work represented by the 3.9 billion dollars listed in Table 2 for environmental R&D would

Table 2. Support for three specific categories of R&D by the federal government in 1995 (partly extracted from AAAS 1994; expected or proposed).

Budget Items	**Millions of Dollars**
Federal Environmental R&D by Agency	
National Aeronautic and Space Administration (Mission to Planet Earth)	1200
Environmental Protection Agency	570
National Oceanic and Atmospheric Administration (Operations, Research & Facilities)	490
National Science Foundation (Bio environmental 73, Bio global change 21, Engineering environmental 28, Geo environmental 23, Geo global change 134, Oceans 208)	487
Department of Energy (Biological & Environmental)	427
U.S. Geological Survey	367
National Biological Survey	177
Department of Defense (Oceans, Basic, via ONR)	122
U.S. Department of Agriculture (Natural Resources & Environment)	27
National Park Service	20
U.S. Fish and Wildlife Survey	0
Total	**3887**
Inland Water Resources R&D	
Environmental Protection Agency	444
U.S. Geological Survey	193
U.S. Department of Agriculture	140
National Science Foundation	104
National Biological Survey	69
Bureau of Mines	24
Bureau of Reclamation	12
Other	2
Total	**988**
Limnological Research	
Applied	48
Basic	12
Total	**60**

not be classified as research by most scientists. Therefore, the statistics must be interpreted cautiously.

Table 2 also provides a breakdown of the 1 billion dollars attributable to research on inland water resources. Much of this is focused on hydrology and toxicology, and is only remotely related to limnology. The programs of the USGS, for example, emphasize hydrology, although USGS is becoming an increasingly significant contributor to limnological research through its hiring of career scientists with limnological interests. The National Water Quality Assessment Program (NAWQA), which has strong limnological components and is of national scope, is the sole program in the USGS budget to increase in 1995. This shows some receptiveness on the part of Congress and federal budget analysts to the limnological perspective, particularly over broad geographic scales.

The U.S. EPA has the largest portion of the research budget for inland waters. However, only 6% of the total, or 25 million dollars, is designated as research related to water quality. The balance goes for research related to drinking water, hazardous waste, pesticides, multi-media problems, toxic compounds, and Superfund, and thus is not limnological; a portion of the water quality research is also nonlimnological.

The total amount listed for inland waters under the National Science Foundation does not even include limnology, which is too subtly imbedded in the Division of Environmental Biology and other divisions to be extracted by the overview methods used in tabulation of the data shown in Table 2. The 104 million dollars shown in Table 2 reflects NSF support of research in earth sciences, with emphasis on geology, geophysics, geochemistry, and hydrology, tectonics, paleontology, and seismology, and in engineering, with emphasis on bioengineering, environmental systems, and chemical and transportation systems.

The budgets of other agencies listed under inland waters are typically more distantly connected to limnology than those of the U.S. Geological Survey and the National Science Foundation, with the possible exception of the National Biological Survey. NBS programs are not easily identified yet, given that they have been diverted from other agencies, particularly the U.S. Fish and Wildlife Service.

Because it is very difficult to extract from the federal budget a reliable figure for investment specifically for limnological research, a more direct approach is necessary. A recent tabulation of limnologically related proposals funded by the National Science Foundation provides a basis for a rough approximation. According to Firth and Wyngaard (1993), the National Science Foundation supported, in fiscal year 1991, 195 proposals that had some limnological component. For this tabulation limnological subject matter was defined very broadly. In addition, the proposals that were placed in the total in many cases had large non-limnological components. Therefore, the total needs to be discounted by some significant but unknown proportion as a means of acknowledging the mixed functions of support from the 195 proposals. For present purposes, it will be assumed that one-third of the total emphasis of these 195 proposals is limnological. Assuming very roughly an expenditure of $60,000 per year per award, the total investment in limnology by NSF would be approximately 4 million dollars annually. This approximation only establishes an order of magnitude, of course, and not an exact figure. Assuming, once again for purposes of very general approximation, that a wide variety of other sources, including the U.S. Geological Survey, support limnological research amounting to as much as twice that of the National Science Foundation, as judged from program descriptions for agencies listed in Table 2 under Inland Water Resources, the total for basic research would be 12 million per year. If the ratio of applied to basic research can be estimated as approximately equal to the national average, as shown in Table 1, the applied component of limnological research will be four times that of the basic component, which gives a total national support for limnological sciences of about 60 million dollars (Table 2).

A rough check on support of limnology is possible through memberships in professional societies. The American Society of limnology and Oceanography has about 4,000 members, of which about half are limnologists and half oceanographers. Several other U.S. societies have high representation among limnologists. The number of limnologists who do not belong to ASLO, as indicated by non-overlapping memberships in other societies, is not known. Assuming that there are 2,000 limnologists who are members of ASLO and another 2,000 - 6,000 who are not members, the total number of limnologists would be 4,000 to 8,000. Many of these individuals, however, are students, faculty of colleges that lack research programs, or limnologists who are involved in other activities that do not include research. Data from a study of the Ecological Society of America indicate that about one-quarter of ESA members conduct research. If 2,000 limnologists (one-quarter of the upper estimate made here) were involved in research and were to expend $30,000 per year on the average (assuming some intervals of no support), the total research effort would be approximately $60 million per year. Given the great uncertainty in these estimates, its concurrence with the estimate from government budgets is very good. The general conclusion is that U.S. research in limnology presently amounts to some $50 to $100 million per year, of which 10-20 million is basic and the rest is applied.

Support for limnological research is inadequate if evaluated from general principles applicable to support of R&D. Private sector investment in research and development for the U.S. is 2.8% of GNP, an amount that is widely considered too low (OECD 1989). Public sector research typically shows high returns (e.g., 50% for agriculture: Evenson et al. 1979, OECD 1991). An investment equal to 2.8% of environmental protection costs, if designated for basic and applied research on aquatic ecosystems, could easily be justified on the basis of more economical use of funds now committed to protection and management of aquatic resources. For the U.S., taking pollution control alone as the base, and using the EPA's estimate of 50 billion dollars per year, a 2.8% designation for research on inland waters would correspond to 1.4 billion dollars per year, of which limnology should be a significant component. The total investment (1 billion: Table 2) is not so far from the mark as one might expect, but the limnological component is far too small ($60 million).

Other External Factors

It has become increasingly imperative that disciplines be named in the budgets of government agencies in order to maintain an appropriate share of research support, yet no major federal agency in the United States or Canada names limnology in its budget. Within the National Science Foundation, which is the primary agency for support of limnological research in the U.S., limnology is subsumed under other names, including especially ecology (Firth and Wyngaard 1993). The budgetary anonymity of limnology is similar in Canada, where it falls federally under two of 11 NSERC initiatives.

In the U.S., the NSF support system is, from the viewpoint of most individual investigators, not a reasonable basis for the planning of any scientific venture beyond a modest two- or three-year self-contained project. While NSF projects may be renewed, the failure rate for renewals of scientifically successful projects is high, and the investigator is ill advised to plan for continuity.

Robust fields of basic science frequently have two or more sources of federal support receptive to research originated by investigators. As pointed out by Jumars (1990), oceanography has benefited from the availability of substantial support from both NSF and the Office of National Research (ONR). Such fields as animal physiology, neurobiology, and molecular biology are sustained by a combination of sources (NSF and NIH, in the case of the U.S.). Investigators in these fields frequently find that the perspectives of separate agencies differ substantially; proposals that receive virtually no encouragement from one agency may receive support from another. Sometimes these contrasting evaluations result from differences in agency missions, but in other instances they reflect variation of informed opinion across different agencies and different sets of reviewers. The availability of support from more than one agency ensures greater stability for individual research programs, and for the entire discipline.

In the U.S., limnology is not only undesignated within NSF, but is also without any other sustained source of support. Although other sources may be available on an *ad hoc* basis, no agency other than NSF (except for small commitments through NOAA's Sea Grant for the Great Lakes, the USGS, and EPA exploratory research grants) supports limnological work that is planned through the scientific intuition and experience of principal investigators, as some components of research must be. Such agencies as the Army Corps of Engineers, U.S. Fish and Wildlife Service, U.S. EPA, and others make dozens of decisions that have a direct limnological basis, yet these agencies are without sufficient connection to limnology; they do not support an external scientific infrastructure that would provide them with new information in the field of limnology, even though they often spend large amounts of money for very short-term studies to fulfill legal requirements. The working interaction between environmental agencies and sources of new information should be many times more extensive than it is at present.

Limnology is much less familiar in the U.S. and Canada than it is in Europe, where the practical importance of limnology is better acknowledged. In North America, such individuals as science writers, government resource managers, or graduate students in allied fields of science are often completely unfamiliar with limnology or have only a vague notion of its subject matter. Poor external recognition of limnology reinforces the tendency of government programs that are clearly limnological to evolve under other headings and to remain disconnected from limnology and limnologists. In fact, some limnologists believe that a change of name would benefit the discipline. This possibility has numerous disadvantages, not the least of which is the existence of a large contingent of limnologists outside North America who would have much less motivation to consider renaming the discipline.

The weak government support and budgetary anonymity of limnology may have contributed to a decline in the independence and recognition of the field. Federal programs are the *de facto* recognition of significance for any scientific discipline; agencies and individuals not familiar with limnology may take an important cue from the basic science support system, which does not recognize limnology as a distinct discipline. The government system of nomenclature for basic research has potent influence on perceptions within government agencies that are responsible for management or regulation, and upon scientists in other disciplines.

Consistent footnoting of limnology under the main heading of ecology has required academic limnologists to present themselves as ecologists. While this is not a disadvantage in some cases, given that limnology is an ecological science, it has worked against the development of a sense of community among limnologists and against the evolution of a healthy, intradisciplinary perspective that might differ substantially from that of ecology at large. Because specialized studies may be reviewed most beneficially by ecologists in general (Dayton 1979), the present system for support of basic research may in part have encouraged limnologists to lose touch with the broad ecosystem perspective that unifies limnology.

Weak support has also influenced the ambitions and attitudes of limnologists. Aggressive scientific ventures require confidence of the investigator in sustained and significant funding. In the absence of this kind of support, productive investigators frequently fall back upon studies of more restricted scope that still allow them to make original contributions. Thus the inadequate financial support of limnology may account for fragmentation of the discipline into specialized fields of inquiry that have shown progressive weakening in their interconnections.

Deficiencies in the present system for educating limnologists may also be in part a reflection of poor government sponsorship for the field. Inadequate support of research impairs the ability of academic limnologists to sponsor graduate students, purchase equipment, and build teaching traditions that are ambitious and resource intensive. Furthermore, universities increasingly provide resources to academic disciplines in proportion to their production of money through extramural sources. It is far easier to build ambitious teaching programs around well-supported research programs than it is otherwise.

In addition to being subsidiary and meager, the present research support systems for limnology are poorly adapted to the integrative character of limnology. Government systems for administration of science most effectively support research that can be clearly identified with traditional disciplines such as physics, geology, chemistry, or biology. In contrast, integrative disciplines such as limnology are often mismatched with the administrative infrastructure through which they are supported, unless they are explicitly named as a separate program (e.g., oceanography). For example, limnology in the U.S. is supported primarily through the NSF's Division of Environmental Biology, which quite naturally places its priority on biological phenomena. For example, in 1991, NSF supported only 4 proposals in physical limnology (Firth and Wyngaard 1993). In the face of high rejection rates, proposal writers learn to emphasize studies that find favor with biologically oriented reviewers. The result is insufficient emphasis on the physical and chemical branches of limnology that form an essential part of the overall fabric of the discipline.

Greater government sponsorship of limnology in the U.S. and Canada could be well justified by the strength of the limnological communities in these countries. The American Society of Limnology and Oceanography publishes *Limnology and Oceanography*, which is the most widely cited journal internationally for both limnology and oceanography. American and Canadian limnologists also constitute 25% of the global membership of the International Association of Theoretical and Applied Limnology. The U.S. has had a leading role in limnology since the earliest development of the discipline at the turn of the century, and Canadian and U.S. limnologists have repeatedly established new concepts and directions for the field. Limnology in North America, however, has not maintained the growth in technical sophistication and infrastructural support that is necessary for its continued success. Non-north American observers have noted that the opportunities for innovative work in American limnology were the envy of Europe two decades ago, but not now (Hrbáček 1991).

Governments cannot justify the creation of programs for every field of study that may be recognized by name.

Limnology, however, is a large discipline, firmly established worldwide for almost a century, with a scientific community numbering several thousand individuals within the United States and Canada, and it addresses in a unique and proven way problems that are important to society. Limnology in the United States and Canada can easily justify named programs that recognize its potential, its historical contributions, and its practical importance.

Internal Factors

Limnologists must demonstrate persuasively the benefits of additional government investment in limnology. Three kinds of limnological initiatives would improve the rationale for support of limnological education: (1) educational programs that would nurture the connection between basic and applied limnology, (2) coordinated research programs, and (3) more active guidance of the development of limnology in North America by a consortium of professional societies.

Programs that encourage the application of limnological knowledge outside universities have not yet been explored in detail by limnologists as a group (Kalff 1991). In the absence of any such programs, it is not surprising that positions requiring limnological expertise are often filled by individuals from other related disciplines that have been more responsive to the need for expertise outside universities.

It has been clear for more than a decade that science support systems in both the U.S. and Canada are increasingly emphasizing coordinated programs that focus on recognized national needs. This trend toward “big science” has been criticized by scientists in many disciplines. Given that this mechanism has now been established as a major basis for expansion of science, however, no discipline that fails to develop a coordinated framework for at least a portion of its effort can expect to be effective in significantly expanding its base of support, or in receiving its appropriate share of government recognition (Reid and Beeton 1992).

The American Society of Limnology and Oceanography has devoted itself almost exclusively to the communication of scientific advances in the fields of limnology and oceanography. It has been highly successful in this endeavor, as shown by the high prestige of its journal, *Limnology and Oceanography*, and by its well attended and vigorous national meetings and symposia, which often represent the first forum for presentation of major new advances in the fields of limnology and oceanography. ASLO, unlike some societies (Pringle and Ammon 1993, Brouha 1993), has not placed emphasis on practical matters related to government priorities for support of research, strategies for education and training, or the relationship of limnologists to government agencies. It is difficult to explain why ASLO has not pursued more vigorously some of the issues that are clearly critical to the future of limnology. One possibly important factor is the reliance of the Society on volunteer efforts for most of its work; many professional societies have a greater investment in infrastructure than ASLO does at present. Another factor is the combination of limnologists with oceanographers in the same society. While this combination is very beneficial intellectually, it may have hampered the ability of limnologists to focus on practical matters outside the intellectual arena. Furthermore, ASLO has not been able to maintain the allegiance of certain groups of limnologists, including primarily those who deal with streams, rivers, wetlands, and with applications of limnology. Separate societies have developed around these interests. This fragmentation of limnology is undesirable if limnology is to evolve coherent policies for developing the entire discipline. Limnology may in part be suffering from the absence of any organization that focuses exclusively on limnology and that speaks for all branches of the discipline.

Remedies

The strong tradition of limnology in the U.S. and Canada and the infrastructure that has been maintained in the form of faculty positions in universities and research positions within government and a few private organizations are sufficient to ensure the success of policies that deal directly with causes of the present problems in limnology. Strengthening limnology in the United States and Canada will require initiatives that unify the limnological research community, establish higher visibility for limnology, improve its resource base, and allow limnologists to apply their own priorities to the distribution of research support. Initiatives should include the following:

1) Education. Limnologists should strengthen and redesign current educational programs in limnology as necessary to achieve increased breadth of education for limnologists and better connection to applications, as well as public education about the connection between limnology and the management of inland waters.

2) Development of cooperative studies. Government agencies should sponsor, with the advice of limnologists, several cooperative programs that will broaden and unify limnological research, while also addressing serious environmental problems involving inland waters. Examples might include large coordinated programs that deal with acknowledged challenges to the quality of inland waters, such as physical alteration of riparian zones, passage of toxins through food chains, or alteration of community structure under the influence of anthropogenic stress. Alternatively, large cooperative programs could be based upon intensive study of particular subsets of inland waters, such as headwater streams, large lakes, or mainstem reservoirs. These studies should be broadly comparative, geographically dispersed, and oriented around problems related to management and protection as well as improvement in the basic understanding of inland waters.

3) Designated support of basic research in limnology. For the U.S., it may be important that limnology have a designated program within the National Science Foundation, as is presently the case for oceanography. This program need not be derivative of other programs, such as ecology; it could operate through a peer-review system involving primarily limnologists. Similarly, a named program in limnology should be considered in Canada as a means of remedying the present imbalance among limnology, fisheries, and oceanography. A Canadian government report has made many beneficial recommendations for Canada (Science Council of Canada 1988), but the report does not acknowledge the role of limnology, nor have its recommendations been implemented.

4) Development of a coordinated interagency support plan for research. Given that many governmental agencies have direct need for limnological information in support of their missions, cooperative agreements should be made among these agencies for support of a diverse and vigorous program of research in limnology. National limnological research networks, which do not now exist, should be created with the advice of limnologists, and should be developed through the use of a formula that is sufficiently flexible to respond to changes in societal needs. The interagency program should be at least 50% extramurally focused so that management agencies become meaningfully connected to academic limnology.

5) *Increased but selective support of limnological field stations.* Limnologists should seek expanded support of federal agencies for limnological field stations of high quality. Support of field stations should be more stable and should increase the ability of field stations to sponsor students; it should focus selectively on stations that show potential for long-term productivity. In addition, explicit efforts should be made for the support of stations in regions that are limnologically understudied (e.g., non-glaciated regions of the U.S.).

6) *Expanded responsibilities for limnologists.* Professional societies that represent limnological interests, or groups of individuals drawn from all of the societies to which limnologists belong, should organize discussions of the status of limnology and strategies for developing limnology within the U.S. and Canada. Also, the American Society of Limnology and Oceanography in particular should devise new ways of attacking the practical problems of limnology and of cooperating with other societies that have grown up around limnological interests. A useful beginning is already in progress with preparation of the Freshwater Imperative Research Agenda. ASLO should contribute substantially to the leadership that will be essential in expanding and improving limnology. This should include a consideration of advantages that might accrue from a specifically limnological thrust for the Society, or even subdivision of the Society as necessary to achieve a better focus on limnological issues. The Society should consider a broad range of new or expanded roles that might require changes in its publications and its presently modest efforts in external affairs.

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