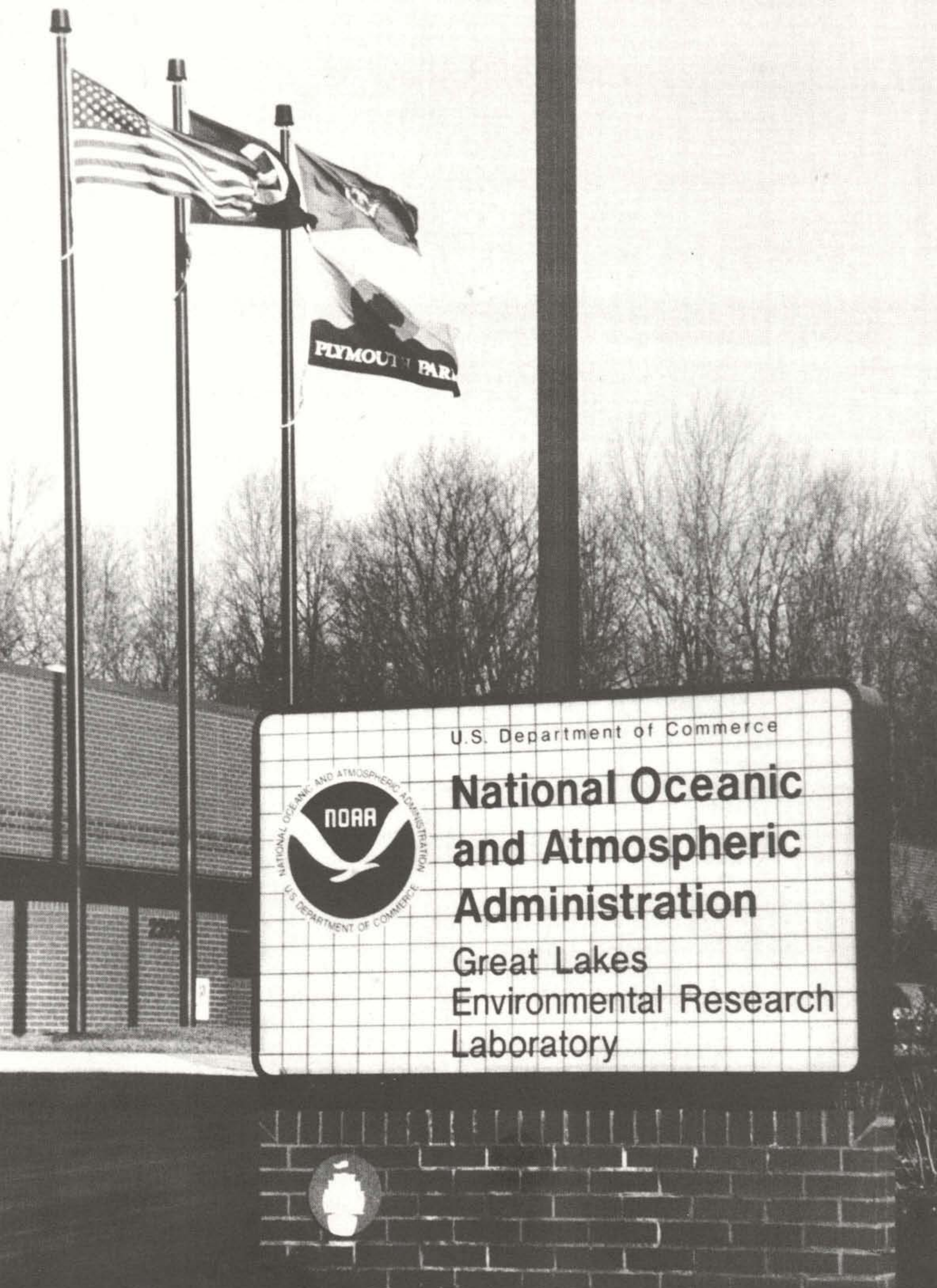

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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
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Great Lakes
Environmental Research
Laboratory

GREAT LAKES ENVIRONMENTAL RESEARCH LABORATORY ANNUAL REPORT FY 86 – FY 87

DIRECTORS

Eugene J. Aubert
Retired, June 1986

Frank H. Quinn
(Acting), June – October 1986

Alfred M. Beeton
Appointed, November 1986

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Office of Oceanic and Atmospheric Research
Environmental Research Laboratories
Great Lakes Environmental Research Laboratory
2205 Commonwealth Blvd.
Ann Arbor, MI 48105–1593

NOTICE

Front Cover: *View of GLERL's new research facility*

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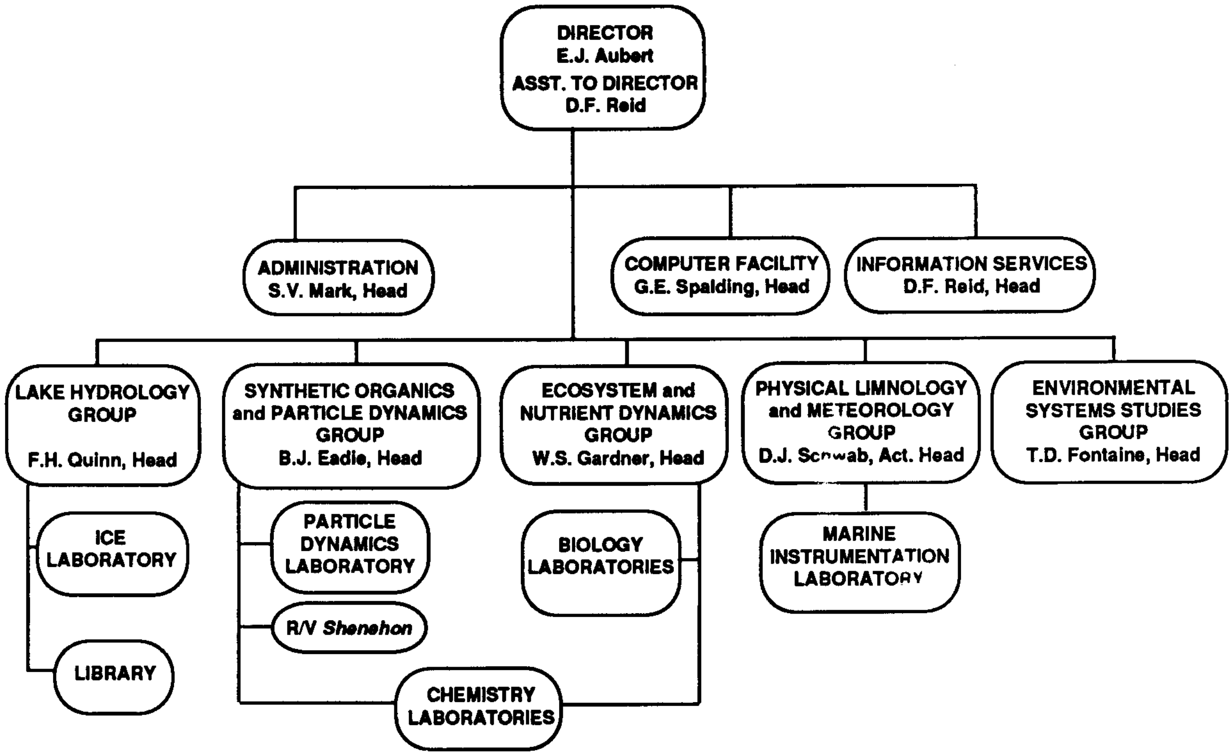
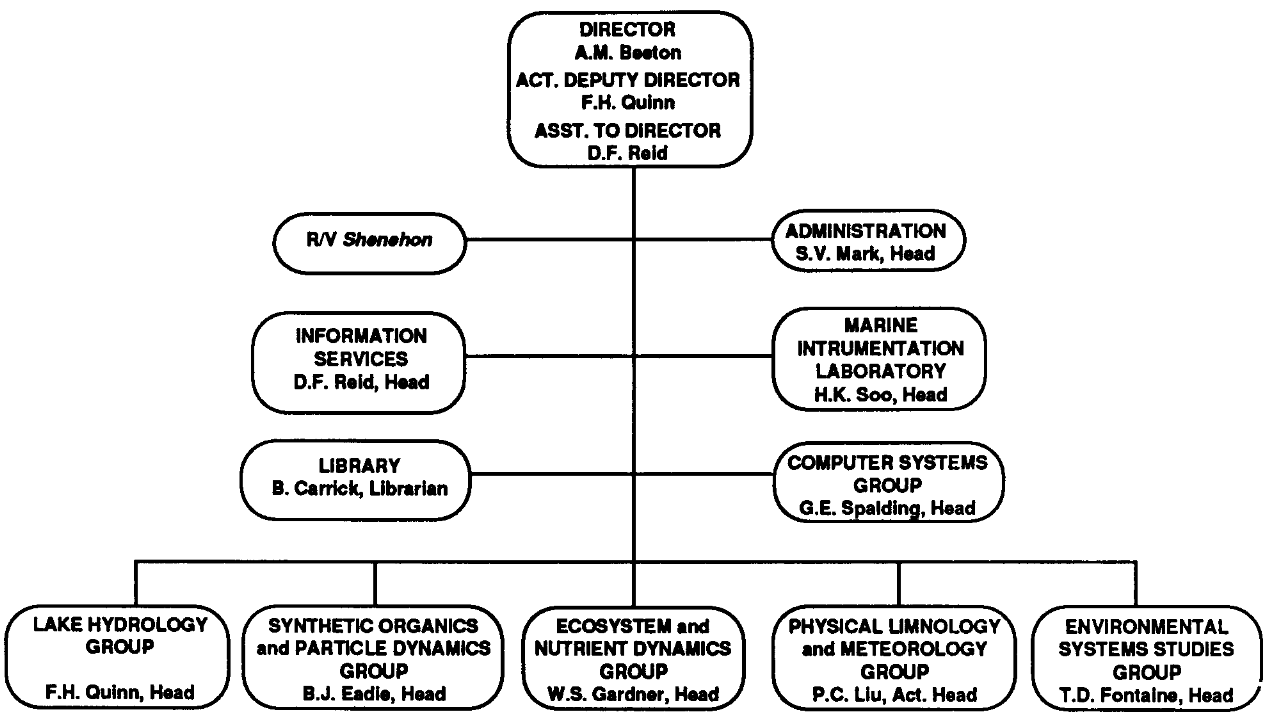


FY 87



INTRODUCTION

GLERL's New Facility – FY 87

With most of the U.S. population residing near the coasts, the ability of the adjacent bodies of water to accommodate wastes, and the ability of people to use those water bodies and the surrounding shorelines safely and effectively for housing, transportation, and recreation, must be given increased attention. The Great Lakes are the largest reservoir of fresh surface water in the United States, but are also sinks for domestic and industrial wastes. Major cities, including Buffalo, Cleveland, Chicago, Detroit, Milwaukee, Rochester, and Toledo are located along the shoreline and more than 30 million people in the United States take their drinking water from the lakes.

The Great Lakes Environmental Research Laboratory (GLERL) was established by the National Oceanic and Atmospheric Administration (NOAA, U.S. Department of Commerce) on April 25, 1974, to provide a focus for NOAA's environmental research on the Great Lakes. GLERL was formed by combining the staff of the International Field Year for the Great Lakes Project Office (IFYGL, Rockville, Maryland) with the Limnology and Computer Divisions of NOAA's Lake Survey Center (Detroit, Michigan). The Laboratory was opened in Ann Arbor, Michigan in August, 1974.

This Combined Annual Report provides a summary of significant GLERL events, accomplishments, and activities during fiscal years 1986 and 1987 (October 1, 1985–September 30, 1987).

GLERL conducts research on significant environmental processes and problems in the Great Lakes region. Research is carried out by five groups with expertise ranging from aquatic chemistry and biology to physics, hydrology, and computer modeling. GLERL's projects are interdisciplinary and are integrated as appropriate for maximal utilization of operational resources in support of NOAA's Ocean and Great Lakes Prediction Research Program. GLERL is also taking part in the Upper Great Lakes Connecting Channels Study (UGLCCS), a multi-agency joint United States-Canada study of water quality and ecosystem dynamics in Lake St. Clair and the St. Clair and Detroit Rivers.

The products of GLERL research are used by governmental, educational, and private organizations to facilitate planning and improve decision making in relation to water resources management and environmental services in coastal and estuarine waters, especially the Great Lakes. GLERL's products are disseminated as technical publications, brochures, posters, and by presentations at scientific and public meetings. During FY 86 and FY 87, over 80 scientific articles, reports, and books with GLERL authors were published, and 165 talks were presented by GLERL staff at scientific or public meetings.

GLERL in Transition

FY 86 and FY 87 were years of significant change at GLERL.

GLERL's first Director, Dr. Eugene J. Aubert, retired in June, 1986 after more than 30 years of federal service. Prior to being selected as the first Director of GLERL, Dr. Aubert was Director of NOAA's IFYGL Office in the early 70s and was strongly influential in the decision to form GLERL and locate it in Ann Arbor, Michigan. Upon Dr. Aubert's retirement, Dr. Frank H. Quinn, Head of GLERL's Lake Hydrology Group, was appointed Acting Director.

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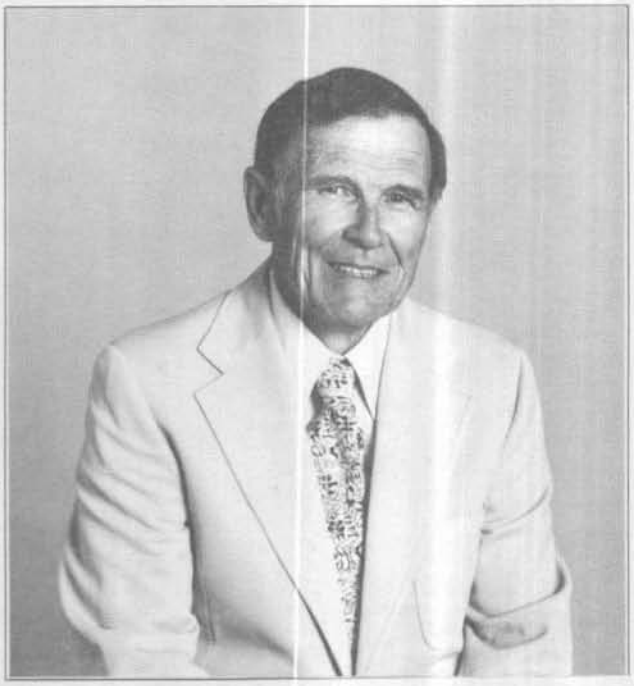
In November, 1986, Dr. Alfred M. Beeton became the second Director of GLERL. Dr. Beeton came to GLERL from The University of Michigan, where he was the Director of the Michigan Sea Grant Program, Director of the Great Lakes and Marine Waters Center, and the Director of the Great Lakes Research Division, as well as a Professor in the Department of Atmospheric and Marine Sciences and Professor in the School of Natural Resources.



Dr. Eugene Aubert, the first Director of GLERL, retired in June of 1986.

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In early FY 86, construction began on a new, modern research and office facility for GLERL, which moved into the completed facility in January, 1987. The new facility, located in Ann Arbor, is leased by the government and provides over 25,000 sq. ft. of usable space, including over 4,000 sq. ft. of research laboratories, an 1,100 sq. ft. computer facility, and a 3,300 sq. ft. warehouse and field staging area.

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In April, 1987 a thorough review of GLERL's recent research projects and accomplishments was conducted in concert with our parent NOAA organization, the Environmental Research Laboratories (ERL). This marked the beginning of a long and deliberate process of programmatic and organizational self-examination and exploration of new initiatives to bring the Laboratory through the 1990s and into the new century. This process will continue into FY 88 and FY 89.

Organization

GLERL's mission statement is as follows:

Conducts integrated, interdisciplinary environmental research in support of resource management and environmental services in coastal and estuarine waters with a special emphasis on the Great Lakes. The Laboratory performs field, analytical, and laboratory investigations to improve understanding and prediction of coastal and estuarine processes and interdependences between the atmosphere, land, water, biota, and sediments. It places special emphasis on a systems approach to problem-oriented environmental research in order to develop environmental service tools. It provides assistance to resource managers and others in obtaining and applying the information and services developed by the Laboratory.

GLERL's research addresses major Great Lakes and national environmental issues, including water quality (toxic chemicals, nutrient overenrichment), water quantity (lake levels, water supply, diversions, consumptive use, management), and physical hazards (waves, storm surges, flooding, and ice). GLERL researchers often engage in team efforts with scientists at universities or with other agencies in the U.S. and Canada. GLERL's products are information and improved technologies and methods. These products are disseminated through a variety of means, including refereed scientific journals, NOAA Technical Series documents, posters; presentations at local, national, and international meetings and public gatherings; and by direct interactions with users. The latter includes national and local governments; international, federal, state, and private agencies; industry, academia, and the public.

GLERL is one of ten laboratories that report to the Director, ERL (Boulder, Colorado), which, in turn, is part of NOAA's Office of Oceanic and Atmospheric Research located in Rockville, Maryland. GLERL is organized into five scientific groups that conduct both basic and applied research on major environmental problems and issues; plus a number of support units that provide technical, operational, and administrative assistance to the scientific staff:

Lake Hydrology Group: investigates the hydrologic and hydraulic processes that affect the water supply to, and amount of water in, the Great Lakes; they provide improved methods of forecasting lake levels and simulating river flows, and conduct research to characterize and increase our understanding of the seasonal ice and snow cover in the Great Lakes Basin;

Synthetic Organics and Particle Dynamics Group: studies the processes that control the movement and interactions of trace contaminants in the Great Lakes and coastal marine ecosystems; their research increases our understanding of, and leads to an improved ability to predict the behavior, fate, and effects of contaminants in the natural environment;

Ecosystems and Nutrient Dynamics Group: studies the ecological systems of the Great Lakes and coastal marine environments, focusing on factors and processes that affect ecological succession and control the flow of nutrients and biochemical energy (and therefore, toxics) through the food web; they provide and improve the information used by resource managers for making decisions that impact both water quality and living resources;

Physical Limnology and Meteorology Group: studies the physical variables that characterize a lake environment and the manner in which those characteristics change with external forces, such as wind, heat exchange, and connecting channel flows; the results of their research help alleviate or reduce the impact of physical hazards and contaminant transport on both the environment and the people who use it;

Environmental Systems Studies Group: develops models of environmental systems based on the premise that cost-effective management of our natural resources requires that we consider the competing human, economic, regulatory, and ecological factors; they use these models to evaluate and compare the probable costs vs. benefits of resource management plans, and to identify alternative plans that optimize the balance between competing and conflicting demands on the marine environment.

These scientific groups are supported by:

- a Marine Instrumentation Laboratory, where instruments and systems for hands-on and automated field collection of data are designed, built, and maintained;

- a Computer Systems Group that maintains GLERL's in-house computer network, and the interface with off-site mainframe and super computers, and provides related user support to the GLERL staff and others;

- an Information Services Group that is responsible for providing editorial and publications support to the GLERL staff, distributing GLERL publications, and responding to related information requests;

- a Library that maintains a research collection tailored to GLERL staff needs and which offers special retrieval services for materials not in the existing holdings;

- the R/V *SHENEHON*, GLERL's research vessel and the primary platform used by GLERL staff for field operations on the lakes;

- and an Administrative Office that provides personnel, budget, purchasing, and facility information and management.

Research Program

GLERL's multidisciplinary research program includes both basic and applied studies and combines experimental, theoretical, and empirical approaches with field, analytical, and laboratory investigations in support of the Ocean and Great Lakes Prediction Research Program of NOAA. It addresses (1) the need for new and improved simulation and prediction models of ecosystem structure and function, and of the effects of stresses and proposed remedial options, and (2) the need to assess other options while taking system dynamics and dimensions into account. Two elements of the Ocean and Great Lakes Prediction Research Program provide the focus for GLERL research: Marine Ecosystems Assessment, and Marine Hazards and Lake Hydrology.

Another major program supported by GLERL during FY 86 and FY 87 is the Upper Great Lakes Connecting Channels Study, an international (United States–Canada) and interagency multi-year study of water quality and ecosystem dynamics in the upper Great Lakes connecting channels. The lead U.S. agency for this study is the Environmental Protection Agency (EPA), but GLERL scientists have significant roles in both the management of the project and the research conducted for it. GLERL support for this project is partially funded by EPA: the rest is provided under both the Marine Ecosystems Assessment and the Marine Hazards and Lake Hydrology elements of the NOAA Program.

RESEARCH HIGHLIGHTS

Marine Ecosystem Assessment

■ A new study was initiated in Lake Michigan to investigate whether phase distribution, after resuspension, is kinetically controlled or can be modeled more simply as an equilibrium process.

■ Extensive resuspension of contaminated sediments was found in all of the lakes. Calculations indicate that sediment recycling via resuspension is the major process controlling the long-term concentration of organic contaminants in the lakes.

■ A comprehensive synoptic data base of particle fluxes in all five Great Lakes has been made possible by intercalibrating U.S. and Canadian sediment traps.

■ Experimental work on the environmental factors that affect the toxicokinetics of xenobiotics in *Pontoporeia hoyi* was completed. Analysis of the data indicates that organism mass is the most important physiological variable and temperature is the most important environmental variable for this organism.

■ Radiotracer experiments were conducted to study the effects of contaminant concentration in sediments on the bioaccumulation of these contaminants by benthic organisms: when a mixture of chlorinated hydrocarbons was added to sediments, toxicity and mortality were produced at even the lowest dose employed, which was within the range of concentrations already measured in Great Lakes sediments.

■ A procedure (gamma scan) was developed and tested to detect the initiation of toxicity to benthic organisms by measuring the rate of sediment reworking in a test cell under increasing concentrations of a particular toxic contaminant. The spread and movement of a thin layer of radioisotope-spiked sediment in laboratory test cells was monitored. The movement of the spiked material was related to the rate of bioturbation by selected organisms placed in each cell. The bioturbation rate is a reflection of the health of the animal and thus, can be a sensitive indicator of the onset of toxicity.

■ A long-term total-phosphorus model for Lake Michigan was completed.

■ A model that simulates Lake Michigan's summer pelagic food web (phosphorus, phytoplankton, zooplankton, and planktivorous fish) was developed to evaluate the relative importance of nutrient loading, competition, and predation in controlling the seasonal dynamics of phytoplankton in offshore Lake Michigan.

■ Results of GLERL's Lake Michigan Ecosystem Experiment show that the ecosystem has been altered dramatically during the last decade. Summer zooplankton dominance changed from calanoid copepods (*Diaptomus*) to cladocerans (*Daphnia*) and filamentous blue-green algae were largely replaced by phytoflagellates. This occurred concurrently with reduced phosphorus load, phosphorus concentration, and abundance of alewife, the dominant zooplanktivore, thus the summer phytoplankton populations of the 1980s are distinctly different from those in the 1970s.

■ Model simulations to evaluate the influence of gradients of both phosphorus load and alewife abundance on predation-competition interactions indicate that summer plankton composition and water clarity in Lake Michigan are controlled largely by predation, and thus top-of-the-food-web management practices can cascade down to affect even water quality.

■ Experiments confirmed that although bacterial growth rates appear to be controlled by the amount of labile organic substrate available, grazing is a major factor in controlling bacterial abundance.

■ Picoplankton (< 3 microns) accounted for 44 percent of the total primary production from March through November in Lakes Huron and

Michigan. These findings add to the growing evidence that the "micro food web" is important to Great Lakes plankton dynamics.

■ Much of the nitrogen added to lake water as dissolved free amino acids was regenerated as ammonium rather than being incorporated into food web biomass. This suggests that the micro food web may be more important for converting organic matter to inorganic nutrients than for transferring biochemical energy into the upper food web.

■ A study of the effect of algal shape and size as defense mechanisms against predation by *Diaptomus* was completed. Except for very long species, algal length was generally not useful against predation by zooplankton.

■ GLERL initiated a pilot study during FY 86 to evaluate the importance of under-ice ecology in the Great Lakes. Results suggest that high light levels and high phytoplankton and zooplankton production may be common features of the under-ice ecology of large lakes and bays.

■ Both FY 86 and FY 87 saw a return of the Johnson Sea-Link II research submersible to the Great Lakes. A GLERL scientist who had participated on the initial surveys in FY 85 again conducted studies using the submersible.

■ Sampling of benthic organisms for GLERL's well-established long-term trends study was continued in Lake Michigan and was expanded to include Saginaw Bay.

■ A laboratory technique was developed to isolate and monitor the feeding activity of individual *P. hoyi*.

■ Experiments revealed that the transfer of phytoplankton energy to *P. hoyi* after the spring diatom bloom may represent an important link in the transfer of energy from phytoplankton to fish.

■ The bottom Ekman layer in Lake Michigan was found to be up to 40 m thick in water depths of 80 m to 100 m. Ekman flow in this layer in combination with the prevailing cyclonic circulation of the lake causes a convergence of bottom water, and thus intense upwelling, in the center of the lake.

■ Nearly 200,000 observations of water temperature from Lakes Erie and Michigan were assembled and used to evaluate four mathematical models of water column temperature structure.

■ A first-generation optimization model that takes uncertainty into consideration was applied to strategies for management of phosphorus loading to the Great Lakes. The results showed that there is a range of goal-achievement vs. cost, for consideration by resource managers. Strategies specified under the 1978 Water Quality Agreement between the United States and Canada are not likely to achieve more than 60 percent of the goal, whereas those identified through the optimization model are less costly and more effective.

Upper Great Lakes Connecting Channels Study

■ A number of environmental models of Lake St. Clair were completed as part of the Upper Great Lakes Connecting Channels Study.

■ Modeling of ^{137}Cs removal indicates a sediment residence time of about 5 years in Lake St. Clair. Less than 20 percent of the total loading of ^{137}Cs to Lake St. Clair was calculated to be in bottom deposits. This suggests that most particle-associated contaminants must migrate through Lake St. Clair and enter Lake Erie.

■ The currents in Lake St. Clair were found to be dominated by hydraulic flow, but wind-induced changes in the circulation pattern can change residence times from 2 days to more than 30 days. The average residence time is about 9 days.

■ During FY 86, GLERL initiated research on the effects of shallow water on wave dissipation and attenuation that includes both field experiments and development of applicable models. The first experiment was a joint effort during FY 86 and FY 87 between GLERL and Canada's NWRI and Atmospheric Environment Service to study shallow-water wave processes in Lake St. Clair. A model developed for the deep ocean proved to be quite acceptable for estimating wave heights in the shallow waters of Lake St. Clair, while a shallow version of the model tended to underestimate the highest waves at all stations.

Marine Hazards and Lake Hydrology

■ A wave climate synthesis system was developed for the Great Lakes. Long-term climate extremes of wave heights can be readily estimated from given long-term wind speed statistics where wave measurements are not available.

■ At the request of the Department of Natural Resources of Michigan and of Ohio, the Army Corps of Engineers (COE), several Sea Grant Programs, and other agencies with responsibility for Great Lakes shorelines, GLERL developed and distributed a PC-based computer program that can assist in planning for storm surges on the Great Lakes.

■ Procedures to access and run a menu-driven computer algorithm to forecast ice conditions on the St. Marys River were demonstrated and documented. Access to and support of the algorithm on GLERL's computer were provided to both NWS and the Army COE for use in making experimental operational forecasts during the 1985–86 winter season on the Great Lakes.

■ During FY 87 we transferred computer code to NWS Cleveland for analysis of freezing degree-days and thawing degree-days and samples of the air temperature files and degree-day data sets. NWS Cleveland and GLERL are now using the same convention for calculating degree-days, and NWS Cleveland can now automate degree-day calculations, access to historical data, and operational use of degree-days for ice forecasts.

■ A study to analyze and report on the engineering statistics of a nearshore ice thickness data base was completed.

■ The barium sulfate reference panel used by GLERL as the primary standard for field calibrations of airborne spectral reflectance was tested for cosine response at different incident angles and wavelengths. Deviations from a perfect cosine response were documented for most angles and at all wavelengths measured, leading to the conclusion that the airborne data must also be corrected for errors due to the imperfect cosine response of the reference panel.

■ A cooperative study was initiated with scientists at NASA's Goddard Space Flight Center to define the reflectance characteristics in the visible and near-infrared range for various types of Great Lakes ice and snow, and to build a library of spectral signatures of different ice types for use in satellite interpretation of the ice cover.

■ A study to define the spectral transmittance of solar radiation through ice and snow in the visible and near-infrared ranges was initiated.

■ An 81-year (1897–1977) degree-day climatology for the Great Lakes region was updated with the addition of data for 6 years (1978–1983).

■ A new task was developed during FY 87 to analyze the effects of climatic change on Great Lakes ice cycles; partial funding for this work was provided by EPA.

■ A description of the fall and winter thermal structure of Lake Superior was completed.

■ The Large Basin Runoff Model and its applications for the 106 upper Great Lakes watersheds above the Niagara River were integrated with estimates of over-lake precipitation and lake evaporation, the Lake Superior regulation plan, and the Hydrologic Response (channel routing) Model to make possible system-wide simulation of the Upper Great Lakes water supplies, connecting channel flows, and lake levels. Automation of all calibration, climatic data reduction, and forecast procedures was completed so that GLERL's water supply technology can be applied to other large lake basins.

■ The Hydrologic Response Model was simplified, extensively documented, and recalibrated to reduce the error in modeled Lake Michigan-Huron levels.

■ The Army COE, Detroit District, initiated a multi-year program to evaluate and compare Lake Superior forecasts made using the GLERL software package with forecasts made using existing operational methods.

■ Development of a generic Thiessen weighting package was completed. The generic package is easily applied to different areas and to different types of data.

■ An improved model for lake evaporation was completed that uses remotely-sensed water surface temperatures in conjunction with a first-order heat balance and heat storage function for each lake.

■ The St. Clair River Winter Flow Experiment was completed after five consecutive years of gathering winter flow data for the St. Clair River.

MARINE ECOSYSTEM ASSESSMENT

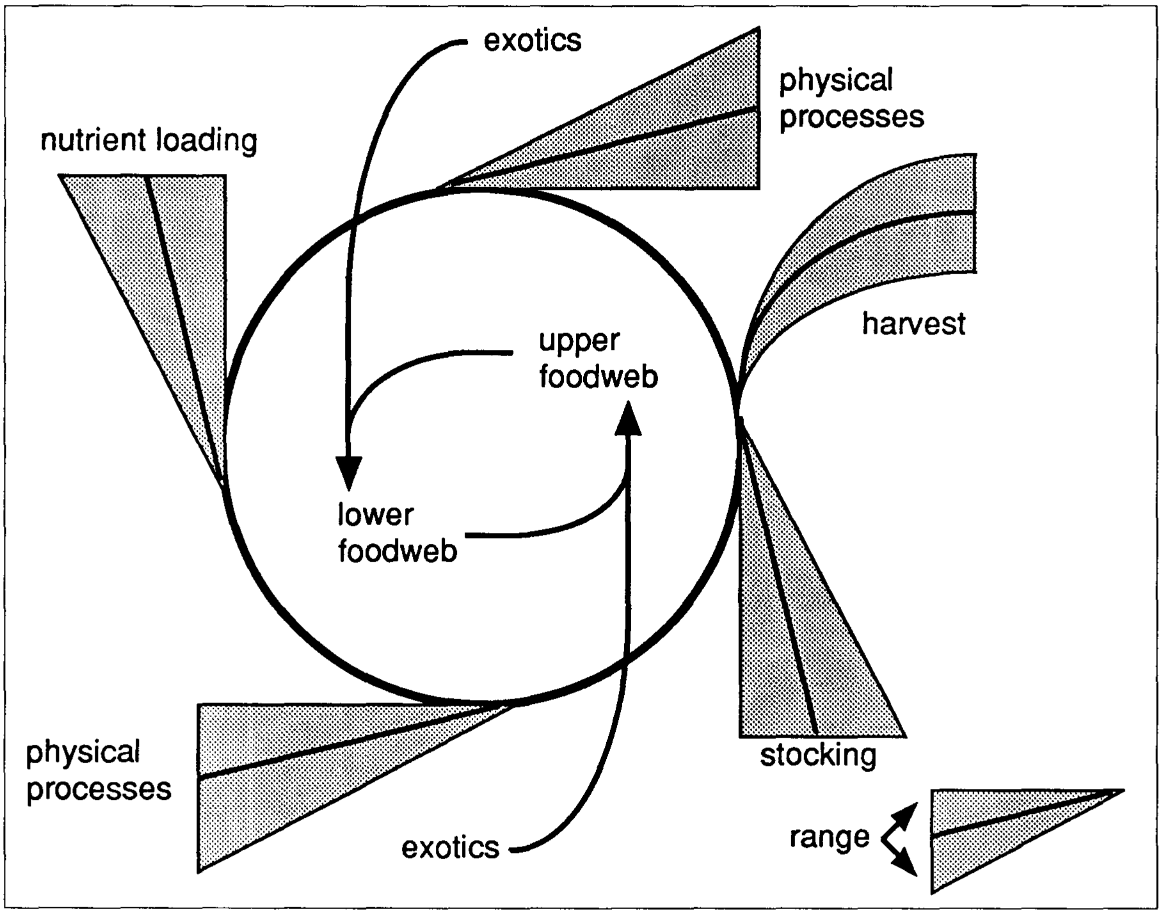

Figure 1. *The productivity of ecosystems, including fish, is controlled by the actions of man and nature. Man influences productivity through waste (nutrients and toxics) management practices and the physical alteration of habitat. Nature influences productivity through a hierarchical interplay of physical, chemical, and biological processes, e.g., the constancy or irregularity of thermal and chemical gradients, currents and waves, predator-prey relationships, and nutrient dynamics. Fisheries productivity can also be manipulated by man through stocking and harvesting. Understanding the relative importance of man's and nature's influences on productivity is essential for accurately predicting the dynamics of ecosystems and their fish populations.*

The Marine Ecosystems Assessment research program at GLERL is designed to (1) improve our understanding of, and predictions related to, natural marine ecosystems, physical phenomena, and the effect of human-induced stresses on the ecosystem, and (2) help provide a sound scientific basis for management decisions pertinent to marine resources, marine pollution, and environmentally sensitive marine activities (Fig. 1). Projects include investigations into the short- and long- term effects of human, agricultural, and industrial wastes on aquatic life and water quality; the structure and function of aquatic ecosystems and the effects of human activities on those ecosystems; the measurement, analysis, and prediction of physical phenomena such as currents, river flows, and air-water-sediment interactions; and sedimentary fluxes and processes, especially sediment-contaminant interactions.

Cycling of Toxic Organics

Toxic organics are considered by many as the premier environmental threat and problem in the Great Lakes; over 1,000 anthropogenic organic compounds have been identified in the Great Lakes ecosystem. More recently, contaminated sediments have become a primary focus of concern by the International Joint Commission (IJC) and the EPA. GLERL has a continuing program in collaboration with the EPA, the U.S. Fish and Wildlife Service (USFWS), and various Canadian agencies to develop and improve our understanding of the processes that control the cycling and fate of organic contaminants.

The combination of high population and industrial density with slow flushing rates (3–200 years) of the Great Lakes make toxic organic contaminants a major problem. In lakes and estuaries, the adsorption of toxic organic contaminants onto particles, followed by settling and eventual burial, is commonly the major internal process controlling the residence time and concentration of these compounds in the water column. Suspended particulate matter thus plays a vital part in the contaminant geochemistry of the Great Lakes by providing a potential mechanism for cleansing the lakes through sedimentation. Understanding the interactions between different types of suspended matter and dissolved organic contaminants, and understanding the processes that affect these interactions, are critical in modeling the behavior of such contaminants in the environment.

GLERL's program has focused on particle-contaminant interactions (sorption, settling, burial, and resuspension) as the major removal mechanism, but also includes research on contaminant bioavailability and effects, and uptake by the bottom-dwelling organisms (benthos), which are highly exposed due to the fact that the sediments are the major reservoir of contaminants.

Particle-Contaminant Interaction Studies

In 1984, experiments were performed to measure the equilibrium distribution (partitioning) of a suite of contaminant organics between the dissolved, the suspended-solid, and the dissolved-organic-carbon phases. The results, primarily from a nearshore station in Lake Michigan, revealed significant seasonal changes in the partitioning between these phases. During FY 86 and FY 87 similar experiments were initiated and completed for offshore waters, with the following results:

- Compound solubility was found to control the distribution of that compound between the dissolved and particulate phases (Fig. 2), but played little role in mediating the association with the lake water dissolved organic carbon (DOC).

- Up to 90 percent of the hydrophobic organic contaminants (HOC) were found to be freely dissolved rather than associated with particles or DOC.

- Sorption to particulate matter accounts for up to approximately 40 percent of the HOC and sorption to DOC is generally less than 10 percent.

A new study was initiated in Lake Michigan to investigate whether phase distribution, after resuspension, is kinetically controlled or can be modeled more simply as an equilibrium. Results to date show that most chlorinated hydrocarbons, such as the polychlorinated biphenyls, are rapidly removed (desorbed) from particles, while the polycyclic aromatic hydrocarbons (PAH) are much more strongly bound. This means that the chlorinated hydrocarbon contaminants may have already reached a steady-state distribution within the lake and thus, the concentrations of these compounds is not likely to change dramatically in the water column. On the other hand, PAHs probably have not yet achieved a steady-state distribution within the lake, and their concentrations may continue to change over time.

Bottom sediments and their sorbed contaminants are mixed by animal activity (bioturbation) and can be reintroduced into the water column by

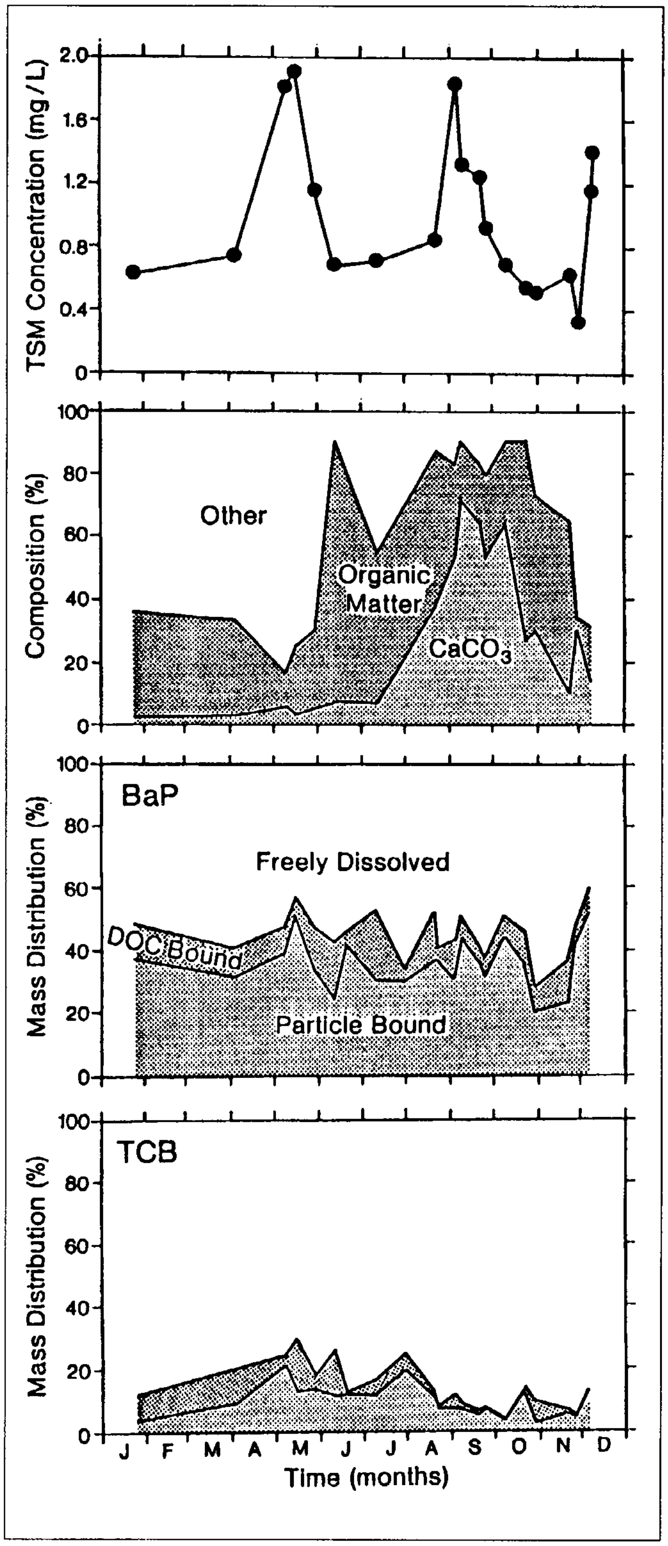

Figure 2. a. *Total suspended matter (TSM) concentration in offshore station surface water samples. The two peaks are spring resuspended matter and $CaCO_3$, respectively.*
b. *Composition of the TSM. Lightshading represents $CaCO_3$ and ranges from 2 to 72 percent of the TSM; dark shading area represents the particulate organic matter [POC (= 2 x POC)]. "Other" is composed of clays, silicious material, etc.*
c. *Mass distribution of benzo-a-pyrene (BaP) in the water samples was remarkably constant considering the changes in TSM and composition. Light shading region represents the fraction of BaP associated with particals; dark shading is the BaP associated with dissolved organic carbon; the remaining BaP is freely dissolved.*
d. *Mass distribution of tetrachlorobenzene (TCB), shaded as shown in C.*

resuspension, especially during the winter months in the Great Lakes. GLERL has an on-going program in Lakes Michigan, Huron, and Superior to measure and study the fluxes of new vs. resuspended particulate matter and associated contaminants, using sediment traps moored in vertical arrays in the water column (Fig. 3). By the end of FY 87 over 200 sediment samples were obtained from such traps. Analyses of samples to date have revealed:

- Extensive resuspension of contaminated sediments was found in all of the lakes.
- Very high concentrations (parts per million range) of chlorinated organic contaminants were measured in trap material collected near the surface.
- Initial calculations indicate that sediment recycling via resuspension is the major process controlling the long-term concentration of these contaminants in the lakes.
- Time constants for removal of particle-associated contaminants are decades long due to the coupling of the processes of bioturbation, resuspension, and burial.

In a related field program, sediment traps of different size and design used by GLERL and Canada's National Water Research Institute (NWRI) were deployed starting in FY 86 in tandem arrays in the northern and southern basins of Lake Michigan to determine relative collection efficiencies over a wide range of mass fluxes. The field

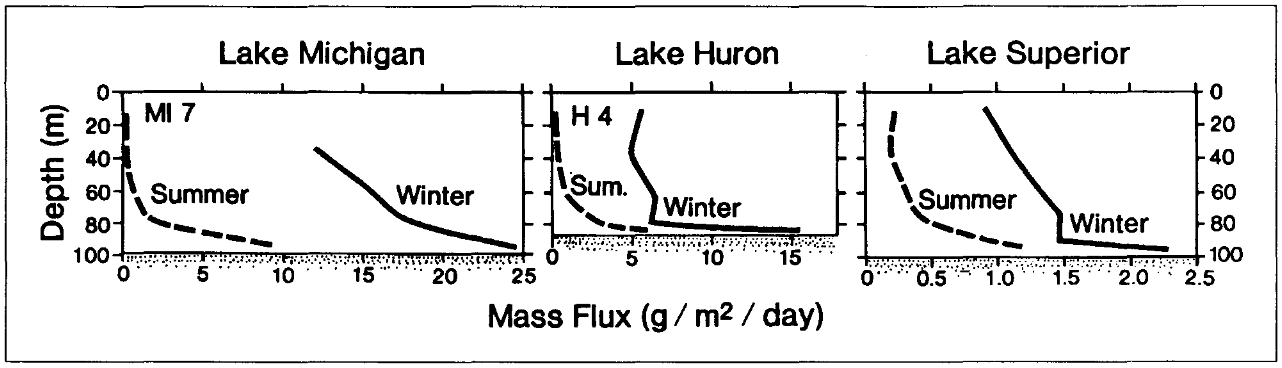

Figure 3. *Sediment trap measured mass flux profiles for the stratified and unstratified periods for stations of 100 m total depth in Lakes Michigan, Huron, and Superior. Note that the scale for Lake Superior is smaller than for Michigan and Huron. Results extend earlier conclusions for Lake Michigan of a decoupling of surface waters from the influence of sediment resuspension during the period of thermal stratification and a large amount of sediment resuspension, strongly influencing lake water chemistry, during the unstratified period.*

work was completed in FY 87. This intercomparison will be used to relate the results of GLERL's studies in Lakes Michigan, Huron, and Superior to NWRI's results in Lakes Erie and Ontario, thus providing a comprehensive synoptic data base of particle fluxes in all five Great Lakes.

A coupled Lakes Model to predict the long-term response of the Great Lakes to time-dependent contaminant loads was previously developed and analyzed for sensitivity to various environmental factors. However, that model assumed a vertically homogeneous water column (i.e., not seasonally stratified), and can incorporate sediment resuspension only as a rather crude approximation. Development of a stratified, single-lake contaminant-fate model was begun in FY 86 and is continuing. This model will explicitly incorporate sediment resuspension as a parameter and make use of the sediment trap data noted above.

Toxicokinetics Studies

A second and apparently important process for remobilizing contaminants out of sediments involves the direct uptake of contaminant compounds by benthic invertebrates and the subsequent transfer of contaminants up the food chain to higher trophic levels. A fundamental question in the toxics issue is what fraction of sediment-associated contaminants is available to the biota in the Great Lakes. GLERL's toxicokinetics program has been studying the uptake, depuration, and biotransformation rates for various toxic organics in Great Lakes invertebrates.

Previous work involving the accumulation of PAH from sediments by benthic invertebrates such as *Pontoporeia hoyi* (*P. hoyi*) showed that the process is complex and is affected by a number of parameters. Experimental work on the environmental factors that affect the toxicokinetics of xenobiotics in *P. hoyi* was completed. Analysis of the data indicates that organism mass (Fig. 4) is the most important physiological variable and temperature (Fig. 5) is the most important environmental variable for this organism.

Experiments were initiated to examine the bioavailability and relative sensitivity of the predominant Great Lakes benthic invertebrates, *P. hoyi* and *Mysis relicta*, to a suite of well-documented toxic organics. The goal of these studies is the development of useful relationships that can aid in the assessment of contaminated environments. Remedial actions have proved to be extremely expensive, and reliable assessment tools are needed. Pentachlorophenol, carbaryl, and DDT are commonly used as "yardsticks" for these types of studies:

- Pentachlorophenol and carbaryl were found to have about the same range of toxicity to both of these organisms as has been observed for other amphipods.

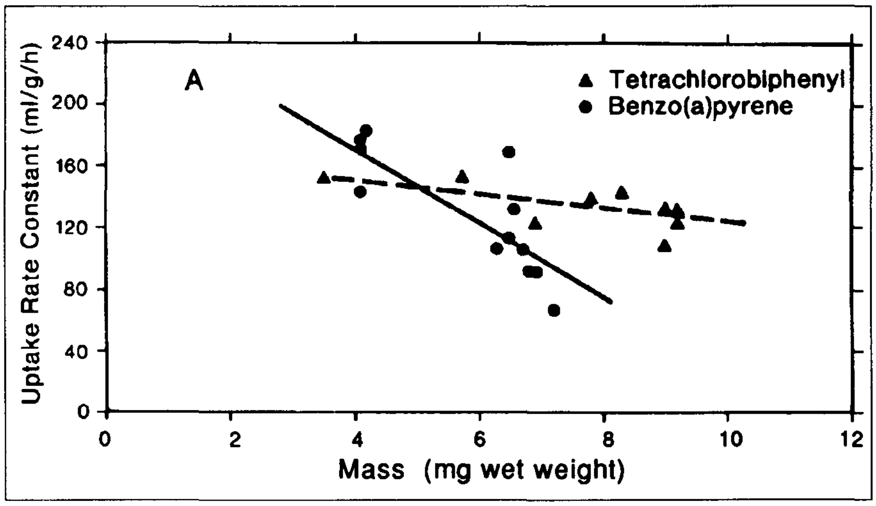

Figure 4. *Reduction in the uptake rate with increasing mass of* P. hoyi *for tetrachlorobiphenyl and benzo(a)pyrene.*

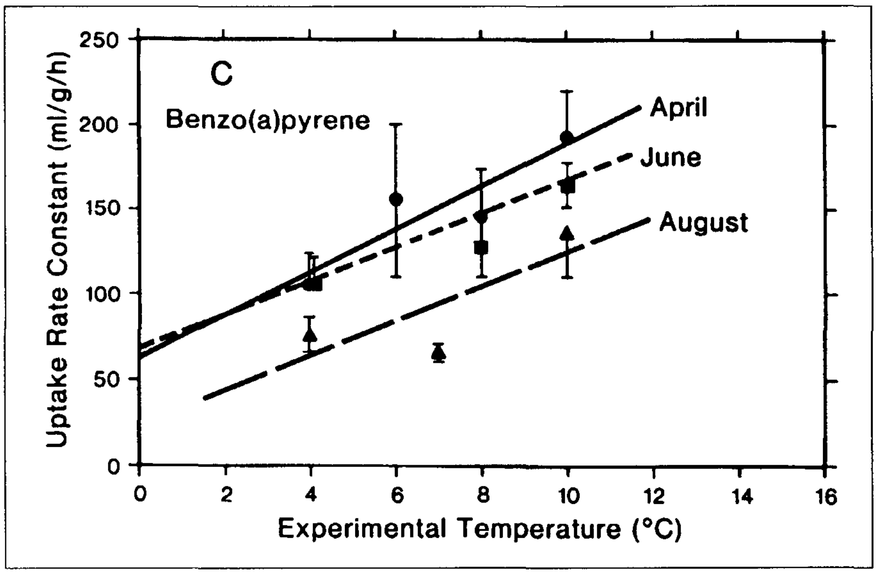

Figure 5. *An example of increasing uptake rate with increasing temperature - similar slopes are observed for tetrachlorobiphenyl and anthracene; Q_{10} for this process is 3.1.*

- DDT was found to be considerably less toxic to *P. hoyi* than has been observed for other amphipods and other crustaceans. This is possibly because *P. hoyi* have a high lipid content; and lipids store the compound, thereby making it unavailable for other reactions.

The environment is plagued with multiple contaminants which, when present together, could change the response and sensitivity of organisms relative to single-contaminant exposure. Therefore, radiotracer experiments were conducted to study the effects of sediment contaminant concentration on the bioaccumulation of these contaminants by benthic organisms. The experiments involved a control plus successively larger concentrations of a mixture of chlorinated hydrocarbons:

- When a mixture of chlorinated hydrocarbons was added to sediments, both toxicity and mortality occurred at even the lowest dose employed, which was within the range of concentrations already measured in Great Lakes' sediments.
- The rate of uptake of contaminant compounds was found to increase in the presence of the chlorinated hydrocarbons mixture, even at the lowest dose employed; since a well-known and classical response to stress is for organisms to show an increase in metabolic rate, these findings suggest that the presence of even small amounts of chlorinated hydrocarbons place benthic organisms under stress.

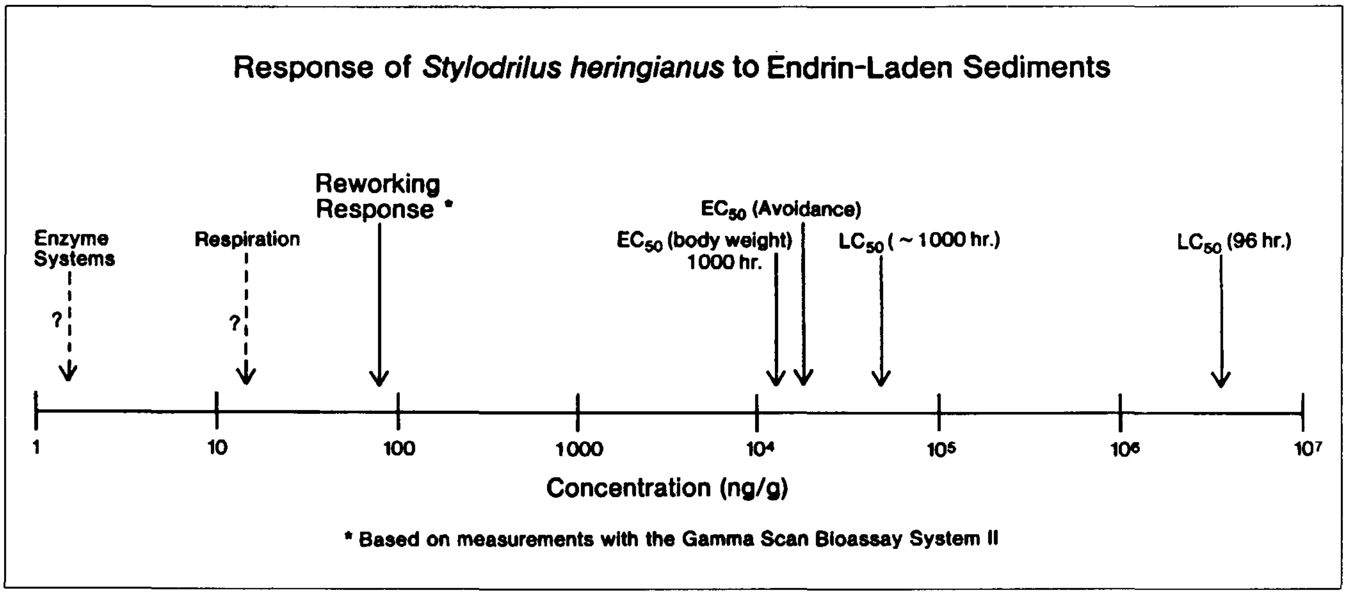

Figure 6. *Response of* Stylodrilus heringianus *to Endrin dosed sediments for several endpoints.*

■ A similar experiment to examine the kinetics of accumulation of a mixture of PAH was completed in FY 87, and data analysis is underway.

The usual measure of the toxicity of a chemical compound to a particular organism is the concentration that is lethal to 50 percent of the test population, known as the LC50. However, LC50 experiments do not provide any indication of what concentration level starts to produce toxic effects. GLERL developed a procedure (gamma scan) to detect the initiation of toxicity to benthic organisms by measuring the rate of sediment reworking in a test cell under increasing concentrations of a particular toxic contaminant. The spread and movement of a thin layer of radioisotope-spiked sediment in laboratory test cells is monitored. The movement of the spiked material is related to the rate of bioturbation by selected organisms placed in each cell. The bioturbation rate is a reflection of the health of the animal and thus, can be a sensitive indicator of the onset of toxicity:

■ Four long-term (40–50 days each) chronic toxicity tests were completed for the oligochaete worms *Limnodrilus hoffmeisteri* and *Stylodrilus heringianus*, using the pesticide Endrin.

■ From these experiments, repeatable sediment reworking rates were obtained for both species in contaminated and uncontaminated microcosms.

■ Additionally, two 96-h acute LC50s were performed.

■ Significant decreases in the rate of sediment reworking were found at sediment contaminant concentrations 4–5 orders of magnitude less than the LC50 concentration (Fig. 6).

■ Worm dry-weights measured after the conclusion of the experiments were also found to be a good indicator of sublethal stress and reflective of reworking rates.

■ Work done in conjunction with an outside investigator used free amino acid pools as a taxonomic tool to differentiate five species of oligochaetes. Currently, potential changes in free amino acid pools are being examined as indicators of sublethal stress in *S. heringianus*.

■ Development and construction of an automated, microcomputer-controlled Gamma Scan hardware system was started in FY 87.

Ecosystem and Food Web Dynamics

An understanding of and an ability to predict the dynamics of Great Lakes ecosystems are necessary ingredients for making wise decisions concerning management of the lakes in relation to both water quality and living resources. Benthic organisms are often good, early indicators of long-term trends in water quality. Invertebrates are important prey for small fish, and their abundance and composition can affect total fish production. Planktonic phytoplankton (small floating plants) directly affect water quality and serve as the base of the aquatic food web.

The complex interactions and cause-effect relationships between different components of the ecosystem and between levels of the food web must be understood in order to assess potential effects of human activities. A critical part of ecosystem dynamics involves the identification and study of the critical first-order processes that control the flow of nutrients and energy through the ecosystem and determine the composition and pattern of succession of biota in the lakes. These processes and their characteristics must be identified and quantified as parts of mathematical models. Such models then form the basis for testing hypotheses and identifying probable areas of impact of specific human activities and allow testing of proposed management approaches to dealing with natural resource problems.

Ecosystem Modeling

A major problem in developing and testing the effectiveness of ecosystem models is the limited amount of comprehensive long-term data available for aquatic ecosystems upon which model development could be based and tested. During FY 84 and 85 GLERL took advantage of a 20-year data base from Lake Washington (near Seattle) to develop a generic heat-diffusion model for lakes, which was then adapted for Lake Michigan (Lake Michigan Heat Diffusion Model). During FY 86 this generic one-dimensional vertical heat-diffusion model, empirically parameterized in terms of the gradient Richardson number and the Brunt-Vaisala frequency, was compared with the observed vertical thermal structure and total heat content in Lake Washington for the period 1963–1976. The comparison demonstrated that the model produces a good parameterization of bulk mixing processes.

The Lake Michigan Heat Diffusion Model was then modified and used to simulate 1985 epilimnetic thermal structure with emphasis on diel stratification. One laboratory and two field experiments were conducted during FY 86 to assess the effect of hourly changes in stratification on Lake Michigan phytoplankton. Analysis of the data indicated that an important suppression of photosynthesis occurs during afternoon stratification and that the effect may be due to ultraviolet radiation. The field and model results support the hypothesis that the wide range (very slow to fast) in epilimnetic mixing times in Lake Michigan strongly affects the fate and transport of seston and thus may also affect primary production and other light-sensitive processes.

GLERL conducted a major Lagrangian ecosystem experiment in Lake Michigan during 1983 and 1984 (Lake Michigan Ecosystem Experiment) to define and quantify biological and chemical processes causing dynamic short-term and seasonal ecological changes in Lake Michigan phytoplankton:

- Data from that field experiment were used to complete a long-term total-phosphorus model for Lake Michigan. The total-phosphorus simulations from the model compare well with observed values, and simulations of annual spring phytoplankton bloom conditions generally reproduce observations.

■ A related model that simulates Lake Michigan's summer pelagic food web (phosphorus, phytoplankton, zooplankton, and planktivorous fish) was also developed to evaluate the relative importance of nutrient loading, competition, and predation in controlling the seasonal dynamics of phytoplankton in offshore Lake Michigan. The model was calibrated against the concentrations and process rates observed during the Lake Michigan Ecosystem Experiment and then used to explore the hypothesis that Lake Michigan's summer food-web structure is sometimes controlled by fish dynamics.

■ The Lake Michigan ecosystem has been altered dramatically during the last decade. Summer zooplankton dominance changed from calanoid copepods (*Diaptomus*) to cladocerans (*Daphnia*), and filamentous blue-green algae were largely replaced by phytoflagellates. This occurred concurrently with reduced phosphorus load, phosphorus concentration, and abundance of alewife, the dominant zooplanktivore (Fig. 7).

■ Model simulations to evaluate the influence of gradients of both phosphorus load and alewife abundance on predation-competition interactions indicated that summer plankton composition and water clarity in Lake Michigan are controlled largely by predation.

■ It was shown that recent documented changes in fish communities have cascaded to affect the deep chlorophyll layer as well.

■ Primary production rates during thermal stratification in the 1980s were similar to those reported in the 1970s. This indicates that even though major changes have been documented in the upper food web (fish) during this time period, these changes have not translated to affect the base of food web carbon production by phytoplankton.

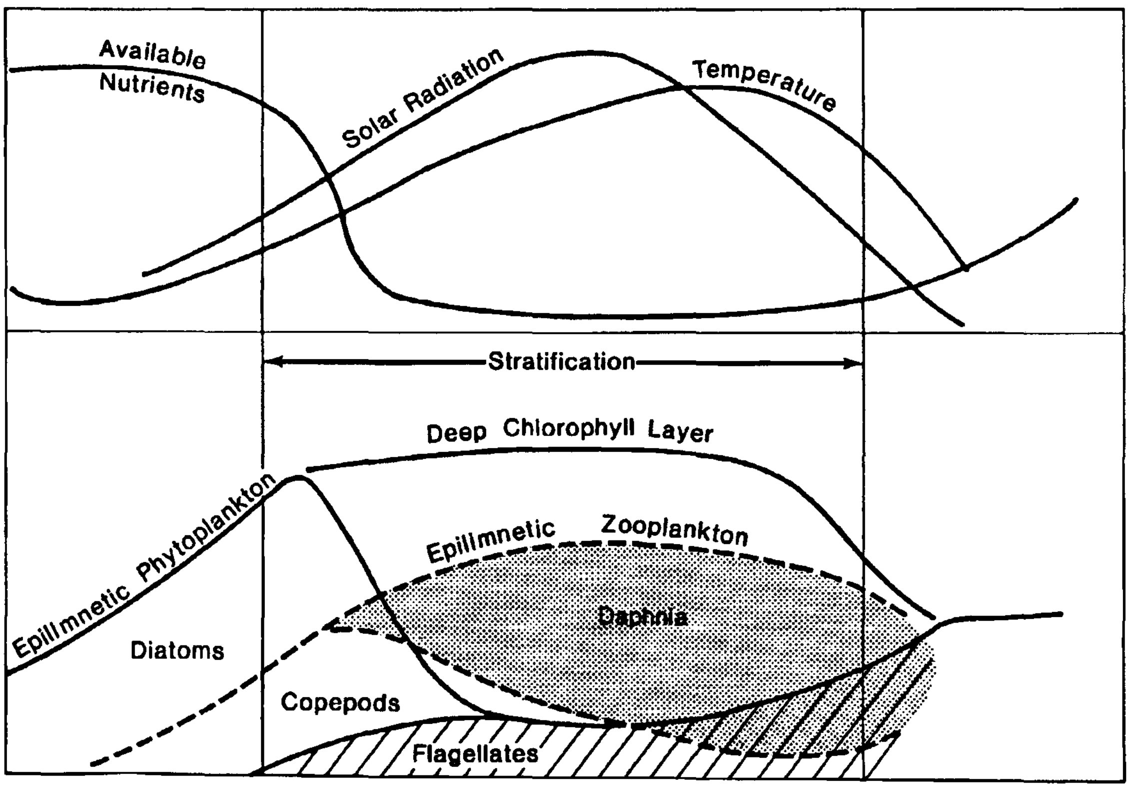

Figure 7. *Schematic diagram of seasonal changes in lake characteristics and plankton abundances in Lake Michigan from spring (left) to autumn (right) for years after 1982.*

■ Types of phytoplankton shifted from diatom-dominance during May to phytoflagellate-dominance during July–August. The summer phytoplankton populations of the 1980s are distinctly different from those in the 1970s. Food web interactions caused by a changing zooplankton composition and nutrient supply changes are two possible causes for this difference which affects the efficiency of energy flow up the food web.

■ A deep chlorophyll layer developed after the onset of thermal stratification due to increased light penetration and availability of nutrients from the deep water. This deep chlorophyll layer may be a source of food for some Great Lakes grazers.

■ Sedimentation was the most important mechanism causing algal removal in spring, when colonial diatoms and calanoid copepods (*Diaptomus*) dominated the plankton. Grazing was the most important loss during summer when phytoflagellates and *Daphnia* spp. dominated.

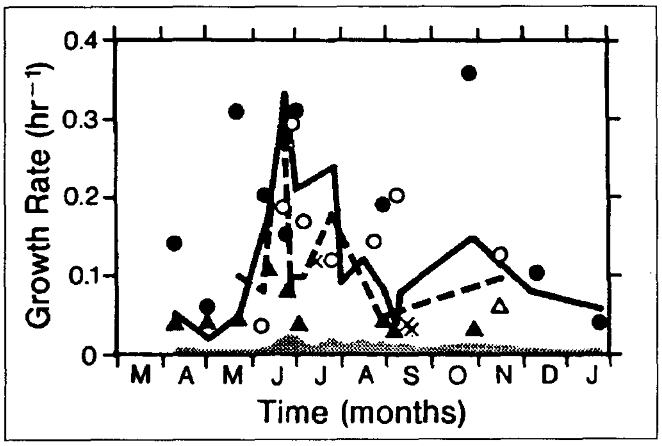

Figure 8. *Bacterial growth rates for 1983 (x), 1984 (dashed line), and 1985 (solid line) calculated from TdR incorporation and empirical conversion factors. The shaded line includes all growth rates determined from TdR incorporation and a theoretical conversion factor (1.25 x 10^3 cells $nmol^{-1}$). TdR=[^{3}H-methyl] thymidine.*

Micro Food Webs

Bacteria are an often ignored part of marine ecosystems. Yet previous studies have shown that bacterial production may account for a significant part of the total production in the Great Lakes. Thus, a more detailed knowledge of bacterial dynamics is necessary to quantify and understand the transfer of food and energy through the Great Lakes ecosystem. Analyses of the results of bacteria field experiments conducted during FY 85 were completed and preliminary findings were confirmed during FY 86 and FY 87:

■ Bacterial populations in the Great Lakes exhibited a decrease in activity and abundance with depth, and a consistent seasonal pattern in which production increased until the onset of stratification and slowly decreased thereafter, with a reasonable balance of growth and grazing rates except during the period (June) when bacteria abundance increased (Fig. 8).

■ Experiments to study the kinetics of the removal of low levels of primary amines by bacteria were completed. The results confirmed that although bacterial growth rates appear to be controlled by the amount of labile organic substrate available, grazing is a major factor in controlling bacterial abundance, and therefore total population uptake activity.

■ The abundance, composition, and production of picoplankton were determined from March through November in Lakes Huron and Michigan. Picoplankton (< 3 microns) accounted for 44 percent of the total primary production. These findings add to the growing evidence that the "micro food web" is important to Great Lakes plankton dynamics.

■ Oxygen-based and ^{14}C-based primary productivity estimates were compared in Lakes Huron and Michigan to provide information about the accuracy of the two methods to measure this important energy-fixing process in Great Lakes food webs. The work suggests that ^{14}C-based productivity measurements provide a reasonable estimate of lake productivity.

■ Dissolved nitrogen transformations by the micro food web were examined using a new "light/dark" approach to estimate the release of free amino acids by phytoplankton and regeneration of ammonium by heterotrophs. Amino acids appear to be important intermediates to ammonium

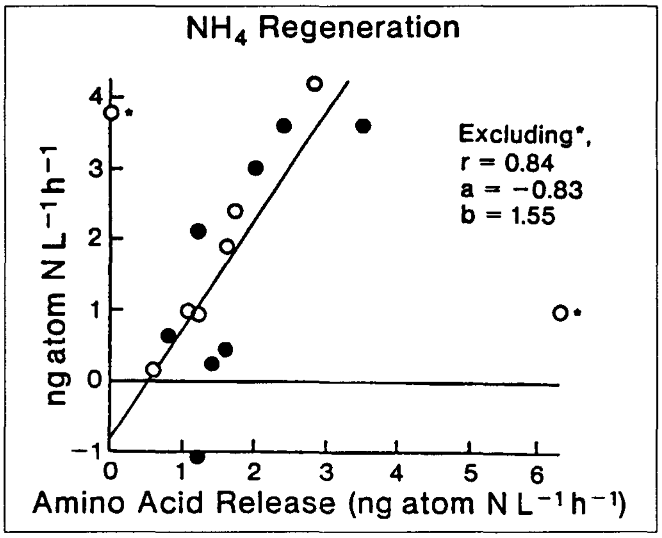

Figure 9. *Comparison of ammonium regeneration to amino acid nitrogen release by phytoplankton in samples of epilimnetic Lake Michigan water collected during the 1986 field season.*

regeneration by the micro food web in Lake Michigan (Fig. 9).

■ Much of the nitrogen added to lake water as dissolved free amino acids was regenerated as ammonium rather than being incorporated into food web biomass. Thus, the micro food web may be more important for converting organic matter to inorganic nutrients than for accumulating biochemical energy into the upper food web.

■ Phosphorus-cycling experiments indicate that dissolved organic phosphorus released by phytoplankton can be readily used as a source of phosphorus by bacteria.

Pelagic Feeding Dynamics

The life cycle strategy of *Diaptomus* in Lake Michigan was studied by examining seasonal lipid (fat) concentrations and reproductive conditions of field animals. Lipid concentration in the animals remained high during most of the year, but decreased as a result of egg production in the spring. The high lipid content during summer months, when other zooplankton (cladocerans) are abundant, suggests that *Diaptomus* is not under competitive stress from the other zooplankton.

GLERL scientists continued to use the new Microcinematography Laboratory established during FY 85. A previous study of the feeding mechanism employed the dominant herbivore in the upper Great Lakes, *Diaptomus* spp., revealed that a significant number of algal cells escaped even though they had been drawn within easy capture range of this copepod. This observation led to FY 86 and FY 87 experiments to examine the effects of algal morphology as a defense mechanism against capture. Traditional feeding experiments were combined with high-speed microcinematographic studies. Information from these experiments provides us with a better understanding of zooplankton-phytoplankton interactions, leading toward better predictions of seasonal plankton succession:

■ A study of the effect of algal shape and size as defense mechanisms against predation by *Diaptomus* was completed. Except for very long species, algal length was generally not useful against predation by zooplankton. However, algae that were long in two directions (e.g. colonies of *Asterionella*) were not grazed readily by *Diaptomus*. Thus, algal morphology may affect the dynamics and efficiency of energy transfer between phytoplankton and zooplankton.

■ Rotifers are small zooplankton in the Great Lakes that may link the micro food web to large grazing zooplankton like *Diaptomus*. Mechanisms of *Diaptomus* predation on rotifers, and of rotifer escape mechanisms, were examined using high-speed microcinematography. This study demonstrated that *Diaptomus* can actively capture rotifers, but some rotifers have distinctive defense mechanisms against *Diaptomus*, such as paddles for quick escape or spines that open up to prevent attacks.

Winter Under-Ice Ecology

Information on the population dynamics of organisms living under the ice during winters in the Great Lakes is scant. Studies in other parts of the world show that significant biological activity can be present under marine ice. GLERL initiated a pilot study during FY 86 to evaluate the importance of under-ice ecology in the Great Lakes.

A pre-ice cruise in late January, a trip on the ice in early March, and a post-ice cruise in April, 1986 were made to determine how well copepods winter-over in ice-covered Grand Traverse Bay, a

190-m-deep fjord-like bay on Lake Michigan. Photosynthetically active radiation transmittance through various types of ice occurring in the bay was determined and an ice thickness time and space series was collected to analyze ice dynamics and radiation transmittance. Benthic samples were collected along a depth transect of the bay through the ice cover in March and again in April after the ice had melted. Inspection of March samples indicated that Grand Traverse Bay possesses a rich and diverse macroinvertebrate community in the winter:

■ In contrast to small lakes, transmittance of light through the ice on Grand Traverse Bay was high. This was because snow, which radically lowers light transmittance, was prevented from building up on the ice by high winds, and in some cases, high temperatures and rain (Fig. 10).

■ Phytoplankton growth was higher during ice cover than before. This bloom was related to water column stability caused by the ice cover as well as by the relatively high transmittance of the ice.

■ Zooplankton took advantage of the under-ice bloom by feeding at high rates; during the bloom, the zooplankton reproduced. In reproducing they used up much of their stored lipids.

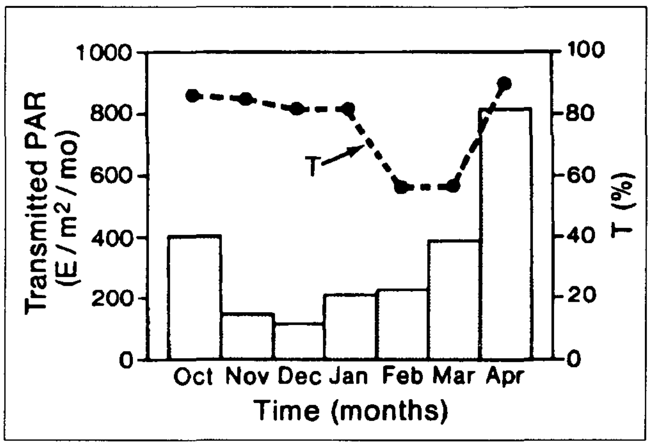

Figure 10. *Ice cover during February and March, 1986 did not greatly reduce surface transmittance (T) and solar radiation (Transmitted PAR) reaching the water column of Grand Traverse Bay, Lake Michigan.*

■ High light levels and high phytoplankton and zooplankton production may be common features of the under-ice ecology of other large lakes and bays.

Benthic Ecology

The Johnson Sea-Link II research submersible returned to the Great Lakes in both FY 86 and FY 87. A GLERL scientist who had participated on the initial surveys in FY 85 again conducted studies using the submersible:

■ A comparison of benthic samples was made to evaluate the sampling efficiency of PONAR grab samplers. Samples collected with the Johnson Sea-Link II were compared with those collected using a PONAR grab sampler from the same locality. Abundances of all the major benthic groups were found to be underestimated from PONAR samples.

■ Fish "exclosures" were constructed and placed at the bottom of Whitefish Bay (125 m depth) in Lake Superior to determine the significance of predation in regulating benthic populations. A dive with a submersible verified the successful placement of the exclosures.

A new method using a computer digitizer and menu-driven software was developed to measure body length and gut fullness of the amphipod *P. hoyi*. This new method is more accurate and precise than earlier methods and provides a rapid and efficient way to transfer raw data to an on-line computer file.

Sampling of benthic organisms for GLERL's well-established long-term trends study was continued in Lake Michigan and was expanded to include Saginaw Bay. This will allow development of an "integrated" picture of water-quality changes in the two locations, and will provide a basis for comparing "top-down" predation (Lake Michigan) from "bottom-up" nutrient effects (Saginaw Bay) on benthic populations.

Studies to evaluate and quantify mechanisms of energy and nutrient transfers between the pelagic (near surface) and benthic (in/on bottom sediments) systems were continued. Emphasis was placed on the amphipod, *P. hoyi*, the most abundant benthic animal in the upper Great Lakes and a favored food for fish:

- A laboratory technique was developed to isolate and monitor the feeding activity of individual *P. hoyi*. This technique permitted calculation of individual gut-throughput rate. Reliable estimates of this parameter are needed to construct valid models of energy and organic contaminant cycling through *P. hoyi* populations.

- Experiments were conducted to evaluate the feeding response of *P. hoyi* to a series of sediment trap materials collected seasonally from a depth of 30 m at a 45 m deep station in southeastern Lake Michigan. The transfer of phytoplankton energy to *P. hoyi* after the spring diatom bloom appears to represent an important link in the transfer of energy from phytoplankton to fish.

- Laboratory and field experiments were conducted to examine the effects of food removal on metabolic characteristics (fat content, nitrogen and phosphorus release rates) of *P. hoyi*. Animals survived approximately 6 months without food (Fig. 11). The ability of this animal to accumulate and store lipids in the spring and early summer and to live long periods without food helps explain why it thrives in the upper Great Lakes, where food input to the benthos is highly dependent on season.

A new instrument for lipid-class analysis was set up. Samples were extracted and analyzed for several GLERL studies. This lipid-class information increases our understanding of biochemical energy transfers in the lakes.

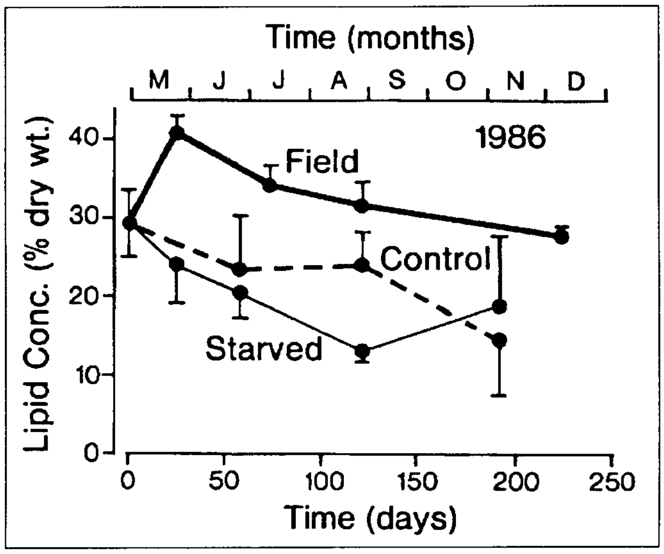

Figure 11. *Lipid (fat) content of experimental and field* Pontoporeia hoyi *in 1986. Field animals were collected from Lake Michigan at various times through the year. Control and starved animals were collected in April and held in the laboratory in filtered lake water with and without natural sediments, respectively.*

Water Movements and Temperature

Winter Bottom Circulation in Lake Michigan

Previous studies of the bottom boundary layer established the characteristics of a bottom Ekman layer in southern Lake Michigan, which produces veering of the near-bottom currents. Winter storms resuspend bottom sediments, causing a redistribution of materials deposited during the summer months, final deposition being determined by the overall winter circulation pattern and the Ekman dynamics of the bottom boundary layer. During the last week of April 1986, GLERL recovered several arrays of current meters moored near the bottom of Lake Michigan. The arrays had been deployed during November 1985 to measure the vertical profile of horizontal currents in the bottom boundary layer during the winter storm season.

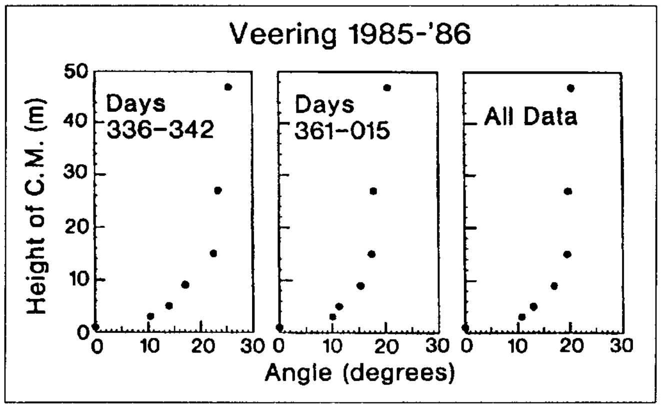

Figure 12. *Currents veer counter-clockwise as the lake bottom is approached through an Ekman layer. The veering shown in this figure was observed during two high speed current outbreaks that lasted for durations of 7 and 20 days. These measurements are compared with the average veering observed for a six-month-long current meter (C.M.) deployment in the winter of 1985-1986.*

■ The bottom Ekman layer was found to be as thick as 40 m in water depths of 80 m to 100 m. Ekman flow in this layer, in combination with the prevailing cyclonic circulation of the lake, causes a convergence of bottom water, and thus intense upwelling, in the center of the lake.

■ At a height of 1 m above the bottom, measured current speeds were in excess of 25 cm s^{-1}. Bottom stresses caused by these currents were found to be sufficient to resuspend the fine-grained sediments that compose the bottom material at the measurement sites (Fig. 12).

Lake Circulation and Numerical Models

Accurate prediction of the movement of contaminants, nutrients, and suspended sediments in the Great Lakes depends on the accuracy of numerical lake circulation models in predicting currents. During FY 86 an alternative to the traditional method of testing model accuracy was developed and applied to GLERL's Numerical Lake Circulation Model (PATHFINDER). The results revealed that the GLERL model shows significant skill in predicting particle trajectories over the course of a storm event. Quantitative bounds were established for the accuracy of trajectory predictions from the GLERL Numerical Lake Circulation Model.

During FY 87, circulation studies were concentrated on Lake Erie and Lake St. Clair. The Lake St. Clair work was in conjunction with the UGLCCS Program and is reported in that section. The circulation in the western basin of Lake Erie has a significant effect on the path of water from the Detroit River and, therefore, significant water quality implications:

■ GLERL and the National Water Research Institute of Canada (NWRI) made three deployments of six satellite-tracked drifters (three from GLERL and three from NWRI) near the mouth of the Detroit River in September and October of 1986 to compare predictions of circulation and particle trajectory models to the observed drifter tracks.

Water Temperature Forecasting

Knowledge of the temperature structure in the water column is a necessary prerequisite to many aquatic environmental studies. However, both theoretical and practical problems have hampered progress toward identifying numerical models useful for work in the Great Lakes. Therefore, nearly 200,000 observations on water temperature from Lakes Erie and Michigan were assembled and used to evaluate four mathematical models. The evaluations showed that:

- With careful calibrations, surface water temperatures can be simulated with nearly equal accuracy by any of the four models.

- Three of the four models were able to accurately track the sequence of break-up of the temperature structure following a late spring storm in Lake Erie (Fig. 13).

- Only two of the models examined were able to reproduce the energy levels indicated by the observations, which suggests that both models are satisfactory for simulating the mixing process. Merging the physics of these models with water quality models should improve the latter.

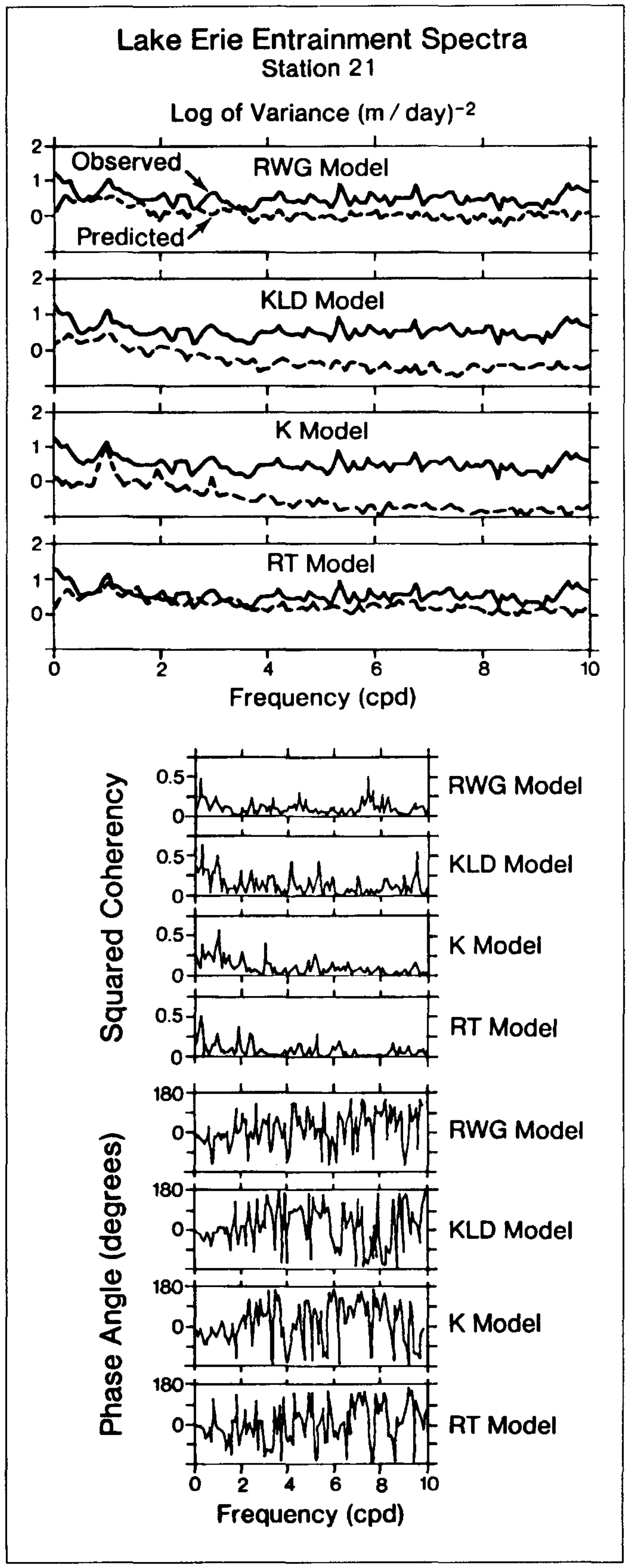

Figure 13. *Observed (solid lines) and modeled (dashed lines) spectra of entrainment from four different models of the thermal structure in Lake Erie.. Squared coherency and phase angle show the amount of similarity between modeled and observed value as a function of frequency. A squared coherency of 1.0 and a phase angle of 0 would indicate perfect agreement.*

Optimization, Uncertainty, and Risk Analysis Applied to Environmental Systems

Contaminant Management Models

Development of contaminant management plans that balance acceptable environmental risks against acceptable costs is a major goal of the Great Lakes community. Optimization, uncertainty, and risk analysis techniques are useful tools for achieving this goal, but have been used only sparingly to date. GLERL established a program in late FY 84 to explore the application of these techniques to improve the management strategies for Great Lakes natural resources.

During FY 86 we completed a first-generation optimization model that takes uncertainty into consideration when determining the cost-effectiveness of contaminant treatment strategies. Management of phosphorus loading was chosen as a test case because of the importance and cost of dealing with this problem; the availability of a large, reliable data base; and the existence of tested phosphorus mass-balance models for the lakes. The results showed that there is a range of goal-achievement vs. cost for consideration by resource managers. Strategies specified under the 1978 Water Quality Agreement between the United States and Canada are not likely to achieve more than 60 percent of the goal, whereas those strategies identified through the optimization model are less costly and more effective (Fig. 14).

In FY 87 work in this area focused on the UGLCCS Program and is reported in that section.

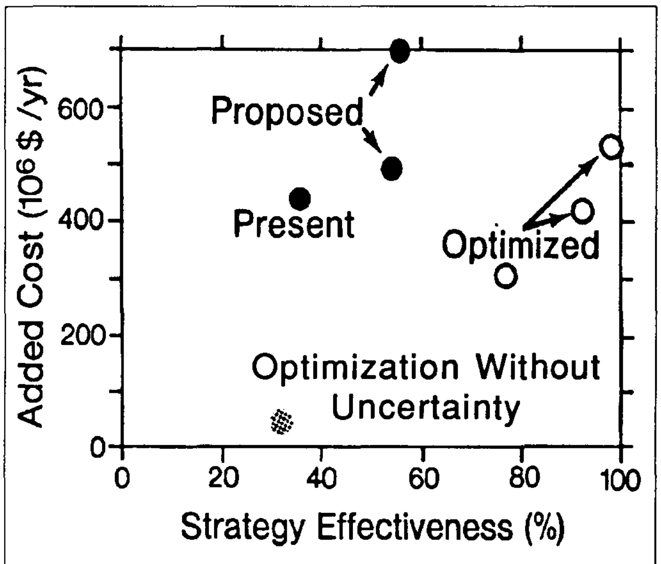

Figure 14. *Cost versus effectiveness of achieving target phosphorus concentrations in all Great Lakes basins. Phosphorus management strategies tested under variable phosphorus loading and settling conditions included: "Present" (1978 Water Quality Agreement), "Proposed" (enhancements to the 1978 agreement), and "Optimized" (optimal strategies identified with combined uncertainty and optimization model). The hatched dot represents the results of an optimization analysis that did not account for uncertainty in phosphorus loading and settling.*

UPPER GREAT LAKES CONNECTING CHANNELS STUDY (UGLCCS)

The UGLCCS is an international (United States-Canada) and interagency multi-year study of water quality and ecosystem dynamics in the upper Great Lakes' connecting channels. Study areas include the St. Marys River, the St. Clair River, Lake St. Clair, and the Detroit River; all are designated by the International Joint Commisson as "Areas of Concern" in which environmental quality is degraded and beneficial uses of the water and biota are adversely affected. The goals of the study are (1) to determine the existing environmental condition of the study areas, (2) to identify and quantify the impacts of contaminant loading on ecosystems and human uses of the study areas, (3) to determine the adequacy of existing or proposed programs for ensuring or restoring beneficial uses, and (4) to recommend appropriate programs for protecting the study areas.

Environmental Models of Lake St. Clair

A conceptual ecosystem model was developed for Lake St. Clair for the purpose of understanding the dynamics of shallow (near-shore) systems, and how these dynamics affect the fate and transport of contaminants. The conceptual model was completed and provided a basis for constructing a model of ecological processes and their interactions with contaminants in Lake St. Clair. During FY 87 it was shown that submerged and emergent aquatic plants appear to be important contributors, both in amount and with time, to carbon flow through the lake food web.

We completed development of a generic model to simulate contaminant fate in Lake St. Clair. The model was based on the EPA's chemical transport and fate model, TOXIWASP, which assumes chemical equilibrium between dissolved, particle-bound, and biota-bound contaminant phases. TOXIWASP was modified and debugged to run on the GLERL VAX 11/780 and the Gaithersburg CYBER 205 computers. In the model, water movement was controlled by wind-induced flow fields generated by a Lake St. Clair hydrodynamic model developed by GLERL's Physical Limnology and Meteorology Group. The model was calibrated and then run against a known data set for PCBs in Lake St. Clair. (Fig. 15).

The generic TOXIWASP-based model was the basis for work begun in FY 87 to test and compare equilibrium and kinetic approaches to modeling contaminant transport and fate (Fig. 16). The validity of the assumption of phase equilibrium, the basis of the TOXIWASP model, is of concern and needs to be evaluated.

A prototype toxic contaminant fate and effects model was developed for plankton systems. The state-of-the-art framework developed in this model is being used to predict the effects of contaminants on plankton populations. Results from this model indicate that it may be unwise to attempt to model contaminant effects without also modeling contaminant fate.

Phosphorus is an important nutrient, and, when anthropogenically enriched, a critical pollutant in the Great Lakes system. As part of the UGLCCS program, the cycling, source loads, and sinks of phosphorus in Lake St. Clair were studied.

A total phosphorus mass balance budget for Lake St. Clair was completed. It was used to identify the relative importance of phosphorus loading sources (Huron > Diffuse Runoff >>> Atmospheric & Point), and to determine if Lake St. Clair is a net source or a net sink for phosphorus (Fig. 17). Over the six-year study period (1975–1980 inclusive), the mean external load (input) and the mean outflow (loss) were not statistically different. Assuming accurate estimates of inputs and losses,

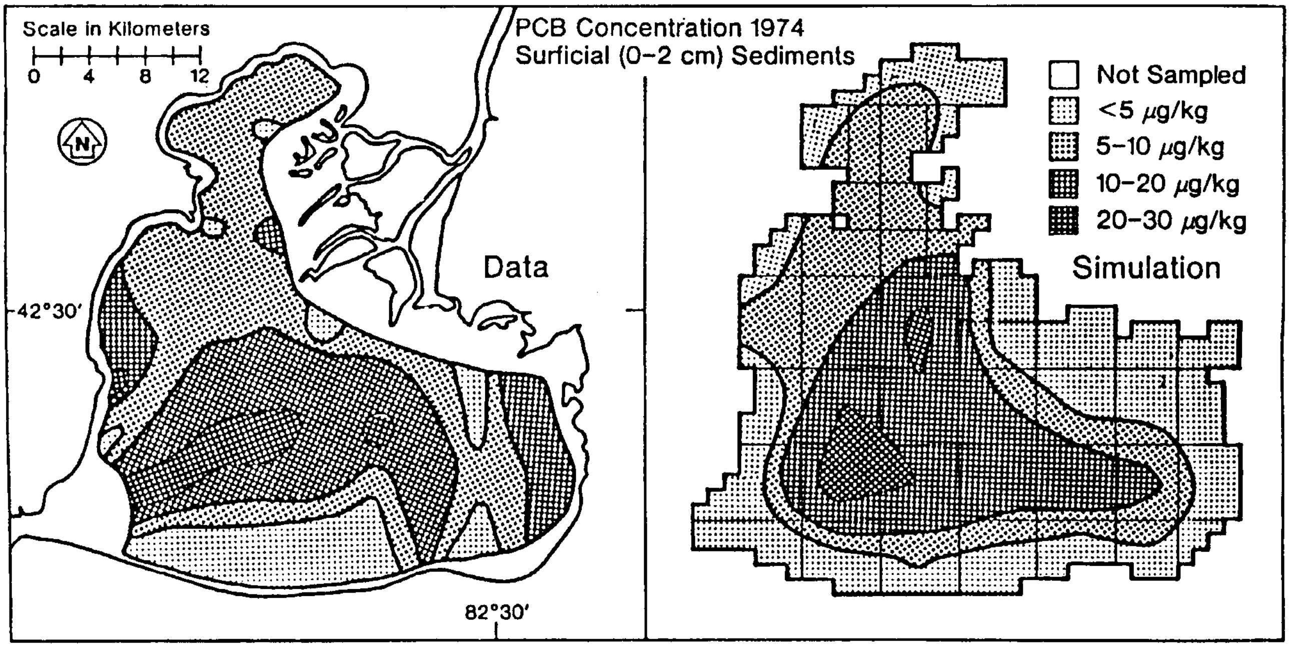

Figure 15. *The contaminant fate model developed by the ESS group reasonably predicts the fate of PCBs in Lake St. Clair.*

we concluded that there is no apparent net source or sink for phosphorus in Lake St. Clair.

Field and Laboratory Experiments

GLERL scientists conducted microcosm experiments to determine how much phosphorus is released from Lake St. Clair sediments. In addition, a survey of mussel populations was completed, and measurements were made of phosphorus filtration, biodeposition, and excretion by mussels in Lake St. Clair. The abundance, biomass, and species composition were estimated, and the age-structure and production of the most abundant species were determined. These data will provide information on the general "health" of the mussel population and will also allow us to estimate the impact of sediment release and mussel excretion on phoshorus cycling within the lake.

Extensive coring was undertaken in Lake St. Clair during May and September, 1985 in collaboration with Canada Centre for Inland Waters. The operation resulted in acquisition of diver-collected sediment cores from an evenly spaced grid covering most of the fine grained sediments in the lake. Two cores were collected from each of 36 sites, sectioned in the field, and materials were divided between participating institutions for laboratory analysis. Results show a pronounced accumulation of ^{137}Cs in areas of fine grained sediments, generally the central areas of the lake. Modeling of ^{137}Cs removal indicates a sediment residence time of about 5 years.

GLERL's previously developed Coupled Lakes Contaminant Fate Model was applied to estimate the time-dependence of ^{137}Cs loadings to Lake St. Clair and the connecting channels. The calculation showed that the dominant source in Lake St. Clair is inflow from Lake Huron, and that if all the ^{137}Cs were retained in the system, a total of 471 Curies should be found in the sediment. We measured an integrated inventory of 37 Curies. Thus less than 20 percent of the total loading of the radionuclide to the system appears to remain in bottom deposits. This suggests that most particle-associated contaminants must migrate through Lake St. Clair and enter Lake Erie.

Three week-long synoptic current surveys were conducted in Lake St. Clair during FY 85 to ob-

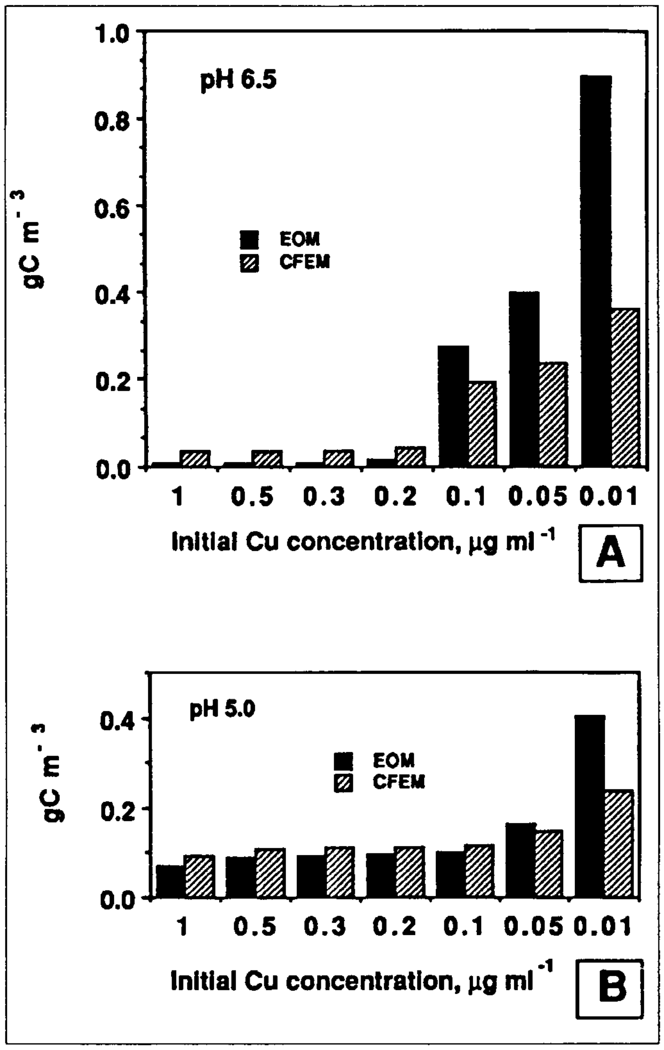

Figure 16. *Comparison of a combined fate and effects model (CFEM) with effects-only model (EOM) shows that marked differences may result in predicted algal biomass (gC m^{-3}). Simulated algal biomass at 96 h for seven initial Cu concentrations and two pH levels are compared. Differences between the two models are more at pH 6.5 (Fig. A) than they are at pH 5.0 (Fig. B). At pH 6.5 and Cu concentrations less than 0.2 ug ml^{-1}, the EOM predicts greater biomass than CFEM does. Conversly, at Cu concentrations greater than or equal to 0.2 ug ml^{-1}, the EOM predicts less biomass than the CFEM does.*

serve and measure flow throughout the basin under calm and storm wind conditions. Analysis of this data set, involving reduction of the raw data to measured currents and comparison of the measured currents to circulation model predictions, was conducted during FY 86 and FY 87:

- Circulation patterns in Lake St. Clair at three-hour intervals were calculated with a two-dimensional numerical circulation model for the period May–November of 1985 using winds measured by the NWRI meteorological buoys and compared to measurements obtained from drifting buoys and from three synoptic ship surveys of currents in the lake.

- The currents in Lake St. Clair were found to be dominated by hydraulic flow, but wind-induced changes in the circulation pattern can change residence times from 2 days to more than 30 days. The average residence time is about 9 days.

During late FY 85 and early FY 86 GLERL and NWRI (Canada) performed an extensive joint field measurement program in Lake St. Clair to measure wave dissipation and the effect of waves on resuspension in shallow water (WAVEDISS '85: Wave Attenuation, Variability, and Energy Dissipation in Shallow Seas). The experiment ran from September to December, 1985 and resulted in the collection of nearly hourly measurements of significant wave height and wave period at three of the six towers. The other three towers recorded data only when the wind speed exceeded a preset threshold, usually set to 7 m/s, so that the data covered only

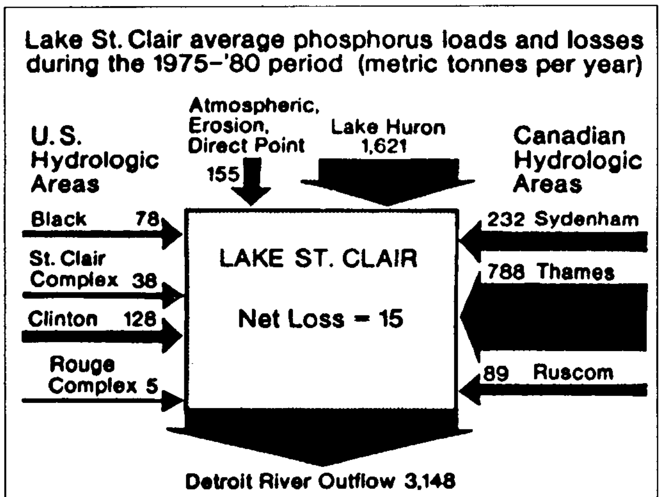

Figure 17. *Phosphorus loads to Lake St. Clair were dominated by the outflow from Lake Huron and non-point loads from primarily agricultural areas.*

the periods of high wind and, therefore, high waves. Meteorological data consisting of hourly measurements of wind speed, wind direction, air temperature, and water temperature were obtained from several meteorological buoys in the lake.

The meteorological data were used to drive the GLERL-Donelan Numerical Wave Prediction Model. This model has been used successfully to predict wave height and wave direction in Lakes Erie and Michigan. In the mathematical formulation, waves are assumed to obey the deep water dispersion relationship, and refraction and bottom dissipation are ignored. In addition to running the regular (deep water) GLERL-Donelan model, a modified (shallow water) version of the model was developed to account for the effects of finite water depth on wave propagation.

The experimental data were used to drive both versions of the model. To our surprise, the deep water version provided quite acceptable estimates of wave height, even for the largest waves at the shallowest station (3–4 m of water). The shallow version of the model tended to underestimate the highest waves at all stations. Plans were made to examine why the deep water model worked so well in Lake St. Clair. One possibility that will be explored is that the wind momentum input function is oversimplified in the model and that if it were formulated more realistically, the deep water model would also tend to overestimate the highest waves.

MARINE HAZARDS AND LAKE HYDROLOGY

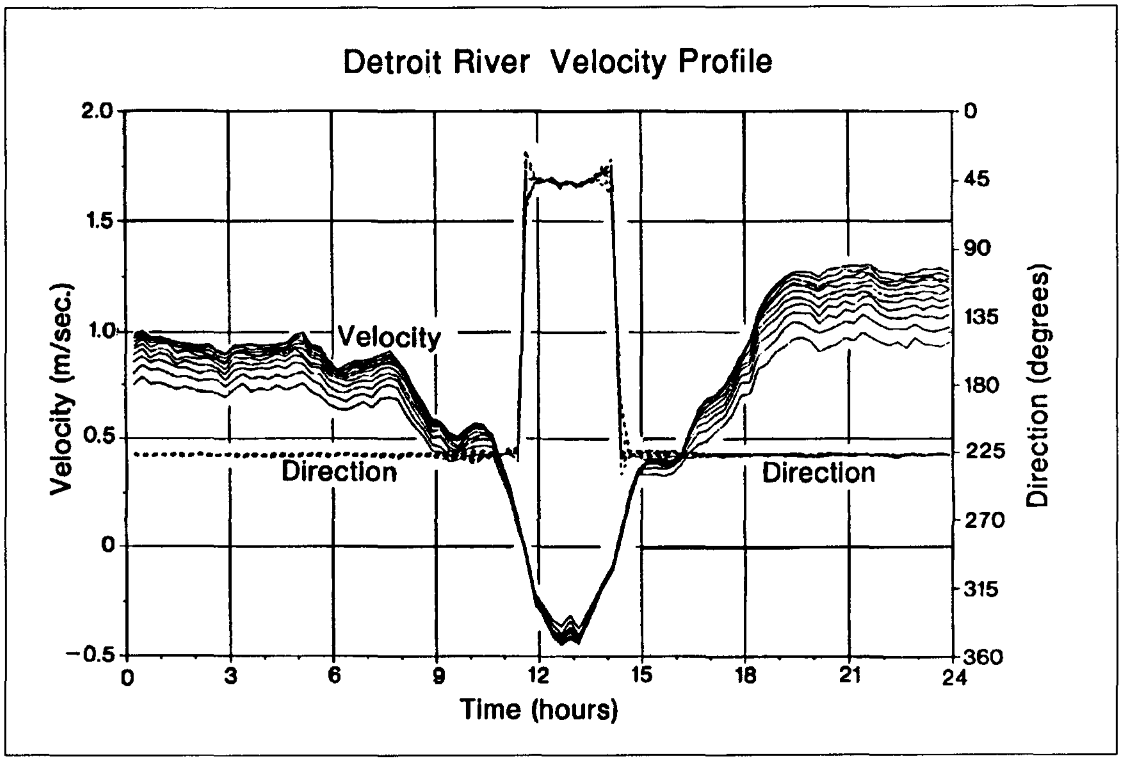

Figure 18. *The normal flow of the Detroit River is from Lake St. Clair to Lake Erie. However, under a combination of meteorological and ice conditions the flow can reverse. These flow reversals are interesting as hydraulic phenomena, but are more important because they disrupt the normal contaminant pathway. Flow reversals could transport contaminants that would ordinarily flow into Lake Erie into Lake St. Clair instead, causing potential detrimental effects upon Lake St. Clair's ecosystem. The use of water gradient procedure in conjunction with computerized unsteady flow models are used to determine the occurrence of flow reversal—their frequency, magnitude, and duration—and prerequisite conditions.*

Marine Hazards and Lake Hydrology research focuses on (1) improving prediction of environmental phenomena associated with the National Weather Service (NWS) marine warning and forecasting services and the U.S. Army Corps of Engineers (COE) forecasting and regulation of Great Lakes water flow, and (2) providing better tools and methods for short- and long- term assessments of water resources of large lakes. GLERL research in these areas includes field and analytical investigations to develop simulation and prediction models of over-water wind and wind-waves, water surface oscillations, storm surges, and flooding; lake ice formation, growth, movement, and breakup; and hydrologic lake levels, water supplies and balance, water quantity management, and flows in the connecting channels (Fig. 18). GLERL staff work closely with colleagues at the forecasting and warning service agencies to assure that GLERL products meet the needs of the operational forecasters. Products released to the user community continue to be improved by GLERL researchers, either by fine-tuning or by the addition of new tools and capabilities.

Surface Waves and Water-Level Fluctuations

The primary driving forces for water movements in the Great Lakes are the wind acting on the surface, the exchange of heat across the water-atmosphere boundary, and the hydraulic flow through the system. Wind-generated surface waves can be a significant hazard to ships and recreational boaters, and storms can produce rapid short-term elevations of water level in the shallower bodies of water such as western Lake Erie, Green Bay, and Saginaw Bay. The ability to predict wind-generated waves, storm surge, and seiches produced by storms is critical to the safety of marine users and shoreline property interests on the Great Lakes.

Shallow-Water Wave Forecasting

Some of the most heavily populated and most intensely used areas of the Great Lakes are also the shallowest (Lake St. Clair, Green Bay, Saginaw Bay, and western Lake Erie, for example). Although wave forecast methods for deep water are well-developed, shallow-water wave forecasting is still in its infancy.

During late FY 85, GLERL initiated research on the effects of shallow water on wave dissipation and attenuation that includes both field experiments and development of applicable models. The first experiment was a joint effort during FY 85 and FY 86 between GLERL and Canada's NWRI and Atmospheric Environment Service to study shallow-water wave processes in Lake St. Clair (Fig. 19). It was conducted as part of the UGLCCS program (see Upper Great Lakes Connecting Channels Study).

Another shallow-water wave measurement program was carried out in early FY 87 to further investigate the relative importance of shallow-water effects and island shadowing on wave generation and propagation in lakes. An instrument tower and a wave buoy were installed in western Lake Erie along with the regular NOAA - National Data Buoy Center (NDBC) buoy (already there and deployed every year). Data were collected through November 1987, after which the instruments were retrieved before the winter freeze-up.

Wave Height Studies and Models

GLERL staff continued to support the use of the GLERL Interactive Wave Prediction Model by marine forecasters at the NWS Great Lakes Weather Service Forecast Offices (WSFOs). The model, housed on the GLERL computer, was accessed several hundred times by NWS forecasters during FY 86 and FY 87.

NDBC has been deploying NOMAD buoys in the Great Lakes for surface wave and meteorological measurements since 1979. GLERL has been actively using these well-archived data in a variety of tasks since the implementation of NDBC buoy measurements:

- A wave climate synthesis system was developed for the Great Lakes. Long-term climate extremes of wave heights can be readily estimated from given long-term wind speed statistics where wave measurements are not available.

- It is known that long-term wave heights can be modeled by log-normal or Weibull distributions, and that wind speed can be represented by a Rayleigh distribution. GLERL scientists postulated the existence of joint distributions between wind speeds and wave heights and between wave heights and wave periods. Since wind data are generally obtainable, the existence of validated joint distribution models can lead directly from wind statistics to wave statistics. During FY 87 wind and wave measurements recorded from the eight NOMAD buoys during 1981–1984 were analyzed for long-term wind and wave statistics for use in testing the joint distribution postulate. A wave climate experiment was undertaken to measure waves in the western basin of Lake Erie with GLERL's satellite-reporting Waverider buoy. The buoy reported wave measurements during September and October of 1986. The data collected from this experiment will be used in conjunction with shallow-water wave studies and for verification of wave prediction models.

Applications of GLERL's Storm Surge Model

At the request of the Department of Natural Resources of Michigan and of Ohio, the Army COE, several Sea Grant Programs, and other agencies with responsibility for Great Lakes shorelines, GLERL developed and distributed a PC-based computer program that can assist in planning for storm surges on the Great Lakes. For a given mean lake level, wind speed, and wind direction, the program provides the maximal and minimal expected water level elevations at selected points on the shoreline of the lakes. The program is being used extensively as a planning tool for disaster preparedness and storm surge planning.

Figure 19. *A wave tower used on Lake St. Clair during the GLERL–NWRI study on wave processes. Ice formed on the tower before it was retrieved December 1986.*

Great Lakes Ice

The seasonal ice and snow cover in the Great Lakes basin has a major effect on both the economic and social well-being of the community. It affects navigation, shoreline erosion and damage, hydropower generation, water supplies, fisheries, recreation, and local climate. Understanding, simulating, and forecasting the ice and snow cover require improved information on the formation, growth, movement, and decay of the ice cover; the extent, thickness, and water equivalent of the snow cover; a better definition of the characteristics of the snow and ice cover; and the development of numerical models depicting the processes governing freeze-up, areal extent, thickness, transport, and breakup of the ice cover, and metamorphosis and ablation of the snow cover.

Operational Ice Forecasts

A menu-driven computer algorithm was developed during FY 85 for NWS to forecast ice conditions on the St. Marys River. The algorithm forecasts date of ice formation, ice growth, and date of ice loss. During FY 86, procedures to access and run the algorithm, data input requirements, and forecast limitations were demonstrated and documented. Access to and support of the algorithm on GLERL's computer were provided to both NWS and the Army COE for use in making (experimental) operational forecasts during the 1985–86 and 1986–87 winter seasons on the Great Lakes.

During FY 87 we transferred computer code to NWS Cleveland for making ice forecasts for the St. Marys River and four bay and harbor sites, and for analysis of freezing degree-days and thawing degree-days. NWS Cleveland and GLERL are now using the same convention for calculating degree-days, and NWS Cleveland can now automate degree-day calculations and make operational use of degree-days for ice forecasts.

Nearshore Ice Thickness

A study to analyze and report on the engineering statistics of a nearshore ice thickness data base was completed during FY 87. Two reports were published which contain statistics for maximal thicknesses, growth and dissipation rates, ice cover durations, and average white and total ice amounts and ranges for each of the Great Lakes as well as for selected individual stations in the network.

Spectral Reflectance of Ice and Snow

During FY 85, airborne measurements of spectral reflectance in the visible and near-infrared region (400–1100 nm) from old snow, open water, and several ice types were made from an altitude of 300 m over Saginaw Bay. These measurements were corrected for the effects of atmospheric attenuation and path radiance by using a combination of existing standardization techniques involving light and dark secondary standards calibrated against a barium sulfate reference panel used as the primary standard (Fig. 20).

Other studies that have used a barium sulfate panel for a primary standard have assumed that it behaves like a perfect diffuse (Lambertian) reflector and therefore follows Lambert's cosine law

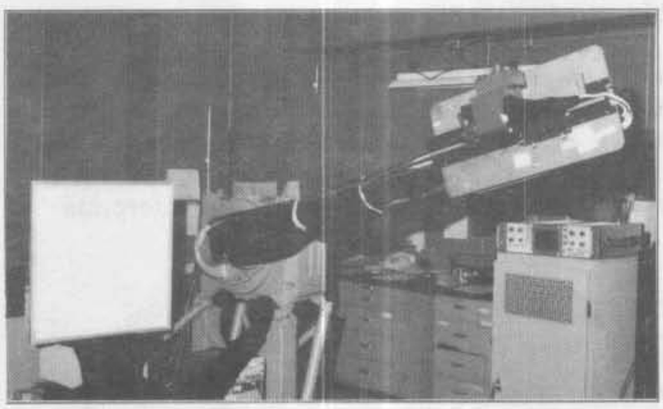

Figure 20. *Barium sulfate panel mounted on five-axis positioner. The rotating boom, on which the detector is mounted, is shown at an angle approximately +20° from normal to the panel.*

(with constant illumination normal to the surface, the intensity or reflectance from a Lambertian surface varies as the cosine of the angle of view, but has a constant radiance of 1). During FY 86 the barium sulfate reference panel used by GLERL as the primary standard for the field calibrations was tested for Lambertian response at different incident angles and wavelengths. Deviations from a perfect Lambertian response were documented for most angles and at all wavelengths measured, leading to the conclusion that the airborne data must also be corrected for errors due to the imperfect Lambertian response of the reference panel. The FY 85 data were corrected for the non-Lambertian response of the primary reference panel, resulting in an average decrease in reflectance of 8.3 percent in the visible band and 3.6 percent in the near-infrared band for the types of ice measured.

During FY 87 a cooperative study was initiated with scientists at NASA's Goddard Space Flight Center to document and define the reflectance characteristics in the visible and near-infrared range for various types of Great Lakes ice and snow. A library of such measurements established for different ice and snow surface types could improve interpretation of satellite sensor data from these surfaces and would help to improve the estimation of hemispheric reflectance from satellite observations. The latter is a parameter needed for most climate and radiation budget models for the shortwave spectrum.

- A sphere-scanning spectroradiometer was used to determine the reflectance in three spectral bands of snow and three types of ice under clear skies.

- Data were obtained from early morning to late afternoon (approximately every 5° of solar zenith angle) and included reference panel diffuse sky irradiance and sun photometer data. The data will aid reflectance modeling and satellite interpretation efforts.

Spectral Transmittance Through Ice

A study to define the spectral transmittance of solar radiation through ice and snow in the visible and near-infrared ranges was initiated during FY 87:

- An underwater spectroradiometer was configured to operate under the ice and in the water column below the ice to a depth of 30 m. This is the first time this type of instrument system has been successfully deployed through freshwater ice; divers are often used in the Antarctic to take similar measurements.

- Data were collected through a wide variety of ice types. Small amounts of radiation penetrate to 10–12 m even on overcast days and in relatively turbid waters. Spectral shifts in radiation intensity were observed at various depths, and radiation transmittance directly under various ice types did not appear to vary widely in spectral composition, although it did vary in intensity.

Degree-Day Climatology of the Great Lakes Region

An 81-year (1897–1977) degree-day climatology for the Great Lakes region was updated with the addition of data for 6 years (1978–1983). The cumulative frequency distribution of the seasonal maximal freezing degree-days at 25 stations for the base period 1897–1983 was used to revise a winter severity index developed in an earlier study. Winter severity class limits were developed for each of the Great Lakes. The period of the update is remarkable in that it contains some of the most severe and one of the mildest winters of the whole 87-year base period.

Effect of Climatic Change on Great Lakes Ice Cycles

A new task was developed during FY 87 to analyze the effects of climatic change on Great Lakes ice cycles; partial funding for this work was provided by EPA:

- Lakes Erie and Superior were chosen as representative of the extremes in climate, water mass, and lake depth for the Great Lakes. Each lake was divided into basins representative of different heat storage capacities.

- Basin mean ice concentration, air temperature, and freezing and thawing degree-days were calculated for three basins of Lake Erie and two basins of Lake Superior and Whitefish Bay over 20 winters from 1960 to 1979.

■ Empirical models to simulate basin mean ice concentration are under development and evaluation.

Thermal Structure of the Great Lakes

Knowledge of the thermal structure of the Great Lakes in fall and winter is important to studies of ice formation, the effects of climate change on the Great Lakes, and the water balance of the Great Lakes:

■ GLERL finished and published its description of the fall and winter thermal structure of Lake Superior.

■ GLERL, in consultation with NWS, planned a program to collect Great Lakes temperature profile data at the suggestion of NOAA's National Ocean Service (NOS). NOS installed a Shipboard Environmental [Data] Acquisition System (SEAS) onboard a Great Lakes commercial vessel. Temperature profile data collected by SEAS are available in near-real time for operational use by NWS.

Hydrologic Properties

The availability of adequate supplies of freshwater is potentially one of the country's most serious long-range problems. The Great Lakes, with a total combined surface area of 247,000 km^2, contain 23,000 km^3 of water, or approximately 95 percent of the United States' fresh surface water. This water is used for navigation, drinking, industrial processes, hydropower, irrigation, transportation, and wildlife and fish habitats. Major changes in water quantity are caused by annual and seasonal variations in the water supply, consumptive use, and interbasin diversions. The usual measure of water quantity is the lake level of the individual lakes. Over the past 120 years the levels have fluctuated about 2 m, and the normal seasonal fluctuation has been 35–50 cm between winter minimum and summer maximum. Superimposed upon the natural fluctuations are a number of anthropogenic changes which have or could have major effects on Great Lakes water quantity.

During 1985, high lake levels set records on Lakes Superior, Michigan, Huron, St. Clair, and Erie (Fig. 21). GLERL's hydrologic research program is directed toward improving our knowledge of the hydrologic and hydraulic processes, improving methods of forecasting and simulating water supplies and lake levels, and improving large-river dynamic flow models. The research assists in water resource planning and management and in the solution of problems related to water supply, water quality, shore erosion, flooding, hydropower, navigation, and recreation.

Rainfall-Runoff Modeling

Deterministic forecasts (outlooks) of accumulated net basin water supply components are required in near-real time for use in regulating water levels of large lakes. The GLERL Large Basin Runoff Model was developed for the runoff component several years ago. This general model has been modified and refined to improve its application to the Great Lakes. To calibrate the model, each lake is divided into sub-basins that drain into that particular lake, and then all available historical data for all sub-basins about the lake are used to perform the initial calibrations. Initial calibrations are complete for Lakes Ontario and Superior. During FY 86 and FY 87:

- Daily meteorological data from 1954 through 1985 over the Lake Erie basin were reduced with updated algorithms; data on the other Great Lake basins were updated through 1985.

- Final calibrations of the Large Basin Runoff Model were made for the 99 watersheds about Lakes Michigan, Huron, St. Clair, Erie, and Ontario, completing the application to all 121 Great Lakes watersheds and 7 Lake Champlain watersheds; the distributed-parameter applications produced correlations for these basins of 0.93, 0.92, 0.89, 0.91, and 0.93, respectively.

- Automation of all calibration, climatic data reduction, and forecast procedures was completed so that GLERL's water supply technology can be applied to other large lake basins.

- GLERL's Hydrologic Response Model was evaluated and compared with the COE hydraulic routing model for determining channel flows in the unregulated portion of the Great Lakes system; our model produces equivalent results, but is 94 percent faster than the COE approach.

- The Large Basin Runoff Model and its applications for the 106 upper Great Lakes watersheds above the Niagara River were integrated with estimates of over-lake precipitation and lake evaporation, the Lake Superior regulation plan, and the Hydrologic Response (channel routing) Model to make possible system-wide simulation of the upper Great Lakes water supplies, connecting channel flows, and lake levels.

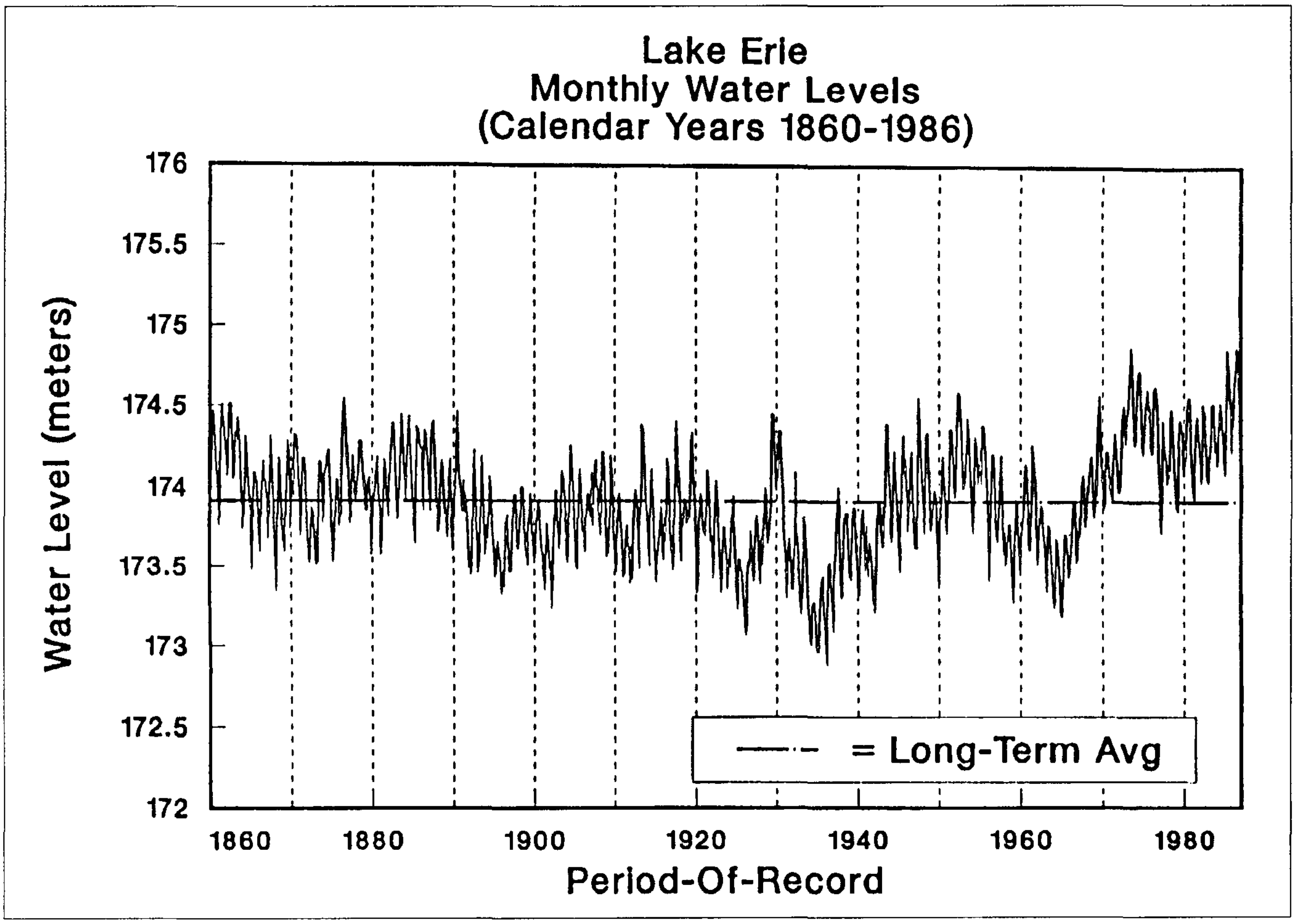

Figure 21. *Monthly water levels for Lake Erie from 1860 - 1986.*

Water Supply Forecasting and Lake Level Simulations

During FY 85, GLERL completed work to semi-automate a forecasting software package that uses the Large Basin Runoff Model, historical overlake precipitation, and lake evaporation estimates to predict Lake Superior water supplies in near-real time. The software may be used with GLERL's Great Lakes Hydrologic Response Model, developed several years ago, to forecast or simulate the hydrologic water balance through the Great Lakes system. It integrates the hydrologic components and simulates water routes through the system into the St. Lawrence River. The model provides the resulting lake levels for each of the Great Lakes and Lake St. Clair, and the flows in the connecting channels. During FY 86 and FY 87:

- An error analysis revealed that about 20 percent of the error in the GLERL forecasts derives from NWS weather outlooks. About half the remaining error results from modeling lake evaporation.

- The Hydrologic Response Model was modified, extensively documented, and recalibrated to reduce the error in modeled Lake Michigan-Huron levels.

- The applications were reinstalled for the Army COE, Detroit District, on its new Harris 800 computer, and GLERL's production of experimental forecasts was terminated. The COE in Detroit initiated a multi-year program to evaluate and compare Lake Superior forecasts made using the GLERL software package with forecasts made using existing operational methods.

■ Wind set-up errors in computed mean lake levels were estimated from linearized hydrodynamic shallow-water equations applied to Lakes Erie and Superior for historical and current gauge networks; optimal network gauge selections were made from the 16 available Lake Erie gauges and the 10 available Lake Superior gauges to minimize set-up error in the estimated spatial mean lake level (Fig. 22). These networks are being used to improve our estimates of historical lake levels and attendant water balances.

■ Testimony from pre-1914 IJC hearings was examined to determine the historical basis for the present IJC limits on Lake Superior levels and revealed that present limits were intended only as regulation goals.

Development of a generic Thiessen weighting package was completed. The generic package is easily applied to different areas and to different types of data. It was installed on the Detroit COE's Harris 500, the Chicago COE's IBM-PC, the NWS Northeast River Forecast Center's (NERFC) Nova Eclipse, and the NWS Office of Hydrology's (OH) Airborne Gamma Radiation Snow Survey IBM/PC-AT. The Army COE, Detroit District, and the NWS NERFC use it to make near-real time areal estimates of snow water equivalents from aerial surveys of Lakes Superior and Champlain, respectively. The NWS OH Snow Survey Program uses the generic Thiessen weighting package for the Lake Superior and Lake Champlain basins and expects to use it for other areas where aerial snow surveys are conducted (Souris-Red-Rainy basin and St. Johns River basin).

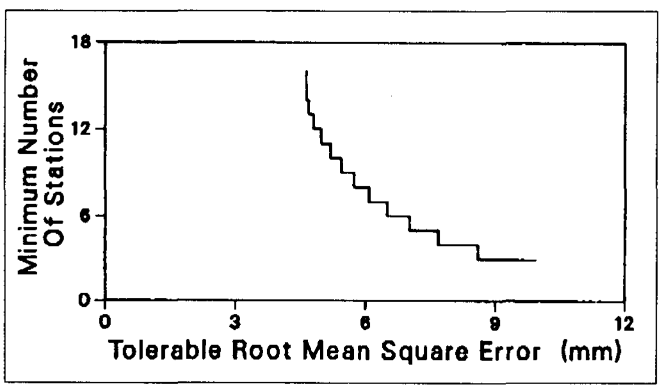

Figure 22. *Number of existing Lake Erie water level gages required to limit error in the spatial-mean water level estimate. Each number was computed by considering predicted wind set-up errors resulting from the spatial-optimum choice of existing gages for each network size. Choice of gages in this manner allows consideration of lake surface tilt from existing hydrodynamical models.*

Lake Evaporation Modeling

Lake evaporation models are needed for lake-level forecasts and simulations, but evaporation estimates are difficult because of data unavailability, process complexity, and lack of heat storage understanding. Model building has always been difficult because no direct observations of Great Lakes evaporation are possible for calibrating or verifying models. Model building, calibration, and verification are now possible with the advent of remotely sensed water surface temperatures for each of the Great Lakes. GLERL developed a model that considers both heat storage and evaporation to extrapolate water surface temperatures for determining evaporation:

■ Based on advice from Environment Canada, GLERL revised its potential evaporation models.

■ A first-order heat balance and heat storage function for Lake Superior was constructed and tested with NOAA's satellite data.

■ The heat balance was used to determine and partially verify evaporation estimates by matching observed Lake Superior water surface temperatures; good agreement was obtained with observed temperatures, spring and fall turnover dates (when the lake water circulates vertically because of density changes), and evaporation (computed as a residual in a water balance for Lake Superior).

Lake evaporation can now be estimated with confidence for other Great Lakes, since observed temperatures are available. The improved evaporation models can be merged with GLERL's near-real time forecast packages for the COE Lake Superior water level forecasts and the NWS Northeast River Forecast Center Lake Champlain water supply forecasts.

Lake Superior Water Balance

Analysis of thermal corrections to Lake Superior's monthly change in storage, based on Expendable

Bathythermograph transects made during 1976, revealed that the thermal component of change in lake storage is an important factor in the water balance of that lake. Thermal change in lake storage was largest during the period of thermal stratification (July, August, and September) when it accounted for more than 10 percent of the uncorrected change in storage. Thermal effects on net basin water supply (NBS) were found to be more than 100 percent of the uncorrected NBS in January, and between 12 percent and 70 percent of uncorrected NBS in February, July, August, and September of 1976.

■ Development of corrections to the Lake Superior water balance, based on the thermal expansion and contraction of water, was extended through joint volumetric and mass balances to consider additional bathythermograph transects that became available last year.

Seasonal Influences on River Flows

The St. Clair and Detroit Rivers are major connecting channels between Lake St. Clair, Lakes Michigan-Huron, and Lake Erie, respectively. Ice buildup and jamming in the St. Clair River can have a significant effect on the seasonal cycle of water levels in the Great Lakes. Ice buildup reduces the channel capacity of the rivers and results in water storage in Lakes Michigan and Huron and reduced flows in the rivers, especially the St. Clair River. Reduced flow in the St. Clair River can have a significant effect on the level of Lake St. Clair. Wind set-up in Lake Erie can push water into the west end of the lake, which can result in a flow reduction and a short-term flow reversal in the Detroit River. The latter may provide a mechanism for the transport of contaminants from the Detroit River into Lake St. Clair.

The St. Clair River Winter Flow Experiment was extended into the FY 87 winter season and was terminated after five consecutive years of winter flow data for the St. Clair River. Data over two consecutive winter seasons have also been collected for the Detroit River (Detroit River Winter Flow Experiment). The results of this multi-year experiment have demonstrated the feasibility of using in situ current meters to monitor winter flows. However, it was shown that electromagnetic current meters are not appropriate for such measurements, owing to the significant loss of sensitivity caused by frazil ice during the winter and by weeds during the summer and fall. Acoustic Doppler current meters, on the other hand, work well in spite of these conditions. The data were also used to evaluate the St. Clair-Detroit River flow transfer method, which was found to be very useful when one of the rivers is free of ice problems.

During FY 86, historical data were examined for evidence of possible flow reversals in the Detroit River during 1900–1985. Eight possible occurrences were identified and selected for further analysis, including one major episode that occurred in April 1984 (when GLERL had meters in the river) and coincided with a massive St. Clair River ice jam. At this time there was a reverse flow into Lake St. Clair, with rates reaching a maximum of 2500 $m^3 s^{-1}$ for several hours. A second major episode may have occurred during February 1939. From this study it would appear that the main condition under which a flow reversal occurs is a severe ice jam on the St. Clair River, coupled with a Lake Erie wind set-up. Thus, although flow reversals are relatively rare events, they may provide a mechanism for the transport of contaminants into Lake St. Clair.

OUTREACH ACTIVITIES

The GLERL mission includes the development of environmental information, data, and service tools in support of user needs in government and private organizations. Identification of the environmental information required in association with GLERL's mission helps guide our research programs and is a vital activity of GLERL staff. Participation on boards, commissions, task forces, and committees is an essential part of this effort. An equally important role is played by the Publications Unit (see Facilities and Services, page 43), which supports all aspects of publishing GLERL's products making GLERL publications available to those who need them, as well as answering information requests, and creating displays and general literature concerning GLERL's products and work.

International and Interagency Participation

Staff participation on boards, commissions, task forces, and committees provides a mechanism for defining new research initiatives, identifying user needs, and guiding the development of usable products. It helps to maintain staff involvement in programs concerned with environmental problems and keeps staff familiar with water- and land-oriented resource development and management issues.

During FY 86 and FY 87 GLERL staff participated as members (unless noted otherwise) of the following International Joint Commission boards, committees, and task forces:

- International Great Lakes Technical Information Network Board (F. Quinn)
  - Hydrology Committee (T. Croley)
  - Systems Evaluation Committee (T. Croley)
- International Great Lakes Levels and Flows Advisory Board (F. Quinn, U.S. Co-chair)
- Great Lakes Water Quality Board, Surveillance Work Group
  - Great Lakes Surveillance Work Group (P. Landrum, FY 87)
  - Lake Michigan Task Force (B. Eadie)
  - Lake Erie Task Force (J. Robbins, Consultant)
  - Lake Huron Task Force (T. Nalepa, FY 87)
  - Surveillance Design in Areas of Concern (D. Scavia, FY 86)
  - Task Force on In-Place Sediment Contaminants, Workshop on Monitoring in Areas of Concern (B. Eadie, Co-chair, FY 86)
  - Upper Connecting Channels Task Force (J. Derecki)
  - Workshop on Atmospheric Input to the Great Lakes (B. Eadie, FY 87)
- Great Lakes Science Advisory Board (A. Beeton, U.S. Chair, FY 87)
  - Council of Great Lakes Research Managers (D. Reid, FY 87)
  - Great Lakes Levels Task Force (F. Quinn, Chairman)
  - Task Force on Great Lakes Modeling (D. Scavia, FY 86)

Other interagency, professional society, and international activities:

- American Geophysical Union
  - Committee on Personal Computers (T. Croley, member)
- American Institute of Hydrology
  - Michigan Section (T. Croley, President)
- American Meteorology Society
  - Hydrology Committee (F. Quinn)
- American Society for Limnology and Oceanography
  - Board of Directors (D. Scavia)
- Coordinating Committee for Great Lakes Hydraulic and Hydrologic Data Riverflow Subcommittee (F. Quinn)
- Department of Commerce Consolidated Scienti-

fic Computing System Technical Committee (G. Spalding)

- Green Bay Study Mass Balance Study (USEPA)
  - Field Operations Committee (N. Hawley, member)
  - Management Committee (A. Beeton, member)
  - Modeling Working Group (T. Fontaine, J. Saylor, members)
  - Technical Advisory Committee (B. Eadie, P. Landrum, members)

- Huron River Watershed Council (D. Scavia, S. Tarapchak, Advisors)

- International Association for Great Lakes Research
  - Board of Directors (F. Quinn, Past-President, FY 86; D. Scavia, Secretary, FY 86; D. Schwab, Treasurer, FY 87; B. Eadie, member)
  - Exhibits Committee, 30th Annual Conference (M. Quigley, Co-chair)
  - *Journal of Great Lakes Research* (F. Quinn, Associate Editor)
  - Technical Committee (D. Scavia, Secretary)

- International Association for Hydrologic Research
  - Section on Water Resources Systems (T. Croley, U.S. Representative)

- International Association on Water Pollution Research and Control Specialist Technical Group on Systems Analysis in Water Quality Management (T. Fontaine, member)

- International Association of Theoretical and Applied Limnology (A. Beeton, U.S. Representative)

- International Steering Committee, Conference on Biomanipulation of Natural and Artificial Freshwater Ecosystems (D. Scavia, FY 86)

- NOAA Estuarine Research and Planning Group Coupling of Primary and Secondary Production (D. Scavia, member)

- NOAA Lake Superior Submarine Committee (N. Hawley)

- NOAA Technical Subcommittee, New Bedford Superfund Action (B. Eadie)

- State of Michigan, Department of Natural Resources
  - Great Lakes Information System, Technical Advisory Committee (E. Aubert, FY 86; A. Beeton, FY 87)
  - Hazardous Waste Assessment Committee (B. Eadie, P. Landrum)
  - Toxic Substances Control Commission (A. Beeton, Commissioner, FY 87)

- Steering Committee for NSF-Sponsored Workshop on Complex Interactions in Lake Communities (D. Scavia, FY 86)

- Third International Conference on Ecology and Environmental Quality, Jerusalem, Israel (S. Tarapchak, Session Chairman)

- University Council on Water Resources (T. Croley)

- University of Michigan
  - Biological Station Executive Committee (A. Beeton, member)
  - Sea Grant Research Advisory Committee (J. Saylor, A. Bratkovich, FY 87, members)

- Upper Great Lakes Connecting Channel Study (UGLCCS)
  - Activities Integration Committee (T. Fontaine)
  - Biota Work Group (T. Nalepa)
  - Management Committee (E. Aubert, B. Eadie, FY 86; A. Beeton, FY 87)
  - Modeling Task Force (T. Fontaine, Chair)
  - Quality Assurance/Quality Control Work Group (W. Faust)
  - Sediment Workgroup (J. Robbins, N. Hawley)
  - Water Workgroup (P. Landrum)

- U.S.-Canada Ice Information Working Group (F. Quinn, U.S. Co-Chair; R. Assel)

- U.S. Soil Conservation Service (A. Beeton, Technical Advisor)

GLERL scientists also:

- developed an Estuarine Research plan with other NOAA components (B. Eadie);
- travelled to the Soviet Union as part of an official EPA-sponsored U.S.- U.S.S.R. Exchange Program for Cooperation in the Field of Environmental Protection, Project on River Basin Water Quality, Planning and Management (P. Landrum);
- served on six doctoral committees at The University of Michigan;
- served as Adjunct Professors at The University of Michigan;
- and conducted cooperative research and exchange visits with scientists from Bowling Green State University, Skidaway Institute of Oceanography, and the U.S. Fish and Wildlife Service, National Fisheries Center - Great Lakes.

Meetings and Presentations

An integral part of the scientific development of GLERL staff is the attendance and participation in scientific and technical meetings. During FY 86 and FY 87 GLERL sponsored over 60 in-house seminars as part of the GLERL Informal Seminar Series, and 165 presentations concerning GLERL work were made by our staff at public and professional meetings. We also co-hosted and Co-chaired the 30th Annual Conference of the International Association for Great Lakes Research, May, 1987, Ann Arbor, MI (B. Eadie, Co-Chair and M. Quigley, Exhibitors Coordinator), and participated in the planning of a symposium held at the 1987 Annual Meeting of the International Association on Water Pollution Research and Control in London, U.K. (T. Fontaine).

Technology Transfers

GLERL staff responded to approximately 2,100 requests for information during FY 86 and FY 87, and provided over 3,400 items to service those requests. Among the products that GLERL produces and distributes, many involve, to some degree, a transfer of technology as well as data. During FY 86 and FY 87 GLERL's outreach of this nature involved the transfer of computer-based software providing improved techniques for resource forecasting and natural hazard preparedness:

Storm Surge Planning Software

Copies of this GLERL-developed software and advice on its proper application and limitations were provided to:

U.S. Army Corps of Engineers
Ohio Department of Natural Resources
Wisconsin Department of Natural Resources
Michigan Department of Natural Resources
Wisconsin Sea Grant
Toledo Edison Electric Co.
Atmospheric Environment Service of Canada
National Weather Service Forecast Offices (NWSFO), various

Lake Superior Water Supply Model

GLERL'S near-real time water supply outlook package was transferred to the Army Corps of Engineers, Detroit District, for use on Lake Superior. To accomplish this involved modifying the programs to work with COE's computer operating system and compilers, running the package to reconstruct the near-real time databases essential to the use of the package, and training Corps staff in use of the package.

GLERL also transferred this package to the National Weather Service Northeast River Forecast Center (NERFC) for use on Lake Champlain. The effort was similar to the above, except that two GLERL scientists were sent to NERFC for 7 days to modify the programs on their Data General Nova Eclipse computer and to train their staff on-site. GLERL helped debug the NERFC system and modified the GLERL package at their request, to allow easy viewing of the most recent additions to their near-real time meteorologic data bases and to allow convenient override of climatic data in generating forecasts. GLERL also provided NERFC with materials for their meeting with the New York and Vermont Department of Environmental Conservation concerning the Large Basin Runoff Model, its application to Lake Champlain, and its potential for application to other large lakes.

Areal Averaging of Point Measurements in Near-Real Time

GLERL scientists developed a generic Thiessen weighting package that allows a user to apply it easily to different types of data. GLERL staff installed it on the U.S. Army Corps of Engineers, Detroit District, Harris 500 computer; the National Weather Service Northeast River Forecast Center Data General Nova Eclipse; and both the U.S. Army Corps of Engineers North Central Division and the National Weather Service Office of Hydrology IBM/PC-ATs. This assistance included rewriting the package in several different languages, testing each on the target machine directly or via telecommunications, and then releasing each package with complete instructions. Modifications to suit differing agency requirements were made at the request of the agencies. The Detroit Corps and the NWS NERFC use this software to make near-real time areal estimates of snow water equivalents from aerial surveys of Lakes Superior and Champlain, respectively. The Office of Hydrology Snow Survey Program uses it for the Lake Superior and Lake Champlain basins and expects to use it for other areas where aerial snow surveys are conducted (Souris-Red-Rainy basin and St. John's River basin). The Corp's North Central Division used the package for all Great Lake Basins for purposes of assessing different meteorological networks.

Software to Unpack and Reformat NOAA Satellite Data

A GLERL software package that reads NOAA AVHRR (HRPT or LAC) 5-channel digital satellite data, unpacks it, reformats it into band-interleaved-by-line (BIL) format, and reverses it (if necessary), was transferred to the following:

- U.S. Army Corps of Engineers, Detroit District
- The University of Michigan (Remote Sensing Laboratory)
- U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory

These recipients use the software to prepare NOAA (AVHRR) digital satellite data for use on their respective image processing systems. The software allows NOAA (AVHRR) satellite data to be processed by systems designed primarily for use with LANDSAT satellite imagery.

Ice Formation, Thickness, and Breakup Forecasting Techniques

A menu-driven computer algorithm was developed for the National Weather Service (NWS) to forecast ice conditions on the St. Marys River. The algorithm forecasts date of ice formation, ice thickness, and date of ice loss based on work described in NOAA TM ERL GLERL–47. Procedures to access and run the algorithm on GLERL's computer, as well as descriptions of the necessary input data and forecast limitations, were presented and demonstrated in a meeting at NWSFO Ann Arbor in October 1985. Modifications were made to the software during the fall of 1985 and the winter of 1986 to make the ice forecasting algorithm more useful in connection with operational ice forecasts. One such modification allowed NWS to change the way it updates the mean daily air temperature file used for making freeze-up forecasts.

FACILITIES AND SERVICES

In January, 1987, after occupying what had been designated "temporary" quarters for 12 years, GLERL moved into a new, modern research facility with over 24,600 square feet of usable space, including 19 laboratories totaling 4,100 sq. ft., 990 sq. ft. of conference rooms, a 1,250 sq. ft. library, and 1,220 sq. ft. for computer resources.

In addition to general laboratory equipment, GLERL has a fully-equipped low-level radioisotope analysis laboratory, several gas chromatographs and liquid scintillation counters, a high pressure liquid chromatography system, a multichannel Coulter Counter, a full complement of growth chambers and incubators, stereo and inverted microscopes and a fully equipped multipurpose epifluorescence microscope.

We also maintain and operate a High Speed Microcinematography Laboratory housed in a temperature-controlled environmental chamber. The combination of high-speed (500 frames per second) and precise control of the temperature between 1 and 30°C allows advanced studies of the feeding behavior of zooplankton over the broad range of temperatures found in the natural Great Lakes environment. In addition, a separate Cold Room is maintained for conducting experiments and for growing biological cultures at low temperatures.

Computer Facility

The GLERL Computer Facility consists of a VAX 11/780 system on-site and includes the capability of accessing either a mainframe computer (Cyber 180/855) or a supercomputer (Cyber 205), both located at the National Bureau of Standards in Gaithersburg, Maryland. GLERL is one of five remote nodes to that facility, which is known as the Department of Commerce Consolidated Scientific Computing System (CSCS). User terminals throughout GLERL's new facility are hardwired to a multiplexed digital switch that allows users to access the VAX system as well as either of the Cybers in Gaithersburg.

Over 80 authorized accounts are supported for a variety of applications, including real-time data acquisition, data reduction, graphics, large scale modeling, statistical/mathematical analysis, telecommunications, and word processing. Off-site access to the system is available to authorized users through several modem-linked telephone lines, while on-site access is supported via graphics terminals, non-graphics interactive terminals, and desktop microcomputers.

Library

The GLERL library staff provides library and related services in support of GLERL's research activities. A program-oriented research collection is maintained, with special retrieval services available when the existing collection cannot meet the needs of individual researchers. Library services include reference, interlibrary loan, photocopying, acquisition, circulation, and online information retrieval for laboratory-affiliated personnel. The GLERL library is open to the public for reference use only.

Collection holdings include 3,550 books, 4,180 unbound periodical volumes, and 2,985 technical reports in the areas of climatology, hydrology, hydraulics, ice, limnology, mathematical modeling, meteorology, oceanography, sedimentation, wave motion, contaminant organics and nutrients, with emphasis on the Great Lakes Basin. Access to the collection of technical reports is supported by an interactive online search capability. GLERL library staff expedite on-demand document retrieval and provide expanded reference capabilities on behalf of GLERL scientists through direct access arrangements with The University of Michigan libraries.

The GLERL library is a member of the Michigan Library Consortium (MLC), Washtenaw-Livingston Library Network (WLLN), Federal Library and Information Network (FEDLINK), NOAA Library and Information Network (NLIN), and the Online Computer Library Center, Inc. (OCLC).

The library receives over 200 periodical titles and retrieves several hundred interlibrary loan requests each year.

Marine Instrumentation Laboratory

The Marine Instrumentation Laboratory (MIL) staff selects, calibrates, repairs, and when necessary, adapts or designs instruments to collect data in the lakes and their environs. The facility includes wood and machine shops, electronics design, fabrication, and repair shops; and houses both the Cold Room and the Microcinematography Laboratory. Engineers and technicians in this unit work closely with GLERL researchers to ensure that instruments are compatible with their needs. MIL staff also participate in field experimentsby providing support for the deployment and retrieval of field equipment, assistance with sample and data collections, and in-field maintenance or repair of equipment.

During FY 86 and FY 87, MIL engineers and technicians also worked to improve real-time automated data return and assisted with the resolution of problems related to GLERL's move into a new facility. Among their accomplishments were 1) development and implementation of a unique building security system that uses an IBM-PC for its management and alarm reporting; 2) development of a property inventory system in DBase III and transfer of that system to ERL in Boulder, CO; 3) construction of a meterological station with satellite reporting capabilities; 4) successful negotiation with the manufacturer of our Doppler current profiler to provide a free enhancement of that instrument's capabilities, such that it can now be used to conduct shipboard measurements while under way.

Information Services - Publications Unit

The Publications Unit staff are responsible for providing editorial and publications support to the scientific staff, distributing GLERL publications, and responding to requests for publications and information; they also produce and update informative fixed and portable displays concerning GLERL's work and/or important environmental issues. The Publications Unit maintains and updates, eight mailing lists covering GLERL products; new NOAA-series publications are automatically distributed according to these mailing lists. All new publications, including journal articles and books, are added to our six-month update listing of new publications, which keeps our users informed of GLERL's latest product releases.

Research Vessel *Shenehon*

The *Shenehon* is owned and operated by GLERL. It is based at the U.S. Army Corps of Engineers' boat yard at Grand Haven, Michigan and is the primary platform used in support of GLERL's open lake field investigations. The vessel is 65.6 feet long, with a 6.5-ft mean draft, a 600-nautical-mile cruising range, and a 10-knot cruising speed. Navigational equipment include a Sperry Gyrocompass, Raytheon Radar, two LORAN-C units, Sperry Auto Pilot, and a Raytheon Depth Sounder. A new LORAN-C system and a new 55-channel radiotelephone have been installed to improve the vessel's navigation and communication capabilities.

The *Shenehon* is a designated NOAA weather reporting station. In FY 86 the National Ocean Service installed a Shipboard Environmental (Data) Acquisition System (SEAS) aboard the *Shenehon*. The system includes equipment to record, process, and plot water temperature data collected using Sippican Expendable Bathythermograph (XBT) probes. This system, the first in the Great Lakes, provides increased capability to collect and transmit weather and water temperature data using satellite communications.

An electro-hydraulic articulated crane is available for deployment and retrieval of water and bottom sediment samplers and heavy instrument moorings. Electro-hydraulic winches handle hydrographic wire and multiconductor cable for sample casts and in-situ measurements of water variables. An on-board laboratory is available for experiments and sample processing. Scientific equipment includes various-sized water samplers, reversing thermometers, bottom samplers including a box corer, and a 25 cm beam path transmissometer coupled to an electronic bathythermograph. A data acquisition system separate from the SEAS system records and plots data. The data are recorded in digital format.

FY 86

PERMANENT STAFF

	Full Time	Part Time	WAE
Office of the Director	12	4	0
Ecosystem and Nutrient Dynamics Group	8	3	3
Environmental Systems Studies Group	3	0	1
Lake Hydrology Group	10	1	4
Physical Limnology and Meteorology Group	11	2	2
Synthetic Organics and Particle Dynamics Group	8	3	2
TOTAL	52	13	12

Office of the Director
Aubert, E. J. – Director (retired June 1, 1986)
Quinn, F.H. – Acting Director (as of June 1, 1986)
Noble, P. – Secretary
Reid, D.F. – Ass't to the Director

Administration
Mark, S.V. – Head
Dunivan, E.M.
James, O.L.
Lee, J.P.
Townsend, G.H.

Computer Facility
Spalding, G.E. – Head
Del Proposto, D.J.
Fenton, J.F.
Herche, L.R.
Lefevre, J.T.
Shrum, A.F.

Information Services
Reid, D.F. – Head
Hannak, J.C.
Hubbard, B.D.

Environmental Systems Studies Group
Fontaine, T.D., III – Head
Darnell, C.M. – Secretary
Hull, S.J.
Lang, G.A.

Physical Limnology and Meteorology Group
Saylor, J.H. – Acting Head
Darnell, C.M. – Secretary
Clites, A.H.
Laba, S.J.
Liu, P.C.
Lynn, E.W.
McCormick, M.J.
Miller, G.S.
Schwab, D.J.

Marine Instrumentation Laboratory
Soo, H.K. – Head
Booker, H.L.
Dungan, J.E.
Kistler, R.D.
Lewis, C.A.
Miller, T.C.
Muzzi, R.W.

Ecosystem and Nutrient Dynamics Group
Gardner, W.S. – Head
Lojewski, N.L. – Secretary
Babbitt, M.T.
Chandler, J.F.
Fahnenstiel, G.L.
Gauvin, J.M.
Laird, G.A.
Liebig, J.R.
Malczyk, J.M.
Nalepa, T.F.
Quigley, M.A.
Scavia, D.
Tarapchak, S.J.
Vanderploeg, H.A.

Lake Hydrology Group
Quinn, F.H. – Head
Lawton, B.J. – Secretary
Assel, R.A.
Bolsenga, S.J.
Croley, T.E., II
Darr, K.A.
Derecki, J.A.
Hartmann, H.C.
Kelley, R.N.
Leshkevich, G.A.
Makuch, L.L.
Norton, D.C.
Poorman, G.M.

Library Facility
Carrick, B.J. – Librarian
Threm, S.M.

Synthetic Organics and Particle Dynamics Group
Eadie, B.J. – Head
Gray, M.J. – Secretary
Bell, G.L.
Faust, W.R.
Hawley, N.
Keilty, T.J.
Lake, B.J.
Landrum, P.F.
Morehead, N.R.
Robbins, J.A.

R/V *Shenehon*
Morse, D.V. – Master Mate
Burns, W.R.
Grimes, J.E.

FY 87

PERMANENT STAFF

	Full Time	Part Time	WAE
Office of the Director	11	3	0
Ecosystem and Nutrient Dynamics Group	9	2	2
Environmental Systems Studies Group	3	1	0
Lake Hydrology Group	10	2	5
Physical Limnology and Meteorology Group	10	3	3
Synthetic Organics and Particle Dynamics Group	8	4	2
TOTAL	51	15	12

Office of the Director
Beeton, A.M. – Director (as of Nov. 1, 1986)
Noble, P.E. – Secretary
Reid, D.F. – Ass't to the Director

Administration
Mark, S.V. – Head
Lee, J.P.
Townsend, G.H.

Computer Facility
Spalding, G.E. – Head
Del Proposto, D.J.
Fenton, J.F.
Herche, L.R.
Lefevre, J.T.
Shrum, A.F.

Information Services
Reid, D.F. – Head
Hannak, J.C.
Hubbard, B.D.

Environmental Systems Studies Group
Fontaine, T.D. – Head
Darnell, C.M. – Secretary
Clites, A.H.
Lang, G.A.

Physical Limnology and Meteorology Group
Saylor, J.H. – Acting Head
Darnell, C.M. – Secretary
Katt, G.A.
Laba, S.J.
Liu, P.C.
Lynn, E.W.
McCormick, M.J.
Miller, G.S.
Muhr, G.C.
Schwab, D.J.

Marine Instrumentation Laboratory
Soo, H.K. – Head
Booker, H.L.
Dungan, J.E.
Kistler, R.D.
Lewis, C.A.
Miller, T.C.
Muzzi, R.W.

Ecosystem and Nutrient Dynamics Group
Gardner, W.S. – Head
Lojewski, N.L. – Secretary
Babbitt, M.T.
Fahnenstiel, G.L.
Gauvin, J.M.
Laird, G.A.
Liebig, J.R.
Malczyk, J.M.
Nalepa, T.F.
Quigley, M.A.
Scavia, D.
Tarapchak, S.J.
Vanderploeg, H.A.

Lake Hydrology Group
Quinn, F.H. – Head
Lawton, B.J. – Secretary
Assel, R.A.
Bolsenga, S.J.
Brook, J.R.
Croley, T.E., II
Darr, K.A.
Derecki, J.A.
Hartmann, H.C.
Hunter, T.S.
Kelley, R.N.
Leshkevich, G.A.
Makuch, L.L.
Norton, D.C.
Poorman, G.M.

Library Facility
Carrick, B.J. – Librarian
Threm, S.M.

Synthetic Organics and Particle Dynamics Group
Eadie, B.J. – Head
MacTaggart, I.R. – Secretary
Bell, G.L.
Chappell, J.L.
Faust, W.R.
Hawley, N.
Keilty, T.J.
Landrum, P.F.
Morehead, N.R.
Rivera, M.P.
Robbins, J.A.

R/V Shenehon
Morse, D.V. – Master Mate
Burns, W.R.
Grimes, J.E.

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Center, University of Colorado, NOAA Environmental Research Laboratory, July 15, 1987, Boulder, CO.

LIU, P.C. Estimating long term wave statistics from long term wind statistics. 20th International Coastal Engineering Conference, Sponsored by the American Society of Civil Engineers, November 9–14, 1986, Taipei, Taiwan.

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QUINN, F.H. Current Great Lakes levels. Water Levels Symposium, Sponsored by the Center for the Great Lakes and Senator Paul Simon, October 10, 1986, Chicago, IL.

QUINN, F.H. Lake Erie water levels. Toledo Metropolitan Council of Governments, October 15, 1986, Waterville, OH.

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SCAVIA, D. Bacterioplankton in Lake Michigan: Dynamics, controls, and significance to carbon flux. Sponsored by the Institute for Ecosystem Studies, January 23, 1987, Millbrook, NY.

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SCAVIA, D. The effects of vertebrate zooplanktivory on ecosystem structure: The Lake Michigan experience. Seminar Series, Kellogg Biological Station, Michigan State University, April 30, 1987, Hickory Corners, MI.

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STEHLY, G.R., and W.L. Hayton. Errors in the use of the accelerated bioconcentration test. American Standards and Testing Materials 11th Symposium on Aquatic Toxicology and Hazard Assessment, May 11, 1987, Cincinnati, OH.

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TARAPCHAK, S.J. Perspectives in aquatic phosphorus dynamics and cycling. Biology Department Brock University, November 20, 1986, St. Catharines, ON.

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