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Research papers

Surrogate modeling-based calibration of hydrodynamic river model parameters

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ABSTRACT

As opposed to other disciplines, automated calibration procedures are not common practice for full hydrodynamic river models, mainly because of the long computation times impeding the accurate assessment of parameter values. Default or text-book values are therefore often used. This paper introduces a methodology to optimize hydrodynamic model parameter values, based on the use of a surrogate conceptual model. Thanks to the spatial lumping and the explicit calculation schemes of these conceptual models, very short calculation times and a large number of simulation runs can be achieved. The surrogate model is coupled with the Shuffled Complex Evolution Metropolis algorithm of the University of Arizona (SCEM-UA) to identify the optimal parameter sets and their uncertainty. Afterwards, the optimized parameter values are transferred to the full hydrodynamic model. The methodology is demonstrated on a case study of the river Molenbeek in Belgium, using streamflow, water level and gate level observations. Results show a decrease of the hydrodynamic model residuals by about 60 percent.

1. Introduction

Detailed one-dimensional hydrodynamic river models are often equipped with a number of parameters whose values cannot be obtained directly from in-field measurements. Examples of such parameters are the ones that describe river bed roughness and those involved in the discharge calculation schemes of hydraulic structures. Calibration of these parameters is usually a manual and time-consuming task and depends on the experience of the modeler (Vrugt et al., 2003). Given that the use of mathematical model results in water management and decision making becomes more and more common practice (Xu and Tung, 2008; Willems, 2012; Brandimarte and Di Baldassarre, 2012), it is of great importance to accurately estimate the aforementioned model parameters. This will lead to a more precise model-based approximation of real-world observations, and hence to a better decision making.

River bed roughness parameters, together with cross-sectional geometry, are considered to have the largest impact on predicting water levels in rivers and floodplains (Aronica et al., 1998; O'Hare et al., 2010; Warmink and Schielen, 2014). The available cross-sectional information is in most cases an approximation of the real geometry and will hence influence the effective roughness parameters. Incomplete cross-section information is often compensated by adjusting the effective bed roughness parameters (Pappenberger et al., 2005a). These parameters therefore play a key-role in the calibration of river hydrodynamic model packages.

Finding an optimum value for bed roughness parameters has been a subject of many studies in the last two decades. De Doncker et al. (2009) and Guerrero and Lamberti (2013), for example, tried to derive Manning roughness coefficients for hydrodynamic models, based on field measurements. Another popular method is the use of sensitivity analyses, whereby a large number of model runs is performed and parameter values are sampled from a given range (e.g. Werner et al., 2005; Parhi et al., 2012; Brandimarte and Di Baldassarre, 2012). The optimal parameter set is then the one that shows the best goodness of fit. More elaborated methods (e.g. Aronica et al., 1998; Pappenberger et al., 2005a; Werner et al., 2005) combine calibration with uncertainty estimation. The generalized likelihood uncertainty estimation approach (GLUE) of Beven and Binley (1992) became a popular approach in this context. The aforementioned methods suffer from the long computational times of hydrodynamic models and are, hence, very time demanding.

The implementation of hydraulic structures in one-dimensional hydrodynamic models usually requires two types of parameters. The

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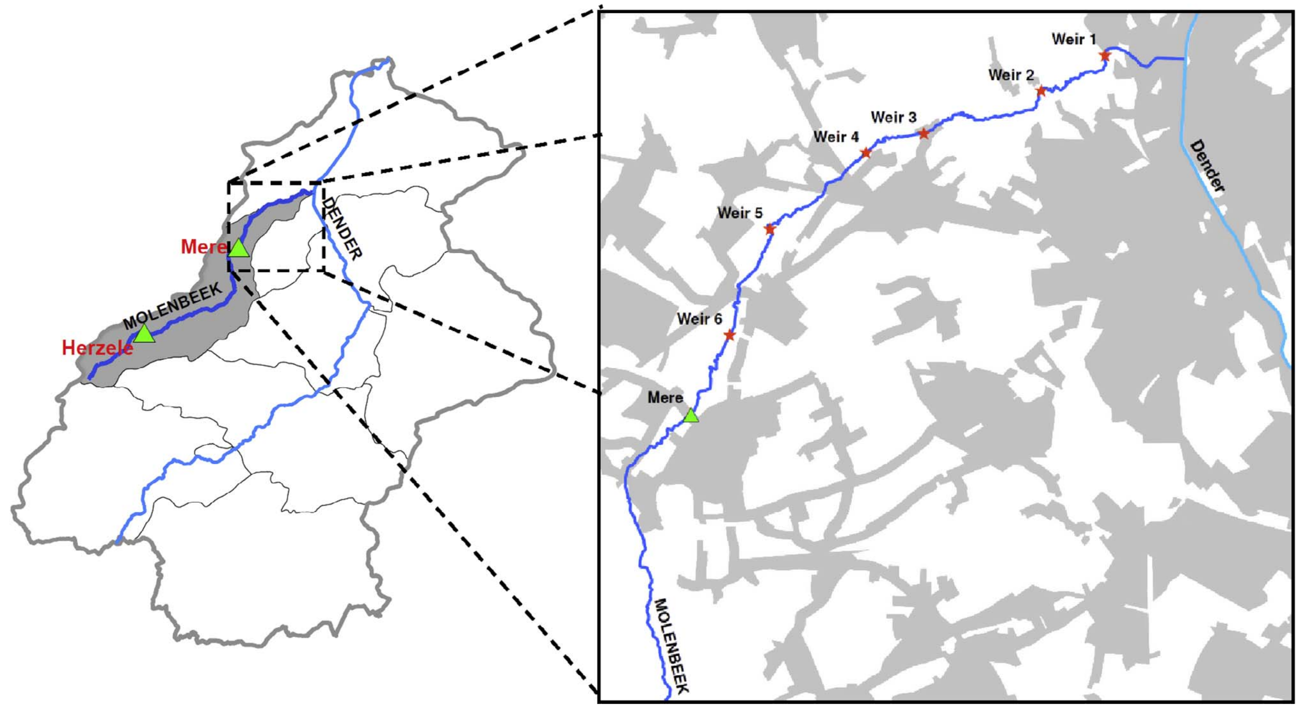

Fig. 1. Overview of the river Molenbeek catchment within the river Dender basin (left). Zoomed view on the measurement locations (right). Green triangles depict limnigraphic stations, red stars adjustable control structures and grey zones the urbanized regions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

geometric properties of the structure such as width, crest level and gate height are relatively easy to obtain. Other parameters used in the discharge calculation scheme, such as discharge coefficients or head loss factors, are much more difficult to quantify. In the literature, numerous studies can be found (e.g. Borghei et al., 1999; Johnson, 2000; Zahiri et al., 2014) that assess discharge coefficients from laboratory experiments. Such experiments are, however, often not feasible due to time and budget restrictions. Furthermore, each software package has its own calculation scheme and accompanying parameter set, which makes it difficult to relate different parameter sets. Text book values or default parameter sets, supplied by the software developer, are therefore often used (Syme, 2001).

Given the strong spatial interactions between the operation of the structures and the model state variables along the river, manual parameter adjustments do not allow to reach an optimal calibration within a reasonable time. Automated parameter calibration and uncertainty estimation with the detailed model face the same difficulties. The huge computational times of hydrodynamic software packages and the large number of model runs will lead to unworkable calculation times. This is further inhibited by the rigidity of the user interface: changes to model parameters and inputs have to be made manually and cannot be fully automated.

This paper presents a novel, alternative methodology to calibrate hydrodynamic model parameters, which is particularly useful in situations where only limited time and resources are accessible. Model simulation times are strongly reduced by using an accurate conceptual surrogate model that aggregates the physical processes and mimics the most important results of the detailed model. Such surrogate models are useful for applications that require a large number of model runs, such as real-time control (e.g. Chiang and Willems, 2015; Vermuyten et al., 2018), sensitivity and uncertainty analyses (e.g. Apel et al., 2004; Willems, 2008; Zhan et al., 2013), or optimization applications (e.g. Wu et al., 2015; Yazdi and Neyshabouri, 2014). Integrated catchment modelling (e.g. Willems and Berlamont, 2002; Wolfs et al., 2016; Keupers and Willems, 2017) and long-term simulations are other applications of this approach. The conceptual model considered in this paper comprises a sequence of storage reservoirs with model structures that are carefully calibrated to the detailed model. After such model-structure identification and calibration, they produce accurate approximations of the detailed hydrodynamic model. The conceptual model can be regarded as a grey-box or physically inspired model, because its structure is based on a simplified physical representation of reality (Knight and Shamseldin, 2006).

The conceptual surrogate model in this study is coupled with the Shuffled Complex Evolution Metropolis Algorithm (SCEM-UA) of Vrugt et al. (2003). SCEM-UA is a global optimization algorithm that can be used to derive efficient estimations of the most likely parameter set and the associated prediction uncertainty in hydrological models. SCEM-UA has proven its usefulness for hydrological applications in many studies (e.g. Feyen et al., 2007; Cutore et al., 2008; Xu et al., 2013), but has to the author's knowledge never been applied for the purpose of calibrating detailed hydrodynamic river model parameters. Most likely because of the high computational times of these models.

This paper is organized as follows. The first section gives a description of the study area of the river Molenbeek in Belgium, the full hydrodynamic MIKE 11 model and the available measurements. This is followed by a discussion on conceptual surrogate modelling and the calibration approach with the SCEM-UA algorithm. Finally, the calibration results are discussed and the proposed approach evaluated.

2. Study area and available data

The Molenbeek catchment is a subcatchment of the river Dender and part of the international Scheldt basin that flows to the North Sea. It is located in Belgium, halfway between the cities of Brussels and Ghent. The catchment has a long and narrow shape, covering approximately 55 km^2, and is characterized by relatively steep slopes. The upstream part is predominately rural with mainly loamy soils, while the downstream part is more urbanized. These characteristics make the Molenbeek a typical rainfall driven river that is very vulnerable to flooding. The average discharge at the gauging station in Mere equals 0.45 m^3/s, but can rise up to above 7 m^3/s during flood periods. Two