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A qualitative model structure sensitivity analysis method to support model selection

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Summary: The selection and identification of a suitable hydrological model structure is a more challenging task than fitting parameters of a fixed model structure to reproduce a measured hydrograph. The suitable model structure is highly dependent on various criteria, i.e. the modeling objective, the characteristics and the scale of the system under investigation and the available data. Flexible environments for model building are available, but need to be assisted by proper diagnostic tools for model structure selection. This paper introduces a qualitative method for model component sensitivity analysis. Traditionally, model sensitivity is evaluated for model parameters. In this paper, the concept is translated into an evaluation of model structure sensitivity. Similarly to the one-factor-at-a-time (OAT) methods for parameter sensitivity, this method varies the model structure components one at a time and evaluates the change in sensitivity towards the output variables. As such, the effect of model component variations can be evaluated towards different objective functions or output variables. The methodology is presented for a simple lumped hydrological model environment, introducing different possible model building variations. By comparing the effect of changes in model structure for different model objectives, model selection can be better evaluated. Based on the presented component sensitivity analysis of a case study, some suggestions with regard to model selection are formulated for the system under study: (1) a non-linear storage component is recommended, since it ensures more sensitive (identifiable) parameters for this component and less parameter interaction; (2) interflow is mainly important for the low flow criteria; (3) excess infiltration process is most influencing when focussing on the lower flows; (4) a more simple routing component is advisable; and (5) baseflow parameters have in general low sensitivity values, except for the low flow criteria.

1. Introduction

Determining a priori which conceptual model structure is most appropriate for a given model application remains a challenging problem in hydrology (Clark et al., 2008). Rather than attempting to find one general model structure capable to perform well over widely differing characteristics (Andréassian et al., 2009; Linsley, 1982; Sten, 1990), an alternative approach resides in addition of flexibility in the model structure building process, allowing to adapt the model structure to the specific conditions and research questions. A fixed model structure will probably provide sufficient predictive performance for certain catchments, but might still not be adequate for many other applications (Kavetski and Fenicia, 2011). Still, the focus must not be to generate an extensive number of model structures, but rather to discriminate between a small number of rival model structures.

Flexible model structures with interchangeable components allow an easy construction of different model structures. The hydrological model structures that were implemented in flexible model environments like in Wagener et al. (2001) are mostly spatially lumped representations and can be summarized by the combination of a soil moisture accounting module and a routing module, where different options can be selected for both parts. Bai et al. (2009) used a modular modeling structure of three modules: Soil moisture accounting, actual evapotranspiration and routing. The Framework for Understanding Structural Errors (FUSE) (Clark et al., 2008) combined modeling options from

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well-known hydrological models to construct new equally plausible model structures, where the model components can be evaluated in isolation. Willems (2011) constructed a flexible model structure based on information coming from a subflow filtering and the hydrological extremes in the measured flow. Fenicia et al. (2011) presented a generic model lay-out existing of elements representing storage–release, lag functions, junction elements and a set of constitutive functions. The latter is a library of functions representing the hypothesized relations (e.g. conceptualisations of saturation-excess runoff). To really benefit from such a flexible approach, formal strategies to diagnose and compare rival model structures in terms of performance, uncertainty, identifiability and complexity are necessary. Bai et al. (2009) used an ensemble of four criteria, representing different time scales, in a fuzzy evaluation to select model structures and assess the necessary level of complexity. Clark et al. (2008) used the Shuffled Complex Evolution optimization algorithm (SCE) to test if all model structures perform equally well, provided an optimal parameter set is given, and tracked a relationship between model performance and model structure. Lee et al. (2005) used the distance between the optimal values of two objective functions as an evaluation of how a model structure can simultaneously meet two different modeling objectives. The Monte-Carlo Analysis Toolbox (MCAT) (Wagener et al., 2001) includes a number of analysis methods to evaluated the results of Monte Carlo parameter sampling experiments or model optimization methods. Vache and McDonnell (2006) used a rejectionist framework to evaluate model structures using residence time data. In general, all proposed methods are commonly based on the exploration of the parameter spaces connected to the different model structures, focusing on model performance. Multiple measures, giving objective guidance as to whether a selected structure is suitable or not, need to be defined (Gupta et al., 1998) in order to reject inadequate model structures. On the other hand, optimal parameter sets of model structures already contain valuable information about the possible relationship between model structural design and performance criteria. However, more information concerning the regions of the combined parameter space that result in model outputs having equally good performance, is needed. Research questions about the relation between model structural criteria and model structure selection remain to be solved (Clark et al., 2008). Instead of comparing the different model structures with respect to their individual performance, we use a sensitivity analysis to guide the model selection. In analogy with parameter sensitivity analysis, evaluating the effect of certain model structure components could reveal the added value of the component towards specific model objectives and as such, assist in model selection.

In this paper we present a new method using sensitivity analysis on model structures. We assume that the effect of a model component can be evaluated based on the change in parameter sensitivities. We define a model component as a conceptual description of a subprocess of the entire model. This can be either the mathematical description of a specific flux (e.g. percolation, evapotranspiration, etc.) or an entity in the model represented by a mass balance (e.g. upper soil layer). In short, when changing a specific component results in increasing parameter sensitivities towards the model objective, the adaptation leading to this increased sensitivity is considered to give the model configuration added value (i.e. predictive performance). The paper introduces this component-sensitivity concept in a qualitative (graph-based) manner. The application is illustrated for a custom implemented lumped hydrological model, which will be presented first. Subsequently, the component-based sensitivity analysis is explained and finally the results are discussed and conclusions are drawn.

2. Materials and methods

2.1. Hydrological model structure

2.1.1. Lumped hydrological model structure

The model structure is an adaptation of the conceptual hydrological model VHM. VHM is a Dutch abbreviation for *generalized lumped conceptual and parsimonious model structure identification and calibration* and is based on a step-wise model structure identification procedure, starting from a preprocessing of the measured river flow data (Willems, 2011). The basic model structure is shown in Fig. 1 and is comparable with other parsimonious hydrological models with a soil storage section and a routing section (Kokkonen and Jakeman, 2001). The flexible nature of the model structure identification described in Willems (2011) forms the basis for the flexible model structure framework used here. The implementation of the flexible approach of the VHM model was done in the scripting language Python, to increase the flexibility and extendibility of the model and to improve the connection with the applied sensitivity analysis.

The main principle behind the VHM is the separation of the rainfall into different fractions contributing to the different subflows by a time-variable distributing valve. A more detailed description of the VHM model can be found in Willems (2011).

The basis of the simulation is the soil storage defining the dynamics of the soil water storage compartment combined with a number of linear reservoirs defining the routing part of the model. The balance of the soil storage is given by

$$\frac{du}{dt} = p - q(u) - e(u) \tag{1}$$

with u (mm) the soil moisture storage, p (mm/s) the rate of rainfall (intensity), q (mm/s) the runoff rate generation and e (mm/s) the actual evapotranspiration rate. The outgoing fluxes e and q are both function of the soil moisture storage. The transformation from potential evapotranspiration to actual evapotranspiration is assumed to be linearly related to the soil moisture storage for all models in this study. The runoff rate generation q is split into different subflows. Flows are calculated based on the attributed fractions from the rainfall with $q(u) = f_x(u) * p$, with x representing the identifier of the specific component and f_x the fraction of component x. Mass balances are closed at all times by verifying that the sum of the fractions equals 1 at all times.

2.1.2. Model component adaptations

Different types of model structural changes can be identified for flexible model structures. For this case, some basic model structure adjustments are used to explain the methodology and for each of them, an example is implemented to test and illustrate the methodology.

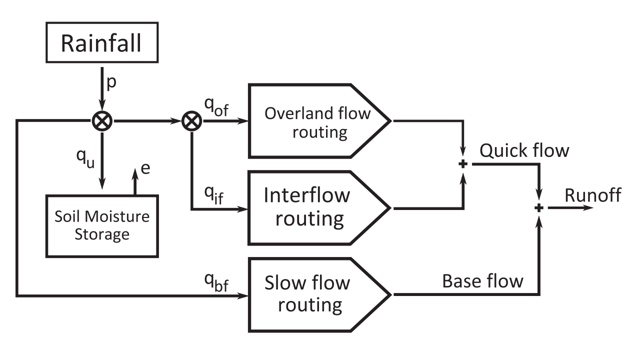

Fig. 1. VHM model structure.