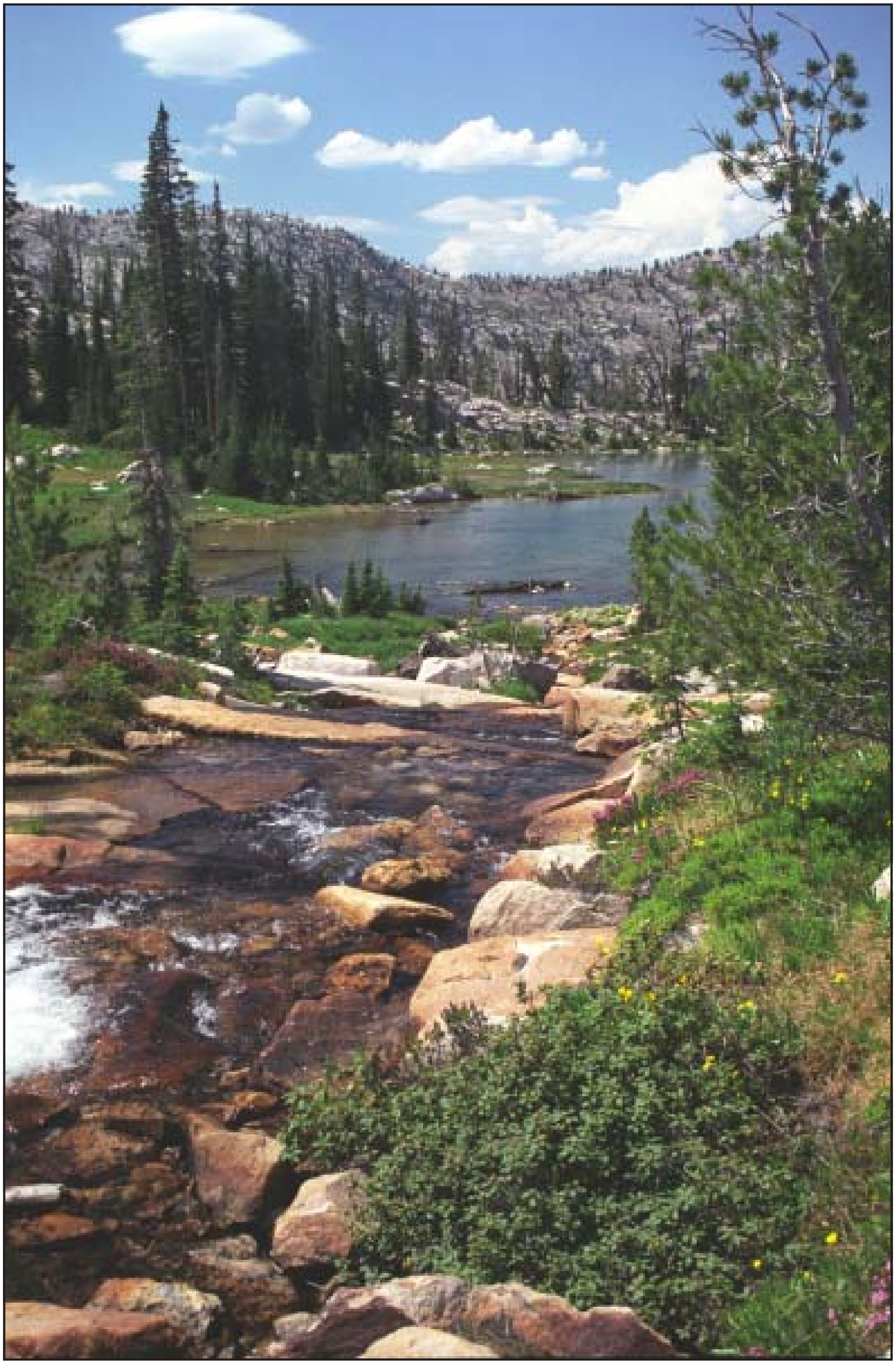
Emerging Research Questions for Limnology
The Study of Inland Waters



American Society of Limnology and Oceanography
2003

Table 1. Participants in the ASLO Workshop

Kenneth Bencala	USGS Menlo Park	hydrology
Elizabeth Boyer	Syracuse	biogeochemistry
Patrick Brezonik*	University of Minnesota	chemistry
Thomas Chapin	USGS Boulder	chemistry
Jeff Chanton	Florida State University	wetland geochemist
Yo Chin	Ohio State University	geochemistry
Jon Cole*	Institute of Ecosystem Studies	lake limnology
Kathryn Cottingham	Dartmouth	modeling, water-borne disease
Alan Covich	Colorado State University	stream limnology
John Crimaldi	Univ. of Colorado	biophysics
Charles Driscoll	Syracuse University	hydrogeology, chemistry
Sherilyn Fritz	University of Nebraska	paleolimnology
Nancy Grimm	Arizona State University	stream limnology
Jud Harvey	USGS Reston	hydrology
Ray Hesslein	Freshwater Institute, Winnipeg	chemistry
Miki Hondzo	Univ. of Minnesota	physical limnology
Jorg Imberger	Univ. of Western Australia	lake modeling
Thomas Johnson	University of Minnesota	lake sedimentology
George Kling	University of Michigan	landscape limnologist
Gene Likens	Institute of Ecosystem Studies	long-term studies
William Lewis	Univ. of Colorado	physical limnology
Frank Magilligan	Dartmouth College	fluvial geomorphology
Sally MacIntyre*	Univ. of Calif. Santa Barbara	physical limnology
Diane McKnight*	University of Colorado	biogeochemistry
John Melack	University of California	remote sensing
John Magnuson	University of Wisconsin	lake limnology
Patrick Mulholland	Oak Ridge National Lab.	streams, watersheds
Heidi Nepf	Massachusetts Inst. Tech.	physical limnology, wetlands
Kenneth Potter*	University of Wisconsin	hydrology
John Priscu	Montana State University	polar limnology
Fred Scatena	Univ. of Pennsylvania	fluvial geomorphology
Alison Smith	Kent State University	paleolimnology
Jack Stanford	Montana State University	river limnology
Jennifer Tank	University of Notre Dame	stream chemistry, biology
Robert Wetzel	Univ. of North Carolina	lake & wetland limnology
John Wilson	New Mexico Tech.	hydrology, CUAHSI representative
Thomas Winter	USGS Boulder	lake hydrology
Wayne Wurtsbaugh*	Utah State University	watershed limnology

NSF Representatives

Pam Stephens, Atmospheric Science
Linda Goad, Ocean Sciences
Elise Ralph, Ocean Sciences
Alan Tessier, Environmental Biology
Walt Snyder, Earth Sciences

Alan Covich, Jud Harvey, George Kling, Sally MacIntyre, John Melack, Heidi Nepf, John Priscu and Jennifer Tank served as discussion leaders or rappetuers for the four break-out groups at the workshop, and they crafted the initial drafts of the four Emerging Themes in Limnology. Koren Nydick, Melanie Whitmire, Steven Beck, Stephanie White, and Peter Jumars assisted with workshop logistics and editing of the report.

*indicates member of the Workshop Steering Committee.

Report of the Workshop on Emerging Research Questions for Limnology: The Study of Inland Waters

Held December 1-4, 2002
Boulder, Colorado

Edited by
Wayne Wurtsbaugh, Jon Cole, Diane McKnight,
Pat Brezonik, Sally MacIntyre, and Kenneth Potter

American Society of Limnology and Oceanography
5400 Bosque Boulevard, Suite 680
Waco, Texas 76710-4446
http://aslo.org/

The workshop was funded by a grant from the Geosciences Directorate of the U.S. National Science Foundation (NSF). Publication of this report was funded by NSF and the American Society of Limnology and Oceanography. The contents of the report reflect the views of the workshop participants and editors and do not necessarily reflect the views of NSF or ASLO.

Table of Contents

Executive Summary

Introduction

The status of freshwater resources has become a crucial global issue. Continuing growth in the human population and increasing use are outstripping available water resources in many regions of the globe, and long-term changes in climate are expected to exacerbate these problems. Demands and impacts on fresh waters influence not only human populations, but also increasingly threaten natural ecosystems. These impacts reach beyond fresh waters. Exported pollutants are degrading coastal waters, and modifications of freshwater systems are altering carbon cycling at a global scale. Recognition of these problems has led many organizations to focus on the critical need for more support for freshwater research[25,166]. Most recently, the National Science Foundation's (NSF) 10-year Outlook on Complex Environmental Systems[1] called for a more integrated, enlarged, and focused program of water research in the United States.

Recognizing the critical importance of fresh waters to human and ecological systems, the Geosciences Directorate at NSF has solicited input from the research community on new directions in freshwater research and education. In response, the American Society of Limnology and Oceanography (ASLO) held a workshop on new research directions for limnology in Boulder, Colorado, in December 2002. Forty-two scientists, representing a broad range of disciplines including limnology, hydrology, and wetland science, attended the three-day workshop. A diverse group of scientists was invited in order to provide synergy to develop new ideas about fresh waters. To obtain broader input, Concept Papers on emerging issues in limnology were solicited from members of eight scientific societies, and the 60 papers contributed by the respondents help guide workshop discussions.

The central objective of the ASLO workshop was to determine major research issues and questions for potential use by the Geosciences Directorate for planning research programs on inland waters for the next decade. Because 47% of the volume of continental waters are saline[56], and many of them have immense economic and ecological values, limnology is considered the study of inland, rather than fresh waters. Issues concerning infrastructure needs of the scientific community and management of aquatic resources were not explicitly treated during the workshop. Recognizing that much of the support for limnology during the previous decades has focused on biological and ecological questions, the Geosciences Directorate is now promoting research on the physics, chemistry, and geology of inland waters and their integration with biological investigations.

The field of limnology is poised to make important and exciting scientific advances in the coming decades that will help us understand and manage inland waters. Because limnology is intrinsically interdisciplinary, it is well positioned to address issues that demand coordinated efforts of scientists from several disciplines (Figure 1 shown later). To develop process-level understanding of aquatic systems, limnologists employ observational studies, modeling, small-scale experimentation, and whole-ecosystem experiments. Additionally, technological advances in modeling, *in situ* sensors, remote sensing and geographic information systems will accelerate understanding of processes of fresh waters in the coming decades.

Emerging Research Issues in Limnology

Four new research foci emerged from the ASLO workshop that hold particular promise for expanding understanding of inland waters, and thus the ability to properly manage them.

- The Hydrogeomorphic Landscape
- Inland Waters as Hot Spots of Biogeochemical Activity
- Hydrodynamic Controls of Biogeochemical and Ecosystem Activity
- Global Change and Inland Waters

Theme 1—The Hydrogeomorphic Landscape

Water movement links fresh waters with the terrestrial and marine environment and connects them in a complex landscape. As water moves across the landscape, it develops characteristics dependent upon the topographic, geological, and biological characteristics of the flow paths, or the *hydrogeomorphic landscape* in which it travels. Linkages between water bodies allow organisms to disperse[97] and to transport nutrients, sometimes counter to the flow of water[110]. Linkages between groundwater, streams, lakes, and wetlands within this hydrogeomorphic landscape will have marked effects on both abiotic and biotic processes in water. Limnologists traditionally have studied individual lakes, streams, and wetlands; only recently have they begun to look at how complex networks of water bodies influence biogeochemical processes and ecosystem properties[77,94,172]. Additional research at the landscape scale undoubtedly will yield novel insights and better predictive capacity for understanding and managing aquatic resources. Three questions are of particular importance:

Increasing access to comprehensive data bases and remotely sensed data allow researchers to address limnological questions at ever broader spatial and temporal scales and to construct models of biogeochemical and ecosystem function for large assemblages of lakes, streams, and wetlands in landscapes, rather than for individual water bodies.

1. *Can quantitative, landscape-level analyses of lakes, rivers, and wetlands further understanding of biogeochemical and ecological processes in inland waters?* Limnologists are beginning to use synthetic approaches to compare sets of freshwater bodies at regional and global scales. New tools allow one to determine whether biotic and chemical processes in lakes are influenced more by geological setting and landscape position or by local controls[8,59,120,123]. For rivers, new predictive models can build upon two principal paradigms in freshwater ecology — the river continuum and nutrient spiraling concepts. The next generation of models, however, must be broadened to incorporate heterogeneity within the river system, including lateral exchanges of materials between the channel and the flood plain through both surface and groundwater flows. These coupled ecological-hydrological-hydrodynamic models will generate new hypotheses to be tested by empirical studies. The models will also be important tools for developing restoration plans grounded in a robust landscape context.

2. *How do landscape positioning and linkages of groundwater, wetlands, streams, and lakes influence biogeochemical processes and ecosystem function?* Because inland waters have more commonly been studied at the scale of individual lakes, wetlands, or stream reaches, relatively little is known about how suites of aquatic elements embedded in the terrestrial landscape function to control the movement of chemicals and energy. Research on linkages between systems at the watershed scale will likely provide novel results at scales necessary for understanding regional, continental, and global processes. For example, recent results have shown that high rates of oxidation of manganese at the groundwater-stream interface influence basin-scale export of this trace constituent[57]. Modeling biogeochemical processes at the landscape level will

require understanding of how hydrologic components with long residence times (e.g., large lakes, ground waters) and short residence times (e.g., streams, ponds) are interspersed, because hydrological residence times regulate how both abiotic and biotic alterations affect inland waters. As water moves through portions of the hydrogeomorphic landscape, differential transport and retention of elements may alter stoichiometric balances of carbon, nitrogen, phosphorus, and trace constituents for areas downstream. For example, stoichiometric imbalances of exported nutrients from inland waters influence algal growth in estuaries and coastal oceans[68].

3. *How can landscape models incorporate terrestrial-aquatic linkages?* Innovative approaches are needed to understand processes controlling biogeochemical linkages between terrestrial and aquatic systems[98]. GIS-based expertise and tools to transform terrain maps and digital elevation data into export models are not commonly used in aquatic sciences, and the expertise to understand and model aquatic processes is not common in terrestrial sciences. Consequently, an interdisciplinary approach is needed to develop robust models linking terrestrial and aquatic processes. To understand and model these terrestrial-aquatic linkages, aquatic chemists will need to move beyond analyses of how underlying geology influences major ion chemistry and instead focus on how lithology, soil development, and biogeochemical processes control the evolution of limiting nutrients in watersheds[63].

A hydrogeomorphic landscape approach will shift the focus from individual systems and help researchers to identify and model patterns at watershed, regional, and continental scales. This research will contribute to global-scale analyses of the transport and fate of carbon, other nutrients, and contaminants. This approach also will increase understanding of how landscape conditions influence productivity and biodiversity of inland waters.

Theme 2—Inland Waters as Hot Spots of Biogeochemical Activity

Inland waters are highly active biogeochemically and exert disproportionately large effects on elemental mass balances and cycling rates, even though these environments occupy a small portion of the Earth's surface. At a smaller scale, biogeochemically active areas occur within rivers, lakes and wetlands when flow paths bring reactants together either in spatially restricted zones or during temporally restricted periods when a disproportionately large portion of transformations and storage of elements may occur. There are many compelling reasons to study these aquatic hot spots and hot moments at both global and drainage-basin scales.

Although inland waters cover <2% of the Earth's surface, they may store three times more organic carbon than the oceans.

Because lakes, reservoirs, wetlands, and rivers cover < 2% of the Earth's surface, inland waters are often overlooked by scientists working on global or regional mass balances of key elements or constituents. Reservoirs, lakes, and wetlands, however, store about three times as much organic carbon as the vastly larger oceans[30]. In contrast to terrestrial storage, lake sediments and peatlands endure for tens of millennia, thus having a significant impact on the global carbon cycle at the time scale of anthropogenic influence. Stallard[152] argues convincingly that a very large fraction of the total carbon sequestration in the North Temperate Zone may reside in aquatic sediments.

River flood plains and wetlands illustrate a different role of inland waters as hot spots in regional elemental cycling. For example, the terrestrial portion of the Amazon River catchment had appeared to be a sink for atmospheric CO_2. This river and its vast floodplain, however, have recently been shown to be an enormous net source of CO_2 to the atmosphere[130]. Combining the aquatic portions of this catchment with the terrestrial revealed the Amazon basin not as a large net sink of carbon, but rather a system in which sources and sinks are essentially balanced. Similarly, although wetlands are important hot spots of biogeochemical activity, they appear to be greenhouse-neutral on time scales of centuries because CO_2 uptake and storage is offset by emission of methane[170], another greenhouse gas. Inland waters also exert disproportionate influence on cycling of macronutrients such as nitrogen and phosphorus, as well as on micronutrients such as iron, and they, in turn, are crucial for mediating carbon fluxes.

At a smaller scale within inland waters, and especially at the interface between freshwater and terrestrial systems, hot spots for critical biogeochemical reactions occur uniquely, or at greatly accelerated rates, compared with the surrounding terrestrial matrix. Examples include methylation of mercury, production and oxidation of methane, reduction of sulfate, and denitrification. These reactions affect mass balances of carbon, sulfur, nitrogen, and mercury at the watershed scale and need to be understood in the context of the aquatic environments in which they occur. Analogously, there can be points in time (hot moments) in which biogeochemical cycling or transport is particularly intense. Identifying and measuring processes in hot spots and during hot moments will be critical for understanding both local and regional biogeochemical cycles, and their impacts on ecosystem function.

Three important questions concerning hot spots and moments in inland waters should be addressed in the coming decade:

1. *What are the precise rates of cycling and storage of carbon and other nutrients in inland waters?* Although current estimates indicate the importance of inland waters for carbon and nutrient cycling and storage, improved quantification in these hot spots is needed to understand and model regional and global budgets of nutrients and greenhouse gases.

2. *What processes govern where and when hot spots and moments occur? Can they be modeled?* These questions can be addressed within a space-time continuum where spatial scales vary from the global to individual water bodies and temporal scales range from those determined by climate variability to those determined by the rapid interactions between flow and substratum in a stream, lake, or wetland. An understanding of these spatio-temporal factors is necessary for accurate determination of the magnitude of biogeochemical processes of inland waters. This problem is especially acute given that many processes are nonlinear.

3. *How are reactive trace constituents influenced by hot spots?* The concept of hot spots and moments will facilitate the study of interactions involving trace metals, anthropogenic organic chemicals, and biogeochemical cycles. Both abiotic (e.g., oxidation/reduction and photochemical reactions) and microbial transformations are focused at hot-spot interfaces. Consequently, processes at hot spots control mobility and bioavailability of reactive trace constituents.

Inland waters not only are hot spots of biogeochemical activity that may affect global cycles of elements, but they also are immensely important for organisms and human societies. The concentration of human activities along lakes and rivers has altered the physical, chemical, and biological properties of these systems, and escalating human demands for these same water resources will generate increasing challenges for natural resource managers. Understanding hot spots will be crucial not only for understanding fluxes and transformations of carbon, nutrients, and reactive trace constituents, but also for maintaining sustainable freshwater resources.

Theme 3—Hydrodynamic Controls of Biogeochemical and Ecosystem Activity Across Space and Time

Understanding the spatio-temporal variability of hydrodynamics will position limnologists to accurately quantify biogeochemical fluxes and to better assess the responses of aquatic ecosystems to climate- and human-induced changes in external forcing.

Water movements exert strong controls on biogeochemical processes and ecosystem function over a range of spatial and temporal scales. At regional scales and at the scale of individual systems, seasonal and interannual variability in meteorological forcing determine hydrological fluxes and hydrodynamic conditions. These characteristics, in turn, influence rates and locations of bio-

Water + nutrients + light = A recipe for intense biogeochemical activity. Wetlands, lakes, and rivers are highly biogeochemically active, and support important ecosystem functions. Everglades National Park, FL.

geochemical processes, as well as the heterogeneity of habitat within streams, rivers, lakes, and wetlands. Within standing waters, seasonal and interannual variability affect persistence of thermal stratification and extent and frequency of convective motions that drive horizontal and vertical transport. Changes in surface meteorology on weekly, daily, and hourly time scales determine the strength and frequency of the turbulence that controls gas flux, pore-water exchanges, sediment resuspension, light attenuation, and even success of feeding and mating of many animals. Based on recent process studies that use new technologies and models, limnologists are developing new understanding of how spatial and temporal variability of turbulence structures aquatic environments and creates the hot spots and hot moments where biogeochemical reactions are enhanced. For example, earlier models of lake mixing assumed that small-scale turbulence occurred equally across entire lake strata, but we now recognize that mixing is induced much more locally by internal waves interacting with lake boundaries and internal topographic features. These advances are producing major paradigm shifts in understanding of the physical dynamics of inland waters, and consequently limnologists are poised to produce major advances relevant to all themes discussed here.

Three important questions should be addressed with the application of exciting new technologies:

> *1. How do hydrodynamic processes control formation and persistence of chemical and biotic patches within lakes and streams?* In lakes, concentrations of organisms and sharp gradients in nutrients and trace constituents can occur in thin strata at depths where wind-induced turbulence would have been assumed to disperse them. Because of the high rates of biogeochemical reactions in these layers, it is important that their temporal and spatial dimensions are characterized and that we understand how hydrodynamic processes allow them to form and persist. Patchiness is also pervasive in streams and rivers due to fluvial geomorphic processes. Nutrient patches in streams have been related to upwelling from streambed pore waters and to spring inputs, causing variations at scales varying from tens of meters to kilometers. Heterogeneity is also induced by the abrupt differences in currents above surfaces, and to enhanced turbulence behind rocks and promontories. Aggregation of particles and organisms occurs at these discontinuities. A diverse suite of hydrodynamic processes leads to patchiness of solutes and particles, and systematic investigation of these processes is needed.

> *2. What are the dominant hydrodynamic processes occurring at interfaces and how do they regulate biogeochemical fluxes across those interfaces?* Important biogeochemical fluxes of solutes and gases occur at a diversity of interfaces and scales in inland waters, ranging from biofilms at the solute-particle scale, to air-water and sediment-water interfaces at lake or stream scales. The interplay of chemical gradients and hydrodynamic processes at these interfaces determines magnitudes of biogeochemical fluxes. Consequently, hydrodynamic processes must be addressed at the appropriate scale for a given interface.

3. What are the implications of the spatial and temporal heterogeneity created by turbulent events and coherent flows for spatial and temporal patterns in biogeochemical processes? Is this heterogeneity more important than the mean condition for system behavior? Persistent patchiness of solutes, particles, and organisms in inland waters means that estimates of rates of biogeochemical processes based on unweighted mean concentrations from random sampling may be erroneous. The problem is further confounded because rates of many physical, biological, and chemical processes are nonlinearly related to concentrations of reactants. In addition, the mixing events that facilitate many of the reactions occur with greater frequency near boundaries and during periods with strong currents and turbulence. Predictive understanding of spatio-temporal variability of turbulent events and patchiness in flowing and standing waters is prerequisite to accurate quantification of rates of biogeochemical processes.

Theme 4—Global Change in Inland Waters

Inland waters are sensitive indicators of global change because their internal physical and biogeochemical processes can amplify the signals of perturbations in energy, water, and chemical fluxes.

Climate change will likely lead to 1 to 5°C increases in temperature worldwide in the next 50 years, with these increases occurring at different seasons on different regions of the globe. What is not currently known is how the changing frequency of disturbances due to wind forcing and alterations in rainfall and cloud cover will influence inland waters. Superimposed on the long-term warming trend are changes in the modal oscillations. These oscillations affect movement of the jet streams that lead to changing wind patterns over large regions with impacts on local meteorology. Studies of El Niño have shown that changes in heat and momentum fluxes across the air-water interface accompany these oscillations.

Modifications of the timing of runoff due to global climate change will modify the functioning of both streams and lakes.

Because the seasonal cycles of stratification and mixing in lakes and wetlands depend on energy exchanges at the air-water interface, an amplified response to these meteorological changes can occur. Some simple consequences of climate warming in lakes are readily predicted: longer periods free of ice in temperate and polar regions, warmer surface temperatures, and larger temperature gradients across thermoclines. Some of these changes have already been documented for lakes and rivers[95]. Other subtle, but potentially more important changes that will result from modified mixing regimes may influence biogeochemical cycling, eutrophication, and success or loss of species. A more quantitative understanding of these amplified responses will require greater understanding of hydrodynamic and biogeochemical coupling in lakes.

Three important research questions are identified relating global climate change to its influence on aquatic biogeochemistry and ecosystem function:

1. How can paleolimnological analyses and related historical studies be better used to assess responsiveness of inland waters and their catchments to changing climate and to help forecast likely climatic trajectories? Paleoclimatic studies indicate that the climate system operates in multiple mean states and can shift from one mode to another, such as from glacial to interglacial, remarkably quickly. How such abrupt climate changes affect aquatic and catchment processes is not well known, although it is clear that the observational record of the 20th century does not encompass the full range of environmental dynamics characteristic of even recent centuries[11,47]. Understanding will be advanced by merging of hydrological and hydrochemical modeling with the paleolimnological record, and with contemporary limnological analyses that reveal the climatic, nutrient, and trophic factors that favor characteristic communities. Technological innovations that will further enable interpretations of paleo-records include improved dating techniques, application of isotopic methods to single particles (allowing improved spatial and temporal resolution), new DNA technologies to improve phylogenetic and functional analysis of cells, and improved methods for characterizing organic matter.

2. How will mixing dynamics and flow regime change in response to climatic drivers and hydrologic inputs and cause changes in biogeochemical processes in inland waters? Changes in the amount and timing of seasonal runoff derived from rainfall and snowmelt are occurring throughout the world, and these changes are altering the functioning of inland waters. Changes in hydraulic residence times can change the biogeochemistry and community structure within lakes[48]. Dramatic changes have been recorded and can be anticipated; some will occur every year — others occasionally. For example, gas exchange rates depend upon the extent of turbulence on both sides of the air-water interface, as well as on the frequency of events that control the deepening of the upper mixed layer of lakes[41,90]. Hence, changes in surface energy budgets on regional scales will likely have major impacts on fluxes from water bodies. In small lakes and wetlands, where a disproportionate amount of carbon dioxide or methane is either stored or released to the atmosphere (see Hot Spots section), regional changes in climate-driven winds and convective lake mixing could induce large changes in release or storage of these greenhouse gases. Other potential changes in lakes, triggered by prolonged drought or exceptionally cold periods, may cause pronounced changes in mixing cycles, and may influence biogeochemical and biological responses such as release of toxins from sediments and fish kills. Many peatlands currently serve as carbon sinks. However, these wetlands are poised on a razor's edge. Climate change, through temperature or moisture variation, could quickly transform this large carbon reservoir into a source of CO_2 to the atmosphere. Exploring the mechanisms causing these major events and shifts in system function should be a major goal of future research.

3. Episodic and seasonal transitions are important now; will they become more important if changing climate trajectories persist? Episodic events and seasonal transitions are important for the functioning of inland waters, and they will likely become increasingly significant as rates and patterns of precipitation and runoff change in response to increasing global CO_2 levels[100]. For example, lakes and streams in alpine and chaparral watersheds are highly influenced by hydraulic flushing. The magnitude of flood events influences stream geomorphology, and these short events can account for more than 90% of annual nutrient losses from a watershed[144]. Collaborative research among climatologists, hydrologists, and limnologists is needed to understand how global climate change will alter these critical transitional events.

Conclusion

The ASLO workshop developed four emerging themes in limnology. These themes are related by the unifying idea that inland waters both affect and are affected by landscape and global-scale processes. As hot spots of biogeochemical activity, lakes, streams, and wetlands are likely critical components of regional and global energy and nutrient budgets. The location and timing of intense biogeochemical activity within these freshwater systems will depend on the organization of aquatic components within the hydrologic landscape. In turn, global and regional-scale changes in meteorological forcing will affect aquatic biogeochemical activity and the role of inland waters in landscape and global budgets of carbon, nitrogen, and many other elements. Increased understanding of these relationships and development of capabilities to model and predict changes will require interdisciplinary efforts. These advancements will be facilitated by rapid development of new technologies, including physical, chemical, and biological sensors; *in situ* instrumentation; remote sensing; modeling techniques; and cyberinfrastructure.

Although inland waters occupy a small fraction of the Earth's surface, the workshop clarified that scientists must begin to focus attention on inland waters. Dividing the earth into terrestrial, oceanic, and atmospheric processes without explicitly addressing inland waters as an equally important component will result in misleading estimates of global-, regional-, and local-scale processes. More importantly, because humans and most of the ecosystems on which we depend are inexorably dependent on inland waters, it is crucial that research institutions throughout the world focus on these environments and on new approaches for understanding, quantifying, and predicting rates of biogeochemical and ecological processes within them.

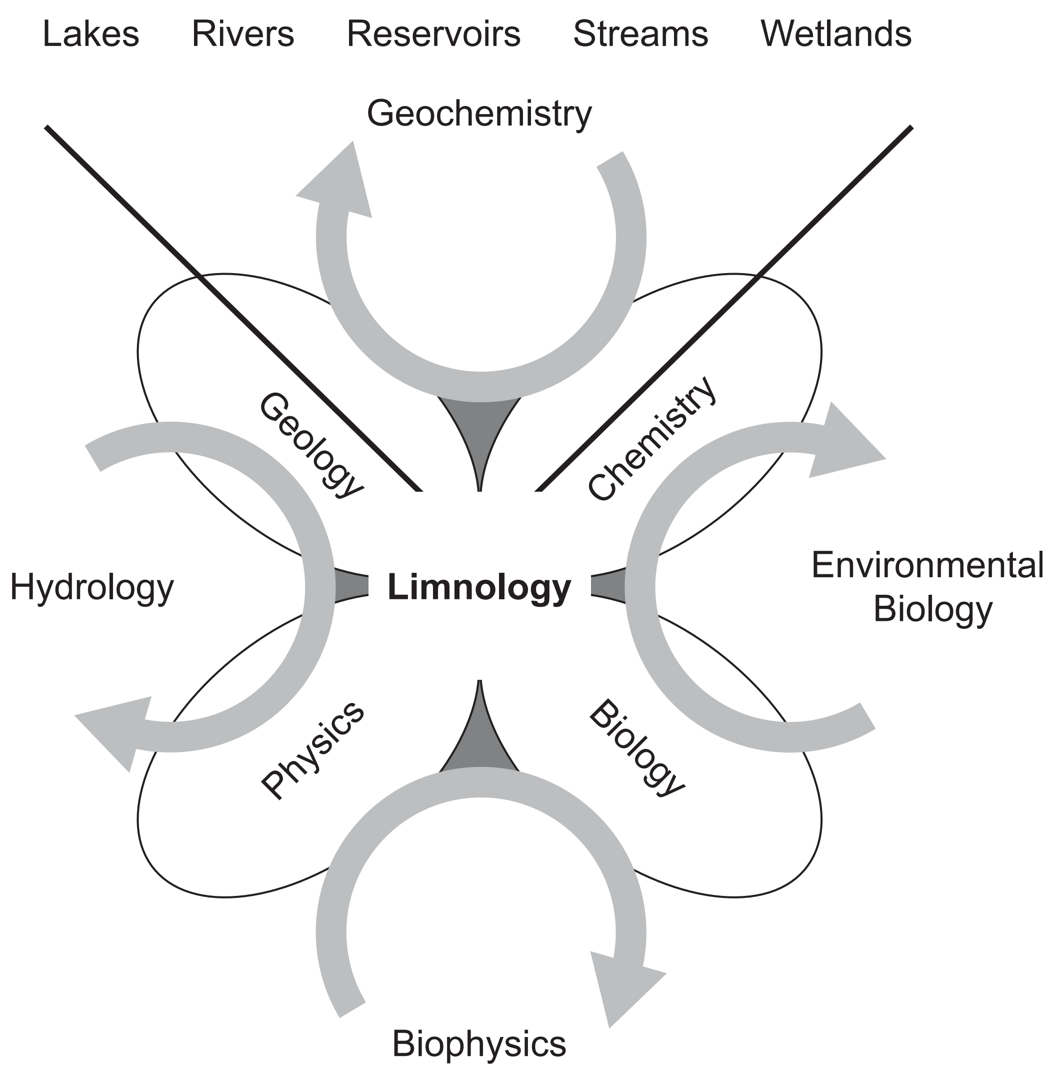


Figure 1. Limnology is the study of inland waters. Like oceanography, it is an integrative science that draws from many disciplines.

Introduction

Inland Waters — A Critical Global Resource

Water is essential for all life on Earth, and it also is a key resource for the development of human society. It is not surprising, therefore, that many of the major cities in the world developed along rivers or on large lakes where water is abundant. Regional developers sometimes have gone to extraordinary lengths (and distances) to obtain water. The extensive aqueducts of the Roman Empire and those of southern California demonstrate that humans have made, and are continuing to make major hydrologic alterations of their environment. Both water quantity and quality are critically important global issues at the beginning of the 21st century. Continuing growth in the human population is outstripping available water resources in many regions of the globe, and long-term changes in climate are expected to exacerbate these problems, especially in semiarid regions. Water quality problems are pervasive both in developed regions and in developing countries. Globally, more than a billion people lack access to safe drinking water and many more lack basic sanitation facilities.

The strategic importance of freshwater resources has been emphasized in numerous recent documents. *Envisioning Water Resources in the 21st Century*, a 2001 report of the Water Sciences and Technology Board of the National Research Council[166], called for greater emphasis on improving both water quality and the availability of water. The Council of Scientific Presidents recently issued a white paper, *Sustainable Water Quality and Quantity*[25], that calls for a more coordinated, enlarged, and focused program of water research. The 10-Year Agenda for Environmental Research and Education at NSF[25] also calls for a major emphasis on freshwater research. These reports all stress the need to study inland waters from an integrated point of view.

Recognizing the critical importance of fresh waters to human and ecological systems, the Geoscience Directorate at NSF is soliciting advice from the research community on new directions in freshwater research and education. In response, the American Society of Limnology and Oceanography (ASLO) developed a workshop on new research directions in limnology that was held in Boulder, Colorado, in December 2002. Forty-two scientists (see Table 1, inside front cover), representing a broad range of disciplines, including limnology, hydrology, and wetland science, attended the three-day workshop. To obtain even broader input, brief statements (Concept Papers) relating to the goals of the workshop were solicited from the membership of eight scientific societies in the aquatic sciences, and the 60 papers received provided additional viewpoints on the future of limnology (Appendix).

The central objective of the workshop was to determine major research issues and questions that can be used by the Geosciences Directorate to plan research programs for the next decade. The workshop emphasized scientific areas in limnology and related disciplines that are within the current mission of the Geosciences Directorate. Recognizing that much of the support for limnology during the previous decades has focused on biological and ecological questions, the Geosciences Directorate is now promoting research on the physics, chemistry, and geology of inland waters and its integration with biological investigations. The workshop and report thus focus on areas of limnology that need additional support to develop a fully interdisciplinary understanding of inland waters and to address comprehensive analyses of inland aquatic resources.

Central Role of Limnology for Inland Water Research

Limnology is the scientific discipline that studies inland waters as systems, by integrating knowledge of geological, physical, chemical, and biological processes at a range of spatial and temporal scales. An integrated approach for studying the dynamic processes of inland waters has been evident since the beginnings of limnology as a formal discipline in the late 19th century, and in this regard there is a striking parallel between the classic texts of limnology and of oceanography. As striking as this parallel is, the infrastructure to advance an integrated understanding of how aquatic systems operate has developed more slowly in limnology than in oceanography.

While limnology is a highly developed science, new perspectives and approaches are adding new vitality to the discipline, leading to major paradigm shifts. The development of new concepts and enhanced understanding are now possible in limnology because of advances in supporting scientific disciplines and in measurement and information technologies. Furthermore, limnology is contributing to exciting developments in other emerging fields of science. For example, saline lakes are being used as model systems to study microbiological processes that may shed light on extraterrestrial life processes[119]. In addition to the inherent value of advancing the basic understanding of limnological processes of inland waters, such advances are of critical societal importance for meeting the water resource challenges of the 21st century[25,69,171]. These challenges include human and ecosystem health, and water resource allocation in the face of global climate change.

The strategic importance of inland water resources, the critical role of limnology in the stewardship of these resources, and the structural limitations for limnological research have stimulated several introspective analyses and agenda-setting reports to improve the research and educational infrastructure of freshwater science in the past 15 years[71,167]. In the early 1990s the American Society of Limnology and Oceanography took the lead in articulating the need for aquatic research and education with two reports: the Freshwater Initiative[161] and the Challenges for Limnology in the United States and Canada[86]. In 1990, a coordinated effort involving the limnological community was initiated to develop a long-range research agenda for limnology. With support from NSF, this effort was carried forward by several scientific societies. The resulting consensus research agenda, *The Freshwater Imperative: a Research Agenda,*[111] sought to develop a predictive understanding of inland waters to address issues of high national priority. Three priority research areas identified for inland waters were (1) biological impoverishment, (2) altered hydrologic regimes, and (3) risks to human health. The report advocated increased collaboration between limnologists, hydrologists, and other Earth scientists to develop quantitative models to help understand and predict the responses of aquatic resources to altered hydrologic regimes.

A committee of the National Research Council (NRC) focused more closely on the need to revitalize educational programs in limnology[24]. This committee identified three major areas of concern: (1) an inadequate funding base that resulted in erosion of faculty positions in limnology; (2) fragmented educational programs; and (3) poor linkage between academic programs and the practice of limnology in the protection, management, and restoration of aquatic resources. As background to the education recommendations, several broad themes of future research in limnology were described. One theme, understanding time and space, encompassed research in paleolimnology, environmental fluid dynamics of aquatic habitats, and linkages of inland waters at regional scales. Another theme, natural water—a chemical world, emphasized interactions among nutrients, detrital organic material, contaminants, and changing climate in influencing biogeochemical cycles and sustainability of aquatic habitats. Recommendations to improve linkages with aquatic resource management, such as development of a federal job classification for limnologists, were based on the outcome of a workshop held with resource managers from federal and state agencies.

The recommendations in these reports have received broad support from the limnological community. Aquatic resource issues that have emerged since these reports were published have reinforced the relevance of many of the identified research areas. For example, widespread coastal-zone eutrophication and the expanding zone of hypoxia in the Gulf of Mexico caused by nitrogen enrichment in the Mississippi drainage basin highlight the need for regional-scale understanding of biogeochemical processes in surface waters. Projected and observed changes in hydrologic regime associated with changing climate, such as decreased summer flows in streams and decreased duration of winter ice-cover in temperate lakes, have highlighted the potential benefits from an improved understanding of the impacts of hydrologic alterations on water quality, biodiversity, fisheries, and other aquatic resources. Thus, the reports reflect a set of shared goals within the aquatic science community and provide a substantial base for developing new and expanded research programs in coupled physical, chemical, geological, and biological limnology and for strengthening interactions between limnology and other geosciences.

Limnology as an Integrative Science

Limnology is intrinsically interdisciplinary, and for that reason is well positioned to address water resource issues that demand coordinated efforts of scientists from several disciplines. The analogy of limnology as "freshwater oceanography" is accurate in many respects, although it is slightly imperfect because 47% of the world's inland water is saline[56]. Like oceanography, limnology is underlain by the major scientific disciplines, including physics, chemistry, geology, and biology, and it is supported by an interlinked set of multi- and interdisciplinary fields (Figure 1). Whereas the field of hydrology is primarily concerned with the distribution and movement of water in the hydrosphere, limnology focuses primarily on the processes within surface waters.

Experimental manipulations are an important tool of limnologists. Whole-lake manipulations and mesocosm experiments in the latter half of the 20th century identified the importance of P, N[141], and iron[175] for aquatic ecosystems. Subsequent experiments demonstrated that predators affect ecosystem processes[18]. More recently, whole-system manipulations such as experimental floods have been used to study riverine processes[142]. Above--UNDERC, Michigan; below--Glen Canyon Dam, Arizona.

The development of limnology has been guided by major organizing principles or paradigms since its beginning as a distinct scientific field in the late 19th century. The earliest organizing principles focused on lakes, and the idea of lakes as microcosms or self-contained, integrated, functioning systems[45]. Much of the limnological research done in the first part of the 20th century was descriptive and comparative (among lakes and lake districts). In the 1950s and 60s researchers recognized that lakes could be manipulated for ecosystem-scale experiments and this led to a variety of whole-lake experiments. This approach greatly enhanced our understanding of important pollution problems, such as eutrophication and lake acidification, and continues to play an important role in understanding other human perturbations of aquatic environments (e.g., nitrogen pollution of streams and mercury pollution of lakes). The ability to manipulate small lakes, streams, and wetlands to study their responses to perturbations is an important feature of limnology that distinguishes it from its sister science, oceanography, in which experimental manipulations are, at best, extremely difficult and costly. Similarly, the idea that lakes could be treated mathematically as "tank-like" chemical reactors, developed by Vollenweider in 1969, was a key for developing quantitative models to predict chemical constituent transport and behavior in inland waters. Much earlier, sanitary engineers[157] developed the concept that streams and rivers could be treated as "tube-like" or plug-flow chemical reactors and derived an "oxygen sag" model to describe the effects of biodegradable organic waste inputs on dissolved oxygen concentrations in streams. This model is the basis for all the more sophisticated water-quality models that have since developed. The paradigm of aquatic systems as chemical reactors continues to play an influential role in improving our understanding and predicting the behavior of reactive chemical constituents (both natural elements and anthropogenically derived pollutants). Reactor-theory models have become much more sophisticated, with various non-ideal reactor models now very accessible and easily adapted to diverse aquatic settings[44].

Several organizing themes for research on aquatic systems have evolved around the concept of ecosystem energetics. Lindeman developed the "trophic-dynamic" concept in the early 1940s and fundamentally changed the understanding of energy flow through aquatic food webs. H.T. Odum[117] applied these concepts to flowing waters in his classic studies on energy flow in Silver Spring, Florida. More recent developments include the concepts of resource ratio theory and trophic cascade theory[18], which have enhanced understanding of the factors affecting energy and mass flows through food webs and have provided practical approaches to controlling these flows and thus affecting the structure of aquatic food webs.

Compared with the long development of research paradigms in lake limnology, the development of integrating theories to guide research is a more recent phenomenon for stream and wetland systems, reflecting the more recent development of these disciplines of freshwater science. The River Continuum Concept[164] was the first landscape-level organizing concept for flowing waters. The River Continuum Concept views fluvial systems as series of predictable physical gradients from headwater streams to river mouths that result in corresponding changes in dominant biogeochemical processes and aquatic biota. The concept focuses on terrestrial and aquatic interactions in a watershed context. Various refinements have been added to the concept over the past two decades to describe the role of flowing waters for nutrient transport and the importance of floods in streams and rivers. Perhaps the broadest and most fundamental organizing concept related to wetlands is that of wetlands as ecotones, i.e., ecosystems that are gradients between terrestrial and aquatic environments. This concept implies that wetland research is not exclusively in the domain of aquatic scientists, and it illustrates the importance of viewing limnology not only as an integrated freshwater science, but also as a science that is closely linked with other natural resource and environmental sciences (see Figure 1).

In the past two decades, limnology has been advanced by new discoveries and important new conceptual approaches for understanding dynamic interactions among the physical, geological, and chemical aspects of inland waters. These advances have led to greater understanding of interactions within and among water bodies and between water bodies and their watersheds, and they have led to important practical advances in protecting, managing, and restoring inland waters. Given the rapid advances being made in the basic sciences and technologies that support research on inland waters, limnology is poised to make additional exciting scientific advances in the coming decades.

Emerging Research Issues for Inland Waters

Four emerging research areas, as well as technological advances that will support this work, were identified during the workshop:

- **The Hydrogeomorphic Landscape**
- **Inland Waters: Hot Spots of Biogeochemical Activity**
- **Hydrodynamic Controls of Biogeochemical and Ecosystem Activity**
- **Global Change and Inland Waters**
- **Emerging Technologies**

Theme 1—The Hydrogeomorphic Landscape

Inland waters are inextricably linked with the terrestrial and aquatic biota, soils, groundwater, and troposphere. Greater emphasis in studying inland waters as interconnected elements on the landscape will lead to new understanding of the processes controlling the movement and fate of materials and the function of aquatic ecosystems.

Background

Water is the primary medium linking inland waters with the terrestrial environment and connecting different types of inland waters together in a complex landscape. As water moves across the landscape, it develops chemical characteristics that depend on the topographic, geological, and biological characteristics of the flow paths, or the *hydrogeomorphic landscape* in which it travels. The origins of this perspective come from disparate sources in hydrogeology, regional surface-water quality, and wetland and river ecology[172]. Different patterns of flow between groundwaters, streams, lakes, and wetlands within this hydrogeomorphic landscape may have marked effects on both abiotic and biotic processes in water. Linkages between water bodies allow organisms to disperse[94], and to transport nutrients, sometimes even counter to the flow of water[110]. A hydrogeomorphic landscape approach to studying watersheds will emphasize the interplay between hydrological, geochemical, and biological processes that determine the concentrations and fluxes of carbon, nutrients, and reactive trace constituents that influence inland waters and affect the chemistry of the oceans and atmosphere.

A landscape approach for studying inland waters has been developing for some time[43,171] but few researchers have focused on more than a single element of the aquatic landscape[52,140]. Likens and Bormann[88] were among the first to recognize the importance of linkages between the airshed, geochemistry, and the biology of watersheds, and their work triggered interest in the field of aquatic biogeochemistry. The River Continuum Concept[164], which has influenced ecological studies of flowing waters for over two decades, employed a fluvial geomorphic template to address biotic processes along stream-river corridors, but did not incorporate other components of the hydrogeomorphic landscape. The River Continuum Concept provides a template against which to evaluate the effect of major perturbations to the hydrologic flow regimes such as dams[155], riparian vegetation degradation[153], and nutrient loading on stream and river systems. In the late 1980s, researchers began to develop the concept of how landforms influence the functioning of aquatic ecosystems[159], and this approach has been used to understand how surface and groundwater connections influence parameters as diverse as water chemistry and fish diversity[94]. Comprehensive approaches at the landscape scale are beginning to provide novel insights and better predictive capacity for understanding and managing aquatic resources[72,77,85,167,172]. These earlier contributions spotlight three critical gaps in our understanding of inland waters that can be filled using a hydrogeomorphic landscape approach.

A hydrogeomorphic landscape approach will shift the focus from individual systems to help identify and model patterns at watershed and continental scales. This research will contribute to global-scale analyses of the transport and fate of carbon, nutrients, and contaminants. This approach will also increase understanding of how landscape conditions influence the production and biodiversity of organisms in inland waters. Three important questions for this research were identified at the workshop.

Question 1. Can quantitative landscape-level analyses of lakes, rivers, and wetlands further our understanding of biogeochemical and ecological processes of inland waters?

Although most limnological research in the past half century has focused on single lakes, streams, or wetlands, some early work was directed at understanding lakes in a regional context[17]. The comparative limnology approach used by these limnologists was primarily descriptive because they lacked the modern tools (e.g., GIS, computers, multivariate statistical methods) needed for quantitative analysis of large data sets. Limnologists now are applying modern tools and synthetic approaches to compare sets of

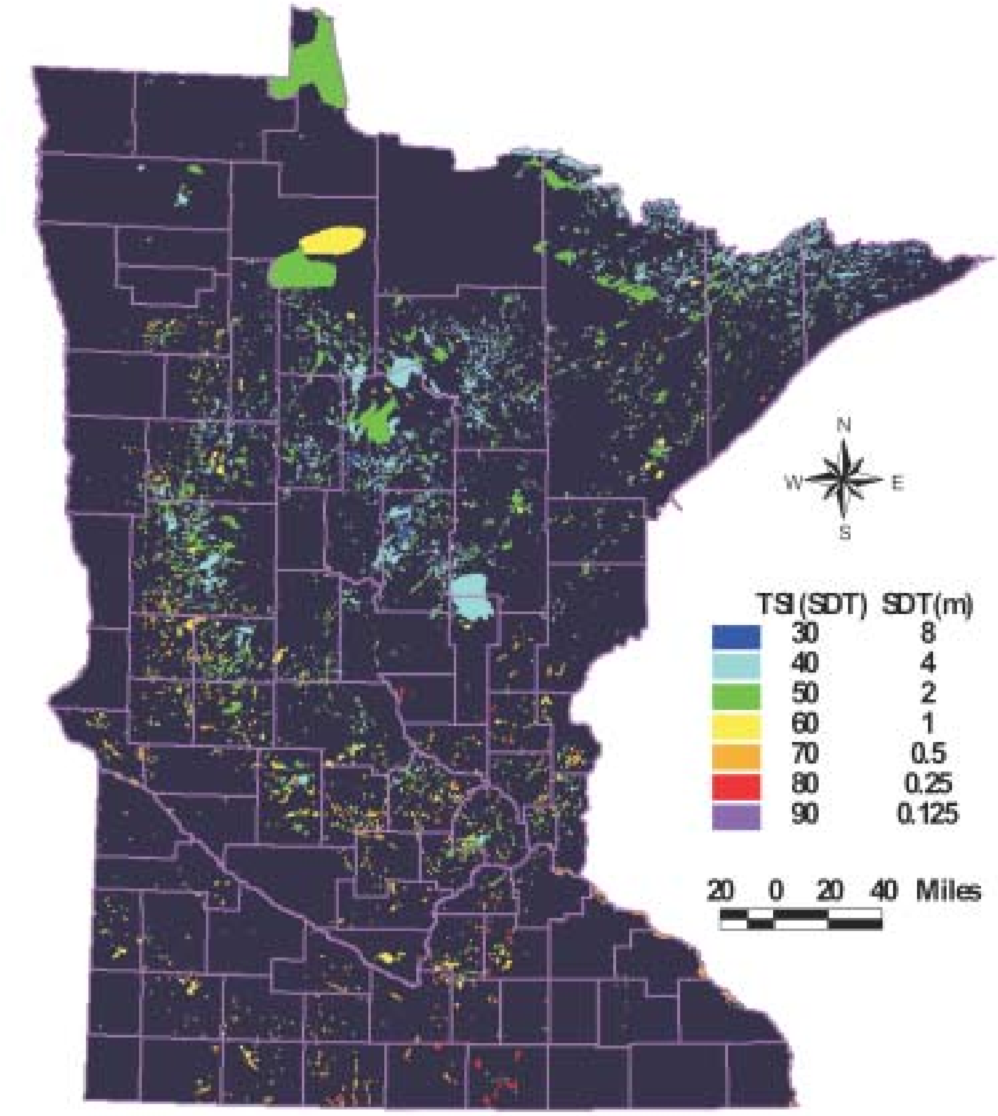


Figure 2. Census-level evaluation of water clarity in 10,469 Minnesota lakes determined from Landsat TM images. Images were processed and calibrated with ground-based measurements of transparency[78]. The trophic state index (TSI) in these lakes varied from those with water transparencies (SDT) of >8 m to highly eutrophic ones with transparencies near 0.1 m.

water bodies at regional to global scales[55] (Figure 2). The idea that some constituents of lakes behave synchronously over time in a region, while others do not, has spawned a theoretical debate on the varying roles of geological setting, landscape position, and local control[8,59,120] of biotic and chemical processes. Similarly, comparisons of nutrient chemistries between pristine watersheds and those traditionally studied in North America and Europe[123] are transforming our understanding of how inland waters function. Increasing access to comprehensive data bases and remotely sensed data will allow research during the next decade to address such questions at increasingly broad spatial and temporal scales and to construct models of biogeochemical and ecosystem function for large sets of lakes, streams, and wetlands rather than for individual systems.

Quantitative analyses of stream and river systems at the landscape scale offer opportunities for understanding biogeochemical processes. This work will be facilitated by synthesizing ideas from the river continuum concept and the nutrient spiraling concept,[113] which has addressed nutrient transport in short stream reaches. Quantitative predictive tools developed from these theoretical constructs are being used in addressing critical research issues at regional scales, such as riparian degradation and stream regulation by dams and diversions. A predictive understanding at the regional scale, however, requires more holistic approaches for modeling. For example, models that couple hydrogeological and ecological processes are needed at larger scales than discrete stream segments (e.g., OTIS model[135]) so that entire river basins and their receiving estuaries can be analyzed. Expanding to larger spatial scales will employ GIS and advanced computing platforms. Spatially explicit and dynamic biogeochemical models (e.g., BIOMEBGC[169]) are needed that realistically move water and materials through the hydrogeomorphic landscape, however altered by human activities, to the ocean.

The next generation of models also must be broadened to incorporate heterogeneity within the river system, including lateral exchanges of materials between the channel and the floodplain, through both surface and groundwater flow[28,72,131]. These coupled, ecological-hydrological models will generate new unexpected hypotheses that will stimulate improved empirical measurements and experiments. The healthy feedback between landscape-level modeling and new empirical studies will lead to many new advances, not the least of which will be an improved eco-hydrologic perspective for restoring damaged systems[154].

Question 2. How do landscape positioning and linkages of groundwater, wetlands, streams, and lakes influence biogeochemical transport and ecosystem function?

Because inland waters more commonly have been studied at the scale of individual lakes, wetlands, or stream reaches, knowledge is lacking about how suites of aquatic elements embedded in the terrestrial landscape function to control the movement of chemicals and energy, and how these fluxes influence ecosystem function. Research on linkages between systems within drainages will provide results at scales necessary for understanding regional, continental, and global processes. For example, recent results have shown that high rates of oxidation of manganese at the groundwater-stream water interface influence basin-scale export of this element[57], and the lateral exchange of materials between a channel, the floodplain, and uplands has a large influence on nutrient and carbon flux[28,131]. Similarly, biotic activity and nutrient transformations at the interface between lakes and their outflows are particularly high[129], but the reason(s) for this are not understood. In wetlands, aquatic plants serve to link the anoxic subsurface with the troposphere.[21] If aquatic systems are focal points of biogeochemical activity, then the interspersion of lakes and streams, wetlands and ground waters, may be more important in affecting fluxes than the absolute areas of these components. Consequently, studying landscape patterns of these linkages will be crucial. Landforms not only influence biogeochemical processing, but the very landforms that we often view as permanent are actually modified by biotic processes. For example, in northern Minnesota peatlands, linkages between groundwater discharge patterns and biota are critical towards shaping landforms[49,145].

Studies on the juxtaposition of “fast” and “slow” hydrological subsystems in the landscape may be crucial for understanding biogeochemical and ecosystem properties, because hydrological residence times regulate both abiotic and biotic modifications of water. After atmospheric processes deposit water, nutrients, and contaminants in a watershed,[87] they follow circuitous pathways through reservoirs that vary greatly in retention time. Some of the water flows into very large storage reservoirs, such as deep groundwater, where it may remain for years to centuries. Other water is stored for months or years in lakes and wetlands[96]. Another portion moves quickly into fast-flowing rivers, spending relatively little time being exchanged with surface and subsurface waters on the floodplain. Because biotic and abiotic rates are often high at interfaces and because residence times may vary by orders of magnitude across subsystems, accurate predictive models of fluxes of nutrients, carbon, and pollutants will require nonlinear estimates of hydrologic and biogeochemical rates that transform and transport materials[149].

As water moves through different portions of the hydrogeomorphic landscape, differential transport and retention of elements may alter stoichiometric balances of carbon, nitrogen, phosphorus, and trace constituents that control ecosystem function[156]. For example, because the atmosphere largely transports nitrogen and not phosphorus, inland waters may be shifted from nitrogen to phosphorus limitation[12].

Similarly, lakes may store phosphorus but recycle and export nitrogen[84], which may contribute to phosphorus limitation in streams and lakes further down a watershed. In contrast, wetlands, riparian zones, and streambed pore waters[10] may denitrify substantial quantities of nitrate, thus potentially contributing to nitrogen limitation of the biota in downstream waters. Imbalances of exported nutrients from inland waters may significantly influence algal growth in the coastal oceans[68]. Changes in stoichiometry across the hydrogeomorphic landscape may thus influence inland waters at both local and even global scales. Nevertheless, stoichiometric imbalances in inland waters at the landscape scale are just beginning to be explored[156].

Question 3. How can landscape models incorporate terrestrial-aquatic linkages?

New, innovative approaches are needed to understand processes controlling the biogeochemical linkages between terrestrial and aquatic ecosystems[98]. Although there have been significant advances in modeling terrestrial and aquatic biogeochemical processes, innovative approaches are needed to link terrestrial, hydrological (surface and subsurface), and biogeochemical processes to aquatic ecosystem function. GIS-based expertise and tools to transform terrain maps and digital elevation data into export models are being used increasingly in aquatic sciences[29,109], but full development and implementation of this approach will require interdisciplinary science and effective collaboration among aquatic and terrestrial scientists.

In order to understand and model these terrestrial-aquatic linkages, aquatic chemists will need to focus on how the terrestrial environment influences major ions, nitrogen, phosphorus, and reactive trace constituents that influence biogeochemical processes. The underlying lithology of a watershed may contribute important nutrients, such as nitrogen[63] or phosphorus[125,174], that often control the growth of aquatic biota. In shallower flow paths through soils, chemistry depends on both geological characteristics and on the microbes and vegetation of the terrestrial environment[26,37]. Terrestrial biogeochemists[112,165] have helped clarify how lithology, soil development, and biogeochemical processes control the evolution of nutrient levels in terrestrial systems, but aquatic scientists have rarely benefited from this approach[37,88]. Long-term soil development[19] affects fluxes of nutrients, major ions, trace constituents, and sediments from terrestrial landscapes to aquatic systems, in turn affecting ecosystem function. These gradual processes of soil development and weathering can vary on relatively small spatial scales[37], and the resulting historical legacies can lead to diverse characteristics and responses of neighboring aquatic systems to natural and anthropogenic perturbations[46].

Linkages among freshwater systems are just beginning to be explored. At the Arctic Long Term Ecological Research site, researchers are studying linkages between streams, lakes, and the terrestrial landscape.[77]

Enabling Technologies

Studies of the hydrogeomorphic landscape will be facilitated by recent and developing technologies. Advances in remote sensing from satellites and airborne units will provide regional-scale information on chlorophyll, water elevations, and other characteristics at fine resolution needed for small water bodies[9,75,108]. Developments in geographic information sciences and digital elevation modeling will allow limnologists to address landscape-scale questions far more efficiently than in the past. Biogeochemical analyses at the landscape scale will be facilitated by the use of isotopic tracers[9,75,108] that will allow limnologists and hydrologists to trace water and nutrient paths through complex flow paths. Development of *in situ* sensors for important water quality variables, such as turbidity, chlorophyll, dissolved organic carbon, dissolved gases (CO_2 and O_2), and specific contaminants, will facilitate their measurement at the same spatial and temporal scales as is now available for hydrologic data.

Theme 2 — Inland Waters: *Hot Spots* of Biogeochemical Activity

Inland waters are biogeochemical hot spots that exert disproportionately large effects on elemental mass balances and cycling rates, even though these environments occupy a small portion of the Earth's surface. Within inland waters, biogeochemically active hot spots occur when and where flow paths bring reactants together. The unique chemical milieu of inland waters and their interfaces with land allows key biogeochemical reactions to occur that are absent or proceed very slowly in other environments. Episodic events represent analogous hot moments during which important chemical transformations or a large portion of an annual cycle or flux may occur in an aquatic environment.

Background

Because inland waters cover <2% of the Earth's surface, these environments are often overlooked in assessments of global or even regional mass balances of key elements or constituents. Historically, limnologists have tended to view lakes and rivers as affected by inputs from their watersheds without fully considering the effects that the aquatic system has on the material balance of the watershed itself. A long history of measuring and interpreting the transport of materials in streams and rivers uses this information in computing losses from land and inputs to the sea[50,64,162]. More recently, limnologists have articulated the view that chemical transformations, storage, and even out-gassing from and within the aquatic systems themselves can be highly significant. Furthermore, many key redox-related reactions that occur predominantly in inland water environments influence nutrient cycles, emission of greenhouse gases, and the functioning of ecosystems. At one scale, inland waters may be viewed as hot spots imbedded in the terrestrial landscape. At a different scale, particular areas within lakes, streams, and wetlands may be especially biogeochemically active and exert disproportionate influence on the aquatic environment and larger biosphere. Inland waters may thus be hot spots that exert disproportionate effect on biogeochemical cycles.

If a hot spot can be defined as a patch that exhibits disproportionately high reaction rates relative to the surrounding matrix[101], one might also identify hot moments as short-term hydrologic or hydrodynamic events that are responsible for a disproportionate amount of material transport or biogeochemical transformation. A high-flow or a strong mixing event in a lake, stream, or wetland may cause a hot moment. For example, in mountainous watersheds, large fluxes of dissolved organic material typically occur during flood events, and contaminants from the land are flushed into the associated inland waters (Figure 3). Similarly, high-flow events can transform a previously dry environment, such as a

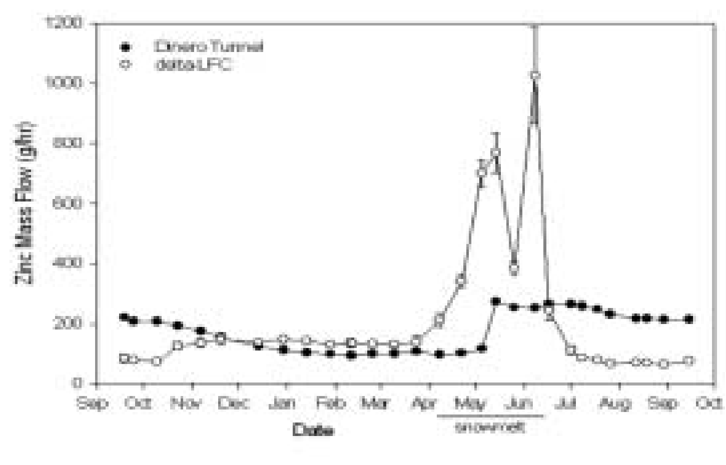


Figure 3. The rapid flux of zinc from a mine-contaminated subalpine wetland during snowmelt demonstrates how important "hot moments" can be[7].

Units: Tg C yr^{-1}

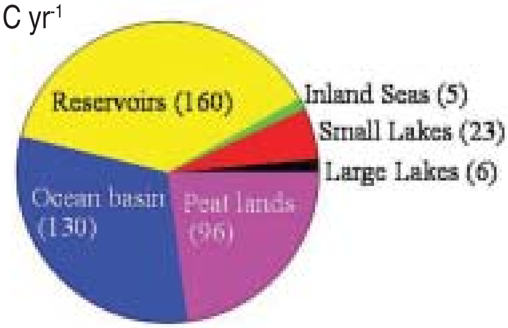


Figure 4. Although inland waters are <2% of the Earth's surface, they store three times as much organic carbon as the vastly larger oceans.

desert arroyo, into a wet one, with an attendant change in biogeochemical cycles[101].

Several compelling reasons motivate increased study of these aquatic hot spots or hot moments. Increased study is vital when the mass balance of a watershed or global biogeochemical cycle changes materially with inclusion of the inland waters. For example, although marine sediments are a large long-term reservoir for the sequestration of organic C, accruing 130 Tg C yr^{-1}, fresh waters may accrue even more. Recent analyses suggest that lacustrine systems, which cover an area <2% of that of the ocean, accumulate about 190 Tg C yr^{-1} in lakes and man-made reservoirs. Peatlands accumulate an additional 96 Tg C yr^{-1}. If these estimates are correct, inland waters store about three times as much organic carbon as the vastly larger oceans (Figure 4). Whereas terrestrial forests may sequester carbon on shorter time scales (decades to centuries), lake sediments tend to endure for tens of millennia, making them an important intermediate storage term that has a large impact on the global C cycle at those time scales. Stallard[152] has argued that when the errors are considered, the entire missing temperate global C sink (some 1.2 Gt C yr^{-1}) could be in lakes, reservoirs, and paddy lands rather than in regrowing forests, as is more commonly thought.

River flood plains and wetlands illustrate a different role of aquatic ecosystems as hot spots in the global carbon cycle. The terrestrial portion of the Amazon River catchment is a sink for atmospheric CO_2. The river itself, however, and the vast area inundated during the annual flood, recently was shown to be an enormous net source of CO_2 to the atmosphere[130]. Combining the aquatic portions of this catchment with the terrestrial portion reveals that sources and sinks are essentially balanced. Similarly, although wetlands are important hot spots of biogeochemical activity, they appear to be greenhouse-neutral on times scales of centuries because CO_2 uptake and storage from photosynthesis is offset by the emission of methane[170].

Global balances of nitrogen and phosphorus also may be strongly affected by inland water environments. Twenty to 30% of the loading of N_2O to the atmosphere comes from rivers, and river networks are responsible for a large fraction of denitrification globally[143]. Freshwater sediments also are implicated as major storage areas for phosphorus. Pre-industrially, freshwater sediments were the major terrestrial receptacle for eroded phosphorus, accumulating some 1.2 Tg P y^{-1}. In support of modern agriculture, enormous quantities of phosphorus are mined and distributed on the land as fertilizer. In the modern phosphorus balance, some 8 Tg yr^{-1} accumulates directly in agricultural soils, but freshwater sediments now accumulate nearly 40% as much as the soils[15]. The role of freshwater sediments in global balances becomes more dramatic when regions or individual catchments are considered. For instance, much of the phosphorus applied to the watershed of Lake Mendota, Wisconsin, or Lough Neagh, Ireland, resides in the sediments of these lakes[151].

Whereas the roles of carbon in global warming and of nitrogen and phosphorus in eutrophication are well known, the roles of other classes of materials in biogeochemical cycling are not as well understood. Anthropogenic perturbations of global cycles of trace elements, such as mercury[81], and anthropogenic organic chemicals are likely to modify rates of biogeochemical reactions and are known to have deleterious impacts on the biota and humans[39]. Further, many significant transformations of these trace constituents occur in inland waters. These compounds are modified through photolysis and interactions with natural organic material in the sediments. Consequently, a number of key questions arise that are related to the fate and transport of these trace reactive solutes in inland waters.

Carbon flux through the immense Amazon River and its floodplain and forest is relatively balanced because the terrestrial portion is a sink, whereas the aquatic components are a source of CO_2.

Rates of key biogeochemical cycles in aquatic systems, particularly at the interface of the terrestrial and aquatic systems, can regulate the mass balances of some elements at the watershed scale. For example, a large fraction of watershed denitrification may occur in the riparian zone[136] or in areas that are periodically inundated with water. Such hot spots or hot moments can determine the amount of N exported downstream. Experimental flooding of a wetland in Canada, to simulate reservoir construction, resulted in enormous increases in both the flux of methane to the atmosphere and the production of methyl-mercury within the water body[74]. The critical task ahead is to quantify the importance of aquatic systems in regional and global geochemical cycles and to determine where and when hot spots and hot moments will occur.

Inland waters not only are hot spots of biogeochemical activity that may affect global cycles, but they are also extremely important for organisms and human societies. The concentration of human activities along inland lakes and rivers is heavily impacting the physical, chemical, and biological integrity of these systems. Forty-seven percent of the endangered species in the United States depend on inland waters[69], and escalating human demands for these same water resources will generate increasing challenges for natural resource managers. Understanding aquatic hot spots thus will be crucial not only for understanding fluxes and transformations of carbon, nutrients, and reactive trace constituents, but also for maintaining sustainable freshwater resources.

Three key questions concerning hot spots and moments were elaborated during the workshop:

Question 1. What are the rates of carbon and nutrient cycling and storage in inland waters?

As mentioned previously, initial estimates suggest that inland waters and wetlands have unusually high biochemical activity and storage rates relative to their area. Only rough estimates of carbon storage in sediments exist, but their large magnitude is a compelling reason to pursue this area further. Additionally, because many dams are under consideration for removal in the United States[34], but are being constructed elsewhere, there may be implications of this management activity on carbon storage. In order to adequately quantify rates of carbon and nutrient cycling, much more work must be focused on dissolved organic compounds. In many water bodies, dissolved organic carbon and nitrogen are the largest pools of these elements[123], yet very little is known about their origins, structure, bioavailability, and turnover times. Similarly, dissolved organic phosphorus and iron are likely important vectors for transporting nitrogen and carbon from terrestrial to aquatic environments, but little is known about their movements.

Question 2. What governs where and when hot spots and hot moments occur? Can this modulation be modeled?

Rates of biogeochemical cycles are enhanced near boundaries where physical processes influence rates of reactions and the pathways of solute flow. The ability to identify these sites has been enhanced tremendously by recent growth in the field of stream ecology and the new instrumentation available to study and model lake hydrodynamics.

Identifying when and where hot spots and hot moments occur is best addressed within a space-time continuum[73] where spatial scales vary from global to small areas within individual water bodies and temporal scales range from those determined by climate variability to those determined by the rapid interactions between flow and substrate in a stream, lake, or wetland. Spatial scales also take into account the groundwater-surface water continuum and the water-air interface with hot spots often occurring at the boundaries between these subcomponents. The temporal view includes a perspective on the importance of antecedent events. That is, there can be a strong event with the potential to force the system, but the outcome depends on previous system state and whether a threshold has been surpassed that allows the system to change. For instance, it is often not the initial strong rainstorm in arid areas that induces flooding, slippage of soils, and high fluxes of terrestrial organic matter, but one that occurs after soils have become saturated.

In lakes, evidence is increasing that a large portion of biogeochemical activity may occur in hot spots in the sediments[163,168] and in thin layers[2] within the water column. Studies with fine-scale optical, acoustic, and hydrographic instrumentation have shown the persistence of thin layers (10-cm scale) with biomasses of phytoplankton, bacteria, zooplankton, and marine snow elevated 3 to 1000 times above background. These layers persist on time scales of days and spatial scales of kilometers. Such layers occur in environments in which turbulent mixing was anticipated to disperse accumulations above background, but, despite strong currents, the layers persist[2]. Such layering in the upper mixed layer was noted by early transmissometry studies in eutrophic lakes and in recent studies in a salt lake[92]. New instrumentation that is now becoming available to limnologists will facilitate the study of these layers and allow understanding of their importance at small scales, but also at whole-lake and regional scales

Question 3. How are trace chemical constituents transformed and transported by hot spots?

The concept of hot spots and hot moments will facilitate the study of the storage, transport, and transformation of reactive trace constituents in inland waters. Trace chemical constituents include naturally occurring elements, such as trace metals, that are present at much lower concentrations than major ions and natural organic material, as well as organic contaminants such as chlorinated pesticides, pharmaceuticals, and antibiotics generated by anthropogenic activity. Many of these compounds are of concern because of potential effects on human health, but they also may have significant effects on aquatic biota and the functioning of aquatic ecosystems. Human activities have greatly altered cycling of many trace metals, at both global and regional scales, especially the cycles of lead, mercury, and zinc. Because the chemistry of both trace metals and organic contaminants is strongly influenced by interactions with natural organic material, their transformation and transport are inherently coupled with carbon and nitrogen cycling in inland waters.

Trace constituents can be concentrated and stored in particular zones of inland waters where there is an accumulation of organic material or a transition in the oxidation-reduction condition, especially in lake and river sediments and wetlands. For example, reduced iron is reasonably soluble under the anoxic conditions created in pore waters through the degradation of sedimentary organic material. As this anoxic water diffuses into overlying oxic water in a lake, stream, or marsh, this reduced iron is rapidly oxidized and precipitated as iron oxyhydroxides, forming an “iron curtain.”[20] These oxidized iron oxyhydroxides sorb significant amounts of phosphate, but may sorb many similarly-charged anions such as arsenate. Another important process occurring in sediments is the concentration by methane ebullition of volatile organic compounds into gas spaces.

Many biogeochemical reactions that determine fluxes of trace constituents occur in the water column. Photochemical reactions (e.g., photolysis of organic compounds and photoreduction of metal species) occur in the upper mixed layer of lakes and in sunlit reaches of streams and rivers, creating reactive intermediate species and a cascade of chemical reactions that can control the concentrations and chemical forms of trace constituents in these zones. These photochemical reactions can alter the bioavailability of trace constituents by releasing sorbed trace metals from binding sites on particulate iron oxides or by degrading hydrophobic organic compounds. Similarly, biotic reactions (e.g., assimilatory uptake, creation of extracellular reactive species) may be most intense in the photic zone of lakes and wetlands and in the layer of algae and bacteria growing on the streambed.

The hot spot or hot moment approach will aid in understanding how trace metals and organic contaminants influence ecosystem function and other biogeochemical cycles. For example, in many Rocky Mountain watersheds, trace metals are flushed from numerous abandoned mines during snowmelt in an abrupt pulse (Figure 3). During this pulse, the metals are sorbed in the sediments, causing elevated concentrations of metals to persist throughout the summer and limiting algal growth, benthic invertebrates, and fishes in the stream[114]. Similarly, wetlands are now understood to be critically important hot spots for methylation of mercury, and lakes with higher proportions of wetlands in their watersheds have higher concentrations of methyl mercury in their fish populations than do lakes in watersheds without wetlands. The short-term depletion of elemental mercury from the Arctic atmosphere associated with the onset of solar spring is thought to be associated with enhanced atmospheric deposition of mercury to Arctic ecosystems during this period and may represent a hot moment in the cycling of mercury at high latitudes.

Enabling Technologies

Technological advances are now allowing easier identification of hot spots and hot moments and facilitating the necessary interdisciplinary studies to evaluate the roles of these hot spots and hot moments. The developing field of chemical reaction engineering[44] may have much to offer in providing a conceptual framework and quantitative models for the prediction of hot spots and hot moments at multiple scales. New tracers and high-resolution temperature, current, optical, and acoustic profilers are opening new vistas in terms of identifying and resolving flow paths and rates of exchange within the hydrogeomorphic landscape[14]. New hydrodynamic models of lakes and streams (see Theme 3) are improving understanding of physical aspects of mixing, and these models can be used in “real time” to guide descriptive and experimental work in complex systems. Advances in numerical analysis need to be continually incorporated into these models, but the mechanistic understanding that they provide is already being used to scale up and test whether insights from one system can be generalized to others.

Theme 3—Hydrodynamic Controls on Biogeochemical and Ecosystem Activity Across Space and Time

Intensified mixing events at boundaries represent a mechanism that can generate the hot spots and hot moments of chemical and biological activity identified in Theme 2. Physical limnology, armed with new understanding from recent process studies, new instruments for making detailed measurements, and powerful hydrodynamic models, is poised to make significant advances in the coming decade.

Background

Enhanced turbulence and intrusive flows at boundaries where fluids with different properties come together greatly enhance biogeochemical reactions. That is, the physically mediated transfers that occur at the boundaries create the hot spots and hot moments that are important for functioning on scales as small as those critical for physiological processes and as large as those critical for lakes and streams. The boundaries or interfaces can be the smallest eddies in a flow (< 1mm) where sperm and egg encounters are enhanced by the localized turbulence[27] or encompass the entire surface area of a riverine system such as the Amazon, where the small turbulent eddies mediate gas transfer at the air-water interface[130].

Wherever and whenever transport occurs near a boundary that separates reactants, rates of chemical reaction will be enhanced. Stronger reactions will, in general, occur with more intense flows and steeper concentration gradients. The challenge ahead is to define the physical processes and measure the concentration gradients at the appropriate scales, as many are extremely localized. Furthermore, flux events need to be quantitatively linked to the meteorological and geomorphological forcing that induced them. Only then can we evaluate the frequency of such events and their potential impact on local, regional, and global scales.

Complex patterns of turbulence and movement of water masses in natural and engineered systems have important consequences for understanding of biogeochemical processes. We must leave behind the simplistic view that biogeochemical processes can be measured at a central station within a lake and extrapolated to the entire system. Likewise, measuring nutrient uptake or other biogeochemical processes in stream reaches without understanding smaller-scale dynamics will not allow modeling and scaling up of these processes to the large scales necessary for understanding stream and river function.

By linking new measurement technologies and modeling approaches in hydrodynamics with tightly coupled interdisciplinary studies of aquatic systems, significant intellectual strides in the near future are highly likely. The following three questions provide a framework for determining the linkages between environmental forcing, hydrodynamics, and biogeochemistry in our inland waters.

Question 1. How do hydrodynamic processes create and control the formation and persistence of chemical and biotic patches within lakes and streams?

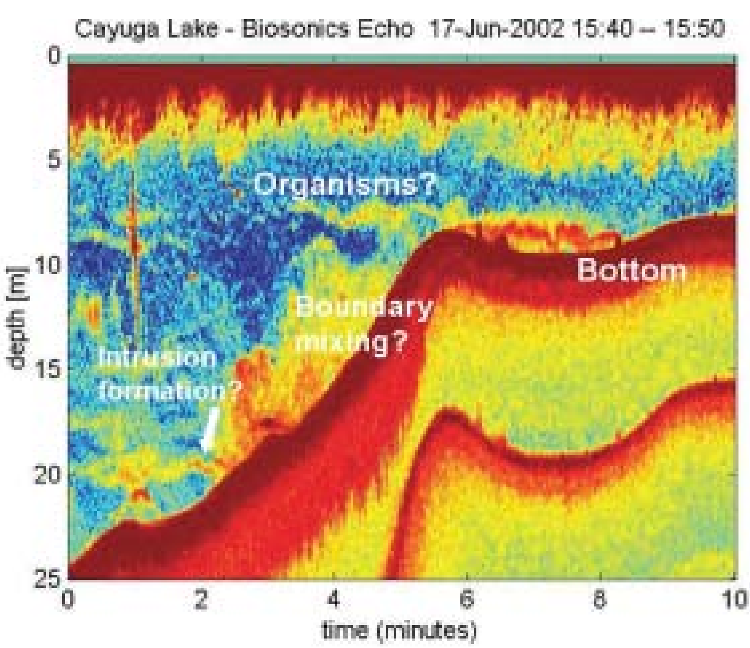


Figure 5. Image of acoustic backscatter indicating mixing events (see near-bottom yellow/red/orange) on the southern slope of Cayuga Lake (NY). Intrusion formation and locations of high abundance of scatterers potentially of biologic origin are highlighted. Image courtesy of D. Farmer and E.A. Cowen.

Recently developed high-resolution water column profilers have illustrated that layers of organisms and sharp gradients in nutrients occur in very thin layers where wind or tidal forcing would have been assumed to disperse them. Interdisciplinary studies by oceanographers first documented the existence of these layers and showed the wide diversity of organisms and high rates of microbial activity within them[2,89,102]. Acoustic measurements and high-resolution microstructure profiling have shown that these layers also occur in lakes at depths where turbulence occurs[66] (Figure 5). The layers persist because turbulence in offshore areas, even of large lakes, is so low that very little vertical transport occurs there[40,91,92,138]. Rather, recent analyses have shown that turbulent mixing is enhanced near the boundaries of lakes[53,91,137,138]. These findings have generated a paradigm shift in limnology with the realization that nearly all the vertical transport through the thermocline occurs during high wind events over sloping bottoms or near topographic features. As strong gradients in dissolved species and microbes occur in these regions, reaction rates are enhanced. The mixing events induce intrusions[103,160] where highly reactive water from near shore areas can flow offshore to produce the layering described above.

A new view of physical limnology is developing and warrants exploration via a number of routes. We must understand when and where turbulence induced by internal wave interactions occurs. We now understand there are linkages between internal waves and turbulence production, but we do not fully understand the mechanisms involved. This understanding is essential to guide coupled biogeochemical/hydrodynamic studies for increased accuracy in hydrodynamic models, and for predicting when intrusions will form and their subsequent transport. Similarly, the circulations induced by spatial variation in surface energy budgets[93,107] require systematic investigation.

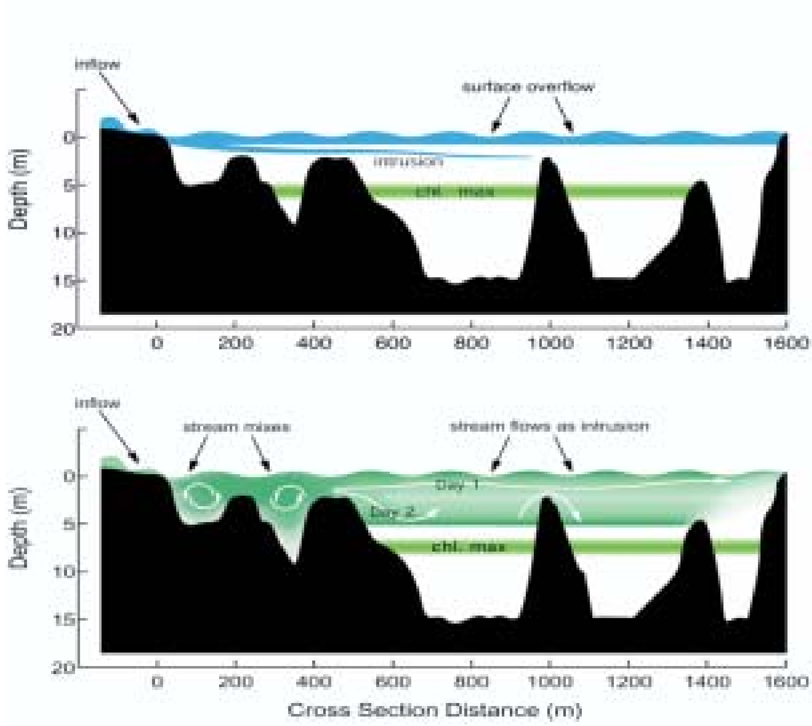


Figure 6. Spatio-temporal variability of the pathways of stream inflows into lakes, and their biogeochemical responses are being studied at the Arctic LTER site. Prior to ice off, river water flows over the lake surface and stimulates microbial growth (upper panel). During lake stratification in summer (lower panel) either surface overflows or subsurface intrusions occur, also with high impact on the system. Integrated studies such as this lead not only to improved understanding of coupling between hydrodynamics and the biogeochemistry of aquatic systems, but also to the linkages between terrestrial and aquatic habitats[61].

The intrusions from boundary mixing, near-shore cooling events[42], or ground or stream water inflows move offshore (Figure 6). Because these intrusions carry solutes, terrestrial organic matter, microbes, and larger organisms, they are hot spots of activity themselves and reaction rates may be enhanced at their boundaries. The presence of vital layers has been conjectured as a vehicle for greater fish larvae success during periods of calm[82,173], but conventional sampling has missed them. Therefore, previous estimates of lacustrine productivity and biogeochemical reactions may be underestimated. In addition, a succession of species is anticipated within these layers as terrestrial organic matter is remineralized[6] and as the stoichiometry of the system changes due to biotic interactions.

Question 2. What hydrodynamic processes occur at interfaces and how do they regulate the biogeochemical fluxes across those interfaces?

Important biogeochemical fluxes of solutes and gases occur at a diversity of interfaces and scales in inland waters, ranging from biofilms at the solute-particle scale to the air-water and the sediment-water interface at the stream or lake scale. The interplay of chemical gradients and hydrodynamic processes occurring at these interfaces determines the magnitudes of biogeochemical fluxes. For example, the flux of pore waters from lake sediments into the overlying water may increase due to the action of surface and internal waves or temperature differences between sediments and the overlying water column. In streams, pressure-driven water movements between pore waters and the main channel may depend upon velocity profiles and the geomorphology of the channel. Because pore waters typically have different chemistries than the overlying water, such as different pH, lower oxygen concentrations, and higher concentrations of reduced species of metals and nutrients, rapid reaction rates can occur at these boundaries (Figure 7). Similarly, gas fluxes across the air-water interface depend on turbulence induced by wind and heat loss.[24,46] The above examples demonstrate how the hydrodynamic conditions at interfaces produce the biogeochemical hot spots in inland waters. Improved hydrodynamic understanding, obtained through field and laboratory studies and dimensional analyses, can be used to predict the location and intensity of these hot spots. Large changes in estimates of rates of biogeochemical processes will likely occur when the full range of processes occurring at boundaries is considered.

Further, there may be hydrodynamic thresholds that produce disproportionate changes in fluxes or chemical forms of elements within and outside inland waters. This possibility can be explored through experiments in natural streams at a range of flow rates or in lakes under a range of wind conditions and associated turbulence in the mixed layer. Biogeochemical processes that can be studied through such an experimental approach include trace-metal and organic contaminant sorption on streambed sediments, microbial nutrient transformations, and evasion of methane, carbon dioxide, and other gases from lakes. These lake- or stream-scale experiments will provide important observations and datasets that will lead to new, physically based hypotheses and will guide development of models that integrate hydrodynamic and biogeochemical processes at these interfaces.

Question 3: What are the implications of the spatial and temporal heterogeneity created by episodic turbulent events and coherent flows for spatial and temporal patterns in biogeochemical processes? Is this heterogeneity more important than mean conditions for system behavior?

Persistent patchiness of organisms and solutes in inland waters implies that estimates of rates of biogeochemical processes based on mean concentrations may be erroneous. The problem is further confounded because the rates of many chemical and biological processes are nonlinearly related to concentrations of the reactants, such that the rate cannot be accurately predicted from the mean concentration. Consequently, accurate estimates of rates must include sophisticated spatial and temporal averaging over microenvironments and times of like kind. Accurate quantification of rates of biogeochemical processes is dependent upon developing a predictive understanding of the

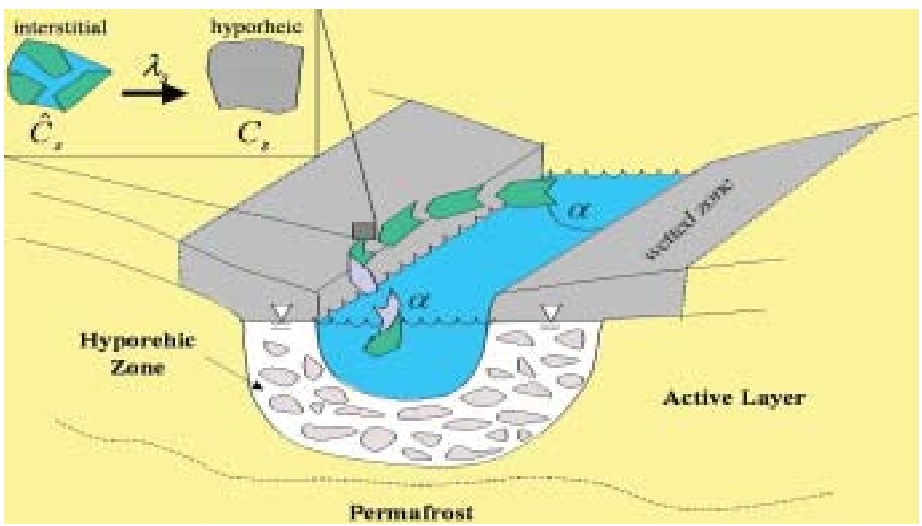


Figure 7. Sub-streambed (hyporehic) weathering of silicate minerals by pressure-driven flows in Antarctic streams is an example of a major hot spot[51]. Global-scale weathering of primary silicate minerals has been hypothesized to increase with global warming because of the expected increase in chemical reaction rates with increasing temperature. Nevertheless, high fluxes of silica may even occur in the cold steams of Antarctica. Measurements and models of the dissolution reactions in the subsurface zone of steam confirmed that rapid water flux resulted in weathering rates comparable to those in temperate regions[97]. Changes in hydrology and hydrodynamics may consequently influence global-scale geochemical weathering under changing climatic conditions.

Extreme environments, such as Wharton Creek and Suess Glacier (Antarctica), are excellent "laboratories" for studying biogeochemical processes of inland waters.

spatio-temporal variability of turbulent events and patchiness in flowing and standing water bodies. To understand these complex interactions requires field studies, laboratory studies, and modeling. The first goal is to develop an accurate representation of the spatial and temporal variability of mixing events and of patchiness, and the second goal is to link biogeochemical processes with hydrodynamics.

Challenges in developing coupled hydrodynamic-biogeochemical models for inland waters

Coupled hydrodynamic-biogeochemical models are essential for calculating net rates of biogeochemical processes and testing interpretation of field-scale measurements. Models of hyporheic zone interactions in streams and rivers are being applied in this manner in studies of nutrient and trace metal dynamics. One-dimensional models of lake physics (e.g., DYRESM) have been used to predict cumulative effects of anthropogenic and climate-induced changes in water inflows over time scales of 50 years or more[132]. Recently, three-dimensional models have had great success in modeling internal waves and three-dimensional evolution of thermal structure[62]. Progress is being made in addressing intermittency of physical forcing, numerical diffusion, sloping boundaries[76,83], and the mixing of riverine inflows.

Although present models are capable of representing the large-scale physical processes, new challenges are to: (1) develop the ability to scale down from the large-scale processes (e.g., the internal wave field) to hot spots of biogeochemical activity (e.g., turbulent mixing at the boundary), and (2) scale up the localized nonlinear biogeochemical and turbulent processes to obtain accurate predictions of transport and diffusion at ecosystem scales.

Theme 4—Global Change and Inland Waters

Inland waters are sensitive indicators of global change because their internal physical or biogeochemical processes can amplify the signals of perturbations in energy, water, and chemical fluxes. Because inland waters also function as hot spots of biogeochemical transformations influencing the carbon and nitrogen cycle, this responsiveness to global change can function as an important feedback in the global system.

While the accumulation of greenhouse gases in the atmosphere is expected with some certainty to lead to 1 to 5°C increases in temperature worldwide in the next 50 years, one of the greatest uncertainties in predicting climate change is how the water cycle will respond in terms of changes in both mean conditions and extreme events. Rates and patterns of precipitation and runoff are gradually changing[32] with general circulation models predicting that these changes will continue as global CO_2 levels rise[100]. Further, simulations in global circulation models show that the direction of change in the water cycle will likely vary regionally, with different regions becoming either dryer or wetter and experiencing concomitant increases in drought or flood events. Other climate change uncertainties are variations in the frequency

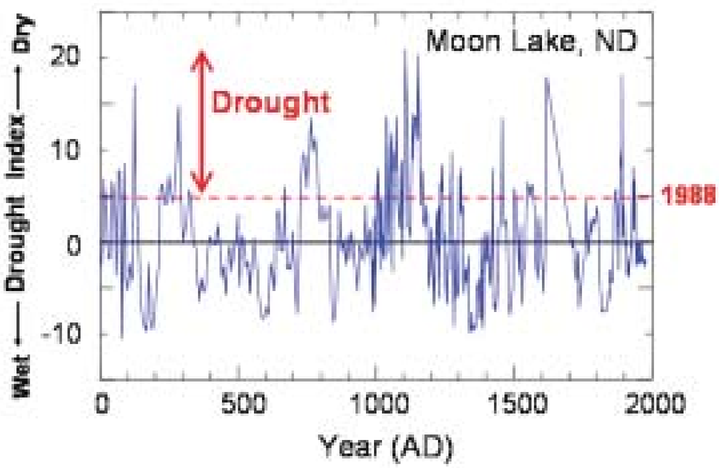


Figure 8. A 2000-year drought history for Moon Lake, North Dakota. Values above +5 indicate droughts more severe than that recorded in 1988-1089 when US agricultural losses exceeded $30 billion. The record shows that severe droughts occur often in the northern Great Plains, can last over 50 years, and are highly unpredictable. The index was derived by using algal remains (diatoms) buried in the sediments to identify changes in lake salinity caused by wet and dry climates in the past. Data from Laird et al. [80], statistical analysis by P. Leavitt and G. Chen (University of Regina).

of disturbances of lakes due to wind forcing, to alterations in cloud cover and to changes in the duration of ice and snow cover in temperate regions. Because of the importance of hydrodynamics in inland waters, all of these changes can be expected to cause cascades of internal changes in inland waters.

Climate change will alter the seasonal pattern of runoff coming into streams and river networks. The seasonal pattern of high and low flow in river and streams has been modified to a large extent, however, by flow regulation in many regions of the world. Therefore, the changes in stream and river systems will greatly depend upon how water resource management practices change. There are two contrasting developments in terms of the impact of flow regulation on stream and river systems. In recognition that flow regulation has sustained ecological and biogeochemical effects, many smaller older dams are being decommissioned rather than being upgraded for relicensing[34]. On the other hand, the willingness to allocate water for in-stream flow may change under less predictable hydrologic regimes. Specifically, the physical infrastructure for flow regulation and the system of water allocation were designed to operate within a range of expected hydrologic variation that will likely be exceeded under a changing climate, and maintenance of in-stream flow during certain seasons may depend upon significant changes in water use within a region. Understanding of the response of streams and rivers to these changes in flow regime will greatly benefit from enhanced capabilities to measure and model the hydrodynamics of these systems, as discussed above. Biogeochemical processes in streams and rivers will also be affected by changes in temperature and changes in riparian vegetation.

Climate change will further influence energy exchanges at the air-water interface of lakes, with pronounced influences on seasonal cycles of stratification and mixing. The first-order consequences of climate warming on lakes are readily predicted, with longer periods free of ice in temperate and polar regions, warmer surface temperatures, and larger temperature gradients across the thermocline. Such changes have been documented in Antarctic lakes[126], and the regional impacts have been shown for northern temperate areas[58,95]. Other subtle, but potentially more important changes that will result from modified mixing regimes may influence biogeochemical cycling, eutrophication, and the success or loss of species. A more quantitative understanding of these amplified responses will require greater understanding of hydrodynamic and biogeochemical coupling in lakes.

Three research questions relevant to global climate change that should be addressed in the coming years were elaborated at the workshop.

Question 1. How well can paleolimnological analyses and related historical studies demonstrate the responsiveness of inland waters and their catchments to changing climate and other anthropogenic impacts, and can we use this information to forecast trajectories into the future?

Paleoclimatic studies indicate that the climate system operates in multiple states and can shift from one mode to another, such as from glacial to interglacial, within just a few years. How such abrupt climate changes affect aquatic and catchment processes are not well known, although it is clear that the observational record of the 20th century does not encompass the full range of environmental dynamics characteristic of even recent centuries[11,47] (Figure 8). Understanding the paleo-record will be advanced by the merging of hydrological and hydrochemical modeling with the paleolimnological record and with contemporary limnological analyses that allow us to understand the climatic, nutrient, and trophic factors that favor characteristic communities. Technological innovations that will further enable interpretations of paleo-records include improved dating techniques, application of isotopic methods to single particles (allowing improved spatial and temporal resolution), new DNA technologies to improve phylogenetic and functional analysis of cells, and improved methods for characterizing organic matter.

Question 2. How will lake mixing dynamics and flow regimes change in response to climatic drivers and hydrologic inputs cause changes in biogeochemical processes in inland waters?

Changes in the amount and timing of seasonal runoff derived from rainfall and snowmelt are occurring throughout the world, and these changes alter the functioning of aquatic ecosystems. For example, increased runoff into saline waters can induce persistent chemical stratification with profound ecological impacts. Permanent stratification in Mono Lake, California, has been caused by increased precipitation associated with ENSO events[132]. Dramatic drops in primary production occurred, with effects felt throughout the food web[70,104]. Increased discharge into freshwater lakes may have a variety of repercussions that will depend upon nutrient and particulate loading and will alter the residence time of water within lakes, and this, in turn, will likely impact the complex community interactions within lakes[48]. These few studies indicate that dramatic changes can be anticipated; some will occur every year; others occasionally.

Several key hydrodynamic processes are likely to vary with climate change and their cumulative effect will have major impacts on biogeochemical cycles. Fluxes of heat and momentum across the air-water interface will change the depth of the upper mixed layer and the stability of the thermocline below. Changes in upper mixed-layer depth will have major impacts on algal physiology via modifications of the light climate. These changes may have large effects on the amount of primary production and the sequestration of carbon and other nutrients.

Gas exchange rates depend upon the extent of turbulence at the air-water interface, as well as on the frequency of events that lead to deepening of the upper mixed layer[90]. Hence, changes in surface energy budgets on regional scales will have major impacts on fluxes from the disparate water bodies within them. In small lakes and wetlands, where a disproportionate amount of carbon dioxide or methane is potentially stored or released to the atmosphere, the frequency of daily winds and the maintenance of convective mixing due to cooling at night determine the gas-transfer velocity[92]. Regional changes in these forcings could induce large changes in release of greenhouse gases.

Ventilation of deep waters, triggered by prolonged drought or exceptional cold, may cause pronounced changes in lakes. For instance, methane fluxes in the Amazon are largest when cold fronts pass[36]. Similarly, persistent drought conditions or exceptionally cold years can lead to turnover in otherwise permanently stratified lakes with the potential for major fluxes of solutes in deep waters. Major fish kills can result and rates of biogeochemical processes vary. The defining variables for these events are often linked to climate change or oscillations. Although the major event may occur during one year, the consequences persist longer. Exploring the mechanisms causing these major events and the shifts in system function should be a major goal of future research. As water bodies eutrophy and persistent anoxia becomes an even more prevalent feature, a thorough understanding of the interplay among climate forcing, hydrodynamics, and biogeochemical cycles becomes ever more important.

Despite the major importance of climatic and meteorological factors in determining mixed layer-dynamics and convective exchanges, few lakes or wetlands have had comprehensive collection of meteorological data or time-series temperature data on appropriate time scales. Such data collection is essential for not only understanding the processes occurring in mixed layers, but also for understanding on a regional basis the likely impacts of climate change. Assessing the changes in inland waters due to climate changes requires time-series data in well-designed interdisciplinary studies. The use of moored instrumentation capable of measuring surface meteorology, and the temperature, currents, nutrients, and optical properties of the water column, is essential. Recent advances in modeling the impacts of changes in hydrological and meteorological inputs and mixing dynamics in rivers, lakes, and wetlands are allowing prediction of the bulk responses (e.g., biomasses of major groups). With further development and validation, these models will guide experimentation in order to extend the knowledge of linkages among physical, chemical, and biological processes.

Question 3. Will seasonal transitions in inland waters become more important in controlling biogeochemical and ecosystem processes under a changing climate?

As discussed above, episodic events and seasonal transitions are important to the ecology of inland waters. Variations in timing and magnitude of seasonal events have been documented and more are projected. In addition to changes in flow regime, changes in terrestrial ecosystem processes will influence these seasonal transitions. For example, alpine and chaparral ecosystems have relatively large episodic releases of nutrients in response to hydrologic flushing. These short pulses can account for >90% of annual nutrient flux into the associated streams and lakes[144]. Periodic nutrient flushing is tied to the timing of transitions from dry to wet periods, from low to high snowmelt runoff periods, and from dormant to actively growing vegetation. Nitrate export in these ecosystems is similar to that found in moderately to severely N-saturated forests, but current work suggests that both alpine and chaparral vegetation is N limited[122]. Similarly, the flux of trace contaminants into inland waters can be controlled by the nature of seasonal transitions. For example, in the Rocky Mountains, greater flux of metals from abandoned mines occurs during higher spring snowmelt associated with greater–than-average snow pack. If these events are not measured, conclusions about how the system operates and is likely to change in the future will be wrong. Unfortunately such events are often understudied largely for logistic reasons. Recent advances will allow episodic events and otherwise logistically difficult periods of the year to be studied properly.

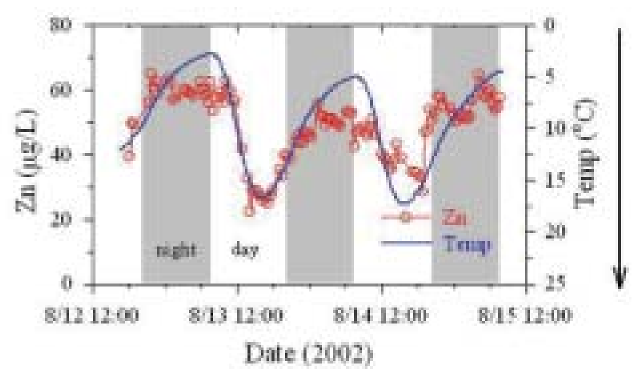


Figure 9. Diel variation in zinc concentrations and temperature in Fisher Creek, MT, measured *in situ* with the Zn-DigiScanner. Submersible autoanalyzers such as this are beginning to provide fine-scale temporal and spatial data that was previously unattainable to aquatic chemists. Data of R. Chapin and R.B. Wanty.

Enabling Technologies

Understanding how global climate change will impact inland waters will be facilitated by new instruments that allow continuous and real-time data acquisition. This instrumentation includes *in situ* chemical, physical, and biological sensors (e.g., MEMS-based chemical detectors, electrochemical probes, DNA microarrays and chip-based PCR, acoustic Doppler and optical profilers, and high-resolution thermistor chains). Improved telemetry systems will allow real-time data acquisition, and improved information transfer and data management systems will allow assimilation and interpretation of large data sets (inherent in all high-frequency data collection). Advanced linkage between near real-time modeling and real-time data acquisition will help guide data collection and experimental manipulations. Better year-round infrastructure (field stations, transportation, safety, communications) will allow limnologists to study important processes in detail throughout the year. Remote sensing of flooding, liquid water content in snow and ice, and algal blooms will greatly enhance our ability to analyze processes at greater spatial scales and in logistically difficult landscapes. Finally, medium-range weather forecasting and availability of real-time weather radar and hydrological data will allow better-designed collection schemes and experimentation.

Emerging Technologies

The ability to make significant advances on the research topics described in previous sections depends on recent advances in a variety of technologies. They include (1) environmental sensors and *in situ* monitoring instrumentation, (2) remote sensing, (3) computer modeling, and (4) cyberinfrastructure. This section briefly describes the status and recent developments in these four fields in relation to research opportunities in limnology.

In situ **Sensors**

Historically, most investigations of biogeochemical cycling in inland waters have involved systematic sampling (e.g., one sample per week or month) over longer time periods or intensive time series studies over a few hours or days. Many biogeochemical processes in aquatic systems are characterized by a wide range of temporal scales (seconds to decades) and spatial scales from micrometers to kilometers that are difficult to observe by traditional sampling approaches (see Hotspots section). Moreover, many important biogeochemical processes occur within short time periods (e.g., storm events) during the course of a year, and a sampling program based on regularly spaced sampling over time likely will miss these events. To overcome this "undersampling" challenge and adequately characterize inland waters, scientists must have a suite of sensors that measure physical, chemical, and biological characteristics at appropriate temporal and spatial scales.

The development of reliable long-term *in situ* sensors thus is crucial for advancing understanding of inland waters, and rapid advances are being made in this field. *In situ* sensors have several advantages over traditional sample collection and laboratory analyses: (1) they can provide large amounts of data to characterize a system at low cost; (2) they reduce sample contamination and problems with sample stability; and (3) they can provide real-time or near real-time data to guide sampling strategies.

Reliable *in situ* sensors for physical variables (e.g., temperature, conductivity, depth, current velocity) and optical properties (i.e., fluorescence, spectral radiance, and turbidity) are well developed and commercially available. Although electrometric sensors have been available for a few chemical characteristics (pH, dissolved oxygen, chloride, fluoride) for decades, *in situ* sensors are lacking for most chemical constituents of interest in aquatic systems, and *in situ* biological sensors are almost nonexistent. Bonito provides a recent review of current *in situ* sensor technology[16].

Major advances in our understanding of inland waters will be driven by new *in situ* monitoring technologies, particularly biological and chemical sensors (Figure 9). These sensors will have longer reliability, smaller size, lower cost, and reduced fouling, and will require less power than most current sensors. One new approach for *in situ* monitoring uses fiber-optic detection to create fiber-optic chemical sensors (FOCS). A current example of FOCS technology is the CO_2 sensor of DeGrandpre[31], and a FOCS-based trace-metal detector is under development[148].

Perhaps the most promising technological area for *in situ* sensor development comprises micro-electro-mechanical systems (MEMS). MEMS use silicon microfabrication to create integrated sensors that incorporate sample handling and detection in one small unit that could be mass-produced inexpensively.

Almost any analytical technique is amenable to the MEMS approach[22,105,106,147]. Sensor development using MEMS currently is focused on biotechnological, industrial, or military applications. To our knowledge no MEMS-based *in situ* chemical or biological water monitoring devices are commercially available, but prototypes of *in situ* chemical analyzers[99] and PCR-based devices to detect microbial species are being developed[133]. Interdisciplinary collaboration between environmental scientists and the instrumentation community could produce a new suite of sensors that will enable examination of the details of biogeochemical cycling in inland waters.

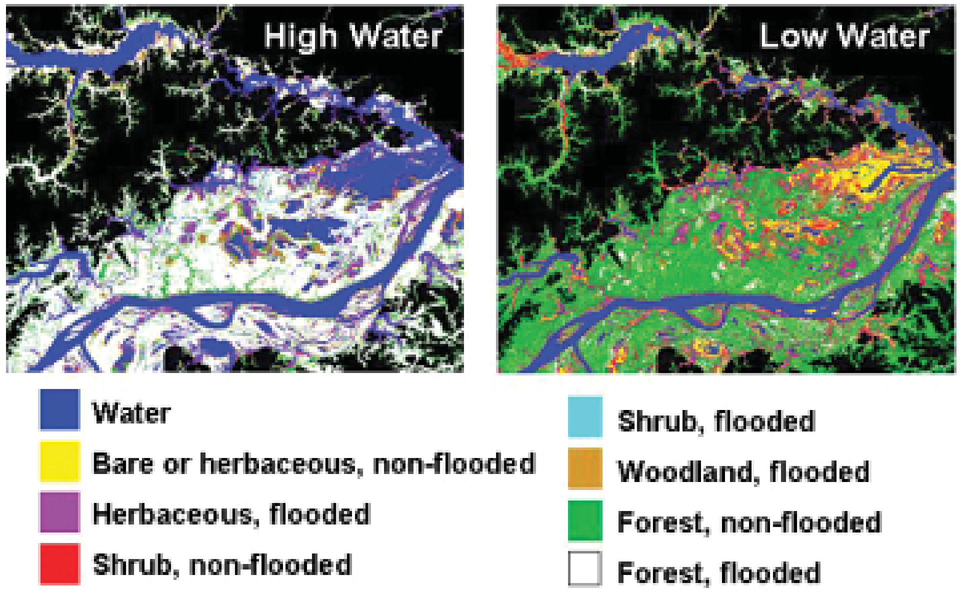


Figure 10. Seasonal changes in water distribution and vegetative cover of the Cabaliana floodplain (Amazon system, Brazil). The image was made with a JERS-1 synthetic aperture radar. Source: L. L. Hess et al. (in press).

Current Status of *in situ* Monitors, Arrays, and Profilers

Development of solid-state or micro-sensors (e.g., using MEMS) is an important factor in the development of more user-friendly and reliable field instruments, but advances in other aspects of the analytical process, including sampling, data storage and telemetry also are critical. Oceanographers have led the development of in situ monitoring instruments, and many devices are commercially available[115]. In situ water quality data sensors capable of long-term continuous monitoring of multiple physical and optical characteristics and a few chemical variables (pH, dissolved oxygen) are well established[65,67,176]. Some of these devices move up and down in the water column to obtain depth profiles of the variables they measure and can telemeter data from remote locations (in lakes or the ocean) to laboratories, providing near real-time access to data[4] .

Advances in chemical and biological analytical techniques have greatly reduced the size, cost, and reagent consumption of laboratory instruments, but efforts to re-engineer these devices into reliable autonomous field instruments are still in their infancy. Nevertheless, continuous *in situ* nutrient monitors capable of >30-day deployments have become commercially available[38,139,158]. Due to their rapid response times and long deployment times, these instruments can be deployed simultaneously with devices to monitor physical processes that may drive many of the chemical reactions.

SCAMP, a portable, lightweight microstructure profiler that measures small-scale (~1 mm) fluctuations of conductivity, temperature, oxygen, and some nutrients, is commercially available[124]. These devices are currently used to study turbulent diffusive fluxes in the water column and near the sediment-water interface in lakes[23] and are being used to address some of the research issues described above in the sections on hot spots and hydrodynamics. Developments in current meters are enabling new understandings of flows in lakes and streams. Acoustic doppler current profilers[127] now have the sensitivity to resolve the low currents found in lakes, and acoustic doppler velocimeters[116,150] permit current and turbulence measurements in streams as well as lakes because of their small size and high sensitivity.

A prototype rotating-field mass spectrometer that has a mass range of 1 to 100,000 amu and detection limits < 1 ppb recently has been developed[121], and efforts are also underway to develop *in situ* trace metal analyzers using inductively-coupled plasma (ICP) spectrometry.

Remote Sensing by Satellite Imagery

Satellite sensors have been used for over 30 years to measure Earth resource conditions, but for most of that time the emphasis has been on terrestrial and oceanographic measurements (e.g., land use and land cover conditions). However, a wide variety of sensors and satellite platforms are now available for use on aquatic systems. These tools will be especially useful in addressing landscape-level questions such as those described in Theme 1 (The Hydrogeomorphic Landscape).

Although only a few sensors have been developed specifically for aquatic systems, many current sensors can be used to collect information on aquatic resources. In the visible and infrared range, sensors and platforms include the well-known Landsat system, which has medium spatial resolution (30-m pixel size) and temporal coverage (every 16 days), as well as satellites with high spatial resolution (1-4 m pixel size [IKONOS and Quickbird]), and with high (daily) temporal coverage but low-spatial resolution (250-500 m pixel size [MODIS sensor on the EOS platform]). The SeaWIFS satellite now measures chlorophyll levels routinely in the open oceans and can do the same in large lakes such as the Laurentian Great Lakes. Landsat imagery has been used to perform census-level assessments of lake water clarity in large regions[128]. The Landsat archive extends back to the early 1970s and provides the possibility of retrospective studies. For example, this technique has been used to assess spatial and temporal trends in water clarity of 500 lakes in the metropolitan area of Minneapolis and Saint Paul, Minnesota, as urban and suburban development expanded over a 25-year period[78,79]. A similar approach was used to conduct a census of water clarity in over 10,000 Minnesota lakes[118].

A new suite of optical and microwave sensing systems and analysis algorithms has been developed in the last decade that has the potential to dramatically advance our understanding of wetlands and inland waters. Imaging spectrometers provide data in many contiguous and narrow spectral bandwidths, covering the visible to near-infrared portion of the spectrum (0.4-2.5 μm). Such hyperspectral sensors usually operate from airborne platforms and have pixel sizes of ~2-20 m, and swath widths of ~1-10 km. These systems permit analyses of optical properties and chlorophyll distributions in inland waters with complex mixtures of dissolved and suspended material.

Another especially promising approach is synthetic aperture radar (SAR), which can image levels of inundation and vegetation, unaffected by cloud cover, season, or time of day. Recent research has developed techniques to accurately classify digital radar images into vegetative classes and inundation status based on airborne and Space Shuttle-borne imaging radar. With the recent advent of satellites with SAR sensors (Europe's ERS-1 and ERS-2, Canada's Radarsat and Japan's JERS-1), monitoring of inundation and wetland vegetation has become feasible. For example, SAR sensors have been used to delineate wetland vegetation and to measure cm-level changes in the flooded vegetation of the central Amazon basin[3,60,146](Figure 10). A global record of passive microwave observations from satellites is available from 1979 to the present. Lidar (light detection and ranging), a laser-based remote-sensing technique, has similar capabilities for measuring water levels from aircraft, and a water-penetrating form of lidar that uses a laser beam in the visible (green) range of the spectrum has potential for mapping submerged aquatic vegetation and other features of the bottom of aquatic systems[54].

Models

Increasing sophistication and realism in simulating transport and fate of solutes in aquatic environments for many decades mirrored the development of computers with increasing speed and processing power, but over the past decade at least three other factors have played important roles in model development. First, geographic information systems (GIS) have facilitated the development of realistic models that can portray the movement of substances from heterogeneous landscapes that are described at fine spatial scales into stream and river networks[109]. Second, modelers have figured out how to interface models of physical, chemical, and biological processes that operate at intrinsically different time scales to produce complex coupled models. These advances often have been facilitated by cross-disciplinary interactions between fluid mechanicians or hydraulics experts and aquatic chemists and ecologists. Third, much-improved visualization methods, including animation methods, have allowed modelers to portray complicated model output more efficiently and effectively.

Limnology is poised to make significant advances in 3-D coupled biogeochemical models of lakes. Tremendous advances have occurred in 3-D modeling of lake hydrodynamics in the last few years[13,62,134]. Combining these approaches with biogeochemical and ecosystem models is a next step[35]. Our new understandings of the microbial loop and its effects on nutrient recycling and community structure with our understanding of spatial variability of physical processes will increase realism of ecosystem models and lead to intriguing new scientific questions.

Not all advances in models for inland waters rely on highly complicated codes and underlying assumptions of quantitative and deterministic relationships among state variables. In fact, quantitative knowledge and functional relationships needed to describe or predict many relationships at the levels of population and community ecology are lacking. Recently, predictive models have been developed that rely on non-quantitative or semi-quantitative information using fuzzy math techniques, decision trees[33], and other probabilistic approaches. Such models appear to be especially useful for resource management; for example, they are beginning to be applied in the analysis of restoration scenarios in the Everglades.

Cyberinfrastructure. Finally, as sensing devices and scientific instrumentation have become more sophisticated, the amounts of raw data they produce will increase to levels scarcely imaginable even a decade ago. Without the corresponding advances that have occurred in the ability to transmit, store, and process vast quantities of raw data into useful information, all the technological developments described above would have little positive impact on the conduct of science. Enabling advances in cyberinfrastructure for a new era of inland water research go far beyond the well-known advances in desktop computing power, although the fundamental advances in microprocessor technology and data storage and retrieval devices are keys to these other advances. Despite the tremendous advances in computing power, scientists can think of ways to produce more data or develop needs to process ever-increasing quantities of data. Consequently, the development of more efficient algorithms has contributed significantly to the enhanced cyberinfrastructure available today.

Similarly, in the past decade, the Internet and the Web have transformed the ways that scientists communicate with each other and with their information resources — libraries, journals, and databases. While extremely impressive and useful for information retrieval and dispersal, the Web primarily is a bi-directional mode of communication. Much more highly interactive multi-nodal networks are under development that will allow scientists in a variety of locations to participate simultaneously in running experiments in yet a different location and to share the data. Wireless communication of data from remote sites for real-time display and analysis has been a reality for over a decade, but the potential of this technology for studies on inland water is still in its infancy. These advances are crucial for the establishment and operation of "environmental observatories" — highly instrumented and networked field sites to study complex environmental problems — that are being proposed in several NSF programs related to aquatic science (e.g., NEON [Environmental Biology], hydrologic observatories [GeoSciences], CLEANER [Environmental Engineering], ocean observatories [Oceanography]).

In summary, huge advances in computer power and electronic communication over the past generation have changed dramatically the way that science is done. These advances are especially critical to data-intensive sciences like limnology. They now provide opportunities to conduct experiments that limnologists could not even imagine a decade ago.

References

1. Advisory Committee for Environmental Research and Education. 2003. Complex environmental systems: synthesis for earth, life, and society in the 21st century. Washington, DC: National Science Foundation (Summary available at: http://www.nsf.gov/geo/ere/ereweb/ac-ere/acere_synthesis_rpt_summary.pdf).
2. Alldredge, A.L., T.J. Cowles, S. MacIntyre, J.E.B. Rines, P.L. Donaghay, C.F. Greenlaw, D.V. Holliday, M.M. Dekshenieks, J.M. Sullivan, J.R.V. Zaneveld. 2002. Occurrence and mechanisms of formation of a dramatic thin layer of marine snow in a shallow Pacific fjord. Marine Ecology-Progress Series 233:1-12.
3. Alsdorf, D.E., J.M. Melack, T. Dunne. 2000. Interferometric radar measurements of water level changes on the Amazon flood plain. Nature 404:174-177.
4. Appraise_Technologies_Inc. 2003. http://www.apprisetech.com/.
5. Arnell, N., C. Liu. 2001. Hydrology and water resources. In: McCarthy J, Canziani O, Leary N, Dokken D, White K, editors. Climate Change 2001: Impacts, Adaptation, and Vulnerability. Cambridge, UK: Cambridge University Press. p 191-234.
6. Artolozaga, I., E. Santamaria, A. Lopez, B. Ayo, J. Iriberri. 1997. Succession of bacterivorous protists on laboratory-made marine snow. Journal of Plankton Research 19:1429-1440.
7. August, E.E., D.M. McKnight, D.C. Hrncir, K.S. Garhart. 2002. Seasonal variability of metal transport through a wetland impacted by mine drainage in the Rocky Mountains. Environmental Science and Technology 36:3779-3786.
8. Baines, S.B., K.E. Webster, T.K. Kratz. 2000. Synchronous behavior of temperature, calcium, and chlorophyll in lakes of northern Wisconsin. Ecology 81:815-825.
9. Baker, M., R. Hall, W. Wurtsbaugh, M. Bozeman, C. Arp. 2003. Dissolved N dynamics in a coupled stream-lake ecosystem during snowmelt quantified using ^{15}N nitrate. North American Benthological Society, Athens, Georgia. Abstract.
10. Baker, M.A., C.N. Dahm, H.M. Valett. 2000. Anoxia, anaerobic metabolism biogeochemistry of the stream water-ground water interface. In: Jones JB, Mulholland PJ, editors. Streams and Ground Waters. San Diego, CA: Academic Press. p 259-284.
11. Barlow, L.K. 1997. Interdisciplinary investigations of the end of the Norse western settlement in Greenland. The Holocene 7:489-500.
12. Baron, J.S., H.M. Rueth, A.M. Wolfe, K.R. Nydick, E.J. Allstott, J.T. Minear, B. Moraska. 2000. Ecosystem responses to nitrogen deposition in the Colorado Front Range. Ecosystems 3:352-368.
13. Beletsky, D., W. O'Connor. 1997. Numerical simulation of internal Kelvin waves and coastal upwelling fronts. Journal of Physical Oceanography 27:1197-1215.
14. Bencala, K. 2000. Hyporheic zone hydrological processes. Hydrological Processes 14:2797-2798.
15. Bennett, E., S. Carpenter, N. Caraco. 2001. Human impact on erodable phosphorus and eutrophication: A global perspective. BioScience 51:227-234.
16. Bonito, G. 2002. Specific in situ Sensor Technologies: LTER Network / San Diego Supercomputer Center. http://www.lternet.edu/technology/sensors/technologies.htm.
17. Brezonik, P.L. 1996. Organizing paradigms for the study of inlands aquatic ecosystems. In: National Research Council, Committee on Inland Aquatic Ecosystems, Water Science and Technology Board, Freshwater Ecosystems: Revitalizing Educational Programs in Limnology. Washington, DC: National Academy Press. p 181-202.
18. Carpenter, S.R., J.F. Kitchell, J.R. Hodgson, P.A. Cochran, J.J. Elser, M.M. Elser, D.M. Lodge, D. Kretchmer, X. He, C.N. Vonende. 1987. Regulation of lake primary productivity by food web structure. Ecology 68:1863-1876.
19. Chadwick, O.A., L.A. Derry, P.M. Vitousek, B.J. Huebert, L.O. Hedin. 1999. Changing sources of nutrients during four million years of ecosystem development. Nature 397:491-497.
20. Chambers, R., W. Odum. 1990. Porewater oxidation, dissolved phosphate and the iron curtain—iron-phosphorus relations in tidal fresh-water marshes. Biogeochemistry 10:37-52.
21. Chanton, J.P., T.J. Arkebauer, H. Harden, S.B. Verma. 2002. Diel variation in lacunal CH_4 and CO_2 concentration and 13C in *Phragmites australis*. Biogeochemistry 59:287-301.
22. Chemsoc. 2003. Lab on a chip network. http://www.chemsoc.org/networks/locn/index.htm.
23. Chen, H.L., M. Hondzo, A.R. Rao. 2002. Segmentation of temperature microstructure. Journal of Geophysical Research (Oceans) 107:C12.

24. Committee on Inland Aquatic Ecosystems, Water Science and Technology Board, Commission on Geosciences, Environment, and Resources. 1996. Freshwater Ecosystems. Revitalizing Educational Programs in Limnology. Washington, DC: National Academy Press.
25. Council of Scientific Society Presidents. 2002. CSSP Issue: Sustainable water quality and quantity. White Paper. http://www.mdsg.umces.edu/CSSP/.
26. Crews, T.E., L.M. Kurina, P.M. Vitousek. 2001. Organic matter and nitrogen accumulation and nitrogen fixation during early ecosystem development in Hawaii. Biogeochemistry 52:259-279.
27. Crimaldi, J., J. Thompson, J. Rosman, R. Lowe, J. Koseff. 2002. Hydrodynamics of larval settlement: The influence of turbulent stress events at potential recruitment sites. Limnology and Oceanography 47:1137-1151.
28. Dahm, C.N., N.B. Grimm, P. Marmonier, H.M. Valett, P. Vervier. 1998. Nutrient dynamics at the interface between surface waters and groundwaters. Freshwater Biology 40:427-451.
29. Dalzell, B.J. 2000. Modeling and evaluation of nonpoint source pollution in the Lower Minnesota River. M.S. Thesis, Univ. of Minnesota. p 280.
30. Dean, W.E., E. Gorham. 1998. Magnitude and significance of carbon burial in lakes, reservoirs, and peatlands. Geology 26:535-538.
31. DeGrandpre, M. 2002. Sunburst sensors. http://www.sunburstsensors.com/.
32. Dettinger, M.D., D.R. Cayan. 1995. Large-scale atmospheric forcing of recent trends toward early snowmelt runoff in California. Journal of Climate 8:606-623.
33. DHI. 2003. MIKE Impact: A decision support system for habitat restoration. http://projects.dhi.dk/impact/.
34. Doyle, M.W., E.H. Stanley, J.M. Harbor, G.S. Grant. 2003. Dam removal in the United States: Emerging needs for science and policy. EOS 84:29-36.
35. Edwards, C., H. Batchelder, T. Powell. 2000. Modeling microzooplankton and macrozooplankton dynamics within a coastal upwelling zone. Journal of Plankton Research 22:1619-1648.
36. Engle, D., J.M. Melack. 2000. Methane emissions from the Amazon floodplain: Enhanced release during episodic mixing of lakes. Biogeochemistry 51:71-90.
37. Engstrom, D.R., S.C. Fritz, J.E. Almendinger, S. Juggings. 2000. Chemical and biological trends during lake evolution in recently deglaciated terrain. Nature 408:161-166.
38. EnviroTech. 2003. http://www.n-virotech.com/.
39. Essington, T., J. Houser. 2003. The effect of whole-lake nutrient enrichment on mercury concentration in age-1 yellow perch. Transactions American Fisheries Society 132:57-68.
40. Etemad-Shahidi, A., J. Imberger. 2001. Anatomy of turbulence in thermally stratified lakes. Limnology and Oceanography 46:1158-1170.
41. Eugster, W., G.W. Kling, T. Jonas, J.P. McFadden, A. Wuest, S. MacIntyre, F.S. Chapin, III. In press. CO_2 exchange between air and water in an Arctic Alaskan and mid-latitude Swiss lake: The importance of convective mixing. Journal of Geophysical Research (Oceans).
42. Fer, I., U. Lemmin, S. Thorpe. 2002. Observations of mixing near the sides of a deep lake in winter. Limnology and Oceanography 47:535-544.
43. Fisher, S.G., N.B. Grimm, E. Marti, R.M. Holmes, J.B. Jones. 1998. Material spiralling in stream corridors: A telescoping ecosystem model. Ecosystems 1:19-34.
44. Fogler, H.S. 1992. Elements of Chemical Reaction Engineering, 2 ed. Upper Saddle River, NJ: Prentice Hall.
45. Forbes, S. 1887. The lake as a microcosm. Bulletin Peoria (Illinois) Science Association. (1887) Reprinted in Bulletin Illinois Natural History Survey 15:537-550.
46. Fritz, S.C. 1989. Lake development and limnololgical response to prehistoric and historic land-use in Diss, Norfolk, U.K. Journal of Ecology 77:182-202.
47. Fritz, S.C., E. Ito, Z. Yu, K.R. Laird, D.R. Engstrom. 2000. Hydrologic variation in the northern Great Plains during the last two millennia. Quaternary Research 53:175-184.
48. Fussman, G.F., S.P. Ellner, K.W. Shertzer, N.G. Hairston. 2000. Crossing the Hopf bifurcation in a live predator-prey system. Science 290:1358-1360.
49. Glaser, P.H., D.I. Siegel, E. Romanowicz, Y. Shen. 1997. Regional linkages between raised bogs and the climate, groundwater and landscape of northwestern Minnesota. Journal of Ecology 85:3-16.
50. Goolsby, D.A., W.A. Battaglin. 2001. Long-term changes in concentrations and flux of nitrogen in the Mississippi River Basin, USA. Hydrological Processes 15:1209-1226.
51. Gooseff, M., D. McKnight, W. Lyons, A. Blum. 2002. Weathering reactions and hyporheic exchange controls on stream water chemistry in a glacial meltwater stream in the McMurdo Dry Valleys. Water Resources Research 38:art. no. 1279.

52. Gorham, E. 1996. Linkages among diverse aquatic ecosystems: A neglected field of study. In: National Research Council, Committee on Inland Aquatic Ecosystems, Water Science and Technology Board, Commission on Geosciences, Environment, and Resources. Freshwater Ecosystems: Revitalizing Educational Programs in Limnology. Washington, DC: National Academy Press. p 203-217.
53. Goudsmit, G.H., F. Peeters, M. Gloor, A. Wuest. 1997. Boundary versus internal diapycnal mixing in stratified natural waters. Journal of Geophysical Research (Atmospheres) 102:27903-27914.
54. Guenther, G. 2001. Airborne lidar bathymetry. In: Maune D, editor. Digital Elevation Model Technologies and Applications: The DEM Users Manual. Bethesda, MD: The American Society for Photogrammetry and Remote Sensing. p 237-300.
55. Hakanson, L., R.H. Peters. 1995. Predictive Limnology: Methods for Predictive Modelling. New York: SPB Academic Publishers.
56. Hammer, U. 1986. Saline Lake Ecosystems of the World. Boston: Dr. W. Junk Publishers.
57. Harvey, J.W., C.C. Fuller. 1998. Effect of enhanced manganese oxidation in the hyporheic zone on basin-scale geochemical mass balance. Water Resources Research 34:623-636.
58. Hauer, F.R., J.S. Baron, D.H. Campbell, K.D. Fausch, S.W. Hostetler, G.H. Leavesley, P.R. Leavitt, D.M. McKnight, J.A. Stanford. 1997. Assessment of climate changes and freshwater ecosystems of the Rocky Mountains, USA and Canada. Hydrological Processes 11:903-924.
59. Hershey, A.E., G.M. Gettel, M.E. McDonald, C. Miller, H. Mooers, W.J. O'Brien, J. Pastor, C. Richards, J.A. Schuldt. 1999. A geomorphic-tropic model for landscape control of arctic lake food webs. BioScience 49:887-897.
60. Hess, L.L., J.M. Melack, S. Filoso, Y. Wang. 1995. Delineation of inundated area and vegetation along the Amazon flooplain with the SIR-C synthetic-aperture radar. IEEE Transactions of Geoscience and Remote Sensing 33:896-904.
61. Hobbie, J., G. Shaver, J. Laundre, K. Slavik, L. Deegan, J. O'Brien, S. Oberbauer, S. MacIntyre. (In press). Climate forcing at the Arctic LTER site. In: Greenland D, Goodin D, Smith R, editors. Climate Variability and Ecosystem Response at Long-Term Ecological Research (LTER) Sites. New York: Oxford University Press.
62. Hodges, B., J. Imberger, A. Saggio, K. Winters. 2000. Modeling basin-scale motions in a stratified lake. Limnology and Oceanography 45:1603-1620.
63. Holloway, J.M., R.A. Dahlgren, B. Hansen, W.H. Casey. 1998. Contribution of bedrock nitrogen to high nitrate concentrations in stream water. Nature 395:785-788.
64. Howarth, R.W., G. Billen, D. Swaney, A. Townsend, N. Jaworski, K. Lajtha, J.A. Downing, R. Elmgren, N. Caraco, T. Jordan, F. Berendse, J. Freney, V. Kudeyarov, P. Murdoch, Z. Zhu. 1996. Regional nitrogen budgets and riverine N and P fluxes for the drainages to the North Atlantic Ocean: Natural and human influences. Biogeochemistry 35:75-139.
65. Hydrolab. 2002. www.hydrolab.com.
66. Imberger, J. 1985. Thermal characteristics of standing waters: An illustration of dynamic processes. In: Walmsley RD, editor. Perspectives in Southern Hemisphere Limnology. Dordrecht, Dr. W. Junk Publishers. p 7-29.
67. In-Situ. 2003. www.in-situ.com.
68. Ittekkot, V., C. Humborg, P. Schafer. 2000. Hydrological alterations and marine biogeochemistry: A silicate issue? BioScience 50:776-782.
69. Jackson, R.B., S.R. Carpenter, C.N. Dahm, D.M. McKnight, R.J. Naiman, S.L. Postel, S.W. Running. 2001. Water in a changing world. Ecological Applications 11:1027-1045.
70. Jellison, R., J.M. Melack. 1993. Algal photosynthetic activity and its response to meromixis in hypersaline Mono Lake, California. Limnology and Oceanography 38:818-837.
71. Jumars, P.A. 1990. W(h)ither limnology? Limnology and Oceanography 35:1216-1218.
72. Junk, W.J., editor. 1997. The Central Amazon Floodplain: Ecology of a Pulsing System. New York: Springer-Verlag.
73. Kalff, J. 2002. Limnology. Upper Saddle River, NJ: Prentice Hall.
74. Kelly, C., J. Rudd, R. Bodaly, N. Roulet, V. StLouis, A. Heyes, T. Moore, S. Schiff, R. Aravena, K. Scott, B. Dyck, R. Harris, B. Warner, G. Edwards. 1997. Increases in fluxes of greenhouse gases and methyl mercury following flooding of an experimental reservoir. Environmental Science and Techology 31:1334-1344.
75. Kendall, C., J.J. McDonnell, editors. 1998. Isotope Tracers in Catchment Hydrology. Amsterdam: Elsevier.
76. Killworth, P.D., N.R. Edwards. 1999. A turbulent bottom boundary layer code for use in numerical ocean models. Journal of Physical Oceanography 29:1221-1238.

77. Kling, G.W., G.W. Kipphut, M.M. Miller, W.J. O'Brien. 2000. Integration of lakes and streams in a landscape perspective: The importance of material processing on spatial patterns and temporal coherence. Freshwater Biology 43:477-497.
78. Kloiber, S.M., P.L. Brezonik, M.E. Bauer. 2002. Application of Landsat imagery to regional-scale assessments of lake clarity. Water Research 36:4330-4340.
79. Kloiber, S.M., P.L. Brezonik, L.G. Olmanson, M.E. Bauer. 2002. A procedure for regional lake water clarity assessment using Landsat multispectral data. Remote Sensing of the Environment 82:38-47.
80. Laird, K., S. Fritz, K. Maasch, B. Cumming. 1996. Greater drought intensity and frequency before AD 1200 in the Northern Great Plains, USA. Nature 384:552-554.
81. Lamborg, C., W. Fitzgerald, A. Damman, J. Benoit, P. Balcom, D. Engstrom. 2002. Modern and historic atmospheric mercury fluxes in both hemispheres: Global and regional mercury cycling implications. Global Biogeochemical Cycles 16:1104.
82. Lasker, R. 1978. The relation between oceanographic conditions and larval anchovy food in the California Current: identification of factors contributing to recruitment failure. Rapp. P.-V. Reun. Cons. Int. Explor. Mer. 173:212-230.
83. Laval, B., B.R. Hodges, J. Imberger. 2003. Reducing numerical diffusion effects with pycnocline filter. Journal of Hydraulic Engineering-ASCE 129:215-224.
84. Levine, S.N., D.W. Schindler. 1992. Modification of the N-P ratio in lakes by *in situ* processes. Limnology and Oceanography 37:917-935.
85. Lewis, W.M., S.K. Hamilton, M.A. Rodriguez, J.F. Saunders, M.A. Lasi. 2001. Foodweb analysis of the Orinoco floodplain based on production estimates and stable isotope data. Journal of the North American Benthological Society 20:241-254.
86. Lewis, W.M., Jr., et al. 1995. Challenges for limnology in the United States and Canada: An assessment of the discipline in the 1990's. University of Colorado, Boulder: American Society of Limnology and Oceanography. p 20.
87. Likens, G. 1984. Beyond the shoreline: A watershed-ecosystem approach. Verhandlungen Internationale Vereinigung fur Theoretische und Angewandte Limnologie 22:1-22.
88. Likens, G.E., F.H. Bormann. 1995. Biogeochemistry of a Forested Ecosystem. New York: Springer-Verlag.
89. Lovejoy, C., E.C. Carmack, L. Legendre, N.M. Price. 2002. Water column interleaving: A new physical mechanism determining protist communities and bacterial states. Limnology and Oceanography 47:1819-1831.
90. MacIntyre, R. Wnninkhof, J.P. Chanton. 1995. Trace gas exchange across the air-water interface in freshwater and coastal marine environments. In: Matson P, Harriss R, editors. Biogenic Trace Gases: Measuring Emissions from Soil and Water. Oxford, UK: Blackwell. p 52-97.
91. MacIntyre, S., K.M. Flynn, R. Jellison, J.R. Romero. 1999. Boundary mixing and nutrient flux in Mono Lake, CA. Limnology and Oceanography 44:512-529.
92. MacIntyre, S., R. Jellison. 2001. Nutrient fluxes from upwelling and enhanced turbulence at the top of the pycnocline in Mono Lake, California. Hydrobiologia 466:13-29.
93. MacIntyre, S., J. Romero, G. Kling. 2002. Spatial-temporal variability in mixed layer deepening and lateral advection in an embayment of Lake Victoria, East Africa. Limnology and Oceanography 47:656-671.
94. Magnuson, J.J., T.K. Kratz. 1999. Lakes in the landscape: approaches to regional limnology. Verhandlungen Internationale Vereinigung fur Theoretische und Angewandte Limnologie 27:1-14.
95. Magnuson, J.J., D.M. Robertson, B.J. Benson, R.H. Wynne, D.M. Livingstone, T. Arai, R.A. Assel, R.G. Barry, V. Card, E. Kuusisto, N.G. Granin, T.D. Prowse, K.M. Stewart, V.S. Vuglinski. 2000. Historical trends in lake and river ice cover in the Northern Hemisphere. Science 289:1743-1746.
96. Mann, C.J., R.G. Wetzel. 2000. Hydrology of an impounded lotic wetland - Subsurface hydrology. Wetlands 20:33-47.
97. Maurice, P., D. McKnight, L. Leff, J. Fulghum, M. Gooseff. 2002. Direct observations of aluminosilicate weathering in the hyporheic zone of an Antarctic Dry Valley stream. Geochimica et Cosmochimica Acta 66:1335-1347.
98. Mazumder, A., W.D. Taylor, F.R. Pick, R. Nordin, R. Roy. 2002. Modeling aquatic-terrestrial linkages for sustainable freshwater resources. Concept paper submitted to ASLO Limnology Workshop.
99. MBARI. 2000. Monterey Bay Aquarium Research Institute. http://www.mbari.org/.
100. McCabe, G.J., D.M. Wolock. 1999. General-circulation-model simulations of future snowpack in the western United States. Journal American Water Resources Association 35:1473-1484.
101. McClain, M.E., E.W. Boyer, C.L. Dent, S.E. Gergel, N.B. Grimm, P.M. Groffman, S.C. Hart, J.W. Harvey, C.A. Johnston, E. Mayorga, W.H. McDowell, G. Pinay. 2003. Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. Ecosystems 6:301-312.

102. McManus, M.A., A.L. Alldredge, A. Barnard, E. Boss, J. Case, T.J. Cowles, P.L. Donaghay, L.B. Eisner, D.J. Gifford, C.F. Greenlaw, C. Herren, D.V. Holliday, D. Johnson, S. MacIntyre, D. McGehee, T.R. Osborn, M.J. Perry, R. Pieper, J.E.B. Rines, D.C. Smith, J.M. Sullivan, M.K. Talbot, M.S. Twardowski, A. Weidemann, J.R. Zaneveld. In press. Changes in characteristics, distribution and persistence of thin layers over a 48 hour period. Marine Ecology Progress Series.
103. McPhee-Shaw, E., E. Kunze. Boundary layer intrusions from a sloping bottom: A mechanism for generating intermediate nepheloid layers. Journal of Geophysical Research (Atmospheres) 107:3050.
104. Melack, J.M. 2002. Ecological dynamics in saline lakes. Verhandlungen Internationale Vereinigung fur Theoretische und Angewandte Limnologie 28:29-40.
105. MEMS_Clearinghouse. 2003. Welcome to the MEMS Clearinghouse. http://www.memsnet.org/.
106. MEMS_Web_Page. http://www.trimmer.net/.
107. Monismith, S., J. Imberger, T. Morrissey. 1990. Horizontal convection in the sidearm of a small reservoir. Limnology and Oceanography 35:1676-1702.
108. Mulholland, P., J. Tank, D. Sanzone, W. Wollheim, B. Peterson, J. Webster, J. Meyer. 2000. Nitrogen cycling in a forest stream determined by a ^{15}N tracer addition. Ecological Monographs 70:471-493.
109. Mulla, D.J., Perillo, C.A., and C.G. Cogger. 1996. A site-specific farm-scale GIS approach for reducing groundwater contamination by pesticides. Journal Environmental Quality 25:419-425.
110. Naiman, R.J., R.E. Bilby, D.E. Schindler, J.M. Helfield. 2002. Pacific salmon, nutrients, and the dynamics of freshwater and riparian ecosystems. Ecosystems 5:399-417.
111. Naiman, R.J., J.M. Magnuson, D.M. McKnight, J.A. Stanford, editors. 1995. The Freshwater Imperative: A Research Agenda. Washington, DC: Island Press.
112. Neff, J.C., S.E. Hobbie, P.M. Vitousek. 2000. Nutrient and mineralogical control on dissolved organic C, N and P fluxes and stoichiometry in Hawaiian soils. Biogeochemistry 51:283-302.
113. Newbold, J.D., J.W. Elwood, R.V. O'Neill, W. Van Winkle. 1982. Nutrient spiralling in streams: Implications for nutrient limitation and invertebrate activity. American Naturalist 120:628-652.
114. Niyogi, D.K., W.M. Lewis, D.M. McKnight. 2002. Effects of stress from mine drainage on diversity, biomass, and function of primary producers in mountain streams. Ecosystems 5:554-567.
115. NOAA. 2002. In-situ instrumentation, platforms, and communication for coastal monitoring. NOAA Coastal Services Center. http://www.csc.noaa.gov/cts/instrument_table.htm.
116. NORTEK_AS. No date. http://www.nortek-as.com/.
117. Odum, H.T. 1957. Trophic structure and productivity of Silver Springs, Florida. Ecological Monographs 27:55-112.
118. Olmanson, L.G., M.E. Bauer, P.L. Brezonik. 2002. Water quality monitoring of 10,000 Minnesota lakes: Statewide classification of lake water clarity using Landsat imagery. Proc. In: 15th William T. Pecora Memorial Remote Sensing Symposium, November 8-15. Denver, Colorado.
119. Oremland, R.S., S.E. Hoeft, J.A. Santini, N. Bano, R.A. Hollibaugh, J.T. Hollibaugh. 2002. Anaerobic oxidation of arsenite in Mono Lake water and by facultative, arsenite-oxidizing chemoautotroph, strain MLHE-1. Applied and Environmental Microbiology 68:4795-4802.
120. Pace, M.L., J.J. Cole. 2002. Synchronous variations of dissolved organic carbon and color in lakes. Limnology and Oceanography 47:333-342.
121. PaceTech. Pacific Environmental Technologies. http://www.pacetechhawaii.com/products.htm.
122. Padgett, P.E., E.B. Allen. 1999. Differential responses to nitrogen fertilization in native shrubs and exotic annuals common to Mediterranean coastal sage scrub of California. Plant Ecology 144:93-101.
123. Perakis, S.S., L.O. Hedin. 2002. Nitrogen loss from unpolluted South American forests mainly via dissolved organic compounds. Nature 415:416-419.
124. PME. www.pme.com/scamp.htm.
125. Pringle, C.M., G.L. Rowe, F.J. Triska, et al. 1993. Landscape linkages between geothermal activity and solute composition and ecological response in surface waters draining the Atlantic slope of Costa-Rica. Limnology and Oceanography 38:753-774.
126. Quayle, W.C., L.S. Peck, H. Peat, J.C. Ellis-Evans, P.R. Harrigan. 2002. Extreme responses to climate change in Antarctic lakes. Science 295:645.
127. RD_Instruments. Acoustic Doppler Solutions. www.rdinstruments.com.
128. RESAC. 2002. Regional Earth Science Applications Center. http://resac.gis.umn.edu/water/regional_water_clarity/regional_water_clarity.htm.
129. Richardson, J.S., R.J. Mackay. 1991. Lake outlets and the distribution of filter feeders — an assessment of hypotheses. Oikos 62:370-380.

130. Richey, J.E., J.M. Melack, A.K. Aufdenkampe, V.M. Ballester, L.L. Hess. 2002. Outgassing from Amazonian rivers and wetlands as a large tropical source of atmospheric CO_2. Nature 416:617-620.
131. Roden, E.E., R.G. Wetzel, R.H. Findlay, C.N. Dahm. 2002. Understanding and predicting hydrobiogeochemical couplings in aquatic ecosystems. Concept paper submitted to ASLO Limnology Workshop.
132. Romero, J.R., J.M. Melack. 1996. Sensitivity of vertical mixing in a large saline lake to variations in runoff. Limnology and Oceanography 41:955-965.
133. Rose, J. 2003. Michigan State University. Personal communication.
134. Rueda, F., S. Schladow. In Press. The internal dynamics of a large polymictic lake. Part II: Three-dimensional numerical simulations. ASCE Journal of Hydraulic Engineering.
135. Runkel, R.L. 1998. One-dimensional transport with inflow and storage (OTIS): A solute transport model for streams and rivers. In: Water Resources Investigation Report 98-4018. Denver, CO: U.S. Geological Survey.
136. Sabater, S., A. Butturini, J. Clement, T. Burt, D. Dowrick, H. M, V. Maitre, G. Pinay, C. Postolache, M. Rzepecki, F. Sabater. 2003. Nitrogen removal by riparian buffers along a European climatic gradient: Patterns and factors of variation. Ecosystems 6:20-31.
137. Saggio, A., J. Imberger. 1998. Internal wave weather in a stratified lake. Limnology and Oceanography 43: 1780-1795.
138. Saggio, A., J. Imberger. 2001. Mixing and turbulent fluxes in the metallimnion of a stratified lake. Limnology and Oceanography 46:392-409.
139. Satlantic. 2003. http://www.satlantic.com/.
140. Saunders, D.L., J. Kalff. 2001. Nitrogen retention in wetlands, lakes and rivers. Hydrobiologia 443:205-212.
141. Schindler, D.W. 1974. Eutrophication and recovery in experimental lakes: Implications for lake management. Science 184:897-898.
142. Schmidt, J., R. Parnell, P. Grams, J. Hazel, M. Kaplinski, L. Stevens, T. Hoffnagle. 2001. The 1996 controlled flood in Grand Canyon: Flow, sediment transport, and geomorphic change. Ecological Applications 11:657-671.
143. Seitzinger, S.P., C. Kroeze. 1998. Global distribution of nitrous oxide production and N inputs in freshwater and coastal marine ecosystems. Global Biogeochemistry Cycles 12:93-113.
144. Sickman, J.O., A. Leydecker, J.M. Melack. 2001. Nitrogen mass balances and abiotic controls on N retention and yield in high-elevation catchments of the Sierra Nevada, California, United States. Water Resources Research 37:1445-1461.
145. Siegel, D.I., A.S. Reeve, P.H. Glaser, E.A. Romanowicz. 1995. Climate driven flushing of pore water in peatlands. Nature 374:531-533.
146. Sippel, S., S. Hamilton, J. Melack, E. Novo. 1998. Passive microwave observations of inundation area and the area/stage relation in the Amazon River floodplain. International Journal of Remote Sensing 19:3055-3074.
147. Smalltimes. 2003. The Nanotech Report. http://smalltimes.com.
148. SOFIE. 2001. Spectroscopy using Optical Fibers in the Marine Environment. http://www.physics.dcu.ie/OSL/projects/SOFIE/.
149. Sojda, R.S., B.L. McGlynn, D.O. Rosenberry. 2002. Water resources: Integrating landscape complexity and dynamism. Concept paper submitted to ASLO Limnology Workshop.
150. SonTek. 2003. http://www.sontek.com.
151. Soranno, P.A., K. Webster, J. Riera, T. Kratz, J. Baron, P. Bukaveckas, G. Kling, D. White, N. Caine, R. Lathrop, P. Leavitt. 1999. Spatial variation among lakes within landscapes: Ecological organization along lake chains. Ecosystems 2:395-410.
152. Stallard, R.F. 1998. Terrestrial sedimentation and the carbon cycle: Coupling weathering and erosion to carbon burial. Global Biogeochemical Cycles 12:231-257.
153. Stanford, J., J. Ward, W. Liss, C. Frissell, R. Williams, J. Lichatowich, C. Coutant. 1996. A general protocol for restoration of regulated rivers. Regulated Rivers 12:391-413.
154. Stanford, J.A., Gonser, T. 1998. Special Issue: Rivers in the landscape: Riparian and groundwater ecology - Preface. Freshwater Biology 40:401.
155. Stanford, J.A., J.V. Ward. 2001. Revisiting the serial discontinuity concept. Regulated Rivers 17:303-310.
156. Sterner, R.W., J.J. Elser. 2002. Ecological Stoichiometry: The Biology of Elements from Molecules to the Biosphere. Princeton, NJ: Princeton University Press.
157. Streeter, H.W., E.B. Phelps. 1925. A study of the pollution and natural purification of the Ohio River. III. Factors concerned in the phenomena of oxidation and aeration. U.S. Public Health Service 146:75.
158. SubChem_Systems. 2002. http://www.subchem.com.

159. Swanson, F., T.K. Kratz, N. Caine, R.G. Woodmansee. 1988. Landform effects on ecosystem patterns and processes. Bioscience 38:92-98.
160. Thorpe, S. 1998. Some dynamical effects of the sloping sides of lakes. In: Imberger J, editor. Physical Processes in Lakes and Oceans, Coastal and Estuarine Studies. AGU. p 441-460.
161. Threlkeld, S.T. 1991. The Freshwater Initiative: An opportunity to enhance limnology at the National Science Foundation. Limnology and Oceanography 36:1062-1065.
162. Treguer, P., D. Nelson, A. van Bennekom, D. DeMaster, A. Leynart, B. Queguiner. 1995. The silica balance in the world ocean: A reestimate. Science 268:379.
163. Vadeboncoeur, Y., M. Vander Zanden, D. Lodge. 2002. Putting the lake back together: Reintegrating benthic pathways into lake food web models. BioScience 52:44-54.
164. Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, C.E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Science 37:130-137.
165. Vitousek, P.M., K. Cassman, C. Cleveland, T. Crews, C.B. Fields, E.B. Rastettner, J.I. Sprent. 2002. Towards an ecological understanding of biological nitrogen fixation. Biogeochemistry 57:1-45.
166. Water Science and Technology Board. 2001. Envisioning the Agenda for Water Resources Research in the Twenty-first Century. Washington, DC: National Research Council.
167. Wetzel, R.G. 1992. Wetlands as metabolic gates. Journal of Great Lakes Research 18:529-532.
168. Wetzel, R.G. 1996. Benthic algae and nutrient cycling in lentic freshwater ecosystems. In: Stevenson R, Bothwell M, Lowe R, editors. Algal Ecology: Freshwater Benthic Ecosystems. San Diego, CA: Academic Press. p 641-667.
169. White, M.A., P.E. Thornton, S.W. Running, R.R. Nemani. 2000. Parameterization and sensitivity analysis of the BIOME-BGC terrestrial ecosystem model: Net primary production controls. Earth Interactions 4:1-85.
170. Whiting, G.J., J.P. Chanton. 2001. Greenhouse carbon balance of wetlands: Methane emission versus carbon sequestration. Tellus B 53:521-528.
171. Wiens, J.A. 2002. Riverine landscapes: Taking landscape ecology into the water. Freshwater Biology 47:501-515.
172. Winter, T.C. 2001. The concept of hydrologic landscapes. Journal American Water Resources Association 37:335-349.
173. Wroblewski, J.S., J.G. Richman. 1987. The nonlinear response of plankton to wind mixing events - implications for survival of larval northern anchovy. Journal of Plankton Research 9:103-123.
174. Wurtsbaugh, W. 1988. Iron, molybdenum and phosphorus limitation of N_2 fixation maintains nitrogen deficiency of plankton in the Great Salt Lake drainage (Utah, USA). Verhandlungen Internationale Vereinigung fur Theoretische und Angewandte Limnologie 23:121-130.
175. Wurtsbaugh, W.A., A.J. Horne. 1983. Iron in eutrophic Clear Lake, California: Its importance for algal nitrogen fixation and growth. Canadian Journal of Fisheries and Aquatic Science 40:1419-1429.
176. YSI. 2001. YSI Environmental. http://www.ysi.com/environmental.htm.

Appendix. Concept Paper Contributions from the Aquatic Science Community

To involve the larger community of freshwater scientists in the United States in defining the future of limnology, one-page Concept Papers were solicited from the membership of the eight major societies dealing with inland waters (Table 2). Objectives of this effort were to: (1) obtain as much additional input on the question as possible; (2) to publicize the potential interest of NSF, ASLO and others in promoting limnological research, and; (3) to promote the common goals of members in the variety of organizations involved in research on inland waters.

Table 2. Organizations from which Concept Papers were solicited to help define the future of limnology.

American Society of Limnology & Oceanography*
American Fisheries Society, Water Quality Section*
American Geophysical Union, Hydrology & Biogeosciences Sections
Ecological Society of America, Limnogeology Section*†
Geological Society of America, Limnogeology Section*†
North American Benthological Society*†
North American Lake Management Society*†
Society of Wetland Scientists
*Members of these societies made contributions. †Societies that provided synthesis papers.

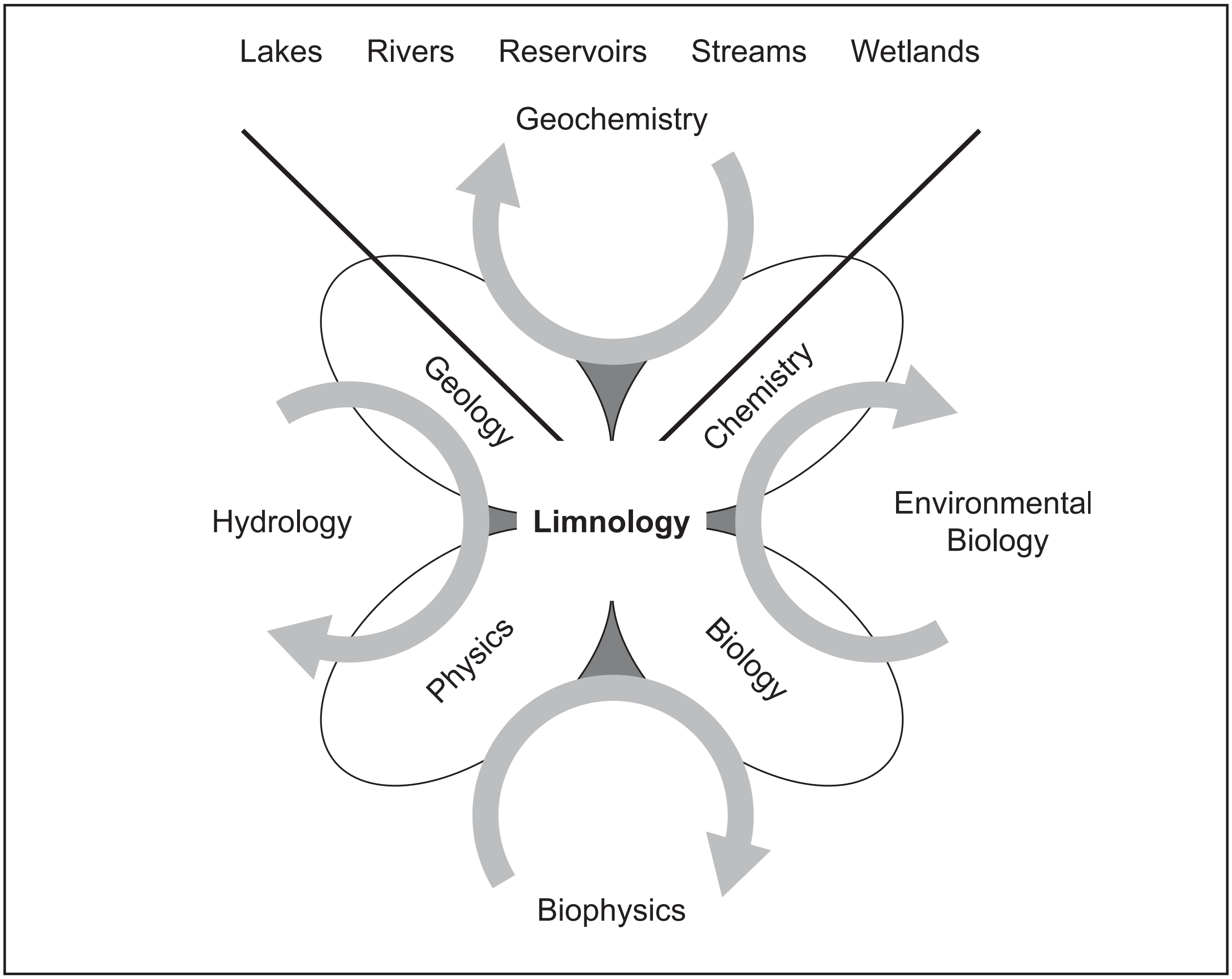
Sixty Concept Papers were contributed and four of the societies provided synthesis papers reflecting the ideas of their members. It is important to note that the contributions are not a random survey of freshwater scientists in the United States, because some of the societies were more effective in marshaling input from their members in the short time frame than were others. Additionally, there are relatively few physical limnologists in the United States because of the dearth of funding support in this area, and we consequently received few responses from this group. Of the respondents, 41% focused on streams and rivers, 35% on lakes and reservoirs, 14% on watersheds, and 10% on wetlands or groundwater.

The respondents provided a very diverse perspective on the limnological themes that should be pursued in the next decade. Many focused on the need for applied limnological research related to water quality and several papers promoted the need for increased funding for taxonomic work to help solve ecological and water quality problems. In addition to these management and biological questions, five major themes emerged regarding basic research relevant to biogeochemical limnology (Table 3). (1) A number of the Concept Papers focused on the need for more interdisciplinary research and education. (2) A large number of scientists indicated that much more research was needed to understand how different watershed components (groundwater, streams, lakes, wetlands, soils) functioned as a unified whole. (3) Others focused on the diverse physical, chemical, and biological stressors that threaten ecosystem integrity. (4) Yet others recognized the need for combining *scales* of research to solve pressing limnological questions. (5) A smaller group highlighted how more sophisticated instrumentation was needed to close the technological gap between oceanography and limnology. (6) Contributors from biologically oriented societies emphasized the need for better taxonomic resources. Participants in the Boulder workshop echoed several of these themes, and contributions from several Concept Papers were incorporated into this report.

Table 3. Major themes derived from the 60 Concept Papers that were submitted prior to the workshop.

Interdisciplinary research and education
We, therefore, strongly urge that the NSF Geoscience and Environmental Biology Panels develop joint research solicitations that indicate successful applicants must be interdisciplinary, and include physical, biological, social and geographic scientist. — Robert Hughes & Carol Couch for the North American Benthological Society
Linking watershed components
Future limnological studies must examine the intra-watershed variations in nutrient cycling, focusing in particular on nutrient transformations and transport between watershed components. We must find a way to extrapolate small-scale measurements accurately to whole watersheds, taking into consideration variation found within those watersheds. — Amy Marcarelli, ASLO member
Stressors and ecosystem integrity
A major, and fascinating, research direction will be to define the combinations of sediments, flow regime, thermal and light properties, chemical and nutrient inputs, and biotic populations that promote integrity and sustainability for freshwater ecosystems. —Jill Baron, ASLO & ESA member
Scales of research
Encouragement of research investigations that combine the large-scale approaches of geographers and hydrologists with the small-scale approaches of microbiologists and some biological oceanographers. — Roger Wooton, North American Benthological Society member
Instrumentation
There is a technological gap between instrumentation used in oceanography and that used for studies of in-land water. In particular, oceanographers have been using for some time non-invasive acoustical & optical…instruments providing high resolution temporal and spatial insights into biogeochemical processes. — Emmanal Boss, ASLO member

Photo Credits: Cover–Yellow Belly Creek, Sawtooth Mountains, ID, A. Marcarelli; page 7–Everglades, FL, W. Huber; page 8–Redfish Creek & Lake, Sawtooth Mountains, ID, W. Wurtsbaugh; page 13–Peter and Paul Lakes, MI, Michael Shoeless Pace; page 13–Glen Canyon Dam, Bureau of Reclamation; page 21–Amazon River, NASA; page 18--I-Series Lakes, North Slope, Alaska,G. Burkhart; page 27–Wharton Creek and Suess Glacier, Antarctica, M. Gooseff; page 32-J. Melack; Above—Wood River, ID, W. Wurtsbaugh.


Lakes
Rivers
Reservoirs
Streams
Wetlands
Geochemistry
Geology
Chemistry
Hydrology
Limnology
Environmental Biology
Physics
Biology
Biophysics