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.

Keywords: Sediment transport modelling; Morphological changes; XBeach; Flood modelling

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 2D frequently applied and often freely available, are 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 FloodModeller2D). 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 procedure, whereby a comparison between the predictions and observations is undertaken and error statistics calculated (Briers Skills Scores).

2 Methods

The approach taken by this study is to extend the existing hydraulic benchmarking of the XBeach software and test the morphological component of XBeach in fluvial environments systematically (using version 19 of the code, released in 2012). The study addresses the differences highlighted in Section 1.3 using four specific tests, which were designed to challenge the ability of XBeach to model morphological responses to; uni-directional flow fields, hydrographs, super-critical flow conditions and complex topographies. The tests benchmark XBeach against industry standard software (a technique which is popular in research and industry e.g Neelz and Pender, 2010; Hartanto et al., 2011) as well as laboratory tests and experimental data, the standard approach for software development (e.g Soares-Frazão et al., 2012). Benchmark 2 compares the code to experiment data (3 tests), Benchmark 3 compares the software to industry standard software and Benchmark 4 compares the code to experimental results (2 tests), and benchmarks the performance of the code to several available morphological codes. In analysing the results the discussion will return to the three questions posed above. The numerical formulation of XBeach is described in Section 2.1, and the benchmark studies are detailed in Section 2.2.

2.1 XBeach governing equations

XBeach software uses the depth averaged shallow water equations (SWE) and includes capabilities for subcritical and supercritical flow, time-varying wave action balance; wave amplitude effect on wave celerity; and the advection–diffusion equation (Roelvink et al., 2009). This paper uses the depth-averaged SWE as well as the advection–diffusion equation, all wave calculations were turned off. A full explanation of the hydraulic formulation can be found in Hartanto et al. (2011), where some comparison between codes is provided, and Roelvink et al. (2009).

The XBeach model uses depth-average (intra-wave) currents as input in the free stream velocity. Velocity at the bed level is computed by parameterisation of the boundary layer velocity. Next velocity at the bed is used to compute Shields value.

XBeach model uses a depth-averaged advection diffusion equation of Galapatti and Vreugdenhil (1983) to calculate the sediment concentration:

$$\frac{\partial hC}{\partial t} + \frac{\partial hCu^E}{\partial x} + \frac{\partial hCv^E}{\partial y} + \frac{\partial}{\partial x}\left[D_h h \frac{\partial C}{\partial x}\right] + \frac{\partial}{\partial y}\left[D_h h \frac{\partial C}{\partial y}\right] = \frac{hC_{eq} - hC}{T_s} \tag{1}$$

where: C represents the depth-averaged sediment concentration; u^E is the cross-shore Eulerian flow velocity; v^E is the longshore Eulerian flow velocity; D_h is the diffusion coefficient; and C_{eq} represents the source term in the sediment transport equation. The entrainment of the sediment is represented by an adaptation time T_s, given by a simple approximation based on the local water depth, h, sediment fall velocity w_s and a sediment transport depth factor f_{Ts}:

$$T_s = \max\left(f_{T_s}\frac{h}{W_s}, 0.2\right) \tag{2}$$

A small value of T_s corresponds to nearly instantaneous sediment response. The entrainment or aggradation of sediment is determined by the mismatch between the actual sediment concentration and the equilibrium concentration.

The differential equations for the advection-diffusion of sediment is solved using a finite difference approach and the first order up-wind scheme, with the water depths from previous time steps and the corresponding velocities at the updated time step. A detailed description of numerical solution approaches using upwind and central schemes is given in (Ferziger and Peric, 1999; Popescu, 2014).

The bed level update is approximated by:

$$\frac{\partial z_b}{\partial t} + \frac{f_{mor}}{(1-p)}\left[\frac{\partial S_x}{\partial x} + \frac{\partial S_y}{\partial y}\right] = 0 \tag{3}$$

where p represents the porosity; S_x, S_y are the sediment transport rate in x – direction and y – direction respectively and f_{mor} is a morphological factor to speed up the bed evolution. In the equation all variables of type z_b represents bed level, and Δx, Δy and Δt represents step in space and time discretisation respectively. The formula for computing the sediment transport is given by Eq. (4) for the x direction. A similar equation can be written for the y direction. The formula includes an advective, a diffusive and a bed slope term:

$$S_x = c_u \cdot u_{rep,x} \cdot h_u - D_c h_u \frac{\partial C}{\partial s} - f_{slope} \cdot c_u \cdot |v_u| \cdot h_u \frac{\partial z_b}{\partial s} \tag{4}$$

where $u_{rep,s}$ is a representative velocity for suspended transport, D_c is the horizontal diffusion coefficient and f_{slope} a correction coefficient accounting for the bed-slope effect.

Different sediment transport equations, calculating total, bed and suspended loads, are implemented into the software to allow flexibility in modelling different types of environment. These are the Soulsby–Van Rijn (Soulsby, 1997) and the Van Rijn formulations (Van Rijn, 2007), modified by Van Thiel de Vries (2009).

The sediment equilibrium concentration from the Soulsby–van Rijn equation is determined as follows:

$$C_{eq} = \frac{A_{sb} + A_{ss}}{h}\left(|u^E| - u_{cr}\right)^{2.4}(1 - \alpha_b m)$$

$$A_{sb} = \frac{0.005h\left(\frac{d_{50}}{h}\right)^{1.2}}{[(s-1)gd_{50}]^{1.2}}$$

$$A_{ss} = \frac{0.012d_{50}D_*^{-0.6}}{[(s-1)gd_{50}]^{1.2}}$$

$$D_* = \left[\frac{g(s-1)}{v^2}\right]^{1/3}d_{50} \tag{5}$$

where the bed load coefficients A_{sb} and the suspended load coefficient A_{ss} are the functions based on the sediment grain size. The threshold current velocity u_{cr} is valid for $d_{50} = 0.1$–2 mm. The coefficients α_b, and m denote the calibration factor of bed-slope. The relative density of sediment $s = \rho_s/\rho_w$.

The sediment equilibrium concentration from the van Rijn equation is determined as follows:

$$C_{eq} = \frac{A_{sb}}{h}\left(-u_{cr}\right)^{1.5} + \frac{A_{ss}}{h}\left(u^E - u_{cr}\right)^{2.4}$$

$$A_{sb} = \frac{0.015h\rho_s(d_{50}/h)^{1.2}}{((s-1)gd_{50})^{0.75}}$$

$$A_{ss} = \frac{0.012d_{50}\rho_s D_*^{-0.6}}{((s-1)gd_{50})^{1.2}} \tag{6}$$

where A_{sb} and A_{ss} are the bed load coefficient and suspended load coefficient, respectively. These formulae have been empirically derived from laboratory experiments and are typically valid over a constrained sediment distribution. Therefore the choice of formula for a given study is dependent on the physical characteristics of the modelled environment and user discretion.

In order to account for dune erosion avalanching, the bed slope evolution is corrected with a term. Avalanching appears when a critical bed-term (defined by the user) is exceeded.

For the morphological calculations, the local profile of the suspended sediment concentration is governed by the one-dimensional vertical advection–diffusion equation. Its inherent non-linearity has attracted the use of numerical methods rather than analytical methods. Numerical approaches allow the use of a concentration-dependent settling velocity as well as time and space-varying eddy diffusivity profiles, whereas analytical approaches tend to assume that the settling velocity and the eddy diffusivity coefficient are constant or in a simple functional form and the water depth is often assumed to be semi-infinite. Only a limited number of analytical solutions are available for the one-dimensional vertical advection–diffusion equation: time harmonic and time average analytical solutions of the finite water depth, for instance (Absi, 2010; Jung et al., 2004). The majority of sediment-transport models use the finite difference method to solve the governing partial differential equations (Ackers and White, 1973; Betrie et al., 2011; van Griensven et al., 2013), hence with this XBeach is comparable to many available codes. The choice of numerical techniques for a particular situation is based on accuracy, stability, and convenience (Alsina et al., 2009; Elkholy and Chaudhry, 2012; Harris and Wiberg, 2001).

2.2 Benchmarking cases

A series of four benchmark cases, specific to fluvial morphological change, were set up to test the applicability of XBeach in the fluvial environment (Table 1).

- Benchmark 1: Simple test cases: *Uniform sediment transport and shoal development*

- Benchmark 2: Laboratory tests: *Uni-directional flow fields (steady flow, hydrographs)*

- Benchmark 3: Idealised dam break: *Complex topographies and super-critical flow*

- Benchmark 4: Laboratory dam break: *Complex topographies and super-critical flow*

Table 1 Description of benchmark cases.

Test	Name	Description
1.1	Benchmark case 1.1	Idealised rectangular channel with narrowed section, uniform sediment transport. Run set up parameters detailed in Table 2
1.2.a	Benchmark case 1.2.1	Idealised rectangular channel, with 3 m high shoal.
1.2.b	Benchmark case 1.2.2	Run set up parameters detailed in Table 2
1.2.c	Benchmark case 1.2.2	
2.1	Benchmark case 2.1	Laboratory scale tests: Sediment movement under uni-directional flow fields:
2.2	Benchmark case 2.2	2.1. Steady flow conditions 2.2. Single flood wave conditions 2.3. Double flood wave conditions
2.3	Benchmark case 2.3	Run set up parameters detailed in Table 2
3.1	Benchmark case 3.1	Idealised dam break over a valley.
3.2	Benchmark case 3.2	Flood wave propagation and associated sediment processes through a river valley. Comparison to Delft3D predictions. Run set up parameters detailed in Table 2.
3.3	Benchmark case 3.3	
3.4	Benchmark case 3.4	
4.1	Benchmark case 4.1.a and 4.1.b	4.1. Laboratory scale test: Single dam break
4.2	Benchmark case 4.2. a and 4.2.b	4.2. Flood wave propagation and associated sediment processes following a dam break. Run set up parameters detailed in Table 2. Note: letter a and b in the two cases refer to two discretization grid sizes.

Table 2 Models Set-up for each benchmark case.

Parameter	Benchmark 1.		Benchmark 2			Benchmark 3		Benchmark 4	
	1.1	1.2	2.1	2.2	2.3	3.1 and 3.3	3.2 and 3.4	4.1.	4.2.b
Dx × Dy [m] × [m]	5 × 5		0.1 × 0.15			50 50		0.1 × 0.1 and 0.05 × 0.05	
No of cells on x and y direction	600 × 40	6000 × 40	220 × 5			256 × 244		286 × 92	572 × 184
Sediment formula[a]	SVR	SVR And VR	SVR			—	VR	SVR	
D_{50} [mm]	0.5		2			—	0.2	1.6	
Boundary conditions Upstream Q - discharge [m³/s]	Steady Q = 1500		Steady Q = 0.041	Unsteady Q = 0–0.0582	Unsteady Q = 0–0.0557	Unsteady Q = 0–3000		Steady Q = 10^{-5}	Steady Q = 10^{-5}
Boundary conditions Downstream Q - discharge [m³/s]	Steady Q = 1500		Absorbing boundary			**In XBeach:** absorbing boundary **In Delft 3D:** Neumann boundary condition		Steady Q = 10^{-5}	Absorbing boundary

		45.5	60			50		50	85
Chézy roughness [m$^{1/2}$/s]		45.5	60			50		50	85
Time step [sec]		0.23	0.02			1.8	1.7	0.013	
Total simulation time span [hrs]		480	40	4		30		20	

[a] Note: SVR is the abbreviation used for Soulsby van Rijn; VR is the abbreviation used for VR.

Output is compared to results from laboratory scale test results and outputs from similar, commercially available software. Where comparisons are possible (between modelled and experimental data) model performance is evaluated using a Brier Skill Score (as detailed in Section 43.1 equation 7).

Each of the benchmarking cases was set-up in XBeach with parameters as described in Table 2.

2.2.1 Benchmark 1: simple test cases Uniform sediment transport and shoal development

2.2.1.1 Test 1.1. River narrowing and widening General widening and narrowing of a river creates particular hydraulic conditions, which result in morphological changes. Narrowing of the river channel can occur for many reasons including land reclamation, navigational necessity or engineering requirement (e.g. bridge abutments). River narrowing increases velocity, and subsequently bed shear stress, in the main channel and may cause some undesirable long term morphological changes such as bed degradation. The degree of upstream or downstream aggradation depends on the length of the narrowed part. This may cause problems to the foundations of structures along the river and increases the chance of bank failure. Consequently an idealised channel narrowing was selected as a key benchmarking test.

This test uses a rectangular channel 3000 m long (Fig. 1) configured with a narrowed section of 1000 m long and 150 m wide (compared to 200 m wide in the remainder of the channel) in the central 1000 m. XBeach run parameters are detailed in Table 2.
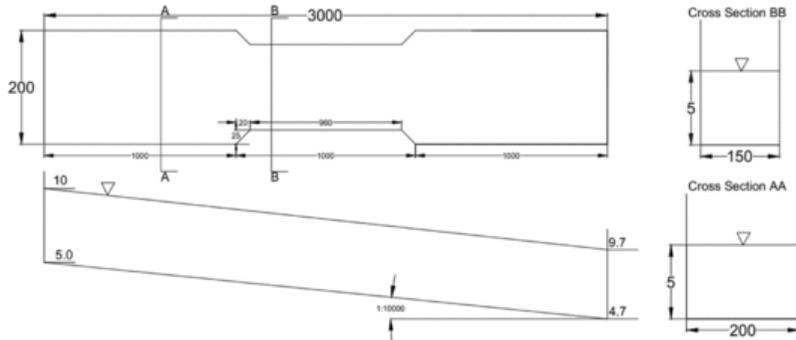

Fig. 1 Benchmark test 1.1 set-up showing the plan (with the numerical mesh indicated), long-section and cross-section through the model. All dimensions are given in metres.

2.2.1.2 Test 1.2. Shoal migration The migrational variations of the bed slope (e.g. shoals or trenches) through river reaches is of great interest in fluvial environments and is an important consideration when investigating long-term morphological trends in rivers, characterised by such features. It is important to test the capability of the code to predict the movement of such features along the river. Test 1.2 uses an idealised set-up to test shoal migration by the software. The test uses a rectangular channel (Fig. 2). Run parameters are detailed in Table 2.
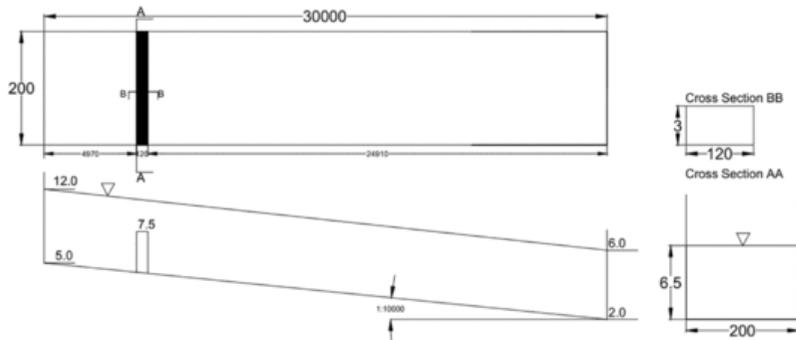

Fig. 2 Benchmark test 1.2 set-up showing the plan (with the numerical mesh indicated), long-section with the location of the shoal and cross-section through the mode. All dimensions are given in metres.

Three different scenarios were investigated to understand the influence of the numerical scheme and sediment transport equation on the eventual predictions. Each scenario included a 3 m high shoal placed 1500 m down the channel, and tracks its migration over 40 h.

A centred scheme for sediment transport, which is 2nd order accurate was compared with a first order upwind scheme. An upwind scheme is more diffusive, but more stable, than a centred scheme.

2.2.2 Benchmark 2: Laboratory tests: uni-directional flow fields (steady flow, hydrographs)

In rivers, flood flows are particularly responsible for episodic movement of river beds (Kashyap et al., 2012; Merritt et al., 2003). Test 2 is designed to benchmark the capability of XBeach in the uni-directional flow environment, against measured data, and tests the capability of XBeach to simulate sediment transport processes during typical fluvial flow events simulated at laboratory scale (Fig. 3). The model replicates the laboratory set up and has an immobile bed at the upstream end of the reach and a mobile bed of $D_{50} = 2$ mm through the comparison reach. The test uses three different flow conditions (Fig. 4) at the upstream boundary: steady state conditions of 0.04 m^3/s; a simulated single peak flood wave of unsteady flow conditions rising to 0.055 m^3/s; and a double peak flood wave rising to a magnitude of 0.055 m^3/s as described in Wang et al. (2013). At the upstream boundary there is no sediment influx applied, resulting in overall degradation of the flume test bed. Run parameters for the XBeach simulations are detailed in Table 2.
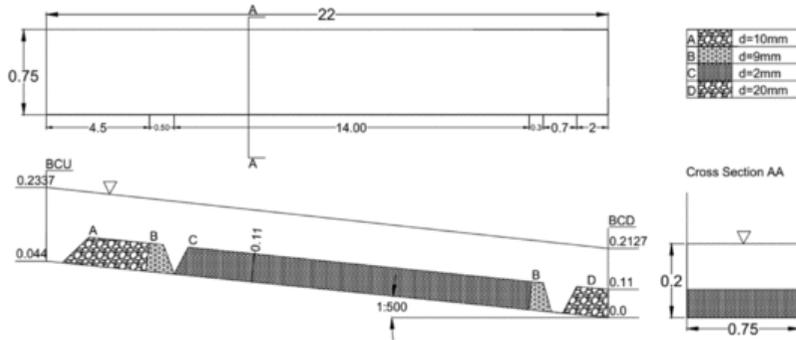

Fig. 3 Benchmark 2 set-up (Laboratory scale) showing the plan (with the numerical mesh indicated), long-section and cross-section through the flume and bed sediment details. All dimensions are given in metres.
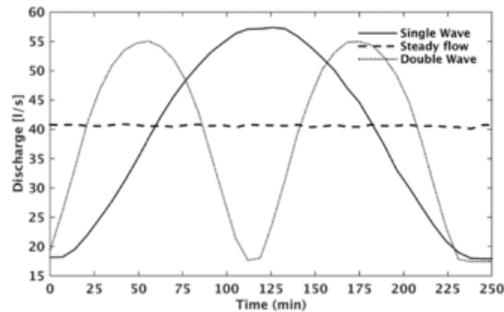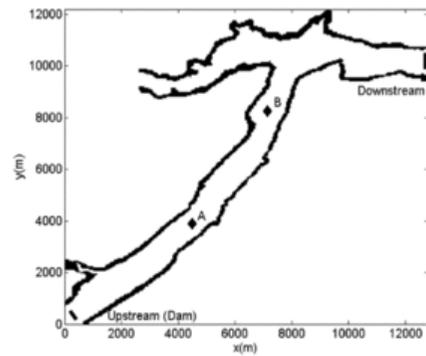

Fig. 4 Upstream Boundary conditions for Benchmark 2 (2.1 Steady flow, 2.2 Single wave input hydrograph, 2.3 Doublewave input hydrograph).

XBeach was calibrated to the hydraulic conditions in the flume by systematically varying the flow resistance coefficient (Chézy) to provide best agreement with the water levels 4.5 m from the upstream end of the flume (Fig. 3).

2.2.3 Benchmark 3: Idealised dam break: complex topographies and super-critical flow

Benchmark 3 tests the capability of XBeach to simulate sediment transport processes during an idealised dam break scenario. The test uses the set-up from Test 7 of the EA2D tests (Neelz and Pender, 2010), as described in Hartanto et al. (2011), and models the simulation of flood wave propagation following a dam failure in a river valley (Fig. 5). The software should replicate a high burst discharge over steep and mild bed slopes involving both subcritical and supercritical flow as demonstrated by Hartanto et al. (2011). This benchmark test is extended to include morphological prediction as a result of the hydraulic event. This is an idealised test. The predictions from XBeach are compared directly to a Delft 3D morphological model set up and parameterized in exactly the same manner (see Table 2). Here we follow the approach used in the EA2D tests (Neelz and Pender, 2010) to compare the performance of different codes for idealized test cases. As Delft3D is considered industry standard, is widely used for morphological simulation, and is routinely used in coastal, transitional (estuarine) and fluvial environments it provides a good comparison for the XBeach software. Run parameters are detailed in Table 2 and the set-up is shown in Fig. 5.

(a)
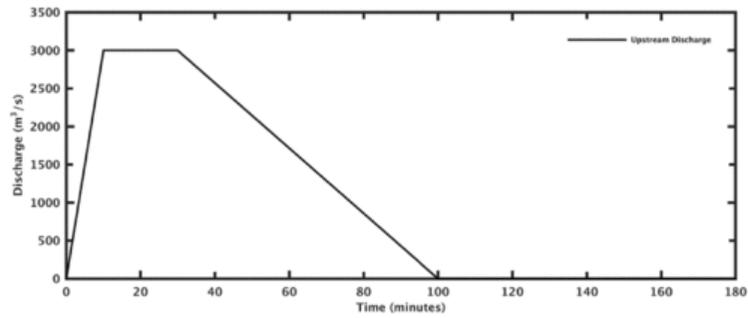
(b)

Fig. 5 (a) Benchmark 3 set-up, with measuring points A and B; (b) Upstream Boundary condition for Benchmark 3.

2.2.4 Benchmark 4: laboratory dam break: complex topographies and super-critical flow

Fast transient and super-critical flows, such as those induced in a dam break scenario can cause significant problems to downstream reaches and those occurring over a mobile bed pose a separate challenge, with predictions of sediment transport rate often reaching similar magnitudes to that of the flow rate (Soares-Frazão et al., 2012). Consequently test 4, furthers the work started in test 3 but benchmarks the performance of XBeach against laboratory experimental results of dam break flows over mobile beds. Additionally XBeach results are compared to the performance of other software tested by Soares-Frazão et al., (2012) in their paper. Two sub-tests are completed firstly with an initially dry bed (Test 4.1) and then with an initially wet bed (Test 4.2).

The laboratory data used for comparison are as reported in Soares-Frazão et al., (2012). The experimental set-up is presented in Fig. 6 and the run parameters are detailed in Table 2. The initial water level in the reservoir is denoted by z_0, while the initial water depth in the downstream part is denoted z_2. The sand bed layer thickness is kept the same for both experiments and the values of water level and bed elevation are given in Table 3. As described in the original paper of Soares-Frazão et al., (2012) where other morphological codes are compared to the experimental data, no calibration was undertaken. The model was set up following the blind benchmark assumption with the Chézy coefficient as 55 $m^{1/2}/s$.
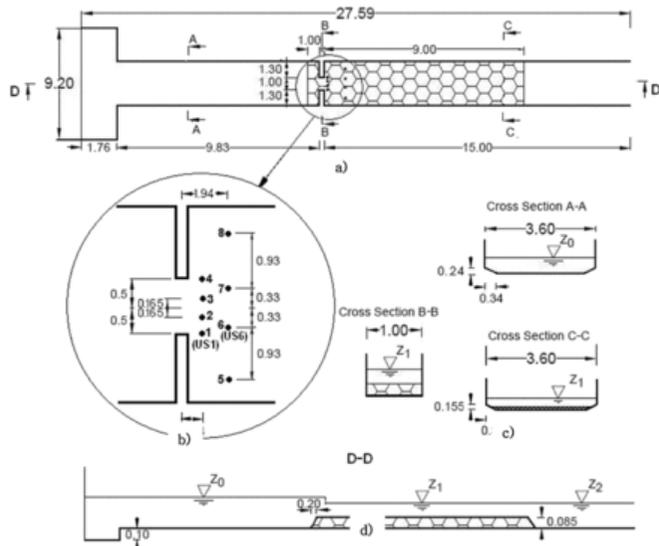
Fig. 6 Benchmark test 4 set-up (Laboratory scale dam break) where a) Plan view of the flume; b) Position of the measuring points 1 to 8; c) Flume cross-section; d) Flume long-section.

Table 3 Benchmark case 4.

c	Case 4.1		Case 4.2
z_0 [m]	0.470		0.510
z_1 [m]	0.085		0.150
z_2 [m]	0.000		0.150

Remark: Parameters in Table 3 represents elevation and distances. Please see Fig. 6, where they are represented.

3 Results

3.1 Model performance

Due to the complex geometry and channel configurations that occur in fluvial environments; and the inherent lack of validation data, model application is generally considered acceptable if they can produce an order of magnitude assessment of the observed aggradation/degradation patterns (e.g. Shvidchencko and Pender, 2008). However, as the results presented here are compared with experimental data, it is more appropriate to quantify the models ability to reproduce the morphology.

In Benchmark tests 2 and 4 the accuracy of the model simulations against observations were assessed using a statistical method comparing the error between prediction and observation. This paper uses a Brier Skill Score (BSS) which has become common practice within coastal morphodynamic modelling and, in particular, with XBeach (Pender and Karaunarathna, 2013; Roelvink et al., 2009). The BSS compares the mean square difference between the prediction and observation, with the mean square difference between the baseline and observation. The formula for calculating the BSS is outlined below, with a score of 1 indicating perfect agreement and 0, the baseline conditions.

$$BSS = 1 - \left[\frac{\langle |z_p - z_m|^2 \rangle}{\langle |z_b - z_m|^2 \rangle} \right] \tag{7}$$

where: z_p are the model predicted profile points; z_b are the measured baseline points (i.e. the initial bed level); and z_m are measured final points. For classification of the BSS, Van Rijn et al. (2003) state that: BSS < 0, 'bad'; 0–0.3, 'poor'; 0.3–0.6, 'reasonable/fair'; 0.6–0.8, 'good'; and 0.8–1.0, 'excellent'.

3.2 Benchmark 1: simple test cases Uniform sediment transport and shoal development

3.2.1 Test 1.1. River narrowing and widening

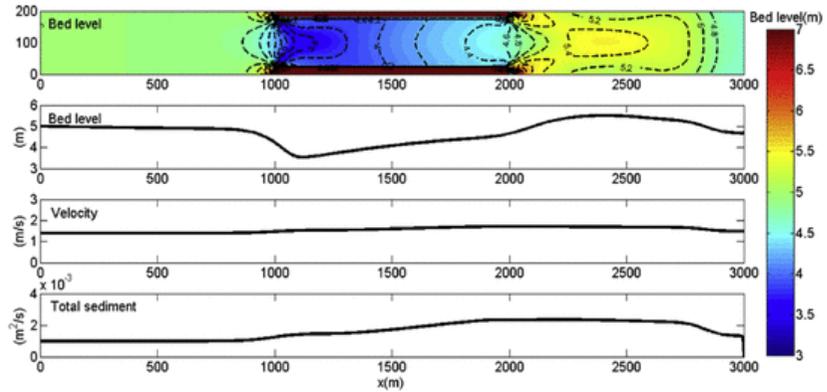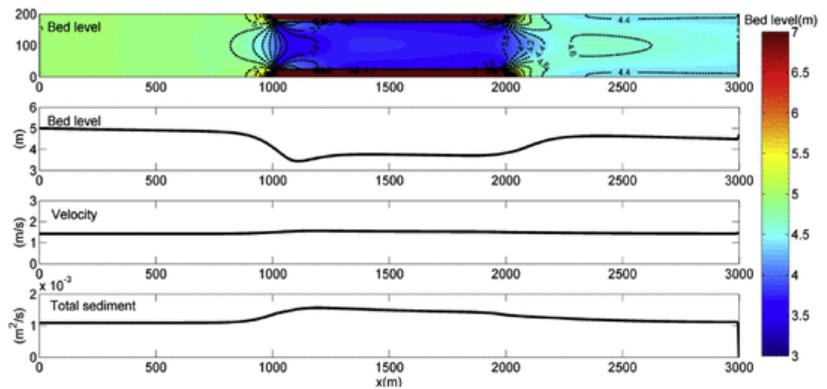Fig. 7 shows the results predicted by XBeach for Test 1.1 at three different times through the simulation: the beginning of the run (5 h), at 80 h, and at the end of the simulation time (at 480 h). The results indicate that the velocity increases through the narrowed section until the model tends towards equilibrium and the velocity becomes stable throughout the domain. This variation drives morphological changes. Degradation is evident at the entrance to the narrowed section, and along its length. When the simulation tends towards equilibrium, a deeper channel is observed through the narrowed section. This section is approximately 1 m deeper than the original channel throughout. These results are a direct effect of the predicted velocities and associated sediment transport. Finally, the sediment transport rate predictions tend towards equilibrium in the last time slice and show greater sediment transport potential through the narrowed section as a result of the different hydraulic conditions in the domain.
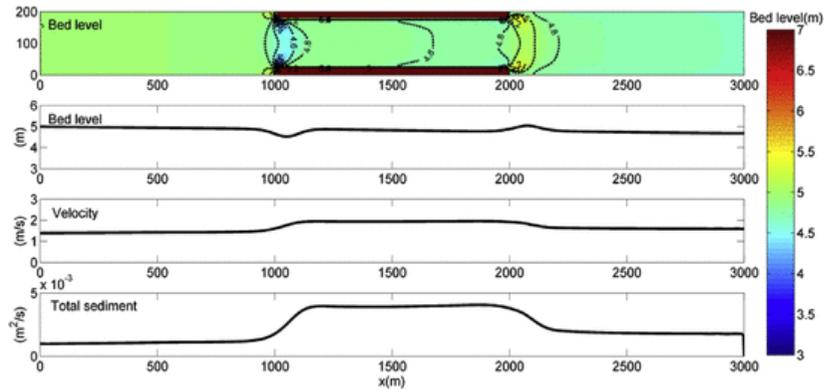
i)

ii)

iii)

Fig. 7 Test 1.1. Bed elevation, bed evolution, velocity and total sediment transport at i) 5 h s; ii) 80 h s and iii) 480 h s.

3.2.2 Test 1.2: Shoal migration

Fig. 8 shows the results predicted by XBeach for Test 1.2 Comparing scenario 1.2.1 and 1.2.3 allows a comparison of results from the Upwind and Central schemes. Only small differences are observed in the distance the shoal has travelled (approximately 5 m over 40 h). The motion of the shoal is faster when the Central scheme is used. Comparing scenario 1.2.1 and 1.2.2 highlights the differences in predictions when using the Soulsby–Van Rijn and the Van Rijn equations. Observations indicate that using the Soulsby–Van Rijn equation predicts significantly quicker migration of the shoal than using Van Rijn (approx. 20–50 m over 40 h).
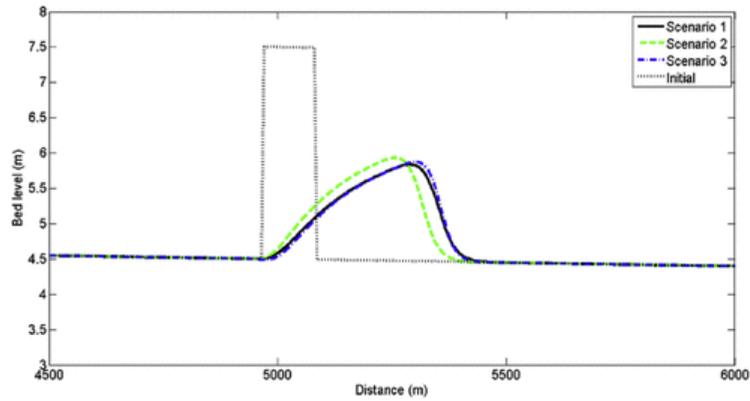
Fig. 8 Benchmark test 1.2. Longitudinal plot of predicted shoal migration at the end of the run (Benchmark 1.2.1: Scenario 1; Benchmark 1.2.2: Scenario 2 and Benchmark 1.2.3: Scenario 3).

3.3 Benchmark 2: laboratory tests: uni-directional flow fields (steady flow, hydrographs)

Final bed level results for the simulations are provided in Fig. 9, where XB01 and XB02 refer to the results from XBeach simulations with the Soulsby–van Rijn (XB01) and van Rijn (XB02) transport formula respectively.
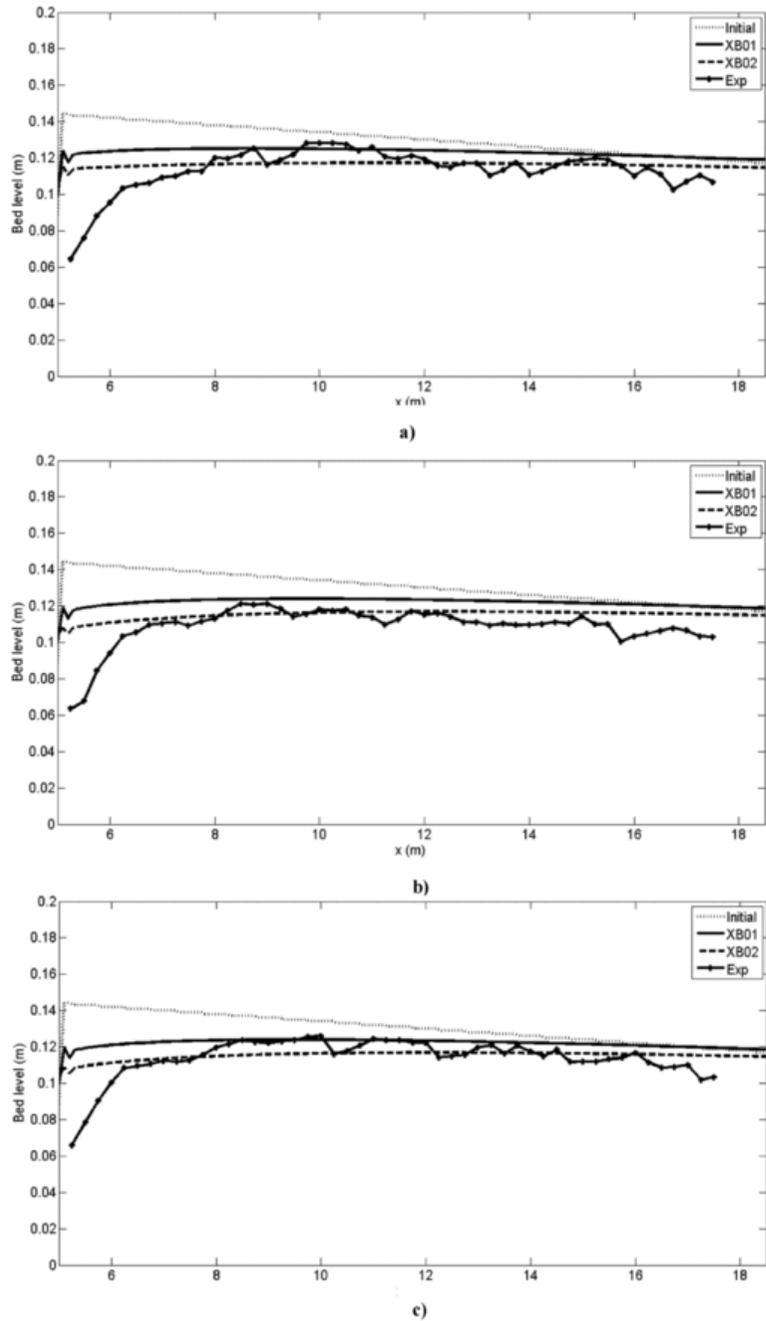
Fig. 9 Benchmark test 2: a) 2.1 Steady flow; b) 2.2 Single wave hydrograph; c) 2.3 Double wave hydrograph, XB01 case uses Soulsby van Rijn formula and XB02 case uses Van Rijn formula.

From these results it can be seen that, overall, XBeach produces comparable results to those obtained in the laboratory. However, the model fails to replicate the degradation observed at the upstream and downstream boundary of the flume for all three

simulations (steady state, single wave and double wave). The results of XB02 tend to be better than those of XB01, resulting in closer predictions along the length of the flume. The BSS results (Table 4) support this with greater scores for XB02. Overall the BSS do

not fall below 0.60, which demonstrates a 'good' level of agreement based on the classification of Van Rijn et al. (2003). Additionally, for the prolonged higher energy double event, the BSS suggest an 'excellent' agreement to the experimental results, with a BSS of 0.82 when the van Rijn transport regime is used. The success demonstrated by these scores can be attributed to the average level of degradation along the flume rather than the ability of the model to reproduce the actual morphodynamic response of the bed.

Table 4 Brier skill scores for BM2.

Model	Case	Code identifier	Sediment equation	Briers skill score
XBeach	Steady state	XB01	Van Rijn	0.60
	Steady state	XB02	Van Rijn	0.77
	Single event	XB01	Soulsby van Rijn	0.62
	Single event	XB02	Van Rijn	0.77
	Double event	XB01	Soulsby van Rijn	0.68
	Double event	XB02	Van Rijn	0.82

Table 5 Brier Skills Scores for longitudinal predictions for BM4 at US1.

Run	Grid size	Brier skill score −1 m from centre line	Brier skill score centre line	Brier skill score +1 m from centre line
4.1	0.1 m by 0.1 m	0.28	0.63	0.39
	0.05 m by 0.05 m	0.01	0.63	0.21
4.2	0.1 m by 0.1 m	0.53	0.75	−0.51
	0.05 m by 0.05 m	0.63	0.42	−0.16

3.4 Benchmark 3: idealised dam break: complex topographies and super-critical flow

The results predicted by XBeach and Delft3D (Industry standard software for both fluvial and coastal environments) are shown in Fig. 10. Results a), c) and e) in the figure show total sediment transport, velocity and water level comparisons between XBeach and Delft3D at point A upstream near the dam; and b), d) and f) show the same parameters for point B further downstream. Detailed assessment of the results indicate the following.

- In Fig. 10 a and b (sediment transport). At both point A and B the predictions of Deft3D are significantly higher (magnitude of 0.95 m3/s/m2 at point A and 0.3 m3/s/m2 at point B) than the predictions of XBeach (magnitude of 0.08 m3/s/m2 at point A and 0.05 m3/s/m2 at point B)

- In figure in Fig. 10c (point A) velocity:

  - Delft3D-H have a peak velocity of approx. 2.5 m/s at approx. 1 hr, while the XBeach-H results have a peak velocity of approx. 2.2 m/s at approx. 1 h.

  - Delft3D-M results have a peak velocity of 3.5 m/s for approx. 3 hrs (between hours 1 and 4, short period of instability between hours 4 and 5), while XBeach-M results have a peak of 3.2 m/s at 2 h, followed by a period of significant instability from hr 3 onwards;

- In Fig. 10d (point B) velocity:

  - Delft3D-H results have a peak velocity of approx. 3.3 m/s at approx. 1.8 h, and XBeach-H results have a peak velocity of approx. 2.5 m/s at approx.1.5 h

  - Delft3D-M results have a peak of 3.4 m/s at approx. 1.8 h, while XBeach-M results have a peak of 2.8 m/s at 1.5 h.

- In figure in Fig. 10e (point A) water level,

  - Delft3D-H reports a maximum water of 167 m at approx. 1 hrs, while XBeach-H reports a maximum water of 165.8 m at approx. 1 hrs

- Delft3D-M reports a maximum water of 165.5 m at approx. 1 hrs, while XBeach-M reports a maximum water of 165.8 at approx. 1 hrs;

- In figure in Fig. 10f (point B) water level,

  - Delft3D-H reports a maximum water of 151.5 m at approx. 2 hrs, while XBeach-H reports a maximum water of 152.2 m at approx. 1 hrs

  - Delft3D-M reports a maximum water of 151.4 m at approx. 2 hrs, while XBeach-M reports a maximum water of 152.2 m at approx. 2 hrs;
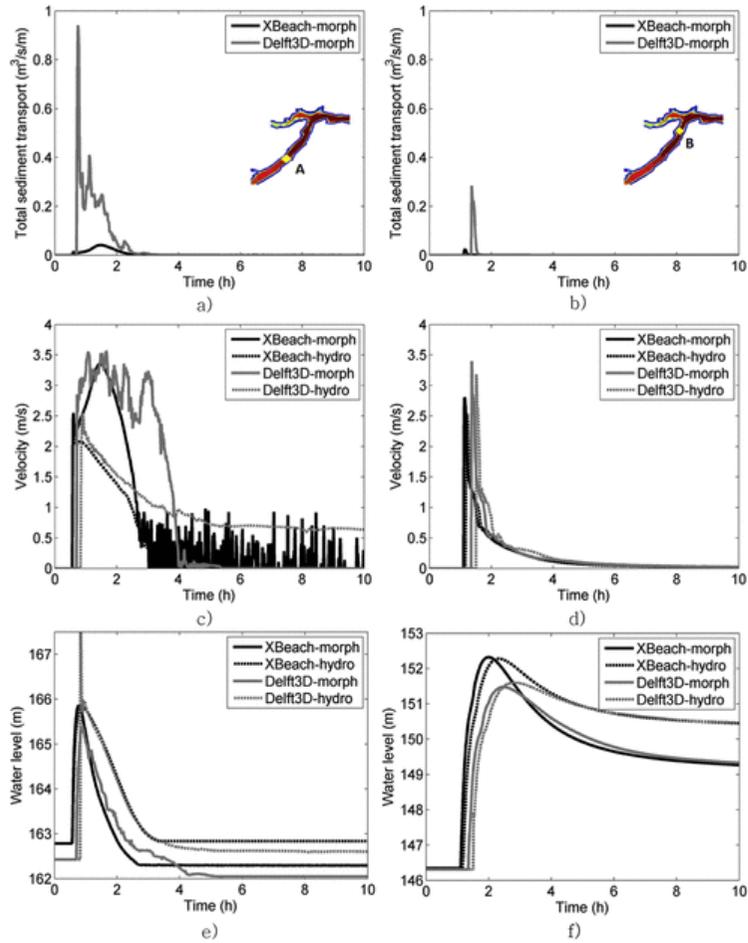
Fig. 10 Benchmark 3: total sediment transport (a, b), velocity (c, d) and water level (e, f) plots for point A and B in the model.

Water level predictions at point A indicate that when run in the hydraulic mode only Delft3D peak water levels are significantly higher than XBeach water levels. When run in morphological mode the peak water level predictions reduce significantly by approximately 1500 mm. At point B the differences are small, the values and trend of the two models are comparable in both hydro and morpho mode. Similarly, when examining the final water levels it is clear that both XBeach and Delft3D in morphological mode predict significantly lower water levels, than in hydrodynamic mode. This is in part due to the bed deformation that has occurred during the simulation, indicating the importance of including the morphology in predictions of this nature.

Velocity predictions by XBeach and Delft3D, when run in the morphological mode, show a different peak velocity prediction at location A of approximately 0.3 ms^{-1}, which is similar to the difference between XBeach-H and Delft3D-H predictions. The

magnitude of the velocities predicted in the morpho versions of the code is however approximately 1 ms^{-1} higher for both software. Delft3D-M predicts higher velocities (of 0.3 ms^{-1}) for a longer period of time than XBeach (approximately 1.5 h longer)., XBeach-M shows a significant numerical instability in prediction (hour 3 until the end), which is also evident in the Delft3D-M simulation, although less so (only between hour 4 and 5). These differences in water level and velocity predictions translate to clear differences in total sediment transport rate (m^3/s/m^2) prediction, with Delft3D predicting a much higher total sediment transport rate over the period of the simulation and a significantly higher degradation (order of magnitude higher).

It is interesting to note that, when run in hydrodynamic mode, the peak velocity and water level of XBeach is comparable to other commercially available fluvial modelling software. This highlights XBeach as a potentially viable modelling option for simulating fluvial hydraulics. However adding the morphological calculations result in different outcomes. Since this is an idealised test (i.e. there are no real data to compare to) only comparisons can be drawn between the performance of the different software, whereDelft3D is considered to be industry standard. Consequently the code is tested against laboratory experimental results in benchmark 4.

3.5 Benchmark 4: laboratory dam break: complex topographies and super-critical flow

Figs. 11 and 12 present the results of the Benchmark 4. Despite the complexity of the scenario it is clear that XBeach is capable of simulating fast transient flows with significant morphological evolution. Water level predictions are compared at gauges US1 and US6 (Fig. 6) with the ones given by Soares-Frazão et al., (2012), while bed profiles are mapped and compared in profile through the flume (centreline and –1 and 1 m transects). Finally BSS scores are calculated (Table 5).

Final bed topography maps for run 4.1 for a grid sizes of 0.1 m and 0.05 m, as well as experimental results obtained are presented in Fig. 11a)–c) respectively. The bed level profile through flume centreline, for test 4.1 is represented in Fig. 11d). Similarly the final bed topography for XBeach test 4.2 for two grid sizes; 0.1 m and 0.05 m; experimental results and bed level profile through the flume centreline in Fig. 12a)–d) respectively. Water level predictions for test 4.1 at flume location US1 and US6 are presented in Fig. 13a) and b) respectively. Water level predictions for test 4.2 at flume location US1 and US6 are presented in Fig. 13c) and d) respectively.

Fig. 11 Benchmark 4.1 a)Final bed topography maps for XBeach (Grid size 0.1 m),b) Final bed topography maps for XBeach (Grid size 0.05 m; c) Experimental results;d) Bed level profile through flume centreline.

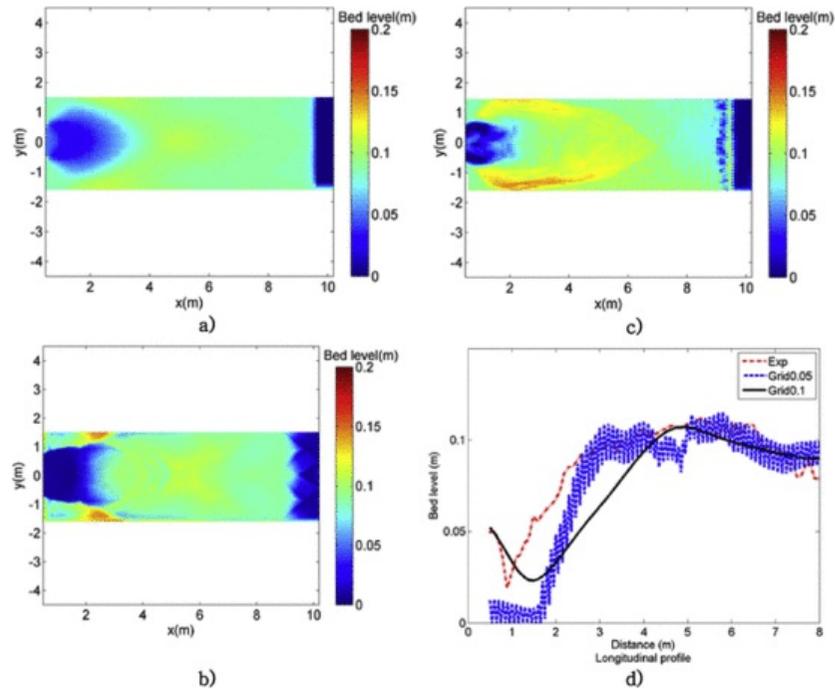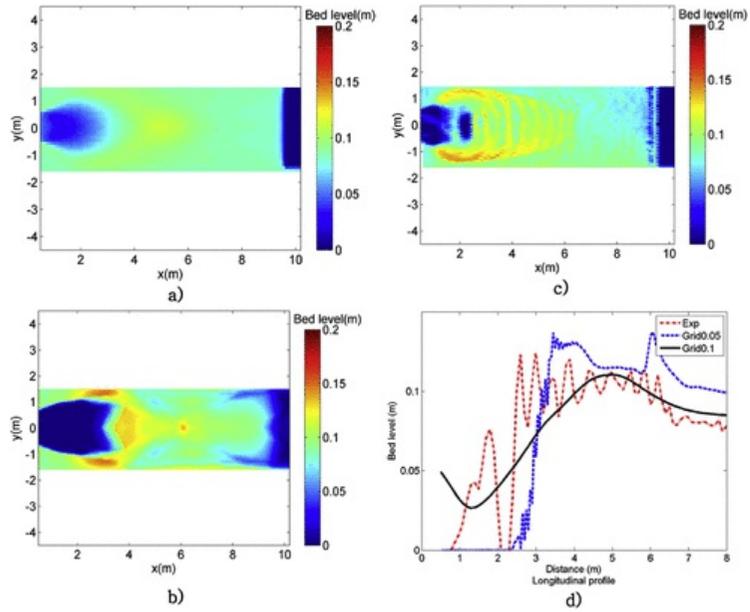**Fig. 12** Benchmark 4.2 a)Final bed topography maps for XBeach (Grid size 0.1 m),b) Final bed topography maps for XBeach (Grid size 0.05 m; c) Experimental results; d) Bed level profile through flume centreline.
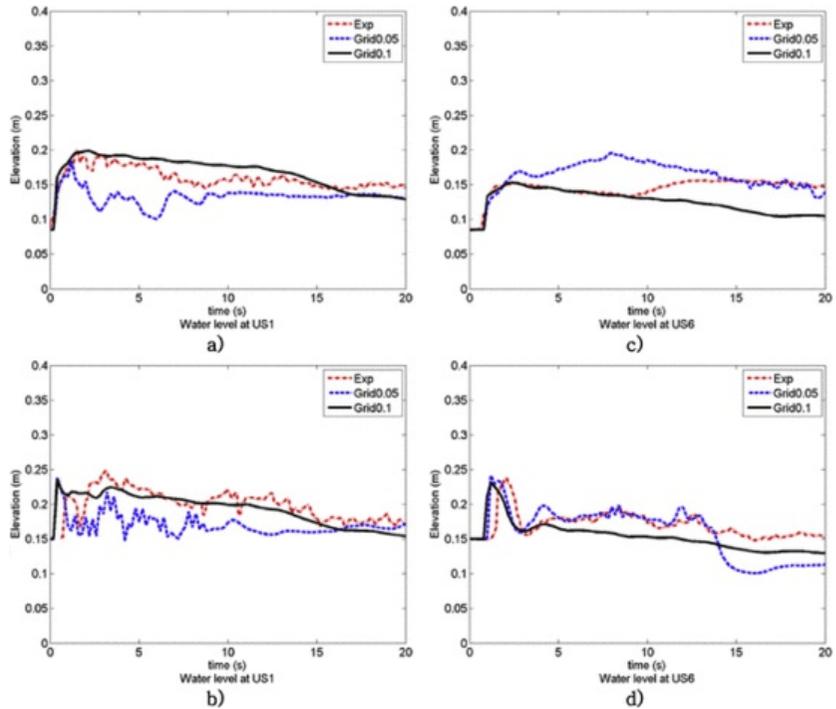

Fig. 13 XBeach Water level predictions a)Test 4.1, flume location US1, b) Test 4.1, flume location US6, c)Test 4.2, flume location US1, d) Test 4.2, flume location US6.

General observations of the results indicates that XBeach follows the general trend for software observed by Soares-Frazão et al., (2012) (who tested several software). Water level predictions have reasonable correlation with those recorded in the laboratory but the final bed predictions are generally under estimated. Similar to that observed by Soares-Frazão et al., (2012), the predictions of water levels by XBeach are better for run 4.2 than for test 4.1, which is in agreement with the other software tested by Soares-Frazão et al., (2012). At US1 both grid sizes predict reasonable agreement with the experimental results, with the 0.1 m grid showing marginally better results. This gauge is located close to the corner of the dam abutment and picks up the 2D spreading effects of the wave.

Both simulated final bed topographies and bed profiles through the centre of the flume allowed comparison of the morphological predictions. Similar to the other tested software by Soares-Frazão et al., (2012), XBeach was found to predict the occurrence of scour downstream of the dam break site in both cases. However, the shape and amplitude of the downstream aggradation is variable and tends to be underestimated. Comparison between results predicted using the two different meshes highlighted grid dependencies. Unlike the finding reported in Soares-Frazão et al., (2012) using a finer grid did not make a significant improvement on predictions. Comparing the BSS in Table 4, looking at the centreline first, it is evident that the XBeach model is providing "good" morphological model predictions for three of the four scenarios under complex fluvial flows. However when the two transects away from the centreline are compared it is clear that a much poorer prediction is available. The reason for this is evident in Figs. 11 and 12 where it is clear that XBeach predicts significant erosion at the upstream end of the flume whereas the experiment shows deposition.

It should be noted that XBeach uses Shields curve to estimate the threshold of sediment mobilization and there is no current option with which to experiment with other thresholds (e.g. Parker et al., 2003). From the findings of Soares-Frazão et al., (2012), this may lead to increased transport predictions compared to the traditional Shields curve approach.

4 Discussion

Firstly, the results of the benchmark tests are used to examine the morphological performance of XBeach in selected fluvial environments and then the discussion returns to the questions posed at the start of the paper.

The simplified benchmark tests (1.1 and 1.2) highlight the influence of the numerical scheme, and chosen sediment transport formula on morphological prediction. The movement of features such as bed forms (e.g. a shoal) is faster when the Central scheme is used because this is less diffusive than the Upwind scheme and is second order accurate. Similarly, the choice of sediment equations influences the speed of the shoal motion. Closer inspection of the embedded codes indicates that suspended and bed load transport are considered separately in both equations however the bedload rate in the more recent van Rijn formulation tends to be lower than that predicted by the Soulsby–van Rijn formulation. This arises from the different derived coefficients of A_{sb} (Eqs. (5) and (6)) which has had the effect of reducing the speed of the shoal migration through the channel.

Benchmarking the performance of XBeach in complex fluvial flows to laboratory results (Test 2) suggests that XBeach is capable of providing reasonable morphological predictions. While specific bed forms observed in the laboratory are not replicated well by XBeach, general bed level changes are simulated to a degree of accuracy for the use within field site modelling studies (e.g. Callaghan et al., 2013; McCall et al., 2010; Pender and Karaunarathna, 2013). Differences between the laboratory predictions and model results can be explained by examining the sediment transport module code. Both the available transport equations (Soulsby–van Rijn and van Rijn formulae) are more suited to coastal environments where the sediments are finer. The sediment in this test has a D_{50} of 2 mm, and with the laboratory conditions predominantly bed load transport occurs. Due to the flume configuration, it is suggested that the transport rate is almost at capacity, which the combination of the current transport equations and the advection-diffusion scheme cannot satisfactorily replicate at this scale. If these results are considered alongside the results from test 1.2 where detailed morphological movement of bed forms was tested it suggests that XBeach is capable of reproducing the general morphological trends in fluvial environments to the correct magnitude but is insufficient at representing the high levels of erosion, and detailed bed forms, that can occur during a flood hydrograph.

Benchmark 3 and 4 tested the performance of XBeach in super-critical flows and with complex topographies. In benchmark 3, both Delft3D and XBeach exhibit numerical instabilities as the simulation progresses. This indicates that the hydrodynamic modules of these codes are not able to capture the full range of conditions exhibited during this complex case. The instabilities for XBeach are observed in the velocity predictions (point A Head of the valley) at the end of the run as the water moves out of the domain and are of significant magnitude (~1 ms^{-1}). This is likely to be as a result of water going out of the computational domain. Some instabilities (of lower magnitude) in the velocity predictions of Delft3D at the same point are observed, however these may be linked to the speed of bed development during this time. These instabilities are not observed at point B. The difference between the magnitude of velocity predictions is significant (~0.3 ms^{-1} point A and ~0.6 m^{-1} point B). Both the peak velocity and the length of elevated velocity is different between codes, and gives rise to a large difference in sediment transport predictions (order of magnitude different). For Benchmark 3, the performance of XBeach is compared to the Industry standard model (Delft3D), and does not perform comparably. Hence it is necessary to analyse it performance against laboratory results and place its performance into context through comparison to other morphological codes (Benchmark 4).

The results of Benchmark test 4 clearly suggest that XBeach is capable of simulating fast transient flows with significant morphological evolution. The 2D spreading effect of the wave is represented well by XBeach and the formation of the bore, upon arrival of the fast dam break wave in the downstream water layer, is predicted reasonably well by the software. Water and bed level predictions are comparable to other similar software tested by Soares-Frazão et al., (2012) and the BSS results indicate that the XBeach model is providing good morphological model predictions to the laboratory results. The under predictions in final bed predictions tend to be replicated by other codes (as tested by Soares-Frazão et al., 2012), and this may in part be due to the current coded entrainment threshold and sediment transport equations which are not sensitive enough to initiate sediment transport under the test conditions.

For the four benchmark tests bed sediment sizes ranging from a D_{50} of 0.2–2 mm have been tested. This represents fine graded sediments (sand-fine gravel), which is typical of a sandy coastal environment and transitional environments such as estuaries or larger continental rivers, however is much less representative of gravel bed small inland rivers. Further research into the capability of XBeach to transport coarser sediments is required, to understand its performance in these types of environments. Laboratory scale experiments are required to properly benchmark the code performance (e.g. Benchmark 2 or 4) against to appreciate where the code could be improved. Additionally, this paper has not investigated graded sediment or armoured bed predictions using XBeach. Representing these conditions is pertinent for smaller inland rivers, and represents necessary further work in order to understand the code capability.

Returning to the questions posed at the outset of this paper:

1. Does XBeach reproduce simple fluvial sediment transport cases? *Benchmark 1.1 and 1.2.*

These tests allowed the software to be assessed for differences in numerical scheme and sediment transport equation choice, which showed that the choice of numerical scheme results in little difference in the simulated morphological changes compared to the choice of sediment transport formula. This confirms the common reasoning that, to provide realistic morphological predictions, the choice of sediment transport formula is of paramount importance.

2. How does XBeach compare to laboratory scale results for morphological change through a range of fluvial flows (steady state, unsteady single peak event and unsteady double peak event)? *Benchmark 2.*

When comparing the software to laboratory scale experimental results under different fluvial events it is clear that the model can replicate general morphological trends (i.e. magnitude of erosion along the channel). However, specific bed forms and rapid erosive response observed in the laboratory are not well replicated by XBeach. Specifically, the software under predicts the immediate scour at the upstream end of the mobile bedfor all three hydrodynamic conditions. Given that the model is calibrated against water level and velocity, it is necessary to look in more detail at the structure of the sediment transport module to understand this under prediction. From this it can be concluded that the sediment transport equations are not sensitive enough to initiate sediment transport at the boundary under the test conditions. This may be due to the predominant sediment transport mechanism being bed load (potentially at capacity at the upstream boundary) and the sediment transport formula and advection-diffusion scheme may be unable to represent this satisfactorily, or it may be as a result of the coded entrainment threshold. It is clear that this demonstrates a potential limitation of the software that should be considered.

3. How does XBeach perform through a dam break scenario, both idealised test case and laboratory scale results? *Benchmark 3 and 4.*

This same trend of under-prediction of degradation and sediment transport rate identified in benchmark 2 is also evident in the dam break tests (benchmark 3 and 4). When XBeach and Delft3D predictions are compared it is clear that Delft3D predicts greater sediment transport potential than XBeach. However, when compared to other morphological codes for benchmark 4, the code performs comparably.

5 Conclusions

This study has tested the ability of XBeach to model sediment transport under a number of different fluvial hydraulic conditions and topographical configurations. The results indicate that a model predominantly applied in the coastal domain, can represent the morphodynamics that occur in complex fluvial situations reasonably well. However, due to the formulation of the sediment transport module, it is less successful at representing situations where bedload transport dominates, which is a significant morphological phenomena in many rivers. There is a major dependence of the results on the grid size in use, obtaining better results for coarser grids than for finer grids.

The results and discussion presented here have shown that XBeach provides a freely available, open source, 2D morphodynamic code, which can satisfactorily represent the morphological patterns occurring in fluvial environments. In most tests, the results are comparable to existing, available software. With future amendment to the model, which is entirely possible given its open source nature, this paper has shown that XBeach has the potential to be applied in the fluvial environment, thereby opening it up for use to a wider audience. The amendments should look to address the grid dependence issues highlighted by benchmark 4, entrainment threshold (benchmark 2 and 4) and the potential for instabilities highlighted by benchmark 3. However, it is important to note that well-developed codes already do exist which can successfully model these environments (e.g. Delft3D (free, open source); MikeZero (commercial), TELEMAC (free, open source)).

Further research must test the capability of the code to reproduce real river reaches where bed sediments are not uniformly distributed and where complex topographical features are common, for example meanders. This paper has not tested the capability of XBeach to model coarse, graded sediments, nor its ability to represent armoured beds. These should be further analysed. Currently XBeach uses a structured staggered grid which can be inflexible for complex fluvial representations (this is similar to other 2D codes e.g. Delft3D, Floodmodeller2D). Further development of the software to include an unstructured mesh option as well as other entrainment options would be beneficial (e.g. TELEMAC).

Acknowledgements

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Highlights

- Evaluation of XBeach numerical scheme in fluvial environments.
- Benchmarking of the code to laboratory experimental results (flume and dam break).
- Discussion of code performance in fluvial and transitional (estuarine) environments.

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