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MODELLING CHANGES IN PHOSPHORUS AND DISSOLVED OXYGEN PRE- AND POST-ZEBRA MUSSEL ARRIVAL IN LAKE ERIE

D.C.L. Lam, W.M. Schertzer and R.C. McCrimmon

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RECHERCHE SUR LES EAUX

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ABSTRACT

By using the NWRI nine-box water quality model calibrated for pre-Dreissena years, with the model coefficients unchanged, we demonstrate that changes in phosphorus and dissolved oxygen in post-Dreissena years can be detected by the deviation of computed results from observed data. Through sensitivity analysis, we excluded other possible mechanisms to conclude that Dreissena can affect the phosphorus concentration in Lake Erie. Specifically, the total phosphorus is decreased in the east basin whereas the soluble reactive phosphorus is increased in the west basin. The dissolved oxygen in the lake is, however, not significantly affected by Dreissena. The impact of these and other findings on the phosphorus-dissolved oxygen relationship and its implication to the Lake Erie lakewide management plan is discussed using the results of this study. A new set of experiments has been proposed and is currently being carried out to better understand the Dreissena-phosphorus-plankton relationship and to improve future modelling and monitoring studies.

NWRI RESEARCH SUMMARY

Plain language title
NWRI modeling study compares phosphorus and dissolved oxygen levels pre- and post-zebra mussel arrival in Lake Erie

What is the problem and what do sicentists already know about it?
Zebra mussel is one of the exotic species introduced to LakeErie since late 1980's. Scientists have known that zebra mussels caused changes in plankton production and nutrient levels, both being important factors in the Lake Erie Lake-wide Management Plan.

Why did NWRI do this study?
In 1987, NWRI published the results of a nine-box water quality model that simulated phosphorus and oxygen dynamics in the three Lake Basins (West, Central and East) and in the associated three vertically stratified water layers in each basin. The model was calibrated and verified with 16 years of data, all in the pre-zebra mussel period. In the present modelling study, we explore and ascertain the relationships further, if any, between the phosphorus and oxygen dynamics and zebra mussels, in the post-zebra mussel years. To do so, instead of adding a new zebra mussel sub-model, the NWRI nine-box model was run as is, without changing any of its coefficients, for selected post-zebra mussel years. The strategy is to detect any deviations in model predictions from observations and attribute them to new processes due to zebra mussels. A sensitivity analysis of the physical, chemical and biological processes before and after the Dreissena arrival then identifies knowledge gaps for the most sensitive processes and key inputs required for model improvement.

What were the results?
It was found that the total phosphorus concentration has decreased in the east basin after the zebra mussel arrival while soluble reactive phosphorus has increased in the west basin. Based on the modelling and sensitivity analysis results, these findings are attributable to possible effects of zebra mussel. On the other hand, there have been changes in dissolved oxygen concentration in the lake pre- and post-zebra mussel

arrival. However, modelling and sensitive analysis results indicate that these changes in dissolved oxygen are due to weather influences and not due to zebra mussels.

How will these results be used?

This study has been supported and funded as a special study for the Lake Erie Lakewide Management Plan as well as an on-going study on climate change in the Great Lakes 2020 program in Environment Canada. The results will be considered by the Lake Erie Lakewide Management Plan for future strategic planning and implementation of phosphorus abatement. The result on the weather influence on dissolved oxygen, in spite of zebra mussel arrival, is also an important consideration for future climate change adaptation strategies. This modelling study has also led to a new set of physical, chemical and ecological experiments being conducted, in collaboration with the University of Waterloo, under an NSERC Strategic Grant, in both the nearshore and offshore of the east basin of Lake Erie to gather missing knowledge and data for the improvement of the water quality model.

Who were our main partners in the study?

Lake Erie Lakewide Management Plan, Ontario Region, Environment Canada; Fisheries Canada; University of Waterloo and University of Guelph; Scientists involved in other Lake Erie studies at NWRI

Modélisation des variations des taux de phosphore et d'oxygène dissous, avant et après l'introduction des moules zébrées dans le lac Érié

par

D.C.L. Lam, W.M. Schertzer et R.C. McCrimmon

RÉSUMÉ

À l'aide du modèle à neuf boîtes de la qualité de l'eau de l'INRE, étalonné en fonction des données sur la période précédant l'introduction de *Dreissena* et utilisé sans modification des coefficients, nous montrons que les variations des taux de phosphore et d'oxygène dissous, durant les années suivant l'introduction de *Dreissena*, peuvent être déterminées à partir des écarts entre les résultats calculés et les données observées. Grâce à l'analyse de sensibilité, nous avons pu exclure d'autres mécanismes potentiels, pour en arriver à la conclusion que *Dreissena* peut modifier la concentration de phosphore dans le lac Érié. Plus précisément, la concentration de phosphore total a diminué dans le bassin Est, alors que le taux de phosphore réactif soluble a augmenté dans le bassin Ouest. *Dreissena* a par contre peu d'effet sur le taux d'oxygène dissous. À partir des résultats de l'étude, nous discutons de l'importance de ces conclusions et d'autres sur la relation entre le phosphore et l'oxygène dissous, et en examinons les répercussions sur le plan d'aménagement panlacustre du lac Érié. Une nouvelle série d'expériences est actuellement en cours, dans le but de mieux comprendre les interactions entre *Dreissena*, le phosphore et le plancton, et d'améliorer les futures études de modélisation et de surveillance.

Sommaire des recherches de l'INRE

Titre en langage clair

L'étude de modélisation de l'INRE compare les taux de phosphore et d'oxygène dissous, avant et après l'introduction des moules zébrées dans le lac Érié.

Quel est le problème et que savent les chercheurs à ce sujet?

La moule zébrée est une des espèces exotiques introduites dans le lac Érié depuis la fin des années 80. Les scientifiques savent que ces moules modifient la production de plancton et les taux d'éléments nutritifs, deux facteurs importants du Plan d'aménagement panlacustre du lac Érié.

Pourquoi l'INRE a-t-il effectué cette étude?

En 1987, l'INRE a publié les résultats d'un modèle à neuf boîtes de la qualité des eaux, simulant la dynamique du phosphore et de l'oxygène dans les trois bassins du lac (Ouest, Centre et Est), ainsi que dans les trois couches d'eau connexes verticalement stratifiées, dans chaque bassin. Le modèle a été étalonné et vérifié à partir de données compilées sur 16 ans, toutes situées dans la période précédant l'introduction des moules. Dans le cadre de la présente étude de modélisation, nous poussons plus loin l'examen et la validation du lien, s'il en est, entre la dynamique du phosphore et de l'oxygène et les moules zébrées, depuis l'arrivée de celles-ci. Plutôt que d'ajouter un nouveau sous-modèle sur les moules zébrées, nous avons utilisé, pour ce faire, le modèle à neuf boîtes de l'INRE sans en modifier aucun des coefficients, et l'avons appliqué à certaines années postérieures à l'apparition des moules zébrées. L'objectif était de déceler tout écart entre les prévisions du modèle et les observations, et d'attribuer ces écarts aux nouveaux processus induits par la présence des moules zébrées. Une analyse de sensibilité des processus physiques, chimiques et biologiques, avant et après l'introduction des *Dreissena*, a permis de mettre en lumière les lacunes des données sur les processus les plus sensibles et les principales données nécessaires à l'amélioration du modèle.

Quels sont les résultats?

Nous avons constaté une baisse de la concentration de phosphore total dans le bassin Est, depuis l'introduction des moules zébrées, alors que la concentration de phosphore réactif soluble a augmenté dans le bassin Ouest. À la lumière des résultats de la modélisation et de l'analyse de sensibilité, ces conclusions ont été attribuées aux effets possibles des moules zébrées. Des changements ont aussi été notés dans la concentration d'oxygène dissous, avant et après l'arrivée des moules zébrées mais, selon les résultats de la modélisation et de l'analyse de sensibilité, ces changements sont dus aux effets du climat et non aux moules zébrées.

Comment ces résultats seront-ils utilisés?

Cette étude a été réalisée à titre d'étude spéciale, à l'appui du Plan d'aménagement panlacustre du lac Érié, ainsi que d'étude permanente sur les changements climatiques, dans le cadre du programme Grands Lacs 2020 d'Environnement Canada. Les résultats seront examinés en regard du Plan d'aménagement panlacustre du lac Érié, et serviront à la planification stratégique et à la mise en œuvre futures des mesures de réduction du phosphore. Les conclusions qui attribuent la fluctuation du taux d'oxygène dissous aux effets du climat, sans égard à l'arrivée des moules zébrées, sont d'autres données importantes dont il faudra tenir compte dans l'élaboration des futures stratégies d'adaptation au changement climatique. Cette étude de modélisation a également ouvert la voie à une nouvelle série d'études physiques, chimiques et écologiques menées en collaboration avec l'Université de Waterloo, grâce à une subvention stratégique du CRSNG, sur des régions situées près et au large des côtes du bassin Est du lac Érié, dans le but de combler les lacunes en matière d'information, et d'améliorer le modèle sur la qualité de l'eau.

Quels étaient nos principaux partenaires dans cette étude?

Plan d'aménagement panlacustre du lac Érié, région de l'Ontario, Environnement Canada; Pêches et Océans Canada; Université de Waterloo et Université de Guelph; scientifiques participant à d'autres études sur le lac Érié à l'INRE.

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MODELLING CHANGES IN PHOSPHORUS AND DISSOLVED OXYGEN PRE- AND POST- ZEBRA MUSSEL ARRIVAL IN LAKE ERIE

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Abstract. By using the NWRI nine-box water quality model calibrated for pre- Dreissena years, with the model coefficients unchanged, we demonstrate that changes in phosphorus and dissolved oxygen in post- Dreissena years can be detected by the deviation of computed results from observed data. Through sensitivity analysis, we excluded other possible mechanisms to conclude that Dreissena can affect the phosphorus concentration in Lake Erie. Specifically, the total phosphorus is decreased in the east basin whereas the soluble reactive phosphorus is increased in the west basin. The dissolved oxygen in the lake is, however, not significantly affected by Dreissena. The impact of these and other findings on the phosphorus-dissolved oxygen relationship and its implication to the Lake Erie lakewide management plan is discussed using the results of this study. A new set of experiments has been proposed and is currently being carried out to better understand the Dreissena-phosphorus-plankton relationship and to improve future modelling and monitoring studies.

1. INTRODUCTION

The arrival of *Dreissena*, commonly known as the zebra mussel, in the late 1980's, in Lake Erie has raised concerns on its possible impact on water quality conditions, particularly the phosphorus-dissolved oxygen dynamics and the on-going phosphorus load reduction program (Charlton et al., 1993). Recently a number of studies (Graham et al., 1996; Millard et al., 1998; Charlton, 1994; Charlton et al., 1999; James et al., 1997) were conducted to investigate the impact of the arrival of *Dreissena* on the water quality and aquatic ecosystem of the lake. Initial evaluations indicated that there appeared to be *Dreissena* consumption of phytoplankton (Graham et al., 1996; Makarewicz et al., 2000), and the removal of phosphorus from the water column by an accelerated settling mechanism through Dreissena burial and fecal deposition, resulting in a net sedimentation (Lesht et al. 1991; Charlton et al., 1999), and the emergence of changed phosphorus/chlorophyll and phosphorus/production ratios (Graham et al., 1996; Millard et al., 1998).

In addition to these observed changes over time, there were also observed changes in spatial trends. Dermott and Munawar (1993) found that *Dreissena bugensis* dwelled mainly in the profundal zone whereas *Dreissena polymorpha* preferred the littoral zone. However, only a few of them were found in the anoxic zones in the central basin. Charlton et al. (1999) showed that the observed seasonal means of total phosphorus concentration were 9.8, 9.6, 12.1 and 22.6 µgP/L for the east, central, west central and west basins respectively in 1997, compared to the values of 11.5, 13.3 and 20.1 µgP/L for the east, central, and west basins in 1986 reported in Lesht et al. (1991). In addition to these horizontal differences, there were also vertical differences due to thermal stratification. Anoxia occurred mainly in the central basin hypolimnion and was more affected by weather patterns than by phosphorus loading (Lam et al., 1987). Makarewicz et al. (1999) reported that while there was a significant decrease in phytoplankton biomass in the west basin from 1983 to 1993, there was no similar reduction in the central or east basins, because the latter basins are deeper and thermally stratified. These studies have contributed significantly to the understanding of the individual processes after the arrival of *Dreissena*. However, the results were often limited to those years with reliable observational data and the conclusions were not definitive because of the variability due to year-to-year changes in meteorological conditions that affected both the horizontal and vertical distributions of the variables measured. This difficulty is further compounded by the lack of long-term data (both chemical and physical observations) due to substantially reduced efforts in monitoring programs in Lake Erie since the 1980's.

One way to circumvent the difficulty associated with data gaps is to use different modelling methodologies (Lam et al., 1987; Lesht et al., 1991). For example, Lesht et al. (1991) used the mass balance modelling approach to show a definitive, quantitative change in the settling rate of phosphorus since the arrival of *Dreissena*. The objective of this report is to extend the modelling approach to delineate both the temporal and spatial changes in the phosphorus and dissolved oxygen dynamics before and after the arrival of *Dreissena*, including changes due to loading input, meteorological conditions, physical

circulation and thermal stratification. The purpose is to highlight key changes over the pre- and post- zebra mussel period by comparing the simulation results from the post-audited nine-box NWRI Lake Erie water quality model (Lam et al., 1987) with observed data. The strategy we employ is to first keep all model coefficients unchanged in the model, before and after the *Dreissena* arrival, so that we can detect any deviations in model predictions and attribute them to new processes due to the *Dreissena* arrival. Then we systematically change the coefficients to arrive at a sensitivity analysis of the physical, chemical and biological processes before and after the *Dreissena* arrival. Based on these two sets of model results, we can identify knowledge gaps for the most sensitive processes and key model parameters. This information is critical for proposing a new set of experiments to improve the model and the general knowledge of the impact of exotic species on the aquatic ecosystem.

2. MODELLING APPROACHES

There are many modelling approaches for water quality studies. The simplest one is a mass balance budget of the total phosphorus on a lakewide basis (Vollenweider et al., 1974). One can extend the same concept for different types of spatial compartments, e.g. by basins or by nearshore and offshore (Lesht et al., 1991). One can also extend the number of variables (e.g. Bierman and Dolan, 1982 and Koonce et al., 1996), for example, to include various forms of phosphorus (particulate or soluble), other water quality parameters (nitrogen, silicate), and different trophic levels (phytoplanktons, zooplanktons, fish). In order to limit the complexities of this investigation while allowing for essential elements in the compartmentalization of model processes, we use mainly the NWRI nine-box water quality model (Lam et al., 1987) for this study. The NWRI 9-box model compartments consist of the west, central and eastern basins in the horizontal and three thermal stratification layers in the vertical dimension. For simplicity, we assume that the west basin is fully mixed. Figure 1 shows a schematic of the major physical processes parameterized in the model and Fig. 2 shows the biochemical submodel. The physical processes (Fig. 1) used in the model includes the hydraulic flows, i.e. the Detroit

River inflow, the Niagara outflow, the inter-basin transport, vertical entrainment processes due to thermal stratification, water level changes, turbulent diffusion and water temperature. The variables (Fig. 2) used in the model are: soluble reactive phosphorus (SRP), organic phosphorus (OP), and dissolved oxygen (DO). The total phosphorus (TP) can be calculated as TP = SRP + OP, and the particulate phosphorus can be obtained from the empirical formula (Lam et al. 1987), PP = OP – 0.005 (mg/L). The biological and chemical processes include the uptake and respiration of nutrient/planktons, the settling of particulate phosphorus, the aeration of surface waters, the anoxic regeneration of phosphorus from sediment, and the physical resuspension of phosphorus due to wind-wave actions. The model includes the factors of water temperature, nutrients and light attenuation in photosynthesis, but it does not separate the phytoplankton into different subspecies. For a detailed discussion of these processes, the reader is referred to Lam et al. (1987). The model has been verified and validated over 16 years of data (1967-82) (Lam et al, 1987; de Brossia, 1984).

There are three stages in this modelling study. First we try to establish an estimate of the net sedimentation (or a general gain or loss term) of the average annual phosphorus in the lake by means of a diagnostic approach with a simple input-output lakewide box model. That is, we assume that the input and output as well as the in-lake concentration are known, and calculate the net sedimentation rate. This estimation will set the stage for the subsequent steps. A positive change in the net sedimentation rate indicates processes that add more phosphorus to the lake. A negative net sedimentation rate indicates processes that remove phosphorus. The second step is to run the NWRI nine-box model with all the model coefficients unchanged. The aim is to identify any deviation from available observed data for each of the basins and vertical layers. These deviations can be attributed to the arrival of *Dreissena* or to the uncertainty in the observed data or the model coefficients. The third step is to perform a sensitivity analysis of the key model coefficients to identify the processes that appear most sensitive to changes and how they may help explain, if possible at all, the deviations in steps 1 and 2. These three steps will not improve the model directly, because we are not aiming to add a new submodel

component for the *Dreissena* at this stage. Instead, our goal is to identify the knowledge gaps in the limnological processes through these three steps from the results of existing models so that we can propose a new set of experiments to capture the knowledge kinetics and processes required to build the *Dreissena* submodel subsequently.

3. RESULTS

3.1   Diagnostic Model Results

As a first step, before we apply the NWRI nine-box model, we use a simple, lakewide model similar to that used in Lesht et al. (1991) to obtain an overall estimate of the main changes in phosphorus dynamics before and after the arrival of *Dreissena*. We assume that the total phosphorus, TP (in g/m^3 or mg/L), is governed by

$$\frac{d(V \cdot TP)}{dt} = I - O - S \tag{1}$$

where t is time (d), V is lake volume (m^3), I is input (g/d), O is output (g/d) and S is the settling term for total phosphorus, $S = \sigma A\,TP$, for the net sedimentation rate σ in m/d for TP and A is lake area (m^2).

Instead of using Eq. (1) to calculate the total phosphorus concentration from known values of I, O and S, we rewrite Eq. (1) as

$$S = \sigma A\,TP = I - O - \frac{d(V \cdot TP)}{dt} \tag{2}$$

and solve for σ, using observed I, O, A and $\dfrac{d(V \cdot TP)}{dt}$.

Figure 3 shows the estimated input loading data for total phosphorus from 1950 to 1994, approximated from 1950-66 from historical loadings (Chapra, 1977), from 1967-82 from detailed summaries (Fraser, 1987) and post-1982 from consideration of several estimates derived from Lesht et al. (1991), Dolan (1993) and Dolan (Pers. Comm.). The rise to the maximum (about 28,000 MT/y) in 1967 from 1950 is followed by a decline due to the phosphorus abatement program resulting from the Great Lakes Water Quality Agreement. From the 1980s on, the loading starts to level at about 9,000 to 11,000 MT/y. The *Dreissena* arrived in the late 1980s (approximately 1988). That is, its arrival is in the middle of this low level of total phosphorus loads. Figure 3 also shows a similar pattern for the soluble reactive phosphorus load. Figures 4a and b show the annual and monthly data, respectively, for the Niagara River outflow used in determining O in Eq. (2) for the same period. Figures 5a and b are for the annual and monthly water level data, which are related to the lake volume V.

Figure 6 shows the observed lakewide-averaged concentration of total phosphorus from 1970 to 1997. The concentration in general follows the loading trend shown in Fig. 3 for this subset of years. There is a data gap between 1987 and 1991 because of reduced monitoring data. To compute the outflow quantity, O, of total phosphorus, we multiply the observed concentration with the outflow (Fig. 4b). If we use the data for the pre-zebra mussel period from 1980 to 1986 in Eq. (2), we obtained σ = 0.04 ± 0.02 m/d (±95% confidence limit with respect to loading). Similarly for the post-zebra mussel period from 1992 to 1997, we obtained σ = 0.07 ± 0.05 m/d. Interpretation of these results requires some caution. Since Eq. (2) is for lakewide total phosphorus concentration, the net sedimentation rate so derived applies only to spatially-averaged and chemically aggregated quantities. The range and variability in the computed σ are large, indicating a high degree of uncertainty. However, the difference in the mean values of σ (0.04 vs. 0.07 m/d) before and after the *Dreissena* arrival is significant. It indicates that, to satisfy the

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mass balance of total phosphorus in the lake, some phosphorus must be removed after the *Dreissena* arrival, be it settling or other processes that may cause the net sedimentation rate to increase. This result is consistent with results from other studies, e.g. Lesht et al. (1991) and Charlton et al. (1999), in which the phosphorus removal was attributable to a number of possible mechanisms, including *Dreissena* uptake and deposition, burial and resuspension, and removal via the outflow, etc. For this study, we intend not to speculate which is the correct mechanism for the phosphorus removal, but to find out more about where and which mechanisms are more likely to explain this diagnostic result (Fig. 6) from the NWRI nine box model (Lam et al., 1987).

3.2   NWRI nine-box model results

As shown in the diagnostic result (Fig. 6), there is a significant change in the net sedimentation rate derived from lakewide averaged total phosphorus concentrations before and after *Dreissena* arrival. To investigate this and other possible changes further, we apply the NWRI nine-box model, which has a spatial configuration (Fig. 1) of three horizontal compartments for the three basins with three vertical thermal layers during the stratification period. The model also has soluble reactive phosphorus (SRP) and organic phosphorus (OP), from which particulate phosphorus (PP) can be derived from the empirical formula, $PP = OP - 0.005$ mg/L (Lam et al., 1987). Since the settling term now applies to the particulate portion of the organic phosphorus (Fig. 2) and there are more spatial compartments compared to the lakewide model used in Section 3.1, the model would provide more information on settling rate changes before and after *Dreissena* arrival. The other processes that may be affected by *Dreissena* include photosynthesis due to nutrient uptake and light availability and the respiration process through grazing of phytoplankton (Fig. 2). On the other hand, processes such as TP and SRP loadings (Fig. 2), outflow, thermal layer movement and entrainment, water level, wind, turbulent diffusion and water temperature (Fig. 1) may affect the phosphorus-plankton-oxygen dynamics. In order to distinguish the influence of these other factors from that of the *Dreissena* on the phosphorus (TP, SRP) and dissolved oxygen (DO) concentration, we run the NWRI nine box model with all the model coefficients unchanged before and after

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Dreissena arrival. Due to a lack of observed data with sufficient spatial coverage to derive basin-wide averages after *Dreissena* arrival, we are limited to the data of 1994 and 1997. Incidentally, during this period, major mussel predators such as round gobies started to spread but had not exerted significant grazing pressure on mussels yet (Ray and Corkum, 1997). So, our choice of 1994 and 1997 data for post- *Dreissena* analysis can be viewed as related to *Dreissena* effects only, not their predators. For the pre-*Dreissena* period, we select 1978 and 1984, because the 1978 data was used for model calibration (Lam et al., 1987) and 1984 is the year that is closest to the *Dreissena* arrival (Fig. 6) with sufficient data for calculating basin averages.

We first use results from 1984 and 1994 as examples of pre- and post-*Dreissena* year, respectively. Comparison with the other two years (1978 and 1997) will follow these test cases.

3.4.3   Model simulations for 1984 : Pre-*Dreissena*

Figure 7 shows the computed and observed results for 1984 (pre-*Dreissena*) for TP, SRP and DO for west, central and east basins and for epilimnion, mesolimnion and hypolimnion layers (for the west basin, we assume only two layers). For TP, the available data for 1984 are limited, but show good agreement between computed and observed results (Fig. 7a), except for the early summer peaks in the central and east basins. The computed SRP agrees well with observations in the central and east basins for all layers (Fig. 7b). For dissolved oxygen, both computed and observed results (Fig. 7c) also agree well, showing anoxic conditions for the central basin hypolimnion. It should be noted, as shown in Figure 3, that the TP and SRP loads for 1984 have already been reduced by more than half from the peak in 1967. The anoxia predicted by the model and confirmed by observation for 1984 is therefore not caused by the phosphorus loads for that year but is a weather-related phenomenon as explained in Lam and Schertzer (1987). In general, the agreement between computed and observed results for TP, SRP and DO for 1984 is commensurate to those reported for 1967 to 1982 in Lam et al. (1987).

3.2.2 Model simulations for 1994 : Post-*Dreissena*

Figure 8 shows the computed and observed results for 1994 (post-*Dreissena*). The observed data show greater variability than those in 1984. In early fall as the lake starts to turn over, the model over-predicts the observation for the east basin. This discrepancy is consistent with the diagnostic model findings that for the post-*Dreissena* period, the phosphorus settling term should be increased. For SRP, one discrepancy is that the model under-predicts the SRP in the spring in the west basin (Fig.8b). This result is consistent with the findings by Makarewicz et al. (1999) and Charlton et al. (1999) that SRP for the post-*Dreissena* period is high due to a faster rate of phosphorus recycling by *Dreissena* and the prevalent full mixing condition in the west basin. For DO, the computed and observed results (Fig. 8c) agree well and there is no anoxia predicted or observed for the central basin hypolimnion.

3.4 Effects of variability of input and changes in model coefficients

The simulations from the NWRI nine-box model with coefficients unaltered show some significant changes before and after *Dreissena* arrival when compared to the limited observations. Since our main goal is to explain these significant deviations, it is necessary to examine mechanisms that are already parameterized in the NWRI nine-box model that may have caused or contributed significantly to them. This means we need to compare the computed and observed results with the time trend shown in the model input and with hypothetical changes in some of the key model coefficients and input data. Only when these factors are accounted for, can we attribute the changes with higher certainty to the *Dreissena* arrival. As examples of analysis of input and model coefficients, we focus on the DO levels in the central basin, the TP concentration in the east basin and the SRP concentration in the west basin. We now extend the database to include those for 1978 and 1997 for these specific targets of comparison.

3.3.1 Testing model coefficients : Effects on DO concentrations

For the central basin hypolimnion, Lam and Schertzer (1987) concluded that anoxic conditions are mostly influenced by weather effects and water levels that can lead to a prolonged period of a shallow hypolimnion – factors which are more dominant on an annual basis than the longterm effects of changes in phosphorus loading. To investigate this factor further, Fig. 5a shows the annual water level data for the period 1950-1997 and Fig. 5b shows the monthly water level for 1970-1997. From these data, the change in water levels between 1984 and 1994 is insignificant and therefore is not an important factor for explaining the anoxia situations. However, the thermal layer thicknesses computed by the thermal stratification model (Lam and Schertzer, 1987) for 1984 and 1994 are very different (Fig. 9). The computed hypolimnion layer for 1984 was much shallower during the stratified period, whereas for 1994 was thicker for most of the stratified season (Fig. 9). This difference in hypolimnion thickness is due to the different weather influences such as heat fluxes and wind mixing (Lam and Schertzer, 1987) and accounts for why there was anoxia in 1984 but not in 1994. That is, the presence of *Dreissena* in 1994 was not the main reason for the anoxic conditions in the central basin hypolimnion. To investigate further, we also compute the central basin hypolimnion thicknesses for 1978 and 1997 (Fig. 9). Both these years have a shallower hypolimnion thickness than that in 1994. As a result, the computed DO concentrations for both years are lower than those in 1994 (Fig. 10a). Fig. 10a also shows that the computed and observed data agree well for all layers in the central basin for 1978, 1984, 1994 and 1997, using the original set of coefficients. An important finding here is that the results confirm that the *Dreissena* arrival did not significantly change the dissolved oxygen in the central basin hypolimnion. That is, we can explain observed differences in the DO concentration between pre- *Dreissena* and post- *Dreissena* years from the nine-box model results using the original set of model structures and coefficients without the introduction of a new *Dreissena* model component.

By varying the turbulent diffusivity, (Fig. 1), we can evaluate the effect of thermal stratification on the dissolved oxygen. For 1984 (pre-*Dreissena*), intensifying (e.g. by

decreasing the turbulent diffusivity by 20%) or weakening (e.g. by increasing the turbulent diffusivity by 20%) the thermal stratification has little or no effect on DO for 1984. However, for 1994 and 1997, intensifying the stratification leads to lower DO levels and weakening it leads to higher DO concentration (Fig. 10a), for the central basin hypolimnion.

Similarly, by varying the water temperature in the water column which was computed by the thermal stratification model (Lam and Schertzer, 1987) and used as input to the nine-box water quality model, we notice greater changes in the DO concentration (Fig. 10b) for the Central basin epilimnion than those (Fig. 10a) obtained by varying the turbulent diffusivity. That is, epilimnetic oxygen is more sensitive to changes in water temperature, whereas hypolimnetic oxygen is more sensitive to thermal diffusion processes.

In general, thermal stratification and water temperature are a result of the weather input such as heat fluxes, wind and air temperature (e.g. Schertzer, 1987; Schertzer and Sawchuk, 1990). The fact that the weather can vary significantly from year to year may explain the difficulty predicting the anoxia in the central basin hypolimnion.

3.4.3   Testing model coefficients: effects on TP and SRP concentrations

A similar analysis can be conducted for the model inputs and coefficients relating to the TP concentration for the east basin. Figure 3 shows the input load for TP during 1970-1997. The lakewide TP loading is about 15,200 MT/d in 1978, 12,500 MT/d in 1984, and 8,000 MT/d in 1994 and 1997, respectively. The computed concentrations for TP in the east basin with all coefficients unchanged (base case, Fig. 11) follows approximately the time trend of the lakewide loading, with the concentration in 1978 higher than that in 1984 which is in turn slightly higher than those for 1994 and 1997. In contrast, the outflow (Fig. 4) and the water level data (Fig. 5) show slight decreases after the *Dreissena* arrival. However, these inputs and the TP load are not as sensitive as the settling rate for particulate phosphorus within the NWRI nine-box model. For example, by decreasing the settling rate by 20%, the TP concentration in 1997 can reach the same level in 1978. Also, by increasing the settling by 20%, the computed TP concentration for

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the east basin epilimnion would fit the observed data better than the results for the base case. This result is consistent with the higher lakewide averaged settling rate calculated by the diagnostic modelling approach. However, the data for both post-*Dreissena* years (1994 and 1997) are too limited to conduct further comparison of computed and observed data by changing the settling rate.

For the SRP in the west basin, the computed concentrations (Fig. 12) for the post-*Dreissena* years (1994 and 1997) are generally lower than those for the pre-*Dreissena* years (1978 and 1984). Again, the results follow the time trend of the lakewide SRP loading (Fig. 3). In this case, the SRP load remains as one of the most sensitive inputs in the NWRI nine-box model. The nutrient uptake rate used in the photosynthesis formula (Lam et al., 1987) is another sensitive model coefficient. As shown in Figure 13, the results due to changes in the nutrient uptake rate are comparable to similar changes in the SRP load. This result is significant since the nutrient uptake rate can be affected by *Dreissena*. The high value of the observed SRP for spring in 1997 is similar to that for spring 1994, indicating the possibility of plankton grazing and faster nutrient recycling by *Dreissena* as discussed earlier.

In summary, for this stage of investigation, we first obtained results by running the NWRI nine-box model with coefficients unchanged (base cases in Fig. 10-13). When compared to the limited set of observations, the simulation results showed that there were changes that may be due to the arrival of *Dreissena* such as the increase in SRP in the west basin and the decrease in TP in the east basin. However, there are also apparent changes (e.g. the central basin hypolimnion anoxia) that could have been attributable to *Dreissena* but were found to be influenced by other factors (e.g. weather). It is therefore critical to identify changes due to *Dreissena* arrival, and also, to identify changes due to others factors. One possible approach is to determine the sensitivity of each process in order to explain the apparent changes. To compare the sensitivity of each of the key model coefficients, we propose to use the normalization method as follows.

3.4   Sensitivity analysis results

As part of the sensitivity analysis, we run the NWRI nine-box model with coefficients changed by ±20%, one at a time, to identify the most sensitive model inputs and parameters. The normalization procedure for the sensitivity analysis results could be explained by means of an example. Thus, for example, we can use the sensitivity analysis results for the TP concentration in the central basin. We do not consider the biochemical uptake or respiration processes in the model (Fig. 2) for TP concentrations because they essentially redistribute the proportions of soluble and the particulate forms of phosphorus within the water column, with the total phosphorus essentially remaining the same. We consider, instead, the physical settling and resuspension of particulate phosphorus in the model. Both processes may affect the TP concentration in the water column: with physical settling, the TP is removed from the water column to the sediment; with resuspension, it is returned to the water column from the sediment. In the NWRI nine-box model, the settling process is governed by a settling rate; for resuspension, it is governed by an empirical function of wind speed (Lam et al. 1987; Lam and Jaquet, 1976). As shown in Fig. 14, the model results show that for 1984, if the wind speed is increased by 20% (see parameter variation, Fig. 14), the total phosphorus in the central basin will increase by about 5.8% (see output variation, Fig. 14). If it is decreased by 20%, the TP in the central basin will decrease by about 4%. Similarly, if the settling rate is increased by 20%, the TP will decrease by about 4.1%; if it is decreased by 20%, then TP will increase by about 7.2%. In order to compare the sensitivity of settling rate and wind speed, we use the mean normalized sensitivity gradient method. For example, for wind speed the gradient is (5.8% - (-4%)) / (20% - (-20%)) = 0.245; for settling rate, the gradient is (-4.1% - (7.2%)) / (20% - (-20%)) = - 0.283. So, the settling rate is slightly more sensitive than the wind speed in terms of their influence on TP in the central basin in 1984. Note that a negative gradient indicates a decrease in the computed value when the value of the model coefficient is increased. The magnitude of the gradient indicates how sensitive the parameter is: if it equals 1.0, it means that the output will change by the same percentage as the parameter. The gradient is usually less than 1.0. This normalized gradient allows us to compare one parameter with another to assess relative sensitivities.

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We adopt this normalized procedure to analyze the sensitivity of some of the key processes that may affect or be affected by *Dreissena* directly or indirectly. Based on discussions in the literature (e.g. Charlton et al., 1999; Lesht et al., 1991; Graham et al., 1996; Millard et al., 1998; Makarewicz et al., 2000), we focus on the following model parameters in the NWRI nine-box model: wind speed, nutrient uptake, respiration, turbulent diffusivity, TP load, SRP load, outflow (Niagara River), water temperature and settling rate. For example, the settling rate can be effectively increased because *Dreissena* may ingest phosphorus and accelerate its deposition. If the wind speed is increased, then some of the phosphorus buried in the sediment attributed to *Dreissena* may be resuspended, particularly in the wind-wave active zones such as the nearshore (Lam and Jaquet, 1976). The effects of nutrient uptake, respiration, turbulent diffusivity, and TP and SRP loads have been discussed earlier in this report. Water temperature affects nutrient uptake, respiration, re-aeration rate and other processes including those of *Dreissena*. To focus the analysis on the sensitivity of these parameters, we apply the normalized procedure for TP, SRP, and DO in the west, central and east basins for 1978 and 1984 (pre- *Dreissena* years) and 1994 and 1997 (post- *Dreissena* years). Table 1 summarizes the sensitivity analysis results showing the top one or two most sensitive parameters for each of the three basins. These sensitivity analysis results are intended to augment the diagnostic model results (Fig. 6) and the nine box model results (Figures 7 to 13) to discern any apparent changes, if any, that can be explainable within the uncertainty of some model coefficients or input without invoking a new zebra mussel model component. Alternately the results may be used to show the possible directions to improve the nine box model should such a zebra mussel component is required. Detail discussions of these sensitivity analysis results for each basin are given.

3.4.1   Sensitivity analysis results for west basin

As shown in Figure 15a, for the total phosphorus concentration in the west basin, the most sensitive parameter was TP loading, a 20% change of which can lead to more than 10% change in the total phosphorus concentration in this basin, although it is slightly less

for post- *Dreissena* years because the TP load is less due to the phosphorus abatement program. The next most sensitive parameters are settling rate and wind speed (i.e. resuspension). While the settling rate is found to be slightly less sensitive in post- *Dreissena* years, the wind speed is now more sensitive. Again, this is due to the relatively lower TP concentration in the post- *Dreissena* years. Since the TP loading is more sensitive (0.5 to 0.6 for normalized sensitivity gradient) than the settling/resuspension (0.1 to 0.2 for normalized sensitivity gradient), further study on the possible change of TP after the *Dreissena* arrival should focus more on the accuracy of the TP load. That is, any study on formulating new *Dreissena* grazing and deposition should be accompanied by a study on the uncertainty in the TP loading in this basin, particularly from the Detroit River and other main tributaries. It is most likely that the uncertainties in the TP loads may mask the calculated TP contribution from any new *Dreissena* model.

For SRP in the west basin, Fig. 15b shows that the nutrient uptake is the most sensitive parameter with a normalized sensitivity gradient of -0.8 to -0.9. The nutrient uptake factor is directly related to the photosynthesis of chlorophyll during primary production (Fig. 2). As shown in Fig. 8b, the NWRI nine-box model under-predicted the SRP in the west basin in 1994 (a post- *Dreissena* year). If the nine-box model was forced to predict SRP better, it would require a lower uptake rate so that less SRP is consumed in the primary production in post- *Dreissena* years. However, since quite a substantial decrease (Figure 15b) would be required, it is beyond the uncertainty level normally associated with the uptake rate. One possible mechanism, for example, is to introduce a new model formulation in which *Dreissena* grazes on the phytoplankton and recycles the phosphorus in soluble form quickly. These mechanisms were considered as highly possible by Makarewicz et al. (1999) for the west basin which is shallow and fully mixed. Figure 15b also shows that the next most sensitive parameter is the SRP load (0.7 to 0.8 for the normalized sensitivity gradient), which is almost as sensitive as the uptake rate. Again, this implies that any new *Dreissena* modelling endeavour will require more accurate loading data or must be accompanied by a study of the uncertainty of the loading.

For DO in the west basin, Fig. 15c shows that the water temperature is the only dominant and sensitive parameter. Since the basin is shallow and full mixing prevails most of the time, the supply of oxygen is therefore mainly from re-aeration which is a function of the water temperature (Lam et al., 1987). The other effects, including water and sediment oxygen demand, on DO in the west basin are not as important as re-aeration. Therefore, one can conclude that the *Dreissena* arrival has not appreciably affected the DO in the west basin.

3.4.2 Sensitivity results for central basin

In contrast to the west basin, the TP load is not the most sensitive parameter in the central basin. The most sensitive parameters for TP in the central basin are settling rate and wind speed (Fig. 16a). The TP load to the central basin is less than that for the west basin, although the central basin receives a substantial portion of TP advected from the west basin. The focus for TP is therefore more on the settling and resuspension mechanisms. Note that the normalized gradients for settling rates and wind speed change from year to year, indicating a strong influence of meteorology for these mechanisms. Also, the discrepancy between computed and observed data for the central basin in 1994 (Fig. 8a) was not as large as that for the east basin. It is likely that the settling and resuspension mechanisms probably remain proportionally the same before and after the *Dreissena* arrival.

For SRP in the central basin, the most sensitive parameter is still the uptake rate as in the case of the west basin, although its effects become less in post- *Dreissena* years (0.6 for the normalized sensitivity gradient in 1997). As shown in Fig. 8b, the computed result of SRP agreed with the limited observed data in 1994 for the central basin. Charlton et al. (1999) reported that the Secchi depths between 1980 and 1997 showed only small changes. These results therefore indicate that *Dreissena* probably does not cycle the soluble form of phosphorus as fast as proposed in the west basin (Section 3.4.1), because

of the increased depth and thermal stratification in the central basin. Thus, any new submodel for *Dreissena* should simulate this relatively slower cycling effect if the proper physical and biochemical submodel for thermal stratification and nutrient uptake are used. The SRP load is the next most sensitive parameter as in the case of the west basin and must be included in the uncertainty analysis in the development of new *Dreissena* models.

Similar to the results for the west basin (Fig. 15c), the DO in the central basin is affected most by water temperature (Fig. 16c). Note that the second important factor, the vertical turbulent diffusivity, also exerts an influence in central basin. As discussed earlier, water temperature affects epilimnetic oxygen whereas turbulent diffusivity affects hypolimnetic oxygen in central basin. Since Fig. 15c represents the combined results for all vertical layers in central basin, water temperature is shown to be more sensitive than turbulent diffusivity for DO. The year 984 is the one with the shallowest hypolimnion (Fig. 9), with a strong and stable thermal stratification and a very small turbulent diffusivity at the thermal layer interface, so that the DO is not greatly affected by perturbation on the diffusivity. On the other hand, the DO concentration can easily be influenced by changes in thermal stratification for years with thicker hypolimnion (i.e. 1994 and 1997, see results in Fig. 10). As a result, the normalized sensitivity gradients are relatively higher in 1994 and 1997. The year-to-year changes in sensitivity to thermal stratification in the case of DO in the central basin are indicative of the need of an accurate thermal stratification submodel and appropriate meteorological inputs. Nevertheless, the main conclusion is that DO in the central basin has not been affected by the *Dreissena* arrival.

3.4.3 Sensitivity results for east basin

For the east basin, as shown in Fig. 8a and 11, the computed result from the nine-box model over-predicted the total phosphorus concentration in early fall. From the sensitivity analysis results in Fig. 17a, the most sensitive parameters are settling rate and wind speed. The third most sensitive parameter is outflow. These processes are coincidentally also the most viable mechanisms in the model to be used in order to simulate the effects of *Dreissena*. For example, the *Dreissena* may affect the settling rate

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of phosphorus by increased grazing and deposition; and/or the resuspension due to wind waves may be reduced by more permanent phosphorus burial due to *Dreissena*; and/or the *Dreissena* larvae having ingested phosphorus may be carried by alongshore currents to the outflow and therefore be an important vector for phosphorus removal from the east basin. All these are possible mechanisms to decrease the computed phosphorus concentration in the east basin and to eliminate the over-prediction in Fig. 8a and 11. Note that the TP load is ranked as the fourth sensitive parameter, indicating that the uncertainty due to loading for the east basin is not as significant as those due to settling, resuspension and outflow mechanisms.

For SRP in the east basin, the most sensitive parameter is the uptake rate, followed by the respiration rate (Fig. 17b) as in the case of the west and central basins (Sections 3.4.1 and 3.4.2). The third most sensitive parameter is SRP load. The model did not under-predict the SRP as much as in the case of the west basin (Fig. 8b) and therefore the same interpretation for the uptake, respiration and SRP load applies as in the case of the central basin (Section 3.4.2).

For DO in the east basin, the most sensitive parameter is again the water temperature. The next sensitive parameter is the outflow (Fig. 17c). However, its influence is very small, with a normalized sensitivity gradient of about -0.04 (cf. -0.18 for water temperature, see Fig. 17c). The vertical diffusivity is the third sensitive parameter and has even much less influence on DO, because the east basin is deeper than central basin (65m vs. 25m) and the hypolimnetic DO depletes at a much slower rate. Therefore, given that the existing nine-box model simulates closely the observed DO in the east basin, e.g. in 1994 (Fig. 8c), there appears to be no need to derive a new model formulation to explicitly include the influence from *Dreissena* on dissolved oxygen.

4. DISCUSSIONS : IMPLICATIONS FOR LAKEWIDE MANAGEMENT PLAN

The main result of this modelling study (Sections 3.1 and 3.2) is that there is a portion of total phosphorus eliminated from the water column of Lake Erie in the post-*Dreissena* years, not accountable by the phosphorus loading reduction. The question is where, when and how this portion of phosphorus is eliminated from the water column. From the NWRI nine-box results (Sections 3.2-3.4), we tried to account for this loss in each basin and in each stratified layer. By purposely not including a *Dreissena* submodel in the nine-box model, we assumed that any deficiency not predicted by loading reduction would show an over-prediction of total phosphorus when compared to observed data. It was then shown that such a deficit existed mainly in the east basin during late summer in the post-*Dreissena* years (Sections 3.3). Also, from the model sensitivity study (Section 3.4), the most sensitive parameter for the NWRI nine-box model are settling and resuspension for the east basin, but not loading. Therefore this confirms that the uncertainty on loading for this basin is not a significant factor. The most sensitive parameters are settling and resuspension as implemented in the nine-box model. Since the model parameters predicted the total phosphorus with reasonable agreement with observed data for pre-*Dreissena* years, there must be other mechanisms needed beyond those of settling and resuspension of phosphorus in order to account for the phosphorus deficit in post-*Dreissena* years. Here, we are in favour of those proposed by Charlton et al. (1999) and Makarewicz et al. (2000) that *Dreissena* grazing and subsequent deposition of phosphorus are very likely to be important mechanisms for phosphorus removal. The results from the sensitivity analysis also suggest that the TP concentration is mildly sensitive to the outflow through the Niagara River. That is, according to these sensitivity analysis results, the apparent loss of TP in the east basin can be simulated with less uncertainties by manipulating the settling/resuspension rates than by changing the Niagara River outflow in the nine box model, within known uncertainty limits. However, since the nine box model does not have a nearshore compartment, it does not simulate possible removal of phosphorus by means of materials (e.g. materials deposited by *Dreissena* or *Dreissena* themselves) being carried by nearshore currents to the Niagara River outflow. Further experimental data and a new nearshore-offshore model compartmentalization are required to ascertain the importance of the outflow processes.

In addition to this main finding, there are other significant possible changes identified in the post- *Dreissena* years. Table 1 shows the summary of the most sensitive parameters identified by the sensitivity analysis of the nine-box model for the variables TP, SRP and DO. For total phosphorus, the effect of *Dreissena* in the west basin is not significant, because the total phosphorus loading is still the dominant factor. That is, the effect of *Dreissena* on TP is not seen to be significant due to the uncertainty in the total phosphorus loading. For the central basin, the settling rate and wind speed (which affects the physical resuspension of phosphorus from sediment) are the most sensitive, indicating that similar processes, as proposed for the east basin due to *Dreissena* grazing and deposition, may be important here. It is possible that such phosphorus removal mechanisms occur in all basins. With a framework of the three basins and the thermal layers as implemented in the nine-box model, the same phosphorus removal mechanism by *Dreissena* can be incorporated in all these basins, but due to the different loadings, depths and stratification conditions, the outcome of the phosphorus removal can be different as indicated by the result of the sensitivity analysis (Table 1). For example, for the west basin, the settling/resuspension mechanisms are masked by the strong presence of the TP load. Again, due to its limitations, the nine box model is not able to test hypotheses concerning more detail nearhore-offshore processes. For example, the model does not capture the importance of the nearshore-offshore distribution of different species (*Dreissena polymorpha* versus *Dreissena bugensis*) and their density that may affect the settling and resuspension processes. This fine-tuning of spatial processes would be required in the model should a new *Dreissena* submodel be attempted.

In terms of the SRP, as shown in Fig. 18, the most sensitive parameter is the uptake rate in all basins. Since the uptake rate is indicative of the primary production function, it is also related to chlorophyll *a* and plankton production. For the west basin post-*Dreissena* years, the SRP is under-predicted by the nine-box model with coefficients unchanged. This change as detected with the nine-box model is the most significant observed change in the post-*Dreissena* years. As explained in Section 3.4.1, this result indicates that the current nine-box model is inadequate to simulate the *Dreissena*-plankton relationship (i.e. the prediction of early summer peaks of plankton growth). The phenomenon, which is

most evident in the west basin, could be attributable to the fast cycling of phosphorus into the soluble form by *Dreissena* grazing and regeneration. Thus, we conclude that a mechanism such as *Dreissena* grazing may have been missing from the existing nine-box model. Table 1 also shows that SRP load is nearly of equal importance to influence the SRP concentration in the west basin. Thus, any new formulation of the plankton-*Dreissena* processes must be accompanied by a good set of phosphorus loading estimates. Moreover, referring to Figs. 7b and 8b, the agreement between observed and computed SRP are already good for both pre- and post-*Dreissena* years for central and eastern basins. If new plankton-*Dreissena* processes are used in the nine box model, changes in the SRP predictions in central and east basins should not be as substantial as those in the west basin. This difference in response is possible, because of the deeper basin depths and thermal stratification conditions in central and east basins leading to slower recycling than in the west basin. That is, the inclusion of a new *Dreissena* grazing submodel may improve the prediction of SRP and primary production for the west basin but may essentially produce the same agreement with observed data in the central and east basins in post-*Dreissena* years.

As for DO, the main finding is that the *Dreissena* arrival has not affected the DO concentration significantly in all three basins, because the DO predictions agree well with observed data for pre- and post-*Dreissena* years (e.g. Figs. 7c and 8c), by the nine box model with the model coefficients unchanged. As shown in Table 1, the DO in the west basin is primarily influenced by water temperature, because the basin is shallow and effectively fully mixed so that re-aeration, which is governed by water temperature, is the dominant process. For the central basin, the most sensitive parameter is also water temperature, followed by vertical diffusivity. As explained in Section 3.4.2, the results for pre- and post-*Dreissena* years confirm that the hypolimnetic thickness is the key to the anoxic condition in this basin (Figs. 9 and 10). In addition, the DO level in the central basin hypolimnion is found to be dependent on the vertical diffusivity which in turn depends on weather. The phosphorus loading is so low in post-*Dreissena* years that it has no significant effect on the sediment oxygen demand for the central basin. The amount of soluble reactive phosphorus regenerated during anoxia is too small in terms of spatial and

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temporal extent to be significant in this basin (Charlton et al., 1999). As for the east basin, the most sensitive parameter for DO is also the water temperature (Table 1), with less influence from the vertical diffusivity because of the deeper depth.

Thus, for consideration in the lakewide management plan, this study shows that the presence of *Dreissena* has led to a decrease in the total phosphorus concentration in the east basin and an increase in the soluble reactive phosphorus in the west basin. For the west basin, the continuation of monitoring programs for phosphorus load and in-lake concentration is required to evaluate further changes in the already altered aquatic ecosystem and to evaluate the effectiveness of the phosphorus reduction program. For the central basin, the most prominent disruption is the occurrence of hypolimnion anoxia that is increasingly a function of weather, and almost unrelated to the *Dreissena* arrival. As the climate changes to warmer and less windy conditions and leads to a further decrease in water level, the anoxic condition in the central basin hypolimnion will be one of the most serious impacts of climate change in Lake Erie (e.g. Schertzer, 1999; Lam and Schertzer, 1999). For the east basin, the decrease in total phosphorus is a quite a concern for phosphorus and fish management. To improve the understanding of the phosphorus dynamics in the east basin, a new set of experiments are required to obtain the knowledge about the key physical, chemical and biological processes governing the phosphorus dynamics in the presence of *Dreissena* arrival. For example, a new experiment proposed by R. Smith (Pers. Comm., U. of Waterloo) has been proposed (Fig. 18) and is urrently being conducted with emphasis on the nearshore and offshore processes on the pelagic and profundal species for *Dreissena* and their relations to phosphorus settling, benthic forms, thermal stratification, nearshore resuspension and outflow. With new knowledge on these processes, models such as the NWRI nine-box model can be improved to predict the complex nutrient-plankton- *Dreissena* relationships in Lake Erie.

5. CONCLUSION

By applying an existing water quality model, the NWRI nine-box model, we showed that changes in post- *Dreissena* years can be detected by the deviation of computed results from observed data. Through sensitivity analysis, we excluded other possible mechanisms to conclude that *Dreissena* can affect the phosphorus concentration in Lake Erie. Specifically, the total phosphorus is decreased in the east basin while soluble reactive phosphorus is increased in the west basin. The dissolved oxygen concentration in the lake is not significantly affected by *Dreissena*. It is recommended that monitoring programs be instituted that would provide more accurate information on phosphorus loading and in-lake concentration in Lake Erie, particularly for the west basin where the loading is shown to be the most sensitive parameter. There is also the need to improve the understanding of the *Dreissena*-plankton-nutrient relationships, particularly in the east basin, through new experiments targeting key processes such as *Dreissena* grazing, deposition and regeneration. As for dissolved oxygen, it is recommended that the anoxic condition in the central basin hypolimnion be viewed as an effective indicator of impact due to weather and potential climate change, but not due to loading reduction or *Dreissena* arrival. We also note that the results and conclusions arrived in this report are based on simulations of the NWRI nine-box water quality model. This model was selected primarily on the basis of verification and validation tests conducted over the 16-year period 1967-1982 for Lake Erie, which showed a high degree of reliability for temperature, phosphorous and DO simulations. In spite of the limitation of available data, the use of the nine-box model as presented has been quite instructive and led to better insight in the phosphorus and oxygen dynamics. As with all models, there are limitations in the model and therefore room for improvement. One deficiency noted is the absence of nearshore-offshore compartments. We require substantial experimental data such as those on circulation patterns and thermal regimes in order to incorporate the dynamics and understand their effects for these zones. Such model development is required to improve future modelling and monitoring studies of Lake Erie.

Acknowledgements

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	West Basin	Central Basin	East Basin
TP	TP Loads	Settling Rate / Wind Speed	Settling Rate / Wind Speed
SRP	Uptake / SRP Loads	Uptake	Uptake
DO	Water Temperature	Water Temperature/ Vertical diffusivity	Water Temperature

Table 1. Summary of the most sensitive parameters in the NWRI nine-box model for total phosphorus (TP), soluble reactive phosphorus (SRP) and dissolved oxygen (DO) in the west, central and east basins of Lake Erie.

HYDRAULIC FLOW

OUTFLOW

ENTRAINMENT

DATUM

WATER LEVEL CHANGE

INTER-BASIN TRANSPORT

WIND →

TURBULENT DIFFUSION
(RESIDUALS)

← EPI

← MESO

← HYPO

TEMPERATURE

T_1	T_2	T_3
T_4	T_5	T_6
T_7		
	T_8	
		T_9
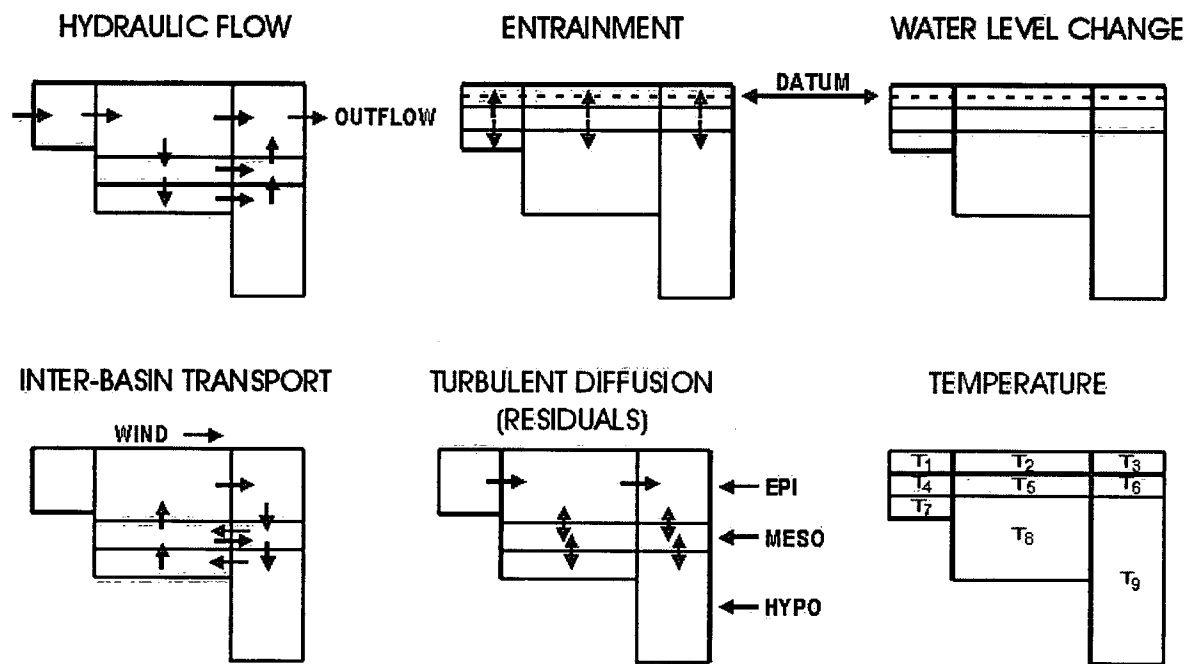
Figure 1. Schematic of the major physical processes parameterized in the NWRI nine-box model of Lake Erie (Lam et. al., 1987).

30
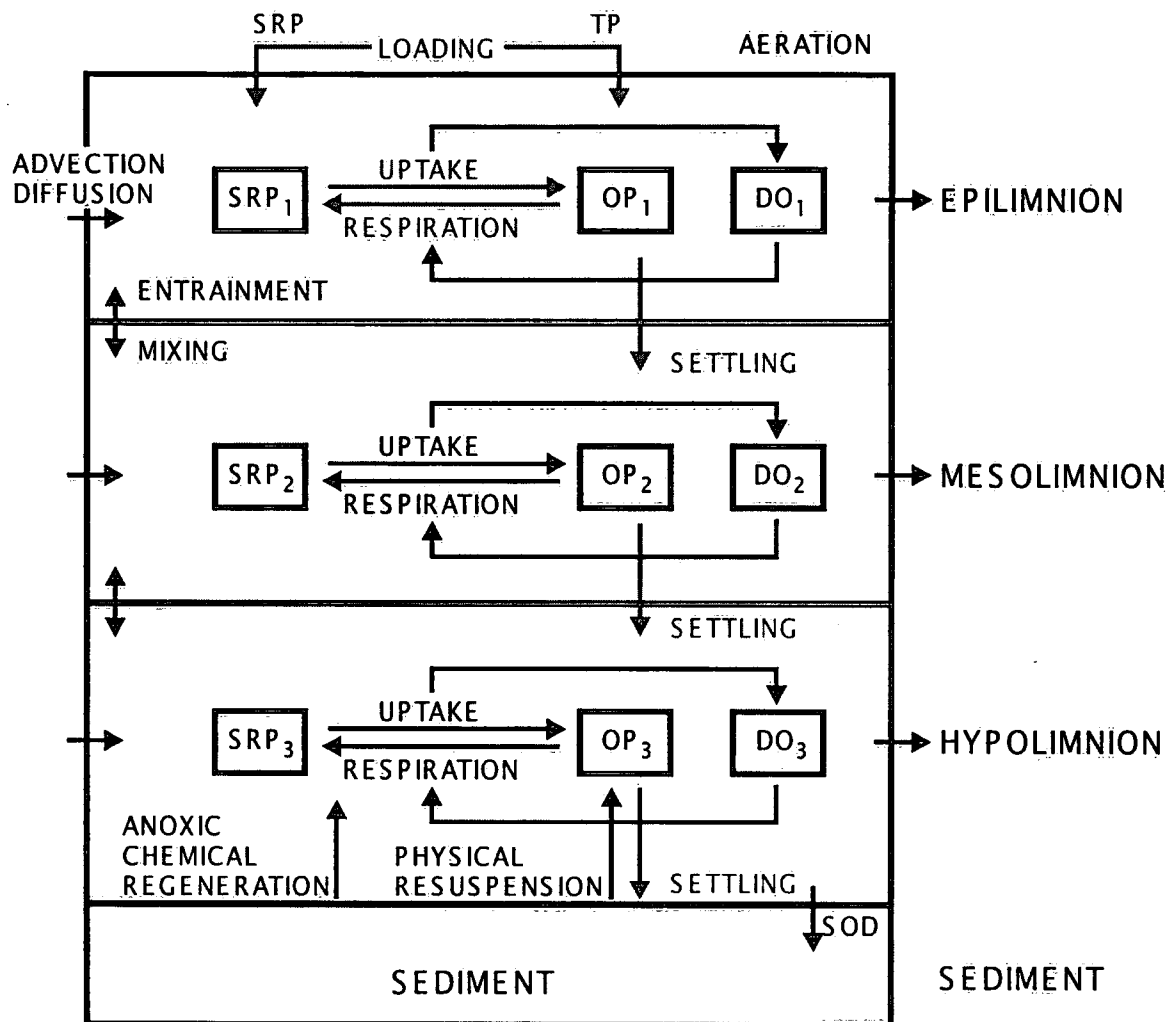
Figure 2. Schematic of the NWRI nine-box plankton–nutrient–dissolved oxygen submodel (Lam et. al., 1987) showing processes in a vertical water-sediment column: Soluble Reactive Phosphorus (SRP), Organic Phosphorus (OP), Dissolved Oxygen (DO), Total Phosphorus (TP) and Sediment Oxygen Demand (SOD).
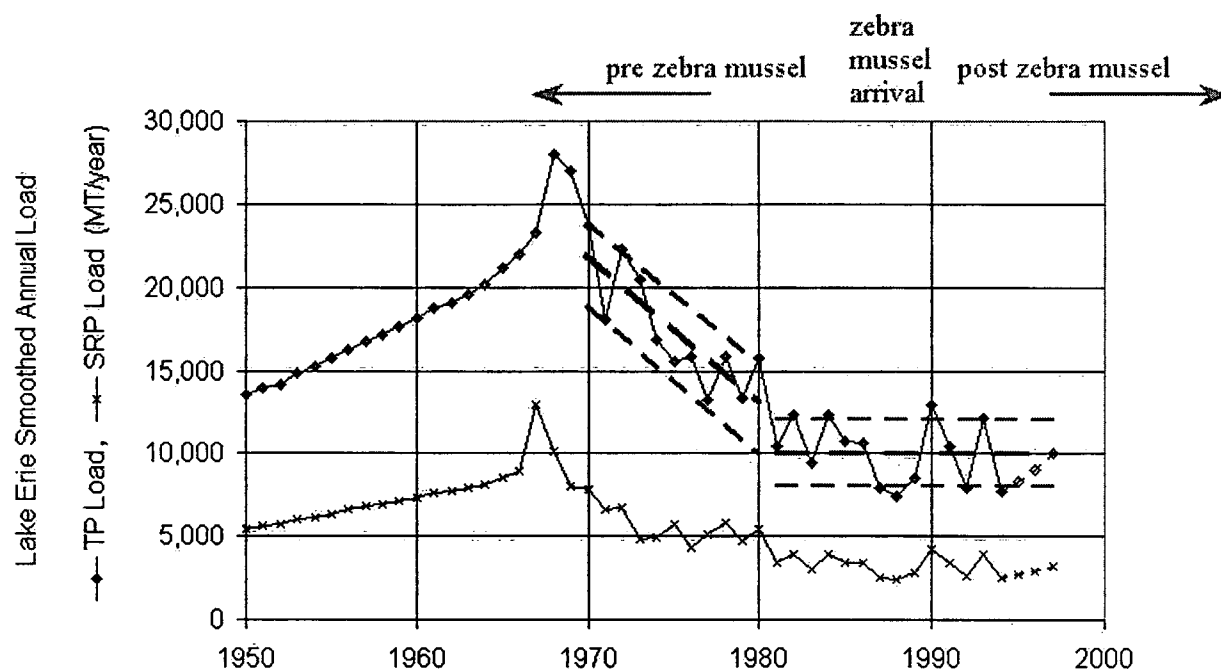
Figure 3. Estimated lakewide TP and SRP load for 1950 – 1997.
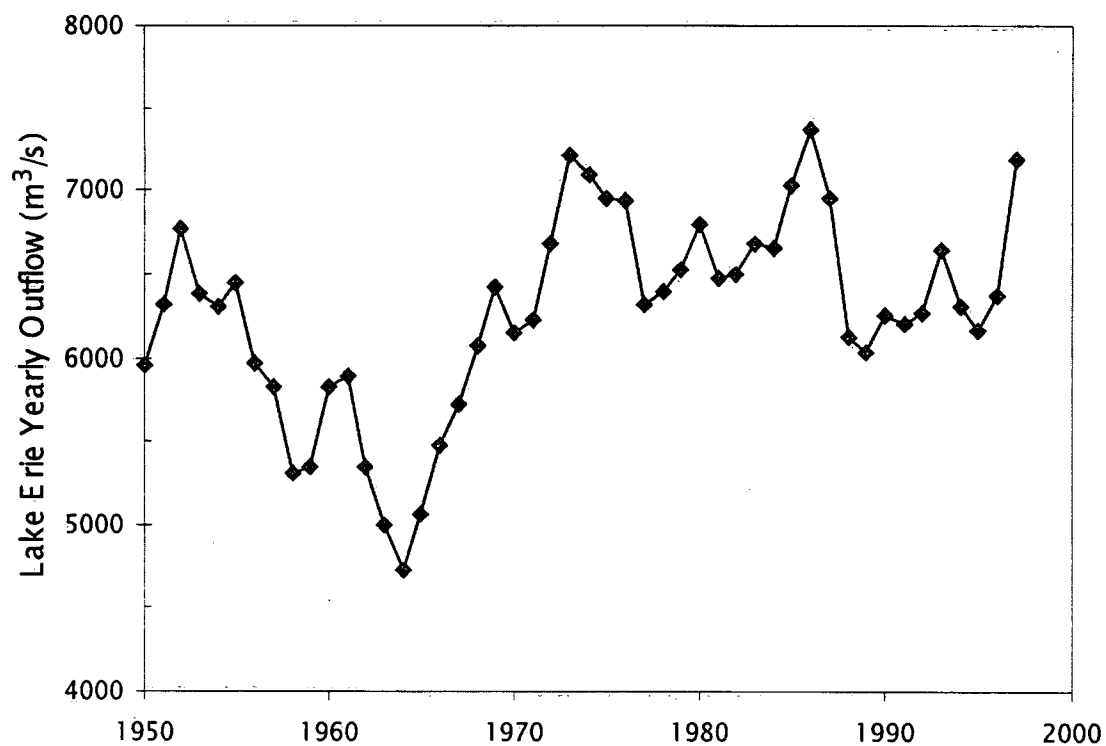
Figure 4a. Yearly outflow (Niagara River) for 1950 – 1997.
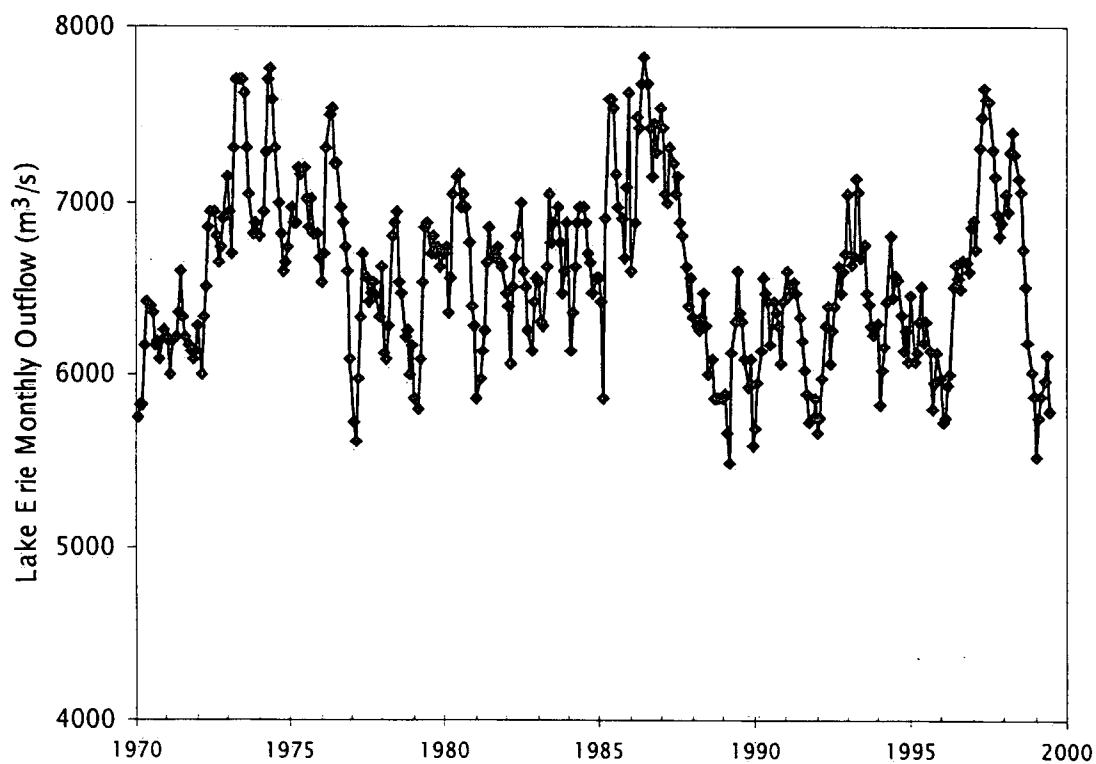
Figure 4b. Monthly outflow (Niagara River) for 1970 – 1997.
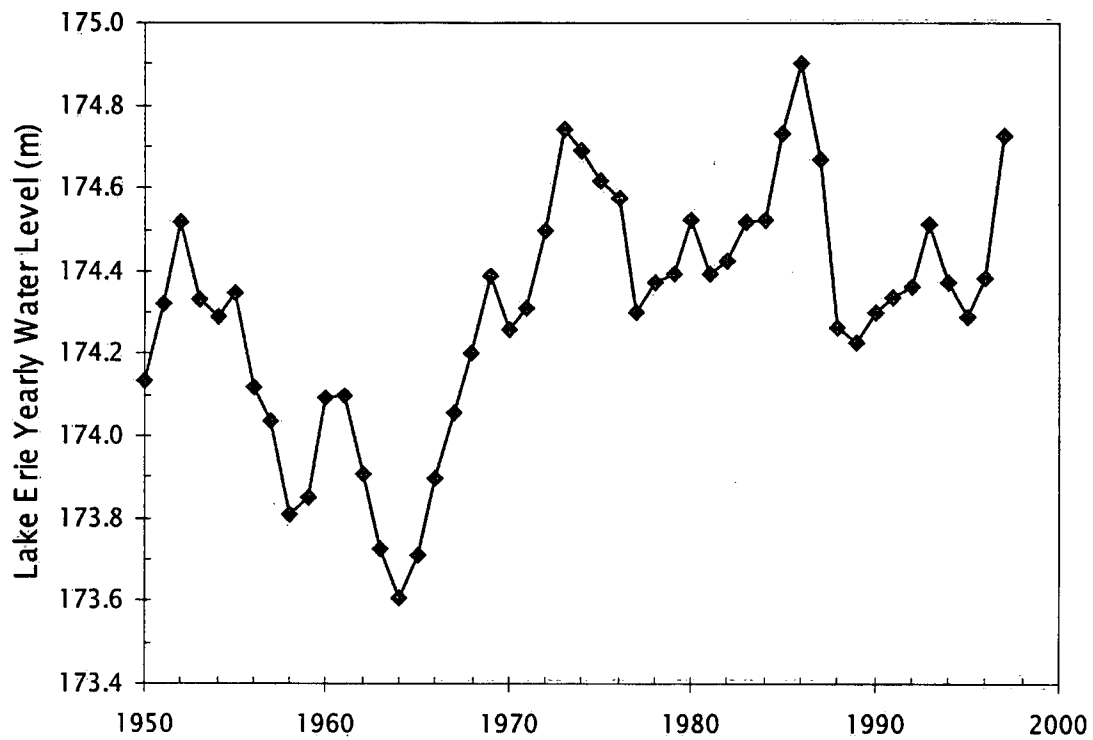
Figure 5a. Yearly water level for Lake Erie, 1950 – 1997.
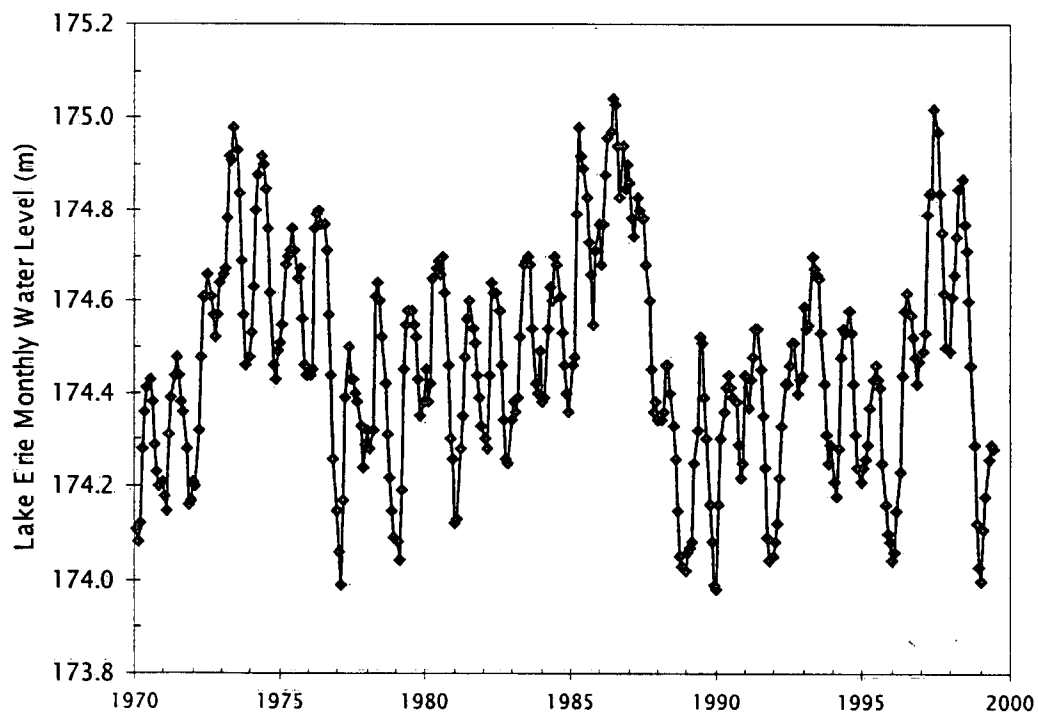
Figure 5b. Monthly water level for Lake Erie, 1970 – 1997.
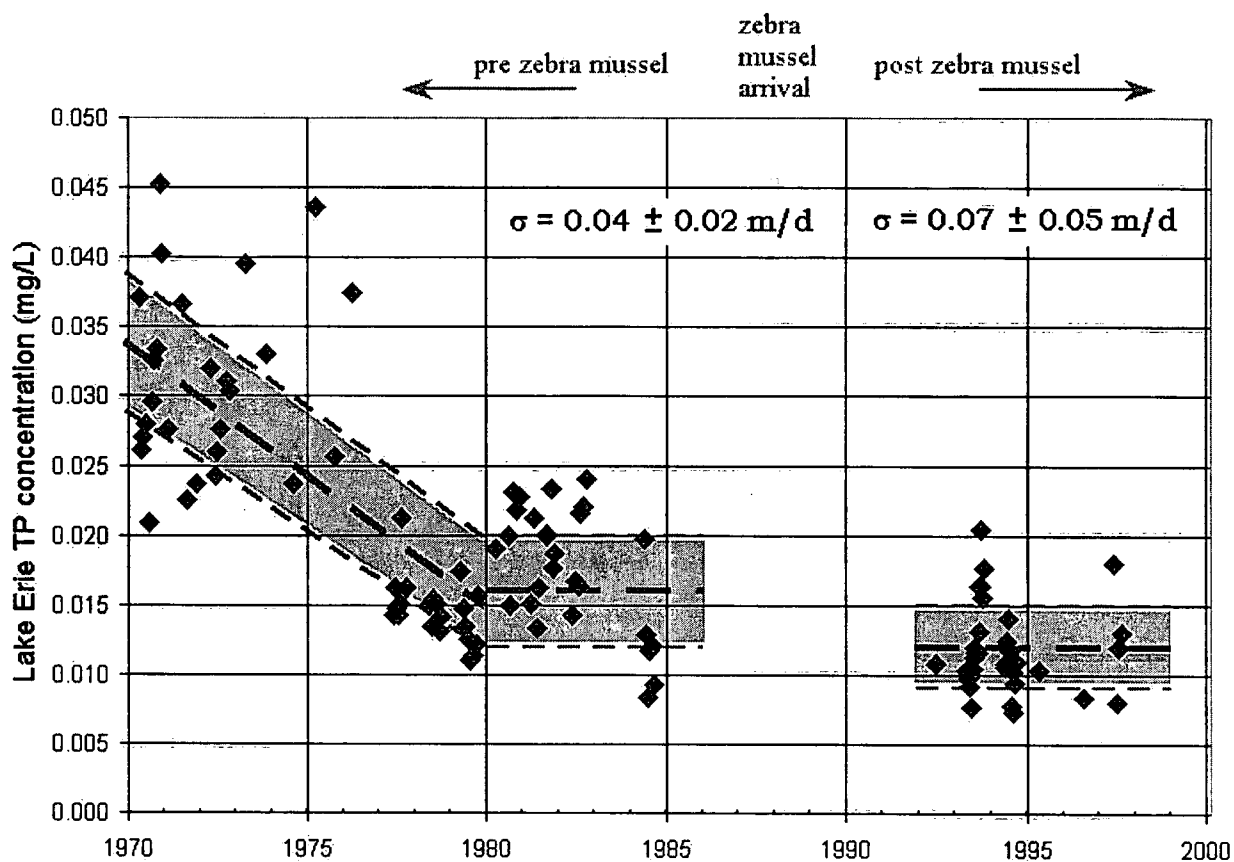
Figure 6. Lakewide average TP concentration, showing linear approximation of mean value and 90-percentiles for three time periods: 1970-1980, 1980-1986 and 1992-1997. The estimated settling rates (σ) for the pre- and post-zebra mussel periods are also shown.
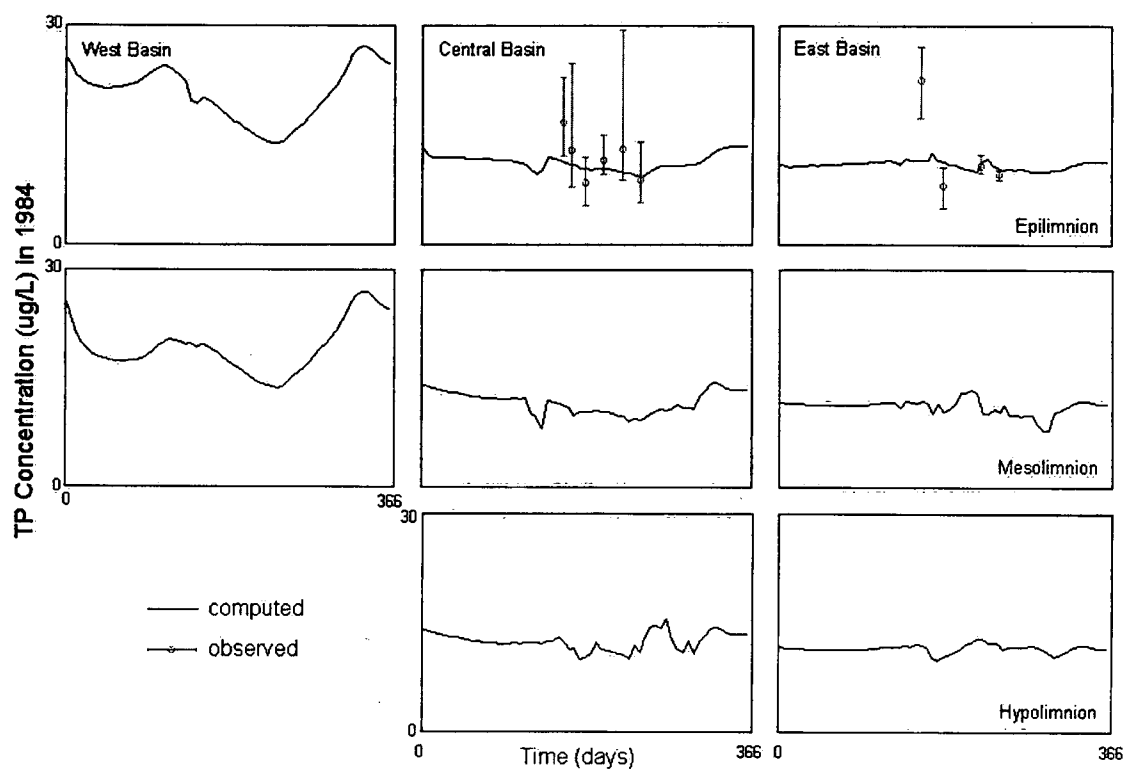
Figure 7a. Computed and observed TP concentration for 1984.
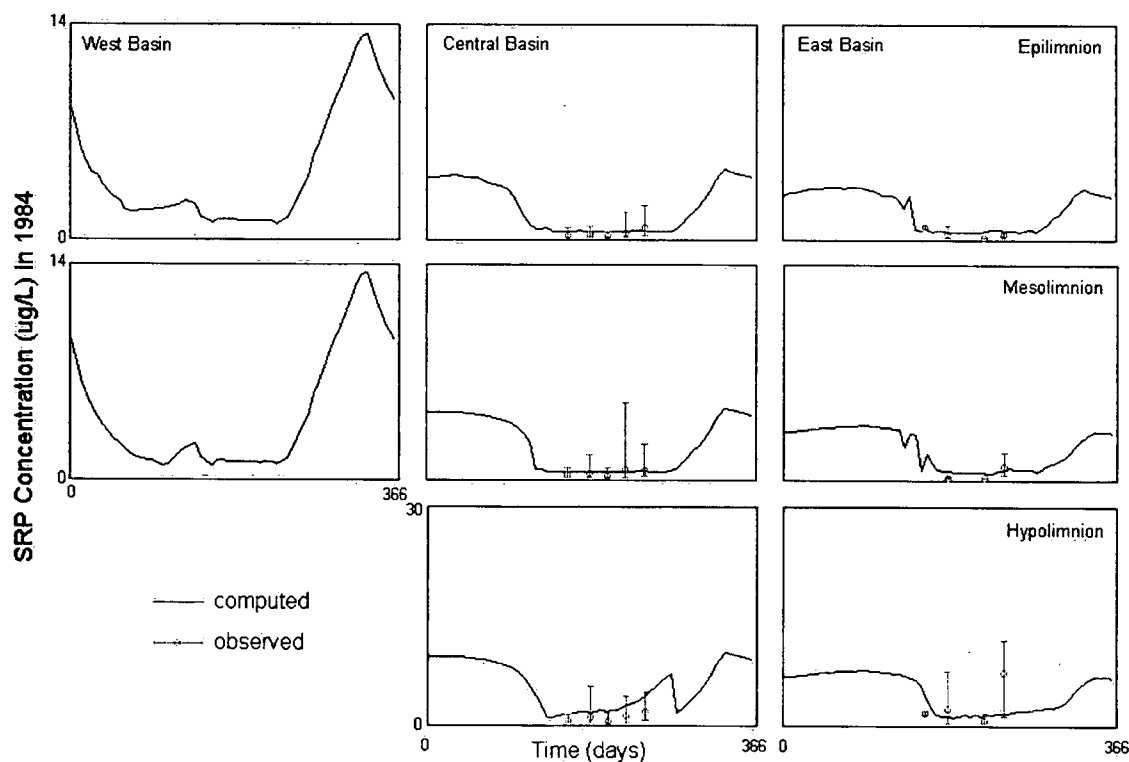
Figure 7b. Computed and observed SRP concentration for 1984.

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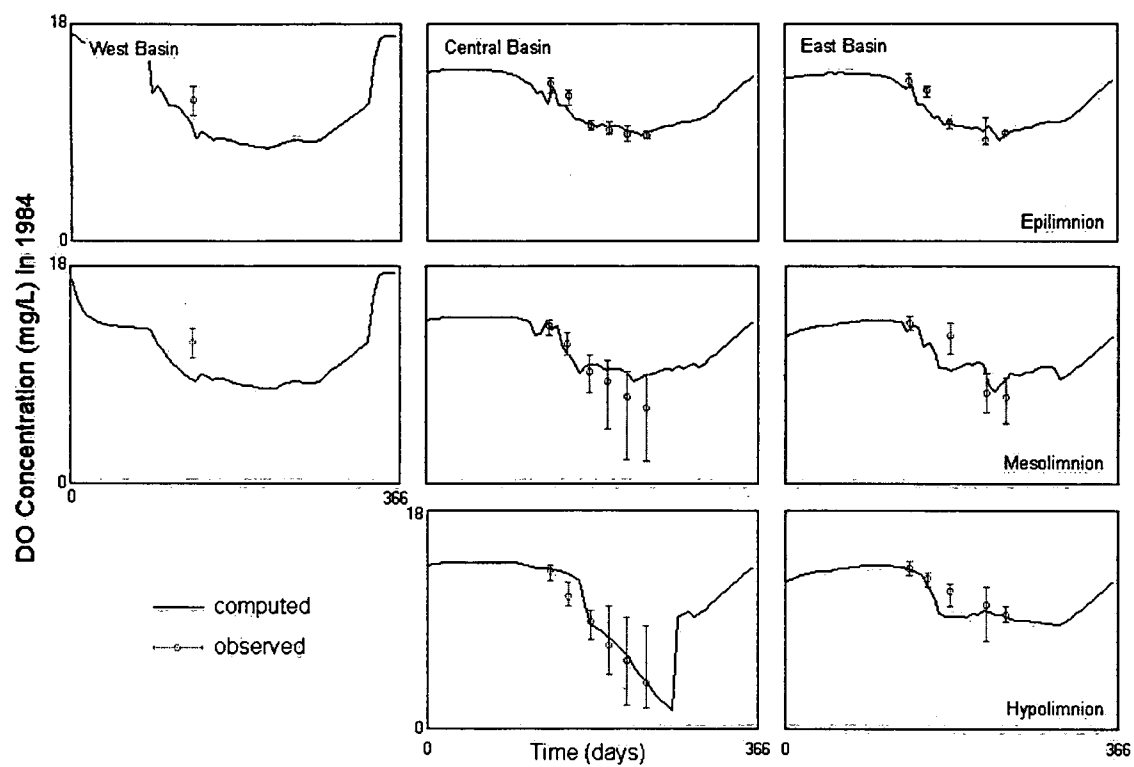
Figure 7c. Computed and observed DO concentration for 1984.
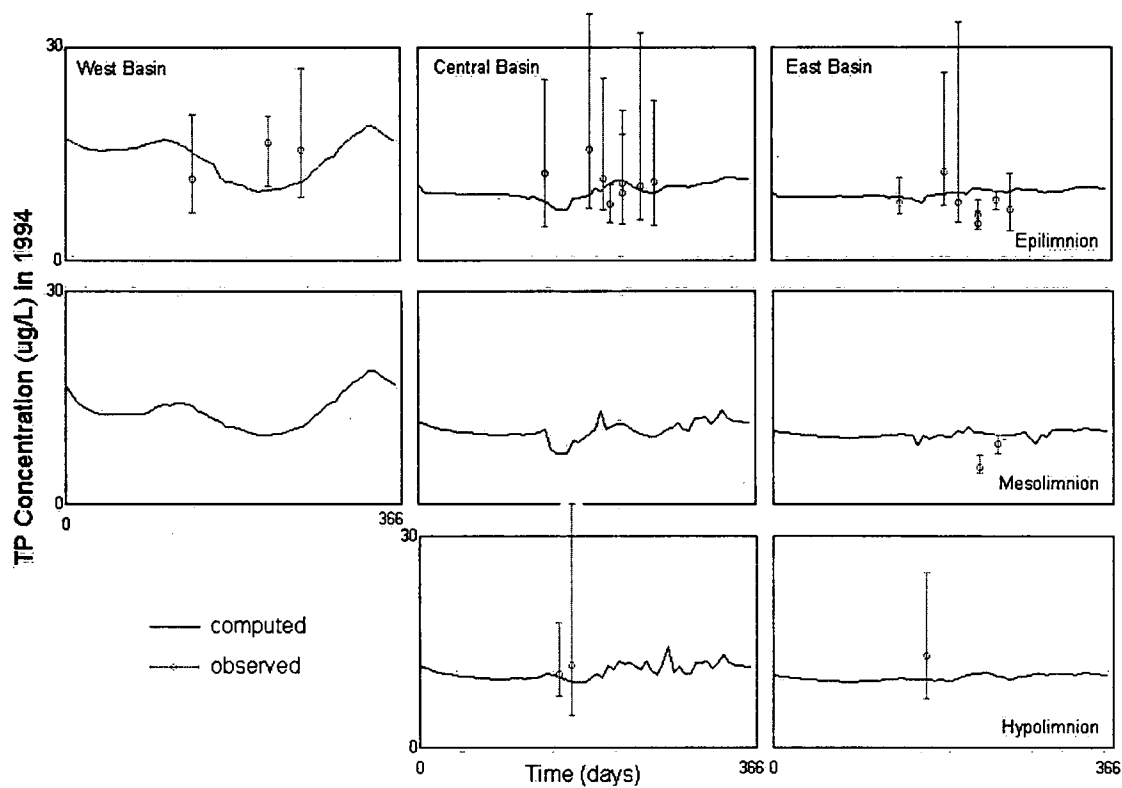
Figure 8a. Computed and observed TP concentration for 1994.
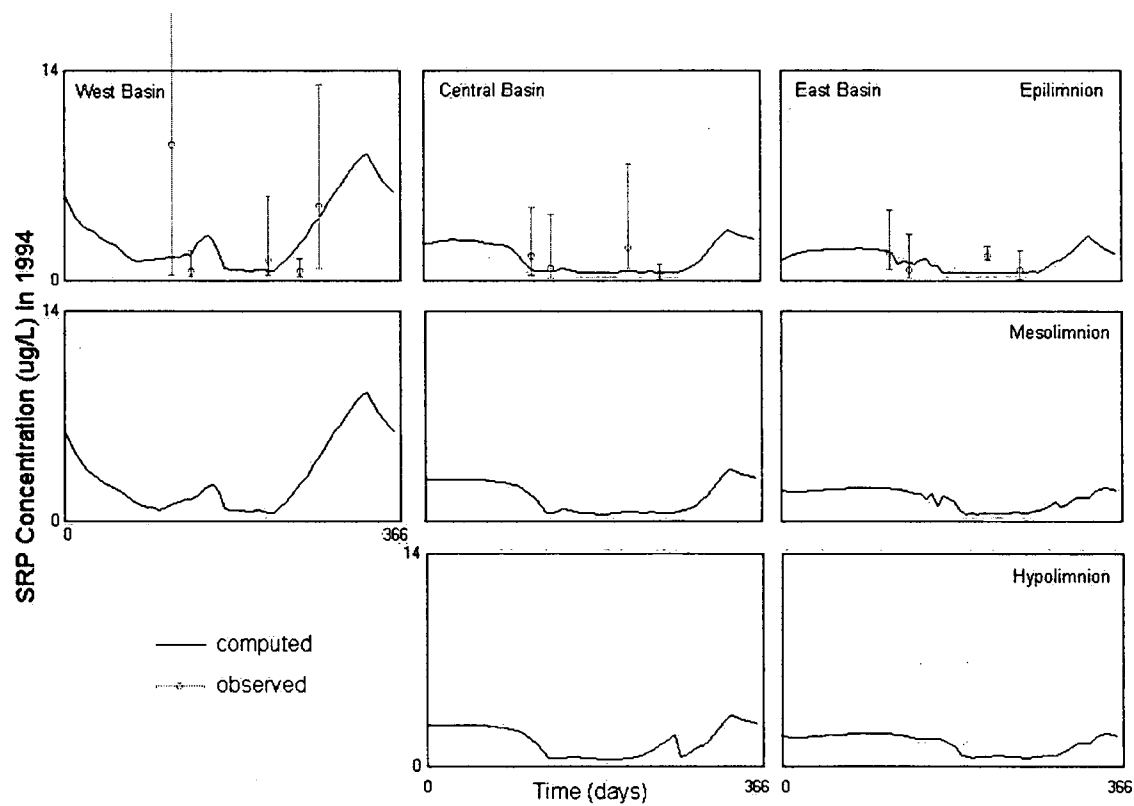
Figure 8b. Computed and observed SRP concentration for 1994.
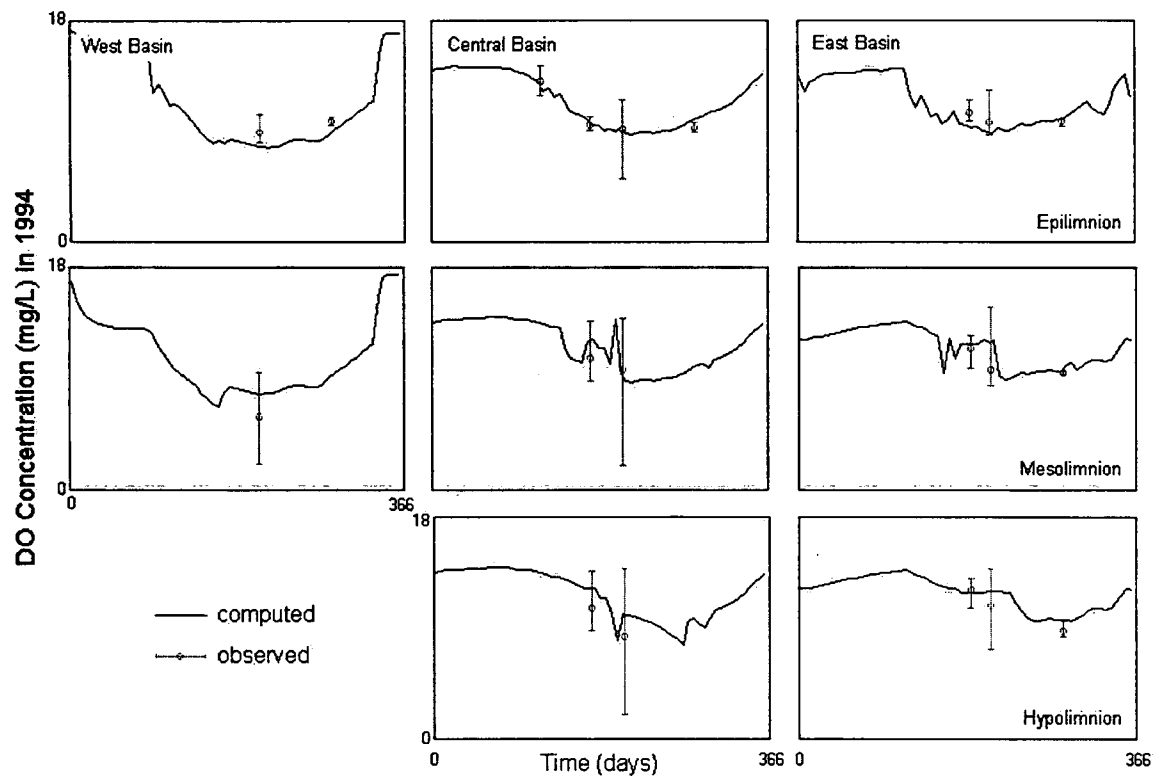
Figure 8c. Computed and observed DO concentration for 1994.

Central Basin

1978

Julian Day

0   100   200   300

Layer Depths (m)
0
5
10
15
20
25

Epilimnion

Hypolimnion

1984

Julian Day

0   100   200   300

Layer Depths (m)
0
5
10
15
20
25

Epilimnion

Hypolimnion

1994

Julian Day

0   100   200   300

Layer Depths (m)
0
5
10
15
20
25

Epilimnion

Hypolimnion

1997

Julian Day

0   100   200   300

Layer Depths (m)
0
5
10
15
20
25

Epilimnion
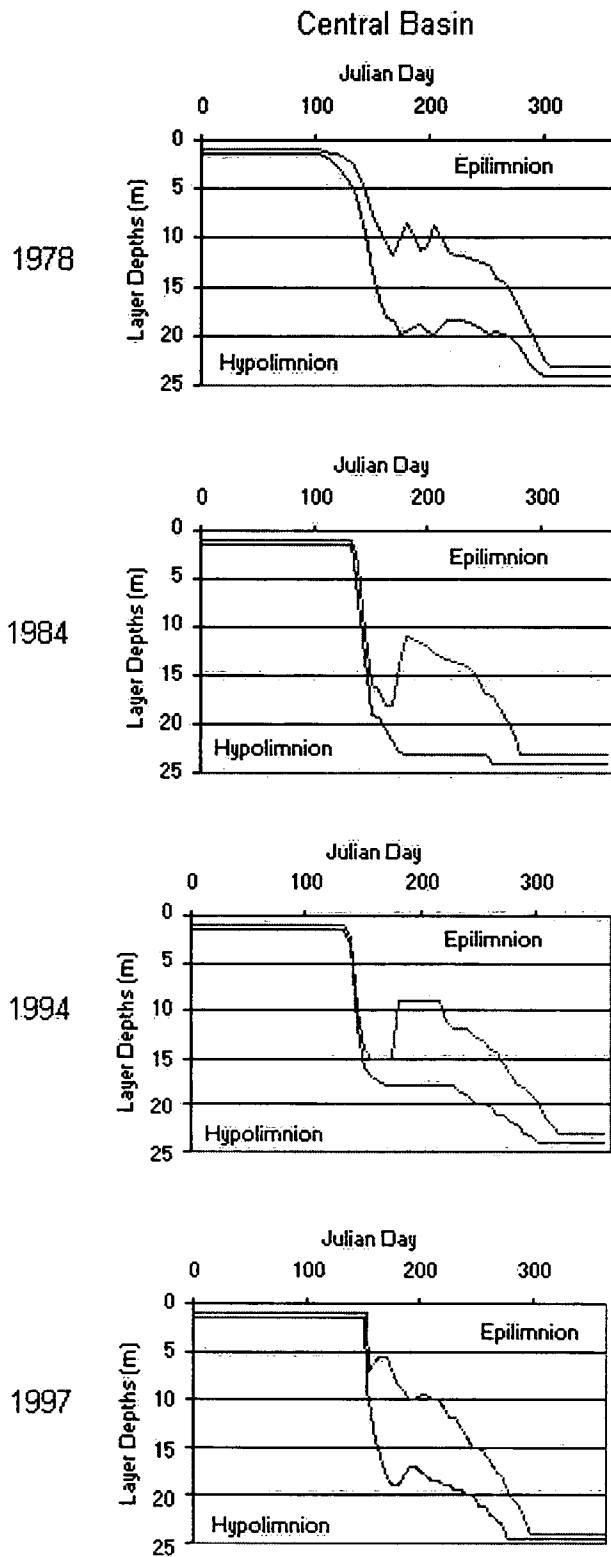
Hypolimnion

Figure 9. Computed thermal layer thickness for central basin, Lake Erie, for 1978, 1984, 1994 and 1997 (shaded areas indicate hypolimnetic thickness).
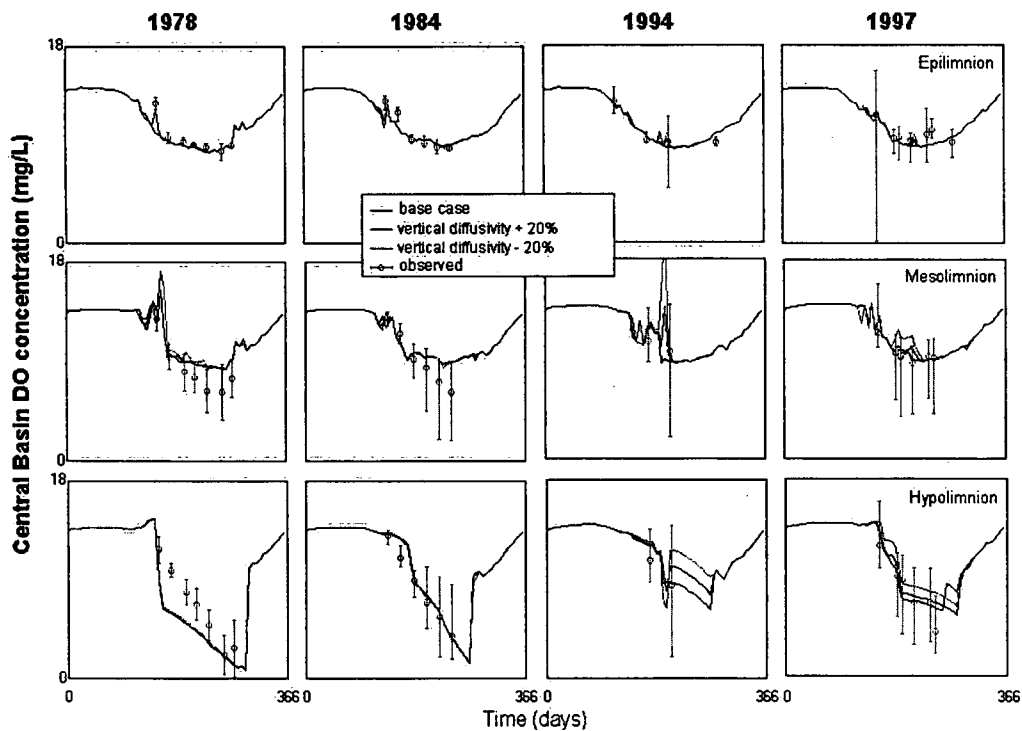
Figure 10. Central basin DO concentration (base case, with vertical diffusivity, ±20%, and observed) for epilimnion, mesolimnion and hypolimnion in 1978, 1984, 1994 and 1997.
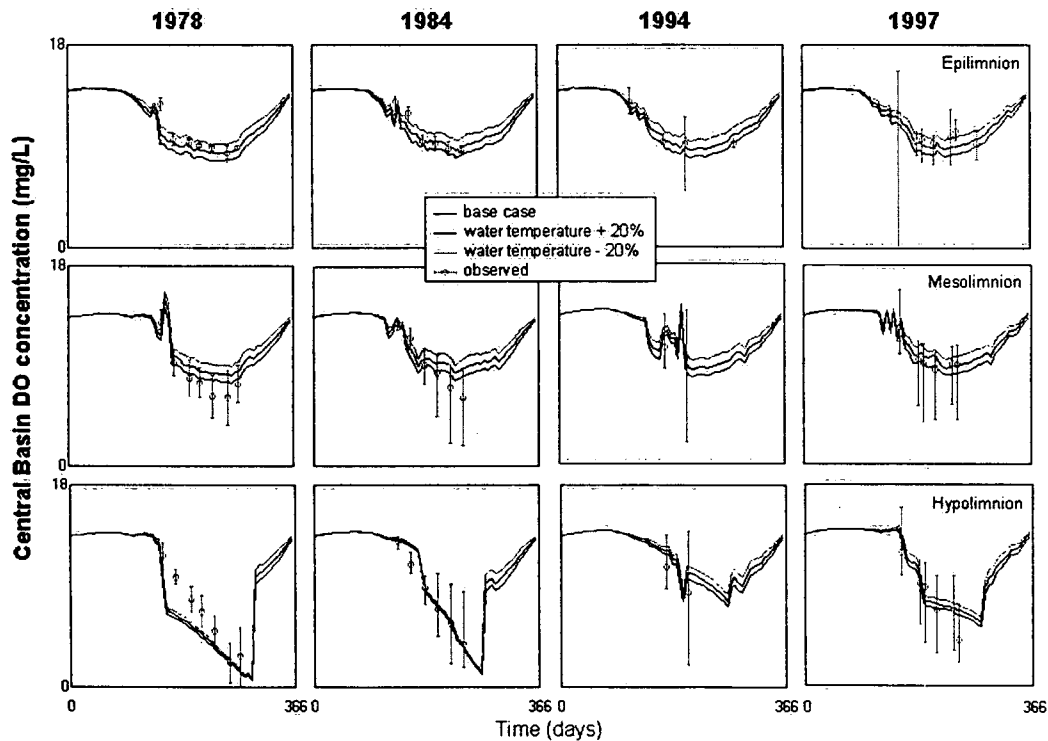
Figure 10b. Central basin DO concentration (base case, with water temperature ±20% and observed) for epilimnion, mesolimnion and hypolimnion in 1978, 1984, 1994 and 1997.
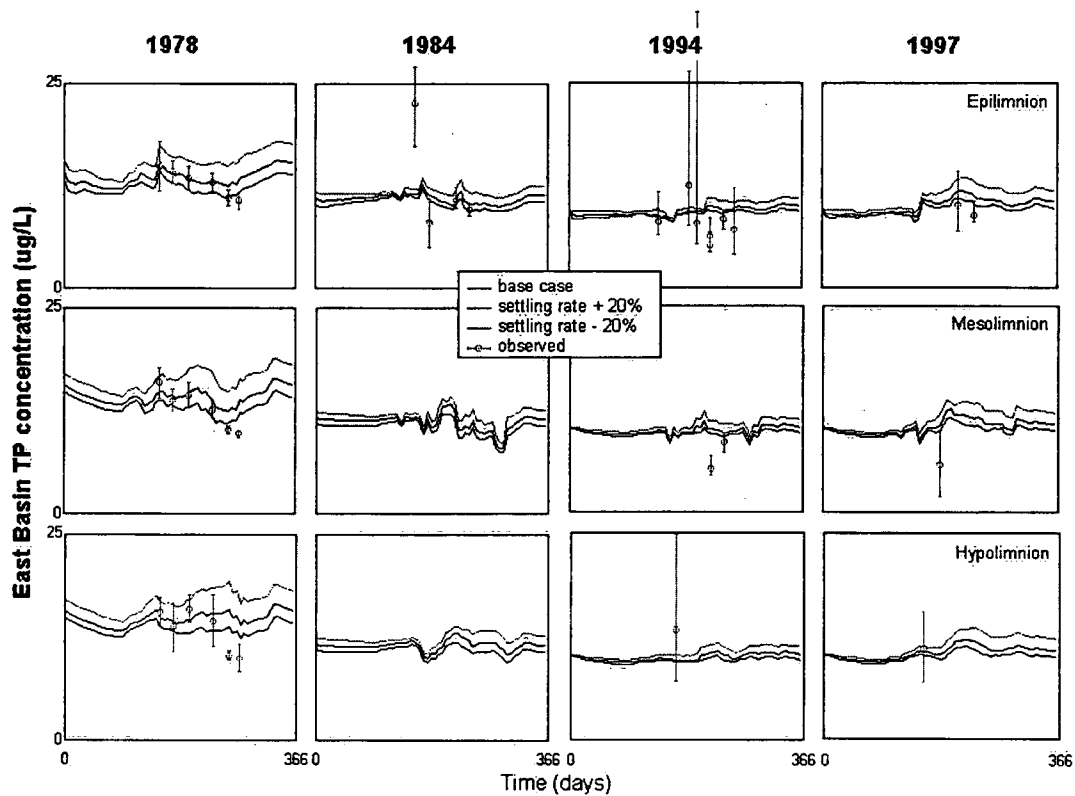
Figure 11. East basin TP concentration (base case, with settling rate ±20% and observed) for epilimnion, mesolimnion and hypolimnion in 1978, 1984, 1994 and 1997.
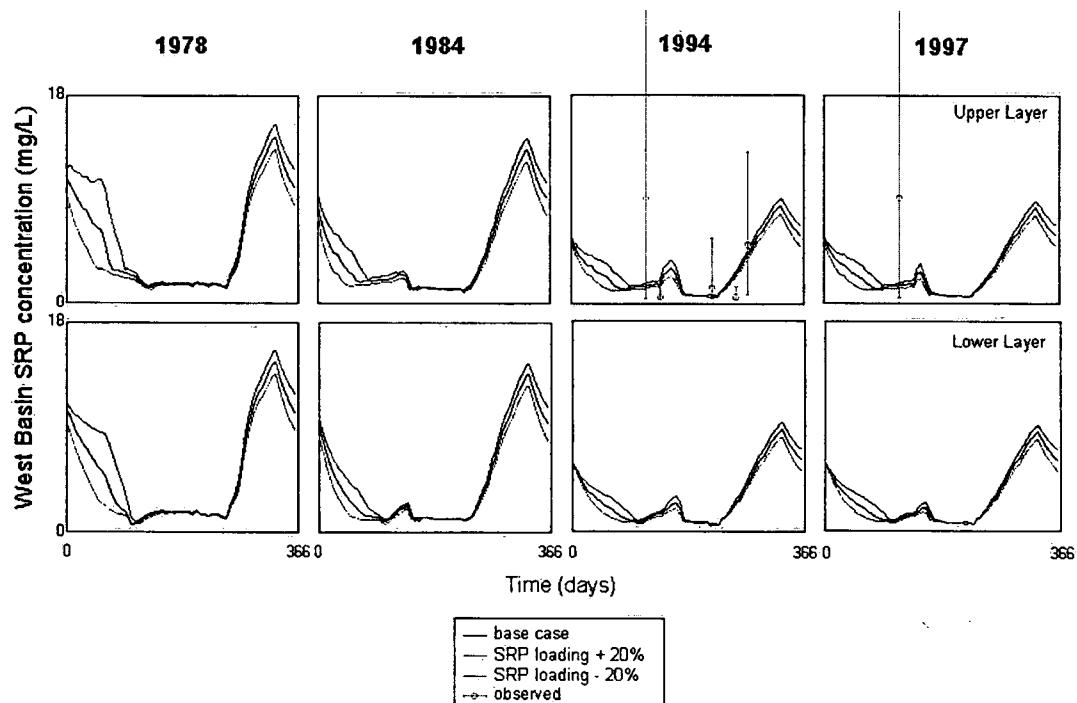
Figure 12. West basin SRP concentration (base case, with SRP load ±20% and observed) for upper and lower layers in 1978, 1984, 1994 and 1997.
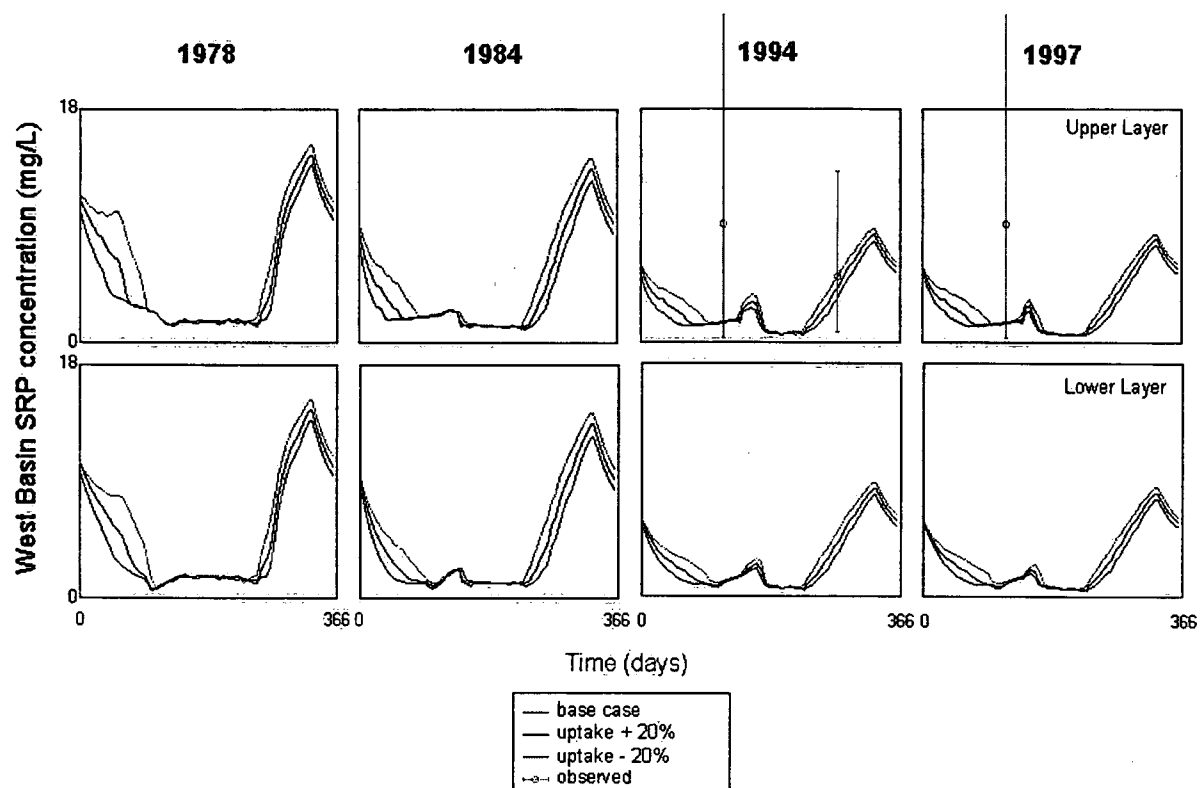
Figure 13. West basin SRP concentration (base case, with uptake ±20% and observed) for upper and lower layers in 1978, 1984, 1994 and 1997.

Sensitivity Analysis: Variation and Gradient for Central Basin TP Concentration
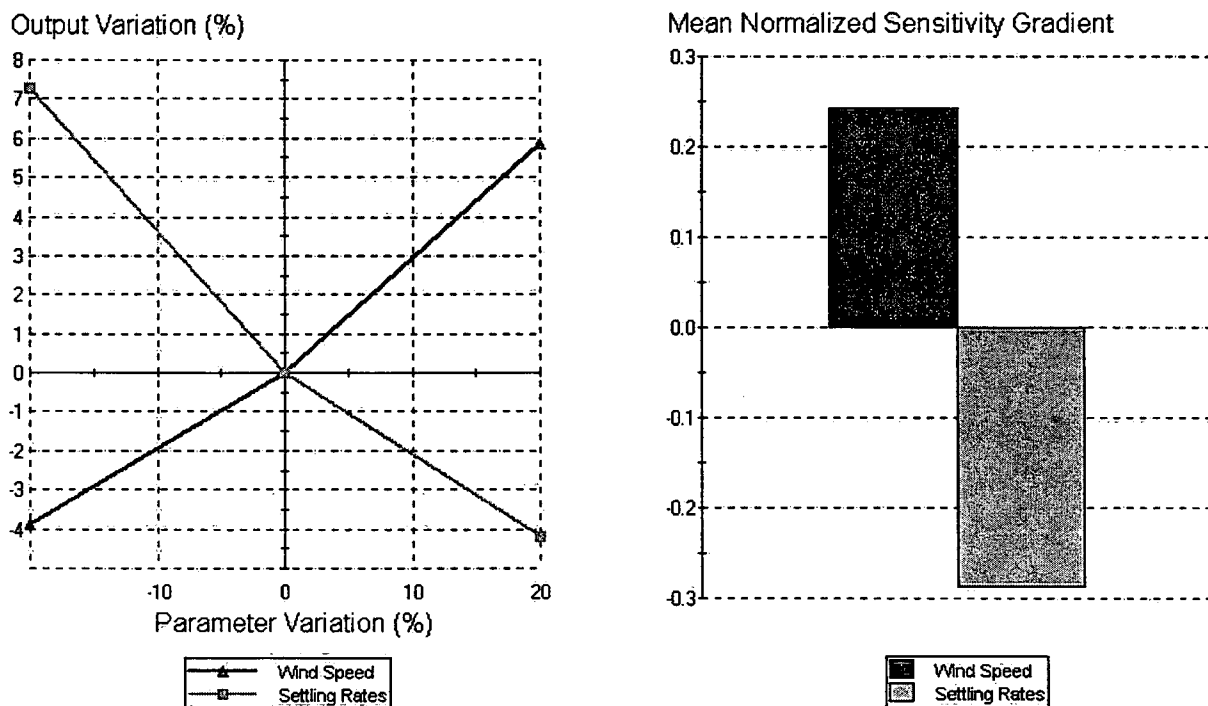
Figure 14.   *Left:* Variation of output (central basin TP) vs. variation of parameters (wind speed and settling rate) for 1984.

Right: Mean normalized sensitivity gradient for wind speed for central basin TP concentration in 1984.

Sensitivity Analysis of TP in Lake Erie West Basin

Total Phosphorus — Average Deviations

Output Variation (%)

1978   1984   1994   1997

Parameter Variation (%)

Gradient

zebra mussel arrival

pre zebra mussel   post zebra mussel

Adjusted Parameters

- Wind Speed
- Uptake
- Respiration
- Vertical Diffusivity
- TP Loads
- SRP Loads
- Outflow (Niagara)
- Water Temperature
- Settling Rates

- Wind Speed
- Uptake
- Respiration
- Vertical Diffusivity
- TP Loads
- SRP Loads
- Outflow (Niagara)
- Water Temperature
- Settling Rates

For West Basin Total Phosphorus, most sensitive parameters are:
- TP Loads
- Settling Rates
- Wind Speed

Figure 15a. Sensitivity analysis (output variation and mean normalized sensitivity gradient) of TP in Lake Erie west basin for 1978, 1984, 1994 and 1997.
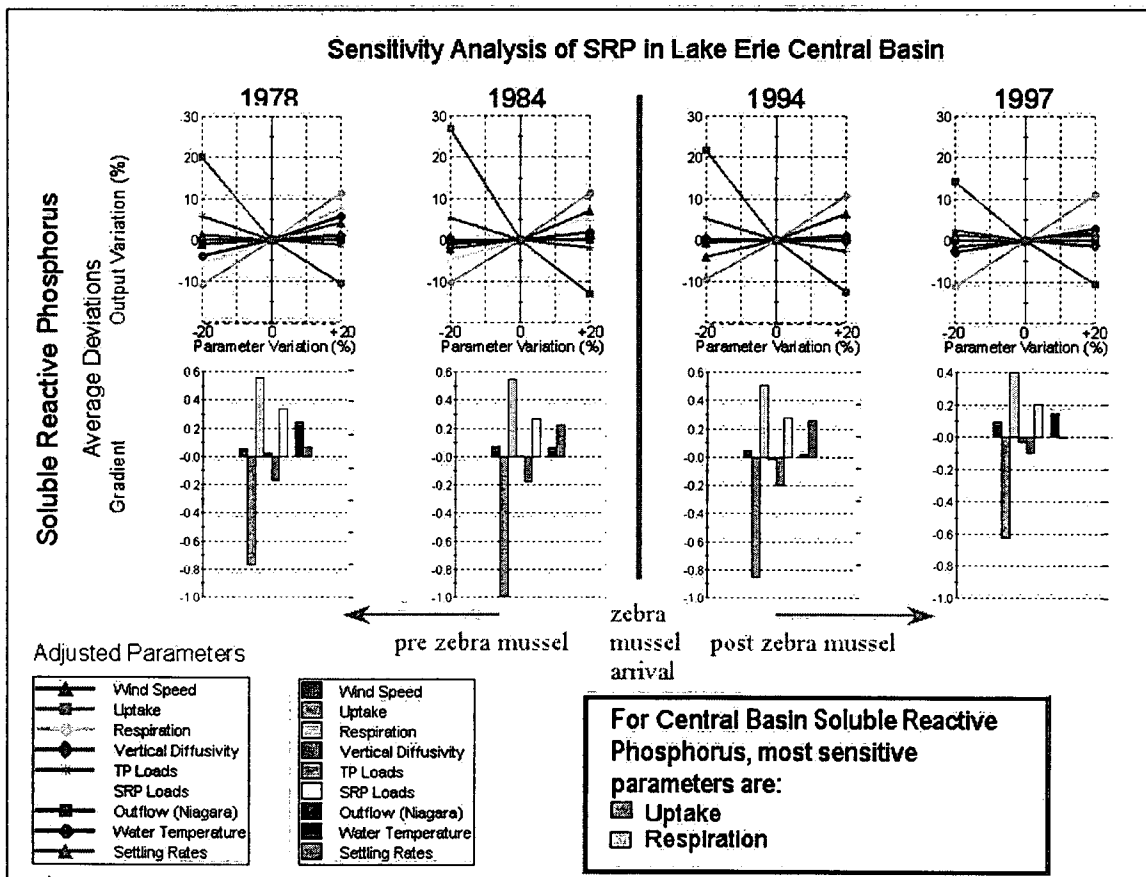
45
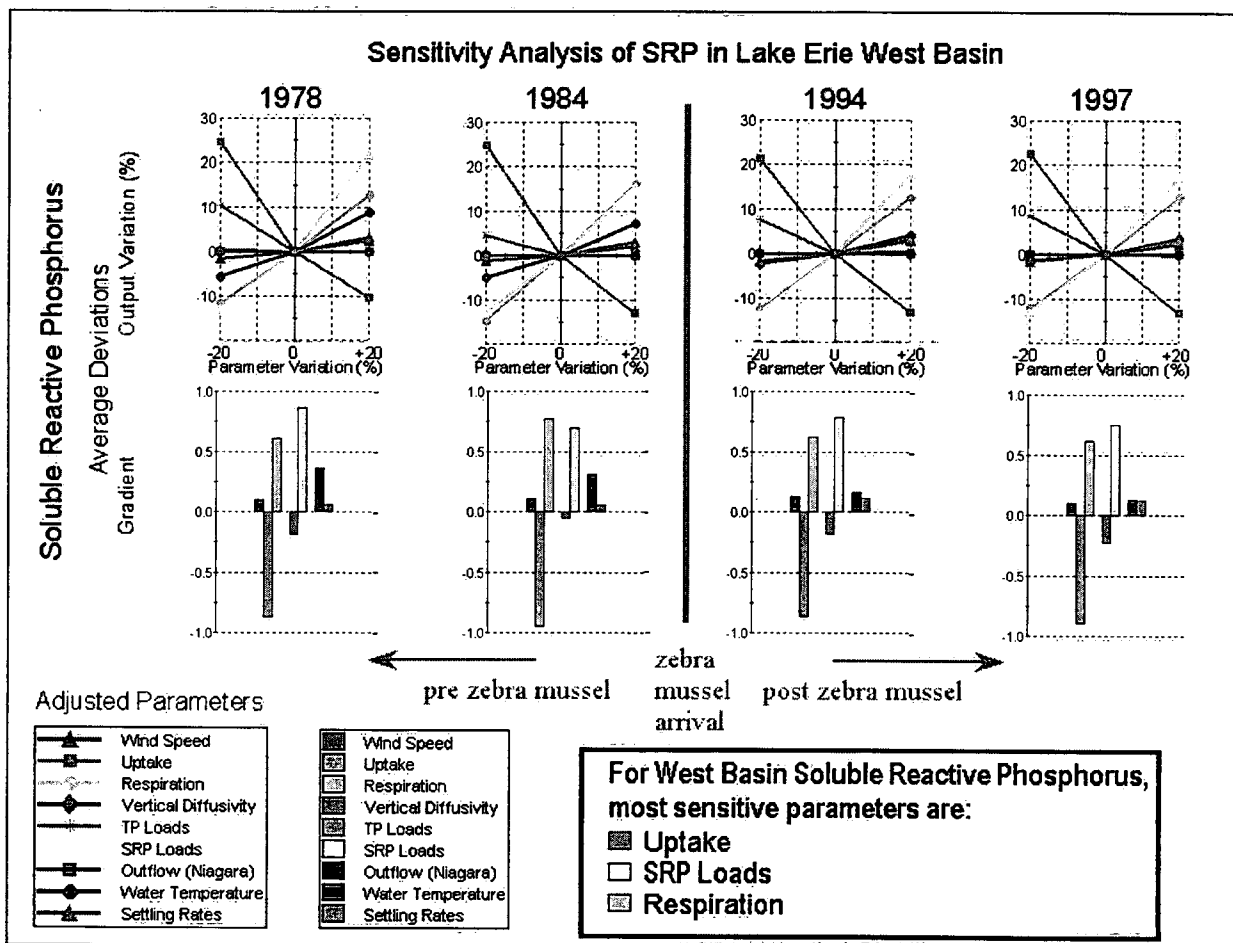
Figure 15b. Sensitivity analysis (output variation and mean normalized sensitivity gradient) of SRP in Lake Erie west basin for 1978, 1984, 1994 and 1997.
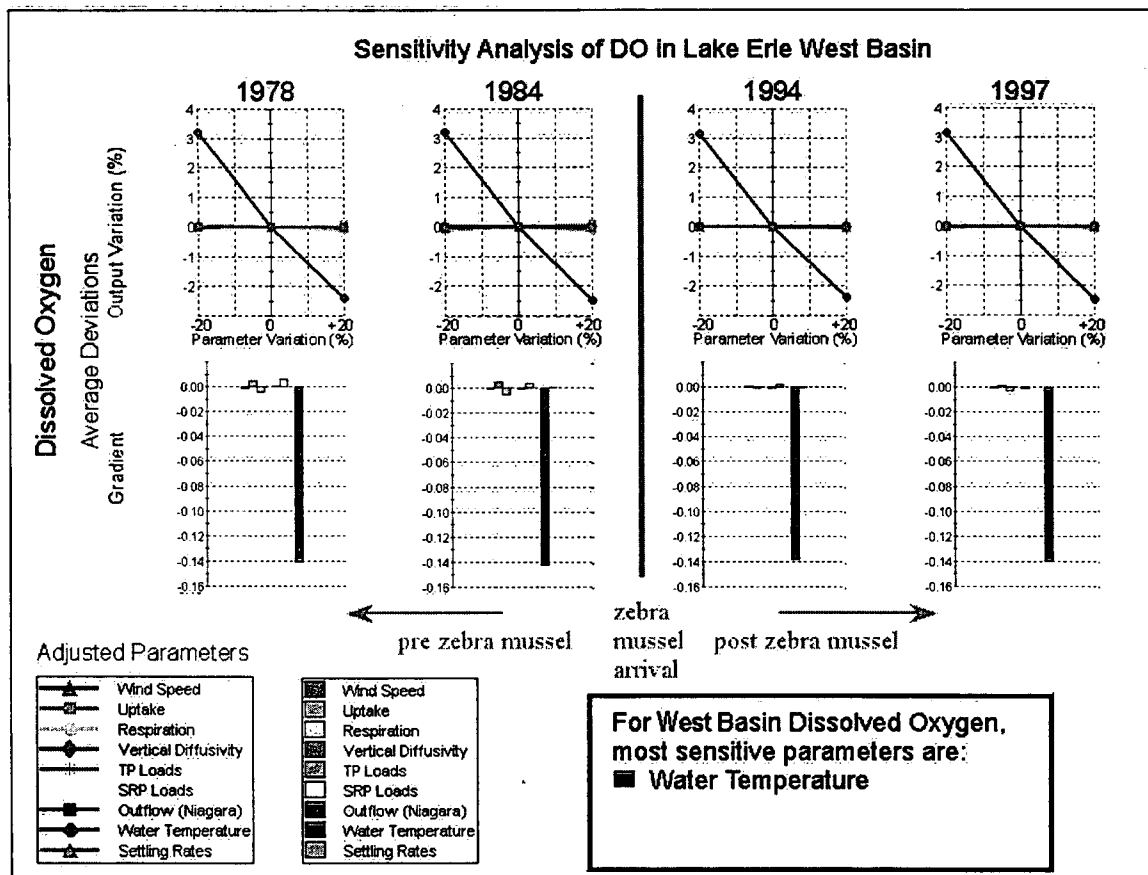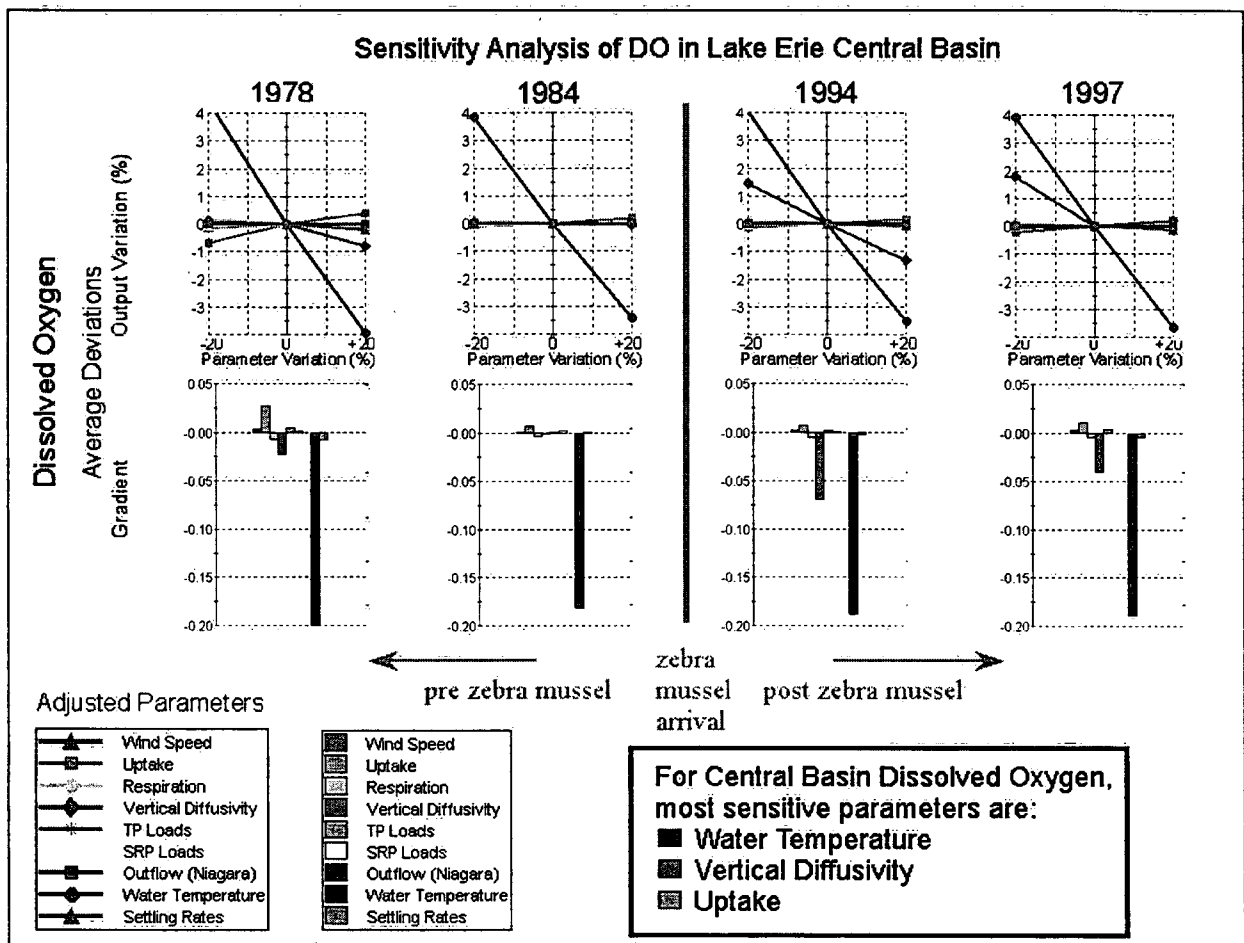
Figure 15c. Sensitivity analysis (output variation and mean normalized sensitivity gradient) of DO in Lake Erie west basin for 1978, 1984, 1994 and 1997.
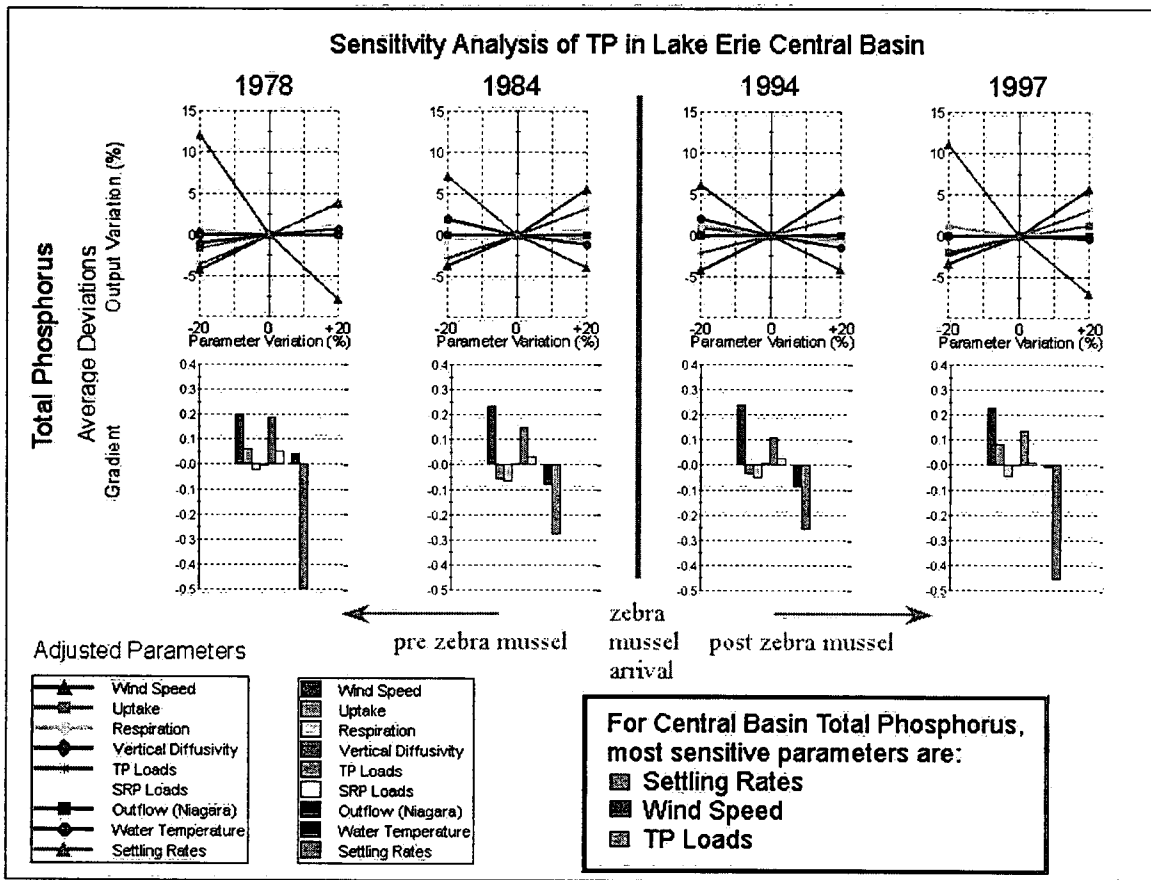
Figure 16a. Sensitivity analysis (output variation and mean normalized sensitivity gradient) of TP in Lake Erie central basin for 1978, 1984, 1994 and 1997.
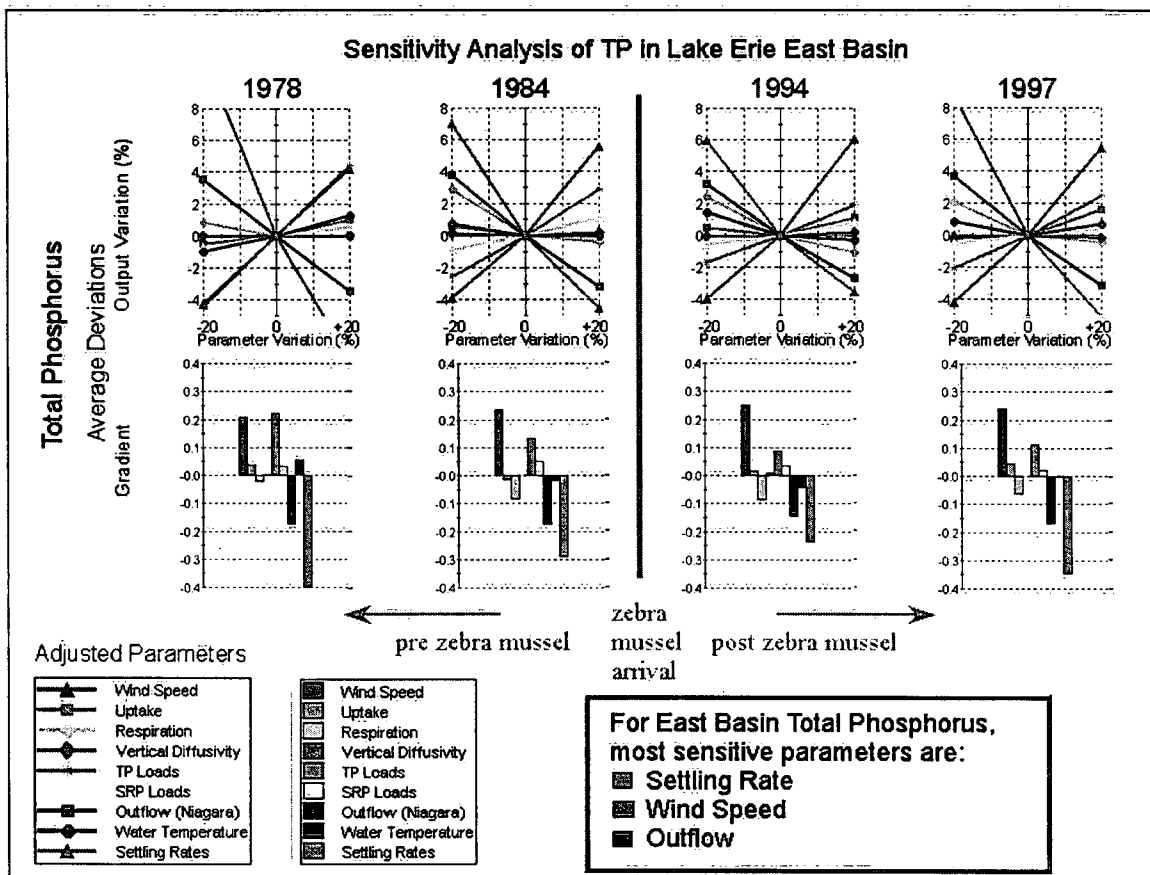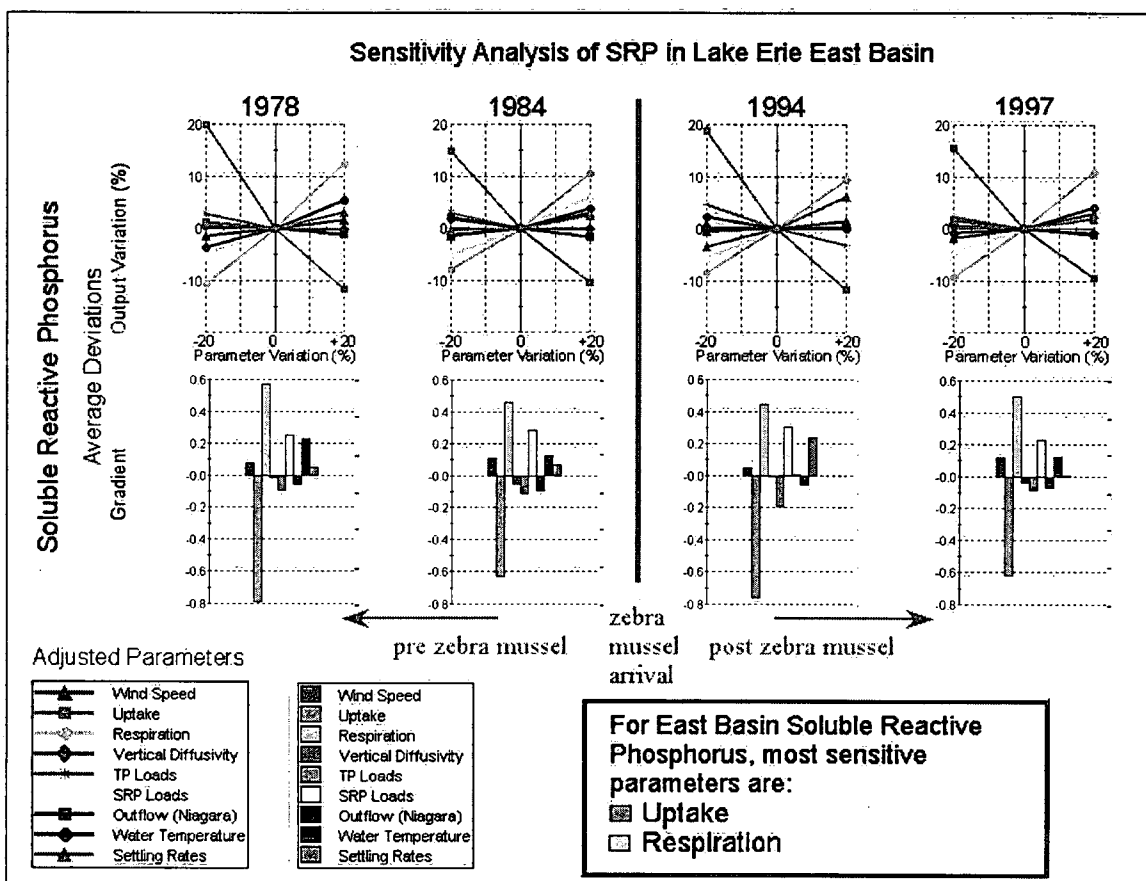
Figure 16b. Sensitivity analysis (output variation and mean normalized sensitivity gradient) of SRP in Lake Erie central basin for 1978, 1984, 1994 and 1997.

Figure 16c. Sensitivity analysis (output variation and mean normalized sensitivity gradient) of DO in Lake Erie central basin for 1978, 1984, 1994 and 1997.

Figure 17a. Sensitivity analysis (output variation and mean normalized sensitivity gradient) of TP in Lake Erie east basin for 1978, 1984, 1994 and 1997.

Figure 17b. Sensitivity analysis (output variation and mean normalized sensitivity gradient) of SRP in Lake Erie east basin for 1978, 1984, 1994 and 1997.
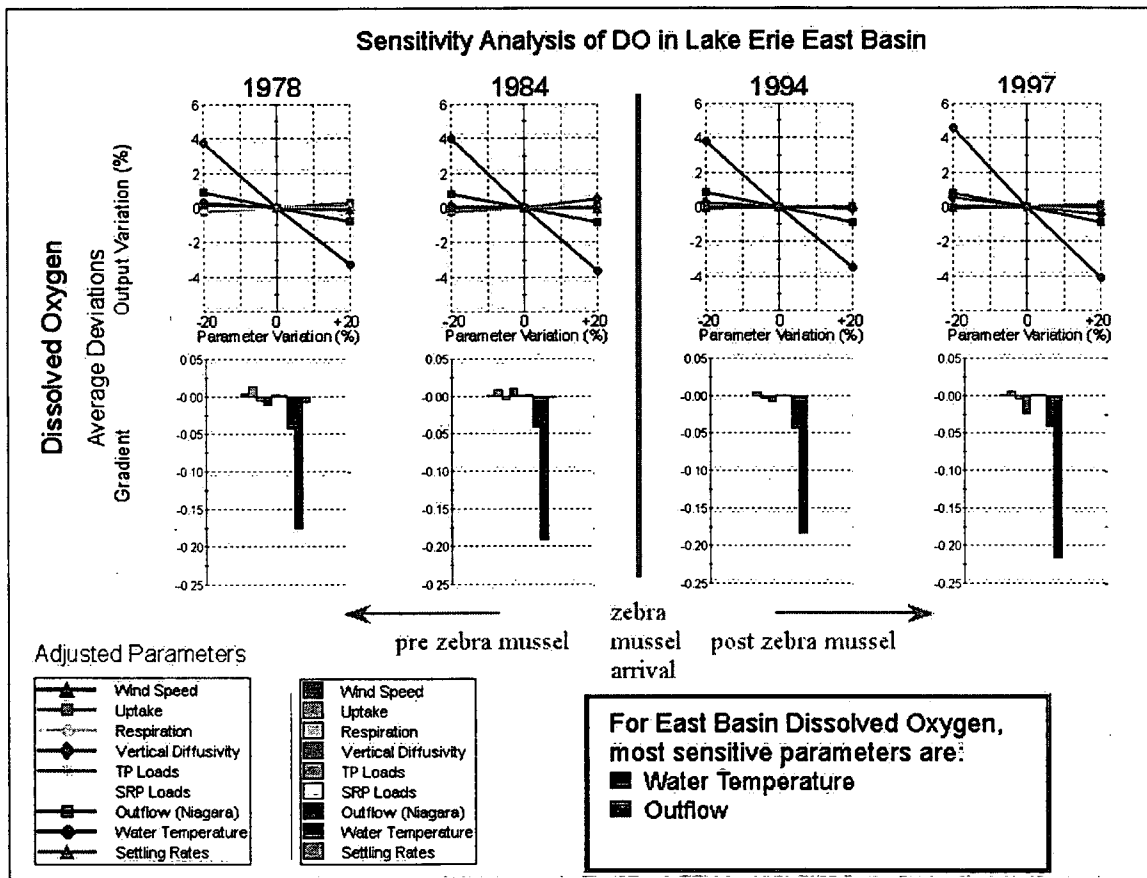
Figure 17c. Sensitivity analysis (output variation and mean normalized sensitivity gradient) of DO in Lake Erie east basin for 1978, 1984, 1994 and 1997.
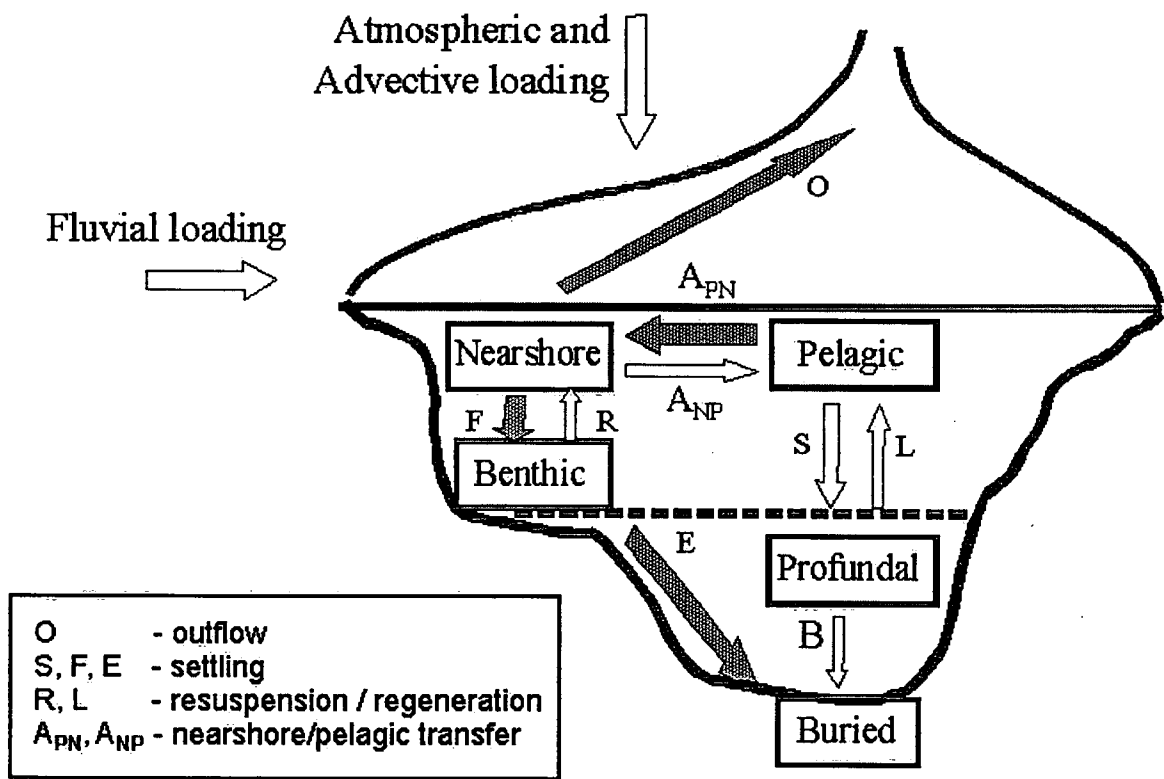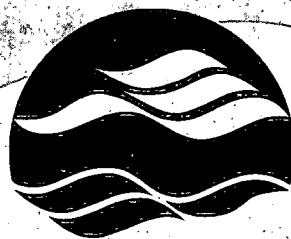
Figure 18. Model and experiment proposed by Dr. Ralph Smith (Pers. Comm., University of Waterloo).

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