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REPORT

LARGE LAKE MODELS – USES, ABUSES, AND FUTURE

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ABSTRACT. Mathematical modeling has played and should continue to play an important role in Great Lakes management and scientific development. Great Lakes modeling is entering a phase of relative maturity in which expectations are more realistic than in the past. For example, it is now realized that the modeling process itself is valuable even if the resulting models are not immediately useful for management. The major thrust in the past has been water quality (eutrophication) modeling, but there has been a recent shift toward developing toxic substances models. Modelers and model users have been limited by a lack of knowledge of Great Lakes processes, limited data availability, and incomplete or improper validation. In the future, greater emphasis is needed on specifying prediction uncertainty and conducting proper model validation – including calibration, verification, and post-audits. Among the Great Lakes modeling activities likely to have the greatest payoff in the near future are (1) the development and refinement of toxic substances models, (2) post-auditing and improvement of eutrophication models, and (3) the adaption of models for use on personal computers to allow greater model utilization.

ADDITIONAL INDEX WORDS: Mathematical models, deterministic models, stochastic models, toxic substances, eutrophication.

INTRODUCTION

The Great Lakes Science Advisory Board to the U.S./Canadian International Joint Commission, having identified "computer modeling and validation" as one of ten key Great Lakes research issues (Great Lakes Science Advisory Board 1982), established a task force to evaluate Great Lakes modeling activities. This task force was charged with examining the past, present, and future roles of mathematical models applied to research and management of the Great Lakes environment. As a result of the task force's deliberations, a report was prepared for the Great Lakes Science Advisory Board (Modeling Task Force 1986). This paper summarizes that report and provides recommendations applicable to large lake models in general.

The discussion below examines the uses of mathematical models, the scientific process of model development, and the general limitations of models. It is based on a critical analysis of existing large lake toxic contaminant and eutrophication models, as well as circulation/transport, nonpoint source and fishery models. Most models considered deal directly with the Great Lakes or their watershed. For a more general review of water resources modeling, see Office of Technology Assessment (1982).

USES OF GREAT LAKES MODELS

Great Lakes (and other large lake) models have found many applications including:

(1) organizing existing knowledge and data,
(2) identifying data and research needs,
(3) facilitating technical and non-technical communication,

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(4) improving fundamental understanding about relationships among components of systems, and the consequences of change,
(5) setting regulations or objectives, and
(6) providing quantitative predictions of the impacts of alternate management strategies before they are implemented.

Many of these uses get overlooked when evaluating the benefits of modeling efforts. For example, models that described PCB cycling in the Great Lakes clearly demonstrated the need for more basic physical-chemical information (e.g., solubilities, vapor pressures, sediment-water partitioning, etc.) on the 209 PCB congeners. This need stimulated considerable basic research over the last several years on defining the properties of PCBs.

The most obvious use of Great Lakes models has been in a management context. In fact, models have probably been used in managing the Great Lakes system more than in any other water resource in the world. Eutrophication control, toxic substances management, water diversions, and fish stocking are but some of the Great Lakes issues that have or are currently being addressed by models.

Probably the most prominent example of model use for management decisions was in the renegotiation of the United States-Canada Great Lakes Water Quality Agreement in 1978. The earlier 1972 Water Quality Agreement between the United States and Canada called for total phosphorus concentrations in all major point source discharges in the Lake Erie and Lake Ontario watersheds to be limtied to 1 mg/L. However, the 1978 Agreement contains specific phosphorus loading objectives. These objectives, which are a unique approach to managing such a large resource, were based to a large extent on mathematical models developed during the early and mid-1970s.

In developing the phosphorus objectives, a bilateral technical Task Group used five mathematical models to estimate lake responses to changes in the phosphorus loads. Two of the models used were the Vollenweider (1976) phosphorus loading/chlorophyll *a* model and the Chapra (1977) dynamic phosphorus loading model, both of which are mathematically simple models based on empirical (observed) relationships. The other three models (Thomann *et al.* 1975, DiToro and Connolly 1980, and Bierman *et al.* 1980) were more complex models utilizing a series of differential equations describing basic limnological processes. These complex models account for and trace a number of variables throughout the system. All five of the models, when supplied with the same input data, were found to be consistent in their general predictions. The fact that the models were independently derived and were based on conceptually different approaches instilled confidence in the predictions, and, in fact, led to the inclusion of phosphorus loading objectives in the 1978 Water Quality Agreement that were largely based on the model results. Consequently, such models have had a very major influence on the multi-billion dollar Great Lakes phosphorus control program.

LIMITS FOR MODELS AND MODEL APPLICATIONS

Despite the unquestionable value of models to Great Lakes management and planning, models do have limitations. When used without knowledge of these limitations, models can lead to incorrect conclusions or approaches. Overall, four factors limit the use of models: (1) conceptual simplification, (2) inadequate or inappropriate input data, (3) lack of complete validation, and (4) lack of quantitative measures of uncertainty. Each of these factors is discussed below.

Conceptual Simplification

Models are, by nature, conceptually incomplete. Even with elaborate or complex models, only a limited number of features of a system can be considered, requiring averaging or aggregation of many factors. The selection of model variables depends on the nature of the problem as well as the experience and judgment of the modeler, since model development requires decisions to be made regarding model complexity, cost, ease of use, data requirements, and so forth. The final model design is based on compromises or tradeoffs. To illustrate, consider that a model of lake trout population dynamics in a large lake is unlikely to deal with the intricacies of nutrient uptake by several functionally-distinct classes of algae. Yet, nutrient uptake ultimately does have an effect on lake trout populations, albeit an indirect and probably small one. Nevertheless, the necessity to limit the size of models means that they will necessarily distort the real world or give an imperfect representation of the system.

Although it might seem that creating a model that considers as many components as possible would provide for the most useful representations of a real system, this is rarely the case. Generally, the best model is the simplest model that provides the required information, as dictated by the needs and objectives of users. For instance, if detailed information about the partitioning of industrial-derived mercury between algae, zooplankton, and fish is needed, a complex ecosystem model which compartmentalizes the lake and traces the states of these compartments in detail over time may be appropriate. Alternatively, if the fish are of greatest economic importance, this may be the only compartment of management interest and a simpler model which predicts fish mercury content from mercury loading and selected key variables (e.g., epilimnetic pH and calcium concentration; Wren and MacCrimmon 1983) may be adequate. If it were already available, the former, more complex model might also serve the latter situation, but it would not be the choice of a modeler attempting to answer the needs of the simpler situation. In either case, the model user must be aware of the conceptual limitations of the model.

Restated in other terms, the creative modeling process involves the selective supression of unnecessary detail in favor of expressing the most relevant and critical processes. In many respects models are like maps; they are of different scales and purposes and should be designed to satisfy the needs of the sponsor. The challenge facing the modeler is similar to that facing the cartographer—deciding what should be included and excluded to give a final product that is the optimal tradeoff between excessive complexity and naiveté.

Complex ecosystem models usually follow a deterministic approach, and utilize differential equations to describe basic limnological processes. Ordinarily, these models track the behavior of a large number of variables throughout the system, and conserve mass, energy, and momentum in space and time (Richardson and Thomas 1976, Lam and Halfon 1978, Scavia 1980a, Lam *et al.* 1983). These models are important as research tools as well as for helping to predict interactions of variables in and among large lakes.

An increase in general computer literacy and in the accessibility of large mainframe computers has made the development and use of deterministic models feasible for many situations. However, one disadvantage of this approach is that it requires much more research time and computer resources than simpler, empirical methods. An additional shortcoming of the deterministic approach is that no complete error analysis is available for these models (Scavia 1983), and the accuracy of their predictions is poorly known (Reckhow and Chapra 1983). Thus, complex modeling efforts do not always improve upon estimates made by more simple and less expensive approaches.

In contrast to deterministic models, empirical models often use simple linear regression (e.g., Vollenweider 1976) or multiple regression analysis (e.g., Smith 1982) to statistically link presumptive driving variables (e.g., phosphorus loading) with other water quality parameters (e.g., chlorophyll *a* or water transparency). They do not require an understanding of complex causal ecological interactions, and as a result, their data requirements are typically much more modest than deterministic models. Thus empirical models can often provide a high benefit:cost ratio for users.

The simple, empirical models do have drawbacks, however. As noted by Klemes (1982), empirical models typically have large uncertainties because of natural variability and sampling error. The accuracy of predictions of empirical models can thus be questioned, emphasizing the need for uncertainty analysis. Furthermore, empirical models must be regarded essentially as interpolation formulas. They have no justification for use outside the range of the calibration data set, and their use for extrapolation beyond these limits involves the risk of major errors. However, when the knowledge of underlying processes is too weak to allow the development of deterministic models, the empirical method provides a powerful management tool. Its track record to date for large lakes has been impressive (Heidtke 1979, Modeling Task Force 1986).

Both complex deterministic and simpler empirical models have legitimate roles in large lakes management. Neither are conceptually perfect, but knowledge and direction can be gained from both. Examples of the two different approaches are given in Table 1, along with a summary of their characteristics. Despite conceptual differences, the models in Table 1 predicted similar results regarding the impact of phosphorus control in Lake Erie. Thus, the use of a spectrum of models for applications is recommended in order to help assess confidence in model conclusions.

Data

Modeling is dependent on the availability of appropriate and reliable data. All too often, especially in a large lake system, the lack of necessary

TABLE 1. Summary of principal model characteristics of several Great Lakes eutrophication models (Bierman et al. *1980)*

	Vollenweider[1] (All Basins)	Chapra[2] (All Basins)	Thomann[3] DiToro[4] (Lakes Ontario and Huron)	DiToro[5] (Lake Erie)	Bierman[6] (Saginaw Bay)
Deterministic			X	X	X
Empirical	X	X			
Time Dependence					
Dynamic		X	X	X	X
Steady-State	X				
Spatial Segmentation					
None	X				
Horizontal		X	X	X	X
Vertical			X	X	
Input Requirements					
External Loads for Primary Variables	X	X	X	X	X
Depth	X	X	X	X	
Volume	X	X	X	X	X
Hydraulic Detention Time	X	X			
Temperature (in-lake)			X	X	X
Light			X	X	X
Water Circulation Rates	X	X	X		
Sediment Nutrient Release Rates					X
Primary Variables					
Phosphorus	X	X	X	X	X
Nitrogen			X	X	X
Silicon				X	X
Total Forms Only	X	X			
Available and Unavailable Forms			X	X	X
Secondary Variables					
Chlorophyll	X	X	X		
Diatom/non-Diatom Chlorophyll				X	
Multi-Class Biomass					X
Zooplankton			X	X	X
Dissolved Oxygen				X	

[1] From Vollenweider 1975.
[2] From Chapra 1977.
[3] From Thomann *et al.* 1975.
[4] From DiToro and Matystik 1980.
[5] From DiToro and Connolly 1980.
[6] From Bierman *et al.* 1980.

data stymies model development or prevents proper verification of models. Perhaps the best example is in the area of toxic chemical modeling, where the lack of appropriate data is currently a major impediment (Halfon 1984a).

Model users must also be cognizant of the issue of data quality. The best of models cannot make reasonable and accurate predictions if these predictions are made using imprecise or inaccurate inputs. Although the adage "garbage in, garbage out" has become modeling jargon, it nonetheless stresses an important point for model users.

On the other hand, the lack of certain types of data does not preclude the use of models, even for predictive purposes. If reasonable assumptions are made, missing data can sometimes be estimated (or a range of values estimated or worst-case scenarios employed) in order to use the model for preliminary predictions. Assumptions can sometimes be tested during the calibration process or a sensitivity analysis. Such predictions can have great uncertainty (see below), but the implications of the assumptions can be assessed using techniques such as Monte Carlo simulation.

Validation

In very few cases have Great Lakes predictive models been subjected to a rigorous three step validation program consisting of: 1) calibration, 2) verification, and 3) post-audit. Unfortunately, it is often impossible or impractical to conduct all of these steps. Consequently, users must be aware of limitations due to the lack of or incomplete validation.

In model calibration different sets of values for equation coefficients may not give uniquely different outputs (Scavia 1980b). Also, different sets of coefficients may fit data equally well but may lead to quite different model predictions. The variation and random nature of some model inputs, such as temperature, light, and flow, will often give different results depending on how the values for each input are calculated. Thus, users must be aware that a model that is "calibrated" is not necessarily valid for any purpose other than that for which it was calibrated.

Model verification is achieved when the model output compares favorably with a data set independent from that used during model calibration. In the case of complex deterministic models, this can be an imposing task. Consequently, it is rarely done in practice, and in some cases all or part of the data set used in the model calibration phase is used in the verification step as well; such a procedure is not proper verification. In the final analysis it is crucial that independent sets of data be used to check model output. Once this has been done, quantitative methods can be used to examine the fit between the predicted and observed data (Thomann 1982).

Even if good verification statistics are obtained, it is still not guaranteed that a model will accurately predict the future (Thomann 1982). Some uncertainty will always remain which arises from (1) the coefficients of the model, (2) the model variables, and (3) the model structure itself (Simons and Lam 1980). Therefore, large lake models should be subjected to post-audits in which their predictions are tested with data from the actual results of environmental control programs or other management actions. Unfortunately, post-audits rarely occur. Only recently has there been some activity in this phase of validation (DiToro and Winfield 1984).

An example of where a post-audit would be extremely valuable is the Great Lakes phosphorus control program. As mentioned previously, one of the key uses of models in the Great Lakes has been to develop phosphorus loading control strategies. Now that phosphorus controls are largely in place, it follows that the response of the lakes to the phosphorus input reduction should be measured and compared to model predictions. Since large sums have been spent in the United States and Canda in what is undoubtedly the largest eutrophication control effort in the world, it would seem prudent to closely follow the effects of this reduction and to use the information to conduct post-audits on the models used to help develop the program. Such a process might uncover new knowledge that could lead to adjustments in the current program (and the models that led to it) or could help shape future strategies in the Great Lakes and elsewhere. A relatively small investment in a well-coordinated, multi-national post-audit could conceivably save millions of dollars in the future. Such a study is also likely to have many scientific and technical spinoffs that will help advance our understanding of the Great Lakes ecosystem.

Uncertainty

In addition to model structure, the choice of input variables and constants can lead to uncertainty in model results (Scavia *et al.* 1981a, b). Generally, environmental data sets consist of a range of values for any given parameter. Limitations of sampling, natural variability, and measurement error contribute to uncertainty. For example, in lake models using phosphorus loading as an input variable, phosphorus loading estimates will be affected by the enormous sampling problems and the difficulty in accurately measuring low levels of phosphorus in water and in atmospheric precipitation. Moreover, the annual phosphorus load varies naturally from year to year. Ideally, the uncertainty of the values used in models will be quantitatively accounted for in model results. Techniques such as Monte Carlo analysis can be used to develop this information. Reckhow and Chapra (1983) and

Chapra and Reckhow (1983) have documented various ways to quantify the effects of uncertainty in water resources models.

Although it will not be possible to estimate uncertainty in all cases, the use of uncertainty analysis as part of the modeling process is strongly recommended. As elucidated by Reckhow and Chapra (1983), planners and managers can make use of uncertainty measurements in several ways:

1. Use uncertainty measures to gage the value of the model results. If the uncertainty of a prediction is high, the prediction will have limited value.
2. Differences among predictions can be better assessed using uncertainty analysis. Uncertainty analysis allows the user to determine the range of results which are statistically indistinguishable, and discourages misinterpreting the significance of quantitative differences in model output.
3. Parts of the model that cause high uncertainty in predictions are often identified through uncertainty analysis.

While uncertainty analysis is recommended, it is only fair to say that most large lake models will have relatively high uncertainty. This sometimes leads the user to conclude that the model lacks sensitivity—that is, the model uncertainty is so large that predictions for different planning or management scenarios produce statistically indistinguishable results. Nevertheless, uncertainty analysis is still encouraged, as is more research on uncertainty analysis techniques. As Reckhow and Chapra (1983) pointed out, uncertainty is sometimes large since errors are double-counted in some error analysis methodologies. A better understanding of how to measure and express predictive error, and how the model user should interpret this information in practical situations, is thus needed (see Halfon 1984b). Uncertainty analysis could also help define the risks connected with certain management options where risk analysis is important.

USER ROLE IN MODEL APPLICATIONS.

Just as a manager or planner typically utilizes total phosphorus concentration measurements without a knowledge of the detailed chemical reactions and colorimetry of the analytical method, so too can one utilize results from models without complete knowledge of the intricacies of the model. However, a certain degree of responsibility must nonetheless be placed on the user of models results.

The user should also be aware of the assumptions and limitations of any model used and should not place more trust in predictions of the models than is actually warranted. A model provides convenient output values which are seductively simple; only rarely is the model output accompanied by a statement of uncertainty or error. Thus, it is common for users to believe that a model provides more precise information about a system or problem than exists in reality. Accordingly, it should always be recognized that a model output is only an estimate of a system's true response.

Since unwary users may be misled by information provided by models, potential users should, whenever possible, be involved during the model development stage. Users should specify the issues or questions that they are attempting to resolve through the modeling process, and development should proceed after question refinement involving both user and modeler. The precise definition of problems will ensure that modeler and user alike understand what is to be expected and will also permit subsequent evaluation of the validity of model projections.

TECHNOLOGY TRANSFER

As models are developed, calibrated, and verified, their credibility and utility to management increases. At some point in the modeling process, the computer programs must be documented and user manuals prepared. However, questions always remain on how best to transfer models to users who may not be familiar with their limitations. Thus far there has been little success in "turning over" models to managers or other users. Particularly for the Great Lakes where the levels of complexity are great and where scientific uncertainty concerning many of the key processes remains high, there is a need to maintain qualified modeling experts ready to assist managers or management organizations. Most modelers are willing to respond to specific management requests and to become involved with model applications, but are concerned that unsupervised use of models could result in incorrect conclusions being drawn. Indeed, it would be ideal to have a model's originator(s) available when the model is run. However, such a practice is often not possible and usually not practical. Documentation, therefore, becomes essential to the proper use of the model.

One new approach to technology transfer is the use of personal computers and the development of user-friendly modeling software. A model that can be run on a personal computer allows intimate involvement in the modeling process. For example, using a model directly, a planner or manager could quickly ascertain the effect of a decision. Such a person could optimize a solution by trial-and-error evaluations. Consequently, a major resistance to the use of models—the lack of control and the feeling of not being part of the process—can be overcome by using personal computer technology. Designing predictive models so they can be run on personal computers is likely to be a major activity in the future.

Maintaining models, particularly those using computer programs that require mainframe computers, is no trivial matter, especially if a model is to remain operational. Basically, it requires long-term funding to ensure that models will not be lost or become unuseable. Recent budget problems in both the United States and Canada have highlighted the need for such long-term commitments. Even models that are well documented can be lost if they are not maintained. For example, if budget cuts force the abandonment of programs to maintain large, mainframe computer models (such as some of the complex ecosystem models), the cost to activate the model years later would likely far exceed the cost of model maintenance. Further, expertise developed is often irrevocably lost during a funding hiatus. Obviously, not all models warrant continued maintenance, but those that do should not be neglected.

Since the state-of-the-art of modeling is being constantly enhanced by new and less expensive computer technology, it is important that models be kept up-to-date. Compared to only a few years ago, model output can be displayed more efficiently using graphics software, and model set-up can be improved by new sophisticated input techniques. As models are revised it is especially important to keep the user community aware of changes, including new applications. Generally, it is more cost-effective to revise existing models than to build new ones as additional technical information becomes available.

Linking different models together to solve a problem is becoming increasingly important. For example, a hydrodynamic model might be linked with a chemical model, which in turn might be linked to a biological model to assess the effect of a chemical spill (see Lam *et al.* 1976). The approach of building an overall model based on a series of sub-models has many advantages, not the least of which is economic efficiency. Certainly this approach is advantageous when building models *de novo.* It can, however, result in a greatly increased level of complexity and, hence, of uncertainty.

STATE-OF-THE-ART GREAT LAKES MODELING TECHNOLOGY

In the past 15 years the use of models in Great Lakes management and research has increased markedly. During this period the major thrust of model development, at least until recently, has been in the areas of water quality (mostly eutrophication) and lake circulation or hydrodynamics. More recently, however, considerable interest in the development of toxic substances models has occurred. An inventory of Great Lakes models and highlights of their characteristics may be found in Heidtke (1979), Sonzogni and Heidtke (1980), and Modeling Task Force (1986).

Water quality models have been applied to study eutrophication in all of the Great Lakes, with the least attention given to Lake Superior. These models have been generally used to evaluate average, whole-lake effects for individual basins or for their major embayments (e.g., Lake Huron's Saginaw Bay). The water quality variables most frequently simulated include phytoplankton, zooplankton, nutrients, and dissolved oxygen. Several of these models have been used to evaluate the long-term response of receiving waters to hypothetical management scenarios as noted previously. Newer models have focused on more specific water quality problems, such as growths of *Cladophora* along shorelines (Canale *et al.* 1982), as distinct from whole lake effects.

Several circulation models have been used to examine water movements in Lakes Michigan, Erie, and Ontario, with less attention being devoted to Lakes Superior and Huron. In the past, the majority of circulation models were limited to the study of average, two-dimensional horizontal open-lake current patterns for fixed wind directions and magnitude. However, the state-of-the-art in this area has advanced now to incorporate vertical water movements, as well as time-dependent circulation in both the central lake and nearshore zones. Recent interest in modeling nearshore circulation and transport is particularly significant. One type of circulation transport model, the heat dispersion model (used to predict temperature distributions in waters receiving heated effluent discharges) has been well-developed. However, recent model development in this area has waned as concern over thermal pollution has decreased.

Although the number of toxic chemical models has increased over the last several years, toxic substances continue to be the area in greatest need of model development. One of the primary reasons for this gap is a lack of quantitative information on toxic chemical inputs to the lakes. A lack of appropriate environmental data for model calibration and verification further compounds the problem. There is thus an obvious need for increased research in developing modeling techniques and data acquisition systems to broaden our understanding of the effects of toxic inputs to the Great Lakes. Other examples of toxic chemical modeling needs include comparison of equilibrium versus kinetic approaches for predicting toxicant fate and organism exposure, and models of organism response to low-level toxic substances. The development of toxic substances models will undoubtedly benefit and build upon models already developed for water quality and circulation/transport.

Several models of land runoff water quality and quantity have been developed and used to assess nonpoint source pollution loadings from rural and urban land. Their application to the Great Lakes has increased as the relative importance of nonpoint sources has become recognized. Models of land runoff typically rely upon detailed information on the physical and chemical characteristics of a given watershed. Input data generally include predominant land use and soil types, topography, rainfall, snowmelt, temperature, and land management practices. These models can then be used to predict runoff quantity and quality over very short time intervals (every 15 minutes) or over relatively long periods (average annual conditions). Alternately, relatively simple empirical models designed to be used directly by planners to make decisions about nonpoint source controls have been developed for the Great Lakes basin. It should also be mentioned that a variety of nonpoint source models have been developed for locations outside the Great Lakes basin that could be used within the basin.

Most fisheries models to date have dealt with evaluating the effect of alternative fish stocking and harvesting programs. Such models are of great importance, because the sports fishery program is a multi-million dollar endeavor. However, little modeling effort has gone into linking the fisheries with other management aspects, such as toxic substances or eutrophication control. This linkage is particularly important from an ecosystem management perspective (Scavia *et al.* 1986). Part of the reason for the sparse activity has been the lack of basic data needed to develop such models. More model development in this area is likely to occur in the near future. One notable exception to the above has been in the area of bioenergetics modeling, which is based on the flow of energy between different trophic levels. Bioenergetics modeling has provided useful insights into the linkages between toxic substances and fish (Kitchell and Breck 1980).

CONCLUSIONS AND RECOMMENDATIONS

A spectrum of opinion now exists about Great Lakes modeling (as well as large lakes modeling in general), ranging from disappointment and cynicism to enthusiasm and optimism. Part of the reason for these differences of opinion is that communication between model builders and model users has not always been optimal. However, large lake modeling is now entering a phase of greater maturity in which expectations are more tempered and realistic. Scientists now generally accept that the modeling process itself produces valuable information and insight, even if a model does not prove immediately useful for actual management. In an age where computer literacy is becoming commonplace, the value of modeling is likely to be more universally realized.

Despite the often successful use of models in large lake management, models may be abused if their limitations are not fully appreciated. These limitations include the simplifying assumptions that modelers must make in order to avoid making their models unnecessarily complex. Other limitations include the lack, poor quality, or natural variance of the data that are used in the model. Whenever possible, these uncertainties should be clearly specified using quantitative uncertainty analysis techniques. Models should also be validated for application to a specific situation. Ideally, validation is a three-step process, including calibration, verification, and, finally, a post-audit. One other aspect of modeling that needs attention is the transfer of technology from modeler to user. Improving the transfer process would contribute to better appreciation by the user of the uncertainties and limitations inherent in a given model.

For the future, the modeling activities likely to have the greatest payoff are: 1) development of toxic substance models applicable to the myriad of xenobiotic chemicals which have been identified in the Great Lakes; 2) post-auditing and improvement of eutrophication models (a major international research effort is recommended); 3) construction of hydrodynamic models of water level and flow changes that will result from diversion or climatic change; 4) development of fisheries models related to stocking strategies and water quality/fish yield links; 5) the use of models to optimize strategies for surveillance, monitoring, and research; and 6) the use of the modeling process to identify research needs. Although not likely to have near-term practical application, the development of Great Lakes ecosystem models integrating the many physical, chemical, biological, economic, and even social processes is a worthy, long-range research goal. Finally, the development of more user-friendly software that can be used with personal computers is highly recommended as a means of expanding the use of large lake models.

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