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A copula-based sensitivity analysis method and its application to a North Sea sediment transport model

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ABSTRACT

This paper describes a novel sensitivity analysis method, able to handle dependency relationships between model parameters. The starting point is the popular Morris (1991) algorithm, which was initially devised under the assumption of parameter independence. This important limitation is tackled by allowing the user to incorporate dependency information through a copula. The set of model runs obtained using latin hypercube sampling, are then used for deriving appropriate sensitivity measures.

Delft3D-WAQ (Deltares, 2010) is a sediment transport model with strong correlations between input parameters. Despite this, the parameter ranking obtained with the newly proposed method is in accordance with the knowledge obtained from expert judgment. However, under the same conditions, the classic Morris method elicits its results from model runs which break the assumptions of the underlying physical processes. This leads to the conclusion that the proposed extension is superior to the classic Morris algorithm and can accommodate a wide range of use cases.

1. Introduction

Suspended particulate matter (SPM) is composed of fine-grained particles of both inorganic and organic origin, which are suspended in the water column. This material plays an important role in the ecology of coastal areas, as it influences the underwater light conditions (directly connected to the phytoplankton growth), the amount of nutrients in the water, the material transfers to the seabed and other environmental processes. As such, the SPM concentration plays a crucial role in the dynamics of aquatic ecosystems. At the same time, the increasing number of human activities along the shorelines (fishing, sand and gravel extraction, tourism, industry) often disturb the natural equilibrium of the sediment transport processes. To assess and monitor the possible impacts on the sediment transport patterns, models are used to estimate and forecast their movement, under the combined action of both natural factors and human interference.

The current study concerns the southern North Sea area, a marine system significantly affected by SPM, since it receives the run-off from major rivers and coastal industries. This area has seen rising interest in the scientific community (Fettweis et al., 2006; Pietrzak et al., 2011), which has led to the continuous development of the Delft3D-WAQ (Deltares, 2010) sediment transport and water quality model (see El Serafy et al., 2011; Blaas et al., 2007). Delft3D-WAQ makes use of the hydrodynamic conditions (velocities, discharges, water levels, vertical eddy viscosity and vertical eddy diffusivity) and wave characteristics (important in the sediment resuspension and settling) to simulate the complex interplay between the hydrodynamic, chemical and biological processes involved in the sediment transport system.

However, calibrating this model is made difficult by the large number of input parameters, some of which are strongly correlated, due to physical constraints. Also, the high running time for one simulation - approximately 11 h in full resolution and 3 h on a coarse grid - imposes additional restrictions on the calibration efforts. This gave rise to the question of whether the model parameters can be ranked, such that the calibration process can be focused on only the subset to which the output is most sensitive. The remaining parameters can be fixed to their maximum likelihood values (determined, for example, using an expert judgment exercise).

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According to van Griensven et al. (2006), over-parameterization is a widespread problem for environmental models. At the same time, Shin et al. (2013) point out that only few studies in the literature (see, e.g., Schmid et al., 2003; Francos et al., 2003; Shen et al., 2008; Plecha et al., 2010; Kurniawan et al., 2011) employ sensitivity analysis methods (Campolongo et al., 2000; Makler-Pick et al., 2011) to rank parameters and identify redundancies. Among these, the method developed by Morris (1991) is especially popular (Campolongo and Saltelli, 1997; Portilla et al., 2009; Arabi et al., 2008) due to its simplicity and computational efficiency. However, in its initial formulation, the method assumes independence between model parameters. This can be a limiting factor, since, in many cases, the physically-induced dependencies can not be overlooked. For example, in Campolongo and Gabric (1997) the authors had to eliminate certain parameters from their analysis, specifically because of this limitation. Also, in Salacinska et al. (2010), the sensitivity of the simulated chlorophyll-a concentration to a subset of ecologically significant input factors 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 a few selected locations in the domain. The second step was crucial to obtain results in agreement with expert knowledge of the ecological processes in the North Sea.

This paper proposes an extension to Morris' method which opens the possibility to control the sampling pattern of the necessary model runs for sensitivity analysis, based on prior information about dependencies between model parameters. More specifically, this work incorporates this information into the sampling strategy of the elementary effects in the Morris method. The dependencies can be specified in terms of parameter correlations or, more precisely, by providing their joint distribution. This leads to the construction of the corresponding copula (Nelsen, 2007) – a joint distribution on the unit hypercube with uniform marginals – which is, finally, used to determine the set of model simulations required to conduct the sensitive analysis study.

The application on the computationally expensive Delft 3D-WAQ sediment transport model confirms that the method is able to provide physically sound results regarding the parameter ranking, even in cases where the feasible number of simulations is limited. This confirms the relevance of the method in identifying the parameters having the strongest impact on the variability of the model predictions.

The content of the paper is structured as follows. First, the Delft3D-WAQ sediment transport model and the dependence relationships between the governing model parameters are introduced. Next, the classic Morris sensitivity analysis method is reviewed, which presents the opportunity to devise a geometrical reinterpretation of its elementary effect sampling strategy, separating it into three successive stages. This new insight leads to the formulation of mechanisms to constrain each stage of Morris method, by incorporating the prior information about parameter dependencies in the form of a joint distribution with corresponding copula. In Section 4, the basic theory concerning copulas is summarized and Section 5 presents the newly developed copula-based Morris method. Finally, both methods are applied to the Delft3D-WAQ model and the results are compared, leading to the conclusions.

2. The Delft3D-WAQ sediment transport model for the southern North Sea

With an extensive history of maritime commerce, the North Sea is one of the most intensively traversed sea areas. It is bordered by highly industrialized and densely populated countries, which are actively engaged in mineral extraction, diking, land reclamation and other activities. The main sources of sediments are the Dover straits, the Atlantic Ocean, river bed and coastal erosion (Kamel et al., 2014). The SPM concentration varies in both time and space, as a response of the seabed to the hydro-meteorological forces that result from the interaction between river inflows, waves, winds, currents and external factors.

For example, the breaking waves in the near-shore areas, together with various horizontal and vertical current patterns are constantly transporting beach sediments. Sometimes, this transport results in only a local rearrangement of sand. However, under certain conditions, extensive displacements of sediments along the shore take place, possibly moving hundreds of thousands of cubic meters of sand along the coast each year. During calm weather conditions, the SPM settles and mixes with the upper bed layers. Subsequently, strong near-bed currents, generated by tides or high surface waves, can trigger the resuspension of the SPM from the seabed into the water column.

The Delft3D-WAQ (Deltares, 2010) model is capable to describe the erosion, transport and deposition of SPM in the southern North Sea with a good degree of accuracy (El Serafy et al., 2011). In the model, SPM consists of three different fractions (Jiménez and Madsen, 2003): medium (IM_1, diameter 40 μm), coarse (IM_2, diameter 15 μm) and fine sediments (IM_3, diameter 1 μm). These appellations are a Delft3D internal name and will be used to refer to three sediment types throughout the remainder of this paper. The model computes the convection-diffusion, settling and resuspension of the three silt fractions of SPM, given the transport velocities, mixing coefficients and bed shear stress adopted from the hydrodynamic and wave models. The spatial domain is covered by an orthogonal grid of 134×165 cells, with a resolution that varies between $2 \times 2\ km^2$ in the coastal zone and $20 \times 20\ km^2$ further offshore, as illustrated in Fig. 1. Also, in order to capture the vertical structure of the flow, together with the stratification and mixing of SPM caused by the tidal influence in the domain, the water depth is modeled by 12 so-called *sigma layers*, with different thicknesses (increased resolution near the seabed). The water surface is represented by the first layer and represents 4% of the column depth.

Recently, Delft3D-WAQ has been extended with an improved parametrization of the resuspension and buffering of the silt fractions (related to both IM_2 and IM_1) from the seabed (van Kessel et al., 2011). This parametrization enables a more realistic description of the periodic and relatively limited resuspension

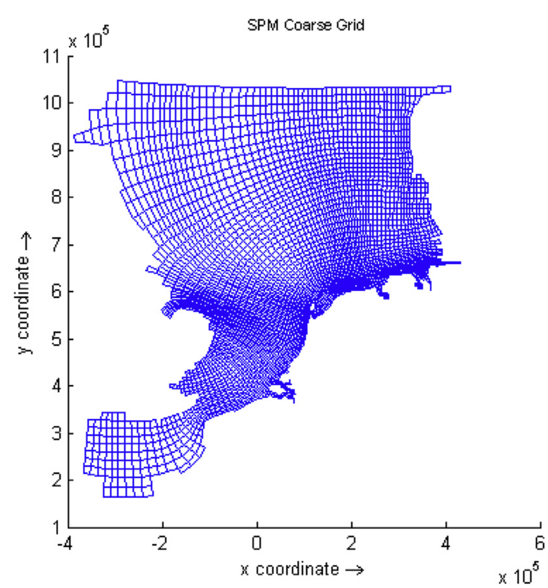

Fig. 1. Delft3D-WAQ spatial discretization grid for the North Sea.