Research Frontiers in Environmental Engineering

A Report of a Workshop Sponsored by the National Science Foundation
and the Association of Environmental Engineering Professors
January 14-16, 1998
Monterey, California

September 15, 1998

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Introduction

On January 14-16, 1998, a meeting was held at the Asilomar Conference Center in Monterey, California to discuss Research Frontiers in Environmental Engineering. Participants were selected by the Conference Chairs, Bruce Logan and Charles O'Melia, based on either membership in the National Academy of Engineering (NAE) or the Association of Environmental Engineering Professors (AEEP), and exceptional national and international reputations. Of the 16 participants, ten were from the NAE, five from AEEP, and (as an observer) one from the National Science Foundation (NSF; see below). The goal of the conference was simple: to identify the most important environmental problems—for which there are no known or easy solutions—that environmental engineers will be called upon to solve in the coming decades. As you read this report, it will become evident that the environmental needs identified by this group represent such large and exceedingly complex problems that it will take a concerted research effort by both engineers and scientists to find new and innovative solutions to environmental problems facing the world today.

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Over the next few decades, societies throughout the world will face new and challenging obstacles on the path to progress and protection of human health and the environment. Progress can no longer be evaluated within limited confines, such as an immediate benefit to a local economy. Instead, changes made on a local scale must be evaluated within the context of a global economy, and in concert with the impact on local, regional and global ecosystems. The industrialized nations now exist within a global economy that includes developing nations and all of their health, water and pollution problems. A global economy brings not only increased communication and a broader dissemination of manufactured goods, for example, but also an intensified circulation of people creating an increased potential for the dissemination of infectious disease. World travel brings people into intimate contact with disease agents that might once have remained in equilibrium with an afflicted, but isolated, human sub-population. The recent example of the emergence of influenza from areas such as China is proof that no country is an island in terms of pubic health.

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It is clear that there are enormous environmental challenges to be faced both in the US and across the globe, but how can solutions to these environmental problems be devised for both local and global environments? The starting point must be science and technology that provide new tools and a better, more fundamental understanding of the processes that affect the quality of our environment. Environmental systems—water, air, and land, together or separately—are complex by their nature. While scientific investigation can unravel aspects of key issues related in each of these systems, a larger, integrative view of these systems is essential.

Environmental engineering and science has, as its central mission, the *analysis* of environmental systems and the *design* of plans, criteria, and technological systems for the solution of environmental problems. The intellectual challenges for environmental engineers and scientists have been, and continue to be the identification of critical environmental problems, the acquisition of scientific knowledge crucial to achieving effective solutions, and the application of that knowledge in real-world settings. Environmental engineers meet these challenges by integrating new tools and methodologies from scientific fields and disciplines, including biological, physical, chemical, earth, and atmospheric sciences. Similarly, environmental engineers must be sure to draw upon all branches of engineering, but especially from the fields of chemical, civil, electrical, and mechanical engineering. Engineering analysis and design can create effective environmental systems, whether engineered natural systems, such as groundwater basins or wetlands, or constructed treatment facilities for communities and industries, but the success of these systems will depend on our understanding of how these systems function and respond to environmental disturbances and stress.

One thing is certain about the role of environmental engineers in the future: rather than just responding to pollution and environmental damage, we must do a better job of anticipating adverse environmental impacts. In the past, environmental engineers often have dealt with problems after they have occurred. A new paradigm for the profession is to play a more anticipatory role in preventing and addressing problems before they become widespread. This will require the profession to embrace interdisciplinary approaches to an even greater extent to formulate new analysis tools and design methodologies. An example of this is the production and wide distribution of new chemicals that have not been sufficiently evaluated for potential of environmental harm. One very recent example is the introduction of MTBE (methyl tertiary butyl ether) in gasoline to cut down on air pollution without considering that MTBE will significantly worsen groundwater pollution. A second recent example is the switch from CFCs (chlorofluorocarbons) to HFCs (hydrofluoro-carbons) without good knowledge of the environmental impact of refractory trifluoroacetic acid that will form in the atmosphere and then rain down all over the earth. How do we assess their potential harm, and determine the ability of natural systems to adapt to these new chemicals and to degrade them? Important questions concern biological adaptation to new chemicals, genetic control of the processes, and the exchange of genetic information between species so that the ability to degrade chemicals becomes widespread among many species. We know too little about these processes, but they are fundamental to sound engineering of treatment systems and to the understanding of chemical fate and effects in the environment.

In order to identify the most important environmental problems that environmental engineers will be called upon to solve in the coming decades—for which there are no known or easy solutions—a workshop was held at the Asilomar Conference Center in Monterey, California in January of 1998. Workshop participants included ten members of the National Academy of Engineering, five members of the Association of Environmental Engineering Professors (most of whom were current or past presidents of that organization), and the Director of the Environmental

Engineering Program at the National Science Foundation. Since the research and applications of environmental engineering and science depend so strongly on multidisciplinary resources, the Frontiers Workshop participants asked the following questions: What new scientific tools and knowledge and what new technologies hold out the greatest prospect for quantum improvements in our ability to prevent pollution, to design out toxics use in products and processes, and to innovate better strategies to protect and improve environmental quality today and for the future? In this report we offer several answers to these important questions. The report is divided into four sections: A Sustainable Environment, Complex Systems, Analytical Tools, and Engineered Processes. The first two sections address the unique challenges that society is handing to environmental engineers and scientists. The third and fourth address exciting new tools and processes that we can bring to bear as we seek to meet society's needs and address pollution problems in a global environment.

1. A SUSTAINABLE ENVIRONMENT

Safe, adequate and sustainable water use. The issue of sufficient quantities of water of the quality required for specific vital uses at specific times and places is rapidly approaching critical conditions in many parts of the world, including certain areas of the U.S. Per capita water use in the less developed countries continues to increase as these countries become more industrialized, and overall the world population continues to increase. However, while water use throughout the world continues to increase, the total quantity of water on Earth remains essentially constant. The increased anthropogenic alteration of fresh water as it cycles through the Earth's geosystems continues to produce a progressive overall decline in water quality. When viewed within the context of sustainability of human health and balanced ecosystems, this situation of deteriorating water quality requires that strategies and technologies to conserve, reduce and reuse water must be integral to research priorities in environmental sciences and engineering in the years ahead.

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The net effect of constantly expanding uses of fresh water, and the increasing frequency of short-circuiting the intrinsic hydrologic cycle, makes distinctions between natural waters, water supplies and municipal, agricultural, and industrial wastewaters increasingly artificial. To ensure that society can survive in an acceptable state, environmental engineers must address the realities of a limited water source, the need for water conservation, and the need for development and application of the technologies required for transforming any specific water to a quality required for a particular use. Three major interrelated research thrusts are proposed to meet the needs of providing a sustainable water supply.

The first thrust concerns issues related to protection of human health and the well being of the environment. A fuller and more refined understanding of the toxicological implications (both human and environmental) of the chemical and microbiological properties of water is required to ensure whole system protection. Typical raw water supply sources contain arrays of impurities that chronicle their histories and positions in the hydrologic cycle. While such impurities vary widely not only in their chemical and biological characteristics but in their concentrations as well, the human and ecological effects of common water contaminants need to be better understood. In particular, the impact of trace impurities at or below detection limits needs investigation from other than a purely one-chemical, carcinogenic-potential perspective. For example, the concern about estrogen-mimicking compounds that may cause hormone disruption in humans and ecosystems needs to be investigated relative to the occurrence and activities of these chemicals in water and wastewater.

The second research thrust centers on development of a strategic scientific agenda designed to advance the competence of water science and technology. Specifically, an agenda designed to significantly increase our scientific capability to completely repurify previously used fresh waters more aggressively and effectively with engineered systems (e.g., membrane, sorption, and advanced oxidation systems) than is done by this planet's intrinsic hydrology, i.e., to develop the technologies required to repeatedly recycle waters of suitable quality at specific points of use and reuse with complete confidence. It is clear that the end objective of this second research thrust is integrally related to that of the first research thrust. Fail-safe processes are needed to cope with chemicals, viruses, and disease-causing bacteria.

The third important need is for more innovative approaches to promote the cascading use of water in order to reduce overall water consumption. In most regions of the world agriculture is the largest consumptive use of water; changes are needed to accepted social, economic, and engineering approaches to reduce wasteful practices. New ways also must be found to eliminate water use in various industrial settings by promoting complete water reuse. In some areas, the development of separate gray water systems may prove feasible. Finally, domestic water use must also be curtailed. An existing water-use-intensive work and home infrastructure must be replaced with a lower water use system.

Terrestrial and coastal aquatic resources. The failure to maintain healthy and sustainable terrestrial and coastal aquatic resources (ecosystems) leads to natural resource damage and loss, as well as the contamination of other parts of the environment, such as ground and surface waters, crops and the atmosphere. Terrestrial and coastal aquatic ecosystems have a capacity for assimilation and utilization of many of the products of anthropogenic activities. When that assimilative capacity is exceeded, adverse environmental effects occur. Environmental engineers can contribute to the use and maintenance of these vital resources. This can be done by applying physical, chemical and biological fundamentals to identify site-specific waste assimilative capabilities. This will require a recognition by environmental engineers of the need to benefit from interactions with experts from the fields of geologic sciences; hydrology; soil, crop and forest sciences; and the biological sciences. The challenges are to (*i*) recognize and respond to the multidisciplinary character of these resources, (*ii*) avoid narrow, regimented perspectives, (*iii*) think in terms of a systems approach to the management of these natural resources, and (*iv*) understand the limited assimilative capabilities of the terrestrial and coastal aquatic ecosystems.

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There are several research areas to be considered. Basic (versus applied) research is aimed at gaining an improved understanding of the chemical, physical and biological relationships that determine the intrinsic assimilative capacity of saturated and unsaturated soils and associated vegetation. Such knowledge is needed to understand how to use, but not abuse or overload, the capabilities of the soil and vegetation for waste management. The current state of knowledge lacks integration, depth, breadth, and context. With a better understanding of the fundamentals and system dynamics that are involved, we will be better able to utilize and protect the vital role and assimilative capacity of these resources. The second research need is methodology to incorporate the fundamentals and dynamics of systems into designs of appropriate site specific uses, remediation and restoration of such systems, or in other words, to bridge basic and applied research. The current empirical approaches rarely allow full consideration of the complex and varied geologic, microbial, and vegetative nature of such systems, and lack suitable methodologies for incorporating exposure and risk assessment into management scenarios.

Examples of environmental situations to which these research thrusts can apply include land application for treatment of wastewaters and sludges; remediation of contaminated soils and groundwaters; restoration of brownfields and other contaminated sites for beneficial use; use of constructed and natural wetlands for point and non-point source discharges; suitable application of landfill and funnel-gate/permeable in-situ reactor techniques; determination of environmentally-acceptable endpoints for remediation processes and identification of the types and amounts of chemicals that can be left in the subsurface without the likelihood of adverse effects. Because terrestrial and coastal aquatic ecosystems are key media for the assimilation and permanent management of the residues of a society, it is mandatory that environmental engineers engage in both basic and applied research to protect these resources that are so important to the sustainability of the planet.

Assessment of chronic exposure to trace contaminants. In industrialized countries, there is a concern that humans are being chronically exposed to a number of organic and inorganic contaminants that may have adverse health effects, even at low concentrations. These chemicals may be present in the air that we breathe and the waters that we drink due to improper disposal and/or release of these chemicals into the environment (e.g. from leaking underground storage tanks, emissions of chemicals from cleaning agents used in the home, applications of pesticides in the watershed), or may be formed by processes that are used to purify the air or water, such as the presence of disinfection by-products like chloroform that are produced by the chlorination of drinking water. These agents may be responsible for carcinogenic, reproductive, developmental, or other adverse public health outcomes. A need exists to quantify the level of exposure of humans to these potentially harmful chemicals so that health professionals can assess the impact of these exposures. The level of exposure is often difficult to quantify for a given population because of the inability to make the number of measurements necessary to assess overall population exposure on both a temporal and spatial scale. Environmental engineers are uniquely qualified to determine levels of exposure because of their understanding of the sources of contaminants and their transport, transformations, and fate in the environment. Better quantification can be obtained through the development and verification of more reliable mathematical models, better understanding of the transport and reactivity of these chemicals, and better analytical techniques for their identification and measurement. This modeling should have a stochastic component, and the development of novel biomarkers would help to better characterize the extent of exposure for purposes of model verification.

2. COMPLEX ENVIRONMENTAL SYSTEMS

Complex biogeochemical systems. Learning to apply analytical and problem-solving skills to complex environmental systems is a critical component in the education and training of environmental engineers. Through exposure to many scientific and engineering areas, and by learning to use a team-based approach to engineer large systems, environmental engineers are well suited to direct the analysis of large biogeochemical systems and to devise solutions for their repair. Examples of such systems include the urban atmosphere, in which gaseous and colloidal pollutants react to form smog which affects all oxygen-respiring organisms; lakes, oceans, and coastal waters, where pollutants can affect phytoplankton and other organisms that support a food chain utilized by the fisheries industry; and underground (subsurface) settings used by various industries but contaminated by petroleum products, industrial solvents, and the residues from nuclear materials to an extent that exceeds the intrinsic degradative capabilities of the soil microbial community. To deal with these problems within such systems, engineers identify solutions and in some cases, design reactors to decontaminate the different phases (water, soil, and air) either at the source or at the point of use. Although these systems vary widely in size and character, they share a common feature: a large number of biological and chemical species interact through a web of reaction and transport processes. In the future, greater emphasis must be placed on a more holistic view of the system, an approach that must be based on understanding how different system components interact. Examining multiple species and their web of relationships demands high-level scientific expertise from disciplines previously viewed as quite disparate, e.g., geology, chemistry, microbiology, ecology, and physics. The quantification of the system dynamics requires mathematical modeling so that we can systematically integrate and quantify the roles of many species with reaction and transport mechanisms.

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Atmospheric systems. Research on acid rain, urban smog, stratospheric ozone depletion, and climate change underline the fact that the atmosphere in particular is a complex system linked to the land and water systems. Our understanding of anthropogenic influences on the atmosphere relies on quantitative descriptions of emissions of gas and particle phase contaminants; their optical, physical, and chemical properties; the transformation, transport, and fate of these species within the atmosphere; and exchanges with the land and water. New research frontiers and applications lie in each of these areas. For example, further research in heterogeneous chemistry will be necessary to predict how well CFC replacements mitigate ozone depletion, and understanding how aerosol particles are formed from gaseous precursors will be an important part of controlling atmospheric concentrations of fine particles.

Climate change research will continue to be challenging because it requires an interdisciplinary/team approach spanning the technical, applied and social sciences. A variety of scientific and engineering disciplines and backgrounds will be necessary, for example, to address technical issues such as chemical exchanges between different phases around the planet. This information will need to be linked to physical and biological aspects of global climate change and combined with social, political and economic issues in order to fully address the impact of these climate changes on the diverse communities and nations throughout the world.

One immediate need for climate research is additional measurements on contaminant concentrations throughout the atmosphere and around the globe. These data could be provided by next-generation remote sensing instruments using ground- or satellite-based platforms. Fundamental information, such as the refractive indices of atmospheric aerosol species and how particles grow when exposed to humid air, will be key to predicting the direct effect of aerosol particles on the earth's radiative balance. How aerosol particles form and affect clouds is crucial to describing aerosol particles' indirect effect on climate and is a major challenge in climate change research. Further research is also needed in the sources, sinks, and atmospheric concentrations of greenhouse gases. All of these interactions must be incorporated into reliable climate change models that describe the complex nature of feedbacks among atmospheric radiation, sources and sinks of climatically active species, and temperature and circulation in the atmosphere and ocean.

Special attention is needed for improving the identification of chemical sources and sinks involved in exchanges primarily between land and water bodies. An excellent example of how linking sources and sinks can affect global biogeochemical cycles is the increase in atmospheric CO_2. Fossil fuel combustion involves the oxidation of organic carbon stored in geological formations and the release of CO_2 to the atmosphere, potentially resulting in an increase in the atmospheric CO_2 concentration by a factor of 3 to 6 over the next few centuries. Although the predicted increase in the Earth's temperature is the most dramatic effect of anthropogenic activity on the carbon cycle, the rapid transfer of carbon from organic deposits to inorganic carbon in the biosphere can alter biogeochemical cycles as well. When CO_2 releases occur slowly, the chemistry and biology of the ocean adjust so that the input of calcium from weathering of the lithosphere is balanced by the deposition of calcium in the ocean sediments. However, a rapid increase in atmospheric CO_2, as is now occurring, can accelerate weathering reactions and alter steady conditions. The dynamics of the dissolution of rock, formation of new deposits, and exchange of inorganic carbon between the atmosphere are poorly understood. The removal of carbon from the inorganic pool requires that it be incorporated into organic carbon, either on the land or in the waters. How increases in CO_2 and temperature affect this sink mechanism for CO_2 is also not well defined. Environmental engineers will be involved in finding creative responses by society to whatever changes occur from increased CO_2 in the atmosphere. One such response may be to develop strategies and/or technologies to remove CO_2 from the atmosphere.

Ecosystems. Within the broad category of complex environmental systems, the most widely useful concept is that of an *ecosystem*, in which living organisms play a dominant role in defining the web of interactions among the organisms and their environment. Ecosystems can be described by their *structure* and *function*. Structure refers to the biological species and how they are spatially arranged. Elucidating the structure of an ecosystem means answering the questions, "What species are present," and, "Where are they," questions answered primarily by biologists. Function refers to the metabolic reactions catalyzed by the organisms and the flow of energy and elements through the system, and addresses the questions, "What reactions are the different species carrying out," and, "How are these species interacting with each other and their environment," and requires more integrative work by both scientists and engineers.

Ecosystems of interest to environmental engineers vary tremendously in size, structure, and function. At one extreme, we might consider the entire biosphere of Earth as an ecosystem comprising all organisms. Practically, it is much more useful, scientifically and for problem solving, to define an ecosystem as lying within some identifiable boundaries. Some key examples include a forest stand, a small lake, a wetland, a section of contaminated aquifer, and a treatment reactor. Once rational boundaries are defined, analysis tools can link inputs, outputs, and internal sinks, sources, and cycles for the critical organisms, nutrients, and contaminants.

Many ecosystems contain plants and animals of great interest to human society. We are concerned about the loss of species and their genetic information, the sustainability of food sources, the bioconcentration of pollutants in our food supply, the viability of the many products that these plants and animals supply, and the transmission of infectious diseases.

All ecosystems contain microorganisms, such as bacteria, algae, and protozoa. Particularly for aquatic ecosystems, microorganisms provide a large amount of the primary production (photosynthesis) that ultimately supports the larger life forms. In all ecosystems, microorganisms are responsible for the decomposition and recycling of nutrient elements. Some systems contain only microorganisms. Examples include the subsurface and engineered reactors used to treat contaminated waters, soils, and air. Most of the microorganisms in nature exist as biofilms, which are microorganisms attached to surfaces. Biofilms cause important problems, such as corrosion, fouling, and infection, but they also are gaining use in microbiologically based technologies to treat contaminated waters and gases.

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Even though microorganisms are essential components of all ecosystems and comprise all of the ecosystem in some cases, their ecology, or *microbial ecology*, has been relatively unexamined until recently. This inattention can be attributed mainly to a lack of tools to answer the fundamental ecological questions. Microorganisms are poorly differentiated based on size and morphology: they have no characteristic and easily recognized special features, such as legs, gills, wings, and coloration patterns. The result is that a traditional tool of ecology, direct observation, is severely limited for describing the structure of a microbial ecosystem. In addition, many bacteria function within communities (such as biofilms and suspended flocs) and, as a result, the critical reactions and flows characterizing the function of the microbial ecosystem often must be measured on scales too small for conventional chemical techniques.

Microbial ecology emerges as a new frontier by virtue of the availability of new *molecular tools*, described in the section on Scientific Tools, to answer fundamental ecological questions by linking genetic codes to function. Species inter-relationships are being investigated using a new generation of microsensors to probe chemical concentrations and gradients in microbial biofilms. When coupled with mathematical modeling of the chemical, microbiological, and transport processes, these new molecular and chemistry tools will help define the structure and function of microbial ecosystems. This combination of tools also is the key for designing strategies to overcome ecosystem dysfunctions and to better exploit microbial ecosystems for environmental restoration and protection.

Stressed ecosystems. Environmental engineers bring a unique perspective to microbial ecology because they constantly deal with stressed ecosystems. Three unique types of stress are input of toxicants, loading perturbations, and engineered stress.

The introduction of new, toxic chemicals into a system can severely stress its functioning. Obvious examples include industrial solvents, polynuclear aromatic hydrocarbons, and radionuclide heavy metals from the manufacture of nuclear weapons. In general, a toxicant affects the range of organisms very differently, depending on how well the organism takes up the toxicant and whether or not the organism has detoxification/resistance mechanisms. Some microorganisms benefit from transforming the contaminant if they can oxidize or reduce it to generate energy. While toxicant-induced stress clearly alters the structure of an ecosystem, the effects on function cannot yet be predicted. Using the rapidly expanding tools for studying ecosystems, especially microbial ecosystems, we can now begin to assess the dynamic impacts that toxicants have on structure and function. In many cases, we will be able to apply that knowledge to control ecosystem changes considered to be detrimental and to remove the stress, a process generally called bioremediation. The beneficial effects of bioremediation may be brought about by direct microbial transformation (i.e., biodegradation) or by an indirect alteration of the biogeochemical environment (e.g., immobilization of a heavy metal by microbially induced precipitation).

> ***“New molecular level tools in chemistry and biology should enable environmental engineers and scientists to understand environmental processes in ways never imaginable before.”***

The second type of stress is a loading perturbation for a material that is a normal part of the ecosystem web. An excellent example is CO_2, which is a natural end product of metabolism and the carbon-supplying nutrient for organisms active in photosynthesis and oxidation of inorganic electron donors, such as NH_3 and Fe^{2+}. The gradual rise in atmospheric CO_2 and global temperatures could favor some organisms (perhaps those that use CO_2 as a carbon source) and disfavor others, but other changes will occur in ways that we can hardly begin to predict. Because ecosystems contain a variety of major sources and sinks, understanding ecosystem response to planetary changes such as global warming is a critical need that requires an integrated and analytical approach.

The recent fish kills in North Carolina and in the Chesapeake Bay, attributable to *Pfiesteria piscicida*, appear to be another example of ecosystem disruption produced by a loading perturbation. In this case, the outbreak appears to be a result of increased levels of nutrients in the aquatic system. The frequency and extent of toxic outbreaks attributable to a number of different dinoflagellates and other microorganisms appears to be increasing worldwide and, therefore, is of concern. Many of these incidents are occurring in poorly flushed bays and lagoons subject to heavy surface runoff. The stress response involving *Pfiesteria* raises important new questions about microbial genetic change. How and why does a harmless amoeba transform itself into a lethal dinoflagellate within hours? Could environmental stress to the microbial ecology trigger such change? Stress-forced genetic change or accelerated evolution of microorganisms and microbial systems has been observed but is not well understood.

The final type of stress—engineered stress—is one employed constructively to expand or improve the performance of engineered systems, particularly those used for treatment of contaminated water, soils, and air. The idea is to create stress to select for microorganisms that carry out the transformations we desire. Controlling the specific growth rate, regulating the availability of electron donors and acceptors, and cycling the cells through a series of environmental changes are engineering stresses proven to be practically effective. Although the *Pfiesteria* example was a negative result from stress, genetic or evolutionary changes can have positive implications, e.g., the adaptation of selected bacterial strains to specific chemical substrates, thereby enhancing biodegradation. Although microbiological treatment systems were developed from a strictly empirical foundation beginning in the early part of the 20th century, our greatly expanded ability to understand and direct ecological structure and function is making microbiological treatment more effective for traditional treatment goals (e.g., removal of BOD from wastewater) and an essential tool for more contemporary challenges, such as nutrient removal from wastewaters, production of drinking water, and detoxification of industrial organic chemicals found in wastewaters, sediments, soils, the subsurface, and gases. Our rapidly expanding capabilities in microbial ecology may ultimately allow us to exploit engineered stress to create biotechnological processes to control greenhouse gases and minimize the environmental impacts of radionuclides improperly disposed of after the manufacture of nuclear weapons.

3. ANALYTICAL TOOLS IN MOLECULAR SCIENCES

Molecular sciences hold the key to major advances in environmental engineering for the three central questions that underlie the analysis and design of natural and constructed systems: *i*) What are the *chemical species* actually present in waters, in the atmosphere, and at environmental interfaces; where do such chemical species reside; with what sort of biogeochemical environment are they associated; and how do these factors impact the availability of such chemical species to the environmental and organisms? *ii*) What are the chemical *reactions* and chemical and biological *interactions*, their rates and pathways, that control chemical fate in environmental systems; *iii*) How is the *genetic information* that codes for the behavior of organisms transferred and regulated in the natural environment? Our abilities to quantitatively describe the fate and transport of environmental chemicals; exposure, bioavailability and toxicity; concentrations of waterborne pathogenic organisms; and the microbial ecology of complex water and soil environments can be expected to improve dramatically during the next decade. New molecular level tools in chemistry and biology should enable environmental engineers and scientists to understand environmental processes in ways never imaginable before. For example, a great number of new molecular biological tools—the results of basic research in molecular biology—are becoming available and completely change how environmental engineers view and monitor the many different biological organisms and processes with which they work. Applications of molecular biology to environmental engineering to date have been very limited, but an explosion of activity is beginning. This is one of the newest and most important areas for concentration of basic and applied research in environmental engineering and science over the next decade.

Molecular biology tools. In biotechnology, genetic engineering receives the greatest press and causes the largest fear of biotechnology by the public. Yet, the potential opportunities here are probably over-rated and probably are not where the greatest opportunities exist for environmental engineering. Instead, we need to know how organisms with abilities of interest survive in natural and engineered environments and, just as importantly, how the genetic information that codes for their metabolic activities is controlled and moves among species. These issues are of para-

Table 1. Tools from Molecular Biology

Oligonucleotide Probes. An oligonucleotide probe is a small piece of DNA that is designed and synthesized so that its sequence of 15 to 25 nucleotide bases (C, T, G, and A) is exactly and uniquely complementary to a sequence of bases in target DNA or RNA. When the match is perfect and under the appropriate assay conditions, the probe chemically binds to the target DNA or RNA, a phenomenon called hybridization. The bound probe is then detected through a radioactive or fluorescent molecule (its marker) that was attached to it during its synthesis. Oligonucleotide probes can give us several different types of information about cells, depending on what type of DNA or RNA is targeted:

Target	Information
Ribosomal RNA	The phylogenetic identity of the cell
DNA	The presence of a gene of interest, or the cell's genetic potential
Messenger RNA	The expression of a gene, or the realization of the genetic potential

Fluorescent *In Situ* Hybridization (FISH). In FISH, an oligonucleotide probe is labeled with a fluorescent molecule, and the hybridization takes place with cells that remain physically intact. The results of hybridization are viewed with a fluorescence microscope. The physical relationships among different microbial types can be observed with FISH.

Polymerase Chain Reaction (PCR). PCR uses a special enzyme to make millions of copies of a particular piece of DNA. This amplification process is useful when we want to identify or study DNA that is present in limited quantities. PCR requires a primer, which is an oligonucleotide that tells the PCR enzyme where to start copying.

Denaturing Gradient Gel Electrophoresis (DGGE). In DGGE, small DNA fragments (usually 200-700 base pairs) are electrophoresed through a gel under gradually increasing denaturing conditions (usually increasing formamide/urea concentration), causing them to partially denature (melt) and reducing their mobility in the gel. Because different base pair compositions and sequences have different melting points, it is possible to detect small differences in DNA, allowing identification of DNA and/or providing a DNA "fingerprint" for a complex microbial community.

Reporter Genes. A reporter gene is inserted into the DNA of a cell in such a way that the reporter gene is expressed (i.e., its enzyme is produced) whenever the genes around it are being expressed. This is a way to use an easy-to-detect measurement, such as light generation, to detect if the enzymes for hard-to-detect reactions are being produced.

mount importance, because all the microbial communities and consortia of interest to environmental engineers are ecologically complex.

Fortunately, molecular biology already provides the tools to directly interrogate the microorganisms' genetic makeup, i.e., its DNA and RNA. We are able to identify microorganisms and their genes by hybridization with oligonucleotide probes (Table 1). By using the polymerase chain reaction, (PCR), we can amplify the genetic material of organisms present as only a tiny fraction of the community. Several genetically based methods are being developed to fingerprint complex communities, even when we have no information on the genetic composition of its member. Developing these new molecular tools and learning how to use them to understand microbial communities are research issues being pursued now with high levels of enthusiasm and success.

> ***"...exciting new areas of study are opened up by the integration of biological and chemical molecular tools."***

Environmental engineers have perhaps made their greatest contribution in the control of water borne diseases. Yet it is evident that the problem is not completely solved. In fact, new water-related diseases continue to be identified. Examples over the last few decades are causative agents of infectious hepatitis, Legionella, Giardia lamblia, and Cryptosporidium. Pathogenic strains of E. coli have emerged widely in the United States and possibly could be transmitted through water. Because wastewater reuse is increasing, virus and microbial pathogen presence is of great concern.

One difficulty in the control of pathogens is the lack of quick and easy methods to monitor their presence. By amplifying selected genetic information through PCR, we can detect the presence of any species of interest to exceedingly low numbers. Although PCR offers great promise, environmental engineers and scientists must play key roles in overcoming major stumbling blocks: (i) a need to greatly improve sensitivity; (ii) a need for development of probes or procedures for the great number of possible pathogens in water; (iii) difficulties presented by samples with high concentrations of nonpathogenic strains, particulate matter, and other interfering materials; and (iv) the current lack of simple procedures to allow analyses to be applied inexpensively and on a routine basis at water laboratories.

Treatment of wastewaters with microbiological processes dates to the beginning of the 20th century and is an outstanding example of applying principles of microbial ecology to achieve a remarkable degree of environmental protection. Yet, despite the success of such microbial treatment systems, they often have unsatisfactory reliability. For seemingly unknowable reasons, performance deteriorates or never achieves design goals. Our inability to monitor the microbial communities that carry out the desired reactions is a main reason why process distress seems to occur suddenly and without warning. An example of a problem that has long plagued environmental engineers is the sudden growth of filamentous organisms in activated sludge systems. We need the ability to monitor the growth of different troublesome filamentous species so that the nature of the problem can be well understood and its control can be taken long before a serious problem develops. Another example is biological phosphorus removal, a process that is being widely applied, but knowledge of the microorganisms that make it work is far from complete. The enzymes and genes involved in polyphosphate formation and decomposition are known, hence, probes to monitor and control this process could become available. Finally, methane fermentation is a widely used and inexpensive energy-saving process for treatment of municipal sludges, but has not yet been applied widely for industrial wastes because of a lack of confidence in its reliability. Molecular tools that allow one to readily sort out the important ecological interactions and to easily monitor the activities of key organisms, which are slow growers, would be of great benefit. For any of these applications, as well as many others, environmental engineers and scientists need to develop molecular tools into useful sensors for monitoring and controlling the process.

Chemical tools. The chemistry of environmental systems usually occurs in complex mixtures and is controlled by reactions at interfaces. An unprecedented array of chemical tools is available to acquire fundamental understanding of molecular interactions in the complex mixtures and at the mineral, organic, and biological interfaces that charcterize environmetal systems (Table 2). Yet many of these techniques and associated methods of data interpretation were developed to study well defined systems (e.g., single crystals) under ideal conditions (ultra-high vacuum). Application of these tools to environmental samples is very challenging due to their amorphous, complex, and multiphase nature, and to the fact that meaningful results necessitate that analysis be made under in situ conditions. To provide insight into environmental phenomena and systems, the environmental engineer and scientist must determine how to adapt, modify, or refine a particular analytical technique to an environmental application, devise a characterization strategy that combines multiple techniques to fully characterize the many components of environmental samples, and develop alternative ways of interpreting and quantifying the data generated by these sophisticated methods.

Use of these novel chemical tools promises to produce dramatic advancements in the understanding of many of our more difficult and persistent environmental problems. For instance, it has been shown that mechanistic descriptions of chemical behavior in laboratory systems may differ drastically from observed behavior in natural systems, indicating the need for analytical tools to determine speciation and probe reactions under real conditions. A very powerful suite of in situ methods that detail atomic structure and composition of materials in any matrix (e.g., crystalline and non-crystalline surfaces, adsorbates on surfaces, compounds in solution) is emerging with the new generation of synchrotron radiation sources. Chemical imaging techniques such as these can be coupled with time-resolved spectroscopic methods to follow chemical reactions in real time. In general, a combination of molecular tools is required to characterize comprehensively the important structural and functional relationships that explain environmental chemical fate. The novel aspect of this strategy may be in the tools themselves, or in their combination. Furthermore, since many critical environmental processes are influenced by biological processes, exciting new areas of study are opened up by the integration of biological and chemical molecular tools.

The pace at which compelling new molecular techniques are developed is extremely rapid and is certain to provide unparalleled mechanistic insights into complex systems. Application of the new generation of molecular tools to environmental problems will probably not be limited by the availability of methodologies, but rather by the those individuals capable of devising protocols for and interpreting the results of these sophisticated techniques. Serious consideration must be given to establishing educational and

Table 2. Tools from Molecular Chemistry

Microscopy Techniques. The structure and composition of atomic scale surface features and phases can be determined by High Resolution Electron Microscopy (HREM). Scanning electron microscopes (SEM) provide details about surface morphology, size/shape analysis, local chemistry, and crystallography/texture. Analytical transmission electron microscopic (TEM) techniques provide surface characterization at scales less than nanometers. TEM applications include nanodiffraction/convergent beam electron diffraction (CBED) to probe the crystal structure and defects of surfaces; and energy dispersive spectrometry (EDS) and electron energy loss spectrometry (EELS) to determine local and electronic structure. Some instrumental systems combine these capabilities with the surface analyses provided by X-ray photoelectron and Auger electron spectrometers. These systems typically require ultra-high vacuum (UHV) conditions and model surfaces. Atomic force microscopy (direct contact; tapping mode; electric field; and lateral, shear, and magnetic force techniques) can be used to directly measure the topography and composition of a surface at atomic scales by monitoring the position of a tip relative to the surface.

Synchrotron Radiation Sources. A suite of in situ methods that can detail atomic structure and composition of materials in any matrix (e.g., crystalline and non-crystalline surfaces, adsorbates on surfaces, compounds in solution) is emerging with a new generation of synchrotron radiation sources. These include X-ray Absorption Spectroscopy (XAS), X-ray Absorption Fine Structure (XAFS), X-ray Absorption Near-Edge Structure (XANES), X-ray Standing Wave (XSW), and Grazing-Incidence X-ray Diffraction (GIXD). X-ray beams of high brilliance allow investigations of weakly scattering, dilute, surface and/or rapidly changing systems that are common in environmental samples. These techniques complement structural characterization obtained using HREM. Because of the intrinsic nature of polymorphic environmental samples, however, detectors of increasing specificity and sensitivity are needed.

Spectroscopy techniques. Recent advances in spectroscopy, such as surface plasmon resonance spectroscopy (SPRS), time-of-flight-secondary ion mass spectrometry (TOF-SIMS), laser pyrolysis-gas chromatography-mass spectrometry (LP-GC/MS), and surface, UV, and/or time-resolved resonance Raman spectroscopy, have produced powerful new methods for probing molecular interactions between individual chemical species and organic/mineral surfaces. Larger magnets and increasing resolution have made it possible to use NMR to probe complex chemical-water-soil systems. Recent research using ^{13}C NMR, pyrolysis-GC-MS, and stable isotope GC-MS to quantitatively and qualitatively fingerprint macromolecular structure and ^{129}Xe to examine microporous domains of natural organic matter (NOM) have significantly improved our understanding of NOM chemical characteristics. In situ techniques, such as transient infrared microspectroscopy, can be used to follow transformations on surfaces obviating the need to infer results based on observations in homogeneous systems.

research training programs at the interface of basic science and environmental engineering in order to create a new generation of "bridging scholars and researchers" and the next generation of environmental scientists.

4. PROCESS TECHNOLOGY

The creation, design, and operation of process technologies have historically been central to environmental engineering. Although existing processes are effective, virtually every system could be more efficiently designed to improve reliability and cost-effectiveness. For that reason alone, process technologies must continue to be a subject of ongoing research. However, several key process areas can be considered frontiers emerging through the advent of new research tools, by making possible substantial advances in existing process technologies, and from addressing challenges posed by the enormous and severe environmental problems from the non-industrialized nations. The topics most likely to be new frontiers in process technologies are reactive separation systems and targeted chemical destruction; new membrane technologies; process engineering of subsurface systems; development of more reliable treatment systems; and process technologies for non-industrialized nations.

Reactive separation systems/targeted chemical destruction. Advances in designing specific reactions at the molecular scale may make it possible to begin to develop reactors that can remove and, ideally, degrade specific compounds in chemically complex mixtures. Many present treatment technologies are aimed at removing types of materials (such as particles) or broad classes of chemicals (such as volatile organics or specific heavy metals) when only one pollutant may be present. In many instances this broad control approach is effective, but greater pollutant specificity could allow for avoiding the removal of large amounts of non-target (non-toxic) materials. For example, why remove all metal cations in water if a resin could be devised to selectively remove a single ion? Advantages include extending the life of the resin and perhaps producing a recoverable side product during resin regeneration. To accomplish targeted organic chemical treatment using membranes, either new membrane materials must be developed or catalysts or other materials that can be embedded within the membranes or packed beds must be devised. Reactive membrane materials could be designed to react with chemicals so that both the filtrate and membrane brine solutions would no longer contain the pollutant and could be safely disposed. Bonding microbial enzymes or other materials into activated carbon, for example, to produce catalytic reactors could extend the life of the carbon or produce self-regeneration.

Perhaps the key to the development of such systems will be to adapt scientific advances made in other fields to the environment of waters containing large amounts of natural organic matter. In this regard, techniques used by chemists (such as combinatorial chemistry and computational molecular modeling) could be adapted to environmentally relevant conditions of air or water streams for identifying reactions that will carry out specific molecule destruction. The relatively recent use of zero-valent metals to treat waters contaminated with chlorinated aliphatics provides a good example within this context. For many years, it was known by physical chemists that such reactions could be accomplished, but such technologies had never been adapted for the passive treatment of groundwater in iron walls until this property of zero-valent metals was recently "rediscovered" by hydrologists.

Engineering subsurface systems. Limited water sources and increasing water needs due to population growth have depleted groundwater resources, especially in Florida and the arid western and southwestern regions of the United States. Recharge is becoming a common practice in these states to replenish aquifers, but use of the groundwater aquifer for storage alone does not fully utilize the potential of this system. In order to maximize the use of limited water supplies, it will be necessary to make a transition from using the aquifer for storage to using the subsurface environment as an engineered reactor. A soil-aquifer system is intrinsically capable of treating wastewater to produce potable water, but these systems will need to be engineered on large scales to be successfully used for this purpose. Some progress is being made in designing systems for subsurface treatment. Several cities in the Southwest are starting to conduct pilot scale wastewater treatment in soil aquifer systems. The injection of the water into a non-controlled environment is not without risk, however, because chemicals already in the ground can contaminate the recharged water. In Tucson Arizona, for example, large portions of the aquifer are contaminated with trichloroethylene (TCE).

Environmental engineers have been studying methods to manipulate above-ground engineered systems (through control of cell recycle or setting hydraulic detention times of tanks or ponds) for decades, but at present, the biological and chemical processes that occur in the complex subsurface environment have not been examined from such a perspective. We need to study the microbiological and chemical factors that are important in cleaning water in a soil environment in order to help direct these processes for the purpose of using aquifers as water treatment systems. While it is possible to envision engineering such wastewater-to-water treatment systems (not unlike that accomplished in above ground systems) the engineering methods necessary to accomplish this are not yet known.

The development of subsurface systems as whole aquifer reactors must be accompanied by models of hydraulic flow and flow control. In order to accomplish flow control we will need to invent new ways to hydraulically isolate certain zones, such as landfills, Brownfields and other contaminated zones, from the part of the aquifer used as the engineered system. In this way, the merging of hydraulic, chemical and microbiological controls in a soil-aquifer system could lead to a reliably engineered system for essentially complete water reuse.

Membrane technologies. Advances in membrane technologies will continue to have profound impacts on our approach to solving water and wastewater treatment problems, ultimately allowing complete conversion of wastewater to potable water. The potential for membrane technologies will initially occur in a variety of settings, including as a replacement for granular media filtration in the treatment of potable and reclaimed waters, achieving levels of particulate removal that have not been possible in the past; as a pretreatment for reverse osmosis (RO), making RO feasible in new situations; as a part of novel sensor technologies that can increase the sensitivity of measurements; and in the removal (via size exclusion) of pathogenic microorganisms from water sources. These engineering applications will be made possible through the development and application of new thin film composite RO membranes that allow higher performance at lower cost than in the past.

> ***"Membrane pretreatment of secondary-treated wastewater effluents, by microfiltration or ultrafiltration, will permit treatment by RO for long periods of operation..."***

Improvements in membrane materials will permit the use of reverse osmosis (RO) for new applications, as is already being shown by recent wastewater treatment projects. Membrane pretreatment of secondary-treated wastewater effluents, by microfiltration or ultrafiltration, will permit treatment by RO for long periods of operation (6 months) due to little or no fouling of the RO membranes. Some production-scale thin film composite (TFC) membranes, for example, have demonstrated sustained rejection levels above 90%, achieving levels of dissolved organic carbon (DOC) less than 0.2 mg/L (versus 1 mg/L with current technologies), and do not suffer from a classic problem with cellulosic membranes of hydrolysis of the membrane itself. Reduced fouling and increased efficiencies will continue to allow more cost-effective implementation of RO processes in many applications, such as treatment of seawater and problem surface waters.

Developments in membrane technologies also show promise to improve our ability to monitor and control the performance of environmental processes. Membrane probes that employ new technologies can improve selectivity and sensitivity for chemical measurements. A recently developed membrane, for example, has improved the sensitivity for measuring divalent ions by nearly six orders-of-magnitude. The integration of membrane probe technology, and molecular probes being developed in molecular biology, show great promise as an environmental frontier.

Membranes are an area where environmental engineers must do research because the polymer chemists responsible for developing these technologies may not fully appreciate the context of their environmental applications and the dynamics of the environmental systems that limit the performance of the membranes they design. For example, when the first TFC membranes were not successful in treating secondary effluents, environmental engineers identified the cause: a rough membrane surface that promoted the attachment of microbiological consortia. This led to the design of new, smoother membranes, that have been much more successful. Using this same information, environmental engineers demonstrated that MF and UF pretreatment could play an import role in preparing secondary effluent for RO treatment.

Development of more reliable treatment systems. One of the long-standing challenges to environmental engineers is ensuring reliability of environmental control processes. Inadequate reliability stems from the fact that inputs are uncertain and frequently change dramatically and without warning. The traditional and empirically based way to buffer process performance against uncertainty has been to use large reactor volumes and conservative design criteria. Compact and highly cost-effective designs for pollution-control processes cannot rely on the traditional approaches. Instead, modern process-control techniques must be applied to the environmental realm. Promising approaches involve greatly enhanced on-line monitoring of process streams and computer-based control strategies that integrate mechanistic understanding of process phenomena with probabilistic-based data filters.

Process technologies for the non-industrialized world. In order to address environmental health and pollution problems on a global scale, the needs of non-industrialized nations must be more fully considered relative to economic factors related to process technologies. Although a large menu of processes is available in the industrialized nations for potable water and treatment of wastewater, many of these technologies are inappropriate for solving the short- and long-range health and exposure problems of the non-industrialized world. Basic human health problems of the non-industrialized countries, particularly in the rapidly expanding mega-cities, is high disease incidence through the exposure of the populace to pathogenic organisms caused by inadequate treatment and inactivation of organisms in potable water and wastewater. There are severe limitations to solving the human health problems of these nations based on their limited economic resources. Therefore, an important issue is, "Should the non-industrialized world follow the technological development model for wastewater treatment of the industrialized world?" Also, "Is there an alternative sustainable sanitation process approach?" Some experts conclude that the urban wastewater infrastructure of the industrialized world is not sustainable or transferable.

"Should the non-industrialized world follow the technological development model for wastewater treatment of the industrialized world?"

Mexico City is a good example of some of these issues. Greater Mexico City, with a population of 21 million, has no natural source of fresh water or drainage. Raw sewage is used to irrigate vast agricultural areas with a high prevalence of pediatric and parasitic disease among the workers. The pressing need is for a minimum level of treatment that will protect the health of the workers while not unnecessarily removing organics and nutrients in the effluent. To create effective engineering solutions to this problem, we must proceed in a way that is compatible with local conditions and constraints—technical, economic, and cultural—following the path of transferring appropriate technology and following through with technical support as long as needed for the solutions to become established.

The use of existing technology in non-industrialized nations for potable water treatment by coagulation, filtration, and pathogen inactivation may not be initially affordable. Alternative interim steps should focus on protection of existing sources from contamination by inadequately treated wastewater or the development of alternative sources. For example, instead of drawing water directly from rivers polluted by upstream discharges, it may be better to develop wells adjacent to the river by taking advantage of the natural filtration capacity of the groundwater. This approach, known as bank filtration, has demonstrated its utility in protecting against contaminated water sources in the industrialized countries. Field research will be needed to demonstrate the feasibility of this approach. Similarly, interim technologies must be devised for wastewater treatment. For example, physical-chemical treatment of municipal wastewater, using only small doses of metal salts and polymers, can provide a low-cost and efficient single-stage process with high removal of suspended solids and organics that allows subsequent pathogen inactivation. Biological treatment stages, when added later, are smaller and more efficient because of the reduced organic loading of the first stage. Research and development is needed to make the low dosage physical-chemical treatment more widely acceptable.

In all cases, proper sanitation is needed to prevent the spread of communicable diseases. The responsibilities of controlling rapid disease dissemination on a global scale will fall to the technologically advanced countries to share in the burden of assuring safe water supplies and instituting basic sanitation protections in poor countries that lack the technical and financial resources to help themselves. Environmental engineers can contribute by helping to establish high priority research directed towards characterizing disease agents, elucidating paths of infection, and developing protective technologies within our realm of expertise, such as the means for affordable, efficacious disinfection without harmful environmental side effects.

Conclusions

Environmental Engineers are increasingly expanding their concerns to larger and more global-scale environmental issues. In order to protect whole ecosystems, produce new and sustainable technologies, prevent the outbreak of diseases across global scales, and protect the environment from damage due to the production of new chemicals, the nature and functioning of these large and complex systems must be better understood. The analysis of these systems can be stimulated by a host of new biological and chemical tools, but in order to make substantial advances in pollution prevention and treatment, there must be greater interactions between applied and social scientists, and environmental and other engineers. Working together, these groups may forge new approaches and open new frontiers in advancing human efforts in ways that are compatible with our environment.

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