LAKE ERIE RESEARCH:
RECENT RESULTS, REMAINING GAPS

by

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MANAGEMENT PERSPECTIVE

This paper summarizes the results of the 1979 and 1980 Lake Erie experiments. Particular emphasis is given to processes affecting the oxygen depletion rate in the Central Basin hypolimnion, long considered to be an indicator of the "health" of that basin. The observed changes in the Central Basin are reviewed, starting with the recognition of eutrophication as a problem and continuing to the present recovery phase following the installation of sewage treatment plants that remove phosphorus. Phosphorus concentrations in the water and algal growth have decreased, but the rate at which dissolved oxygen is consumed in the hypolimnion appears not to have changed. Evidence collected to date points to the surficial sediments as a "reservoir" of oxygen demand that may postpone significant decrease in the hypolimnetic oxygen depletion rate. The influence of water movements on the oxygen budget of the Central Basin hypolimnion has been studied intensively, first the observational records, and later the synthesis of hydrodynamics and biogeochemistry through systems modelling. The experiments led to several new findings leading to a better understanding of physical processes and their simulation in models. The near-uniform depth of the Central Basin increases the response of that basin to the curl of the wind stress whereas circulation in the other deeper basins is more strongly influenced by topography. Transient thermocline features, such as shallow mixed layers developed during periods of surface heating and light wind, are shown to be important to vertical mixing throughout the water column.

Sediment oxygen demand is recognized as an important but poorly-understood process. Measurements are reviewed and it is concluded that the oxygen demand is positively correlated with resuspension events. Systems modelling of physical and biogeochemical processes dates back to the HYPO project of the early seventies. In the following decade significant advances have been made; the models are simpler but simulate the oxygen budget of the Central Basin more reliably. Models have played an essential part in our growing understanding of Lake Erie. A major conclusion of the paper is that a better knowledge of sediment-water interactions, among them the physical resuspension and settling of sediments, is required in order to assess the changes now taking place in the lake. It is also concluded that well-designed, multi-disciplinary, and multi-agency studies have been particularly beneficial in developing our present understanding of Lake Erie. Such experiments are necessarily long term in the planning, execution and analysis.

PERSPECTIVES DE GESTION

Le présent document résume les résultats des expériences faites dans le lac Érié en 1979 et 1980. Une attention particulière est accordée aux processus qui influent sur le taux d'épuisement de l'oxygène dans l'hypolimnion du bassin central, longtemps considéré comme un indicateur de la "santé" de ce bassin. Les changements observés dans ce bassin font l'objet d'un examen allant de la reconnaissance de l'eutrophisation comme problème à la phase de récupération actuelle subséquente à la construction d'usines de traitement des eaux usées dans le but d'éliminer le phosphore. Les teneurs en phosphore de l'eau et la croissance des algues ont diminué, mais le taux d'épuisement de l'oxygène dissous dans l'hypolimnion ne semble pas avoir varié. Les données recueillies jusqu'à maintenant indiquent que les sédiments de surface constituent un réservoir de demande en oxygène qui pourrait retarder toute baisse importante du taux d'épuisement de l'oxygène dans l'hypolimnion. L'impact des mouvements de l'eau sur le bilan d'oxygène de l'hypolimnion du bassin central a fait l'objet d'études exhaustives, qui ont commencé par des relevés d'observation et se sont poursuivies par la synthèse de l'hydrodynamique et de la biogéochimie au moyen de la modélisation fonctionnelle. Les expériences ont permis de recueillir plusieurs nouvelles données et de mieux comprendre les phénomènes physiques et leur modélisation. De par sa profondeur quasi uniforme, le bassin central est régi de plus en plus par les vents tandis que la circulation dans les autres bassins plus profonds est influencée davantage par le relief. Les manifestations transitoires dans la thermocline, comme des couches mixtes peu profondes formées en période de réchauffement à la surface et de vents faibles, influent sur le brassage vertical dans la colonne d'eau. La demande en oxygène des sédiments constitue un processus important mais encore mal connu. Les mesures sont examinées et on conclut que la demande en oxygène est en corrélation positive avec la remise en suspension. La modélisation fonctionnelle des processus physiques et biogéochimiques remonte au projet HYPO du début des années soixante-dix. Au cours de la décennie suivante, des progrès importants ont été réalisés; les modèles sont plus simples mais simulent mieux le bilan d'oxygène du bassin central. Les modèles ont joué un rôle essentiel dans l'enrichissement de nos connaissances sur le lac Érié. L'une des principales conclusions du présent document est qu'une meilleure compréhension des interactions entre les sédiments et l'eau, notamment la remise en suspension physique et la sédimentation , est requise pour évaluer les changements en cours dans le lac. Les auteurs concluent également que les études multidisciplinaires bien orchestrées et faites par de nombreux organismes ont joué un rôle particulièrement important dans notre compréhension du lac Érié. La planification et l'exécution de ces expériences ainsi que l'analyse des résultats sont nécessairement à long terme.

ABSTRACT

Evidence that oxygen depletion rates in the Central Basin hypolimnion were increasing and would lead to increasingly severe late summer anoxia resulted in a large public investment in both the U.S. and Canada to construct sewage treatment plants in order to reduce the phosphorus load to Lake Erie. Improvements in the water quality indicators, phosphorus and chlorophyll, have been achieved in the decade since these measures went into effect. There is no clear evidence, however for a corresponding "recovery" in hypolimnetic oxygen depletion. It is now recognized that physical processes, driven by winds and solar heating with strong interannual fluctuations, influence the timing and severity of late-summer anoxia, and make it difficult to detect long term trends. As a result of the 1979 and 1980 intensive field experiments, many of the physical processes are better understood, better documented, and possibilities exist for improved numerical hydrodynamical modelling. Systems modellers have exploited the voluminous Lake Erie data to generate convincing water quality models that account for the physical variability as well as simulating biochemical parameters. In some respects the modellers have pushed beyond the frontiers of established knowledge of biochemical processes and thus challenge process-oriented researchers to confirm or reject their findings. A consensus is forming among Lake Erie researchers that the key

to understanding the lake's response to changing external loading lies in a detailed understanding of the sediment/water interaction. Study of sediment-water interactions calls for interdisciplinary efforts that will involve physicists, biologists, chemists, and modellers. An appendix to this paper lists specific research recommendations.

RÉSUMÉ

En raison de l'accroissement du taux d'épuisement de l'oxygène dans le bassin central et du risque d'anoxie de plus en plus grave à la fin de l'été, des sommes importantes ont été consacrées, tant aux États-Unis qu'au Canada, à la construction d'usines de traitement des eaux usées dans le but de réduire la charge en phosphore du lac Érié. Depuis l'application de ces mesures, les indicateurs de la qualité de l'eau, soit la teneur en phosphore et en chlorophylle, se sont améliorés. Rien toutefois ne laisse croire à une neutralisation du processus d'épuisement de l'oxygène dans l'hypolimnion. On reconnaît maintenant que les processus physiques, régis par les vents et le rayonnement solaire avec de fortes variations interannuelles, influent sur l'occurence et la gravité de l'anoxie à la fin de l'été, et permettent difficilement de dégager des tendances à long terme. Suite aux études sur le terrain entreprises en 1979 et 1980, de nombreux processus physiques ont été mieux compris et analysés, et les modèles hydrodynamiques numériques pourraient être améliorés. Les modélisateurs fonctionnels ont exploité les données volumineuses recueillies sur le lac Érié pour établir des modèles fiables de la qualité de l'eau qui tiennent compte de la variabilité physique et des paramètres biochimiques de simulation. À certains égards, les modélisateurs ont repoussé les frontières du connu en matière de processus biochimiques et incité les chercheurs à corroborer ou infirmer leurs résultats. Un consensus s'est dégagé parmi les charcheurs du lac Érié, soit que la compréhension des réactions du lac à la variation de la charge externe repose sur l'analyse détaillée des interactions sédiments-eau. L'étude de ces interactions requiert la participation de chercheurs de disciplines variées, notamment de physiciens, de biologistes, de chimistes et de modélisateurs. Ce document comprend une annexe qui énumère les recommandations relatives à des recherches particulières.

THE OBSERVATIONAL RECORD: MONITORING CHANGE IN LAKE ERIE

Of all the Great Lakes, Lake Erie has been most seriously impacted by eutrophication. The effects, among which numbered floating algal scums and disappearance of certain benthic organisms, were most clearly evident in the Western and Central Basins, while the Eastern Basin remained less impaired. Studies during the 1950's and 1960's confirmed that the bottom waters of the Western and Central Basins were subject to anoxic conditions through the stratified period. However it was not until 1970 when two intensive study programs were undertaken that the scientific community began to understand the extent and magnitude of the problem. The open lake survey spanning the entire field season (April - December, 1970) remains as a bench mark and data base (physical, chemical and biological) here used as a reference point to evaluate the current status of the lake. The second 1970 study "Project Hypo" was a bi-national effort designed specifically to examine the processes involved in depleting the oxygen from the Central Basin hypolimnion. Those combined efforts provided the information necessary to develop a strategy for retarding and perhaps reversing the eutrophication of the lake. Specifically the Hypo Study concluded:

"Phosphorus input to Lake Erie must be reduced immediately; if this is done, a quick improvement in the condition of the lake can be expected; if it is not done, the rate of deterioration of the lake will be much greater than it has been in recent years."

Based upon results from the 1970 effort, a program was implemented under the 1972 US/Canada Water Quality Agreement to reduce phosphorus loading to the Great Lakes. For Lake Erie, the goal of this effort was to re-establish year round aerobic conditions in the bottom waters such that fish could inhabit them. A phosphorus target load of 11,000 metric tonnes per year was proclaimed in the 1978 Great Lakes Water Quality Agreement, based upon model predictions (Fifth Year Review, 1978) It was projected that at the target level, open lake phosphorus concentrations would be reduced sufficiently to curtail phytoplankton development. This in turn would reduce the oxygen depletion of the bottom waters (hypolimnion) far enough so as to eliminate the occurrence of anoxic conditions.

Evaluation of the phosphorus abatement program is an ongoing activity. The first and most important step involved the programs designed to reduce phosporus loading to the lake and to monitor the progress of the reduction effort. To follow the results of the reduction effort, phosphorus loadings to Lake Erie from all sources were estimated (Fraser, 1987, this issue). By 1982 the total load had been reduced to 58% of that in 1968. The actual calculated load has been reduced from over 20,000 metric tonnes to values currently approaching the target load. Fraser points out that the reduction of phosphorus entering from the Detroit River has been responsible, more than any other single factor, for the reduction in phosphorus entering the lake. The municipal phosphorus abatement programs together with the limitation on detergent phosphate concentration (exception Ohio) have brought about this reduction. Control of the phosphorus loading from agricultural activities may be necessary if further loading reductions are required.

It was thought that reduction of phosphorus loading would cause a decrease in concentrations of phosphorus in the open lake. Papers presented by F. Rosa and A. El-Shaarawi evaluate this response (Rosa, 1987, this issue; El-Shaarawi, 1987, this issue). Focusing on the Central Basin, Rosa reports a decrease in mean concentrations of total phosphorus from 22 ug/l in 1968 to 12 ug/l in 1982. For every thousand tonne reduction in annual loading in the interval 1967 through 1982, the mean phosphorus concentration has decreased almost 0.5 ug/l. Similarily, El-Shaarawi examined phosphorus trends for all three basins. His results indicate a decrease in total phosphorus concentrations in the Western Basin (1968 to 1978) and in the Central Basin (1968 - 1980). The Eastern Basin showed a smaller decline.

The phosphorus reduction program was implemented specifically to reduce the nutrient that controlled the growth of phytoplankton biomass (1978 Great Lakes Water Quality Agreement).

Consequently, the success of the phosphorus reduction program would be evident in the decreasing concentrations of chlorophyll, itself an indicator of phytoplankton biomass. El-Shaarawi examined the chlorophyll trend for the three basins and found, as with phosphorus, a decreasing concentration from 1968 - 1980 for both the Central and Eastern Basins. Since data from the Western Basin was limited (1968 - 1972) it was not possible to project a similar trend. In addition, El-Shaarawi was able to show that the relationship between phosphorus and chlorophyll can be reasonably described with a straight line, further substantiating the conclusion that the phosphorus reduction program has been effective in reducing phytoplankton biomass.

The ultimate objective of the phosphorus reduction program was to restore oxic conditions to the bottom waters of the Central Basin during summer stratification (1978 Great Lakes Water Quality Agreement). This would result in two benefits to the lake. First, it would restore the use of the sediments and overlying waters to biota intolerant to anoxic conditions. Second, the rapid internal recycling of phosphorus, ammonia and silica which occurs during periods of anoxia would be eliminated. The recycling of phosphorus from the sediments, also known as internal loading, under anoxic conditions may be as much as several thousand metric tonnes (Lam et al. 1983) and might eventually overshadow external loadings if the duration of anoxic conditions were prolonged.

The oxygen depletion rates for the Central and Eastern Basins have been measured annually since the 1970 "Hypo" study. In an effort to determine the amount of degradation that the lake has suffered since the influx of European settlers and industrialization, historical data have been used to calculate oxygen depletion rates prior to the 1970 study. In recent years, several attempts have been made to assess the historical change in the oxygen depletion, refining the earlier and pessimistic work of Dobson and Gilbertson (1972). Students of this particular aspect of Lake Erie will be aware that scientific opinion has ranged from the bleakest predictions of impending disaster to assertions that the Central Basin has exhibited occasional late summer anoxia since prehistoric times and that a reliable trend for either improvement or worsening cannot be established. Details of individual approaches and methods are provided in the three manuscripts included in this issue (Charlton, 1987, this issue; El-Shaarawi, 1987, this issue; Rosa and Burns, 1987, this issue). In general, the authors agree that the oxygen depletion rate has increased since the early 1950's in response to increased phosphorus loadings and that, if phosphorus levels are reduced, the probability of anoxia will also be reduced.

To date we have seen unmistakable and significant reductions in open lake concentrations of phosphorus and chlorophyll; but the anticipated decrease in the measured hypolimnetic oxygen depletion rate has not materialized in neither the Central nor the Eastern Basin. If one were to assume a linear relationship between depletion rate and phosphorous loading, then the small observed trends in depletion rate suggest there is a large background depletion rate not influenced by the control measures. If this is true then recovery will be limited too, and we will have to accept sporadic anoxia as part of the Central Basin environment. That the reduction of phosphorus and chlorophyll in the water is not yet accompanied by a reduction of the oxygen depletion rate suggests that the depletion rate is controlled by other factors, possibly by processes occurring at the bottom. It is then possible that the oxygen depletion rate exhibits a lagged response to changing load, and that we are not measuring now, nor have we ever measured an equilibrium situation. The latter interpretation seems more plausible, but what are the underlying mechanisms? In the introductory paper to this issue, Mortimer (1987, this issue) points out the large and dynamic sediment movements that are characteristic of Lake Erie alone of the Great Lakes. As we shall see, the role of bottom sediments is only partially understood. An additional consideration is the effect of changing water levels on the hypolimnetic volume. A 1m change in hypolimnetic thickness represents a large fractional change in the Central Basin of Lake Erie.

HYDRODYNAMICS OF LAKE ERIE: A POST HYPO UPDATE.

Throughout the HYPO study it was recognized that physical processes mediate biochemical processes and that observed changes in biological or chemical parameters may be the result of water movements as well as locally-acting biochemical processes. Among the physical processes considered to influence this budget were the mechanics of thermocline formation and decay, surface fluxes of heat and momentum, and particularly the mechanism of the entrainment of non-turbulent but stratified fluid into an actively stirred layer. An array of current meters provided evidence of a mean northwest drift of hypolimnion water across the Central Basin but gave few details as to how this movement was compensated at the edge of the hypolimnion. The flow of subsurface water from the Eastern Basin to the Central Basin hypolimnion was considered as a mechanism for the resupply of oxygenated water. Diffusion processes within the hypolimnion were studied as were the mechanisms of sediment-water interaction.

In the years immediately following the HYPO experiment, numerical hydrodynamic modelling was energetically pursued and extended to include some of the biochemical processes. The papers of Simons, Lam and Jacquet appearing in the special issue of JFRB are noteworthy (Simons, 1976; Lam and Jacquet, 1976). Assessments of the modelling studies to date are included in this issue (Lam and Schertzer, 1987, this issue; Lam, Schertzer, and Fraser, 1987, this issue;, DiToro et al. 1987, this issue). This initial activity would not have been possible without the 1970 database. The understanding that the severity of oxygen depletion in the Central Basin hypolimnion depended in part on the physical structure of the hypolimnion itself, its thickness and its temperature was articulated by Charlton (1980) and was boldly synthesized by Lam and his colleagues in a report first appearing in 1983 (Lam, Schertzer, and Fraser, 1983). The heart of this study is a thermocline model that is discussed in detail in this issue (Lam and Schertzer, 1987, this issue). Inputs to the model are surface fluxes of heat and wind stress; the model is verified against basin-wide observations of thermal structure. Climatological reviews of the fluxes and the resultant thermal structure form part of this issue (Schertzer, 1987, this issue; Schertzer et al., this issue), establishing the interannual variability. This work has alerted the limnological community to the probabilistic elements of long-term forecasting, a facet approached by El Shaarawi from a statistical point of view (El Shaarawi, 1987, this issue). Measurements of the exchange between the Central and Eastern Basins of the lake were conducted in the summers of 1977 and 1978 and analysed by Boyce et al. (1980) and Chiocchio (1981), providing useful estimates of the hypolimnetic interchange. The matter of interbasin exchanges is reviewed in this issue by Bartish (1987, this issue).

The intensive experiments of 1979 and 1980 and their subsequent analyses have extended substantially the HYPO findings as well as revealing areas of poorly developed knowledge that will require further study. Basin scale circulation analysed by Saylor and Miller (1987, this issue) confirms the findings of the HYPO study concerning the northwestward drift of hypolimnion water in mid-basin (Blanton and Winklhofer, 1972). Unfortunately, the failure of current meters on the northwest shore of the Central Basin precludes any firm evidence of how this circulation is completed, although the pattern seems to consist of closed horizontal gyres. A companion modelling study (Schwab and Bennett, 1987, this confirms the findings of Saylor and Miller that the basin-wide subsurface circulation of the Central Basin is highly changeable. The two-gyre circulation common to the other, deeper Great Lake basins occurs during strong winds, but the circulation may also comprise only one gyre rotating in either a clockwise or an anticlockwise direction. Lacking the bottom topography that steers flow into preferred patterns, the Central Basin circulation is sensitive not only to the strength of the winds but also to the variation of the wind stress across the basin. Hamblin's study of storm-surge modelling (1987, this issue) points to our present unsatisfactory ability to infer the overlake wind field from shore observations only, and this concern is also expressed by Schertzer (1987, this issue).

Relationships between land and lake winds have been developed empirically (Schwab and Morton, 1984), but Hamblin recommends that the relationship be approached as a research problem in meso-scale meteorology. Onshore/offshore temperature transects made on the northshore (Chiocchio and Boyce, 1987c) show persistent upwelling within 3 km of the shore but provide no evidence for the topographic waves that so perturb this system along the north shore of Lake Ontario (Simons, 1983). The slow warming of the Central Basin hypolimnion is consistent with a mean vertical heat conductance slightly greater than the molecular value; this would not be so if the bottom transport across the basin were compensated by large vertical circulation at the edges (Boyce, 1981). The question of edge effects returns again in considering how the energetic and coherent mid-basin inertial frequency current oscillations adjust to the shoreline (Boyce and Chiocchio, 1987b, this issue). Nothing in the study of basin-wide circulations would invalidate the Project HYPO conclusion that the offshore region of the Central Basin is one of relative homogeneity. Study of the more dense mid-basin array of current meters and thermistor strings (Boyce and Chiocchio, 1987a, this issue) confirms the large-scale horizontal coherence of the meteorologically-forced and resonant motions and demonstrates that a substantial portion of the motion can be ascribed to local forcing modified by the closed nature of the basin. Subject to direct confirmation, the evidence indicates that the Central Basin hypolimnion, once formed, and with the exception of influx from the Eastern Basin, is subsequently modified through vertical exchanges with the layers above.

If the Central Basin hypolimnion is modified primarily by vertical exchanges, then the signature of these changes ought to be visible in time series of physical and biochemical parameters in mid-basin. This reasoning prompted the inclusion of anchor stations into the 1979 and 1980 experiments in which physical, chemical, and biological parameters were measured at least often enough to track diurnal fluctuations. Study of these data (Robertson and Boyce, 1987) revealed many instances where short term changes in bottom temperature or dissolved oxygen, for example, could not easily be ascribed to local changes, but seemed rather to imply the advection of water of different quality into the the experiment area. As a test of this hypothesis, a heat budget of the Central Basin experiment site was assembled (Royer, Boyce, and Chiocchio, 1987, this issue). If vertical fluxes alone were active, then to within experimental error, the estimated surface heat flux should equal the time rate of change of the heat content of the water column. It was found that the two quantities differed on daily timescales by amounts that are significantly greater than expected error. The average difference, over many days, however, is small. Large differences between daily heat flux and daily heat content change should then agree with estimates of the horizontal flux of heat into the control volume based on data from current meters and thermistor strings. This calculation is greatly hampered by the lack of flow information above the 10 m depth. Closing the heat budget with an estimated advective term proved impossible in any rigorous way despite approximate correspondance of major events. It was concluded that distributions of temperature, oxygen, and presumably other parameters the Central Basin offshore region are undersampled at horizontal separations of 10 km or more. Estimates of horizontal diffusion relative to the spatially averaged flow based on current meter time series at horizontal separations of 10 km suggest that the diffusion process is relatively weak, and that patchiness can be sustained for long periods of time. Thus the homogeneity alluded to earlier refers to statistical distributions and not instantaneous values.

Bearing in mind the intrinsic variability of the mid basin environment at scales of 10 km or less, we now examine the studies of vertically acting physical processes based on the 1979 and 1980 data. This material is reviewed in detail by Royer, Boyce, and Chiocchio (1987, this issue). Entrainment of thermocline water into the hypolimnion was inferred from the HYPO ship cruise data (Burns, 1976) and its potential for resupply of oxygen to the hypolimnion was assessed. Ivey and Boyce (1982) were able to document this process in the 1979 current and temperature time series data. The downward entrainment process is clearly visible on two occasions in the 1979 records but these two events alone are not sufficienbt to make a significant long-term impact on the oxygen budget of the hypolimnion. A subsequent paper by Ivey and Patterson (1984) demonstrated that the mixed layer concepts used to simulate thermocline development in deep lakes could be extended to both the upper and lower mixed layers in the Central Basin of Lake Erie to track the process of downward entrainment. Boyce and Chiocchio, (1987b, this issue) show how the energetic inertial frequency component of the mean flow may be simulated from inputs of wind data and thermal structure. A major conclusion from this study is that the vertical distribution of mean flow in the lake depends on details of the temperature profile that might easily be overlooked. Under light-to-moderate winds in mid-summer, the Central Basin may have three independently moving layers, reverting to two layers under sustained strong winds. The thicknesses of the moving layers, particularly during the three-layer stage, may vary rapidly. A further important conclusion, articulated by Saylor and Miller (1987), and affirmed by subsequent authors, particularly Royer, Hamblin, and Boyce (1987, this issue) in their description of the profiling current meter (GVAPS) data, is the necessity to extend the measurements of current into the top 10 metres of the water column. Finally, an obvious next step in the simulation of vertical structure is to combine the mixing model and the mean velocity model into a model that simulates not only the evolving layer depths and temperatures but also the mean velocities that contribute importantly to shear-generated turbulence. The development of thermocline models that allow for the detailed structure of both currents and temperature will permit a more quantitative assessment, among other things, of the entrainment of overlying water into the Central Basin hypolimnion.

SEDIMENT OXYGEN DEMAND IN THE CENTRAL BASIN HYPOLIMNION.

The conventional view holds that the oxygen demand of the hypolimnion is in two parts, a demand in the water column itself (WOD) and a demand at the sediment water interface (SOD). Oxygen is physically resupplied to the Central Basin hypolimnion with the occasional entrainment of thermocline water into a turbulent hypolimnion, and the lateral flow into the hypolimnion of water from the Eastern Basin. Both of these processes are reviewed in this issue (Bartish, 1987, this issue; Royer, Boyce, and Chiocchio, 1987, this issue).

Accounting for the sediment oxygen demand has proven to be difficult. Again, physical processes are involved as mediators of oxygen transfer across the interface when there is no resuspension of bottom sediments, and importantly, through the physical process of resuspension itself. Using apparatus to measure deposition and entrainment in the laboratory, Lick and Kang (1987, this issue) found that freshly sedimented material resuspends more readily than material deposited only a few days earlier. Thus compaction and cohesiveness are important to the fate of sediment materials introduced to lakes. Near active sediment sources, this means that the character of sediment is likely to change through the season as easily resuspended material, loaded in the spring, is moved away, leaving behind coarser material in the summer. Offshore, resuspended sediment is in equilibrium with the bottom in that deposition rates match resuspension rates. The amount of material that is ultimately movable is finite and depends on the stress applied to the bottom. Sediment trap results show the natural seasonal variation of bottom stress; resuspension in the fall was increased enough to deposit visible layers in the traps during storm events (Charlton and Lean, 1987, this issue). Bedford and Abdelrhman indicate (1987, this issue) that direct measurement of sediment resuspension is a difficult task, particularly in the Central Basin of Lake Erie where at least three different bottom flow regimes (steady, unsteady, and oscilating) may be encountered singly or in combinations. Progress has been made in the measurement and interpretation of flow distributions, but the necessary parallel measurements of suspended sediment distributions have yet to be made. Remote sensing yields useful synoptic views of horizontal, near-surface distributions of seditments (Mortimer, 1987, this issue), but quantitative assessment via remote sensing awaits the development of appropriate optical models.

During SOD experiments, the initial rate of oxygen uptake was high due to the disturbance of sediments when the chamber was placed on the bottom. As Davis and Fay (1987, this issue) explained, those resuspended sediments have a high percentage of easily oxidizable substances that consume oxygen when exposed.

Charlton (unpublished data) found that the instantaneous oxygen consumption of 1 cm thickness of surface sediment is equivalent to a 1 mg/l depletion of the oxygen in a typical hypolimnion. These observations are consistent with the idea that resuspension of bottom sediments contributes to the amount and stability of oxygen depletion.

The methods used to measure SOD yield differing estimates depending on the amount of stirring of the sediment surface. Experiments are hampered by an inability to match or to compare the flow field at the sediment surface in the experiments with that in the lake. Although the SOD rates measured by Snodgrass and Fay (1986) are lower than those reported by Davis and Fay (1987, this issue), they are still equivalent to the total net rate calculated from changes between surveys.

The sum of SOD and WOD measurements is at least twice the observed net depletion rate in the hypolimnion and there is as yet no explanation of where the oxygen comes from to make up the difference. WOD (respiration) estimates from closed bottle experiments appear less uncertain than the SOD estimates and they are consistent with observed 14C uptake rates and the rate of change of biomass in the water. This lends some credence to the WOD estimates. Nevertheless, the only measurement with any real certainty is the net oxygen depletion rate.

Sediment trap studies of Charlton (1983), Charlton and Lean (1987, this issue), and Rosa (1985) have shown that an important source of particles in the hypolimnion is the bottom itself. Although some of the particles caught in the traps must be from shoreline erosion, the increasing flux of particles into traps close to the bottom leads to the conclusion that both horizontal and vertical transport of sediments results from sediment-water interactions. The flux of particles into sediment traps increases as the traps are placed closer to the bottom of the lake. Generally, particles seem to be correlated with oxygen depletion (Charlton and Rao, 1983). Thus, when WOD is measured in bottles, some portion of the oxygen uptake may be due to particles which came from the bottom.

The particles, solutes, and gases resuspended or entrained in an SOD experiment are prevented from mixing with the water column. If we consider that the oxygen consumption of the particles suspended in an SOD experiment would normally occur in the water column and is measured by WOD experiments, then some portion of the total hypolimnion oxygen consumption is represented twice in the sum of WOD+SOD derived experimentally.

The scale of this double counting of oxygen consumption is not yet known, but we can conjecture from the sediment trap results (Charlton and Lean, 1987, this issue) that it may be important. The double counting is not removed by the usual practice of subtracting the volumetric WOD from apparent SOD. A correction could be made by subtracting the areal resuspended consumption from apparent SOD but present information is insufficient to do this. There must, however, be some oxygen consumption in the sediments and we do not propose that this is inconsequential. Since the "sediment water interface" is not an interface but is really a mobile gradient of sediment/water concentration, there is a question of how to define what is a water sample and what is a sediment sample. Nevertheless, the results of SOD experiments are dependent on the stirring speed because both diffusion and resuspension are augmented by water motion. As pointed out by Lam et al. (1987b) the oxygen depletion of ice covered lakes (Mathias and Barica 1980) is related to mean depth and this allows the sediment related effect to be interpolated. In eutrophic lakes the sediment effect was equivalent to 0.23 g O_2/m^2 /day compared to 0.08 g O_2/m^2 /day in oligotrophic lakes. Even after doubling these rates to correct for temperature differences, the rate (SOD = 0.88 g O_2/m^2 /day) of Davis and Fay (1986, this issue) seems too high for Lake Erie. In Mathias' and Barica's study, chlorophyll in the eutrophic lakes was 4-20 times higher than in Lake Erie and sediment organic matter was up to 25% of the total dry material by weight compared to the 10% in Lake Erie. Lake Erie most closely resembles the "oligotrophic " lakes in Mathias and Barica (1980). If we assume then that the real consumption in Lake Erie sediments is between 0.08 and 0.16 g O_2/m^2 /day much of the apparent discepancy between experimental consumption rates and the observed oxygen depletion is eliminated.

The hypothesis that the bottom sediment acts on oxygen partly by supplying oxygen-consuming materials to the water column is consistent with: (1) the observations that part of the depth effect on oxygen depletion is due to sediment /water interactions; (2) the notion that there is a short and long term buffering or stability in oxygen depletion caused by storage of sediment organic carbon; and (3) observations by Burns (1976) and Charlton and Rao (1983) that the difference in oxygen depletion between the Central and Eastern Basins correlates well with differences in particle concentrations in the water; and (4) observations by Charlton and Lean (1987, this issue) that sediments are routinely resuspended and the downflux of new organic matter into the hypolimnion is insufficient to maintain the oxygen depletion process during stratification.

If we could assure repeatability of or at least account for changes in the oxygen-consuming potential of sample sediments, then we might consider laboratory oxygen demand experiments in which both particle concentrations and turbulence are measured variables. The problems of recreating "natural" boundary layer turbulence in an artificial enclosure may force the adoption of a simple grid-stirring device such as that utilized by Tsai and Lick (1986) to compare sediment samples. The loss of exact dynamic similarity would be offset by repeatability and easily-measured energy input.

SYSTEMS MODELLING OF LAKE ERIE

Readers of (Lam and Schertzer, 1987; Lam, Schertzer, and Fraser, 1987a and 1987b;Di Toro et al. 1987, all in this issue) together with their antecedents will be impressed with the enormous task of synthesis undertaken by these workers and by the skill of the models they have produced in simulating water quality in Lake Erie (in particular the dissolved oxygen concentrations in the Central Basin hypolimnion). Not only have these models reproduced the annual cycle of dissolved oxygen in any given year, but they have also been able to incorporate the substantial interannual variations in weather and significant changes in nutrient loading.

The success of the models demonstrates that the system is predictable within the ranges of the forcing variables encountered to date. It is not certain in all respects however, that the models are exact analogues of the system itself, a condition that should be met if the models are to be used in a predictive mode with complete accuracy. Provided that the models are applied to simulate conditions that fall within the tested range and that the confidence limits of the results are taken into account, useful predictions can be made.

The situation is relatively clear on the physical side. The extension of the concepts of molecular diffusion to a turbulent environment provides a robust mixing model that is readily adjustable to particular systems (Lam et al. 1986a, 1986b). The turbulent kinetic energy models applied to a mixed layer, such as that of Ivey and Patterson (1984) provide another approach, equally robust. Both approaches are combined in the model of Mellor and Durbin (1975) where the turbulent kinetic energy equation is solved to generate values of the effective diffusivity. One of the conclusions of the physical studies reported in this issue is that the major exchanges between the hypolimnion and the rest of the Central Basin take place as vertical fluxes (with the exception of the horizontal exchanges with the Eastern Basin that are explicitly accounted for). The driving forces, heat flux and wind stress, vary little across the basin. On the other hand, the mixing model used by DiToro and his colleagues is not as exact an analogue of the physical system since interface depths are fixed, except in extreme cases, although heat transfer is adequately simulated by diffusion.

On the biological and chemical side, each model represents an individual act of synthesis on the part of its creators for there are few clear indications in the biological literature that a relationship should take one shape and not another. The Lam model arises out of earlier work by Simons and Lam (Simons et al. 1979) in Lake Ontario and these authors admit that some biologically unconventional formulations were needed. Clearly, there has to be some grouping of the many recognized nutrient forms, the many active and interactive species in the food web, and possibly some elimination of compartments, species, and interactions of minor importance. Just as clearly, there is a limit to the degree of simplification allowable if the complexity of response is to be followed. The DiToro model lists 15 biochemical variables to be simulated in each of three layers. The Lam dissolved oxygen model operates with three. This difference between these two models reflects the modellers' purposes. Unlike the physical component of the models, we do not know whether or not the biochemical parts are proper analogues of the system, whether or not they are working simplifications arrived at from a deliberate scaling and lumping of a set of primitive equations. This state of affairs is a consequence of the lack of quantitative information on biochemical processes.

Note that the models of Lam and associates predict a mild response of oxygen depletion to reduced phosphorus loadings similar to the 0-2 mg/L in the historic response to increased loadings in Charlton (1987, this issue). The response predicted by DiToro et al. (1987, this issue) seems to be larger than in

Lam et al. and is perhaps somewhat optimistic in the light of anoxia occurences in 1985 and 1986.

A major advance in approach to the modelling work has been the translation of the effects of stochastic factors such as weather into probabilities based on the historic data. This means that long term forecasting now can contain, for example, the probability of certain oxygen levels likely to occur under steady nutrient loading. Thus, there has been progress from the realization that weather driven physical factors affect the biology and chemistry (eg: Burns, 1976, Charlton 1980) to the use of weather and nutrient loading data to predict conditions in the lake.

The modelling results tend to confirm the original management decisions to reduce nutrient loads but the need for surveillance monitoring of water quality and further research into lake processes remains. For example, the response of oxygen to reduced phosphorus loads is so weak, and experimental data sufficiently unreliable, that the modelled response of Lam et al. is based on fitted parameters of SOD. New research by Manning and Mayer (1986) indicates that sediments have become increasingly oxidized and have increased phosphorus retention capabilities in the last five years. Thus, while the effects of lake management are occurring, the continuing research helps delineate the changes and provides the information to interpret how and why the changes occur. Gaps in modelling include the apparent lag in responses to changing loads and the processes associated with particle settling, cohesion, resuspension and, carbon storage. Indeed, these sediment/water interactions may be important in the recharge of contaminants to the water and their subsequent volatilization and burial.

The use of either model as a predictive tool is subject to the restrictions mentioned above. With each season's data comes the opportunity to verify the models anew and to extend the range of inputs over which they function reliably. Models serve functions other than the prediction of the system's response to hypothetical inputs. They can provide insights that are beneficial to many study elements:

i) On the physical side, it has been stated by Royer et al. (1987a, this issue) and demonstrated by Boyce and Chiocchio (1987b, this issue) that in a variable, unevenly forced environment, cause and effect relations are very difficult, even impossible to establish from observations alone and that models play an essential role in developing and testing hypotheses. That the present system models work with the data now in hand should be a positive and creative challenge to biologists and chemists to explain why or to offer for testing alternative, more realistic, relationships.

2) The models can be exploited as a guide to an economical and effective monitoring strategy. Time series of temperature and dissolved oxygen distributions measured at one or two locations in the Central Basin could be extended to the whole basin using a model. Such an approach might repay the development and deployment costs out of savings in ship usage, and at the same time provide data that is much better suited to surveillance requirements. An integration of modelling and surveillance activity could pay off handsomely.

3) A major conclusion of this entire experiment is that a careful reassessment of the so-called sediment oxygen demand is needed. There is evidence that the conceptual models through which the available data have been interpreted may be incorrect. The study of sediment-water interactions, crucial not only to the issue of eutrophication of Lake Erie, but also to the recycling and/or removal of toxic contaminants in Lake Erie and elsewhere, is one where modelling will be essential to interpreting the difficult but necessary field experiments.

CONCLUSIONS

We hasten to point out that not all of the work presented in this issue has received equal weight in this summary. This reflects the biases of the present authors as well as their desire to tell a cogent, if simplified story. We hope that readers approaching this issue with many different points of view will all find something of value. At the same time we do not suggest that we have summarized all the important Lake Erie work to have been completed in the decade since the "Lake Erie in the early seventies" issue of the Journal of the Fisheries Research Board of Canada (Vol. 33, No.3).

In that special issue of JFRB, Burns and his colleagues (Burns et al., 1976) evaluated the scientific knowledge and data available in 1975 in the hope that an overall model or " ...at least a qualitative description of processes in the lake could be given such that water movements, sediment characteristics, and nutrient loadings could be linked to explain phytoplankton, zooplankton, and fish distributions." In their summary discussions they concluded that "...in nearly every study, some necessary rate process had not been investigated with the consequence that the results and findings of the study remained inadequate for incorporation into a truly predictive model." They published a diagram summarizing their view of the model components (Figure 1) that we reproduce here. At that time, only the physical transport model was considered to be adequate for predictive purposes. In that paper, the authors present a list of sixteen studies required to complete the scheme. A measure of the far-sighted care with which the diagram and the list were drawn is the fact that many of the items remain as valid research topics; it is a measure of the energy devoted to Lake Erie studies in the intervening decade that useful progress has been made with many of them. In Appendix A we display a summary assessment of our progress down the list of 16 items; in Appendix B we present our own list.

We do not, however, present an updated version of Figure 1, for the modelling studies of Lam et al. and DiToro et al. (1987, this issue) challenge the reductionist viewpoint on every side and demonstrate that realistic simulations are possible with a much simplified network of processes.

Scattered through this issue, and indeed in this summarizing paper, are many individual conclusions. Holding to the agreed focus on processes relating to oxygen depletion in the Central Basin, we would conclude that with the exception of sediment resuspension, physical processes are reasonably well accounted for. That is to say they can be ordered and scaled. Modelling studies convincingly demonstrate that vertical exchange processes responsible for the formation and maintenance of stratification strongly influence the susceptibility of the Central Basin hypolimnion to late-summer anoxia. Physical studies, notably those of Royer, Boyce, and Chiocchio (1987, this issue) show the difficulties of inferring vertical fluxes from direct control volume experiments, and underline the importance of simulation modelling in testing hypotheses over time intervals long enough to average out variability. The non-physical studies seem to converge on the conclusion that the sediment/water/benthos interactions require better understanding. The pursuit of this understanding will involve further multidisciplinary work and eventual synthesis of it through modelling.

As a community resource, it is no exaggeration to say that Lake Erie is the most valuable of all the Great Lakes (Burns, 1985). But the population density in its basin both defines and undermines its value. As a result of scientific study of Lake Erie, we are now engaged in one of the most important large scale ecological experiments ever undertaken - to determine if and when eutrophic conditions can be reversed in a large lake through control of loadings. Beyond that experiment there looms another, perhaps more important still - to determine the potential for recovery after reduction in inputs of toxic chemicals. As J. Vallentyne (personal communication) has often pointed out, it is not just the Great Lakes Basin that is involved in the outcome, it is most of the industrialized world.

For if the wealthy and energetic society of the Great Lakes Basin cannot find the will, the resources, and the stamina to follow this venture through, the chances of success elsewhere are small.

In 1985, the International Association for Great Lakes Research was invited to submit a brief to the Joint National Research Council/Royal Society of Canada Committee to Review the 1978 Great Lakes Water Quality Agreement. Although the Association in its brief made many specific recommendations, it was most concerned with the viability of long-term research. When we think on the long tradition of multidisciplinary Lake Erie work, we share the same concerns and we quote at length from the IAGLR brief:

"...the Association finds it necessary to examine the present day status of the research community and to comment on the philosophy of environmental research. First of all, we note a tendency among administrators and managers, and certainly among many of the public, to suppose that environmental problems can be solved once and for all like crossword puzzles....We are of the opinion that the environmental stresses we impose on lakes are persistent in time although they may change in nature. These stresses reflect the evolution of the surrounding society, and as we learn to cope with one (eutrophication), another (toxic contaminants) arises....Nothing in our experience would suggest that scientific research would not be required to learn how to cope with a "new" stress, and the likelihood that new stresses will continue to appear argues for a continuity of research effort."

There are indications that medicine, in addition to concern with the management of illness, is devoting more energy to maintaining wellbeing. The latter is an appropriate role for environmental science, too. And another role for environmental scientists is that of curator, charged not only with the protection of the treasure entrusted to his care, but also with fostering public enthusiasm and respect for it. Unlike the troubleshooter, these roles require continued contact with the subject. They are oriented to process, not products. While this special issue on Lake Erie is indeed a product, it is also part of the process of staying in touch with the Lake during a period of rapid, and we think hopeful change. Although the decision to work together to prepare a joint report with some thought towards its integration has had its cost in terms of delay, it has maintained and we hope strengthened an international network of scientists who have long term interests in Lake Erie. We recognize that analysis and interpretation cannot be planned with the same rigour as a field experiment, but we recommend greater efforts to include adequate resources for them in the overall definition of projects.

The 1979 and 1980 experiments did not occur spontaneously but were developed in conjunction with the I.J.C.-sponsored intensive surveillance program. We feel that such programs have provided excellent incentives for focussing energy on Great Lakes problems in quantities sufficient to make real progress. In keeping with the philosophy described above, we recommend that not only the background plus occasionaly more intensive fieldwork be included as part of the regular ongoing surveillance program, but also , and at reasonably regular intervals, intensive efforts to interpret and synthesize the results. The collection of studies presented here is evidence of scientific progress, yet there remains interesting and useful work to be done. But that is only partial justification for continued work. The ecology of Lake Erie should include its students.

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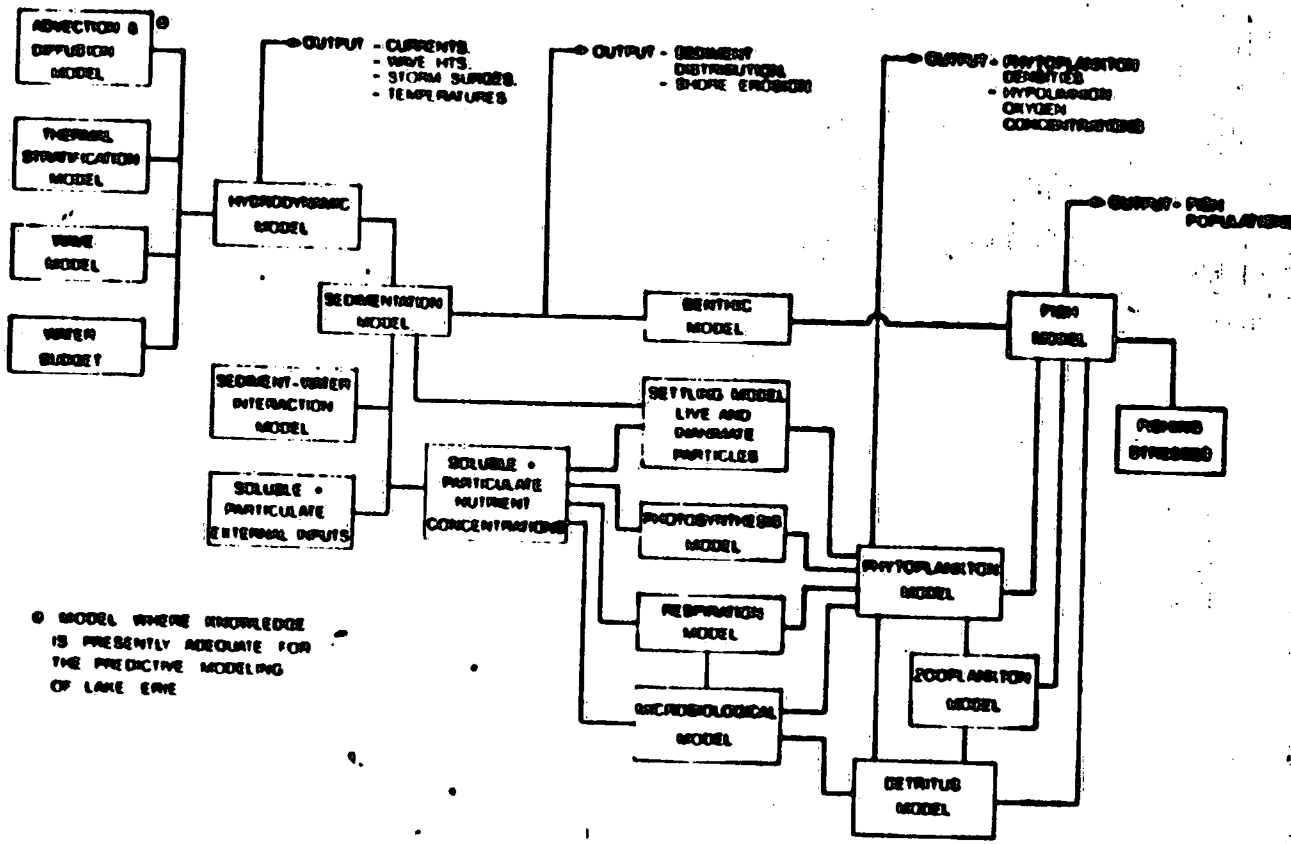

FIG. 1. Schematic outline of the more important data inputs, models, and linkages between models required to formulate a predictive model for a whole-lake system. (Many possible linkages have been omitted to maintain a manageable level of simplicity.)

APPENDIX A: ASSESSMENT OF PROGRESS WITH THE 16-ITEM LIST OF BURNS ET AL. (1976)

....

a) Careful measurements of the pattern of water mass exchange between the three basins....

Exchange mechanisms are largely understood and rough quantitative assessments have been made of the exchange between the Central and Eastern Basins. More work is needed to delineate the importance of intrusions of the Central Basin hypolimnion into the Weatern Basin.

....

b) An investigation of the resuspension of fine-grained sediments by currents and wind-waves, together with the extraction of nutrients from the sediments as a result of the hyrodynamic action.....

These processes continue to be recognized as a potential key to our understanding of the Central Basin response to changing nutrient loading. Measurements are difficult but capabilities are growing. Much work has been accomplished on the potential bioavailability of sediment phosphorus, but little information is available on actual in-lake utilization (Young et al., 1985). The issue may also be central to contaminant/water interactions.

....

c) An investigation of storm-episode sediment transport within the lake in contrast to sediment transport under non-storm conditions....

Related to b) above. Some studies are underway in the Sandusky area. Remote sensing can describe whole-basin patterns quantitatively; but quantitative assessment by this means awaits development of appropriate optical models, based on joint field work and image analysis.

....

d) A careful examination of the sediment-water interface with emphasis on on the form of nutrients and toxic materials in the centimeter below the interface and in the meter of water above....

Related to b) above. Studies are underway in the Sandusky area and in the Central Basin.

....

e) River inputs of phosphorus, nitrogen, and suspended solids, in particular, should be examined as a function of flow so that accurate loading estimates of materials can be calculated; atmospheric inputs of nutrient elements should also be measured....

More emphasis on event-sampling has increased the accuracy of loading estimates, but substantial uncertainties remain.

....

f) The apatite content of river waters should be measured and a test of apatite solubility in Lake Erie waters and sediment interstitial waters should be carried out....

Apatite has been found to be incapable of supporting algal growth in availability experiments (Young et al., 1985).

....

g) The loading estimates of fine-grained materials and associated elements to the sediments should be improved by ensuring adequate basin coverage in the cores examined....

Extensive sediment surveys have not been continued. New work reveals substantial downward mixing in the sediments (Robbins, 1982). Some studies have been carried out by Robbins and Mudroch (reference) on sedimentation rates in each basin as related to the input of metals, particularly lead.

....

h) A major study of aerobic heterotroph bacterial activity in the lake should be carried out in conjunction with the studies (i) and (j) described below....

Bacterial numbers seem to be correlated with oxygen depletion (Charlton and Rao, 1983).

....

i) Respiration and other oxygen-consuming processes should be studied to the same extent as a complementary study of primary productivity. These processes should be investigated both in the water and at the sediment-water interface....

A report on primary production and respiration is in preparation (Charlton, personal communication). Most new carbon is respired in the epilimnion. Net community production is of the same order of magnitude as the Central Basin oxygen depletion rate. The interpretation of direct measurements of sediment oxygen demand is under discussion.

....

j) The rates of decay and formation of detritus and soluble organic material should be carefully determined....

No progress.

....

k) Phytoplankton (including microplankton) species and densities, together with their associated productivity at all depths in the lake, should be determined....

This has not been attempted; expensive, multi-year studies are needed. A less reductionist approach is now popular.

....

l) The vertical migration of both phytoplankton and zooplankton should be studied in relation to epilimnion nutrient budgets....

Not attempted.

....

m) The cause of major algal blooms should be determined, if possible....

Algal blooms have been infrequent since 1970.

....

n) Rotifers must be included in the study of the zooplankton and the grazing pattern of all the major species should be examined....

Not attempted.

....

o) A lake-wide program to study the benthos should be carried out....

A program is in the planning stages at the National Water Research Institute.

....

p) The effect of fish on phytoplankton and zooplankton populations should be determined....

Not attempted but is possibly important with the resurgence of the walleye fishery and the impact of stocked species on the forage fish in Lake Michigan.

....

APPENDIX B: SPECIFIC RESEARCH RECOMMENDATIONS.

1) An array of instruments deployed through the stratifed period on the northwest shore of the Central Basin would improve our understanding of the hyplolimnion circulation and the importance of upwelling on that shore. With the existing ship data, we are unable to gauge the variability of this phenomenon under changing wind conditions.

2) Time series measurements of currents and temperatures in Pelee Passage using the new current meters and temperature recorders are needed to document the frequency of intrusions of Central Basin hypolimnion water into the Western Basin.

3) The question of the importance of sediment resuspension will require much fuller investigation, first in an assessment of available, unanalyzed data, and later in the form of a multidisciplinary experiment. The interaction of the resuspended sediment with the water column needs to be determined for both uptake and release processes. Furthermore, the possible effects of volatilization of contaminants from resuspended sediments

should be investigated. Physical components are under active development in the course of the UGLCC study referred to above. The Central and Western Basins of Lake Erie are good places for this study.

4) The implications of the lag in oxygen response to reduced phosphorus loadings should be extrapolated to other issues such as toxic contaminants. Since some toxics accumulate in the sediments, how do sediment mixing and rapid burial caused by basin erosion combine to produce a response in sediment characteristics? Is there a linkage between trophic state, mean depth, and sediment inputs that may render Lake Erie relatively insensitive to contaminant loads?

5) What is the in-lake untilization of "bioavailable" sediment-bound phosphorus, and what will be the effect of reduced erosion of farmland in the basin?

6) The Eastern Basin has been relatively unresearched due to the concentration of effort on the Central Basin oxygen problem. Although the hypolimnion oxygen is suitable for fish in the Eastern Basin, there are local depressions in the thermocline oxygen that approach levels hazardous to fish. The cause of this phenomenon should be determined and other aspects such as sediment storage/export and the effect of shoreline development on nearshore water quality should be investigated.

7) The difference between summer and winter processes should be studied. Total phosphorus tends to disappear from offshore water in the summer. The lake appears to be more productive in the cold water period when the entire water column in in contact with the sediments.

8) What are the biological implications of the success of the generalized simulation models? Can these models be used to delineate the appropriate degree of complexity in biological investigations?