Environmental Modelling & Software 67 (2015) 89–107

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Enhancing river model set-up for 2-D dynamic flood modelling

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ARTICLE INFO

Article history:
Received 7 August 2014
Received in revised form
9 January 2015
Accepted 11 January 2015
Available online

Keywords:
Accuracy
Flood mapping
Case studies
2-D modelling
Hydrologic/hydraulic modelling
River model

ABSTRACT

Flood hazard mapping is a topic of increasing interest involving several aspects in which a series of progress steps have occurred in recent years. Among these, a valuable advance has been performed in solving 2-D shallow water equations in complex topographies and in the use of high resolution topographic data. However, reliable predictions of flood-prone areas are not simply related to these two important aspects. A key element is the accurate set up of the river model. This is primarily related to the representation of the topography but also requires particular attention to the insertion of man-made structures and hydrological data within the computational domain. There is the need to use procedures able to 1) obtain a reliable computational domain, characterized by a total number of elements feasible for a common computing machine, starting from the huge amount of data provided by a LIDAR survey, 2) deal with river reach that receives significant lateral inflows, 3) insert bridges, buildings, weirs and all the structures that can interact with the flow dynamics. All these issues have large effects on the modelled water levels and flow velocities but there are very few papers in the literature on these topics in the framework of the 2-D modelling. So, in this work, attention is focused on the techniques to deal with the above-mentioned issues, showing their importance in flood mapping using two actual case studies in Southern Italy. In particular, the simulations showed in this paper highlight the presence of backwater effects, sudden and numerous changes in the flow regime, induced by the detailed river model, that underline the importance of using 2-D fully dynamic unsteady flow equations for flood mapping.

1. Introduction

In the last few decades, the numerical modelling of flood events has been significantly enhanced due to the development of reliable numerical methods, computing power and innovative topographic survey techniques. This amount of progress has progressively encouraged the use of 2-D flood simulations, not only in the academic context but also in technical studies, replacing 1-D approaches that, despite their efficiency and the potential for their improvement in compound channels (see, for example, Helmiö, 2005; Proust et al., 2010; Costabile and Macchione, 2012) present conceptual problems when applied to overbank flows (Horritt and Bates, 2002; Tayefi et al., 2007; Costabile et al., 2015a).

Paradoxically, the significant improvements related to the flood simulation processes have raised worries in the literature because of the tendency of giving too much reliability to them. In particular, there is a well-founded concern that "sophisticated high-resolution models might be dangerous from this viewpoint as the false sense of confidence derived from their spuriously precise results might lead to making the wrong decisions" (Dottori et al., 2013).

Indeed, flood hazard assessments are affected by several sources of uncertainties which have significant consequences on the simulations accuracy. In particular, uncertainty concerns the hydrological data, the hydraulic parameters, calibration and validation data, the governing equations describing the physical processes, the way to take into account man-made structures interacting with the flow and so on (among the most recent ones see Merwade et al., 2008b; Di Baldassarre and Montanari, 2009; Bales and Wagner, 2009; Di Baldassarre et al., 2010; Hall et al., 2011; Stephens et al., 2012; Warmink et al., 2011; Brandimarte and Kebede Woldeyes, 2013; Grimaldi et al., 2013; Domeneghetti et al., 2013; Dottori et al., 2013; Jung and Merwade, 2015).

In the uncertainty assessment, nowadays there is a tendency to overcome the deterministic approach by the development of probabilistic ones. The difference between these two approaches

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http://dx.doi.org/10.1016/j.envsoft.2015.01.009
1364-8152/

can be summarized in the following way (Di Baldassarre et al., 2010). Advanced deterministic models consist of three steps: development of a 2-D fully-dynamic physically-based hydraulic model, model calibration using historical flood data, re-organization of the simulation results aimed at flood hazard mapping in a GIS environment. As regards the probabilistic approach, the authors identify three steps: construction of flood inundation models, sensitivity analysis of the model using historical flood data and use of the multiple behavioural models to perform ensemble simulation using an uncertain synthetic design event as hydrological input. According to Di Baldassarre et al. (2010), a fully dynamic 2-D model is not necessarily required in a probabilistic approach because the latter is not based on the assumption that the hydraulic model represents the physical behaviour of both the channel and flood-plain flow.

Indeed, reduced-complexity approaches are often sufficient to provide accurate results with respect to inundation extent, when compared to the more complex schemes (Horritt and Bates, 2001, 2002), even though there is some evidence that reduced complexity approaches tend to overestimate the inundation extent at coarser grids compared to the fully dynamic wave equations (Falter et al., 2013). This consideration is of course true in those situations in which the analysis is limited to the flood extent mapping and attention is focused on the probability of a given cell to be wet or dry.

However, in those studies for which the hydraulic variables are used for hazard assessment throughout the flooded area, a more accurate approach should be required. In particular, information on the propagation of the flood wave, water depths and velocities and the rate at which the water level rises is very important for emergency planners in charge of evacuation and to estimate the potential of loss of life (Jonkman et al., 2008; Gómez-Valentín et al., 2009; Gómez et al., 2011; Xia et al., 2011; Russo et al., 2013). Moreover, further analyses are required to evaluate other important parameters necessary for assessing the flood hazard. For example in steep upstream areas and next to dyke breach locations, flow velocity is a very important factor for flood damage (de Moel et al., 2009; Qi and Altinakar, 2011). For this reason, accurate and local assessments of flood hazard in each point of the domain should require the use of 2-D fully-dynamic models (Ernst et al., 2010; Balica et al., 2013). It should be added that this not only applies to the deterministic approaches but also to the probabilistic ones, if the goal is to assess the probability of occurrence of hazard parameters related to the hydrodynamic variables.

Obviously, the computational times related to the use of 2-D fully dynamic modelling can be time demanding, even though a significant reduction is expected over the next years due to the increasing availability of parallel computing technique in flood analyses (see, for example, Neal et al., 2010; Yu, 2010; Kalyanapu et al., 2011; Vacondio et al., 2014).

The main purpose of this paper is to give a contribution on three important aspects related to the application of the 2-D modelling for flood hazard assessment, for which there are very few studies in the literature. In particular, the attention will be focused on:

1) correct representation of the flood-prone areas topography. The purpose is to get a reliable computational domain, characterized by a total number of elements feasible for a common computing machine, starting from the huge amount of data provided by a LIDAR survey;
2) interaction between hydrologic and hydraulic models;
3) insertion of bridges, buildings, weirs and all the structures that can interact with the flow dynamics

The correct topographical representation is a key aspect as it brings the model closer to reality allowing water volumes and river conveyance to be correctly modelled (see, for example, Horritt and Bates, 2001; Sanders, 2007). Fewtrell et al. (2008) concluded that the model resolution has to be set up to the characteristic scale of buildings size and street width in order to obtain accurate predictions of flooding. Generally speaking, creating topographic representation of river systems is a challenging task because of issues associated with interpolating river bathymetry and then integrating this bathymetry with surrounding topography (Merwade et al., 2008a). For example, Cook and Merwade (2009) showed that the flood inundation area reduces not only with improved horizontal resolution and with vertical accuracy in the topographic data but also by incorporating river bathymetry in topography data. A more detailed geometry has a significant impact on the hydraulic modelling results, not only concerning the flood extent but also, above all, regarding the distribution of flow velocities and bottom shear stresses. The latter are equally important for estimating the risk potential in hazard zone mapping (Mandlburger et al., 2009). The great importance played by the micro-scale topographic and blockage effects, has led researchers and modellers to use high-resolution input data for flood simulation in urban areas and floodplains with human settlements, where the majority of at-risk assets are located. Airborne remote sensing such as LIDAR provides high quality digital terrain models, reducing the uncertainty in topography for numerical flood modelling. The direct use of the LIDAR survey as a computational grid is not possible due to the huge amount of data. Therefore, there is the need to use suitable procedures to obtain a reliable computational domain characterized by a total number of elements feasible for a common computing machine. Several papers claim that the computational grid is obtained by a LIDAR survey but, very often, the procedure used to do that is not clearly explained (see, for example, Bates et al., 2003). Mandlburger et al. (2009) presented a method for the generation of a hydraulic grid. In that work, the main purpose is the development of a DTM thinning approach, based on adaptive triangular irregular network (TIN) refinement, which allows an effective compression of the point data while preserving the most relevant features. Apart from the techniques used for getting the computational grid, particular attention has to be paid also to the so called “quality” of the generated grid, checking some main parameters such as: the angle criterion, aspect ratio and expansion ratio (Ferziger and Peric, 2002).

The second issue analyzed in this paper concerns the interaction between hydrologic and hydraulic models. Almost all the studies in the literature show applications of numerical models for the propagation of just one upstream hydrograph. However, in practical studies, a river reach may have several lateral inflows and, therefore, the treatment of the tributaries requires particular attention. An accurate approach is the analysis of this problem at the basin scale, using a physically-based distributed rainfall-runoff model, but in practical cases the tributaries discharge hydrographs should be computed by a hydrological method. If the goal of the flood analysis is the study of flooded areas induced just by the main river, the separation between hydrologic and hydraulic models require to face us the problem of the choice of the boundary cross-section in which to insert the hydrological data. In particular, if the boundary cross-section is too close to the main river then the backwater effect induced by the latter can influence the boundary condition imposed on the tributary side. On the other hand, if the input section is too far from the main river, there is also the problem of the hydraulic simulation of the stretch of the tributary between the input section and the main river. This problem is not trivial because the selected section may have important consequences on flood extent predictions. In this paper, we will discuss this aspect and highlight the approach we have used in two real cases.