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Sensitivity analysis of distributed environmental simulation models: understanding the model behaviour in hydrological studies at the catchment scale

A. Francos[a,b,*], F.J. Elorza[b], F. Bouraoui[a], G. Bidoglio[a], L. Galbiati[a]

[a]Institute for Environment and Sustainability, Joint Research Centre, via Enrico Fermi 1, Ispra 21020, Italy
[b]Department of applied mathematics, Technical University of Madrid, Spain

Abstract

The development of new hydrological simulation tools allows for the modelling of large hydrological catchments, with the aim of comprehensive management of the water resources, control of diffuse pollution processes, such as the fate of agricultural fertilizants and finally, with purposes of economical optimization of the crop yields as a function of the expected climate, the watershed characteristics and the socio-economical conditions of the region where the catchment is located. This paper describes the sensitivity analysis of a hydrological distributed model applied in one large European watershed by using a two-step procedure. Firstly, it allows for the consideration of a huge input parameter data set by using an implementation of the Morris screening procedure, eschewing the huge computational requirements arising from the necessary repetitive simulations. In the second step it provides quantitative estimations of sensitivity in terms of variance decomposition procedures based upon the FAST method for both the hydrological and the water quality determinants.

Keywords: Sensitivity analysis; Morris screening method; FAST method; ANOVA methods; MayDay; Hydrology; Water quality; Agricultural management; Large scale hydrological modelling

1. Introduction

In recent years, water management became an important issue increasing the need of enhancing existent hydrological models. Major advances on this issue include the development of codes allowing the distributed simulation at the catchment scale on a daily basis, accounting for the hydrological and the water quality processes in both the inland and the channels. Usually the calibration and validation of such models require a huge amount of data, including both in situ and laboratory measurements as well as good quality meteorological records.

The implementation of sensitivity analysis procedures is a useful tool in the calibration of the models and also in their transposition to different watersheds. However, the huge number of parameters becomes a drawback with respect to the capabilities of the sensitivity analysis methods, whose computational requirements increase noticeably with the number of parameters analysed. The present paper shows a two-step procedure allowing for the analysis of complex distributed hydrological models. The first step consists of a screening procedure leading to a qualitative ranking of the whole set of input parameters for different model outputs with relatively low computational cost. During the second step, a Fourier amplitude sensitivity test (FAST) technique is applied to the most relevant parameters for a set of specific model output obtaining quantitative measures of sensitivity in terms of their contribution to the output variance.

A theoretical background of both the hydrological model and the sensitivity analysis methods is briefly introduced in Section 2. Section 3 is devoted to describe the methodology proposed in the paper from an algorithmic point of view, and focusing especially in the preliminary sampling of the input parameters. The description of the investigated watershed is presented in Section 4.1. Several important aspects are also discussed along with: the influence of the desegregation scheme of the basin is commented in Section 4.2; in Section 4.3 some results from the calibration of the model in a monthly basis are introduced. Regarding the input/output sets, the probability density functions (PDFs) adopted for the set of parameters and the list of investigated

* Corresponding author. Address: Environment Institute, Joint Research Centre, via Enrico Fermi 1, Ispra 21020, Italy.

E-mail address: antonio.francos@hispavista.com (A. Francos).

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variables are enumerated in Sections 4.4 and 4.5, respectively. The results of this work are described in detail in Section 5. The qualitative ranking obtained in the first step, its convergence and its analysis are, respectively, described in Sections 5.1–5.3, whereas the FAST quantitative estimates are summarized in Section 5.4. Finally, some conclusions and lines of further research are introduced in Section 6.

2. Theoretical background

2.1. Model description

The computer model used in this research was soil and water assessment tool (SWAT) [1]. SWAT accounts for the hydrology and the nutrient fate processes in both the inland and channel areas of the catchment. The model allows also for the consideration of pesticides and water quality determinants which, however, were not taken into account in this work. An updated description of the model can be found in Neitsch et al. [2].

The simulation procedure for water is carried out on a daily basis using a mass balance scheme (SWRRB model, see Ref. [3]) based on the equation

$$\mathrm{SW}_t = \mathrm{SW} + \sum_{i=1}^{t} (R_i - Q_i - E_i - P_i - \mathrm{QR}_i) \quad (1)$$

where SW_t is the final soil water content, SW is the soil water content available for plant uptake, t is the time (days), R_i is the precipitation (mm), Q_i the surface runoff (mm), E_i the evapotranspiration (mm), P_i the percolation to the aquifer (mm), and QR_i the return flow leaving the aquifer (mm). The contribution of these components is computed in a daily step in the basis of the algorithm depicted in Fig. 1.

SWAT implements the phosphorus and nitrogen cycles including both their organic and mineral forms, see for example Ref. [2, p. 18 and 19], tracking the fate and transformation of the nutrient species through the watershed by surface runoff, groundwater flow and crop uptake.

The inland discharges to inner outlets are then routed through the river network to compute the total outflows and nutrient losses in the final outlet of the basin. Routing is simulated in SWAT using a scheme and a command language (HYMO, see Ref. [4]) including the channel processes such as the infiltration and the chemical reactions, see Fig. 2.

The basin heterogeneity is represented by desegregating the catchment into smaller subbasins (delineated according to the topography) and then subdividing the subbasins into lumped homogeneous (soil type, land use) parts (hydrological response units, or HRU). The model equations are solved separately for each HRU and the discharges aggregated, see Section 4.2 for extended details.

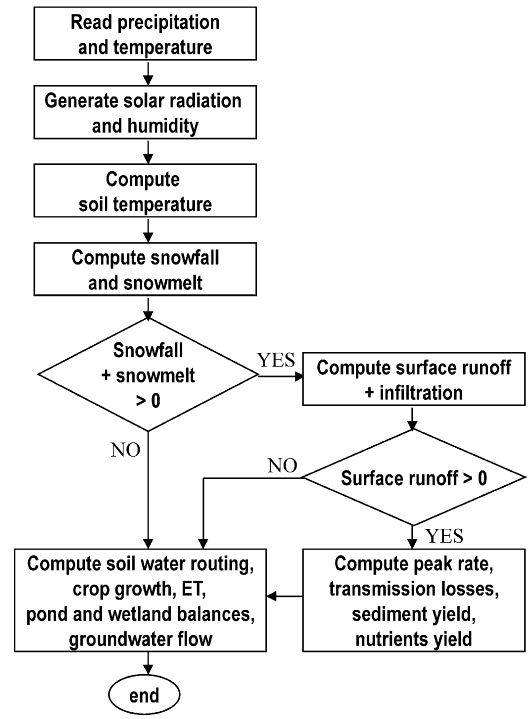

Fig. 1. SWAT daily algorithm of the distributed hydrology module [2].

The main inputs to the model consist of the meteorological records (daily temperature and precipitation), and spatially distributed maps (digital elevation model (DEM), soil and land use maps). SWAT includes crop, fertilizer, soil and weather built-in databases. However, it is recommended to use catchment specific measurements, especially outside the US. The climatic data is assigned to the catchment subbasins according to the meteorological gage geographical positions.

The data handling was mainly carried out by using the SWAT–Arcview interface [5] which allows to desegregate the watershed into subbasins and hydrological units according to, respectively, the DEM and the soil and land use maps, facilitating the initial set-up of the model.

2.2. The Morris screening method

The Morris screening method [6] proposes a random One factor At a Time (OAT) design, in which only one input parameter x_i is modified between two successive runs of the model. The change induced onto the model outcome $\mathbf{y} = \mathbf{y}(x_1, x_2, \ldots, x_n)$ can then be unambiguously attributed to such a modification by means of an elementary effect e_i defined by

$$e_i = \frac{\mathbf{y}^* - \mathbf{y}}{\Delta_i} \quad (2)$$

where $\mathbf{y}^*$ is the new outcome, $\mathbf{y}$ the previous one, Δ_i is the variation in the parameter i. The set of variations Δ_i are arbitrary albeit Morris [6] demonstrated