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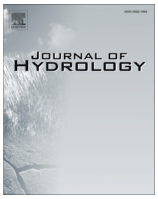

Efficient incorporation of channel cross-section geometry uncertainty into regional and global scale flood inundation models

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SUMMARY

This paper investigates the challenge of representing structural differences in river channel cross-section geometry for regional to global scale river hydraulic models and the effect this can have on simulations of wave dynamics. Classically, channel geometry is defined using data, yet at larger scales the necessary information and model structures do not exist to take this approach. We therefore propose a fundamentally different approach where the structural uncertainty in channel geometry is represented using a simple parameterisation, which could then be estimated through calibration or data assimilation. This paper first outlines the development of a computationally efficient numerical scheme to represent generalised channel shapes using a single parameter, which is then validated using a simple straight channel test case and shown to predict wetted perimeter to within 2% for the channels tested. An application to the River Severn, UK is also presented, along with an analysis of model sensitivity to channel shape, depth and friction. The channel shape parameter was shown to improve model simulations of river level, particularly for more physically plausible channel roughness and depth parameter ranges. Calibrating channel Manning's coefficient in a rectangular channel provided similar water level simulation accuracy in terms of Nash–Sutcliffe efficiency to a model where friction and shape or depth were calibrated. However, the calibrated Manning coefficient in the rectangular channel model was ~2/3 greater than the likely physically realistic value for this reach and this erroneously slowed wave propagation times through the reach by several hours. Therefore, for large scale models applied in data sparse areas, calibrating channel depth and/or shape may be preferable to assuming a rectangular geometry and calibrating friction alone.

1. Introduction

Recently there has been substantial interest in simulating river hydraulics at regional to global scales, most notably for the purpose of flood hazard and risk assessment. There is currently no clear definition of what constitutes a large scale hydraulic model, however for the purpose of this paper it will be assumed that the model has a structure that can be applied to simulate water levels and flows over an entire continent. Implicit to this definition is that some form of specialisation of the model structure will have occurred to facilitate its application in data sparse areas where only remotely sensed data can be obtained. Furthermore, in our definition, large scale does not limit the model to large sized rivers. This means the large scale model would be expected to include a substantial number of smaller streams a tributaries, with the minimum stream size determined by the application and data available rather than the model structure.

Approaches to regional or global scale river and floodplain simulation (Alfieri et al., 2013; Neal et al., 2012a; Paiva et al., 2011; Sayama et al., 2012; Winsemius et al., 2012; Yamazaki et al., 2011) often make a number of simplifications from the one- or two-dimensional shallow water models widely used at the reach scale (e.g. river lengths of 10–100's of km). Most of these simplifications are forced on the modeller due to insufficient information about the river geometry, channel roughness, floodplain topography and river discharge, and are compounded by limited

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computational resources that restrict the choice of model resolution, numerical complexity and ensemble size. River channel parameters such as depth, cross-section shape and friction are perhaps the most difficult to estimate on account of not being remotely observable (Alsdorf et al., 2007) and may therefore need to be estimated to obtain simulations of sufficient accuracy. Furthermore, current large scale inundation models are limited to using either no channels or simple rectangular ones, which is a situation that contrasts greatly with reach scale models where channel geometry can be complex and parameterised from survey data.

Despite a lack of data and suitable model structures, accurate simulation of channel flow and water level dynamics is essential to inundation simulation because even during large flood events the channel will still convey a significant proportion of the flow. Furthermore, a complex interaction between channel and floodplain flows might also be expected along the river plan form (Harwood and Brown, 1993; Trigg et al., 2012). As stated earlier, channel geometry data are unlikely to become available for many regions in the near future, meaning an alternative approach to using direct observations is needed. This is most likely to involve treating channel geometry as a model parameterisation, which can then be estimated along with friction. In this context, treating all channels as the same shape (i.e. rectangular) may introduce model structural errors that must then be compensated for, along with numerous other potential error sources, by calibrating the channel friction and depth parameters. By not allowing channel shape to vary, the friction and depth parameter will become more 'effective', which could lead to a number of spurious non-physical effects as friction and channel shape affect wave propagation in rather different ways and with different spatial signatures. At the reach scale, a number of studies have analysed the sensitivity of level and inundation simulations to model parameters, such as friction, and input data and have tried to identify the sources of uncertainty that are most prevalent (Apel et al., 2004; Domeneghetti et al., 2012; Pappenberger et al., 2005, 2006). From these studies numerous modelling frameworks that account for uncertainty have been developed (Di Baldassarre and Montanari, 2009; Hall et al., 2011; Hostache et al., 2009). However, it is unclear to what extent the understanding of error sources and model sensitivity gained from these studies can be transferred to regional and global modelling, where the scale of the river network and observation data available differ. Previous large scale modelling studies have evaluated channel depth and friction as calibration parameters (Neal et al., 2012a; Paiva et al., 2013; Schumann et al., 2013), however the approaches lack the flexibility in model structure to incorporate more complex channel geometries. The method presented here will for the first time extend a large scale model to consider channel shape as a single continuous parameter (based on a power curve) using a unique method for determining channel wetted perimeter. This is the paper's fundamental novel conceptual advance, a model scheme that allows for structural changes to channel shape where computational efficiency is maintained while only introducing a single model parameter, thus maintaining a parsimonious model structure. Many existing models allow for complex channel geometries (e.g. Brunner (2010)) and trapezoidal channels, but the authors are unaware of any previous model that have taken this parameterised approach.

The overall aim of this work is to separate the effects of friction and geometry on wave propagation and river level such that more realistic large scale inundation models can be built and structural alternatives tested. However, there are a number of technical challenges to be overcome in order to be able to achieve this and this is what this paper describes. In subsequent sections of this paper, a hydraulic model structure is presented where the river channel depth, shape and friction can be described by three physically meaningful but continuous parameters, which might be calibrated or estimated from observations. Specifically, a method for approximating the channel shape using a power law is outlined, along with a novel and computationally efficient method for estimating the wetted perimeter of these channels. The approach to modelling the river channel is integrated within a two-dimensional inundation model (LISFLOOD-FP) using a simple-to-implement one-dimensional channel model (Neal et al., 2012a). After validating the method using a simple test case, the influence of channel shape friction and depth on river dynamics was investigated with the aid of a test case from a 60 km reach of the River Severn, UK.

2. Hydraulic modelling

To facilitate the development of the continuous channel geometry parameter a regional scale flood inundation model is needed. For this task, the hydraulic model of Neal et al. (2012a) and its approach to modelling sub-grid scale river channels within a two dimensional Cartesian grid floodplain inundation model was chosen. This model is implemented within the LISFLOOD-FP program because the authors are familiar with the code, however it should be possible transfer the proposed channel shape treatment to most one-dimensional hydraulic models because the variables being calculated are cross-section area and wetted perimeter. In the Neal et al. (2012a) model, river channels of any width below that of the floodplain model's cell resolution Δx and any bed elevation below that of the floodplain could be simulated. However, the channel geometry was assumed to be rectangular in order to keep the numerical scheme simple and computationally efficient. In this paper the model retains that functionality and computational efficiency, however an extension to the model is presented allowing channel cross-sectional geometry to be defined by a power function. This function relates the flow width w_{flow} for a given depth of flow h_{flow} to the bank-full width w_{full} and bank-full depth of the channel h_{full} using a single shape parameter s, such that the flow width for any flow depth below bank-full depth is defined as:

$$w_{flow} = w_{full}\left(\frac{h_{flow}}{h_{full}}\right)^{1/s} \tag{1}$$

The parameter s can take any value above 0 and produce a geometry. However, in physical terms, values below one will result in convex shaped banks, a value of one will lead to a triangular channel, and values above 1 will result in concave channels (e.g. a value of two is a parabolic channel, while the channel will tend towards trapezoidal then rectangular as s increases towards infinity). These geometries are illustrated by Fig. 1a. The channel is assumed to be symmetrical, which allows simple analytical relations to be derived between the flow width h_{flow} and flow area A_{flow}, given any value of s, as illustrated by Fig. 1b and Eq. (2):

$$A_{flow} = w_{flow}h_{flow}(1 - 1/(s+1)) \tag{2}$$

Bank-full width and depth are required as inputs to the numerical scheme, and are typically estimated from observations, hydraulic geometry theory or model calibration. The hydraulic radius (see Appendix A.1 for details) is defined by the flow area $A^t_{c,flow}$ divided by the wetted perimeter $P^t_{c,flow}$, where *flow* denotes the flow area between two cells and c will be used from now onwards to denote a channel. For a rectangular channel the wetted perimeter is the channel width plus twice the minimum of the flow depth and the bank-full depth. However, for the power function shaped channel the wetted perimeter is determined by the function arc length. Unfortunately, calculating the arc length of a power curve is computationally expensive because there is no analytical