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Applicability of a coastal morphodynamic model for fluvial environments

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ABSTRACT

The dominant processes of sediment transport and morphological changes are different between rivers and coastal areas. In many situations rivers, estuaries and coasts need to be modelled together in an integrated way. This paper investigates the capability of a freely available, open source, coastal morphodynamic software (XBeach) to estimate sediment transport and morphological changes in fluvial environments. Four benchmark tests were designed to test code performance and included simple unidirectional flow cases, complex topography, fluvial flood flows (hydrographs) and dam break scenarios (fast transient, supercritical flow fields). The results were compared to laboratory experimental results or simulations results from industry standard software. Analysis suggested that the coastal morphodynamic code is able to simulate sediment transport and morphological changes in a fluvial environment, but there are limitations to what can be modelled and the accuracy to which they are modelled. General morphological trends are replicated reasonably well by the code however specific bed forms and rapid erosive responses are less well modelled. Suggestions are made for applicability of the code, code improvement and future work.

1. Introduction

1.1. Background

Aggradation and degradation processes are strongly associated with the hydraulics of any system, and in water resources management they add another dimension to the already complicated process of decision making, for example in flood risk management, engineering development or water resource allocation. The processes of degradation, transportation and sedimentation are natural, have occurred throughout geological time and have helped to shape the present landscape of the world. When morphological processes interact with the engineered landscape they can exacerbate existing problems such as flood risk (e.g. Bhattacharya et al., 2013; Pender et al., 2015).

Investigation of river morphodynamic and sediment processes is of interest to scientists and engineers; hence over the years many tools have been developed to model these processes mathematically (Amsler et al., 2005; Brown, 2006; Canestrelli et al., 2014). These approaches tend to utilise computational engines to solve the equations of motion for flow and sediment transport. Often modellers chose to represent fluvial models either as 1D channels or as linked 1D-2D models, characterizing the channel in 1D, and the floodplain in 2D. For hydrodynamic assessments there is benefit in this simplification where a static bed is assumed, and hence many of the tools have developed to reflect this need. However when morphodynamics are included, understanding the variation of the bed evolution through time across the river cross-section as well as downstream, as is possible using a 2DH code, is desireable as it provides greater information. In rivers of significant width (>30 m) and transistional environments such as estuaries, the use of 2DH codes for morphological studies is useful. Many mathematical models, both commercial and academic, have been developed such as HEC (1D; US Army core of Engineers, US), MIKE Zero (1D/2D Danish Hydraulic Institute, Denmark), TELEMAC (2D Laboratoire National d'Hydraulique et Environnement France), ISIS/Flood Modeller sediment (1D/2D; Halcrow/CH2MHill, U.K), Sobek and DELFT 3D (1D/2D; Deltares, The Netherlands). Some commercial software, although frequently applied and often freely available, are

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not provided as open-source (e.g. MIKE Zero), meaning that users are unable to make changes to the program through changes to the code itself, to suit the requirements of individual projects. Recent trends have moved towards offering more open source software (e.g. TELEMAC or Delft3D). This is more attractive to wider audiences due to the associated flexibility; but support for developing codes can be limited. Numerical codes are numerous (commercial or otherwise, open source or not) and the choice to use a specific code is often driven by many factors (user determined).

1.2. XBeach software; benchmarking

Rather than developing new codes to add to those currently available, it is important to understand the applicability of available codes, and their transferability between hydraulic environments (often codes are developed for either coastal or fluvial environments), such that the maximum utility of any one code can be appreciated. Understanding the limitations of a code can open up its use to a new community, or alternatively ensure that a code is not used inappropriately. Hydraulic and sediment conditions vary between coastal and fluvial environments, meaning the subsequent development of computational codes reflect this. Parameters such as wind and tidal forces, which have a significant influence in the coastal environment, have minor effects in fluvial environments. Conversely, bathymetric conditions such as significant variations in the planimetric slope through river reaches, which are very important in fluvial modelling, are considered less important in coastal modelling. Despite these technical differences in model set up, the basic hydraulic calculations required are the same. Consequently understanding the transferability of codes between environments is important in order to appreciate code limitations.

XBeach (Roelvink et al., 2009; http://oss.deltares.nl/web/xbeach/home) is a 2DH process based model, which was developed and tested to predict nearshore hydrodynamics and morphodynamics during storms. The software was built specifically for coastal environments and has been extensively tested in coastal conditions (de Alegria-Arzaburu et al., 2010; Bolle et al., 2010; McCall et al., 2010; Roelvink et al., 2009; Williams et al., 2012). Previous research has benchmarked the hydraulic components of the XBeach software in a fluvial environment (Hartanto et al., 2011), and found the flow module reliable, providing the upstream boundary conditions are adapted for river flow (e.g. inflow hydrographs). XBeach when run in hydraulic only mode is comparable to commercially used codes such as TELEMAC and Delft3D (numerical formulations can be found in Hartanto et al., 2011), however some limitations in the code for fluvial environments were noted, e.g. the use of a structured mesh (similar to that available in Flood-Modeller2D). Other limitations were noted when modelling supercritical flow conditions (a common occurrence in fluvial environments e.g around or over structures), in particular in dam break scenarios, when a shock is developed over a short period of time.

To continue the initial research and to understand the performance of the morphological component of this code it is necessary to benchmark its performance in fluvial environments. This paper expands on the fluvial benchmarking of XBeach by Hartanto et al. (2011) by assessing the capabilities of the sediment transport and morphological modules, thus, further testing the validity of applying this software in fluvial environments. If successful, this would open up the use of the code for modelling large continental rivers or transitional environments (e.g estuaries).

1.3. Coastal versus fluvial morphological requirements

Although modelling sediment processes in the coastal environment uses similar equations to modelling in a fluvial environment there are significant differences when it comes to the technical set up and requirements for each.

Firstly, significant differences exist in flow requirements. In the fluvial environment flow is typically uni-directional, where nuances in the flow field across the river is key to sediment processes across a river cross-section and down a river reach. In comparison, a coastal environment flow field tends to be dominated by waves and tides working in two or more directions. These present different challenges for modelling packages. For example, a varying upstream flow regime is required in fluvial environments where hydrographs tend to be a standard upstream boundary. The hysteresis effect on sediment transport as a result of fluvial events (e.g. hydrographs) is of great importance when modelling fluvial environments. Additionally, software generally need to be able to deal with supercritical flow conditions which may arise as a result of structures in the river, and the subsequent sediment transport predictions which these entail.

Secondly, the topography requirements differ. In fluvial environments needs tend to include variable bed slope, complex topography (e.g. around features in the river such as dams, bridge abutments etc.) and meander representation, whilst in many coastal environments a more uniform representation is likely. In fluvial modelling, where 1D modelling has been a mainstay, often structures are modelled discretely using separate units. However, this approach is less useful if the morphological impacts around or through a particular structure are of interest. Consequently, it is important to test XBeach using complex topographies to understand morphological response.

Finally, differences exist between coastal and fluvial sediment grain sizes. Sediment in coastal areas tend to be of a largely uniform nature, or from a constrained distribution. However in fluvial settings sediment sizing can vary widely with distributions ranging from boulder sizes to sand or mud grains. In fluvial environments it is common to encounter graded or armoured beds, which may in some instances simplify this issue of widely graded sediments, however, these requirements pose challenges to software developed for coastal environments, and potentially presents limitations for XBeach. Significant flexibility is required in the representation of fluvial environments, and specific additions to the basic sediment equations may be required to account for these differences.

In this paper the applicability of XBeach in the fluvial environment is investigated through a number of key questions:

1. Does XBeach reproduce simple fluvial sediment transport cases? *Benchmark test 1.1 and 1.2*. The capability of the code in a unidirectional flow field to represent (1.1) complex topographical changes and (1.2) the movement of morphologic features such as shoals.
2. How does XBeach perform when compared to laboratory scale results for morphological change through a range of varying fluvial flows (i.e. uni-directional flow fields: steady state (2.1), unsteady single peak event (2.2) and unsteady double peak event (2.3))? *Benchmark test 2*.
3. How does XBeach perform through a dam break scenario with complex topographies, both an idealised test case and laboratory scale results? *Benchmark tests 3 and 4*. This tests the code in significant super-critical flow situations. In fluvial environments super-critical flow can be reasonably common, particularly in response to structures.

The suitability of XBeach is assessed by comparison with laboratory scale data and outputs produced by widely used commercially available software. Where the model is compared to experimental data, the assessment follows a model performance