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Computationally efficient modelling of tidal rivers using conceptual reservoir-type models

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A B S T R A C T

Conceptual reservoir-type models of river systems, that mimic the results of detailed hydrodynamic models, provide a powerful tool for numerous river management applications. Thanks to their computationally efficient model structure they are very well suited for applications that require long term simulations or a large number of model iterations. However, one well-known problem is that conceptual models have difficulties to account for backwater effects. For this reason, their application to tidally influenced river reaches so far was almost non-existent. This paper introduces an extension of an existing grey-box reservoir modelling technique to incorporate tidally influenced river reaches. The methodology is demonstrated for the downstream part of the rivers Zenne and Rupel in Belgium. Results show a minor loss of accuracy when the detailed model is replaced by the surrogate conceptual model. Also, the tidal effects are well represented.

1. Introduction

Over the last decades, water authorities all over the world have developed a large variety of detailed hydrodynamic models in support of their water management tasks. Despite this vast modelling capacity, the current tendency towards integrated catchment modelling is impeded by a number of practical obstacles. One of the main restrictions is that the natural catchments may be managed by up to three or more different authorities, each with their own responsibilities and modelling tools. The basin of the river Zenne in Belgium, for example, is managed by the W&Z authority for the navigable rivers in Flanders, the Flemish Environment Agency (VMM) for the non-navigable rivers of first category in Flanders, the provinces and cities for the non-navigable rivers of higher category, the Direction génerale operationelle de la Mobilité et des Voies hydrauliques (DGO2) for the rivers in Wallonia, the Brussels Environment Agency (BIM/IBGE) for the rivers in the Brussels Capital Region, Aquafin for the urban drainage systems in the Flanders Region, Vivaqua for the urban drainage systems in the Brussels Capital Region, etc. This has resulted in a large number of hydrodynamic models which are mostly limited to individual components of a catchment, that can hardly interact with each other and are all computationally demanding. Furthermore, there exists an overlap in the areas covered by these models, resulting in areas that are modelled twice or more, by different model types and by different authorities, and which might provide different results for the overlapping areas.

In recent years, several generic modelling packages have been developed to analyze the behavior of river basins under varying hydrological conditions and to assist decision makers in short-term operations and long-term planning at basin scale, such as the RiverWare tool (Zagona et al., 2001), the spatially distributed LISFLOOD model (Van Der Knijff et al., 2010), the RIBASIM package (Deltares, 2010) and the Source Integrated Modelling System (IMS; Welsh et al., 2013). RiverWare, for example, is a river and reservoir modelling tool that contains a library of pre-programmed physical process algorithms to permit site-specific detailed modelling. IMS is an Australian multidisciplinary modelling environment for catchments and river systems in transboundary basins. These generic packages use simplified river routing techniques, like the Muskingum routing (Cunge, 1969) or Laurenson's non-linear routing with lag method (Laurenson, 1986), and can provide

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powerful solutions to overcome the above mentioned obstacles. Simulations with these model packages are usually performed at daily (or even larger) time step, making them suitable for long-term catchment water balance calculations, but less suitable for modelling individual flood events, which requires smaller time steps and a higher spatial resolution of calculation nodes. In order to meet these drawbacks, this paper makes use of conceptual models, that emulate the results of the detailed models, based on a concatenation of reservoir-type model elements. The conceptual models considered here can be regarded as physically-inspired or grey-box models, since they have a structure that is based on a simplified representation of reality (Knight and Shamseldin, 2006). The explicit calculation scheme of these models allows for very short calculation times, making them useful not only for integrated catchment modelling, but also for other applications that require long-term simulations or a large number of model runs, as in forecasting, real-time control, sensitivity analyses, etc.

So far, conceptual models have mostly been applied to the free flowing, upstream parts of river systems, where no influences are present of the backwaters induced by downstream water level boundary conditions (e.g. Wolfs et al., 2015; Van den Zegel et al., 2014; Vaze et al., 2011; Kožar et al., 2010). The application of conceptual models to tidally influenced river reaches was therefore almost non-existent. This paper presents an extension of the methodology presented in the paper by Wolfs et al. (2015), that is applicable to the tidally influenced parts of a river system and that is also compatible with the existing conceptual modelling approach. This will allow to construct conceptual reservoir-type models for a complete river system, and make these models useful for integrated catchment modelling applications.

A large variety of computationally efficient modelling techniques to simulate the tidal propagation in estuaries and tidal rivers exists. The techniques vary in quite a number of aspects: applicability of boundary conditions, the number of processes accounted for, accuracy of the model results, etc. Empirical or black box models are the most elementary type of models: they attempt to find a relation between a model input x and the model outputs or physical quantities y, without accounting for the underlying physical processes. Surface analysis methods (e.g. Bárcena et al., 2012) can be mentioned as examples of these straightforward empirical models. An important premise of these models is that a unique relation must exist between model inputs and outputs. Data driven models like artificial neural networks have become widely used in all fields of hydrology and have recently also been applied in simulating tidal propagation (e.g. Fazel et al., 2014; Chang and Chen, 2003; Supharatid, 2003). The problem with such black-box models is that there is almost no physical basis incorporated in the model, thus limiting the applicability and accuracy outside the calibration range (e.g. to extreme events).

Examples of more physically-based and computationally efficient models are idealized models and water stage routing methods. Idealized models (e.g. Schramkowski et al., 2004; Schuttelaars and de Swart, 2000; Lanzoni and Seminara, 1998) try to provide analytical solutions of the de Saint–Venant equations to simulate the propagation of a tidal wave in an estuary. Both the geometry of the estuary and the boundary conditions are therefore highly schematized. Water stage routing methods (e.g. Si-min et al., 2009; Perumal and Ranga Raju, 1998; Franchini and Lamberti, 1994) are based on the same principle as classical discharge routing methods, like the well-known Muskingum method (Cunge, 1969), but simulate the propagation of a flood or tidal wave in terms of water levels, rather than in terms of discharges. This adaptation makes it possible to use them for water-stage modelling and forecasting in tidal rivers.

Most of the above mentioned modelling techniques are not fully suited for the aims of the research in this paper, since they start from premises that constrain the conditions on which they are applicable. Problems arise for example in predicting water levels in river parts that show an important interaction between the tidal influence downstream and the fresh water discharges upstream. Furthermore, the accuracy of the simulation results of the above mentioned models and methods can be rather poor, limiting their use in practice. Another important limitation is the fact that none of them ensures an explicit conservation of the water mass in the system, which impedes an accurate incorporation of (variable) human interactions on the water system, like for example hydraulic structures that regulate flood control areas or pumping stations that control the water level in polders and land reclamation areas. The modelling approach presented in this paper is based on the mass balance equation and can therefore address the problems discussed here. In addition, the approach is 'open' enough, so that it is compatible with other (existing) reservoir routing techniques and independent of the type of hydrodynamic model that is used for the detailed simulations.

This paper first describes the study area and the available data of the rivers Zenne and Rupel in Belgium. Next, the existing conceptual modelling approach and the extension of this technique to incorporate the tidally influenced parts of the river system are discussed. This is followed by an overview of how the detailed hydrodynamic model is transformed into a lumped conceptual model. Finally, the simulation results of the presented approach are compared with the results of a hydrodynamic model to show the accuracy of the conceptual model.

2. Study area and available data

The river Zenne catchment is part of the international Scheldt basin that flows to the North Sea and is located in the central part of Belgium (see Fig. 1). The basin has a total area of 1162 km^2, which is divided over three administrative regions: the Walloon Region (574 km^2), the Brussels-Capital Region (162 km^2) and the Flemish Region (426 km^2). The upstream part of the river (before entering the city of Brussels) has a natural meandering course. In Brussels and further downstream the river has been canalized: straightening of the meanders, re-profiling of the river bed and a vaulting over approximately 8.3 km. The river basin is crossed by a canal that connects the cities of Brussels and Charleroi with the Scheldt river and the North Sea. The canal and the river form a very complex system that is highly influenced by human interactions and activities (Leta, 2013). The total runoff from the catchment is divided over the river (58%) and the canal (34%) and a remaining fraction (8%) that is normally flowing to the river, but diverted to the canal during flood periods. After approximately 100 km the river Zenne meets the river Dijle, which is 1 km downstream joined by the river Nete to form the river Rupel. This 12 km long river is connected with the tidal river Scheldt, causing the last 13 km of the river Zenne to be tidally influenced. In the near future, four flood control areas will be installed at the confluence of the rivers Zenne, Dijle and Nete to reduce the food hazard of the surrounding land. Some of these control areas will be installed with reduced tides to simulate the natural functioning of a tidal river and to restore the rare freshwater tidal nature of this region.

A detailed one dimensional hydrodynamic model of the rivers Zenne and Rupel and the Canal was made available by the Flanders Hydraulics Research institute. This model was set up in the MIKE11 software of DHI (DHI, 2011) and incorporates the main water courses of the Zenne catchment, ranging from the Walloon border at the upstream side, till the confluence with the river Scheldt at the downstream side. The model contains measured cross-sections approximately every 100 m as well as all relevant hydraulic