Training of Aquatic Ecosystem Scientists: Continue to Languish or Accept Our Responsibilities?

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Introduction

Limnology is an integrative discipline of inland waters. The subject clearly should address the coupled spatial and temporal variations in physical, chemical and biological properties, how these properties influence aquatic biota and their growth, dynamics, and productivities, and how the community biological metabolism affects geochemical properties. The aquatic components are integrated in an interactive ecosystem that extends considerably beyond the traditional shoreline boundary of the lake, reservoir, wetland, or stream (Likens, 1984; Wetzel 1990; Wetzel and Ward 1992). Physical, geological, hydrological, chemical, and biological characteristics and processes are examined along a large range of scales, for example from individual chemical reactions to chemical fluxes within entire ecosystems. A fundamental aspect of aquatic ecosystems that is frequently overlooked, however, is that they are biogeochemical systems; biological processes are essential components of all qualitative and many quantitative aspects of chemical and many physical processes of inland aquatic ecosystems. Aquatic ecosystems cannot be considered as chemical or hydrological reactors, but rather are biochemical systems in every regard.

The Ecosystem Perspective in Training

During the last and present decades, limnologists began to recognize the inadequacy of examining pelagic communities and processes independently from the littoral-wetland and land-water interface regions of most lake and river ecosystems. Couplings of the biogeochemistry of all components of the ecosystem, the drainage basin, land-water interface communities, and the open water communities are critical to both the qualitative and quantitative understanding of lake and river ecosystems. This essential ecosystem perspective is now being widely discussed and gradually incorporated into management of inland waters. For a number of complex reasons discussed below, however, the ecosystem perspective is not being effectively incorporated into the undergraduate and graduate training of students in aquatic ecology.

Underpinnings. Two major limnological needs emerge. Foremost, the true economic values of freshwater resources must be integrated properly in our teachings at all levels of education. The importance of the availability of high quality freshwater resources, including groundwater, is almost universally underappreciated as essential to the economic viability of individual societies. Many developed countries, such as the United States, have made concerted and partially successful efforts toward regulated treatment and release of used water. With exponentially increasing demands from increasing human populations, it will be difficult to maintain present standards of water quality in both developed and emerging countries (Wetzel 1992). The constructs of true economic valuation of fresh water at all levels of acquisition, use, and technological manipulations, including water reclamation, that are important to effective utilization and management are not being incorporated effectively into the scientific educational programs of most aquatic ecologists.

A second major need is recognition that the most effective and economical management of aquatic ecosystems results from an understanding of the mechanisms governing the integrated hydrology, chemistry, and biology of these ecosystems. The correct diagnoses of freshwater problems and their corrective management are most effective when the dynamics of controlling processes are quantified.

Many decisions concerning the management and use of freshwater resources, however, are presently based on trial and error or correlative methods that may have little application to real-world conditions. Many management decisions are made, based largely on assumed physical processes and chemical reactions from models or pure solution chemistry, by default because of lack of real information. The pivotal roles played by organisms and biological metabolism in these physical (e.g. altered heating and stratification cycles) and particularly chemical processes are still often held subservient or discarded as irrelevant in freshwater supply and quality management. Biogeochemical regulation of metabolism, energy fluxes, and productivity of inland waters, all at the ecosystem level of integration, is relevant to all managerial procedures. The education of limnologists must best match these needs for understanding and managing inland waters as multidimensional ecosystems. That educational need can be made more effective than has been the case in the past by enhanced foundational understanding from research into the causes and control relationships, and by application of this understanding to managing of the integrated ecosystems. Both are essential and limnologists should be versed in the basics of both.

Fragmentation of Disciplines

The ecosystem perspective is uniformly recognized and espoused as essential to both research and training in aquatic ecology. Because of specialized training among most instructional staff, the interdisciplinary essence of this approach requires integrated approaches and perspectives. In few cases do integrated formal educational programs exist, particularly at the undergraduate levels to adequately prepare students for advanced training in aquatic sciences. The opposite conditions prevail in nearly all educational institutions of North America. Some universities claim to have comprehensive and integrated programs in limnology. Most fail in reality and exist largely on paper.

Based on my review of limnological programs at a variety of U. S. universities, I conclude that faculty in needed component subdisciplines (e.g., hydrology, aquatic chemistry, applied health, aquatic law, or engineering facets) may exist on campus, but most do not participate in training of aquatic ecologists. Stated specialty courses, if taught, are disparate, infrequently offered, and are almost always optional to aquatic ecology students as electives. Importantly, essential courses, such as hydrology for non-engineering majors or limnology for non-science majors, are rarely offered; extant courses often have excessive requirements for an ecosystem-oriented program. Such specializations, such as for professional water chemists or hydrologists, should remain for specialized training but they alone inhibit the essential interdisciplinary training needed by aquatic ecologists in other specialized tracks in aquatic ecology. Couplings and true instructional integrations among faculty of different departments or colleges within universities rarely exist in reality. Members of the aquatic faculty of the same university in many cases never meet or interact because of physical or conceptual separatism, elitism among departments and divisions, and the general time constraints in a very demanding profession.

Research Synergism with Education

Strong programs in the education of aquatic ecologists are most frequently associated with strong research programs. As is set forth below, excellence in instruction at both the undergraduate and graduate levels is irrevocably coupled to research where students have opportunities for direct field and experimental involvement in problem solving. In the context of modern needs for training, ecosystem-oriented programs are essential. Such instructional programs are rare owing to a number of synergistic inhibitory factors.

Government support to faculty-student research programs in limnology is inadequate in relation to the value of freshwater resources and the crucial importance of basic and applied research and education to effective management of these resources (Lewis et al. 1994). The National Science Foundation (NSF) is the only significant agency for support of fundamental limnological research in academic institutions. With extremely severe competition for these limited funds, the probability for long-term support, as is required for ecosystem research, is low. Alternative funding sources without specific mission commitments are very few. This support structure has also contributed to fragmentation of the discipline into specialized fields of inquiry and weakening of their interconnections. University researchers tend to conduct research in small, specialized areas in which specific results can be obtained relatively rapidly. Extreme competition for scarce resources promotes isolation among faculty and researchers. Instruction by faculty also tends to become specialized and insular as well, with minimized interdisciplinary interactions and collaboration.

Accompanying the inadequate Federal funding of limnological programs and shifts of greater proportions of fiscal responsibilities for higher education to state and internal sources, universities commonly encourage subdisciplines that are currently popular and relatively well funded, such as molecular biology or those strongly coupled to human medicine. A number of particularly strong research and instructional programs in aquatic ecology in major universities (Yale University, Indiana University, University of Washington, others) have been terminated in the past decade. This decline is in sharp contrast to the marked increase in aquatic ecosystem programs in many other industrialized countries where the critical importance of research foundations to effective management of fresh waters is recognized. Strong instructional and research programs in limnology have emerged in Denmark, Sweden, and Norway where the research and instructional liaisons between universities and environmental agencies are particularly vigorous. Important in these research and management couplings is the recognition of the need to know quantitatively the primary controlling environmental factors causing problems in order to be able to effectively manage and restore freshwater ecosystems.

By default among the weakened aquatic ecological programs in the United States, several alternatives have emerged. Limnology has often languished in departments of biological sciences because they tend to be too narrowly based to exhibit leadership in a field as encompassing as limnology. Limnologically oriented programs related to stream ecology and wetlands have emerged in departments of fisheries and schools of natural resources. Aquatic chemistry and environmental hydraulics programs related to lakes and rivers have developed in engineering departments as natural extensions of those fields, but with minimal training on the importance of biogeochemistry to ecosystem functioning. Environmental resource programs have proliferated in geography and resource groups with minimal scientific underpinnings. Certainly an understanding of geographic and use relationships of fresh waters is useful, but effective solutions of water resource problems require an understanding of the functions and operational constraints of the ecosystems and of the biogeochemical dependencies of ecosystem functioning. These examples of fragmentation indicate obstacles facing students to obtain essential interdisciplinary training, and impediments for faculty to communicate and collaborate in both instruction and research. Many small aquatic foci within a university also compete less effectively with larger, departmentally-oriented programs for funding, positions, and program development.

Optimal Criteria

Effective management of freshwater resources ultimately must be based on an in-depth understanding of the structure and physical, chemical, and biotic mechanisms governing the biotic development within lake, river, and wetland ecosystems. This critical inquiry must be taught rigorously in sufficient detail to understand both the individualities of the ecosystems, as well as the functional commonalities that prevail among them.

Limnological education should have the combined objectives of training persons (1) with the critical *scientific* underpinnings required for understanding integrative ecosystem processes and (2) with sufficient understanding of the ecosystem components to allow individuals to solve problems and make effective managerial and regulatory decisions. Because of several complex but coupled reasons, these objectives are rarely accomplished in training programs.

Students specializing in limnology frequently are trained in general biology or environmental engineering and may have been exposed to specialized facets by means of a course in general limnology and one or more courses in biology of aquatic organisms (e.g., algae, aquatic insects). Often none of these courses expose students to field conditions. Limnology is usually taught as a brief lecture course. Rarely are students more than superficially versed in ecology, quantitative statistics, the conditions of natural communities (particularly, for example, under ice cover or during high river flows), dominating irregular non-equilibrium conditions, growth and reproductive characteristics, environmental heterogeneity, etc. Dissertational research in graduate school, although often of excellent quality, is frequently narrow and laboratory oriented. Certain schools loudly advocate empirical correlational modeling in limnology with no appreciable understanding of causality or controlling variables.

A strong bias exists toward zoological aspects of limnology. Deeply rooted in historical foundations, limnology has been, and still is, taught primarily by biologists with zoological training and interests. The importance of consumers in determining the biomass, species composition, and production of prey is paramount among the principles governing aquatic food web structure. Size-selective predation by fish on zooplankton is among the most predictable community phenomena. Yet generally less than 10-20% of aquatic ecosystem energetics and regulation is associated with animals (Wetzel 1995). The pivotal importance of organic matter produced by photosynthetic organisms both within the lake or river and within the drainage basin and imported to the water body, and of degradation, biogeochemical cycling, and energy fluxes is markedly understudied and poorly taught. It is important that the enormous existing zoological information be correctly integrated into our educational and research evaluations of ecosystem operations and regulation.

Integration at the ecosystem level is required of studies and teaching of system components. Limnology is a composite of physical, chemical, geological, and biological topics, and an integration among these subdisciplines is essential for the interdependent ecosystem perspective and effective management of inland aquatic ecosystems. Research and teaching are inseparably coupled to achieve this training.

A National Initiative: General Education

Educational programs in limnology should be redesigned and strengthened to achieve the breadth of the ecosystem perspective and to couple that perspective to prudent uses and management of freshwater resources. The importance of ecosystem-oriented limnology to the wise management of inland waters must be communicated to the public. Limnology should be taught as a general subject of interest to non-majors. It is extremely important that the educated public be taught the essential characteristics of inland waters and the value of these resources. Instruction in general limnology or aquatic ecology (not just biology) should be conducted at *every* institution of higher education. Such courses are preferably taught by faculty with some interest and training in limnology. Training for professional limnologists (= inland aquatic ecologists) obviously must be much more intensive and interdisciplinary.

A National Initiative: Coordinated Schools of Limnology

An urgent need exists to train properly limnologists in the United States at both a research level and at a practical practising level. Many viewpoints of course exist about how limnological training could be accomplished. The inertia of our present education of aquatic ecology is large, and laissez faire attitudes among faculty are common. It is my thesis that programs must be structured more rigorously than has been the case in the past and that the research and practical training are best done simultaneously and interactively.

Altered and improved programs of instruction and training must be phased into the existing spectrum of largely biology and engineering programs. The proposed schools of limnology are designed to ***augment*** existing programs, ***not to supplant*** them. Most of the existing educational routes, largely through departments of biological sciences, would continue their traditional programs in aquatic biology, water resources, fisheries management, etc. Freshwater resources are of such value to the economy and human health of the country (e.g., Francko and Wetzel 1983; van der Leeden, et al. 1990; Wetzel 1992; Callow and Petts 1993; Gleick 1993) that these national needs demand greatly expanded rigorous training of limnological leaders to enhance our understanding and invigorate management of fresh waters.

Several universities in the United States should make coordinated commitments, rigorously screened by a panel organized by the National Academy of Sciences with national scientific societies in aquatic ecology and supported by the federal government, to develop regional ***schools of limnology*** (Wetzel 1991). These schools would train both limnological ***practitioners and researchers*** from the undergraduate through the doctoral/postdoctoral levels. Excellence in the medical profession emanates from medical schools that both train practicing physicians and conduct basic research to advance the understanding of human physiology. Similarly schools of limnology should train limnologists to function as effective diagnosticians and problem-solvers and also train professional researchers to conduct active research on the fundamental "physiology" of aquatic ecosystems. Just as in the medical profession, professional researchers and faculty would be very few in relation to the practitioners that are applying their results of research to practical problems. Professional researchers advancing to these positions must have demonstrated capacities for continuing innovative contributions to the discipline.

The interdisciplinary nature of limnology mandates that programs of schools of limnology consist of ***integrated*** instruction from disciplines not normally aggregated into a single department or even division. Rigorous instructional programs are needed. Just as chemists are required to be versed in physical, inorganic, organic, and other facets of chemistry *before* specialization, limnologists should be required to be versed in the basics of geomorphology, hydrology, aquatic inorganic and organic chemistry, biochemistry, biology from bacteria to fishes, biostatistics, and other facets of limnology. Ideally, students would commit early to limnological training. A basic two-year curriculum in mathematics and science should be followed by upper level courses that maximize understanding of inland aquatic ecosystems, their biota, and biogeochemical cycling, and their management.

A rigorous program of instruction of this depth and thoroughness will require discipline and perseverance. Time is inadequate in a traditional four-year curriculum to include necessary training in addition to practical experience. Electives in liberal education aspects are limited to the early phases of the curriculum, as is the case in every structured professional program (e.g., engineering, medicine, nursing, business). Claims that limiting liberal arts electives would produce narrow-minded graduates are not substantiated. In contrast, there is abundant experience that graduates poorly trained in aquatic ecology are often functionally disadvantaged and require many years of expensive, inefficient "on the job" training before becoming moderately productive.

Options include a four-year program in which two or more full summers are devoted to internships with governmental environmental agencies, consulting firms, university research projects, and other training programs. Alternatively a five-year curriculum can be implemented, as is common to all professional nursing programs. The fifth year is relegated to "practicals", in which participants analyze problem ecological situations at an integrated ecosystem level. Limnological conditions and problems would be diagnosed, evaluated, and correctives or mitigative alternatives prescribed. Students must participate in field courses and be encouraged to gain experience in on-going field experiments and analytical programs. In the final or fifth year, students would also be expected to interact extensively with graduate students and their research programs. A mandatory examination, consisting of oral and written components, needs to be passed in order to receive the B.Sc. degree throughout most universities of Europe. Professional examinations ('boards') are required upon completion of the B.Sc. degree in many disciplines (e.g., nursing) in the United States in order to practice. Similar minimal national examination standards are essential if limnology is ever to develop to a rigorous professional discipline that management of freshwater resources deserve.

Graduate Programs

Most graduates of the schools of limnology at the B.Sc. and M.Sc. levels would become practitioners that apply their training in diagnostic and advisory capacities. Only a small percentage would enter the advanced research training stages toward higher degrees. Entrance into the advanced degree program in a school of limnology also must be rigorous. For example, students with a basic undergraduate degree from another university would be required to fulfill the minimal standards of the undergraduate program in the school of limnology before being able to participate in the graduate program within that school of limnology. A minimal screening entrance comprehensive examination in ecology should be passed, as well as demonstration of acceptable Graduate Record Examination grades, prior to admission to graduate school.

The masters degree should serve several purposes simultaneously. A primary objective is to gain additional experience in limnology concerned with the regulation of biotic growth and productivity, biogeochemical dynamics, and other community processes in inland waters. Small, concise independent research projects are mandatory to gain experience in the design and execution of research and communication of results to scientific peers. The fundamental final step of research is communication of those results to scientific peers. Although the research conducted at the M.Sc. level is often preliminary and designed largely for training purposes, excellent studies must be mandatory and summaries of the results published, minimally at the regional level. Research conducted at the Ph.D. level must provide advances to fundamental knowledge of the discipline. Results that are not publishable in refereed journals are not satisfactory for the Ph.D. degree.

In both the masters and doctoral degree programs, a number of advanced speciality courses should be mandatory to broaden, extend, and give greater depth and experience to the students. Students could select a number of different areas of specialization or 'tracks'. Particularly to be encouraged are interdisciplinary areas, such as wetland ecology, aquatic environmental law, groundwater pollution, etc. In the schools of limnology, however, it is essential that a uniform and rigorous undergraduate training be acquired. I contend that the weaknesses and wide disparities in undergraduate training place such a burden upon graduate programs that corrections are not made well and that the quality of graduate training and research is often compromised. Field experience is not just desirable at the undergraduate level, but must be mandatory. The most effective research programs couple in situ analyses with the rigor of controlled experimentation both in the laboratory and the field. In all cases, undergraduate students should be incorporated into research programs wherever possible, both to give them experience and also to gain their fresh insights on problems, environmental circumstances, and management.

Graduate instruction and an active research program, preferably at the interdisciplinary ecosystem level, are critical to effective professional instruction. The professionals in the faculty and associated research scientists provide the essential personnel and milieu for dynamic teaching at all levels. Conversely, the fresh insights and perceptions of students are critical to advances in basic research. The collective integration of teaching and research at all levels, undergraduate through post-doctoral, is the most effective means of increasing fundamental understanding of aquatic ecosystems. Several named schools of limnology should be developed nationally to the minimal standards suggested here. It is most important that some or most of these schools be developed in the least understood limnologically, non-glaciated regions of the United States where most of the human population resides. We must recognize that limnology is a profession and that professionally trained practitioners are needed in nearly every county of every state. Several enlightened European countries have professionally trained limnologists in every county assisting with resource decisions. In Sweden, for example, nearly every county has at least one Ph.D.-level limnologist who works with resource planners and management specialists to assist in science-based decisions. Progress in management depends upon acquiring fundamental understanding of aquatic ecosystems. Research advancement and its applications are interdependent and self-reinforcing.

Coordination

Some coordination of programs would be desirable to assure minimal standards of limnological education are being met in all schools of limnology. Standards should be initiated through the National Academy of Sciences and administered through an independent overseeing group, perhaps coordinated by limnological sections of the American Society of Limnology and Oceanography, the Ecological Society of America, the North American Benthological Society (containing most stream/river limnologists), the North American Lake Management Society, and possibly certain specialty groups such as the Society of Wetland Scientists. The initial phases of the development of regional schools of limnology to rigorously selected universities should be subsidized by the federal government, likely through the auspices of the National Science Foundation. Once several programs are in place and operation, their programs should become self-sustaining by means of direct support and other subventions.

At least four regional schools of limnology should be established initially. Instructional programs should be unified at functional levels. The current emphasis of limnological training in glaciated lakes regions, however, is a historical artifact. Limnological needs for understanding and management in other non-glaciated regions are acute. Further neglect is not only unrealistic but unwise economically. Training should include river/reservoir characteristics and problems of the Southeast and Southwest, surface and groundwater resources of the great plains, as well as the traditional lake analyses of the alpine and northern regions of the United States.

The universities that develop such schools of limnology must emphasize instructional objectives in both the undergraduate and graduate programs, and recognize that teaching and research are synergistic and self-reinforcing.

The importance of problem-solving and research components within the training program and the feedback mechanisms between practitioners and researchers cannot be over-emphasized. An analogous situation often occurs in the best of medical and dental schools as the problems of the practitioners and the developmental advances of the researchers are exchanged, applied, and used to rapidly advance the disciplines.

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