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Beyond equilibrium: Re-evaluating physical modelling of fluvial systems to represent climate changes

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ABSTRACT

The interactions between water, sediment and biology in fluvial systems are complex and driven by multiple forcing mechanisms across a range of spatial and temporal scales. In a changing climate, some meteorological drivers are expected to become more extreme with, for example, more prolonged droughts or more frequent flooding. Such environmental changes will potentially have significant consequences for the human populations and ecosystems that are dependent on riverscapes, but our understanding of fluvial system response to external drivers remains incomplete. As a consequence, many of the predictions of the effects of climate change have a large uncertainty that hampers effective management of fluvial environments. Amongst the array of methodological approaches available to scientists and engineers charged with improving that understanding, is physical modelling. Here, we review the role of physical modelling for understanding both biotic and abiotic processes and their interactions in fluvial systems. The approaches currently employed for scaling and representing fluvial processes in physical models are explored, from 1:1 experiments that reproduce processes at real-time or time scales of 10^{-1}-10^{0} years, to analogue models that compress spatial scales to simulate processes over time scales exceeding 10^{2}–10^{3} years. An important gap in existing capabilities identified in this study is the representation of fluvial systems over time scales relevant for managing the immediate impacts of global climatic change; 10^{1} – 10^{2} years, the representation of variable forcing (e.g. storms), and the representation of biological processes. Research to fill this knowledge gap is proposed, including examples of how the time scale of study in directly scaled models could be extended and the time scale of landscape models could be compressed in the future, through the use of lightweight sediments, and innovative approaches for representing vegetation and biostabilisation in fluvial environments at condensed time scales, such as small-scale vegetation, plastic plants and polymers. It is argued that by improving physical modelling capabilities and coupling physical and numerical models, it should be possible to improve understanding of the complex interactions and processes induced by variable forcing within fluvial systems over a broader range of time scales. This will enable policymakers and environmental managers to help reduce and mitigate the risks associated with the impacts of climate change in rivers.

1. Introduction

Global climate change is a grand challenge facing the Earth across numerous spatial and temporal scales (IPCC, 2014; EEA, 2017) and the supply of water through the river networks is critically important for the Earth's population (de Wit and Stankiewicz, 2006). Expected impacts of climate change in fluvial and fluvially-affected systems such as river deltas and estuaries (Fig. 1) include altered hydrological regimes

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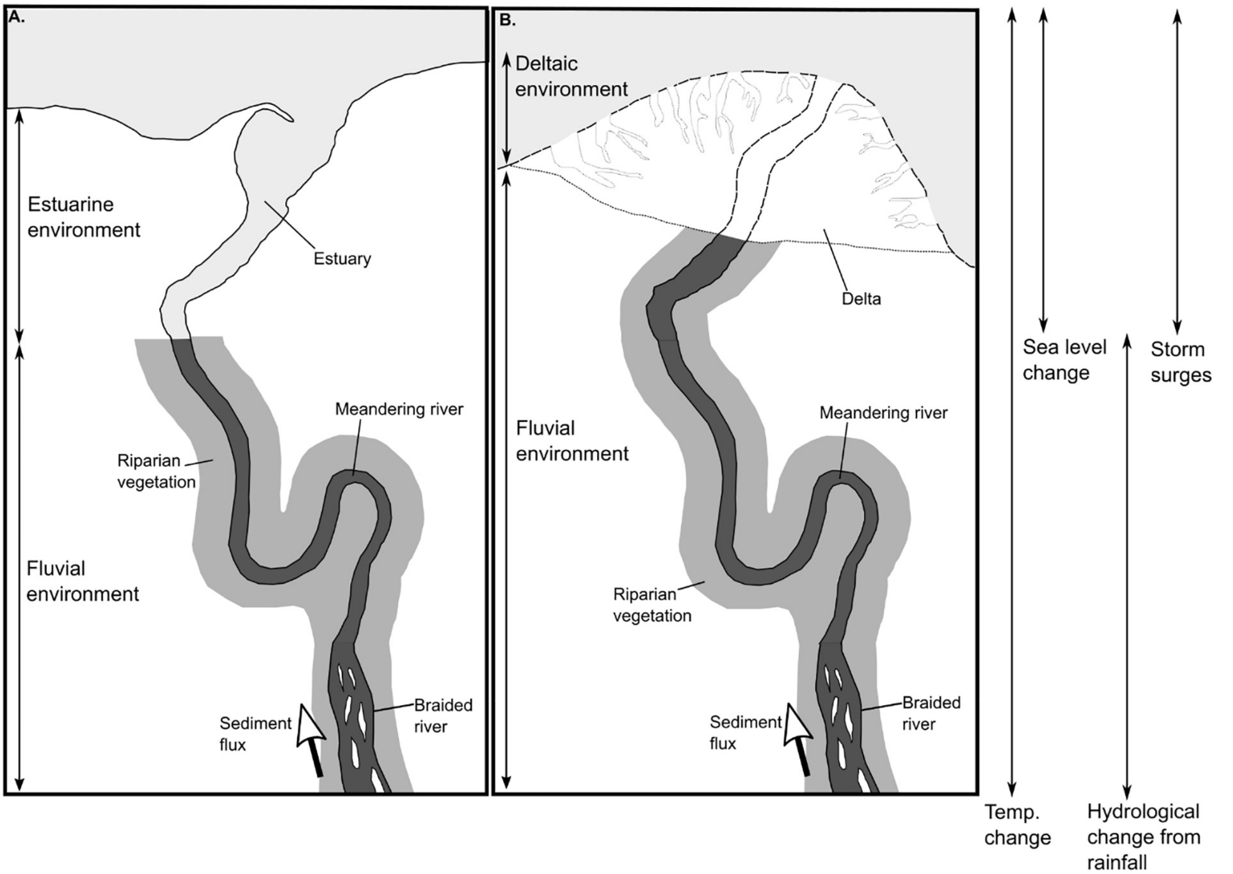

Fig. 1. Schematic diagram to highlight the environments within the scope of this review paper, with an estuarine environment shown in (A) and a deltaic environment shown in (B). Potential climate change impacts in these systems are identified. See Table 1 for details of expected changes in the environments induced by climate change.

and sediment fluxes (Nijssen et al., 2001; Syvitski et al., 2005), variations in biota distribution and growth patterns (Harley et al., 2006), and more frequent extreme events such as storm surges (Lowe and Gregory, 2005), river floods (Garssen et al., 2015) and droughts (Garssen et al., 2014). Understanding and adapting to these potentially irreversible and detrimental impacts associated with new rates of environmental change and shifts in the frequency and magnitude of events associated with climate change is therefore a fundamental priority for potentially vulnerable fluvial environments, especially in regions where the human population are dependent on the local water supply (de Wit and Stankiewicz, 2006). In fact, management of fluvial environments presents challenges in a changing climate, and requires an improved understanding of the feedbacks and interactions between the driving mechanisms at work.

Physical modelling is an important tool for research in fluvial systems and an established technique for the design and testing of hydraulic structures. The high degree of experimental control in physical scale models allows for the simulation of varied, or rare, environmental conditions and hence measurements of conditions which cannot be measured in the prototype (i.e. the real site to be modelled). Moreover, physical modelling provides an essential link between field observations and theoretical, stochastic and numerical models which are required to predict the impact of environmental changes on aquatic ecosystems (Thomas et al., 2014). Physical modelling can therefore play a key role in the development of a better understanding of climate change impacts by improving our ability to predict these impacts and, in turn, help adaptation to climate change-related challenges (Frostick et al., 2011, 2014).

Physical scale models are a key tool to simulate and investigate complex processes and feedback mechanisms, with experimental designs that reflect the spatial and temporal scale of the problem under investigation. Such techniques have been used for > 100 years to investigate the interaction amongst flow, sediment transport, morphology, and interactions with biota, enhancing the understanding of many different and complex sediment transport and morphological processes across different spatial and temporal scales (Kleinhans et al., 2015).

Physical modelling for climate change adaptation faces the challenge of incorporating, and scaling, non-linear responses across a range of temporal and spatial scales resulting from long-term changes in event frequency and magnitude. Recently, physical models have started to explore the impact of climate change on the aquatic environment by examining boundary conditions that reflect a possible future climate state, often using a simplified representation of the systems (i.e. single grain size sediment, or no biotic elements). In addition to evaluating the behaviour of a system at the final stage of a future climate scenario, work is required that explores the progressive development of the system, including time-varying processes, from one state to another as a consequence of climate change (IPCC, 2014; EEA, 2017). In particular, the morphology of riverine, deltaic and estuarine environments will develop and change over time in response to long-term changing boundary conditions and process rates. To address the challenges related to climate change, it is crucial to develop a further understanding of the complexity of the systems, and how the environments adapt over longer periods of time, whether this change is gradual or sudden, and how they behave under a different climate regime.

In this context, this review will examine current techniques and capabilities in physical modelling experiments for representing climate change induced impacts on aspects of fluvial systems such as hydrodynamics, sediment transport, morphodynamics and ecohydraulics.

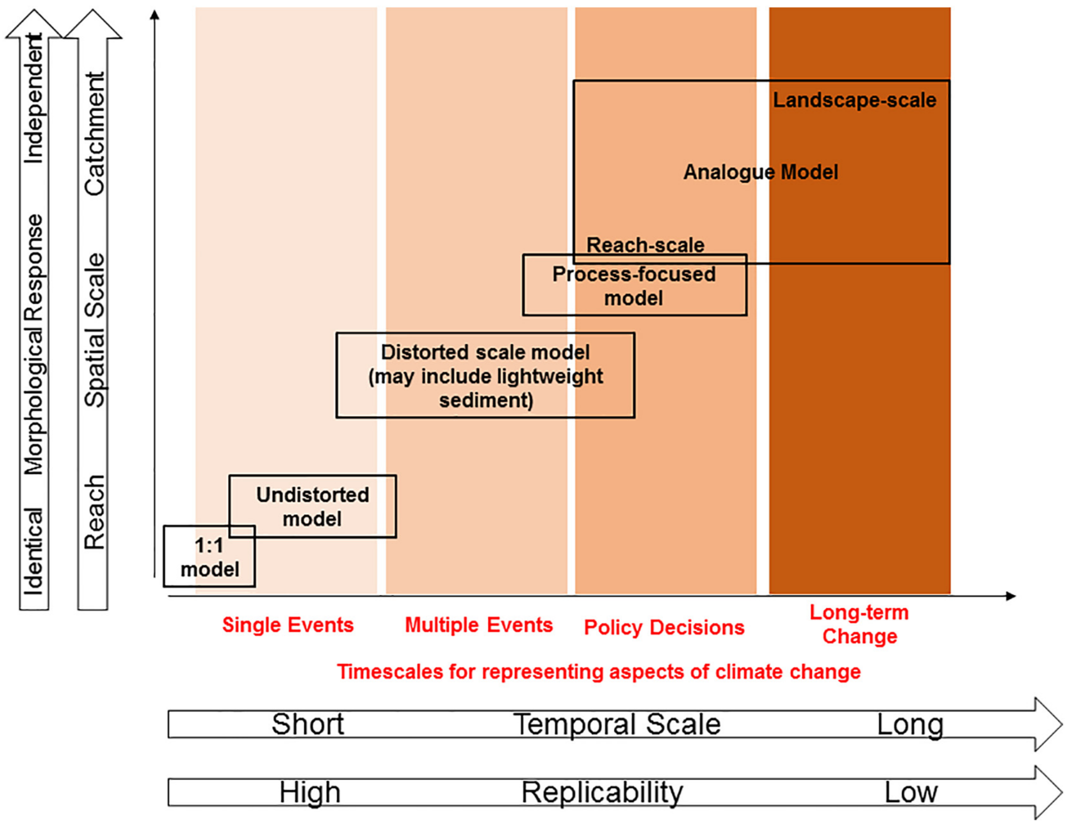

Fig. 2. The relative application of different approaches for physical modelling, with different approaches being more appropriate for modelling processes over different spatial and temporal scales. Developed from Peakall et al. (1996).

Firstly, this review provides a technical discussion of different modelling approaches and the formal scaling laws that they obey (Section 2), before identifying the challenges that physical models face for representing variable forcing and the impacts of climate change within experiments (Section 3). Section 4 provides detailed examples of recent innovative approaches at the forefront of the physical modelling in environmental systems and how these modelling approaches may be enhanced in the future.

2. Scaling approaches and challenges in representing different time scales in physical modelling

Fig. 2 presents a schematic overview of different model types and their ability to replicate the relevant spatial and temporal scales of the prototype. In the discussion below, we explain the essence of each of these approaches, the scaling laws that they must successfully achieve and provide some examples of their application for the understanding of fluvial processes and systems.

In scaled models, the time passes generally faster than in the prototype, which makes them attractive for the study of climate change impacts. However, as will be outlined below, their design and the interpretation of results can be challenging because the hydrodynamic time scales are generally quite different from those for morphodynamic fluvial adjustments (Tsujimoto, 1990), and the scaling of biota is even more uncertain. Models based on both geometrical and dynamic similarity (i.e. by scaling important force ratios; see below) are a well-established approach for designing hydraulic structures at larger spatio-temporal scales while distorted models (models with different geometrical scale ratios in the horizontal and vertical directions), and relaxed-scale analogue models attempt to reproduce some selected properties of the prototype (Peakall et al., 1996).

The scaling laws used to design physical models can be derived based on a dimensional analysis (Buckingham, 1914; Barenblatt, 2003). An important prerequisite for the design of a physical model is the dynamic similarity that ensures a constant prototype-to-model ratio of the masses and forces acting on the system (Einstein and Chien, 1956; Yalin and Kamphuis, 1971; Hughes, 1993; Frostick et al., 2011), i.e. that the derived dimensionless parameters are equal in model and prototype. Important force ratios defining these dimensionless numbers can be obtained by considering inertia, gravity, viscosity, surface tension, elasticity and pressure forces, respectively. A perfect dynamic similarity for all possible force ratios cannot normally be achieved for model scales that deviate from the prototype scale since the same fluid (water) is normally used in both prototypes and models. This means that it is not possible to design a downscaled model so that the relative influence of each individual force acting on a system remains in proportion between prototype and model as outlined by e.g., Yalin (1971), Hudson (1979), de Vries (1993), de Vries et al. (1990), Hughes (1993), Sutherland and Whitehouse (1998), Ettema and Muste (2004) and Heller (2011). Scale models need therefore to be designed in a way that maintains important force ratios whilst providing justification for neglecting other force ratios. Neglecting force ratios will result in scale effects if the model is operated at boundary conditions where the neglected force ratios are important; in other words, there will be a divergence between up-scaled model measurements and real-world observations. Scale effects become more significant with increasing scale ratio and their relative importance depends on the investigated phenomenon (Heller, 2011), i.e. scale effects will have to be accepted.

In the following discussion of the different modelling approaches, it is assumed that the model studies are carried out with water as model fluid so that the ratio of fluid properties in model and prototype such as fluid density ρ_r, fluid dynamic and kinematic viscosity μ_r and ν_r, respectively are equal to 1; the subscript r denotes the ratio between model (m) and prototype (p). Moreover, scale effects due to fluid temperature will not be considered although it is worth mentioning that Young and Davies (1991) used heated water (30 °C) in their experiments in order to achieve closer similarity in Reynolds numbers. Finally, although beyond the scope of this review, experiments using dense fluids have been used to study grains at the threshold of motion (e.g. oil (Best, 1998) and glycerol (Guerit et al., 2014)), and scaling for morphological processes in extra-terrestrial environments is also possible (e.g., aeolian dunes on Mars and Venus (Claudin and Andreotti, 2006); morphological development on Mars (Kraal et al., 2008; Marra et al., 2014; Dietrich et al., 2017).

2.1. 1:1 Physical models

Models that replicate the prototype with no reduction in dimensions can be described as 1:1 physical models (Fig. 2). 1:1 models are mainly used to study physical processes at the smallest spatial and temporal scales under controlled conditions. Examples include experiments aimed at replicating flow turbulence structures in open channels to predict incipient motion and sediment transport (Shields, 1936; Grass, 1971; Nikora et al., 2001; Zanke, 2003; Hofland et al., 2005). Full-scale replication of the larger components of rivers such as channels, levees and bars requires a lot of space with associated high operational costs and these experiments are therefore rare. An example of a 1:1 model is provided by the Smart Levee project in which a river dike is replicated (Fig. 3, http://www.floodcontrolijkdijk.nl/en/experiments). The full-scale physical model allows for experiments on piping, micro- and macro-stability, and flow slide in the absence of scale effects.

2.2. Undistorted models

Geometrical similarity means that all scales with dimensions of length x, y, z are equal: $r_x = r_y = r_z$ (Fig. 2), and in undistorted models the geometry of the model is consistent with the geometry of the prototype. The most commonly used scaling approach for fluid flow in undistorted models is Froude-scaling, which requires similarity in the Froude number in model and prototype:

$$Fr = U/(gh)^{0.5} \tag{1}$$

where U denotes the mean flow velocity, g the gravitational acceleration, and h the water depth. This scaling law, ensuring a constant ratio between inertia and gravitational forces in model and prototype, is most significant for open channel flows and ensures that the water surface will be adequately replicated in the model (Kobus, 1978).

Considering a uniform open-channel flow with a fixed bed in a wide channel, i.e. a width to depth ratio > 30 so that the hydraulic radius can be replaced by the water depth h, dimensional analysis results in four important dimensionless parameters, which are the Froude number as defined above, the flow Reynolds number $Re = Uh/\nu$ (where ν is the viscosity), the relative roughness k/h (with k = roughness length scale, which is often expressed in terms of the grain diameter d), and the slope S. Requiring Froude number similarity in model and prototype means that the flow Reynolds-number (*Re*) will differ between the model and prototype (it can be shown that for Froude-scaled models $Re_m < Re_p$). To avoid corresponding scale effects, the flow in both model and prototype needs to be fully turbulent so that viscosity effects are negligible. The roughness (or friction losses) can be scaled considering similarity in the Darcy-Weisbach friction factor or alternatively in the Chézy-coefficient or Manning number, and the model slope equals by definition the prototype slope in undistorted models.

Fig. 3. Example of a physical model of a river dike taking a 1:1 approach (http://www.dijkmonitoring.nl/en/projects/).

Movable bed models represent a two-phase flow with a solid (particles) and fluid phase (Yalin, 1959). While the flow is generally Froude-scaled, the similarity in sediment movement depends on a set of additional dimensionless parameters which are the grain Reynolds-number $Re_* = v_* d/\nu$, densimetric Froude number (Shields-number) $Fr_* = \rho v_*^2/[(\rho_s - \rho)gd]$, relative sediment density ρ_s/ρ, relative submergence h/d, and relative fall speed v_s/v_* (see Yalin, 1971; Hughes, 1993; Peakall et al., 1996 for details). Peakall et al. (1996, 2007) argued that the 90th percentile of the sediment grain size (D_{90}) should be used in the calculation of the grain Reynolds-number (Re^*), as the coarsest grains contribute the most to the definition of the hydraulic conditions due to their impact on the roughness of the sediment surface. Recently, Kleinhans et al. (2017) argued that percentiles lower than the D_{90} can be used when the sediment mixture contains a wide range of grain sizes, as long as the percentile used protrudes above the viscous flow sublayer to contribute to roughness. In these definitions, ρ denotes the fluid density, ρ_s denotes the sediment density, v_* the shear velocity, and v_s the fall velocity. To obtain perfect similitude for sediment transport processes in model studies using water as fluid (i.e., $\rho_r = \nu_r = 1$), all these quantities would have to be equal in the model and prototype resulting in:

$$Re_{*r} = d_r v_{*r} = 1 \tag{2}$$

$$Fr_{*r} = \frac{v_{*r}^2}{(\rho_s - \rho)_r\, d_r} = 1 \tag{3}$$

$$\rho_{s,r} = 1 \tag{4}$$

$$\frac{h_r}{d_r} = 1 \tag{5}$$

$$\frac{v_{s,r}}{v_{*r}} = 1 = \frac{\sqrt{L_r}}{t_r} \tag{6}$$

L_r is the horizontal length scale ratio, and t_r is the hydraulic time-scale. Eqs. (2)–(6) were formulated for unidirectional flow conditions for which the shear velocity can be determined via $v_* = (ghS)^{0.5}$ so that, for example, Eq. (3) can be written as:

$$Fr_{*r} = \frac{h_r^2}{(\rho_s - \rho)_r L_r d_r} = 1 \tag{7}$$

A general problem encountered in the scaling of shear velocity v_* (or bed shear stress) is that this similitude assumes a flat bed. This is not necessarily the case because the bed topography of most riverine environments is characterised by bedforms or other morphological features (Hughes, 1993), i.e. scale effects may be induced if such morphological features are not adequately reproduced or if d_r deviates from the vertical scale ratio h_r (Gorrick and Rodríguez, 2014). Based on the similarity in *Fr* it becomes possible to derive the hydraulic time scale t_r (Kobus, 1978):

$$t_r = \frac{L_r}{\sqrt{h_r}} \tag{8}$$

For a non-distorted model $t_r = L_r^{0.5}$, indicating that time related to mean properties of the flow field in the model passes faster than in the prototype.

The mechanism for suspended sediment transport differs from the mechanism for bed load transport. This is reflected by the criterion defined by Eq. (6) corresponding to the ratio of settling velocity to shear velocity, i.e. the Rouse number, which is most important for suspension-dominated models. Such models are more common in coastal modelling applications than in alluvial river studies and require the reproduction of the uplift of particles due to turbulence induced by waves or currents, and their subsequent transport in the water column. In this context it is worth mentioning that, in the case of waves, such models require the consideration of different physical parameters in Eqs. (2)–(6) than fluvial bed load models, such as the characteristic velocity $(gH_b)^{-0.5}$ instead of the shear velocity v_* and the breaking wave height H_b instead of water depth h (Hughes, 1993).

Assuming Froude-similarity for the flow and inserting the corresponding hydraulic time scale given by Eq. (8) into Eq. (6) yields:

$$h_r = L_r \tag{9}$$

i.e. the dynamics of the suspended load transport can only be modelled exactly using an undistorted model. Considering all scaling criteria, it is therefore only possible for one transport mode to be modelled following similarity criteria while the other mode will be affected by scale-effects (Hughes, 1993). Nonetheless, physical model experiments that simulate both modes of sediment transport have been attempted (Grasso et al., 2009). If movable bed models need to be distorted, the distortions should not be so large that the type of sediment transport changes (i.e. from bed load to suspended load or vice versa).

When maintaining the similarity in sediment density ($\rho_{s,r} = 1$ or $(\rho_s - \rho)_r = 1$), undistorted models fulfil the criteria given by Eqs. (3) to (5) while violating the fall velocity (Eq. (6)) and the grain-Reynolds number criterion (Eq. (2)). The latter corresponds for this model type to $Re_{*r} = L_r^{1.5}$ indicating that they should be operated in hydraulic rough conditions, i.e. $Re_* > 70$, to avoid scale effects arising through viscous forces as Re_* in prototype conditions will be larger than in the model. Recent work has indicated that the value of $Re_* > 70$ to define hydraulically rough conditions may be overly conservative, with the value potentially as low as 15 being sufficient (Parker, 1979; Ashworth et al., 1994; Kleinhans et al., 2017). An important limitation of this type of model in regard to the scale factor arises from the requirement to scale the sediment with the same factor as the model length scale. If, for example, fine sand is already present in the field, fulfilling this requirement could easily result in using sediments that are cohesive, which generates additional problems due to the different behaviour of cohesive sediments compared to a granular material. To minimize this problem, special materials may be used such as Ballotini® (non-cohesive glass microspheres with diameters as small as 45 µm) or different model types as described below.

2.3. Distorted physical models

Distorted models are characterised by different horizontal and vertical length scales so that $S_r \neq 1$ (Fig. 2). The distortion leads directly to scale effects in the flow field (see e.g. Lu et al., 2013; Zhao et al., 2013) and geometric similarity may be replaced by geometric affinity (De Vries, 1993). Distortion is not acceptable in a model where the vertical velocity components are important, but vertically distorted models are acceptable for uniform, non-uniform and unsteady flow conditions with relatively slow vertical motion (Novak et al., 2010). For example, considering scale models of river reaches, the horizontal dimensions involved are commonly much larger than the vertical dimensions and this will lead to unrealistic scale models if the vertical scale ratio (h_r) is selected equal to the horizontal length scale ratio (L_r) (De Vries, 1993). Additional care needs to be taken with regard to potential scale effects due to water surface tension if the water depth in the model is low (Hughes, 1993; Peakall and Warburton, 1996; van Rijn et al., 2011) or if the model is operated with varying background water levels (e.g., to simulate tidal effects) because the effect of wetting and drying bank material will change its behaviour (e.g, Thorne and Tovey, 1981). The key issue in reproducing mobile bed morphology is sediment mobility. Particle size cannot be reduced to the same degree as the other x, y, z dimensions of the experiment relative to the prototype because properties such as incipient motion and cohesion of silt and clay are significantly different from those of sand and gravel (Lick and Gailani, 2004). Given the small water depth and flow velocities in this model type, sediment mobility is typically lower than in the prototype or may even be below the beginning of sediment motion. Three methods have classically been applied to overcome this issue (Kleinhans et al., 2014): i) a vertical distortion of the model leading to increased gradients and reduced surface-tension effects (Peakall et al., 1996); ii) tilting of the bed, which further increases the gradient; or iii) the introduction of lightweight sediment.

Vertical exaggeration of the model compared to the prototype has a range of effects on sediment transport, morphodynamics and resultant stratigraphy. Stronger bed gradients combined with small water depths affect the threshold for the beginning of sediment motion (Shields, 1936; Vollmer and Kleinhans, 2007), which cascades into differences in sediment sorting patterns between the model and the prototype (Solari and Parker, 2000; Seal et al., 1997; Toro-Escobar et al., 2000; Wilcock, 1993; Peakall et al., 2007; Stefanon et al., 2010). In addition, it can be shown analytically that wavelengths, migration rates and amplitudes of river bars are a function of channel width-to-depth, sediment mobility as well as channel curvature, width variations and sinuosity (Struiksma, 1985; Seminara and Tubino, 1989; Talmon et al., 1995). This implies that any vertical distortion in the scale model will alter the morphology and resultant stratigraphy as seen in the prototype. The introduction of lightweight sediments results in similarity in both Re_* and Fr_* while violating intentionally the sediment density as well as the relative roughness criterion. As indicated by the name, this type of models makes use of model sediments with a lower density than the prototype sediment. For models focusing on bed load transport it may be reasonable to relax the criterion defined by Eq. (6). Low (1989) found in experiments with lightweight materials of different specific densities $1 < \rho_s/\rho < 2.5$ and a grain diameter of d = 3.5 mm that the specific volumetric bed load transport rate q_s was related to $v_{*r}/v_{s,r}$ by a simple power relation and that $q_s \sim v_*^6$ and $\sim v_s^{-5}$. Zwamborn (1966) argued that the Fr_* criterion (Eq. (3)) is essentially the same as the v_{*r}/v_{sr}-criterion and that a good similarity in river morphology can be expected between model and prototype if the latter criterion is used together with an appropriate friction criterion and near similarity in Re_*. More details in regard to the scaling laws considering or neglecting the fall-speed dependency for such models can be found in Hughes (1993) and van Rijn et al. (2011).

Distorted physical models with vertical exaggeration have been used extensively in the past across a range of scales, including extremely large basin-wide hydraulic models designed for engineering purposes. A notable example is the Mississippi Basin Model (MBM) constructed by the US Army Corps of Engineers (Fatherree, 2004); a physical model of the entire Mississippi river and its core tributaries at a horizontal scale of 1:2000 and a vertical scale of 1:100 (Foster, 1971). The MBM was used to study the dynamics of peaks of individual flood hydrographs within the Mississippi basin, such as identifying areas where levees would be overtopped during an expected flood on the Missouri River in 1952 (Foster, 1971) and proved to be an invaluable tool in studying the storage and dynamic effects of backwater areas (Louque, 1976). The operating cost of the MBM and similar scaled basin models such as the Chesapeake Bay (Fatherree, 2004) or the San Francisco Bay-Delta Tidal Hydraulic Model (Wakeman and Johnston, 1986), was impractical due to their size, but they demonstrated the ability to accurately replicate the dynamics of individual flood events within basins over large spatial scales that is impossible using reach scale physical models.

2.4. Process-focused physical models

Here we introduce the term process-focused physical models (Fig. 2) to describe Densimetric Froude models that relax the similitude in Re_* (Eq. (2)) whilst maintaining similarity in Fr_* (Eq. (3)), but do not have a particular target natural prototype in mind. These models allow the investigation of the processes and generic planform morphologies such as channel braiding by reproducing fundamental sediment transport processes such as bedload transport and exploring the sensitivity of processes and morphologies to different experimental conditions. Bed sediment must be mobile in the bedload regime to replicate gravel-bed rivers in nature and mobile in the suspension regime to replicate sandbed rivers, which is challenging due to cohesive effects for silt and clay if used to represent scaled down sand (Smith, 1998; Hoyal and Sheets, 2009). This class of models simplifies the representation of both discharge regimes and sediment properties using simple flow regimes (constant discharge or single events to represent annual floods) and a hydraulically rough bed to minimize scale effects, which conflicts with sediment mobility requirements. This conflict is generally solved by applying a poorly sorted sediment mixture in which the coarsest fraction ensures hydraulic rough conditions (Peakall et al., 2007; van Dijk et al., 2012). Examples of process-focused models include the experiments aimed at river meandering by Friedkin (1945) and the braided river experiments by Ashmore (1988). Many practical applications of such models indicate their suitability in studying morphodynamic processes within river reaches as well as for coastal environments (Hughes, 1993; Willson et al., 2007; Kleinhans et al., 2014).

There is an overlap between distorted models and process-focused models when similitude in Re_* may be close to specific natural protoype situations (Fig. 2). Similarly, the point at which a process-focused model should be described as an analogue physical model is not always clear since it is not known when simplifications in sediment characteristics or discharge regimes make model behaviour differ significantly from a natural system.

2.5. Analogue physical models

The evolution of river morphodynamics over larger spatial and temporal scales is often investigated in so-called analogue models (Davinroy et al., 2012), which are designed to represent larger prototype environments over longer periods of time (Fig. 2). Analogue models are designed to study analogies or 'similarity of process' between the model and prototype and are not designed to keep strict similarity in the above scaling criteria (Hooke, 1968), although they can theoretically be classified according to the model types defined above. However, the aforementioned model types are generally stricter in terms of similarity criteria than analogue models for which the validation or "effectiveness" (Paola et al., 2009) depends on the judgement of similitude in bed-sediment movement (Ettema and Muste, 2004) or on the operator due to the lack of a specific methodology for describing the degree of morphodynamic and stratigraphic similarity in model studies (Gaines and Smith, 2002). Yet, well-designed analogue models have been shown to be an essential tool for studying morphodynamic processes and stratigraphic expressions across a wide range of spatial scales for different river channel morphologies and fluvially-affected coastal environments (Bruun, 1966; Hudson, 1979; Peakall et al., 2007; Wickert et al., 2013; Green, 2014; Bennett et al., 2015; Yager et al., 2015; Baynes et al., 2018), despite violating the aforementioned scaling rules in many ways (Paola et al., 2009; Kleinhans et al., 2014; Peakall et al., 1996; Kleinhans et al., 2015).

Due to the large range in spatial and temporal scales covered by analogue models, two sub-groups can be identified (Fig. 2). First, analogue-reach scale models are process-focused physical models with an added degree of scaling relaxation. Examples include the introduction of alfalfa as vegetation into the models as a representation of vegetation effects in nature. A host of experiments has highlighted the important role vegetation can have in controlling bank erosion, river pattern formation and channel mobility under the simplest conditions (Gran and Paola, 2001; Tal and Paola, 2007; Tal and Paola, 2010; Braudrick et al., 2009; van de Lageweg et al., 2010; van Dijk et al., 2013a; Wickert et al., 2013). The addition of fine silica flour in the experiments of Peakall et al. (2007) and van Dijk et al. (2013b) as the finest sediment into the models as a representation of cohesive silt and clay in nature can also be considered an analogue-reach modelling approach, and has been shown to lead to active meandering systems due to the added cohesion of incorporating fine grained material (Peakall et al., 1996, 2007; Kleinhans et al., 2014). The addition of nutshells has been used to represent low-density and highly-mobile sediment acting as floodplain filler (Tambroni et al., 2005; Hoyal and Sheets, 2009; van de Lageweg et al., 2016; Ganti et al., 2016). Similarly, a wide range of extracellular polymeric substances (EPS) has been introduced into models to represent biological cohesion (Hoyal and Sheets, 2009; Kleinhans et al., 2014; Schindler et al., 2015; Parsons et al., 2016). For example, EPS has been used in analogue delta experiments to increase the range of natural morphodynamics processes that can be reproduced, by increasing the cohesion of the sediment material (Hoyal and Sheets, 2009). The polymer-sediment mix, developed at the ExxonMobil Upstream Research Company (Hoyal and Sheets, 2009) performed best in the presence of clay and sand, and the deltas produced during the experiments had geometries characteristic of natural deltas composed of sandy non-cohesive sediments, allowing experimental investigations of forcing factors such as sea-level rise on channel mobility and shoreline dynamics (Martin et al., 2009).

Second, analogue-landscape models represent the spectrum of scale models associated with the largest spatial and temporal scales shown towards the top right in Fig. 2. Such models typically concern an entire landscape (e.g. delta or mountain range) and aim to explore its evolution across longer (e.g. geological) time scales. River-delta landscape experiments provide an example of this type of scale model (Fig. 4). The analysis of these experimental data allowed the identification of a small, but significant, chance for the preservation of extreme events in the stratigraphy due to the heavy tailed statistics of erosional and depositional events (Ganti et al., 2011). This quantified understanding of the evolution of a river delta system under rising base level would only be possible using the analogue-landscape modelling approach, where processes characteristic of larger delta systems are replicated and monitored at high spatial and temporal resolutions that would be impossible in the field.

3. Challenges representing climate change impacts in physical models

The impacts of climate change, and more broadly, non-constant forcing, will affect fluvial systems over a range of time scales. Increased magnitude of individual events to millennial-scale shifts in long-term forcing dynamics such as the total volume and seasonal variations in annual precipitation and changes in the biological characteristics could have dramatic impacts on the state and functionality of fluvial systems (Wobus et al., 2010). This section identifies the current challenges in representing these impacts on the fluvial environment using physical models.

3.1. Differing timescales of morphodynamic and hydrodynamic processes

Hydrodynamic processes usually occur at a much shorter time scale than morphodynamic processes and, as will be shown below, time scales related to different morphological processes do not necessarily coincide in physical models (Yalin, 1971). This can, in turn, result in undesired scale-effects that become more significant with decreasing physical model scale (i.e. of the reproduction of the prototype) (Fig. 2).

The determination of sedimentological time scales in movable-bed models is difficult and often subjective. In fact, the sedimentological

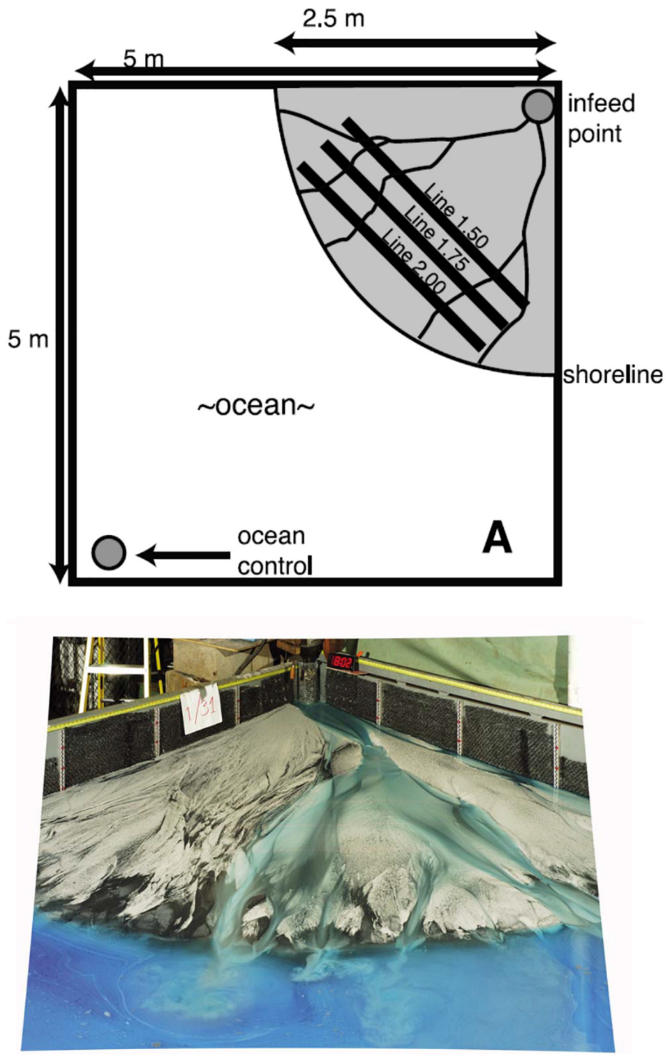

Fig. 4. Example of an experiment using an analogue-landscape modelling approach (Sheets et al., 2002; Ganti et al., 2011). (a) Schematic of the experimental set up. (b) Photography of the delta after 11 h of experimental run time. From Ganti et al. (2011).

time scale cannot be freely chosen as it results from the chosen scales of the other model parameters (Hentschel, 2007) and, hence, depends on which scaling criteria are intentionally violated. Moreover, there is the need to distinguish between different time scales for different morphological processes such as individual grain movement ($t_{sg,r}$) and the evolution of the bed surface in the vertical ($t_{\eta,}$) and horizontal (t_{Lr}) directions, respectively. Corresponding time scales are presented in general terms in.

According to Yalin (1971), the movement of an individual bed load grain is governed by the geometrical scale of the particle diameter d and the kinematic scale v_*, respectively resulting in the time scales $t_{sg,r}$ defined by Eqs. (10) and (11), where Eq. (12) results from the additional requirement of similarity in Re_* (Table 2).

Considering the temporal development of a movable bed surface in a physical model, different scales in the horizontal and vertical directions need to be taken into account. For fluvial environments, the most common approach to derive the time scale for the formation of a movable bed surface is based on the comparison of the model response time to known prototype response times (Vollmers and Giese, 1972; Kamphuis, 1975; Einstein and Chien, 1956). This is typically achieved by considerations of the variation of the bed surface level η in vertical direction with time and the volumetric sediment transport rate q, i.e. the Exner equation (Paola and Voller, 2005; Coleman and Nikora, 2009). Thus, the corresponding time scale can be defined according to Tsujimoto (1990) and Hughes (1993):

$$t_{\eta r} = \frac{L_r h_r (1-\phi)_r}{q_r} \tag{10}$$

where ϕ denotes the porosity of the bed material. A similar formulation can be obtained considering the movement of river dunes assuming their geometrical similarity in model and prototype. Introducing the dimensionless volumetric bed load transport rate $q_* = q/(v_* d)$, Eq. (10) can be rewritten according to:

$$t_{\eta r} = \frac{L_r h_r (1-f)_r}{q_{*r} d_r v_{*r}} \tag{11}$$

Assuming similarity in q_* in model and prototype (i.e. $q_{*r} = 1$), Eq. (11) represents the basis for Eqs. (12) to (15) in Table 2 for which it was assumed that $v_{*r} = (h_r S_r)^{0.5} = h_r L_r^{-0.5}$. Note that for geometrically similar grains with a similar grain-size distribution, $(1-\phi)_r = 1$ (Hentschel, 2007). Also, for practical purposes, the sediment transport rate is often determined from existing bed load formulae. Using such relationships in Eq. (11), instead of a measured q_*, can result in different time scale calculations.

Eq. (16) in Table 2 was derived by Yalin (1971) and describes the time scale related to the evolution of the mobile bed surface in horizontal direction. This equation is based on single grain movement considerations and the relation of the diameter scale with the longitudinal scale.

Comparing the different time scales given in Table 2 it becomes apparent that

$$t_{\eta r} < t_{Lr} < t_r < t_{sgr} \tag{12}$$

i.e. the vertical evolution of the bed surface has the shortest time scale, followed by the longitudinal displacement of the grains and the hydrodynamic time scale. The longest time scale is for the individual motion of a grain (Peakall et al., 1996). Other time scales than those discussed here may be derived based on the consideration of the evolution of morphodynamic features such as meander bend migration rate, floodplain evolution and biological development (Tal and Paola, 2007; Kleinhans et al., 2014, and references therein).

The time scales can also be linked to the bed-load models defined above. In undistorted similarity models with unidirectional flow $t_{sg,r} = t_{\eta r} = t_{Lr} = L_r^{0.5}$, which is equal to the hydraulic time scale t_r. Geometric similarity models therefore offer the opportunity to study the effects of hydrographs on bed evolution. The time scales for distorted lightweight models can be derived as $t_{sg,r} = (\rho_s - \rho)_r^{-2/3}$, $t_{\eta r} = h_r^3 (1-\phi)_r (\rho_s-\rho)_r^{-2/3}$, $t_{Lr} = h_r^2 (\rho_s-\rho)_r^{-1}$ thereby assuming $q_{r_*} = 1$ and that bed shear stress can be determined from the depth slope product.

The time scales for process-focused models are defined by Eqs. (14) and (15) where the latter formulation by Tsujimoto (1990) was derived by considering the Manning-equation, i.e. by considering additional similarity in bed roughness. Time scales for models with suspended load were summarized by e.g. Hughes (1993) and van Rijn et al. (2011), but in almost all cases a morphological time scale of suspended models was derived corresponding to $t_{\eta r} = h_r^{0.5}$ (where the vertical length scale characterizes wave characteristics). These similarity conditions can result in rather impractical scaling ratios, especially when considering both vertical and horizontal directions, and result in a challenge in developing strictly scaled models containing both sediment and water.

3.2. Representing variable forcing and sequences of events

Future climate regimes are anticipated to be characterised by increased variability and higher frequency and magnitude of extreme events such as river flooding (Table 1, Fig. 5). Due to the difficulties in scaling unsteady flows and sediment transport in physical models (see

Table 1
Details of expected climate change induced impacts on fluvial and fluvial-affected estuarine and deltaic environments. Physical modelling studies can be used to understand these processes and test possible adaptation strategies.

Climate induced change in forcing	Predicted change	Associated impact on estuarine and fluvial environments	Source
Global mean surface temperature	By 2100: 0.3–1.7 °C temp. Rise (scenario RCP2.6[a]) 2.6–4.8 °C temp. Rise (scenario RCP8.5[a])	Implications for vegetation growth in all environments	IPCC (2014)
Sea level rise	By 2100: 0.26–0.55 m (scenario RCP2.6) 0.45–0.82 m (scenario RCP8.5) 70% of coastlines worldwide experience change within 20% of global mean	Drowning of estuarine environments. Encroachment of saline water and associated impacts on biota. Increased aggradation of river deltas, accelerated channel and floodplain deposition and to higher channel avulsion frequency	IPCC (2014), Jerolmack (2009)
Storm surges	Largest increase in 50 year return period storm-surge height at UK coastline = 1.2 m (Scenario A2)	Increased risk from hazards (e.g. coastal flooding, coastal erosion) associated with storm surge events	Lowe and Gregory (2005)
Precipitation	Scenario RCP8.5: Increase in mean precipitation in high latitudes and equatorial Pacific. Decrease in mean precipitation in mid-latitudes. Increase in extreme precipitation over most of mid-latitude landmasses and wet tropical regions become more intense and more frequent	Rivers: increased frequency and magnitude of higher peak flows, and possible prolonged drought periods with associated impacts for riparian vegetation distribution. Potential shifts in timing of seasonal hydrological regimes	IPCC (2014), Garssen et al. (2014, 2015)
Waves	Latitude dependent: 0.6–1 m increase in 20 year return period wave height between 1990 and 2080 in NE Atlantic. Wave with 20 year return period in 1990 will have 4–12 year return period in 2080	Modification of the dynamics of estuarine and coastal systems	Wang et al. (2004)

[a] RCP2.6 and RCP8.5 refer to two end-member Representative Concentration Pathways for anthropogenic greenhouse gas emissions. RCP2.6 refers to a stringent mitigation scenario, and RCP8.5 refers to a scenario with very high greenhouse gase emissions (IPCC, 2014).

Table 2
Time scales for bed load dominated models, $\rho_r = \mu_r = \nu_r = 1$, and assuming $v^* = (ghS)^{0.5}$.

Time scale	Eq.	Criteria and comments	Source
$t_{sg,\ r} = d_r L_r^{0.5} h_r^{-1}$	(10)	- individual grain movement	Yalin (1971)
$t_{sg,\ r} = L_r h_r^{-2}$	(11)	- individual grain movement - similarity in Re_*	Yalin (1971)
$t_{\eta r} = L_r h_r$	(12)	- similarity in dimensionless transport rate - similarity in Re_* - porosity equal in model and prototype	Yalin (1971)
$t_{\eta r} = L_r^{1.5} d_r^{-1}(1-\phi)_r$	(13)	- similarity in dimensionless transport rate	Hentschel (2007)
$t_{\eta r} = L_r^{2.5} h_r^{-2}(1-\phi)_r(\rho_s-\rho)_r$	(14)	- similarity in dimensionless transport rate - similarity in Fr_*	Hentschel (2007)
$t_{\eta r} = L_r h_r^{1.5} d_r^{-7/6}(1-\phi)_r$	(15)	- similarity in dimensionless transport rate - similarity in $Fr*$ - near similarity in $Re*$	Tsujimoto (1990)
$t_{Lr} = L_r^{1.5} h_r^{-1}$	(16)	- individual grain movement	Yalin (1971)

Section 3.1), there are few physical modelling studies exploring sequences of multiple floods (e.g. Braudrick et al., 2009). In terms of improving our understanding of the impact of climate change on fluvial environments, it would be particularly relevant to investigate variations in hydrograph characteristics (i.e. duration, magnitude and frequency) over time scales that are similar to the system recovery time for morphodynamics and vegetation. All systems have a characteristic time scale for recovery following a perturbation (Brunsden and Thornes, 1979). This time scale can range from > 10^3 years in erosive bedrock settings (e.g. canyons; Baynes et al., 2015) to 10^1–10^2 years in alluvial depositional fluvial environments (e.g. sandur plains; Duller et al., 2014) due to the relative differences in the mobility of sediments, although larger systems typically take longer to fully recover following a perturbation (Paola, 2000). This illustrates that the timing of sequences of flood events relative to the time scale of recovery is as important in driving evolution and change in fluvial environments as the magnitude of individual flood events (Fig. 5). With an increased frequency of extreme events, this recovery timescale may be threatened, with subsequent events of possibly greater magnitude occurring before the system has fully recovered from the initial perturbation with potentially unknown consequences. Thus, the accurate representation of non-constant forcing and the relative importance of sequences of events within physical models remains an important goal for the development of the understanding of fluvial system response to future climate scenarios. Additionally, non-linear threshold driven sediment transport processes which respond to constant or non-constant forcing can destroy or "shred" environmental signals, like river avulsions or bar deposits, which could otherwise be preserved in the landscape or sedimentary record (Jerolmack and Paola, 2010). Changes in the external forcing may not be preserved if the timing and magnitude of the events does not exceed the autogenic variability driven by non-linear processes such as bedload transport or river avulsion (Jerolmack and Paola, 2010). As the signal of the external forcing increases in frequency (e.g., Fig. 5), preservation of the impact of the individual events becomes less likely, whilst events of sufficiently large magnitude will change or modify the entire system and will therefore have greater potential to be preserved (Jerolmack and Paola, 2010). If the evidence for changes in external forcing are not recorded or visible in natural systems, physical models provide a unique opportunity to understand how thresholds and autogenic feedbacks within a system can mitigate or enhance the impact of variations in external forcing driven by climate change.

Traditionally, flood events are represented in physical models at the event scale by triangular hydrographs with possibly an asymmetry between the rising and falling stages (e.g. Lee et al., 2004). The gradual increase and decrease of discharge are reproduced by stepped hydrographs with the number of steps for each hydrograph strongly

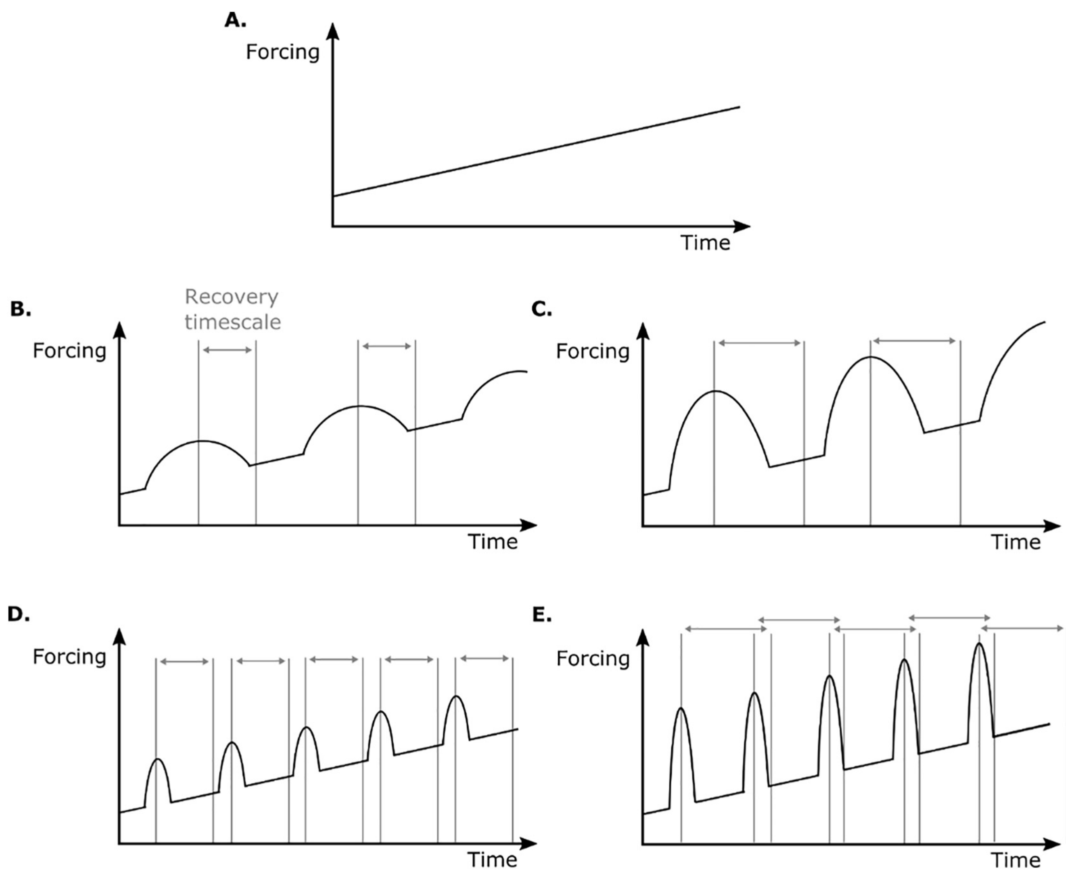

Fig. 5. Conceptual diagram indicating different forcing regimes in fluvial and fluvially-affected systems such as river deltas and estuaries under climate change. (A) A progressive increase in a constant forcing over a long time scale (e.g. sea level rise, or increase in biostabilisation as a result of temperature increase). (B) A forcing regime characterised by infrequent and low-magnitude extreme events, superimposed on the progressive trend shown in (A). (C) A forcing regime characterised by higher magnitude extreme events, but of the same frequency, compared to (B). (D) A forcing regime characterised by extreme events of the same magnitude as (B), but occurring more frequently. (E) A forcing regime characterised by extreme events that are both more frequent and of a higher magnitude compared to (B). The typical time for the system to recover back to equilibrium conditions is shown in grey in (B-E). Due to frequency and magnitude of the extreme events in (E), the system has never fully recovered before the subsequent extreme event, placing the system in a constant state of transience.

dependent on the complexity of the flume control equipment (Lee et al., 2004; Ahanger et al., 2008). Sequences of flood events modelled on a particular system, or the long-term evolution of a system driven by a long-term shift in the magnitude or frequency of forcing are rarely represented in physical models (Fig. 5).

3.3. Representing biology and timescales of biological change

Currently, most hydraulic facilities are not well suited to work with living organisms. These facilities may therefore result in biota being stressed by one or more environmental factors including inappropriate water chemistry (salinity, pH, dissolved oxygen, inorganic carbon), water temperature, substrate (physical and chemical properties, soil saturation), lighting (composition, intensity, timing), and flow characteristics (depth, velocity, drag). The health and behaviour of living plants may also be affected by biological considerations, including insufficient nourishment (type, quantity, and timing), competition for resources amongst individuals and, potentially, the introduction of pathogens. Johnson et al. (2014a) provide a review of these main stressors and their management in flume facilities. Of course, plants are often stressed in their natural environment by competition for resources and by other ecological and biological interactions. Their interactions with their environment are variable and complex, such that there is no ideal stress-free state that must be mimicked. Nevertheless, a basic goal of most experimental work will be to reproduce in the flume behaviours that are typical in nature and, in that case, low levels of stress are desirable, or the development of surrogates that accurately replicate plant/microbial activity and can be time scaled.

Most plants are able to tolerate a range of environmental conditions, with fatality beyond limiting thresholds. As conditions become less optimal, but sub-lethal, the plant will adapt, potentially altering the way in which it interacts with the flow. We know very little about these adaptations and what they mean for hydraulic performance, but existing work suggests that the relations are likely to be complex, especially where multiple stressors are present (Puijalon et al., 2007).

Demonstrating that vegetation is not physiologically or behaviourally stressed during experiments should be a standard element of any physical modelling experiment involving live plants. Without that assurance it is difficult to be confident that measured hydraulic and morphodynamic responses can be properly assigned to treatment effects, not abnormal behaviour caused by the physical modelling environment. While it may be relatively easy to detect serious ill-health or the death of a plant that is part of a flume experiment, earlier stages of decline that affect the plants interaction with the flow, may go undetected, potentially undermining the results obtained.

This leads to the identification of two key challenges for investigating plant-flow-sediment interactions: i) developing protocols that can be used to monitor plant health or stress levels during physical modelling experiments, and ii) developing a fuller understanding of how health and stress levels affect key plant structures, physiological responses and behaviours that are relevant to flow and sediment interactions. Meeting these challenges would provide a basis for making objective decisions about how stressed a plant is and whether the level of stress is sufficient to affect its biomechanical behaviour as that affects its interactions with the flow and therefore the integrity of an experiment.

From a scaling perspective, of primary interest is the role of the hydraulics as a driving force for the growth and, hence, the geometrical and mechanical properties of plants and biofilms. Hydrological modifications, driven by climate change, especially in terms of flood intensity and frequency, are very likely to also modify plant diversity and distribution (Garssen et al., 2015). Importantly, the time scales associated with plant and biofilm growth in the field are very large when compared to the time scales of physical modelling experiments in the laboratory. For photosynthetic biofilms in rivers, for example, growth cycles are associated with time scales of around 30 days, which correlates approximately to inter-flood periods in the field (see e.g. Boulêtreau et al., 2010). Macrophytes or riparian vegetation generally develop and grow over much longer time scales. For biofilms, another issue is the extreme versatility of this biological agent, whose growth and composition adapts very quickly to flow conditions during growth; for example, Graba et al. (2013) demonstrated that in steady-flow growth experiments the biofilms optimized their mechanical properties to fit the imposed steady forcing, and were very easily detached by a slight increase of flow velocity. Incorporating flow unsteadiness associated with typical discharge fluctuations then becomes important for growing representative laboratory biofilms.

Plants and biofilms can be simplified and represented by some physical or chemical surrogates. As far as plants are concerned, the use of physical surrogates offers the opportunity to better control the interactions between aquatic vegetation and a changing hydraulic environment, without the issue of phenotypic plasticity typical from biotic systems (Read and Stokes, 2006; Nikora, 2010). However, the development of surrogates relies on the good understanding of the plant biomechanical properties and requires therefore extensive field data collection prior to the main experiments (Nikora, 2010). Although recent works are relying more and more on plant surrogates (see Johnson et al. (2014b) for a non-exhaustive list), only a few studies investigated the surrogate design process for complex shaped aquatic plants, such as the work carried out by Paul and Henry (2014), and this process is yet to be developed for freshwater aquatic vegetation.

4. Innovative approaches and required future developments to represent climate change impacts in physical models

4.1. Bridging the timescale gap

The range of physical modelling approaches highlighted in Fig. 2 have worked well for both small and large spatial and temporal scales. At the event scale, 1:1 physical models have proven invaluable tools to examine the effects of storm wave on flooding risk and safety (Fig. 3). More extreme storm wave and river flood events are projected as a result of climate change (Table 1). The current hydraulic facilities are however expected to incorporate these more extreme events in their experiments seamlessly by adjusting their test scenarios to include the latest climate projections (e.g., wave height). Other than potentially running into size limitations of the hydraulic facility (i.e. larger events require larger facilities for 1:1 modelling, such as the Mississippi Basin Model; Foster, 1971), these more extreme events do not require additional scaling compared to default extreme event tests. This observation indicates that no problems are foreseen in representing more extreme events associated with climate change in hydraulic facilities.

Also at larger spatial (landscapes) and temporal ($> 10^2$ years) scales, analogue models have worked well leading to agenda-setting research and understanding of landscape evolution processes (Hasbargen and Paola, 2000; Turowski et al., 2006; Tal and Paola, 2007; Bonnet, 2009). Analogue models can act as a tool for exploration, due to the ability to simplify aspects of a complicated system and explore the behaviour of targeted processes under controlled conditions (Bonnet, 2009). The freedom given by foregoing the strict scaling laws can potentially allow innovative experiments to develop an understanding of systems that are manipulated in ways that would not be possible using a strict scaling approach, such as coastal dynamics and response to sea-level rise (Kim et al., 2006) or the exploration of different sequences of events on the overall system behaviour (e.g., Ganti et al., 2011). It is important to note that analogue models are exclusively fit for these "thought-provoking" experiments and hence our primary tool for investigating processes, interactions and feedbacks across longer ($> 10^2$ years) time scales relevant for climate adaptation purposes (Fig. 2).

Intermediate time scales (10^1–10^2 years) have proven difficult to represent in physical models to date, leaving us with a timescale gap in physical modelling capabilities. Yet, in the context of climate change adaptation for planning and policy purposes, the evolution of fluvial systems due to climate change over intermediate time scales is most prevalent and urgent (Fig. 2). Depending on the exact timescale or process of interest, undistorted, distorted and process-focused models may provide physical scaling approaches to study the fluvial system at hand. Undistorted and distorted scaled models are best suited to investigate individual and short-lived events due to the minimum compression of spatial and temporal scales (Fig. 2) extending the individual event scale covered by 1:1 models. Similarly, process-focused and perhaps some distorted and analogue-reach physical models are best placed to condense the timescales represented in analogue models in an effort to study the effects of intermediate timescales of climate change in fluvial systems (Fig. 2) the effects of variable forcing, sequences of events and biological interactions are dominant (Garssen et al., 2015) but poorly understood drivers of fluvial system behaviour for researchers to be able to study the effects of climate change across intermediate timescales. Below, we provide examples of studies on variable forcing, sequences of events, lightweight sediment and biology and we discuss how they can be applied to better represent climate change at intermediate timescales specifically and expand the future physical modelling capability more generally.

4.2. Variable forcing and event sequences

Recently, Martin and Jerolmack (2013) have advanced the knowledge of bedform dynamics for non-stationary flows, including the difference in the scaling of morphodynamic and hydrodynamic processes (Section 3.1). The processes associated with the growth of bedforms following an abrupt increase in discharge and their decay following an abrupt decrease in discharge are complex and very different (Martin and Jerolmack, 2013). The former relies on gradual collision and merging of small structures towards larger ones, while the latter relies on the formation of secondary small scale structures that cannibalize progressively the large structures formed earlier during the rising stage (Martin and Jerolmack, 2013). The timescale of the bedform response under these conditions is proportional to the reconstitution time, defined as $T_r = V/q_s$ where V is the volumetric sediment displacement for the bedform adjustment and q_s is the sediment flux (Martin and Jerolmack, 2013). The reconstitution time is a function of the equilibrium bedform heights, and celerities under the initial and secondary discharge magnitudes, such that taller and longer bedforms take longer to return to equilibrium following an abrupt change in discharge.

Additionally, the mechanism and characteristics of the forcing change (i.e., discharge) was found to be important in setting the mechanism of bedform response on the channel bed (Fig. 6). Dependent on the rate of a gradual increase and decrease in the discharge (Fig. 6a–b), bedforms either respond through a phase of hysteresis or through a linear response of the length and height (Fig. 6c–f). Under the 'fast flood wave' conditions, the timescale response of the bedform adjustment is shorter than the timescale of flood wave discharge, forcing the hysteresis response. These observations following their experiments under

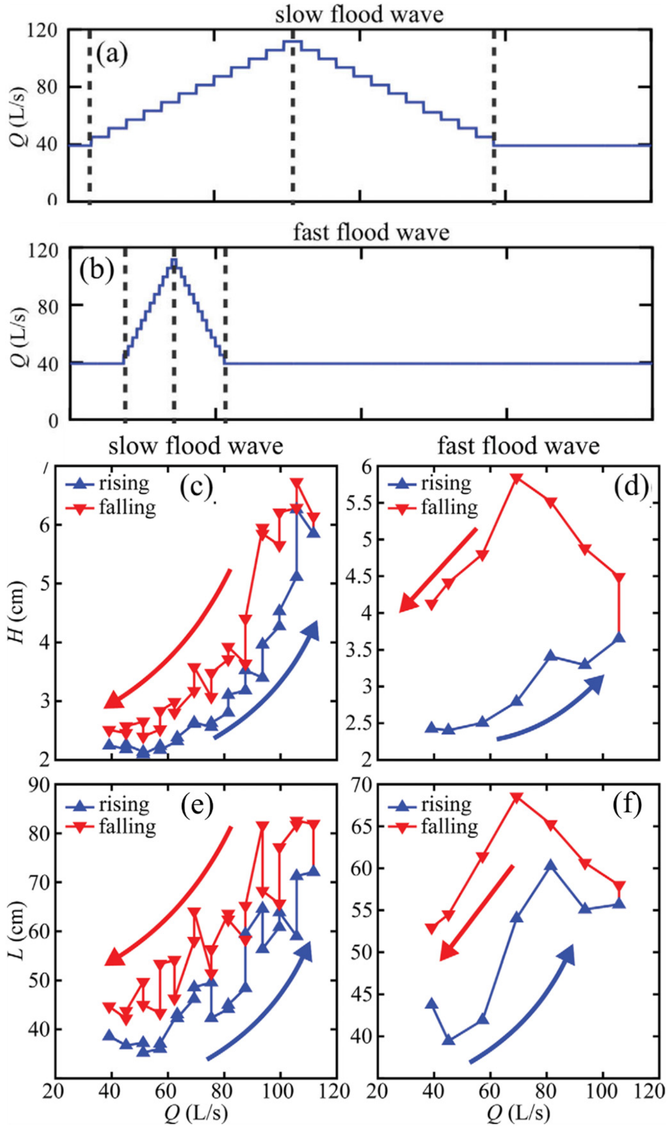

Fig. 6. Comparison of bedform dynamics under different variable discharge regimes. (a) Hydrograph simulating a slow flood wave. (b) Hydrograph simulating fast flood wave. (c–d) Evolution of bedform height during the hydrographs. (e–f) Evolution of bedform length during the hydrographs. A clear hysteresis is apparent in the evolution of the bedforms during the fast flood wave, due to time lag of response of the bedforms is greater than the timescales of the flood waves. Adapted from Martin and Jerolmack (2013).

variable forcing allowed Martin and Jerolmack (2013) to propose a simple model framework for the quantitative prediction of bedform adjustment timescale and the occurrence of bedform hysteresis in natural rivers during individual or sequences of events. This innovative example demonstrates the future potential for physical models in advancing the understanding of the processes and response of fluvial systems under variable forcing conditions, aiding the understanding of the possible impacts of climate change. The identification of response timescales of morphodynamic processes to individual events (i.e., Martin and Jerolmack, 2013) can act as a starting point for evaluating the response to sequences of multiple events of different frequencies and magnitudes (Fig. 6).

The order of events can also be important for experiments investigating the impact of sequences of events, due to differences in sediment transport rate for flood events of different magnitude and duration. However, the reorganisation of bed morphology either in terms of bedform size or bed structure through events will impact on the state of the system for the next event, which means that the order of events could be significant and this should be addressed in flume experiments that investigate longer time scales.

4.3. Lightweight sediments

Lightweight materials have been used to study local erosion processes such as scour development downstream of weir structures (e.g., Ettmer, 2006, and references therein), bridge piers and abutments (Fael et al., 2006; Ettmer et al., 2015) and the impact of jets (e.g. Rajaratnam and Mazurek, 2002). The latter studies, in particular, made use of the fact that erosion processes are accelerated when lightweight sediments are used instead of natural fluvial sediments, i.e. that the equilibrium dimensions of the scour can be reached faster, allowing the time scales of study to be extended (Fig. 2). At a larger scale, Willson et al. (2007) reported on a distorted scale model focusing on river and sediment diversions in the lower Mississippi river delta with L_r = 1:12,000 and h_r = 1:500 and a model sediment with a density $\rho_s = 1050\,kg/m^3$ covering 77 river miles and an area of about 3526 square miles. In this model, the flow was scaled via the Froude law and the lightweight sediment was scaled based on considerations for the incipient motion of the particles so that incipient motion and resuspension were similar in model and prototype. The resultant sediment time scale was given by the authors with 1:17,857 (one year of prototype time equals roughly 30 min of model time). This model was run for different scenarios, including sea-level rise, and used to enhance the general understanding of the impact of planned measures for US State and Federal Agencies (Willson et al., 2007). Such approaches, specifically using lightweight sediment to reduce the time scale of the environmental processes in the physical models can extend the timescale of scaled models (Fig. 2) to bridge the gap in modelling capabilities over the timescale relevant for climate change.

4.4. Representing biology

Time scales associated with the growth and behaviour of vegetation are inherently difficult to downscale in physical models using undistorted or distorted models. Therefore, it is more convenient to use living or artificial surrogates within the analogue modelling approach, where the effects of vegetation in the system are replicated, but not necessarily directly. Plant surrogates also offer new possibilities to test hypotheses in the context of changing fluvial systems. Johnson et al. (2014b) detailed the various benefits and the limitations of using inert physical surrogates, and these points will therefore not be detailed here. Yet, surrogate development is still in its infancy and depends on a detailed knowledge of the morphology and biomechanics of the species of interest, and we present here some of the major issues yet to be tackled, in the context of changing fluvial systems.

The morphology and mechanics of aquatic plants can vary based on seasonal patterns. In flume experiments, the potential interaction between the different time scales such as the seasonal growth and the time between active and inactive hydrological regimes needs to be considered. In the case of experiments involving time compression (analogue or process-focused models always active/in flood, see e.g. Paola, 2000) effects due to seasonal changes of plant characteristics may be lost. A good understanding of the plant biomechanical properties requires the use of a solid dataset from real-life conditions (Nikora, 2010), collected using well identified techniques (Henry, 2014, 2018). Additionally, the required level of complexity of a plant surrogate is still uncertain, as it is critical not to simply redesign the plant structure (Denny, 1988). Understanding the existing structural organisation of a plant is key to the identification of the environmental factor that defined it, and should highlight the features to be reproduced in an experiment, depending on the processes and scales to be investigated. The most important part in a design process, i.e. performance tests, should be conducted systematically to ensure that the dynamic behaviours of the surrogate correspond to the original criteria, i.e. the reproduction of the process observed in nature (flexibility, plant to plant interaction, effect on sediment transport).

The application of models without scaling to address questions relating to climate change has some limitations because model time is no faster than prototype time, but for understanding some interactions between organisms and their surroundings, there are no satisfactory scaling relationships (e.g. Wilcock et al., 2008). Kui et al. (2014) present results from the StreamLab experiments that are used to elucidate the eco-geomorphic feedbacks between riparian tree seedlings and flood events. These 1:1 physical models investigate the use of flood releases to control invasive vegetation, however this type of model has the potential to improve our understanding of the response of trees and other organisms to extreme events that could be associated with climate change.

In theory, it is possible to scale down plant properties within the distorted scale modelling approach, which may lead to a distortion in time and/or space of the hydraulic model (Johnson et al., 2014b). In practice, no such work has been published to the best of our knowledge, and investigations related to scaled plant properties are just about to start. The interaction of this new distorted 'plant time scale' with the other time scales applying to sediment transport and larger morphological evolutions, is yet to be characterised but offers a potentially important avenue for future work into the holistic evolution of river systems under climate change forcing.

For plants, several studies have relied on the use of alfalfa because of its size and growth time scale fit with a downscaling approach to physical modelling of sediment and flow dynamics and their interactions with vegetation. This analogue modelling approach leads to floodplains vegetated by a single species that resembles a very fast growing tree (Fig. 7). Vegetation is able to stabilise river banks, focus and organise the flow and hence convert the planform morphology from braided to single-thread (Gran and Paola, 2001; Tal et al., 2004; Tal and Paola, 2007, 2010; Braudrick et al., 2009; van de Lageweg et al., 2010; van Dijk et al., 2013b; Bertoldi et al., 2014). It should be noted, however, that vegetation alone does not lead to fully meandering channels (Desloges and Church, 1989) and fine grained material is also required (van Dijk et al., 2013b; Santos et al., 2017a,b). Morphological trends associated with the colonisation of a floodplain by riparian vegetation are an increased sinuosity, lower lateral migration rates, a reduced number of channels, deepening of the channels, and a reduction in the wetted area, and potentially can provide insights into the large-scale evolution of river systems under climate-induced variability into vegetation patterns.

In addition to plant surrogates, it may be possible to use chemical surrogates to simulate aspects of biofilm mediated stabilization processes. Xanthan gum (a rheology modifier often used in the food industry) is one example of such a surrogate and has been employed in a number of studies to mimic natural biofilm behaviour (Black et al., 2001; Tolhurst et al., 2002). Even though it has been demonstrated that Xanthan gum is not a perfect analogue of natural biofilms (Perkins et al., 2004), primarily because natural biofilms are more complex, it is seemingly useful in studies on sediment erosion, with increasing quantities of Xanthan gum having a clear effect on the morphology of bedforms (Malarkey et al., 2015; Schindler et al., 2015; Parsons et al., 2016; Fig. 8). A recent experimental investigation compared the stabilization effects for sand of Xantham Gum to three other chemical surrogates; Alginic Acid, Carrageenan and Agar (van de Lageweg et al., 2018). Alginic Acid and Agar had a limited effect, as the erosion threshold for the sediment did not increase while the erosion threshold increased linearly for increased concentrations of Xantham Gum and Carrageenan (van de Lageweg et al., 2018), potentially providing a method of speeding up time scales of physical modelling experiments investigating biostabilization effects.

4.5. Infrastructural developments

A potential barrier preventing the implementation of the innovative approaches discussed above are the physical limitations of the infrastructure associated with the available physical modelling facilities. An obvious example, given the potential stresses placed on growing plants and vegetation in the unnatural conditions of many physical modelling laboratories, is improved facilities designed for optimal biological growth. Potential developments include climate and light-controlled conditions, nutrient delivery, and stress monitoring protocols during the set up and duration of experiments (Johnson et al., 2014a). An additional infrastructural development that is required relates to the measurement and monitoring techniques employed during physical modelling experiments. Especially as the understanding of the impact of climate change and variable forcing in fluvial systems requires a quantification of both short-term and longer-term dynamics (e.g. the impact of single storm events on top of the longer term impact of gradual sea-level rise). Monitoring and measuring remains a challenge for studies that aim to quantify and disentangle the impact from individual short-lived events to longer-term trends due to the lack of high resolution monitoring and quantification techniques that can operate over multiple time scales (Kim et al., 2006). It is recommended that future studies investigate deltaic and estuarine environments with combined fluvial and tidal currents, and the Metronome tidal facility at the University of Utrecht is an innovative facility that has been developed in recent years (Kleinhans et al., 2017). These experiments could provide the ability to observe, monitor and characterise the driving processes that lead to the transition between different equilibrium conditions, and the balance of different aspects of the fluvial landscapes and ecosystems in tidally-dominated environments. This would also improve the parameterisation of such processes in numerical models and associated predictions of how fluvial systems may respond to variations in climatic forcing.

4.6. Linkages with numerical simulations

It is anticipated that combining physical modelling and numerical modelling has the potential to be a robust way forward to address the current gap in the capability to model climate change adaptation. For example, physical modelling can be used to perform focussed sensitivity analyses on the impact of individual parameters in controlled environments, aiding the parameterisation of numerical models that simulate processes such as flow-vegetation interactions (Marjoribanks et al., 2015). Numerical models parameterised from empirical data have explored scenarios and provided projections for the evolution of fluvial landscapes (Coulthard et al., 2007; Nicholas and Quine, 2007; Attal et al., 2008; Nicholas, 2013; Edmonds and Slingerland, 2010;

Fig. 7. Example of a physical model in which the original fluvial braided plain has been colonised by small-scale alfalfa vegetation. Flow is from right to left and the panel is 6 m long and 2 m wide.

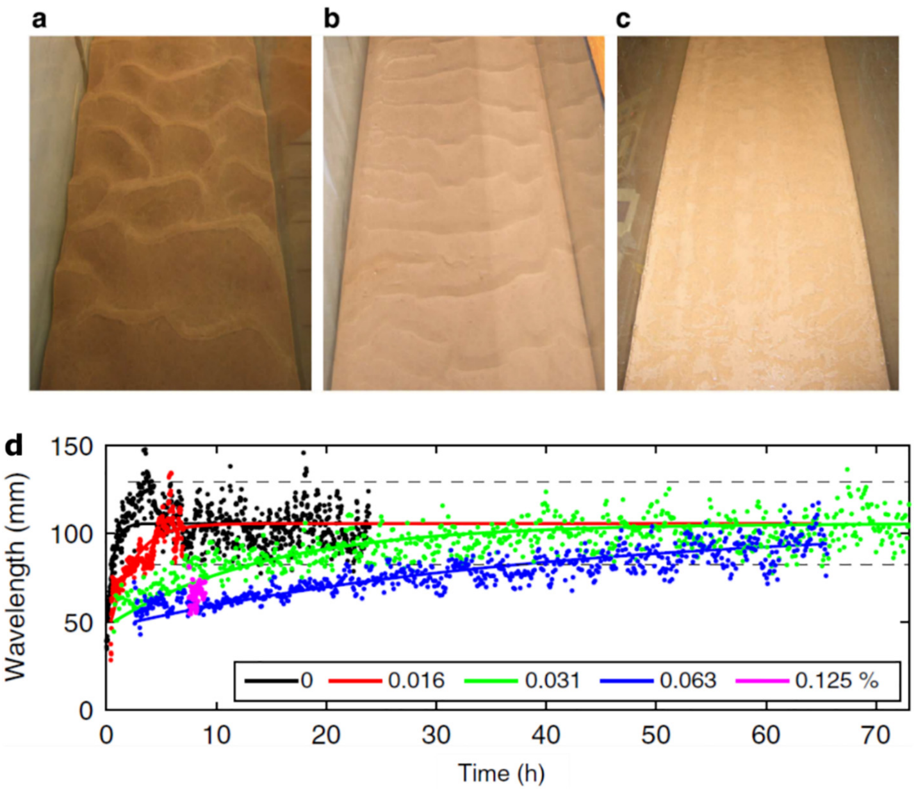

Fig. 8. Effect of extracted extracellular polymeric substances (EPS) content on bedform morphology. (a) 0% EPS, (b) 0.125% EPS content, (c) 1% EPS content. (d) Ripple height development for different EPS contents (black: 0%, red: 0.016%, green: 0.031%, blue: 0.063%, pink: 0.125%). Adapted from Malarkey et al. (2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Schuurman et al., 2013; Liang et al., 2016), sediment-vegetation interactions in these systems (van Oorschot et al., 2016), and the evolution of coastal barrier systems (Castelle et al., 2013). Using datasets from the Barrier Dynamics Experiment (BARDEX II; Masselink et al., 2013), allowed the testing of existing numerical models and to identify priorities for their existing development in order to reproduce processes such as onshore/offshore sandbar migration (1DBeach model, Castelle et al., 2010), barrier erosion sequences (XBeach model; Roelvink et al., 2009) and the impacts of overtopping (SURF_GN model; Bonneton et al., 2011). Testing of numerical models against physical modelling datasets could increase the confidence in numerical simulations, improving the capability to model climate change adaptation. It may be noted that the development of the use of inert plant surrogates may also help and be done in parallel to numerical modelling studies replicating fluid flow around vegetation (Marjoribanks et al., 2014, 2015), whose effects can be included into larger numerical simulation addressing fluvial adaptation at a larger space and time scale.

Numerical models can be used to explore which combinations of variables are most worth studying in physical experiments and can aid with the planning of such experiments. Once accurately parameterised and calibrated in physical models, process-based numerical models could be upscaled to cover larger spatial scales and longer time periods that are appropriate for climate change adaptation (i.e. intermediate scales). Also, numerical model simulations can be useful predictive tools because they can cover multiple spatial and temporal scales and they can easily be forced with a multitude of climate change scenarios that would be impractical using physical models. However, these numerical simulations often contain associated uncertainty due to the inability to determine whether the observed behaviour is a result of true landscape dynamics or merely an artefact of the model set up. Physical models could potentially improve this confidence by replicating some of the same scenarios and comparing the behaviour and interactions between processes in both the numerical and physical simulations.

5. Conclusions

Physical modelling has contributed significantly to our understanding of fluvial systems. This is expected to continue into the future as different physical modelling approaches are well suited to investigate the response and potential adaptation to climatically driven changes in forcing over various timescales. Based on a review of the state-of-the-art in physical modelling of fluvial systems, this study highlights that: (i) physical modelling offers a prime opportunity for furthering the current understanding of variability of forcing in fluvial systems. (ii) For the policy focused studies of fluvial systems undergoing climate change adaptation, the modelled time scales using 1:1, undistorted or distorted scale models need to be extended and the modelled time scales using process-focused or analogue models need to be reduced to address issues relevant to decadal timescales. (iii) Representing the response of plants and organisms to changing conditions and the resulting feedback on physical processes requires more attention and better techniques than presently available, using both distorted scale and analogue surrogate modelling approaches. (iv) Coupling of physical modelling output with numerical model parameterisation and development is crucial for producing accurate predictions of how fluvial systems will respond in the future to a range of possible forcing scenarios over multiple time scales.

Within the context of climatic change in fluvial environments, future focus and investment is recommended towards the physical modelling of the detailed interactions between riverine biology, hydrology and morphology, non-constant forcing and an understanding of the impacts of single events, multi-decadal oscillations and longer term trends. This will enable the development of appropriate and effective mitigation strategies for fluvial ecosystems and environments under threat from climate change, that are grounded in robust physical experimentation.

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