Naturally Occurring Chemicals:

Monitoring and Modelling

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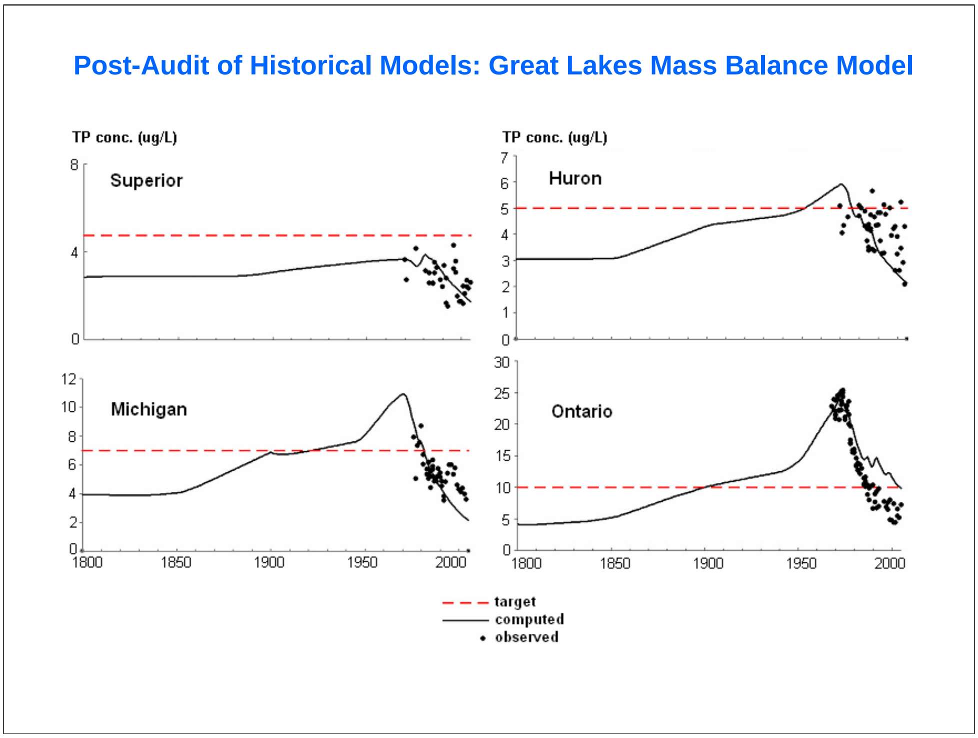
Thank you, Chairperson.

In this presentation, we will learn how models and supporting monitoring data are being used to predict Great Lakes water quality. First, I will provide an overview of my talk. The presentation will cover a post-audit of historical models for Great Lakes water quality. We will look at the Mass balance model and monitoring data (Lake Superior, Huron, Michigan, Erie, Ontario). We will then take closer look at mass balance models; the examples being: the Total phosphorus removal rate, river and lake monitoring data, Lake Erie. We will also examine Multi-processes models and look at modelling of dissolved oxygen in Lake Erie Central Basin. Finally, we will look at current efforts of nearshore modelling, which include nearshore-offshore interactions; cladophora models (for Lake Erie, Michigan, and Ontario); non-point source models (Lake Ontario); and land-lake interactions: municipal/rural loads, source protection (Lake Ontario)

Overview

- Post-audit of historical models for Great Lakes water quality
  - Mass balance model and monitoring data (L. Superior, Huron, Michigan, Erie, Ontario)
- A closer look at mass balance models
  - Total phosphorus removal rate, river and lake monitoring data, Lake Erie
- Multi-processes models
  - Dissolved oxygen in Lake Erie Central Basin
- Nearshore modelling: current efforts
  - Nearshore-offshore interactions
  - Cladophora models (L. Erie, Michigan, Ontario)
  - Non-point source models (L. Ontario)
  - Land-lake interactions: municipal/rural loads, source protection (L. Ontario)

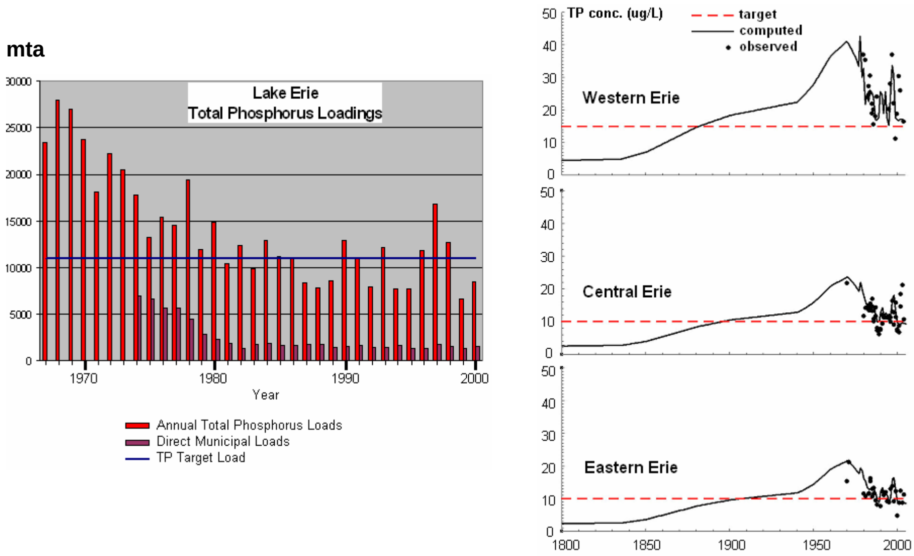
First, we will look at some historical models. There are many models presented in my talk—some from my own work and some are the work of my colleagues. I'll make the acknowledgement of those authors who kindly provided me with their slides at the end of this talk.



The first example shown here **(Slide 3)** is the Great Lakes Mass Balance Model from Steve Chapra. It is one of several historical models that were used to establish target loads for the Great Lakes. It uses loading estimates to calculate the lakewide average Total Phosphorous (TP) concentration. Shown here are the results for Superior, Michigan, Huron and Ontario. The horizontal scale is for the 200 years from 1800 to 2000's. The vertical scale is the TP concentration. The dots are observations starting in late 60's. The black solid line is the computed results and the red dotted line is the target water quality objectives.

As you see, for the Upper Lakes, both computed and observed are mostly below the target objective in the last two decades or so. For Lake Ontario, the observed data are below the target line, but the model results overestimated them.

Great Lakes Mass Balance Model (cont'd)



The figures on the right are the results for the three basins in Lake Erie. Here, the Western basin is almost always above the target line. For the central and eastern basins, we see both instances where the line succeeds and fails to meet the target. These fluctuations are due to the shorter residence time in Lake Erie which are therefore most sensitive to the loading which is shown here on the left hand side. This loading figure is provided by Dave Dolan. It shows that loading has been reduced substantially since the 1970's and is below the target load (the blue line) in some recent years, but not always below it. On the whole, the model simulates well the lake concentration responses to the loading reduction, particularly for the Upper Great Lakes. There is room for improvement for the Lower Great Lakes.

A Closer Look at Mass Balance Models: Lake Erie Application

Equation (1):

change in mass over time	=	loads	-	outflow loss	-	removal
↑		↑		↑		↓
data from in lake monitoring		data from tributary monitoring		data from tributary outflow & concentration monitoring		To be solved as an unknown

Equation (2):

removal	=	σ	x	Area	x	TP
(known)		(unknown)		(known)		(known)

Normally, when we use the mass balance equation, shown in blue as Equation (1) at the top here, we assume we know everything on the right side of the equation and then predict the change in mass over time on the left.

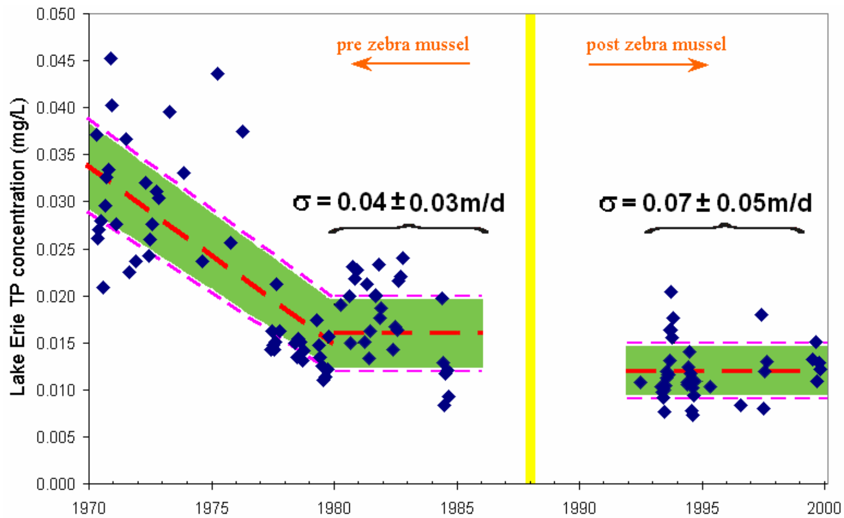
However, as shown in the orange colour boxes, one can turn it around and say one knows the change in mass from the lake monitoring data, and the loads from tributary monitoring and the outflow loss again from monitoring data. Then we purposely assume the only unknown in the equation is the removal term.

If this removal term is obtained, then we further define a removal rate, sigma, as shown in Equation 2 at the bottom.

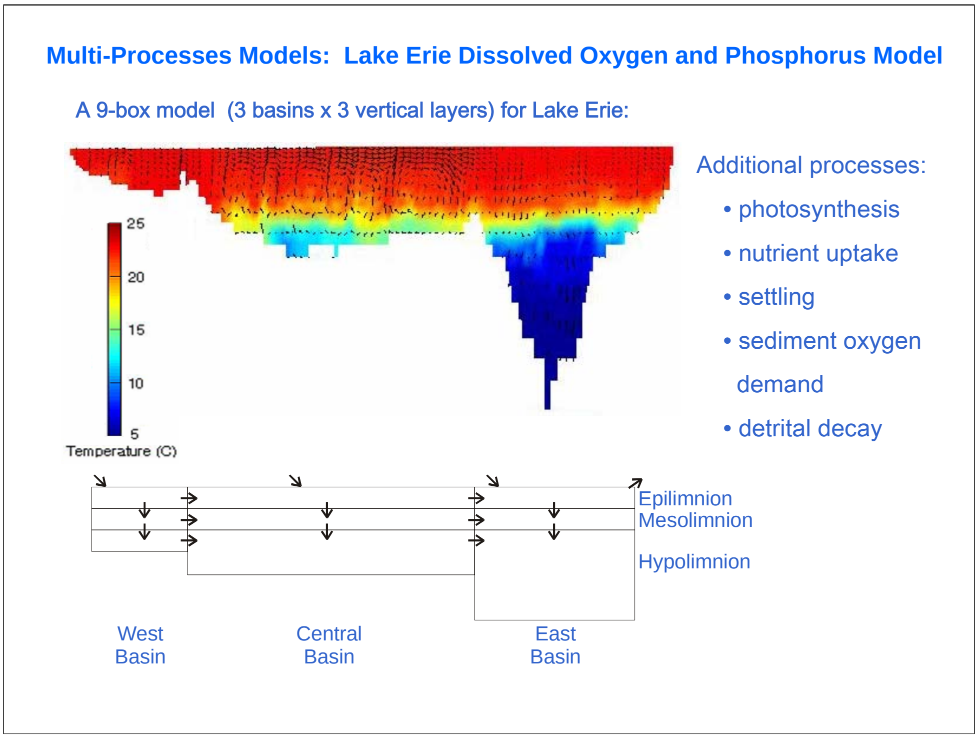
This removal rate is an interesting one. One may even think of it as some kind of indicator.

Next, we will look at this type of mass balance model closely.

A Closer Look at Mass Balance Models: Lake Erie Application (cont'd)



In this figure, the vertical axis is for the lakewide average TP concentration in Lake Erie and the horizontal axis is for the years between 1970 to 2000. The dots are observed lake monitoring data. I have selected two periods, before and after the zebra mussel's arrival and computed the sigma for these two periods. As you see, the sigma increased quite significantly after the arrival of the zebra mussel. The uncertainty in these estimates is quite high. Nevertheless, it shows that the removal rate of TP has changed after zebra mussel arrived. In other words, if we use a higher removal rate in the mass balance model, then the results should fit the observation better for the post zebra mussel period.



Now, this takes us to the third part of my talk on multi-process models. One way to improve the mass balance model is to add more relevant processes. For example, if we are to simulate the dissolved oxygen, we need to consider the thermal stratification processes.

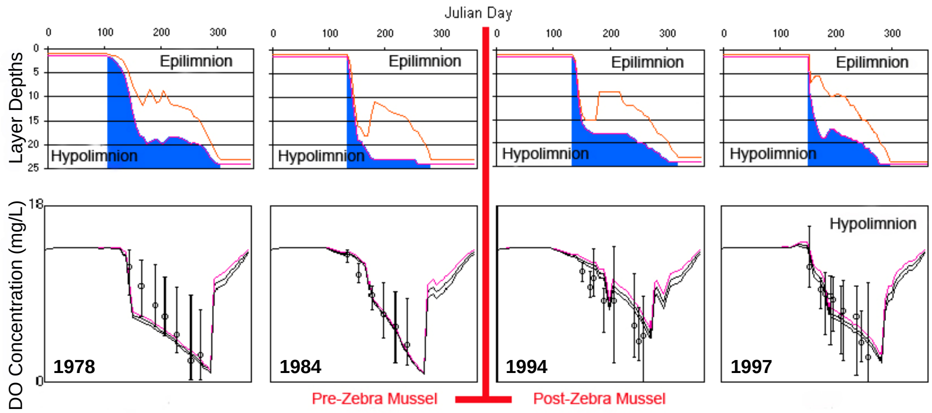
Here, we show a longitudinal vertical cross-section of Lake Erie. The western basin on the left is the shallowest (about 12 m deep); the central is in the middle (about 25 m deep); and the eastern basin in on the right (about 60 m deep). Shown here, are the temperature simulation provided by Luis Leon. As you see on the left, the western Basin is fully mixed with temperatures above 20 degrees in this case and is seldom having anoxic conditions. On the right, in the case of eastern Basin, it is stratified but with a bigger hypolimnion with temperature below 10 degrees. The oxygen in the eastern Basin may be depleted but not to anoxic level.

Now, turning to the central Basin as shown in the middle, we see that it is stratified, but with a shallow hypolimnion. When oxygen is depleted by such processes, there is sediment oxygen demand. It can be depleted faster to anoxic level, particularly for the light blue area on the left where we sometimes call the "dead zone". This kind of thermal process combined with the special basin geometry of central Basin gives it a unique situation for anoxia to occur. This kind of anoxia is not observed in other Great Lakes or even for other basins in the same lake.

Thus, in order to simulate the connection of loading reduction and TP concentration and dissolved oxygen, one needs to include more vertical layers in the three basins as shown in the bottom of this figure. As well, we need to include more processes as indicated on right hand side of the slide: photosynthesis, detrital decay.

Multi-Processes Models: Lake Erie Dissolved Oxygen and Phosphorus Model (cont'd)

Results: Central basin layer thickness and bottom-layer dissolved oxygen



The following are some examples of a multi-processes model for Lake Erie.

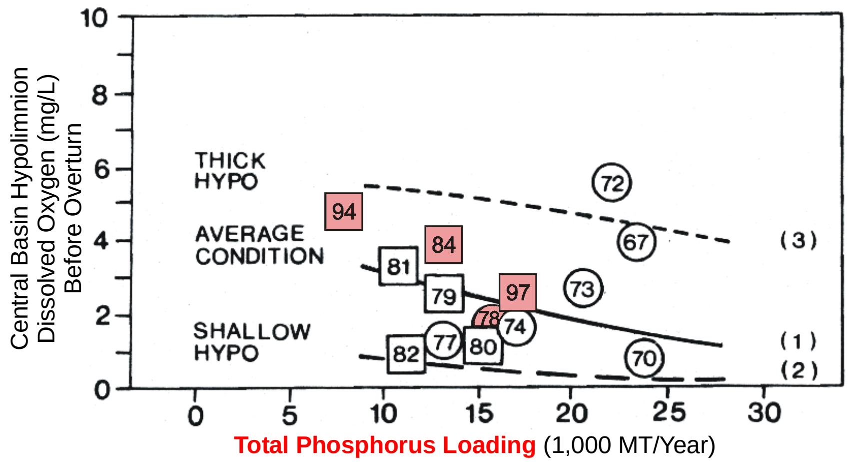
Here we see two rows of figures. Each row has four individual figures representing four years: 1978, 1984, 1994, and 1997. The top row shows the thermal layer thicknesses. The attention is on the blue area which indicates the hypolimnion thickness for that year. For example, in the third figure to the right (showing results for 1994), is the thickest here.

The bottom row shows the computed and observed dissolved oxygen in the hypolimnion, and as you can see, oxygen level is higher when the hypolimnion is thick, and vice versa. It seems to be independent of the zebra mussel arrival.

So, the question is, do dissolved oxygen level respond to TP loading reduction as well as the influence of thermal stratification? Lets see these two effects together.

Processes Models: Lake Erie Dissolved Oxygen and Phosphorus Model (cont'd)

Combined effects of TP loads and thermal stratification



This figure shows the combined effects of loading and thermal stratification. In this figure, the horizontal axis represents the loading and the vertical axis represents the dissolved oxygen in the hypolimnion just before overturn in the fall. The circles and squares are the observed values, with the four years from the previous slide marked in the colour pink here.

There are three lines in the figure. You can see, I have run the model with different loading values and for three thermal stratification conditions. The middle line is for model results with average stratification conditions. The line above this represents thick hypolimnion. The line below shows shallow hypolimnion.

As you see, the middle line or curve shows that by reducing the load, (i.e. moving from right to left), the dissolved oxygen increases. That is, reducing the nutrient load can improve the oxygen level. However, if the condition is suitable for thick hypolimnion (i.e. the top curve), it is always with high level of oxygen. In 1994, we see that conditions were ideal, because the loading response whereas there is greater central basin layer thickness hypolimnion.

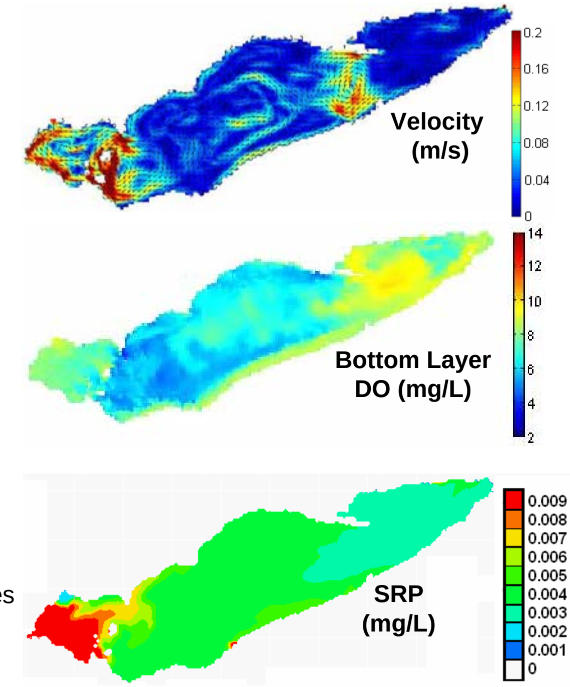
The opposite can be said with the bottom curve for shallow hypolimnion. This shows that if it is shallow then the loading reduction effects are often masked by the stratification effects and the DO level remains low, e.g. comparing 1970 and 1982.

So, loading reduction is helping the improvement of DO level in central basin hypolimnion, but it is often affected by meteorological or stratification effects. One needs to look at both. And that is the message from this type of multi-processes modelling.

Actually, there are other factors besides thermal stratification too. Water level is one of them, but I will leave this topic now and move to the part 4 of my talk.

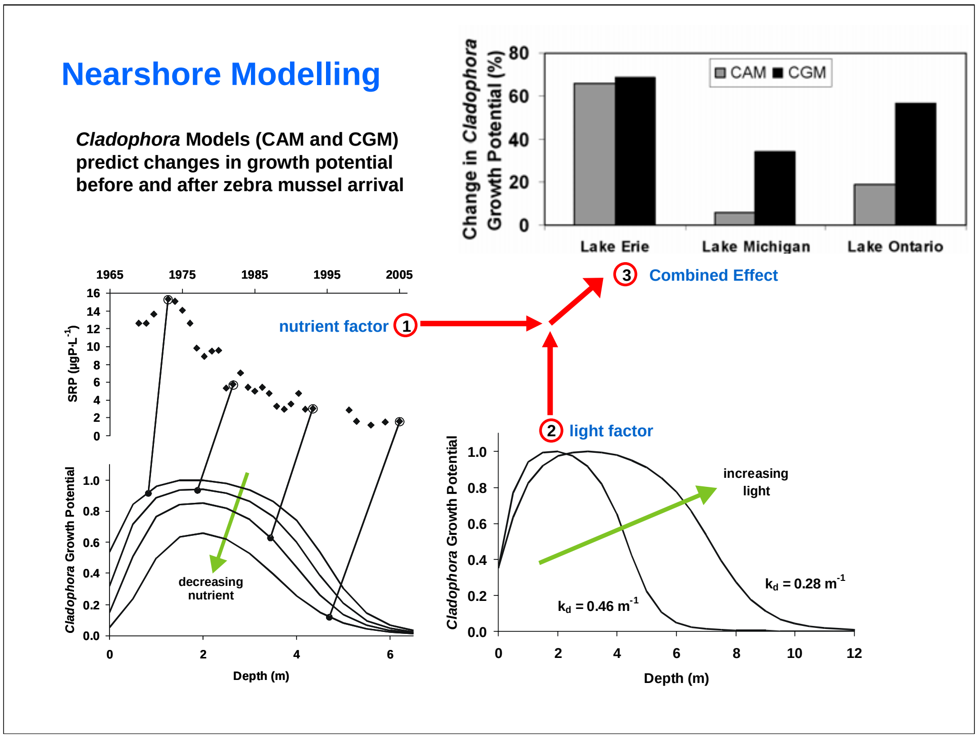
Nearshore Modelling

- 3-dimensional circulation
- upwelling and downwelling
- rural and municipal loads, nearshore-offshore exchanges



We now come to the last part of my presentation on nearshore modelling. This is quite a complex topic. There are several on-going efforts in both Canada and U.S. The first consideration in modelling nearshore environments is the physical influence. You see an example of this in the complex 3-dimensional circulation shown here at the top for Lake Erie as an example. Then there is the upwelling-downwelling effect in the nearshore zone. As shown in the middle diagram for simulated distribution of DO, again for the bottom layer for Lake Erie, there is a green coloured belt on the south shore, showing a downwelling phenomenon, i.e. relatively high level of DO going down from the upper layer to the lower layer. Accompanying this is an upwelling zone on the north side indicated by the vibrant blue colour.

As well, then there are the effects of rural and municipal loads and nearshore-offshore exchanges of nutrients.

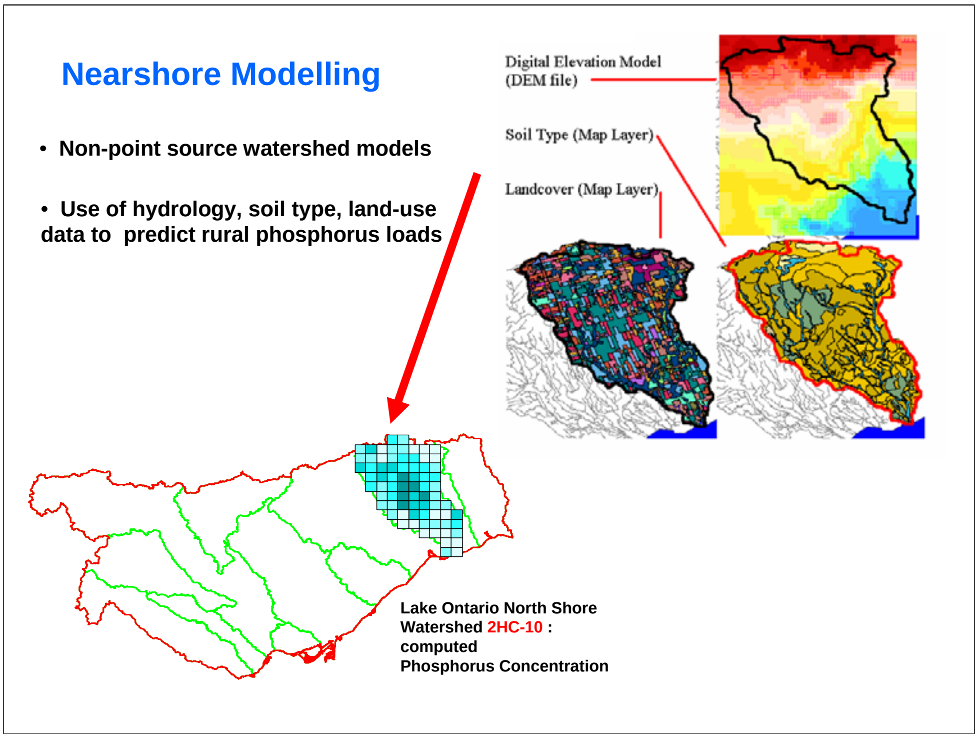


The algal problem in the nearshore must also be considered. The content of this slide, provided to me by Marty Auer, examines the process of Cladhora modelling. It shows that Cladophora growth potential may have changed after the arrival of the zebra mussel for Erie, Michigan and Ontario. Here, they considered two factors that may affect the Cladophora growth potential before and after zebra mussel arrival: nutrient and light. As shown on the bottom left here, in the case of factor 1, for nutrient, the SRP is decreasing from the 1970's to present day. This should result in a decrease in the Cladophora potential.

Then, as shown on the bottom right, for factor 2 on light effects, the arrival of zebra mussel makes the water clearer and therefore there is increasing light available for the Cladophora to grow. This is opposite to the effects of the exchange of nutrients. So, it is a game of tug of war.

Now, as shown on the top right here, combining factors 1 and 2, we have the net change in Cladophora growth potential after zebra mussel arrival for Erie, Michigan and Ontario. There are two model formulations here but they both show a positive change in the growth potential in all three lakes, particularly for Lake Erie. It seems to show that the light effect is more important.

At present, there are several other studies to explain this phenomenon. One hypothesis is that there is actually a rapid recycling of the nutrients taken by the zebra mussel and returning to the Cladophora to encourage its growth. Marty will discuss this further in the afternoon workshop on modelling.

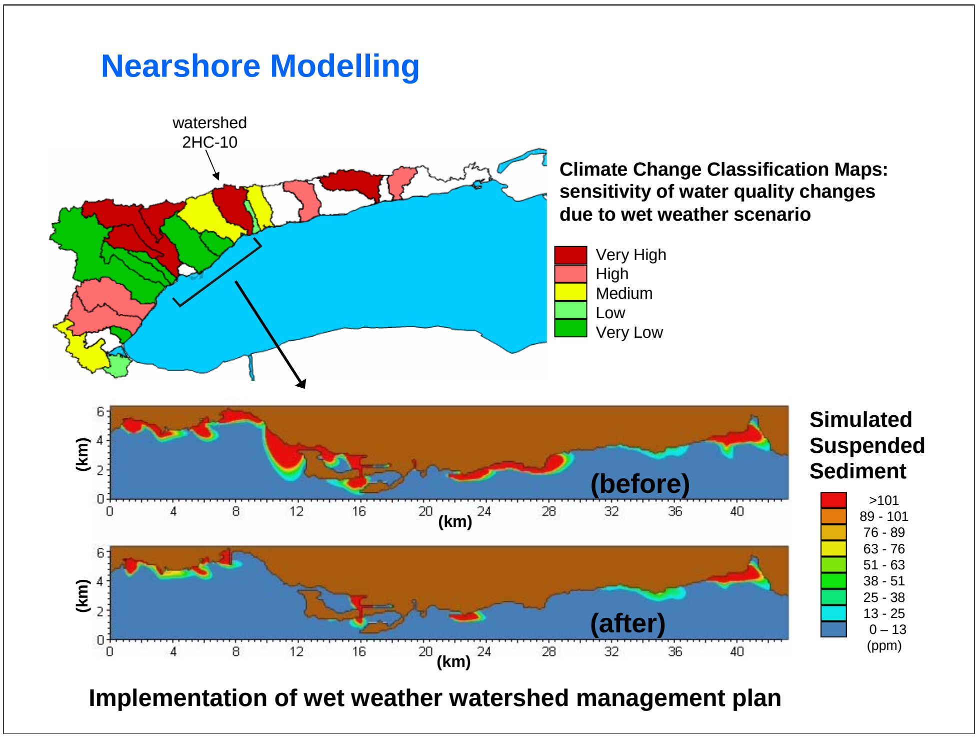


The other consideration for nearshore modelling is the non-point source load from watersheds. There are many examples. Here is one from Bill Booty. As shown on the top right here, maps for watershed topology or digital elevation, soil types and land use are input to this model.

For any given rain event, the model will produce the runoffs as well as nutrient concentrations and loads distributed over the watershed and at the outlet.

As shown in the bottom left here, for the case of watershed 2HC-10, on the north shore of Lake Ontario, the computed phosphorus concentration is shown. The dark shades here indicate more polluted areas and that is where watershed management should be focused. This kind of model application has been applied to many watersheds for better management practices for wet weather scenarios.

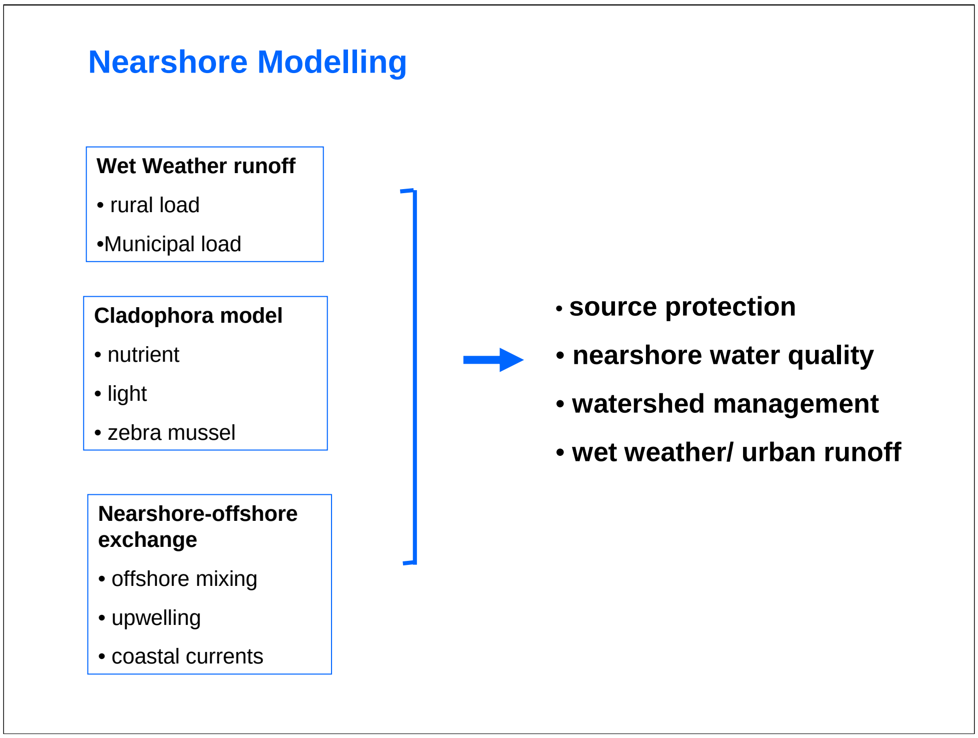
We'll see more about it next.



The top figure shows Watershed 2HC-10 that we have just seen in the midst of about 20 neighbouring watersheds along the north shore on the west side of Lake Ontario. The non-point source model has been applied to all these watersheds where data is available. The idea here is to classify them according to the sensitivity of water quality changes due to wet weather scenarios from climate change. The red ones are the most sensitive ones and the green the least sensitive. This kind of model results would be good for targeting watershed management practices on those watersheds that are sensitive and need more attention.

This type of information and others such as urban runoff controls can be used to implement an integrated approach to the implementation of wet weather watershed management plan. The bottom figure provided by Bill Snodgrass shows the possible effect of both rural and urban discharges on nearshore water quality before and after an implementation of management plan. In this case, the simulated suspended sediment is featured from several sources affecting the drinking water intake sources. Obviously this requires the connection between land and lake, i.e. the linking of the watershed models with nearshore hydrodynamics and pollutant transport models.

Let me summarize the nearshore models discussed so far.



So, in summary, for nearshore models...

...(reading each text box)...

This integrated land-lake watershed modelling approach will help managers plan better source protection, improve nearshore water quality, better watershed management and wet weather runoffs.

This will require the continuing dialogues between scientists, managers and modellers. It is a challenging task, but one that comes with interesting results that will benefit many people in this field.

Concluding Remarks

- Post-audit of historical models show general success on target load effects
- Improvement in lake and tributary monitoring network required for models
- Uncertainty on unmonitored loads (urban, rural, atmospheric, wet weather)
- Models to resolve multiple issues and factors (nutrient, temperature, light)
- Current modelling efforts: nearshore modelling (Cladophora, drinking water protection, integrated land-lake models)

Now, let me acknowledge all those who have helped me with this presentation.

This concludes my presentation. Thank you.

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