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Sensitivity analysis of the two dimensional application of the Generic Ecological Model (GEM) to algal bloom prediction in the North Sea

K. Salacinska[a], G.Y. El Serafy[b,*], F.J. Los[b], A. Blauw[b]

[a] Delft University of Technology, Department of Applied Mathematics, The Netherlands
[b] Deltares, P.O Box 177, 2600 MH Delft, The Netherlands

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ABSTRACT

Harmful algae can cause damage to co-existing organisms, tourism and farmers. Accurate predictions of algal future composition and abundance as well as when and where algal blooms may occur could help early warning and mitigating. The Generic Ecological Model is an instrument that can be applied to any water system (fresh, transitional or coastal) to calculate the primary production, chlorophyll-a concentration and phytoplankton species composition. It consists of physical, chemical and ecological model components which are coupled together to build one generic and flexible modelling tool. In this paper the model has been analyzed to assess sensitivity of the simulated chlorophyll-a concentration to a subset of ecologically significant input factors. Only a small number of approaches could be considered as suitable for several reasons including the model complexity, engagement of numerous interacting parameters and relatively long time of a single simulation. Thus, sensitivity analysis has been carried out with the use of the Morris method and later enriched by the computation of the correlation ratios of the selected parameters on the model response at more than a few locations in the modelled area. The obtained results are in agreement with expert knowledge of the ecological processes in the North Sea and correspond well with local characteristics.

1. Introduction

Phytoplankton is an important indicator for water quality, as it affects many factors related to the ecological quality of the water, such as turbidity, oxygen depletion and productivity of the system. Extensive amounts of basic nutrients like nitrogen or phosphorus, which are greatly released into the environment as a result of human activities, may contribute to the process of eutrophication, excessive phytoplankton growth. Further, they may lead to bad odours, cause lack of oxygen, block filters in water transportation systems, harm co-existing organisms, damage recreation, fishing, etc.

Unquestionably, the Netherlands is a densely populated country. Moreover, it receives a major part of its water from the polluted and nutrient loaded river Rhine. Therefore, control and reduction of undesirable ecosystem changes in Dutch water bodies are considered as main items in not only local but also international legislator's precedence. Certainly, it is of major importance to analyze the present situation in the North Sea and gain knowledge of potential effects of some management strategies and of future scenarios that might occur due to the changing environmental conditions. Over the past decades, a large number of models have been developed for the simulation of nutrient cycles, primary producers and ecosystem functioning. They all differ markedly in model complexity expressed in terms of description of the water quality and ecological processes, area included, and level of temporal and spatial resolution. Most phytoplankton models solve a set of differential equations, in which the growth of each species is expressed as the product of several terms based upon the availability of resources. However, this approach is not very well suited to describe competition between a relatively large number of phytoplankton species that must be considered because many of the eutrophication's impacts depend on the dominant group of species (Los, 1991). Then, the competition between numerous phytoplankton species becomes a fairly complicated function of limiting and non-limiting resources, especially when it is combined with a great number of taxonomic groups. Other approaches such as data-driven models including learning machine paradigms was employed recently to mimic dynamics of algal blooms as discussed by Muttil and Chau (2007) and Lee et al. (2003). Other applications uses the ecological models driven by the hydrodynamics as in Trancoso et al. (2005) which improves the description of the macro algae in shallow estuaries and confirms that the hydrodynamic conditions can be significant in the competition between the two primary producers, determining the predominant groups as well

* Corresponding author at: Rotterdamseweg 185, 2629 HD Delft, The Netherlands. Tel.: + 31 0 15 285 8879; fax: +31 0 15 285 8582.
E-mail address: ghada.elserafy@deltares.nl (G.Y. El Serafy).

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as their limiting factors. The application of the three-dimensional hydrodynamic-eutrophication model in the Korean Kwang-Yang Bay presented by Park et al. (2005), the Tolo Harbour presented by Chau (2004) and in Pearl river estuary by Chau and Jiang (2004), simulating the flow field, transport, and eutrophication processes throughout the water column and of diagenetic processes in the benthic sediment also proves the significance of applying integrated models in describing the water quality.

The Generic Ecological Model, so-called GEM, integrates the best aspects of other models. It includes physical, chemical and ecological processes at a sufficient level of detail and in the consistent way (Blauw et al., 2009; Los et al., 2008). The model has been developed for more than 20 years. It produces sufficiently accurate results in a reasonable time and has been used as the basis for several major policy and management decisions.

Sensitivity analysis can be of use in the growing field of numerical simulation, where mathematical and computational models are used for the study of systems. One possible definition of sensitivity analysis that appears most often in the literature is as follows: the study of how the uncertainty in the model output can be apportioned to different sources of uncertainty in the model input. In other words, it allows identification of the input parameters that have the greatest influence on the change in the model response. It reveals how the model responds to variations in its inputs. It is essential to carry out sensitivity analysis as it can improve our understanding of the model and check if the model resembles the system under study. It can help to identify weaknesses and establish priorities for future research, by defining the parameters that are not sufficiently precise for the model to give reliable predictions (Frey and Patil, 2002; Smith et al., 2008; Newham et al., 2003; Gallivan, 2008). The knowledge obtained can help to aim further research at reducing the uncertainty in the most significant parameters and give insight into robustness of the outcome (Saltelli et al., 2000). Sensitivity analysis forms a part of the process of model development, verification and evaluation. As an example, fields where assessing model sensitivity is of crucial importance are reliability engineering, medicine, economics and environmental sciences (e.g. Braddock and Schreider, 2006; Duintjer Tebbens et al., 2008).

Sensitivity analysis is closely linked to uncertainty analysis, which quantifies the overall uncertainty in the model output as a result of uncertainties in the model input. The model's evaluations that had to be run for the sensitivity analysis can be also used to estimate means, standard deviations, confidence bounds and cumulative distribution functions of the response variables.

Several methods for conducting sensitivity analysis are available in the literature (Saltelli et al., 2008; Hamby, 1994; Frey et al., 2005). They vary in the implementation effort and in the nature of the information they provide. Recent literature on sensitivity analysis considered multivariate sensitivity analysis in order to have a statistical framework for analyzing the simulated data and assessing input importance (Fassò et al., 2003) and considering correlated inputs as in Jacquesa et al. (2006) where they propose a new application of the multidimensional generalization of classical sensitivity indices, resulting from sensitivity of the output of the model to a group of inputs, and describe an estimation method based on Monte-Carlo simulations. Moreover, the probabilistic sensitivity analysis (Oakley and O'Hagan, 2004) which is formulating the uncertainty in the model inputs by a joint probability distribution and then analysing the induced uncertainty in outputs. The Bayesian approach is computationally highly efficient. It allows effective sensitivity analysis to be achieved using far smaller numbers of model runs than standard Monte Carlo methods. Furthermore, all measures of interest may be computed from a single set of runs. The choice of proper methods for a given application depends on such considerations as the type of analysis (qualitative or quantitative); number of input factors, model dependence structure and finally it is also limited by the computational cost of running a model. Due to the difficulty of simulating future scenarios of complex ecosystems, ecological models are usually large-scaled, sophisticated and expensive in sense of computational cost. Their development takes a great amount of time in order to embrace all important aspects of ecosystem functioning, i.e. temporal variation and spatial variation. Naturally, the model complexity is also expressed in the involvement of large number of parameters and greater effort needed to calibrate the model. Some examples of facing the challenge of parameter sensitivity study for huge ecosystems appear in the literature (Yoshie et al., 2007; Brugnach, 2005). With respect to algae modelling, the sensitivity analysis of the eutrophication model for Lake Washington (USA) (Arhonditsis and Brett, 2005) and the analysis of an aquatic ecosystem model for the North Sea (Köhler and Wirtz, 2002) are worth mentioning. Interestingly, sensitivity analysis might be also used as a tool to replace complex models with much simpler models that exhibit the same behaviour as original models (Rose, 1978). However, when a time of a single simulation is relatively long and many factors have to be investigated, a selection of global sensitivity analysis methods becomes limited.

As the sensitivity of GEM has not been mathematically investigated yet, the first objective of the paper is to present the methods suitable for the sensitivity analysis of its 2-dimensional application to the North Sea with respect to prediction of algal blooms. Consequently, the second objective is to improve our understanding of the model, by conducting the analysis.

2. Model description

GEM is part of Delft3D (Stelling and van Kester, 1994; Lesser et al., 2004), an integrated modelling system of Deltares (former WL|Delft Hydraulics) which contains separate modules to investigate hydrodynamics, sediment transport and morphology, and water quality for rivers, estuarine and costal waters. In order to apply the model to a specific area one has to define, besides the ecological processes and parameter settings, the input for schematisation and transport, loadings, boundaries, forcings and initial conditions.

Each model application requires a hydrodynamic calculation which is coupled with the ecological part of the model. The transport of model substances is a function of advective and dispersive transport, provided in particular by Delft3D-FLOW, a special module within Delft3D offering a large selection of numerical schemes to solve the advection-dispersion equation.

GEM considers three nutrient cycles, namely nitrogen, phosphorus and silicate and the competition between four species of algae: diatoms, flagellates, dinoflagelates and *Phaeocystis* as shown in Fig. 1. The nutrient cycles have three major pools: dissolved inorganic nutrients, living organic matter and dead organic matter. Within each of the species groups, three phenotypes are defined regarding the adaptation to different environmental conditions: energy type, nitrogen type and phosphorus type (Blauw et al., 2009). They are all modelled as separate variables with specific parameter settings, i.e. growth rates, mortality rates, settling velocities. In total 30 state variables are used in the model, including algae concentrations, salinity, chemical organic compounds like orthophosphate, nitrogen, silicate etc. One or more state variables might change into another state variable due to some physical, biological or chemical reactions. Algae are involved in the primary production, respiration and mortality.

The variation in the water conditions causes a shift in the species composition. Linear programming is used as an optimization technique to determine the species composition that is best adapted to current environmental conditions (Blauw et al.,