International Conference on Hydroinformatics

2014

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11th International Conference on Hydroinformatics
HIC 2014, New York City, USA

ASSESSMENT OF BLACKBOX OPTIMIZATION METHODS FOR EFFICIENT CALIBRATION OF COMPUTATIONALLY INTENSIVE HYDROLOGICAL MODELS

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INTRODUCTION

Many studies have shown the effectiveness of blackbox optimization algorithms for the automatic calibration of lumped conceptual hydrological models. [2, 7] However, literature shows a trend toward the use of distributed and more physically-based hydrological models in the last decades. These models offer some advantages such as the ability to generate hydrological predictions on a finer scale than the lumped models or the opportunity to study some undetectable hydrological processes on a global scale (e.g., spatial distribution of snow cover) [14, 16]. However, their calibration is not trivial and brings computational efficiency issues. Running a single simulation may take several minutes and the optimization (or calibration) process may require more than thousands of simulations [12, 13, 15]. An efficient blackbox optimization algorithm should therefore be chosen. One such algorithm should ideally be able to find the highest-quality parameter set within the smallest number of model simulations (henceforth model evaluations).

OBJECTIVES

The main objective of this study is to assess the efficiency of three different optimization algorithms for the calibration of computationally intensive hydrological models. The results are then used to formulate recommendations on the use of these algorithms.

In a secondary objective, the study also looks at the impact of the type of hydrological model (distributed physically-based vs. lumped conceptual) on the behavior of the three optimization algorithms. Information is then obtained about the differences (and/or similarities) between the two underlying optimization problems.

METHODOLOGY

Optimization algorithms

The three optimization algorithms used in this study are:

(1) The "Shuffled Complex Evolution" method developed at the University of Arizona (SCE-UA) [6, 7]. Since its first appearance in the literature, this algorithm has been widely used for the calibration of hydrological models, and hence provides a "state-of-the-art" level of performance for comparison with other algorithms. Default SCE-UA algorithm parameters recommended by Duan *et al*. [7] were used.

(2) "Dynamically Dimensioned Search" (DDS) [17]. Previous studies [2, 15, 17] have shown that the search strategies used by DDS perform efficiently for the calibration of computationally intensive hydrology models, quickly targeting high-quality parameter sets. The single algorithm parameter was set to the default value as recommended by Tolson & Shoemaker [17].

(3) "Mesh Adaptive Direct Search" (MADS) [3]. Unlike the previous two algorithms, which are heuristics methods, this third algorithm ends with a solution that satisfies first-order optimality conditions, and if locally convex and smooth, second-order optimality conditions (in other words, the final parameter set will be a local optimum) [1]. The MADS algorithm was implemented through the NOMAD software ("Nonlinear Optimization by Mesh Adaptive Direct Search") which includes multiple functionalities for blackbox optimization [11]. The "Latin Hypercube Search" functionality was employed to improve MADS global search capabilities, and the algorithm parameters were set to the default values recommended by Audet & Dennis [3].

A fourth algorithm was added to this list, namely: a completely random search algorithm (CRSA). It is used as a benchmark for comparison as it does not include any sophisticated search strategy.

Hydrological Models

The distributed and physically-based HYDROTEL model [8, 9] was used in this study as the computationally intensive model. Calibrating the model over a five-year time period on a medium-sized watershed (5 000 km²) with a budget of 1000 model evaluations takes more than one hundred hours on an Intel Core i7 3.40-GHz processor. Two versions of the model were considered, one with 10 calibration parameters and one with 19 calibration parameters.

In order to assess the impact of the type of hydrological model on the behavior of the three optimization algorithms, the lumped conceptual HSAMI model [5, 10], which has 23 calibration parameters, was also used.

Studied watersheds and calibration datasets

Both hydrology models have been applied to two different watersheds located in the province of Quebec (Canada). The first one is the Cowansville watershed (215 km²), an upstream sub-basin of the Yamaska River basin which is occupied by forest and agriculture. The second one is the Ceizur watershed (6 928 km²), an upstream sub-basin of the Gatineau River basin which is mainly forested. The meteorological data used for calibration include daily minimum temperature, daily maximum temperature, and daily precipitation obtained from gridded datasets at a 10-km resolution (CEHQ data for the Cowansville watershed – see the

Acknowledgements section, and NLWIS data for the Ceizur watershed [www.agr.gc.ca/nlwis-snite]). The calibration periods span from October 1, 2000 to September 30, 2005, and from October 1, 1988 to September 30, 1992, for the Cowansville and Ceizur watersheds, respectively. Daily observed streamflows at the outlets of the watersheds were also available.

RESULTS

Each one of the six model-watershed combinations was calibrated with each one of the optimization algorithms: SCE-UA, DDS and MADS, and with the CRSA (hence creating 24 different case studies). The objective function was computed as 1 minus the Nash-Sutcliffe Efficiency criterion (1-NSE; minimization problem), and was computed between simulated and observed streamflows. For every one of the case studies, 32 calibration trials were performed for better statistical representativeness of the results since it is well-known that hydrology model calibration is characterized by equifinality [4]. In each calibration trial, the algorithms were allowed a budget of 2000 model evaluations (based on previous studies [17] and on the authors' experience with the HYDROTEL model). Fig. 1 gives an overview of the results obtained for the Cowansville watershed, where the mean value of the best objective function value is shown, as a function of the number of model evaluations (solid lines). Very similar results were obtained for the Ceizur watershed.

Looking at Fig. 1, it can be first noted that the random search algorithm (CRSA) contributes to the improvement of the objective function value at the beginning of the calibration process, but it is rapidly outperformed by the three optimization algorithms (in all three model-watershed combinations shown). Clearly (and as expected), the level of complexity of the calibration problem asks for "smarter" optimization methods (like SCEUA, DDS or MADS).

HYDROTEL Calibration

Fig. 1 also shows that for the HYDROTEL model calibration (10 and 19 parameter versions), DDS stands out over the course of the calibration process. The DDS average curve dives much more quickly than the SCE-UA and MADS curves. Clearly DDS is able to identify good-quality parameters sets much faster than the other two methods, and remains the one that yields the best results on average. However, if we focus on the end of the calibration process (2000 model evaluations), DDS still gives the best results but the difference in the final objective function value between the three algorithms is within a 0.02 interval for both versions of the HYDROTEL model. Although DDS definitely shows better efficiency, SCE-UA and MADS still provide high-quality final results.

HSAMI Calibration

For the calibration of the HSAMI model, very different behaviors from the three optimization algorithms are observed. In the first place, SCE-UA is the one that reaches the best final solution which is 0.08 away from the DDS final solution. In the second place, a 2000 model evaluation budget appears to be insufficient since the average curves of MADS and SCE-UA seem not to have completed their descent toward the "final solution". In the case of DDS, the average curve seems to have "stabilized" but this characteristic of DDS since it adapts its search strategy to the model evaluation budget available. This gives information about the influence of the type of hydrological model and the underlying structure of the optimization problems on the behavior of the optimization algorithms.

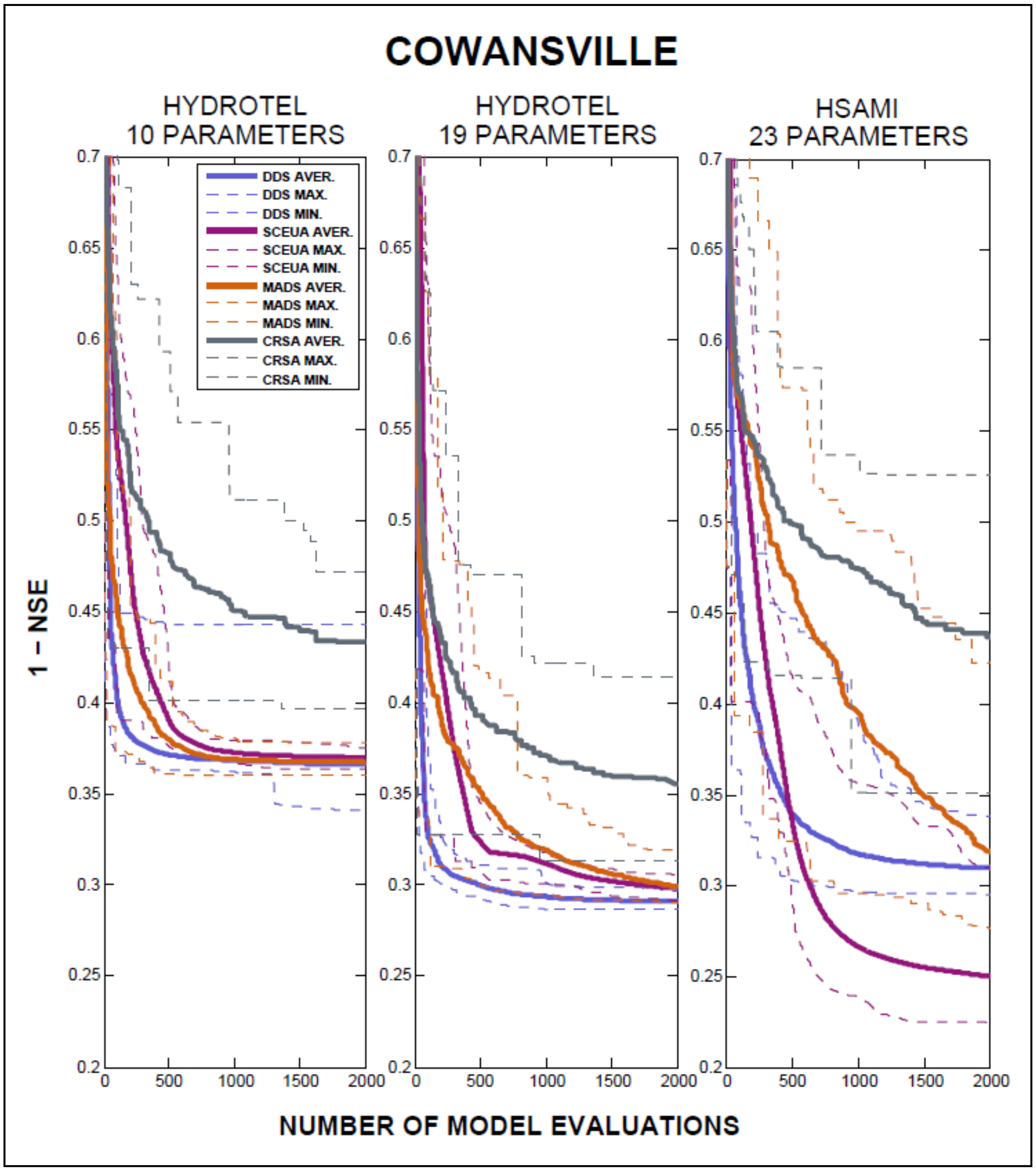

Figure 1. Evolution of the best objective function value (1-NSE) as a function of the number of model evaluations for the optimization algorithms: SCE-UA, DDS, and MADS, and for the CRSA on the Cowansville watershed for the HYDROTEL model (10 and 19 parameters) and HSAMI model (23 parameters). Solid lines show the mean value of the objective function and dashed lines show the minimum and maximum trajectories of the objective function value.

DISCUSSION AND CONCLUSIONS

The present study aimed at assessing the behavior and efficiency of three different optimization algorithms (SCE-UA, DDS and MADS) when employed for the calibration of computationally intensive hydrological models. The results show that the DDS algorithm offers significant potential for reducing the number of model evaluations. It can identify higher-quality solutions within a smaller number of model evaluations than SCE-UA and MADS. Results also show that the choice of the algorithm is dependent on the available simulation budget. When the budget exceeds 1500 model evaluations, the three algorithms are able to provide equally good solutions, given the very small difference among the average solutions obtained. That said, validating the solutions on different time series could help identify the most robust parameter sets.

Considering the different behaviors of the three optimization algorithms for the calibrations of the HYDROTEL and HSAMI models, results suggest that both types of models may lead to different characteristics of the optimization problem in terms of response surface landscape (or, in a more illustrative way, the "search space topology"). Moreover, calibration of the HSAMI lumped conceptual model seems to involve a more complex optimization problem than the calibration of the HYDROTEL model. This could explain why, in the case of the HSAMI model, the SCE-UA and MADS algorithms seem to be still descending after 2000 model evaluations and would need more evaluations to reach even better quality solutions. This particular issue will be more deeply investigated in future works. Model-related characteristics of the optimization problem will be studied using metrics that can better characterize the response surfaces when different types of hydrology models are used.

ACKNOWLEDGEMENTS

Funding for this project has been provided by a scholarship from the National Sciences and Engineering Research Council (NSERC) of Canada. The meteorological gridded dataset for the Cowansville watershed have been provided by the *Centre d'expertise hydrique du Québec* (CEHQ)[1].

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