

Using a Mechanistic Eutrophication Model for Water Quality Management of the Neuse River

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Introduction

As part of the MODMON project, work is now underway to predict the water quality improvement that would result from a 30% reduction in nutrient loading to the Neuse River estuary. The predictions will be made through the use of the mechanistic water quality model CE-QUAL-W2 (Cole and Buchak 1995). This phase of the MODMON project has been referred to as “short-term” modeling. CE-QUAL-W2, or some other mechanistic model, is also being considered for longer-term use as a component of a decision support framework that would include a comprehensive (watershed-river-estuary) water quality model. This article is intended to assist in the consideration of mechanistic modeling options by addressing some of the common questions regarding mechanistic eutrophication models.

Eight separate questions are asked and answered in the following section. Each of the eight questions is shown in italics and is followed by a brief answer. This is in no way an attempt to pose and answer all of the relevant or interesting questions regarding mechanistic models. It is hoped, however, that this information will encourage a thoughtful discussion of the pros and cons of using mechanistic models for managing the water quality of the Neuse River Basin.

Mechanistic Eutrophication Models – Questions and Answers

1. *What is a mechanistic eutrophication model, anyway?*

Models like CE-QUAL-W2, WASP5 (Ambrose et al. 1993), and others are referred to as “process-based”, or “mechanistic”, or “deterministic” water quality models. Process-based or mechanistic (either is appropriate) water quality models have as their basis a set of equations that attempt to describe all the relevant processes, or mechanisms in the water body. One equation is written for each water quality constituent to be predicted. These equations are based on the principle of mass conservation. In coupled hydrodynamic/water quality models like CE-QUAL-W2, additional mass, momentum, and energy balance equations are also written to predict water circulation, mixing, and the temperature of the water body. A deterministic model is one that produces a single prediction, rather than a range of possible predictions. Mechanistic models need not be deterministic, if the modeling effort includes an analysis of prediction uncertainty.

A eutrophication model is a type of water quality model that can be used to predict the growth dynamics of phytoplankton. The water quality constituents of primary interest in eutrophication modeling studies are typically nutrients, phytoplankton, and dissolved oxygen (DO). Other constituents are also included in order to predict the relevant processes. Eutrophication models have between approximately 5 and 25 constituents, or “state variables.” Typically these models model phytoplankton growth as a function of available nutrients, temperature, and light, and include other processes such as phytoplankton mortality, sinking, and exudation.

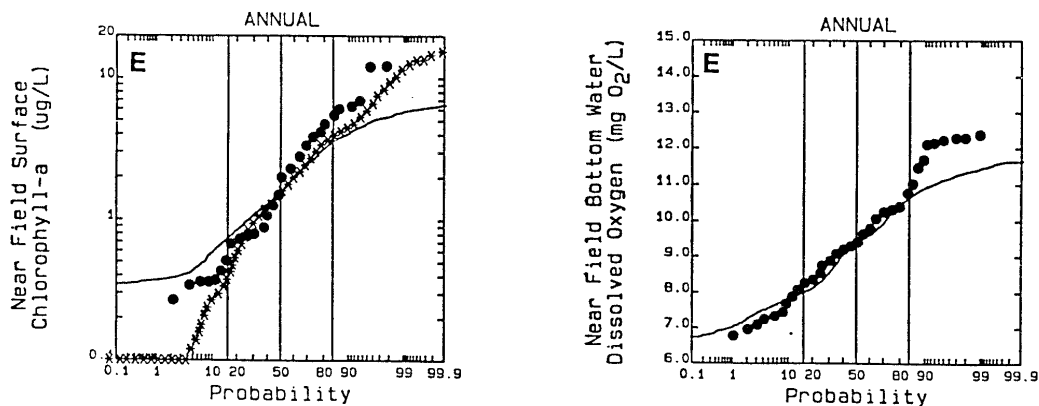
2. *Have eutrophication models been used for this purpose before?*

Mechanistic water quality models are commonly used to predict the impact of environmental manipulations. Eutrophication modeling makes up only a very small percentage of the water quality modeling that is performed to predict environmental impacts. Nonetheless, eutrophication models have been used for environmental management purposes throughout the world. In the U.S., eutrophication models have been used recently in the Tar-Pamlico Estuary (Hydroqual 1995b), the Chesapeake Bay (Cercu and Cole 1993), Long Island Sound, and Massachusetts and Cape Cod Bays (Hydroqual 1995a), to name a few.

3. *How well have these eutrophication models performed?*

There is no easy answer to this question, in part because there are many possible performance measures that we might apply to evaluate eutrophication models. As a partial answer, however, let's look at the results of a eutrophication model of Massachusetts and Cape Cod Bays (Hydroqual 1995a). One performance measure might be how well the model reproduces the variability in the observed data. This is an important consideration when models are used for environmental management, where extreme events (e.g. high chlorophyll, low DO) are of particular concern. In this case, the minimum dissolved oxygen agreed well between the prediction and observation, but the model under predicted the maximum concentrations (Figure 1). The general shape of the DO distribution agrees well with the observations. For chlorophyll, the model under predicted the peaks by as much as a factor of two, but did a good job of representing the median values (Figure 1).

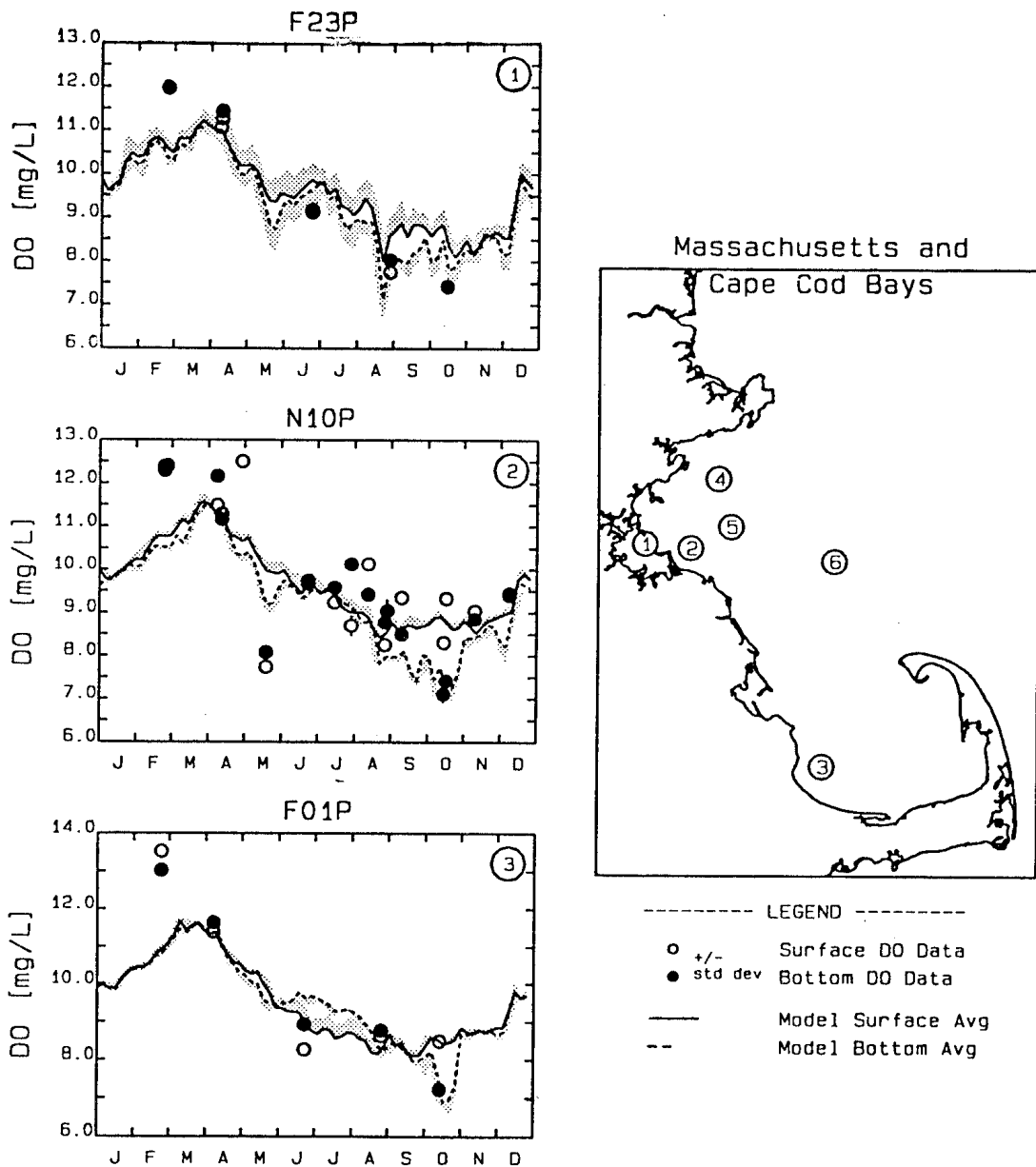
Figure 1. DO and Chlorophyll Probability Distributions for Model Predictions (lines) and Observations (symbols) (from Hydroqual 1995a)



A second performance measure might be how well model predictions of DO and chlorophyll-a concentrations agree with the individual observations made through water sampling

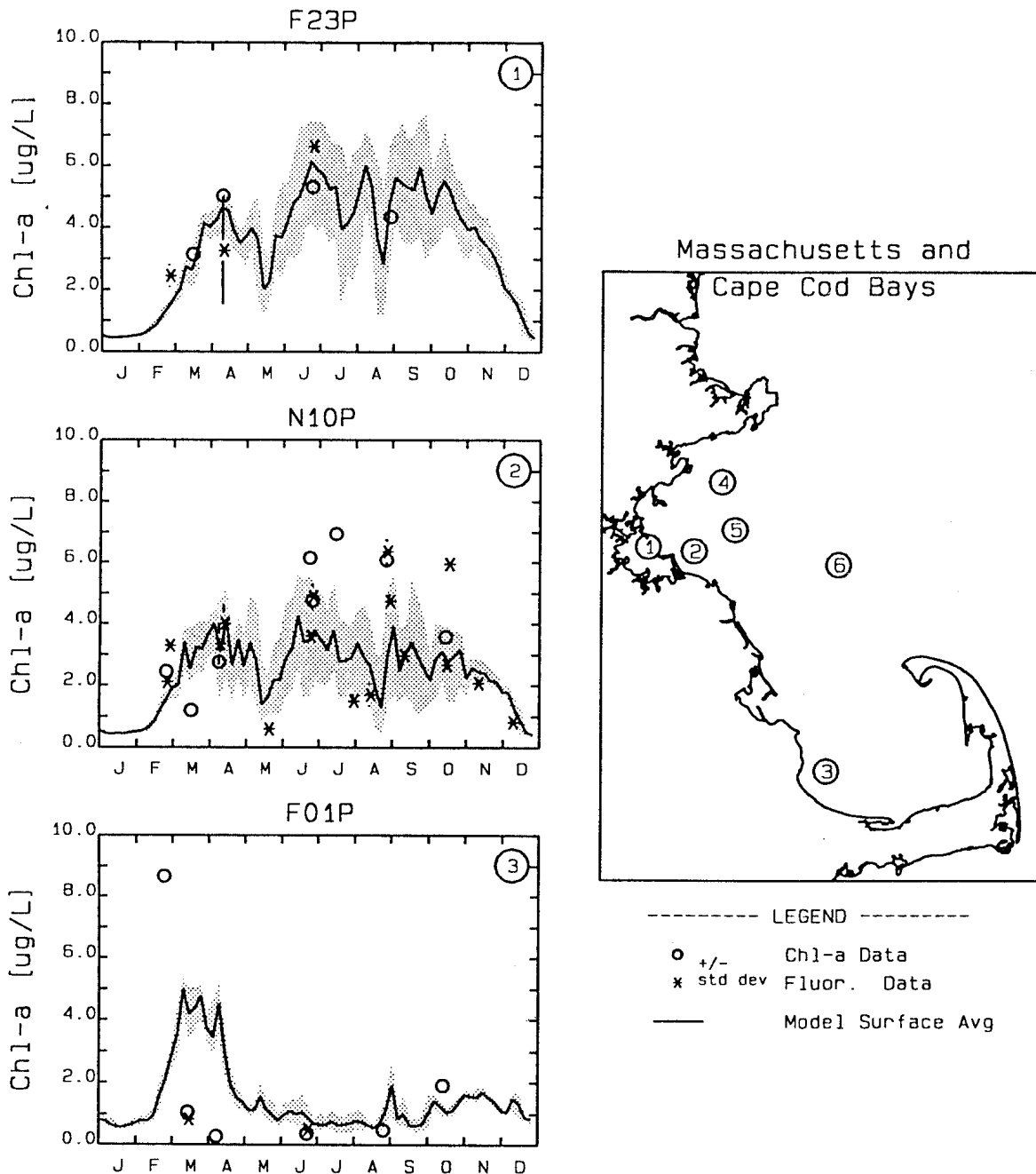
and analysis. In general, the model predictions capture the seasonal pattern of dissolved oxygen and chlorophyll, and are usually within 25% of the measured values (Figure 2, Figure 3). Dissolved oxygen predictions reflect the observed seasonal decline through the summer months, the vertical variations, and the spatial across the Bay (Figure 2). The relative difference between prediction and observations is somewhat bigger for chlorophyll than it is for dissolved oxygen (Figure 3). Summertime highs at station N10 are consistently under predicted by the model,

Figure 2. Model Predicted and Observed Dissolved Oxygen Concentrations in Mass Bay During 1992 (from Hydroqual 1995a)



and the winter bloom in Cape Cod Bay is also under predicted by the model. The model does predict a winter bloom, but underestimates its magnitude. In general, eutrophication models produce good predictions of seasonal and spatial trends of water quality conditions, but have difficulty in predicting the magnitude of “events.”

Figure 3. Predicted and Observed Chlorophyll Concentrations in Massachusetts Bay During 1992 (from Hydroqual 1995a)



4. *How does the model chosen for the short-term modeling, CE-QUAL-W2, compare to other eutrophication models?*

CE-QUAL-W2 is a model of intermediate complexity, as compared with other eutrophication models used in the U.S. in an environmental management setting. The most complicated models, such as the Chesapeake Bay model (Cercio and Cole 1993) or the Bays Eutrophication Model (Hydroqual 1995a) compute three-dimensional variations in over 20 state variables, and include a predictive sediment diagenesis sub-model (Di Toro and Fitzpatrick 1993). These models are used in conjunction with hydrodynamic models that use sophisticated predictions of vertical mixing intensity. CE-QUAL-W2 is laterally averaged, includes only 13 state variables, and has a simplistic model of sediment diagenesis that ignores certain processes, such as denitrification. In addition, the vertical mixing routines in CE-QUAL-W2 are less sophisticated than these other two models. CE-QUAL-W2 is, however, more complex than models using “WASP” kinetics (Ambrose et al 1993, Shen and Kuo 1996), where eight state variables are used to describe nutrient-organic matter-phytoplankton-dissolved oxygen dynamics. WASP5 is also less sophisticated than CE-QUAL-W2 in how it models sediments and vertical mixing.

5. *Isn't it possible to get any result that you wish when you have so many adjustable parameters?*

Even a eutrophication model of medium complexity like CE-QUAL-W2 has a great number of kinetic parameters. In the version of the model currently being used as part of the “short-term” modeling, 57 separate kinetic parameters must be specified. More complicated models, such as the Chesapeake Bay (Cercio and Cole 1993) model or the Bays Eutrophication model (Hydroqual 1995a) have 100 – 120 kinetic parameters. Clearly, model predictions can be drastically different, depending on parameter specification. For this reason, it is imperative that a rigorous calibration and verification procedure be undertaken for any eutrophication model application. The calibration exercise generally shows that only a very small fraction of the possible parameter combinations produces results that meet calibration criteria. Parameter sets that produce results meeting calibration criteria are generally not unique (e.g. Shen and Kuo 1996), yet the range of possible model predictions for different parameter specifications is greatly reduced when the parameter sets are limited to those that produce a calibrated model (Bowen 1997).

6. *How uncertain is the answer that a eutrophication model produces?*

The uncertainty in the answer will depend on the particular question being asked. In general, mechanistic models are better at predicting the magnitude of a response to an environmental manipulation than they are at predicting the water quality conditions of the manipulated system. For instance, a modeling study was performed to predict how much dissolved concentrations would increase in the Sampit River if the BOD loading from a paper mill was reduced by 30% (Gong et al. 1997). A model uncertainty analysis found that the DO would be predicted to increase by between 0.05 and 0.18 mg/l (Figure 4), depending on exactly how the model parameters were specified (Bowen 1997). The uncertainty in the dissolved oxygen concentration was much larger, ranging from 0.0 mg/l to 2.5 mg/l (Figure 5).

Figure 4. Predicted Increase in Sampit River Dissolved Oxygen Concentrations for a 30% Reduction in BOD Loading

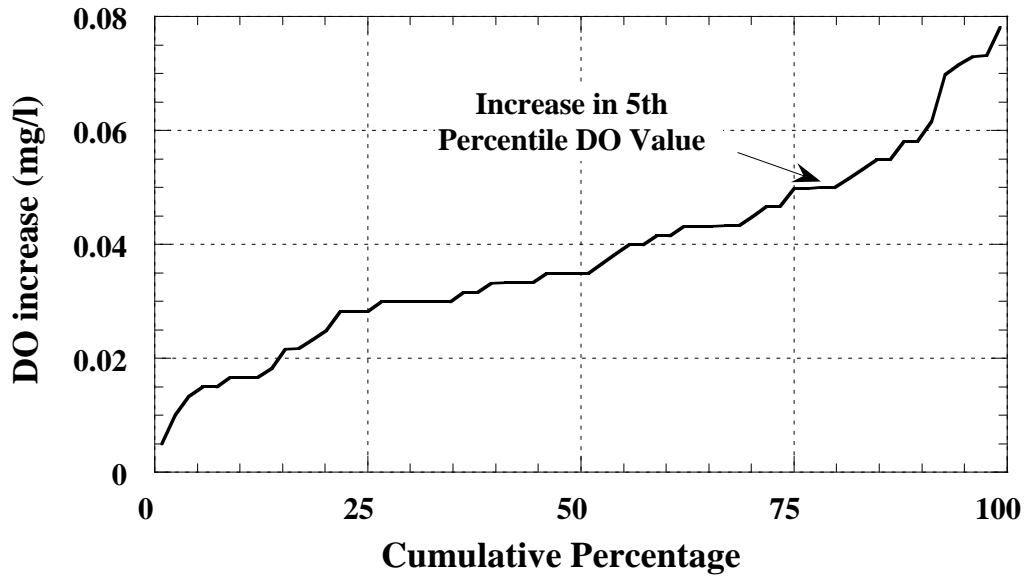
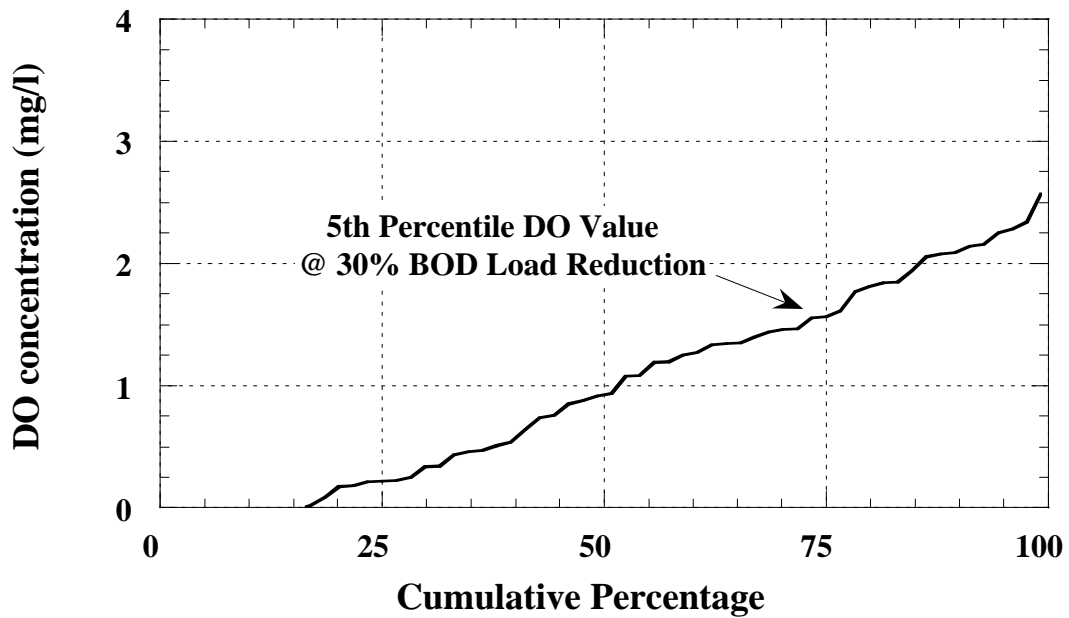


Figure 5. Predicted Sampit River Dissolved Oxygen Concentrations for a 30% Reduction in BOD Loading



It is expected that this finding will also be true for water quality predictions resulting from reduced nutrient loading in the Neuse. A mechanistic model can be expected to produce a prediction, with acceptable certainty, of the change in water quality conditions. Any predictions of the absolute water quality conditions will be less certain.

7. *How can a model that simplifies reality to such a great extent (e.g. no lateral variations, only a small number of phytoplankton groups, no sediment denitrification, fixed carbon/chlorophyll ratios, no bacterioplankton, no grazers, no sediment carbon fixation, etc.) hope to model what really goes on in the Neuse River?*

The appropriate degree of model complexity for the Neuse Estuary Eutrophication Model is still an open question. The choice of CE-QUAL-W2 seems appropriate given current thinking about how the Neuse Estuary operates. Valuable new information relevant to this issue is now being collected as part of the monitoring component of the MODMON project. It is expected that much will be learned about circulation patterns, cross-channel variations in water quality constituents, longitudinal variations in water quality downstream of New Bern, and in sediment/water column transport of nutrients and dissolved oxygen. The knowledge of how the Neuse functions as an environmental system will increase immeasurably in the next year. In the meantime, much will be learned by using CE-QUAL-W2 for water quality predictions. It will be appropriate to revisit the issue of model complexity once more observations are available, and after having gained experience with the current model. It seems likely that additional work will be needed to improve the sediment submodel and to include more phytoplankton functional groups.

8. *Which of these water quality indicators can be predicted with the model:*
 - a) *frequency and severity of fish kills,*
 - b) *location, frequency, and severity of Pfiesteria blooms,*
 - c) *frequency and severity of algal blooms in general*
 - d) *dissolved oxygen concentrations,*
 - e) *health of benthic fauna,*

Eutrophication models are limited in their predictive ability. They cannot predict algal blooms, in their current form, since the phytoplankton state variables represent a species assemblage, rather than a particular species, such as Pfiesteria. In the future, eutrophication models may be able to forecast algal blooms. In addition, eutrophication models in their current form do not include either benthic macroinvertebrates or fish as state variables. "Food-web" models of this sort do exist, but their predictive ability is insufficient for this application. The current model predicts phytoplankton biomass and dissolved oxygen concentrations, and these can be related to other environmental endpoints of concern for now. It is hoped that through model development, predictions of the endpoints of concern will be possible in the future using mechanistic eutrophication models.

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