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Modular conceptual modelling approach and software for river hydraulic simulations

Vincent Wolfs [a, *], Pieter Meert [a], Patrick Willems [a, b]

[a] Hydraulics Division, Department of Civil Engineering, KU Leuven, Kasteelpark Arenberg 40, BE-3001, Belgium
[b] Department of Hydrology and Hydraulic Engineering, Vrije Universiteit Brussel, Belgium

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A B S T R A C T

Numerous applications in river management require computationally efficient models that can accurately simulate the state of a river. This paper presents a reduced complexity modelling approach that emulates the results of detailed full hydrodynamic models. Its modular design based on virtual reservoirs allows users to combine different model structures depending on the river dynamics and intended use. A semi-automatic software tool (Conceptual Model Developer, CMD) was developed to facilitate model set-up. To prevent instabilities during simulations, a highly efficient discrete calculation scheme is presented with a variable time step. To illustrate the effectiveness of the presented approach, the Marke River in Belgium was conceptualized based on simulation results of a detailed model. Results show that the derived conceptual model mimics the detailed model closely, while the calculation time is reduced by more than 2000 times. Finally, several applications are discussed that employ conceptual models built according to the presented approach.

Software availability

Name: Conceptual Model Developer
Developers: Vincent Wolfs and Patrick Willems
Primary contact: Patrick Willems
Department of Civil Engineering, Hydraulics Division
Kasteelpark Arenberg 40 – bus 2448, 3001 Leuven, Belgium.
+ 32 16 32 16 58
patrick.willems@bwk.kuleuven.be
Hardware required: General-purpose computer. We recommend using a high-speed processor and at least 4 GB of RAM.
Software required: MATLAB and a C compiler
Programming language: MATLAB and C
Availability: Contact authors

1. Introduction

Models used to predict stages and flows in rivers are well developed and widely adopted in practice. They are often used for optimization applications that necessitate accurate quantitative predictions, such as conjunctive water use and resource management (e.g. Peralta et al., 1995; Fredericks et al., 1998; Rejani et al., 2009; Montazar et al., 2010), operation of reservoir systems (e.g. Yeh, 1985; Faber and Stedinger, 2001; Forster et al., 2008; Alemu et al., 2011; Castelletti et al., 2012a) and operation of hydraulic structures for flood control (e.g. Breckpot et al., 2013; Van den Zegel et al., 2014; Yazdi and Salehi Neyshabouri, 2014). River models also form a vital tool to generate real time flood forecasts (e.g. Pedregal et al., 2009; Van Steenbergen et al., 2012; Wolfs et al., 2012), to predict the river's state for different input time series such as for ensembles of rainfall forecasts (e.g. Demeritt et al., 2007; Cloke and Pappenberger, 2009; Van Steenbergen and Willems, 2014) and to asses various impact and scenario analyses, such as climate or land use change (e.g. Ashley et al., 2005; Booji, 2005; Dobler et al., 2012). At the same time, it is important to have an understanding of the model diagnostics and inherent uncertainty of the employed models, such as that of the initial conditions, selected model structure and parameters (e.g. Pappenberger et al., 2005; Yang et al., 2008; McMillan et al., 2010). All these share the need of a computationally efficient model. Indeed, optimization problems and probabilistic analyses often require numerous iterations, while assessing different scenarios can involve simulating long term time series. Besides these applications, there has been a change in design

* Corresponding author. Tel.: +32 16 322 369.
E-mail address: vincent.wolfs@bwk.kuleuven.be (V. Wolfs).

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procedures induced by new guidelines and policies that require looking at the water system as a whole, such as the EU Water Framework Directive (EU, 2000) and the European Water Initiative (European Commission, 2012). Authorities and practitioners start to recognize the importance of a broader and multi-disciplinary approach, in which not only the river system itself is considered, but also sewage systems, spatial planning and even social and economical factors. From this perspective, integrated catchment modelling has gained momentum. Due to this paradigm shift in the design and management of water systems and the associated scale enlargement (both in space and scope), the need for computationally inexpensive river models becomes even more acute.

The current gamut of river modelling methods can roughly be divided into three groups. The first group originates from the equations of de Saint–Venant. Different software packages are available that numerically solve the full de Saint–Venant equations, such as MIKE by DHI, InfoWorks RS (IWRS), HEC-RAS and SOBEK. These distributed physically based models are highly accurate but require long simulation times. To alleviate the computational burden of solving the dynamic form of these equations, different approximations were developed that omit one or more terms in the momentum equation (e.g. the kinematic, diffusive and quasi-steady simplifications; see Miller and Yevjevich (1975) for a summary). The second group consists of empirical models. These models are purely data-driven and most parameters lack a direct physical interpretation. The most simple variants are so called gauge models that relate one or more states at one location in the river directly to another (e.g. Goswami and O'Connor, 2007; Archer and Fowler, 2008), while more advanced models exist that also quantify the uncertainty (e.g. Porporato and Ridolfi, 2001; Krzysztofowicz, 2002; Romanowicz et al., 2008; Beven et al., 2009) or apply machine learning techniques, such as neural networks (see Maier and Dandy, 2000 and Maier et al., 2010 for a comprehensive overview of neural networks used for forecasting water resources variables) and adaptive neuro fuzzy inference systems (e.g. Bazartseren et al., 2003; Chang and Chang, 2006). Such purely data-driven models generally require long term simulations for calibration purposes. Since their parameters often cannot be physically interpreted and the models are built on historical observations, they usually cannot be employed for scenario analysis. The third group finds itself between the previous two and includes hydrological (or conceptual) models. This category comprises a wide variety of models that emanate from the continuity equation and, in contrast to the first group, have a different implementation of the momentum equation. Usually, a self-defined relationship between storage and flow is employed, as in the Muskingum, Muskingum-Cunge and later improvements (Cunge, 1969; Khan, 1993; Ponce and Chaganti, 1994; Kumar et al., 2011) and the Kalinin-Milyukov methods. In fact, most of these approaches are variants of the kinematic wave or diffusion analogy models as demonstrated by Weinmann and Laurenson (1979). Several expansions and novel approaches are being proposed, such as multi-linear discrete (lag) channel routing methods (e.g. Perumal, 1994; Camacho and Lees, 1999) and straightforward raster-based flood inundation models, which use Cunge-type storage cells (Cunge, 1975) in combination with simple equations to calculate the intercell fluxes (e.g. Estrela and Quintas, 1994; Bechteler et al., 1994; and see Hunter et al. (2007, 2008) and references therein). The LISFLOOD-FP approach proposed by Bates and de Roo (2000) is probably the most well-known and adopted conceptual raster-based model.

However, none of these methods is ideally suited for the applications listed earlier. Most of the discussed approaches are (still) computationally too expensive, lack physical soundness and/or are too simplified or restricted to be used in practical operations. More specifically, two of the main methodological shortcomings are the inability to cope with backwater effects and (externally) controlled structures and discharges. Therefore, this paper presents a flexible and modular conceptual modelling methodology that is able to generate nominal emulation/prediction models that comply with the following requirements:

- be highly computationally efficient;
- be numerically stable and robust during model simulations;
- have a transparent parameterization that can be interpreted in a physically meaningful way;
- be able to incorporate crucial elements such as dike levels, floodplains and (movable) hydraulic structures explicitly;
- be capable of modelling various types of flows and dynamics, including backwater effects;
- allow semi-automatic model structure identification and calibration;
- be compatible with other modules, such as sewer or water quality models.

Applying solely a structure-based dynamic emulation approach (Castelletti et al., 2012b), in which the mathematical structure of a full hydrodynamic model is manipulated to produce a simpler and computationally more efficient form (e.g. the simplification from the full dynamic equation to the kinematic formulation), yields models with insufficient computational improvement. Instead, a data-based mechanistic approach is applied to configure a conceptual model with different model structures using simulation results of a detailed model or measurements. To strike a balance between computational efficiency, and model credibility and accuracy, the presented modelling methodology manipulates the original model on two levels, namely the network topology and the momentum equations used to estimate the states in the system. The so-called lower-fidelity approach (e.g. Razavi et al., 2012) is used to simplify the network topology by applying the storage cell concept, in which the entire system (both river and floodplains) is divided into distinct units. Such division can be physically based and preserve the main topology of the system, but lumps the processes in space and is less detailed than a full hydrodynamic (high-fidelity) model. Surface response surrogate relationships, which are data-driven function approximations of the true response, are derived to calculate the states of the cells and inter-cell fluxes. Flows can for instance be estimated via the more traditional approach of storage–flow relationships, but can also be related to water levels. The latter is imperative for dealing with externally controlled discharges as pointed out by Fenton (1992). The presented approach applies different state-of-the-art model structures. Depending on the intended applications and the dynamics of the river system, different modules can be combined. Hence, model set-up is highly flexible and can be tailored to the user needs.

A semi-automated software tool named Conceptual Model Developer (CMD) was developed to facilitate the time consuming and often difficult process of model structure identification, calibration and build-up. It collects the required data, guides the user in a step-wise manner through the set-up process and proposes the best suitable model structures using advanced identification and optimization techniques for model calibration. Finally, the different configured modelling elements are automatically gathered and combined into a model script that comprises the derived conceptual model, together with the requisite boundary data to simulate selected events. An innovative discrete solver based on the Runge-Kutta family was developed that uses an adaptive time step during simulations to ensure stability and maximize the computational efficiency. This solver can be applied to all calculations in individual cells.