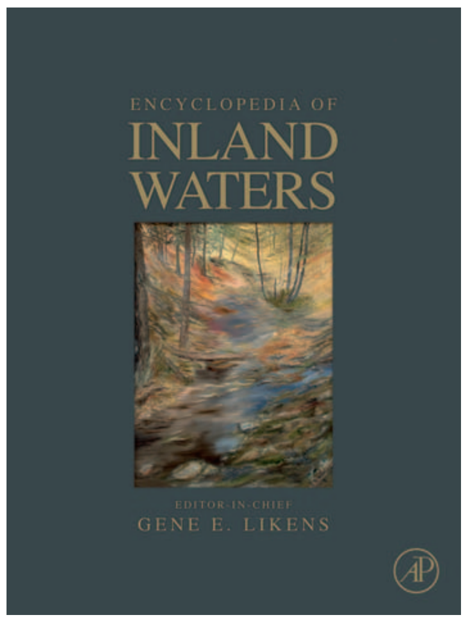

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Limnology as a Discipline

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Limnology – An Integrative, Multidisciplinary Science

The objective of limnology is a comprehensive, integrated, scientific understanding of inland waters. As Gene Likens points out in the introduction to this Encyclopedia, limnology can be viewed as the Queen of Science because of its inherent interdisciplinary nature. As the scientific study of inland waters, limnology incorporates knowledge of geological, physical, chemical, and biological processes at a range of spatial and temporal scales. Although some limnology textbooks greatly emphasize lakes, the inland waters within the purview of modern limnology include lakes, streams, rivers, ground water, and often wetlands. Like oceanography, limnology is a highly integrative and interdisciplinary science and frequently adopts an ecosystem perspective to approach research questions or applied problems. This need for integration to understand 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 fields of limnology and oceanography. With one important caveat, it is instructive to think of limnology as 'freshwater oceanography.' Forel was a little too narrow for modern limnology when he referred to it in 1892 as the "oceanography of lakes." Nevertheless, both limnology and oceanography are focused on types of environment (as are atmospheric science or forestry) and both are integrative sciences constructed from the strengths of the traditional scientific disciplines. When I wear my jacket with the word 'limnology' emblazoned on the back, I find this definition as 'freshwater oceanography' to be the one that best conveys limnology to the general public or scientists from diverse fields. The important caveat is that many inland waters are saline. So, one has to be careful here with the analogy.

In some ways it is unfortunate that François-Alphonse Forel (1841–1912), the first to use the term *limnology*, was both conversant with ancient Greek, and unwilling to compromise linguistic purism by combining perhaps a more widely recognized Latin word for inland water with the Greek '-logos' (the study of). The Greek, "λίμνη" (limni) can be translated as lake, pool, lagoon, or lough. Even if most people knew Ancient Greek, 'limni' does not represent limnology well because limnologists study both flowing and standing waters, and a host of systems that are neither lakes, nor lagoons, nor loughs. More problematic is that, for the few non-Greek speakers among us, there is no familiar everyday cognate for 'limni.' Thus, we have a scientific endeavor that studies a resource that is critically important to human welfare but exists under a rubric that is almost universally not recognized by the general public. Many practicing limnologists, and some entire universities, have chosen to drop the term limnology and describe the discipline other ways, such as 'water science,' 'aquatic science,' 'aquatic ecology,' 'freshwater ecology,' or by a subdiscipline (e.g., 'freshwater microbiology'). None of these are perfect. Both aquatic and water could just refer to the ocean as well as to inland waters, and in most definitions, ecology is too biological to represent the full spectrum of science in limnology (but see Likens, 1992). Sometimes the term 'hydrology' is used in place of limnology. While etymologically reasonable, hydrology, especially in North America, as a discipline is well entrenched as the study of the water cycle and the movement of water. Limnology and hydrology are related sciences, but are not synonyms. Certainly other disciplines with otherwise obscure Greek names have caught the imagination of the public. Is 'astronomy' well recognized because of its cognates, or are we aware of 'astro-' because the space program, and some of its more visible proponents, made sure of it?

Limnology – Integration and Subdisciplines

Although the science of limnology is by definition integrative and comprehensive, limnology is built upon its interacting subdisciplines. We can recognize four or five major subdisciplines. Physical limnology is focused on water movement at all spatial scales (from large-scale water balances to turbulence); heat and gas transfers; the optical properties of water, and often, the effects of physical properties on chemical reactions or organism function, and vice versa. Geological limnology is concerned with the formation and morphology of lake basins and river networks, the record of past events recorded in sediments

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(paleolimnology) and the distribution of aquatic environments over the landscape (which could also be called geographical limnology). Chemical limnology attempts to understand (a) the distribution of chemical constituents in water bodies, (b) the transport and retention of these constituents, (c) the chemical and biological reactions that control the forms of these constituents. Because of the strong direct and indirect roles that organisms, and especially microbial organisms, have on many chemical constituents much of chemical limnology would be classified as biogeochemical limnology. Biological limnology is concerned with the numbers and kinds of organisms that inhabit inland waters; their evolutionary adaptations, genetic relationships, and autoecology; their trophic and behavioral interactions with other organisms; food webs; and the effects of organisms on ecosystem-level processes such as whole-system metabolism and the effects of organisms on major biogeochemical cycles. Because of its rapid growth and high visibility, paleolimnology should probably be treated as a subdiscipline separate from geology. Paleolimnologists use the geological, chemical, or organismal records preserved in sediments to reconstruct conditions in the aquatic system itself (usually lakes), in the watershed, or more broadly as a record of paleoclimatic conditions.

The Teaching of Limnology

Although limnology, as 'freshwater oceanography,' is a broad and interdisciplinary topic in theory and origin, the teaching of limnology has progressed mainly in university departments that are most closely associated with biology and ecology. Even the historic and famous Center for Limnology at the University of Wisconsin at Madison is part of the larger Department of Zoology. Thus, the teaching of limnology at most institutions tends to emphasize biological aspects. Basic physics, chemistry, and geology are covered, but not in the depth to which biology is. Where there is a clear distinction in oceanography between Marine Biology (the study of marine organisms and their interaction with the marine environment) and Biological Oceanography (how organisms effect the biogeochemical cycles in the ocean and vice versa), these distinction are blurred in the modern teaching of limnology. Many courses in limnology are really courses in freshwater biology, with physics and chemistry playing a supporting role. Many students are able to take a course in limnology (under whatever name) without a strong background or prerequisite courses in either chemistry or physics.

While limnologists sometime complain about either a decline in the field of limnology or lack of recognition (see Jumars, 1990), an internet search in Google (with no date restrictions) reveals there are 473 000 hits for the parameters 'limnology and course.' The names 'freshwater biology' and 'aquatic science' brings the total to about 800 000 hits. This value is only somewhat smaller than a search for 'oceanography and course,' which recovers 1 200 000 hits and quite a bit less than the 19 000 000 for 'ecology and course.' Thus the teaching of limnology continues to have adherents and visibility, but not nearly what it should have because of the importance and relevance of the topic. The basic principles of limnology are also covered in other course work. Frequently, high-school students will have had a section on limnology in a basic course in either Earth Science or Environmental Science, as will university students who follow a course of study in areas like Natural Resources, Ecology, or Conservation Biology.

Principal Limnological Text Books

The material covered in the principal texts used to teach limnology is generally broad, but tends to be more focused on biology as a discipline and lakes as an environment than the field aspires to be (Table 1). G.E. Hutchinson's four-volume *Treatise on Limnology* devoted one volume to geography, physics, and chemistry with the other three covering biological topics: Volume 2 – *Introduction to Lake Biology and the Limnoplankton*; Volume 3 – *Limnological Botany*; and Volume 4 – *Zoobenthos* (coauthored with Yvette Edmondson). Though wide ranging in the topics covered, the *Treatise*, nevertheless, is nearly entirely devoted to lakes. Ruttner's 1953 *Fundamentals of Limnology* devoted about half its length to biology, and thus more to chemistry, physics, and geology, and does give a single chapter on flowing waters. Goldman and Horne's 1983 *Limnology* is used in many university courses. It devotes three chapters to physics, and four to chemistry, but the chemistry focuses on the more biologically relevant chemical cycles (oxygen, carbon, nitrogen). Interestingly, this text has sections on organisms in streams and estuaries as well as lakes. Esteves' 1988 *Fundamentos de Limnologia* (in Portuguese) covers a similar scope, with somewhat less on physics. G.A. Cole's 1994 *Textbook of Limnology*, like Esteves (1988), covers chemistry but largely from the perspective of biology and the text is nearly entirely devoted to lakes. The most comprehensive of the modern textbooks are R.G. Wetzel's 2001 *Limnology: Lake and River Ecosystems* and W.K. Dodds 2002 *Freshwater Ecology*. Both Dodds' and Wetzel's texts explicitly include flowing waters, and both devote much space

Table 1 Some of the more widely used text books of limnology

Author	*Date*	*Title*		*Scope*	*Domain*
Hutchinson with Edmondson	1957	A treatise on limnology	Volume 1	Geography, physics, chemistry	Lakes
			Volume 2	Biology	Lakes, mostly plankton
			Volume 3	Botany	Lakes
			Volume 4	Zoobenthos	Lakes
Ruttner	1953	Fundamentals of limnology	Was widely used in classes in the 1970s, compact	Geology, chemistry, physics, biology	Mostly lakes, some flowing water
Goldman and Horne	1983	Limnology	Widely used as a college text	Physics, biological oriented chemistry, biology	Largely lakes, some stream biology
Esteves	1988	Fundamentos de Limnologia	In Portuguese	Biologically oriented chemistry, some physics, biology	Mostly lakes, with some rivers
Cole	1994	Textbook of limnology		Biologically oriented chemistry, biology, some physics	Mostly lakes
Wetzel	2001	Limnology: Lake and river ecosystems	More comprehensive than the two prior editions	Very comprehensive, geography, geology, physics, chemistry, biology	Lakes and rivers, some streams
Dodds	2002	Freshwater ecology		Also very comprehensive but more biological/ecological	Balance of stream, river, lake and reservoirs
Kalff	2002	Limnology	Strong on empirical relationships.	Comprehensive with more strength in ecology and biogeochemistry than physics or chemistry	Balance of river, lake, stream
Dodson	2005	Introduction to limnology	Structured more like an ecology text	Mostly biology but very strong on ecology	Strong on human impacts

Scope refers to the coverage of the major subdisciplines within limnology. Domain refers to the type of aquatic habitats each text emphasizes.

to physics (5 chapters in Wetzel; 4 in Dodds) and chemistry (6 chapters in Wetzel; 4 in Dodds) with about 10 in both devoted to biology. Dodds gives an elegant and comprehensive definition of limnology as "The study of continental waters." Interestingly, though the scope of Wetzel's text does cover the full field of limnology, Wetzel inexplicably defines limnology (p. 4) as "... the study of the structural and functional interrelationships of organisms of inland waters as they are affected by their dynamic physical, chemical and biotic environments." J. Kalff's 2002 *Limnology*, also covers both flowing and standing waters and defines limnology more simply as (p. 1) "... the study of lakes, rivers, and wetlands as systems ..." Kalff goes on to suggest that limnology is the most successful of the ecological sciences. Dodson's 2005 *Introduction to Limnology* is structured differently than the other modern texts in several ways. It is the only text to provide a specific manual for teachers of limnology. The text is also hierarchical and ecological, moving from the diversity of organisms to populations, communities, and ecosystems, a design that is shared with some ecology texts. This text pays little attention to physics or chemistry but strongly includes the interaction of humans with aquatic environments. *Limnological Analyses* by Wetzel and Likens is a manual of field and laboratory exercises but is more oriented toward the student than toward the teacher. It includes physics, chemistry, and biology, but is weighted towards biology and biologically related chemistry. While it has a single chapter devoted exclusively to flowing water, some of the exercises can work in either lakes or streams. We can summarize by saying that the textbooks in limnology continue to evolve. But were one to judge the discipline of limnology entirely from its textbooks, one would conclude it was largely a discipline within biology or ecology and focused mostly on lakes.

Scientific Journals – The Publication of Limnological Research

Exciting limnological research competes for space in the top, broad scientific journals such as *Science*, *Nature*, *Naturwissenschaften*, *Bioscience*, *Proceedings of the National Academy of Science*, and so on reasonably well, but not under its own name. Using the keyword 'limnology' there are only eight entries combined for all of these journals from 1975 to 2007 in Web of Science! There are 188 entries for 'oceanography.' If we were to search for either chemistry, physics, or ecology intersected with lake or river or stream, there would be about 1100 entries (not counting the ones that discuss lakes on other planets and made of fluids other than water). Most limnological research is published in journals dedicated to limnology itself (some including oceanography and some not) or to fisheries or ecology. Taking just the journals of the Ecological Society of America, for example *Ecology*, *Ecological Applications*, and *Ecological Monographs*, there are about 1400 papers that cover limnological topics. This number is about 14% of the total content of these journals. Roughly, one-third of the journal *Ecosystems* covers inland aquatic environments.

There are 18 journals covered by Web of Science with the word 'limnology' (or a linguistic variant) in the title; 32 more with the word 'aquatic'; and a few others that come under different names, such as *Hydrobiologia* or *Freshwater Biology*, are about 55 in total. This number is comparable to the 29 journals with the word 'oceanography' (or a variant) and 87 with the word 'marine.' As in most scientific disciplines, the citation rates or impact factors among these journals are highly variable from a high of 3.29 for *Limnology and Oceanography* to a low 0.14 for *Amazonia*. These factors are based on the most recent data (2006) available for all journals in the limnology grouping as listed by the Institute for Scientific Information (ISI). The higher-impact limnological journals are on a par with higher-impact field-oriented journals such as *Ecology*, *Geology*, and so on.

Limnology – Multiple Scientific Approaches

As with other aspects of ecosystem science, limnology employs multiple approaches. These can be classified, albeit imperfectly, as observational, comparative, experimental, and theoretical (including modeling, see Carpenter, 1997). The observational approach that consists of measurements over time of key parameters of interest, often in a single system, has dominated limnology in the past. The observational approach is purely descriptive. That is, measured variables, their changes over time or space and their apparent interrelations, can be depicted quite quantitatively, but the backbone here is the description of a state or change in state. The observational approach also can suffer from being site specific in some single-system studies, or can be used for an entire network of related systems. Nevertheless, these observations form the background of what we know about aquatic systems and how they vary over time. Further, when such observations are sustained over time (long-term studies), the observational approach becomes particularly powerful at detecting changes or long-term trends and sometimes in identifying the factors that

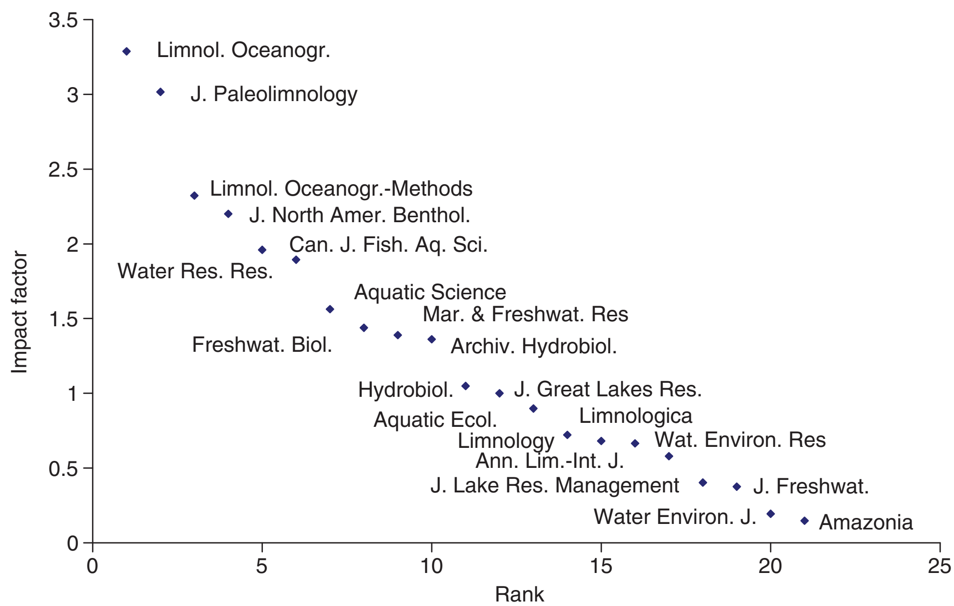

Figure 1 The major limnological journals ordered (*X*-axis) by their journal citation rate (JCR) annual impact factors (*Y*-axis). The annual JCR impact factor of a journal is calculated by dividing the number of current year citations to the source items published in that journal during the previous two years. Data for the impact factors comes from ISI for the year 2006. These impact factors are, at best, a coarse measure of how frequently articles are cited. For comparison to some other fields, the impact factors for the same period for *Ecology* is 4.78; *Geology*, 3.48; and the *American Journal of Physics*, 0.92.

cause the observed changes, and often useful to management or policy about these resources. In the comparative approach researchers often choose to sample a wide variety and number of aquatic systems and then formulate a relationship between aspects of these systems (e.g., lake size, river discharge rate, slope) and the objective of the study (phytoplankton biomass, bacterial secondary production, diversity of fishes, net gas flux rates). When these relationships are strong and based on reasonable connections between driver and observation, they can be used to predict conditions in a system that has not yet been sampled. When the relationships also have strong mechanistic underpinnings, they can be used in management as well. A good example here is the relationships between the loading or concentration of total phosphorus and algal biomass (as chlorophyll *a*). Because aquatic systems are relatively discrete with observable boundaries, limnology has always been a leader in whole-ecosystem experiments, especially in smaller lakes and in streams. Whole-ecosystem experiments also suffer the limitation of being site specific, and from lack of strict controls, but can be used to look directly at a system's response to a perturbation and can be very useful from a management point of view. Whole-system experiments are difficult to replicate and require special care in their interpretations but can be very powerful. As demonstrations, especially to the general public, whole-system manipulations can be particularly convincing and evocative. Modeling and theory are widely used, often in conjunction with data to test the theory of interest. Theoretical approaches are able to look at essentially any spatial or temporal scale and integrate knowledge across these scales. The four basic approaches used are unevenly in the major subdisciplines of limnology (Figure 2).

In modern limnology, some of the best studies combine aspects from the four basic approaches. A few examples are noteworthy. Combining long-term observations carried out in multiple lakes (observational plus comparative), J. Magnuson and colleagues used historical records of ice duration data on lakes to document a warming climate in the Northern Hemisphere over the past 150 years. Combining physical theory and experimental approaches, a number of researchers have added purposeful tracers to lakes, rivers, and streams to estimate the physical basis of gas exchange and the factors that regulate it. In the work that led to the modern understanding of the causes of cultural eutrophication in lakes, we have all four legs of the table in play at various times. The comparative work of R.A. Vollenweider and colleagues showed the initial correlation between total phosphorus (TP) and chlorophyll *a* levels among lakes. Further comparative work has revealed numerous factors such as lake depth, zooplankton community structure that modify the basic TP–chlorophyll

	Geological	Physical	Chemical	Biological	Paleolimnology
Observational	XXX	XXX	XXX	XXX	XXX
Comparative	XXX	X	XX	XXX	XX
Experimental	?	X	X	X	?
Model/theory	X	XXX	XX	X	?

Figure 2 Approaches used in the major subdisciplines of limnology. More X's means more commonly used. Thus, the observational approach (measurements over time in a single system) is widely used in all subdisciplines whereas whole-system experiments are rarely if ever attempted in paleolimnology or geology.

relationships. Whole-lake nitrogen and phosphorus additions revealed that phosphorus was necessary to stimulate large algal blooms. Again, further experimental work that followed showed that the effect of a given level of TP loading could be modified by the presence or absence of piscivorous fishes. Models from the simple empirical type to more refined models that included the effects of hydraulic residence time were added and aided managers to predict the effects of a given increase or decrease in nutrient loads. A number of studies have followed the time course of eutrophication (see Smith, 1997). An important example would be the long-term work at Lake Washington, which was studied both before and after a large-scale sewage–nutrient diversion. The work on acid rain and its effects on aquatic ecosystems is an excellent example of a topic that used all four legs of the table. The work included specific experiments on acid sensitivity of key organisms, following over long term the changes in acidity, organisms and organism health in systems, comparative studies, direct, whole-system experiments in lakes and streams, and rich modeling data that simulated acid from its deposition, through the watershed and into water bodies. Another research area that is richly developed in combining theory with both experimental and comparative approaches is the Lotic Intersite Nitrogen Experiment (LINX), which consists of a large network of stream sites all performing N-isotope addition experiments, linked to a common model to examine nitrogen retention and transformations. The exciting work on regime shifts in shallow lakes is particularly strong in combining theory, experiments, and long-term observation. This body of work endeavors to explain the factors that cause the observed sudden shifts from macrophyte phytoplankton dominance in shallow systems. The advent of reliable instruments that can make high-quality continuous measurements of variables such as temperature, dissolved oxygen, pH, chlorophyll, and so on has opened up a new approach. Persistent high-frequency measurements are being used to measure whole-system primary production and respiration in lakes and in flowing waters and are beginning to be used to reveal the factors that regulate this metabolism. Some limnologists are exploring the value and challenges of a global network of persistent high-frequency measurements. For example, the Global Lake Ecological Observatory Network is a grassroots, international collaboration organized around using these sensors in lake and reservoirs of the world (www.gleon.org).

Current and Emerging Themes in Limnological Research

Several consensus documents (see works by Lewis *et al.* and Wurtsbaugh in Suggested Readings) have attempted to summarize the key unifying and emerging themes in modern limnology. These are useful compilations because both are the result of workshops, sponsored by the American Society of Limnology and Oceanography, and thus, have the consensus of more than a few individuals. Neither workshop attempted to be comprehensive; the list here, derived from both sources, is meant only to be illustrative of selected important themes with a few examples. The Further Reading lists a few studies under each topic where the reader can gain more information. More detailed information on some of these topics appears elsewhere in this Encyclopedia.

Principles governing aquatic food webs This topic covers the role of consumers in determining the biomass, species composition, and production of prey items and primary producers. How changes in piscivorous fish, by removal due to over fishing or addition by stocking, affect the rest of the food web, and both algal and macrophytes communities have become a tool in managing freshwater ecosystems.

The origin, structure, and roles of organic matter in natural waters Organic matter affects the optical properties of water as well as pH and, through chelation, the degree of toxicity of certain metals. The amount of organic matter in a given system is governed by its production from within the system, the rate of input from the watershed and losses due to degradation by light and microbes. Researchers have also been interested in the role of terrestrial subsidies and how terrestrial organic matter does or does not enter the aquatic food web. In addition to the roles of organic matter, other researchers have been advancing our understanding of the chemical make up of dissolved and colloidal organic matter to achieve a molecular understanding of its macroproperties.

Hydrodynamics and fluid mechanics There have been stunning achievements in recent years in understanding water movement and fluid dynamics in all aquatic ecosystems, largely as the result of improved instrumentation such as acoustic Doppler current profilers (ADCP). Interacting with the better measurements has improved theory for modeling thermal structure, advection, dispersion, and turbulence. In streams, the ability to do tracer experiments has led to a much better understanding of temporary storage and mixing in eddys. The work on fluid dynamics extends to the effects on biological and chemical processes.

Biogeochemistry of aquatic ecosystems The transport, retention, and transformation of key elements such as carbon, nitrogen, phosphorus, and more recently, mercury have been an important component in limnology for some time. Balancing input–output budgets often requires the identification of sources and sinks that were not known or realized to be important or biogeochemical reactions that were thought not to occur like the anaerobic oxidation of ammonia. As new toxic materials become of concern, their biogeochemistry becomes relevant and interesting, sometimes in surprising ways. For example, the creation of new, large hydroelectric reservoirs in Canada, Brazil, and China has caused an enormous release of mercury, which is highly toxic.

Energetics of aquatic ecosystems The study of energy as a basic currency in ecosystems is a pervasive theme in all types of ecosystems and particularly well developed in limnology, and has a long history of study. An interesting modern extension has been the expanded use of ecological stoichiometry, which links the ratios of key elements in organisms (N, P, Si, C) to food webs and ultimately to energetic constraints (see Sterner and Elser, 2002).

Land–water and atmosphere–water interactions A key area in limnology is to explore the relationship of the conditions within an aquatic system (chemical constituents, biological productivity, and so on) to the system's links with its watershed or airshed. This endeavor includes the responses of aquatic systems to changes in land cover or land use. With climate change as a potential driver of new land use or land cover patterns, this area of research has become critically important as well as the systems geographical and hydrogeographical position in the landscape. Atmosphere–water interactions include the mechanisms, magnitudes, and of materials that enter and leave aquatic systems at the air–water interface. The exchange processes include aeolian transport of particles, and the exchange of gases.

The Future of Limnology as a Discipline

There is no doubt that the comprehensive, integrative scientific understanding of inland waters (e.g., limnology) is critical to our understanding of the larger terrestrial matrix in which these aquatic systems are embedded. It is becoming increasingly clear that the aquatic systems are often biogeochemical 'hot spots,' which regulate chemical cycles to a much greater extent than their small size would suggest. Certainly, inland waters are critically important habitats and resources for wildlife and humans alike. While the scientific study of these inland waters will continue, it is not clear to what extent that limnology will either maintain its independent identity, or be subsumed into ecology or earth science in the future.

Glossary

Secondary production – The growth of consumer organisms

Colloidal organic matter – Very large molecules or aggregates that have properties intermediate between particles and truly dissolved substances

Dispersion – The spatial mixing of a solute in water or the spatial mixing of more than one water mass

Eutrophication – Nutrient enrichment that leads to increased plant growth

Food-web – An assemblage of organisms that interact by consuming each other

Piscivorous – A predator that eats fish.

See also: Inland Waters.

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