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Flood inundation modelling: A review of methods, recent advances and uncertainty analysis

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A B S T R A C T

This paper reviews state-of-the-art empirical, hydrodynamic and simple conceptual models for determining flood inundation. It explores their advantages and limitations, highlights the most recent advances and discusses future directions. It addresses how uncertainty is analysed in this field with the various approaches and identifies opportunities for handling it better. The aim is to inform scientists new to the field, and help emergency response agencies, water resources managers, insurance companies and other decision makers keep up-to-date with the latest developments. Guidance is provided for selecting the most suitable method/model for solving practical flood related problems, taking into account the specific outputs required for the modelling purpose, the data available and computational demands. Multi-model, multi-discipline approaches are recommended in order to further advance this research field.

Contents

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1. Introduction

Flooding is a global phenomenon that causes casualties and property loss on every inhabited continent. It is probably the most devastating, widespread and frequent natural disaster for human societies. On the other hand, the impact of flooding is not always negative as it is a part of a natural cycle and can have great environmental and social benefits, particularly in areas which have suffered from prolonged drought. Periodic scouring floods are even crucial for ecosystems in most riverine and coastal wetlands.

Throughout human history, there has been a constant endeavour to understand, assess and predict flood events and their impact. Flood inundation models are therefore developed to serve this purpose. As flooding accounts for a significant proportion of the total number of reported natural disasters occurring in the world, and over the last 30 years this proportion has been increasing (Freer et al., 2011), the development and application of flood inundation models and relevant research have become a global endeavour.

Systematic efforts within the research community since the 1970s have greatly improved the capability of flood inundation modelling. The models are widely used in flood risk mapping (Apel et al., 2006; Dutta et al., 2006), flood damage assessment (Bhuiyan and Dutta, 2012; Merz et al., 2010), real-time flood forecasting (Arduino et al., 2005), flood related engineering (Gallegos et al., 2009), and water resources planning (Vaze et al., 2013), as well as having served as an important prerequisite for investigating river bank erosion and floodplain sediment transport (Marriott, 1992; Pizzuto, 1987), contaminant transport, floodplain ecology (Karim et al., 2015), river system hydrology (Dutta et al., 2013) and catchment hydrology (Abbott et al., 1986; Beven, 1989). Combined with climate models, hydrological models, and river models, the application of flood modelling has been extended to modelling that aims to formulate climate adaptation and risk mitigation strategies. Reliable and robust simulation of inundation characteristics has also made it possible to effectively plan for environmental flows in order to maintain healthy aquatic ecosystems.

Typically, the application purpose of any modelling requires contextual attention to the output variables of predictive interest and their time and space scales, the level of accuracy required and computational efficiency demands. For flood forecasting, applications may require considerations of fast run time and real-time data assimilation. Flood risk assessments in urban areas rely on the accuracy of supercritical flow representation that can be offered by a numerical model that simulates fluid dynamics. Velocity should be carefully modelled and reported for dam construction, flood damage assessment, or erosion studies, while maximum flood extent and water depth may be sufficient for hazard mapping, environmental flow assessment, and water resources planning. All these considerations call for the end users to wisely select a model balancing their demands against model complexity and data requirements.

Over the past century, two groups of approaches have attracted the most attention and are the subject of ongoing research: empirical methods such as measurements, surveys, remote sensing and statistical models evolved from these data-based methods (e.g. Schumann et al., 2009; Smith, 1997); and hydrodynamic models. The latter include one-dimensional (1D) (e.g. Brunner, 2016; DHI, 2003), two-dimensional (2D) (e.g. DHI, 2012; Moulinec et al., 2011) and three-dimensional (3D) methodologies (e.g. Prakash et al., 2014; Vacondio et al., 2011) that simulate water movement by solving equations derived from applying physical laws to fluid motion with varying degrees of complexity. In recent years, a third group of approaches has been gaining increasing popularity for modelling very large floodplains (such as for national scale flood risk assessment) and data sparse regions. These models can be labelled as simplified conceptual models and are based on more modest representations of physical processes and have run times orders of magnitudes shorter than hydrodynamic models. They are particularly suitable for large study areas and/or stochastic modelling for probabilistic flood risk assessment.

Despite active research in the field, rapid and accurate flood modelling at high spatio-temporal resolutions remains a significant challenge in hydrologic and hydraulic studies. This is due to the complex and chaotic nature of flooding and uncertainty currently enduring in flood inundation modelling (Freer et al., 2011; Merz and Thieken, 2005). Many new concepts, techniques and philosophical debates have detailed the difficulties of providing effective guidance and an agreement on best practice. And there is a vast literature describing, comparing, and benchmarking various models and algorithms. For instance, Alcrudo (2004) provided a state-of-the-art review on mathematical modelling of flood propagation for the Impact Project (www.impact-project.net). Pender (2006) reviewed the hydraulic models that are used in flood risk management research and classified the models based on the maximum dimensionality of the flow processes represented. Woodhead et al., (2007) provide a comprehensive reference to flood inundation models for the flood manager as part of the FLOODsite project consortium (ww.floodsite.net). From 2009, the report series from DEFRA/Environment Agency, UK reviewed and benchmarked the then latest 2D hydraulic modelling packages (Néelz and Pender, 2009, 2010, 2013). The application of satellite remote sensing to river inundation was reviewed by Smith (1997) and a more recent review by Schumann et al. (2009) report on progress in this field. However, most of these studies focus on a specific group of models or a particular aspect of modelling such as 2D hydrodynamic models, or shock capturing schemes. Moreover, the technologies are constantly evolving and modelling packages are always going through major changes, with some hugely improved and some discontinued.

This paper reviews the current state-of-the-art for the different modelling approaches, analyses their advantages and limitations, how they deal with uncertainty issues, highlights the latest developments and discusses future directions. While informing the novice scientist in this field, it also aims to help emergency response agencies, water resources managers, insurance