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Representative parameter estimation for hydrological models using a lexicographic calibration strategy

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ABSTRACT

We introduce the developed lexicographic calibration strategy to circumvent the imbalance between sophisticated hydrological models in combination with complex optimisation algorithms. The criteria for the evaluation of the approach were (i) robustness and transferability of the resulting parameters, (ii) goodness-of-fit criteria in calibration and validation and (iii) time-efficiency. An order of preference was determined prior to the calibration and the parameters were separated into groups for a stepwise calibration to reduce the search space. A comparison with the global optimisation method SCE-UA showed that only 6% of the calculation time was needed; the conditions total volume, seasonality and shape of the hydrograph were successfully achieved for the calibration and for the cross-validation periods. Furthermore, the parameter sets obtained by the lexicographic calibration strategy for different time periods were much more similar to each other than the parameters obtained by SCE-UA. Besides the similarities of the parameter sets, the goodness-of-fit criteria for the cross-validation were better for the lexicographic approach and the water balance components were also more similar. Thus, we concluded that the resulting parameters were more representative for the corresponding catchments and therefore more suitable for transferability. Time-efficient approximate methods were used to account for parameter uncertainty, confidence intervals and the stability of the solution in the optimum.

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1. Introduction

Many hydrological modelling applications deal with long-term simulations up to 100 years. This includes climate impact research or extreme value statistics. In this context, reliable statements can only be obtained if the model and its calibration are representative for the whole time period. The transferability of calibration parameters to independent validation periods is considered to be an important issue in modern hydrologic modelling tasks, because it is going hand in hand with robust optimisation techniques. Common practice to calibrate a hydrological model is to estimate model parameters iteratively. Due to the increased performance of modern computers, semi- or fully automatic optimisation algorithms have been established for calibration, especially with regard to scientific questions (Efstratiadis and Koutsoyiannis, 2010). Simultaneously, enhanced physically based process descriptions as well as improved available input data were more and more integrated into the spatially highly resolved models. Consequently, these developments induce increased calculation times and effort in calibration, which can hardly be solved with conventional "trial and error" methods (Hogue et al., 2000). Alternatively, automated optimisations methods can be used, albeit the disadvantages of long computation times and insufficient user participation. For this reasons, optimisation methods are mostly used in combination with conceptual models, often on a daily time step or purely for research purposes (Zhang et al., 2009). Applications of both highly developed hydrological models and complex optimisation methods are challenging for operational hydrology due to the enormous computing time (Zhang et al., 2009; Vaze et al., 2011). To overcome this imbalance, Zhang et al. (2016) proposed the use of a parallel optimisation approach by using a high-performance computer (HPC). Since HPCs are often not available, we introduce a lexicographic calibration strategy in this study, whereby the objectives are based on an order of preferences. It delivered representative parameter sets under the constraint of limited calculation effort, while keeping objectivity in contrast to a manual calibration. The hydrological community agrees that expert knowledge should be included in the calibration process (see. e.g. Moussa and Chahinian, 2009). Primarily, expert knowledge is necessary for the following processes: parameterisation of the catchment's properties, the correct choice of the objective function(s), selection of an appropriate optimisation algorithm, plausibility check of the obtained parameter sets

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and selection of the best parameter set. Boyle et al. (2000) coupled expert knowledge with automated optimisation methods by separating the hydrograph into different cases. The criteria of differentiation were periods with and without precipitation. For these two cases different objective functions have been defined. As a result, pareto optimal parameter sets were obtained by using the time-consuming MOCOM-algorithm[1] by Yapo et al. (1998). Hogue et al. (2000) considered the expert knowledge by performing a stepwise calibration. An order of preferences of the objectives has not been set and a global optimisation method (SCE-UA[2]) was used. Similarly, Fenicia et al. (2007) introduced a method for stepwise calibration by using a global optimisation algorithm. Model parameters were linked to processes and objective functions were defined for every one of those processes. Cullmann et al. (2008) grouped observed hydrographs based on hydrological characteristics in several classes. Parameter sets were then detected for each class set, representing the dominant process. The aim was to improve the model results for the flood forecast. For the operational application, a simultaneous use of all sets was not feasible due to the time factor. Hence, all parameter sets were used to train a neural network. This black box model was then applied for the event-based flood forecast. Other hydrological applications with respect to optimisation techniques are stated in the field of flow forecast with artificial neural network techniques, see e.g. Wu et al. (2009), Wang et al. (2015), Taormina and Chau (2015) or Chen et al. (2015). The aim was to improve the neural network performance in the estimate of daily flows. For parameter estimations in highly resolved process based distributed models these methods are not feasible.

Based on all these different approaches, we identified the deficits of representative and efficient parameter calibration: Either the calibration is dominated by mathematical solutions, which may struggle in validation. Alternatively, the calibration is performed manually by an expert (trial and error), which is maybe more representative but often not reproducible (even by the same person) and inefficient. Thus, the first objective of this study was to find representative and robust parameter sets. We incorporated expert knowledge at the beginning of the calibration process by determining an appropriate order of hydrologic objectives. The developed lexicographic calibration strategy (LCS) can be considered as an approach, where the order of preference depends on the scientific framework and hydrological model. Gelleszun et al. (2015) introduced a lexicographic calibration strategy, which delivered a single representative and optimal parameter set by defining an order of preference of the objective functions. The method was validated by using synthetic hydrographs and a distributed hydrological model. To achieve the representativeness of the estimated parameters, the second objective of this study was, to achieve good performances in calibration and particularly in validation. We did not intend to find the mathematical global minimum of one objective or multi-objective function during the calibration period solely, but we expected to identify parameter sets, which were valid for the hydrological system and thus for the validation periods respectively.

In general, we distinguish between optimisation algorithms and calibration strategies. The optimisation itself is considered as a mathematically definite process with the aim to find parameters in order to minimize the objective function. These approaches can be divided into local and global methods. Global optimisation methods include evolution strategies or genetic algorithms. Widespread methods for multi-objective optimisation in applied hydrology are MOCOM (Multi-Objective Complex Evolution) by Yapo et al. (1998), MOSCEM (Multi-Objective Shuffled Complex Evolution Metropolis algorithm) by Vrugt et al. (2003) or SCE-UA (Shuffled Complex Evolution algorithm) by Duan et al. (1992). A broad description of this subject is given in Efstratiadis and Koutsoyiannis (2010). The challenge of linking complex optimisation algorithms with computationally intensive hydrological models was analysed by Zhang et al. (2009). The parameter estimation of a hydrological model was implemented with different global and evolution-based optimisation methods. None of the tested methods required less than 500 iterations. The methods for multi-objective optimisation are computationally intensive, as complex structures within the objective function lead to many local minima (Abbaspour, 2005). Hence, there is generally a conflict between high-resolution models in conjunction with complex optimisation algorithms (Zhang et al., 2009). This leads to the third objective of this study, namely to achieve practicable calculation effort by minimizing the optimisation runs since the calculation time of a physically based distributed hydrological model is often high.

Summarised, in the study at hand, the main focus lays on the reproducibility of the parameter estimations in order to obtain representative parameter sets for gauged catchments. For two areas, the observed runoff time series of ten years length (01.11.2001 to 31.10.2011) were divided into five separate series of two years each. We applied the lexicographic calibration strategy to obtain for each time series an individual parameter set. We expected the resulting parameter sets to be similar to each other, as the individual time series originate from the identic runoff regime. To compare the overall quality of each parameter set, we cross-validated each set for (i) every other two-year period and (ii) the overall ten-year period. In addition to goodness-of-fit-criteria, such as model efficiency (Nash and Sutcliffe, 1970), we analysed the similarities of the obtained parameter sets and the resulted influences on the simulated water balance components. Further, we compared the obtained results with the lexicographic calibration strategy with results received by applying the global multi-criteria optimisation method SCE-UA by Duan et al. (1992). We additionally showed that an uncertainty analysis of complex hydrological models can be performed by applying the approximate first-order second-moment (FOSM) method.

2. Materials and methods

2.1. The hydrological model system PANTA RHEI

PANTA RHEI is a deterministic, semi-distributed, physically based hydrological model for long term or single event simulations. It has been developed by the Department of Hydrology, Water Management and Water protection, Leichtweiss Institute for Hydraulic Engineering and Water Resources, University of Braunschweig in co-operation with the “Institut für Wassermanagement IfW GmbH”, Braunschweig (LWI-HYWAG und IfW, 2012). It has been successfully employed for scientific questions (Hölscher et al., 2012) and in numerous national and international projects (Meon and Pätsch, 2014; Wurpts et al., 2014). Furthermore, PANTA RHEI is applied in the operational flood forecast of the federal state Lower Saxony, Germany (Meyer et al., 2012). The temporal discretisation is adaptive and in many applications an hourly time step is used. The spatial differentiation is divided into three levels: HRUs (hydrologic response units), subcatchments and gauged catchments.

A modified Penman-Monteith method (Penman, 1948; Monteith, 1965) is used to estimate the evapotranspiration. It is one of the most established physically based methods to calculate evapotranspiration (Sentelhas et al., 2010; Chen et al., 2005). Our modification includes the dynamic calculation of vegetational

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[1] Multi-objective complex evolution global optimization method.

[2] Shuffled Complex Evolution – University of Arizona.

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