

## Protocols for scaling biogeomorphology in time

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Lead Authors	Rocio Luz Fernandez (University of Hull), Jasper Dijkstra (Deltares), Moritz Thom (FZK)		
Contributors	Rocio Luz Fernandez (University of Hull) Jasper Dijkstra (Deltares) Moritz Thom (FZK) Stuart McLelland (University of Hull)		
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#### **INTRODUCTION**

In the context of climate change adaptation for planning and policy purposes, ecosystem management has the potential to enhance the development of more sustainable and diverse aquatic environments that have an increased capacity to withstand environmental stresses like more frequent floods and droughts. The requirement to model the impacts of climate change on ecohydraulic environments presents significant challenges to modelling studies since they require a full understanding of the complex interaction between the biotic (flora and fauna) and abiotic (geomorphological) components of ecosystems (i.e. their biogeomorphic or ecogeomorphic functioning) over a range of different timescales. For example, some organisms (e.g. insects) can respond to changes in climate conditions within weeks, whereas riparian vegetation may require several months or years to become established and grow to maturity. Other processes, like catchment formation, are likely to take place over centuries or even longer time periods. Hence, a range of different time scales are needed to study the impacts of climate change on ecosystems.

To address modelling on different timescales, physical modelling offers a unique opportunity to improve the current understanding of ecosystem response to climatically driven changes. There is a wide range of laboratory experiments where vegetation has been included to investigate its effect on the flow field, sediment transport, or soil cohesion at different spatio-temporal scales (e.g. Gran and Paola, 2001; Tal *et al.*, 2004; Siniscalchi *et al.*, 2012; Zong and Nepf, 2010; Perucca *et al.*, 2007, and others). Although in most experiments hydraulics and fluid mechanics in abiotic environments are the main focus of experiments, recently an increasing number of studies aim to reproduce a more complex framework, where vegetation is one of the experimental parameters simulating the plant-geomorphic related processes. However, the main challenge for executing experiments with processes driven by vegetation are accurate scaling of the relevant time scales in the context of vegetation growth and the (seasonal) interaction with floods and in terms of climate change adaptation (i.e.  $10^1-10^2$  years).

Apart from the effects of vegetation, the stabilisation of sediments by benthic microalgae/bacteria and fungi (biofilms) is also a topic that has received increasing attention in recent years. Biofilms are ubiquitous in nature and important for the stabilisation of sediments in marine, intertidal and freshwater environments. Furthermore, it has been reported that biofilms quickly adapt to changes in environmental conditions (Graba et al., 2013; Thom et al., 2015) and there are indications that climate change will have an effect on biofilm development (Piggott et al., 2015; Russel et al., 2013) with consequent implications for sediment stability. The main two challenges in modelling these systems are: (i) biostabilization depends on environmental conditions which change throughout the year (seasonality and climate induced changes), such that physical modelling must necessarily cover a wide range of these conditions resulting in an unmanageable number of experimental settings with extended experimental runs; (ii) growing natural biofilms requires flumes in which environmental conditions (e.g. temperature, lights, nutrients) can be set to specific values and these kinds of environmental flumes are uncommon in hydraulic engineering laboratories. To overcome these challenges research in biofilm induced stabilisation processes could make use of chemical surrogates that represent the complex nature of live biofilms. This has been done in other ecohydraulic disciplines (for example to mimic seagrass: Paul et al. 2012, Ghisalberti and Nepf, 2002) but is in early stages for biofilms.



In addition to using physical modelling approaches for forecasting environmental change impacts, it is also possible to use numerical modelling to represent biotic processes in ecohydraulics. For example, whilst a physical model may be better suited for investigating complex flow and sediment transport processes associated to static vegetation, a computer-driven numerical simulation may be more efficient for investigating processes related to vegetation dynamics (e.g. colonization, survival, growth, succession, etc.).

The aim of this report is to review and identify suitable protocols for scale modelling to forecast biogeomorphic system response over time scales relevant to the management of climate change adaptation (decades). The report is structured into three key sections that review recent work carried out in flume experiments (with both vegetation and chemical surrogates) and numerical studies to gain and improved understanding of:

- The timescale criteria for representing long term biogeomorphic processes in flume studies, in order to better assess biota dynamics, flow characteristics, and reach scale morphological evolution.
- How to investigate and develop artificial biostabilization to better understand the interaction between surrogate EPS (Extracellular Polymeric Substances), sediment and hydraulics and provide fundamental information for designing experiments on biostabilization.
- The use of numerical modelling to test different strategies for time scaling of biogeomorphological interactions, to minimise the experimental tests required or take full advantage of laboratory results (hybrid modelling).

The document presents the following three illustrative examples of biomass modelling, with focus on the considerations of the timescales adopted:

- Experimental approach for long-term river's response characterization. A laboratory study on the mechanism of bed morphology adjustment in response to vegetation growth and flood sequencing is reported. The biota involved in the study is riparian vegetation, and relevant geomorphological factors are bed topography and the transport of sediment.
- Experimental method for scaling biostabilization in time. Artificial biofilms and their impact
  on sediment stability is studied in a physical experiment. The impact of three different
  parameters (grain size, EPS content and stickiness of EPS) on the erosion threshold and the
  mode of erosion is analysed.
- Numerical modelling of eelgrass development. A field campaign by multiple Hydralab+ partners in the Rødsand lagoon in eastern Denmark, during which plant properties, turbidity and hydrodynamic forcings were measured, provided data to construct and validate a numerical model. Subsequently, this model was used to analyse the possible effects of climate change (e.g. increase in temperature, water level and storminess) on this shallow coastal system.



### 1. SCALING BIOGEOMORPHOLOGY IN TIME: FLUME STUDIES

#### 1.1. THE BIOGEOMORPHIC FRAMEWORK

#### 1.1.1. Vegetation as an active component in flume studies

Vegetation is a general term for plant life and understanding its interaction with fluvial geomorphology is critical for determining processes and forms in alluvial rivers. In this context, flume studies have advanced our understanding of the influence of individual plants or patches of plants on turbulence intensities (Nepf, 1999; Wilson *et al.*, 2003; Siniscalchi *et al.*, 2012), flow resistance (Green, 2005; Västilä and Järvelä, 2014), sediment transport (Jordanova and James, 2003; Zong and Nepf, 2010; Yager and Schmeeckle, 2013), morphodynamics around plants (Bouma *et al.*, 2007; Perucca *et al.*, 2007; Meire *et al.*, 2014), and velocity profiles (Jarvela, 2005; Lightbody and Nepf, 2006; Aberle and Jarvela, 2013; Luhar and Nepf, 2012).

In particular, flume experiments have shown that vegetation can be a key ingredient in the simplification of river planform and the maintenance of single thread channels (e.g., Gran and Paola, 2001; Tal *et al.*, 2004; Jang and Shimizu, 2007; Tal and Paola, 2007; Braudrick *et al.*, 2009; Li and Millar, 2010). It has also provided insights into the plant-related processes leading to channel blockage and avulsion (e.g., Tal and Paola, 2010) and landform building (Braudrick *et al.*, 2009; Li and Millar, 2011). Whilst many flume experiments have indicated a simplification of planform in response to bank and floodplain vegetation, other flume studies have showed that vegetation growth in ephemeral rivers may cause the flow to divide (e.g., Coulthard, 2005), increasing the braiding intensity (or number of channels) of the fluvial system.

At a smaller scale, the relative importance of vegetation-related hydrological and hydraulic processes for bank stability has been investigated widely in the laboratory (Thorne, 1990; Simon and Collison, 2002; Tal *et al.*, 2004; Gray and Barker, 2004; Van Dijk *et al.*, 2013). These experiments have revealed important spatio-temporal variations in plant rooting depths and density that are important for bank stability.

While the previous studies have shown how vegetation can control physical processes within the fluvial context, other studies have focused on how hydrogeomorphic processes and fluvial landforms can control plant communities (e.g. Naiman and Décamps, 1997; Steiger *et al.*, 2005).

These one-way relationships between flow dynamics, geomorphology and vegetation investigated by the previous studies have been the main focus of previous studies of river system function. However, more recently studies have begun to look at how biogeomorphic processes lead to reciprocal adjustments (or two-way interactions) between landforms and the biological communities that define fluvial landscape dynamics. In this context, a conceptualization of the fundamental interactions between hydrogeomorphic processes and vegetation dynamics driving the fluvial landscape dynamics was proposed by Corenblit *et al.*, 2007 (Figure 1).



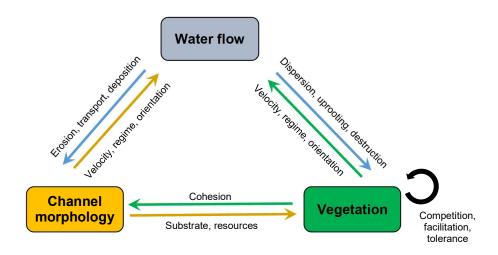


Figure 1 A schematic overview of the vegetation as an active component in fluvial systems (Corenblit et al., 2007).

Moreover, recent studies have investigated the effects of vegetation on fluvial landform development during its growth, from seedling to a mature plant, leading to the notion of the biogeomorphic succession (Corenblit *et al.* 2007, 2009, 2014). The cyclic dynamics of the biogeomorphic succession (regression or progression in time and space) depends mainly on the relation between resisting (sediment cohesiveness, bed and vegetation roughness) and destructive (flood) forces. Here, vegetation acts as a key parameter in controlling the biogeomorphic cycle at a number of different levels: (i) through its ability to colonise and to develop sufficiently quickly between destructive floods on a bare substrate in the channel; (ii) by its ability to trap sediment; (iii) by its ability to resist total destruction by flow; (iv) and finally, by its ability to increase substrate cohesiveness. Then again, the growth and succession of riparian vegetation is highly dependent on the local abiotic conditions, and this leads to feedback cycles that affect the overall natural development of river systems.

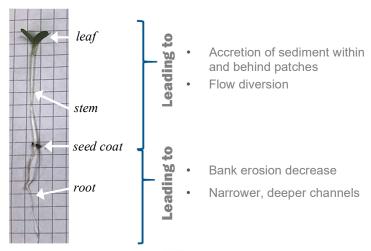
#### 1.1.2. Plant-fluvial geomorphic interactions

In nature, plants have different size and shape according to species, growth stage and environmental conditions. Moreover, each plant has an almost unique combination of height, stem diameter and stiffness, foliage and other properties. In flume studies, this complexity and variability of natural vegetation have been greatly simplified to represent the geometric and biomechanical properties that affect fluvial processes (for instance, see Nepf, 2012).

In experimental studies, the above ground biomechanical properties of a plant include (Figure 2): canopy biomass, flexibility and tensile strength; while below-ground properties are: root biomass, depth, tensile strength, uprooting resistance, architecture and root reinforcement.

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**Figure 2** Geometric properties for a real vegetation (alfalfa) and their influence on the flow field and substrate.

Until recently, the *one-way interactions* between flow dynamics, geomorphology and vegetation have been considered dominantly when studying the functioning of river systems. In relation to this abiotic or *passive role* of vegetation, plants can affect the flow field, fluvial transport processes, and morphology of the river through several mechanisms. Hence, the *above-ground biomass* can modifies the flow field: (i) by reducing flow velocities and near-bed shear stresses, (ii) by increasing turbulence intensities near canopy tops for submerged vegetation and along the interface between emergent riparian vegetation and the main channel, (iii) by reducing the transport capacity of the flow and cause sorting and deposition of sediment, (iv) by creating secondary circulation patterns, and retain sediment (Bennet *et al.*, 2008; Piégay and Gurnell, 1997; Gregory *et al.*, 2003; Corenblit *et al.* 2007, 2009, 2011; Zong and Nepf, 2010), whereas their *below-ground biomass* might affect the hydraulic and mechanical properties of the substrate (Docker and Hubble, 2008, Burylo *et al.*, 2012) and consequently the moisture regime and erosion susceptibility of the soil, potentially changing bank strength and other surface resistance properties.

Regarding the opposite way of the interaction, the effect of the flow on vegetation, it includes: flood-induced death of riparian plants through uprooting, burial, or anoxia, saturation of the soil, and geomorphological impacts through erosion and deposition of sediment, where floodplain elevation determines the type of riparian vegetation that establishes (e.g. Bendix and Hupp, 2000).

Models that consider the two-way interactions or the reciprocal adjustments between the fluvial landform and plant communities have been started to be contemplated in more recent years. These models consider that vegetation ecological actions (competition, colonization, succession, etc.) influence several hydraulic and morphodynamic processes and interact with them to affect riparian vegetation dynamics. For example, after seeds are deposited on landforms created by fluvial processes, they start to germinate and the plants to grow, then the new vegetation starts to affect the local flow field, altering sedimentation/erosion processes and initiating vegetation-induced morphological changes (Camporeale *et al.*, 2013).

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These one- and two-ways mechanisms of interaction between vegetation and hydro-morphological processes have guided the approaches for using live vegetation in flume experiments described in Section 1.2.

#### 1.2. Use of live vegetation in flume studies

A review is presented in Deliverable 8-IV (2018) for the different categories: seagrass, seaweeds, saltmarsh plants, riparian vegetation, grasses and freshwater macrophytes. Here, the class of riparian vegetation is presented in more detail.

The use of live plants in flume experiments for modelling alluvial geomorphology it has been solved in two different ways: as *static vegetation* (which includes the passive role of plants), that considers the mechanical and morphological actions of the riparian vegetation; and as *dynamic vegetation* (which includes its active role), where plant colonization, succession, growth and survival influence hydraulic and morphodynamic processes and interact with them to create the distinct patterns in alluvial morphologies.

Static vegetation experiments consider a *one-way interaction* (i.e., the effects of vegetation on hydromorphological processes, or vice-versa). In this approach, vegetation seeds are usually distributed by hand (uniformly distributed) or by the flow (seeds added in the feed) at the start of the experiment and not reseeded further. Seeds can be pre-soaked (48 - 72 hours) and air dried (6 - 12 hours) before being disperse over the experimental floodplain at different densities and allowed to germinate (4 - 25 days). The use of static vegetation has enabled the assessment of the effects of different densities and ages of vegetation on alluvial morphology. This technique that considers the one-way effects of channel dynamics on vegetation and vice versa has been employed in experiments conducted by Gran and Paola (2001), Van de Lageweg *et al.* (2010), Van Dijk *et al.* (2013), Kleinhans *et al.* (2014). Regarding seed preparation techniques and vegetation growing conditions required for use in flume experiments for both alfalfa (*Medicago sativa*) and oat (*Avena sativa*) a detailed description is reported in Clarke (2014). As an alternative, to the previous studies that used alfalfa and oat, Coulthard (2005) employed three different varieties of similar sized bedding plants: Gomprena, Impatiens and Petunias to simulate trees/shrubs. In this particular case, the static vegetation was planted at random locations along the flume.

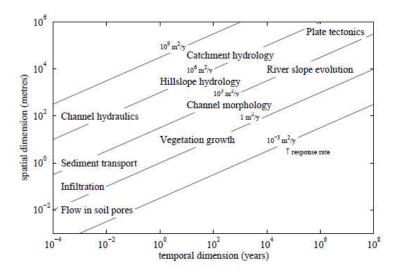
In contrast, dynamic vegetation experiments consider the *two-way coupled interactions* between vegetation and hydro-morphological processes. These experiments include reseeding during the experiment and allow for both vegetation growth and colonization, and there is a co-evolution of riparian vegetation and channel dynamics. For instance, the laboratory channels are allow to evolve through time, letting for both channel migration and successive vegetation growth. In these on-going experiments, vegetation is reseeded following repeat flow events, simulating the natural process of vegetation encroachment on the floodplain and channels. Examples of flume experiments with dynamic vegetation are given in Tal and Paola (2007) and Braudrick *et al.* (2009). This methodology has confirmed that dynamic vegetation plays many diverse roles in alluvial environments beyond simply disturbing the path of flood flows. Notably it has been found that differences in vegetation colonization conditions, density and survival create distinct patterns in alluvial morphology.



#### 1.3. GENERAL APPROACHES FOR SCALING PLANT-FLUVIAL GEOMORPHOLOGY IN TIME

#### 1.3.1. Characteristic time scales

In fluvial environments, one way to deal with different temporal scales is to identify them in terms of a hierarchy of scales (Frissell *et al.*, 1986; Baptist, 2001); i.e., spatial and temporal scale levels are coupled with small-scale phenomena being associated with small-scale processes, and large-scale phenomena with large-scale processes, or potentially with small-scale processes that are coherent over a large scale. In this context, Kirkby (1990) presented an example for the wide variety in scales for river systems (Baptist, 2005). Kirkby proposed a measure for the response rate of systems, defined as a diffusive transport rate, i.e., the ratio of the squared spatial dimension (m²) over the temporal dimension (year) (Figure 3). Vegetation growth has a relatively small response rate (about 1 m²y¹), meaning that changes in vegetation patterns are a less dynamic landscape element than changes in morphology. However, morphodynamics leading over vegetation dynamics might not be always true, like in vegetation-dominated rivers for example.



**Figure 3** Temporal and spatial scales for geomorphological processes. The response rate indicates the evolution rate of the processes. Modified by Baptist (2005) from Kirkby (1990).

Another generalized approach is the classification of Frissell *et al.* (1986), in which streams and their watershed environments are classified within the context of geomorphic features and events, and spatio-temporal boundaries are identified. This classification distinguishes between river basin ( $10^3$  m), river segment ( $10^2$  m), river reach ( $10^1$  m), pool/riffle system ( $10^0$  m) and microhabitat system ( $10^1$  m). Biomorphological interactions can have effects on the different scale levels (Baptist, 2001), but particularly at the river reach scale those interactions become relevant, as it is explained below.

At the hierarchical level of river reach, spatial and temporal scales of development of processes and patterns are smaller than for the river basin. Channel characteristics for river reaches range from one to hundreds of kilometres and typical time scales of development range from tens to hundreds of years. This means that the development processes in river reaches is close to the specific time scales

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for ecological development such as tree growth. In this context, bio-geomorphological interactions become stronger at the river reach scale, and for this reason, it is important to include vegetation in flume studies that model river reaches.

At this reach scale, two major time-scales were distinguished by Kondolf and Piégay (2016); temporary channel changes linked to an episodic event, which strongly modify the channel, such as a large flood event, versus long-term, irreversible changes (in this case, the system is not able to go back to the initial equilibrium state). In this case, the concept of 'dynamic equilibrium' represents the channel to be metastable around an average condition, fluctuating in response to the magnitude and frequency of floods (Hack, 1960). This dynamic equilibrium is broken when the river adjusts to new control conditions and shifts to a new equilibrium state (Kondolf and Piégay, 2016).

In this context, with the increasing recognition of climate change and changes in the pattern of climatic phenomena, it is 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. As highlighted by Baynes *et al.* (2018), all systems have a characteristic time scale for recovery following a perturbation (Brunsden and Thornes, 1979). This time scale can range from >10³ years in erosive bedrock settings to 10¹ - 10² years in alluvial depositional fluvial environments due to the relative differences in the mobility of sediments. With an increased frequency of extreme events, this recovery timescale may be significantly altered, with subsequent events of possibly greater magnitude occurring before the system has fully recovered from the initial perturbation with potentially unknown consequences (Baynes *et al.*, 2018).

In flume experiments, models that replicate the prototype with (or without) reduction in dimensions are typically used to study the physical processes at smaller temporal scales in river reaches (e.g. days, months or years); while the evolution of plant-river geomorphodynamics over larger temporal scales is often investigated in so-called analogue models, which are designed to represent the longer periods of time (e.g. years, decades or possibly centuries). In both cases, reversible channel changes are being modelled.

In this respect, time scales associated with the growth and behaviour of vegetation are inherently difficult to downscale in flume experiments using classical Froude similarity approaches or even distorted models. Therefore, it is more suitable to use living or artificial surrogates within the framework of an analogue modelling approach, where the effects of vegetation in the system are replicated, but not necessarily directly. For plants, many studies have used alfalfa (as described in section 2.1) whose size and growth time-scale fit with a downscaling approach to physical modelling of sediment and flow dynamics.

#### 1.3.2. Selection of temporal scale and model evaluation

Appropriate temporal scales can be selected in plant-fluvial geomorphic models by considering the intended applications and the time-scales over which conditions change in the case study. An experiment designed explicitly to examine the effects of vegetation on bank erosion and channel migration could be intended to evaluate river evolution after a single major storm event. In contrast, a flume experiment intended to estimate the long-term response of a river reach to variations in



hydrograph characteristics (magnitude, frequency) would assess rates over a sufficient period of time to either evaluate or smooth out annual variations. In this last configuration, the identification of response timescales of morphodynamic processes to individual events could act as a starting point for evaluating the response to sequences of multiple events of different frequencies and magnitudes (Martin and Jerolmack, 2013).

In this context, the time scales employed for scaling and representing fluvial bio-geomorphic processes in physical models can be selected from 1:1 experiments that reproduce processes at real-time or time scales up to 100 years, to analogue models that include time compression to simulate processes over time scales of decades or exceeding 100 years, which can include the representation of variable forcing, the impacts of climatic change, land-use and other long-term drivers of system change. As mentioned above, models that replicate the prototype with (or without) reduction in dimensions are typically used to study the physical processes at the small temporal scales in river reaches; while the biogeomorphic evolution over larger temporal scales is often investigated in analogue models. In any case, the performance or evaluation of the models should be conducted systematically to ensure that the characteristic temporal scales are represented.

Within this framework, identification of characteristic temporal scales is important in assessing the rate at which models function and the relationship to spatial characteristics. Typically, a common approach to derive the time scale for the formation of a movable bed surface in a flume-river is based on the comparison of the model response time to known prototype response times (Vollmers and Giese, 1972; Kamphuis, 1975). This knowledge about the scales of characteristic river features is invaluable for model evaluation. For example, characteristic time-scales for a braided river may be defined in various ways. Possibilities include: (i) the time that the system takes to establish its statistical equilibrium; (ii) the average time of existence of channel confluences and bifurcations (Paola, 2000); (iii) the time in which a channel increases sinuosity before a different process such as channel avulsion or cut-off takes place. When considering interactions between vegetation and hydrogeomorphic processes, models should ensure that the dynamic behaviours of the surrogate vegetation correspond to the original criteria, i.e., the reproduction of the process observed in nature (e.g., plant to plant interaction, effect of vegetation on sediment transport). Assuming that validation procedures are achieved successfully, the model can be described as being reliable for a particular context and is ready to be applied in a predictive model the case of experiments involving time compression effects (analogue models) the seasonal changes of plant characteristics may be lost, but those models are potentially helpful to develop an understanding of targeted processes under controlled conditions, such as the exploration of the impact of a sequence of events on the overall system behaviour across longer time scales relevant for climate adaptation purposes.

Below, a case study is examined as an example of how options were selected to address a specific question regarding the long-term (decades) river's response to flood events: with flood frequency increased, is the impact of flood sequencing important to be included in modelling studies? In this respect, the following experiments are a representation of a fluvial reach over time scales relevant for managing the immediate impacts of global climatic change and where knowledge is currently lacking: i.e.,  $10^1 - 10^2$  years.



## 1.4. CASE STUDY: EXPERIMENTAL APPROACH FOR LONG-TERM RIVER'S RESPONSE CHARACTERIZATION (IMPACT OF FLOOD SEQUENCING)

With river flooding being more frequent due to climate change, the interaction between fluvial morphodynamics and riparian vegetation may depend in part on the sequence of the flood events. In this context, the impact of flood sequencing on some of the bio-geomorphic interactions listed in section 1.1.1 was investigated through a physical modelling approach in which a combination of low and high floods were released on a braiding river. The event-based observations could then be translated into an improved understanding of river behaviour over long-time periods. Hence, the time distortion (compression) that is implicit in the analogue model might allow for the characterization of the impact of flood sequencing across a time scale that might be relevant for climate adaptation purposes. The model also investigated the river's response over variable life stages of vegetation, allowing for the characterization of the impact of flood sequencing for different sizes (height) of the plants.

#### 1.4.1. Brief description of experimental data

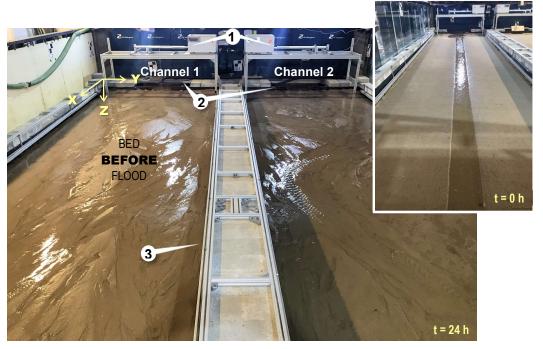
Experimental data used in this case study was collected in the Total Environment Simulator (TES), University of Hull. The TES flume was subdivided into two mobile bed channels (2.5 m wide, 10 m long) with constant longitudinal slope (0.015) and uniform grain size ( $d_{50}$  = 0.46 mm) as shown in Figure 4. A pump located at the upstream end of the flume generated a constant discharge into a small overflowing reservoir located upstream of each channel. Above these reservoirs, sediment feeders released sand at a constant rate in the centre of the overflowing outflows. During the experiment sediment was collected at the downstream end of the flume, while water recirculates. The downstream collecting boxes were located on scales that allowed for a continuous record of the sediment weight, as shown in Figure 5.

#### Overview of experimental procedure and model calibration

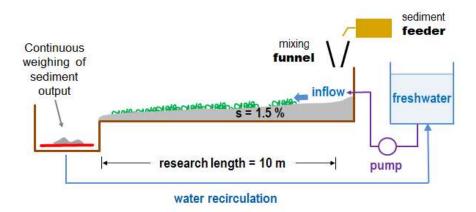
Three sets of experiments were performed to identify the critical role played by vegetation (alfalfa) during the release of a sequence of low and high magnitude flood events. Each set of runs started from a flat sloping bed (0.015 m/m) with an initial straight channel (0.25 m wide and 0.01 m deep) carved down the centre of the entire bed, to encourage the initial river to develop in the middle of the experimental domain.

The first set of experiments had the main objective of calibrating the flows and sediment rates, as the floods were designed to maintain the bed equilibrium (i.e., with no net trend towards either aggradation or degradation) during the experiment. For all the discharges performed, the associated sediment feed rates were initially estimated based on empirical equations (e.g., Meyer, Peter and Muller, 1948) and then they were adjusted in order to keep the initial bed slope. From this calibration process, a discharge of 2 L/s was selected for the small flood event, with an associated sediment rate of 8.0 g/s. The large flood resulted 3 L/s with a sediment rate of approximately 15.5 g/s.





**Figure 4** Overview of the laboratory flume (Total Environmental Simulator at the University of Hull) investigating the morphological response of braided rivers to flood sequencing: 1, sediment feeder; 2, water inlet; 3, lateral rails. At the initial time, t = 0, and after reaching equilibrium conditions, t = 24 h.



**Figure 5** Schematic side view of experimental set-up.

Sediment conditions included runs with the equilibrium loads (described above), but also some flood events with a sediment deficit (in which transport capacity exceeded supply) to quantify the sensitivity of the river's response to significant disturbance events. For these floods with sediment deficit within the inflow the feed rate was reduced to 20% (1.5 g/s).

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Once flows were calibrated, two more set of experiments were carried out for bare and vegetated bed conditions. In both sets, the constant, channel-forming discharge used for the development of the braided bed was the same (1.5 L/s and 6 g/s), which permitted to reach the equilibrium state (i.e. no net long-term trend towards either aggradation or degradation) in about 24 hours. As part of the model evaluation, the agreement of characteristic scales observed in the laboratory (in equilibrium conditions) and predicted from empirical studies was strong (Table 1): total channel width (Van den Berg, 1995), total sinuosity, maximum bar height and maximum scour depth (Robertson-Rintoul and Richards, 1999; Ashmore, 2000).

After the equilibrium bed state was achieved, the braided river system was subjected to the flood sequence that included a succession of the low (2 L/s) and high (3 L/s) floods. The outcomes of each run were characterized by a detailed digital elevation models, DEMs (before and after each flood event), digital imagery and continuous monitoring of the sediment transported through the flume outlet.

Measure	Laboratory river	Empirical estimate	
Total channel width	520 mm	380 mm	
Average number of channels per cross-section	5.3	4.8	
Total sinuosity	2.5	2.0	
Average maximum bar height	2.2 mm	2.4 mm	
Average maximum scour depth	-2.01 mm	-2.2 mm	

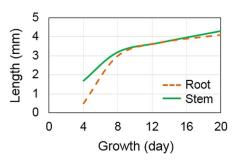
**Table 1** Characteristic scales estimated from empirical studies and observed in the laboratory.

By considering a 1:100 generic scale, the experimental setting described can be well though as a hydraulic model of a non-specific braided stream prototype with a reach length of 1000 m and mean width of 250 m, subject to a sequence of floods of 200 m³/s and 300 m³/s of magnitude; discharges that could be associated to a return period of 2 and 10 years, respectively. A number of rivers can be found in nature with the characteristics scaled above (e.g., upper Drôme River in France, Landon and Piégay, 1999).

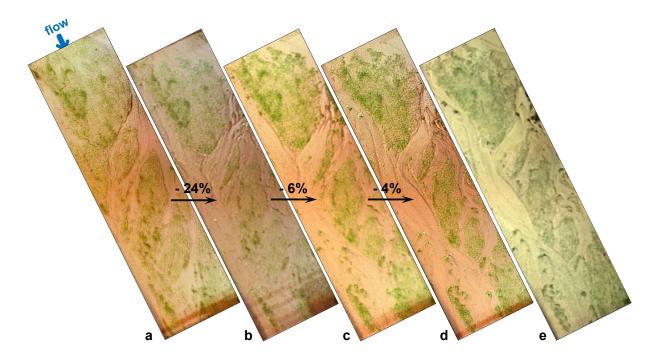
Seeding: In the third set of experiments, alfalfa seeds were uniformly spread on the bed (1 seed/cm<sup>2</sup>) and allowed to grow before the release of the floods. Note that prior to the seeding, the braided bed was in statistical equilibrium, so that, all subsequent alluvial channel adjustment will be a direct result of vegetation and its impact on the flow and morphology.

Four different growth periods (Figure 6) were investigated (4, 8, 14 and 20 days) along with a dying phase, to get insights into the relative role of the plant's age (size) in the geomorphic impact of the sequential floods. A top view of different vegetation patterns through the experiments is shown in Figure 7. The experimental procedure did not allow a recovery of neither vegetation nor morphology in between floods, as the goal was to model the situation where the subsequent event occurred before the system had fully recovered from the previous perturbation. As there was not reseeding, vegetation was continuously removed.





**Figure 6** Mean growth curve of root length and stem length of alfalfa sprouts.



**Figure 7** Top view of remaining vegetation for different plant's life stages in channel 1: **a)** 8 days: before floods; **b)** 14 days: before floods; **c)** 20 days: before floods; **d)** 20 days: after floods; **e)** dried stage: before floods. Percentages indicated the proportion of alfalfa removed.

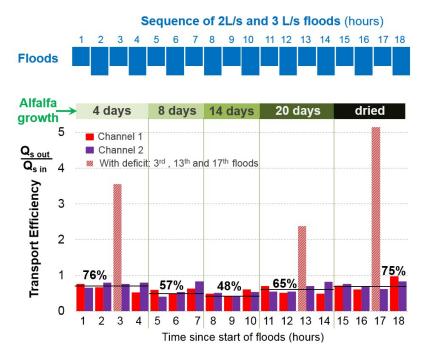
#### 1.4.2. General aspects of experiments

Vegetation significantly impacted on the erosion-transport-deposition processes during the flood sequence (Figure 8) released in the channels. The bedload transport efficiency (ratio between the sediment output and the sediment input of the system) decreased to a minimum value (0.48) when the plants were allowed to grow for 14 days, and started to increase as they were allowed to grow more. Hence, as alfalfa grew for 14 days, the plants provided increasing control on the proportion of sediment transport rates during the sequence of floods. However, at the age of 20 days, bedload transport efficiency slightly increased (Figure 8), which can link to the scour induced by plants in some areas of the river reach as indicated in Figure 9. In this respect, Figure 10 illustrates the increase of the

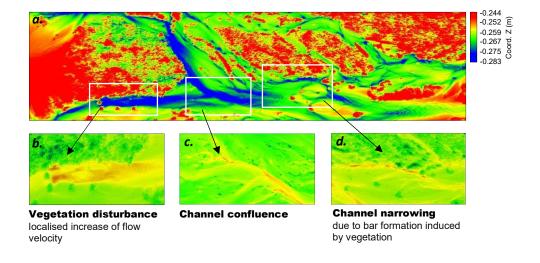
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maximum scour depths measured for the vegetated bed conditions by contrasting them with the scour values measured during the experiments with no vegetation cover.



**Figure 8** Transport efficiency (in channel 1 and channel 2) during the flood sequence released for runs with vegetation cover.



**Figure 9** Examples of scour areas from the DEM measured for the runs with vegetation. **a)** Topography post flood  $10^{th}$  in channel 1. Flow direction is from left to right and the panel is 10 m long and 2.5 m wide. **b), c)** and **d)** scour areas (log-scaled images for visualization purposes).

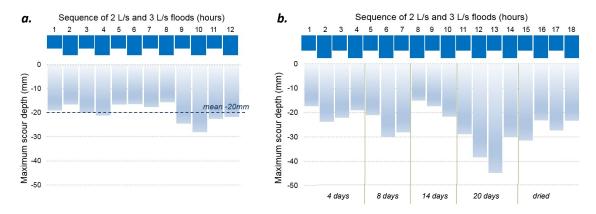
As the recovery of vegetation (colonization, reseeding) was not allowed in the experiments, the initial plant uniform distribution was continuously disrupted by the successive flood events over the

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different life stage of the plants, with the effects of the vegetation disturbing the flow being more significant for the plant's size linked to the 20 days of growth.

In this respect, this type of approach can give basic and useful information on the mechanism of bed morphology adjustments in response to flow variability (flood sequence) under conditions similar to nature where the subsequent event occurs before the system has fully recovered from the previous flood event. Figure 8 also shows the sediment transport efficiency for three floods with deficit in sediment. The inclusion of these disturbances during the experiments can provide information on how the river works and how sensitive it is to management actions. For the experiments performed here, the recovering from those deficit floods, the changes (cutting/filling) were reversible in the short term (during the following flood event).



**Figure 10** Maximum scour depths measured during the release of flood sequence for **a**) bare and **b**) vegetated bed conditions.

#### Forcing effects of vegetation growth

Once the seeds germinates and the plants started to grow, vegetation started to affect the local flow field, altering sedimentation/erosion processes and initiating vegetation induced morphological changes, particularly to the end of the experiment. In this context, Figure 11 shows the evolution of morphological changes of the river at the end of some released floods. As a result of the constant removal of vegetation by the successive floods, the non-uniformly distributed vegetation induced sediment deposition downstream of vegetation patches leading to island development and channel pattern changes. As mentioned earlier, scouring depths also increased for the higher plants conditions, as it is shown in Figure 10. Overall, during the experiment an increase in the forcing effects was established by the vegetation, which magnified as the plants grew up.

Several features observed on the river's response over the plant's life stages (braiding intensity, width/depth relationship) could be then translated into an improved understanding of river behaviour over long-time periods (Fernandez *et al.*, 2019). The seasonal variations of vegetation characteristics and colonization were not included in the referred model, but vegetation dynamics (the different life stages of the plants, so that, different plant's heights) and their effects on the river morphology during flood sequencing were considered in the design executed. In this respect, the model described can

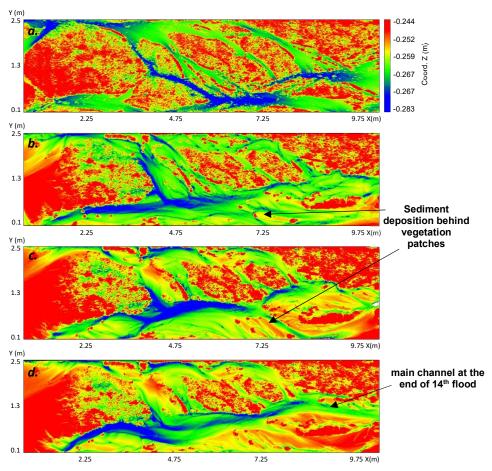
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allow for the identification of different processes in the river's response that could be useful when assessing the long-term dynamics of natural rivers.

These close relationship between morphodynamics and vegetation implies that the two dynamics cannot be modelled separately. If recovering of vegetation is not allowed during the sequence of flood events, the effects of non-uniformly distributed vegetation have a large effect on the morphology and dynamics of the rivers, which may lead them to patchy multi-thread rivers. Whereas a recover of vegetation (by reseeding) on a floodplain of a laboratory braiding river may increase sinuosity and lead to a single-thread meandering river, as it was shown in the experiments performed by Tal and Paola (2010).

The experimental approach presented here underlines the significance and potential for physical models in advancing our skills in representing the ecological actions of vegetation (colonization, succession, etc.) in fume studies (and in hybrid modelling, see section 3). Conveniently, river geometry evolution and vegetation development have comparable temporal scales that allow us to explore hydro-bio-geomorphological interactions with a high degree of control in the laboratory.



**Figure 11** Channel pattern changes due to bar formation induced by vegetation patches. Flow direction is from left to right. **a)** Topography at the beginning of 8<sup>th</sup> flood. **b)** Before 11<sup>th</sup> flood event. **c)** At the end of 12<sup>th</sup> flood. **d)** At the end of 14<sup>th</sup> flood.

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# 2. DESIGN OF BIOFILM SURROGATES: A FIRST APPROACH TO SCALING BIOSTABILIZATION IN TIME

#### 2.1. NATURAL BIOFILMS AND THE USE OF SURROGATES

Biofilms are complex assemblages of bacteria/algae and fungi (Gerbersdorf and Wieprecht, 2015). These communities secrete a glue-like substance called EPS (Extracellular Polymeric Substances), which is often responsible for increased sediment stability (Grabowski *et al.*, 2011) and alterations of (river-) bed morphology (Parsons *et al.*, 2016; Pique *et al.*, 2016).

Biostabilization (this term will be used to describe biogenic stabilization mechanisms by biofilms) has been studied for the last two decades both in the field and in physical flume experiments. Essential information on, for example, the seasonal effects and ranges of the biostabilization index BI (i.e., biostabilized erosion threshold divided by non-stabilized sediment threshold, equation 2) have been gathered in the field but to study the impact of single parameters on biostabilization laboratory experiments are necessary.

However, investigating natural biofilms in flume studies is often not possible since it requires "environmental flumes" in which essential parameters like light intensity, nutrient availability and temperature need to be controlled and maintained. For that reason purpose-built multi-channel flumes have been developed (e.g. Thom *et al.*, 2015) in which, apart from impacts of light intensity and flow velocity, the seasonal effects have also been studied during a cultivation period of approximately one month.

Such purpose-built facilities are still uncommon in hydraulic laboratories and furthermore the time to run such experiments may be a limiting factor particularly when it is necessary to test a number of different environmental conditions. To overcome these limitations and enable modelling biostabilization over even longer time scales (e.g. time scales relevant to climate change processes), the use of surrogate materials has been investigated as part of this Joint Research Activity in Hydralab+.

Surrogate materials, such as cylinders and flexible structures made of different materials, have been used widely in the hydraulic experimentation community to mimic the idealized behaviour of higher level plants (see for example: Frostick *et al.*, 2014). Equivalent approaches however, are not yet widely available for studies of biofilm mediated stabilization even though pioneer work on using a "chemical surrogate" has been carried out by Tolhurst *et al.* in the early 2000s. In their study, Tolhurst *et al.* (2002) studied the erosion (rate and threshold) of a mix between sand and Xanthan Gum (a commercially available EPS produced by bacteria in an industrial reactor) and compared their findings to results from field studies. Another field of application of such polymers is the large scale modelling of e.g. delta morphology simulating the impact of cohesive sediments (Hoyal and Sheets, 2009; Kleinhans *et al.*, 2014). Despite these advances, the fundamental knowledge to guide the handling and design of these EPS sediment mixtures is limited and currently prevents deeper investigations on the scaling of biostabilization.

The aim of this part of the report is to broaden the knowledge on artificial biostabilization by exploring the stability enhancements (in terms of erosion threshold) of an added industrial EPS on different grain sizes in a small erosion flume. The results reported in this protocol should help researchers to



better understand the interaction between a surrogate EPS, sediment and hydraulics and provide fundamental information to design their experiments on biostabilization. Furthermore, differences and similarities between natural biostabilization processes (and more specifically: the mode of erosion) and the surrogates are assessed to approach the important question of transferability of the results.

#### 2.2. MIXING SURROGATE EPS AND EXPERIMENTAL SETUP

To explore the stabilization potential of added EPS two different sets of experiments were conducted. In the first set of experiments different types of commercially available EPS surrogates were mixed at different ratios of EPS-powder to water, since this was expected to result in changes of the surrogate's material properties. For these experiments surrogate-EPS adhesion was measured using the device described in HYDRALAB+ deliverable 9.3. From these tests, Xanthan Gum was identified as the best potential candidate for flume studies since i) the adhesiveness of the material can be easily controlled and ii) the measured adhesion was similar to that of natural biofilms (from an earlier study). For more details of these experiments, the reader is referred to deliverable 9.3.

The second set of experiments, which are described here, concern erosion measurements conducted in a small flume experiment. For these experiments, Xanthan Gum is added to three different size classes of sand, using six different ratios EPS/Sand (+ one with no EPS) and three different mixtures EPS-powder to water (corresponding to three different adhesive mixtures). In total roughly 60 erosion experiments were conducted (see Table 2).

Adhesion			EPS/Sand [	EPS/Sand [g/g]		
[N/m <sup>2</sup> ]	0.02	0.03	0.05	0.07	0.10	0.67
1.0						
3.5			FS/MS/C	CS		
7.7						

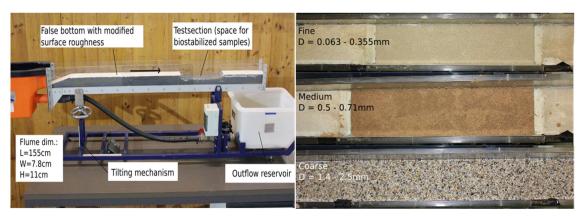
**Table 2** Matrix of EPS mixtures added to FS = fine sand (D= 0.063 – 0.355 mm), MS = medium sand (D = 0.5 – 0.71 mm) and CS = coarse sand (D = 1.4 – 2.5 mm). In addition to these mixtures, also pure sand was eroded acting as a reference for non-biostabilized sediments.

The EPS-sand samples are prepared following the steps described below:

- Xanthan Gum powder is added to 0.5 I of tap water (room temperature) at five different concentrations (C<sub>EPS</sub> = 0.3, 1.0 and 1.5 weight-%) corresponding to measured adhesion values of 1.0, 3.5 and 7.7 N/m<sup>2</sup> respectively.
- The water plus powder is mixed with an immersion blender for 2-3 minutes to destroy larger aggregates and to produce a homogeneous mixture (this is what is called EPS).
- The EPS is mixed carefully with dry sand at ratios EPS/sand of 0.02, 0.03, 0.05, 0.07, 0.10 and 0.67 g/g until all grains appear to be fully saturated.
- Reference samples without additional EPS are also produced (i.e. adhesion = 0 N/m², EPS/sand = 0).



The EPS-sand mixtures are eroded in a small tilting flume (Armfield sediment transport demonstration channel – S8MkII, L x W x H =  $1.55 \times 0.078 \times 0.11$ m). The flume is slightly modified by including a false bottom (made of PVC) within the test section (see Figure 12a). The samples to be eroded are produced in two layers as typically biofilms only occupy the first few millimetre of a bed. Therefore, the bottom layer (thickness = 10 mm) consists of pure sediment and the top layer consists of the EPS/sand mix (thickness = 5 mm, a realistic value as reported by Chen *et al.*, 2017). The surface of both layers is levelled to prevent any hydraulic disturbance at the transition between test section and inlet. Furthermore, the roughness of the false bottom is adapted to the roughness of sand to be eroded by glueing the specific sand size on the PVC bottom (see Figure 12b, note: for the fine sand fraction the medium sand was used).



**Figure 12** *a)* Tilting flume setup for investigations on erosion threshold and observation of bed failure mechanisms. *b)* Top view on the different initial sediments in the test section of the flume.

After preparing the test section, water is carefully filled into the flume and the flow velocity is increased incrementally by adjusting the slope of the flume at a rate of 0.1°/min. The resulting bed shear stress is calculated as:

$$\tau_b = \rho g r_{hy} I_0 \tag{1}$$

where  $\rho$  is the density of water (here: 1000 kg m<sup>-3</sup>), g is the gravitational acceleration,  $r_{hy}$  is the hydraulic radius and  $I_0$  the slope of the flume. The biostabilized bed is carefully observed and the critical bed shear stress (here defined as the increment of slope where most of the surface is mobile) is noted. This step was mostly followed by a complete failure of the bed or the occurrence of characteristic bedforms such as ripples or dunes (see also Thom and Schimmels, 2018).

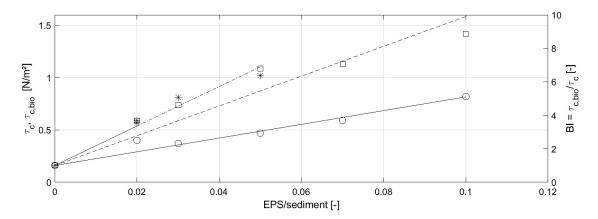
#### 2.3. THE EROSION THRESHOLD OF DIFFERENT EPS-SAND MIXTURES

Figures 13-15 illustrate the results from the erosion experiments for the different sand sizes. Only data from experiments are presented where the sediment surface failed in the middle of the test section, i.e. data from sediment erosion that started at the transition between the roughened surface and the test section was neglected. To compare results from different sediment sizes the non-dimensional biostabilization index (Manzenrieder, 1983) is used:

$$BI = \tau_{c,bio}/\tau_c \tag{2}$$

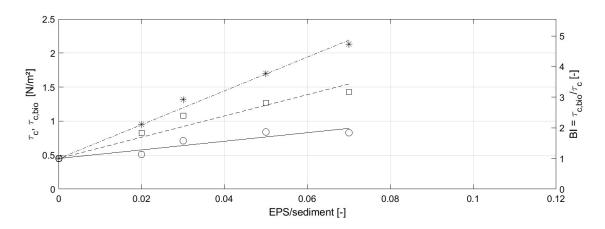


with  $\tau_{c,bio}$  being the critical bed shear stress for EPS stabilized sediments and  $\tau_c$  the critical bed shear stress of the initial sediment.



**Figure 13** Observed erosion thresholds for different mixtures with fine sand (D=0.063-0.355 mm). The symbols indicate the adhesion as measured on the EPS. Asterisk: 7.7 N/m², Square: 3.5 N/m² and circle: 1.0 N/m². The right hand axis informs about the biostabilization index (BI).

Generally, the stability increased in all cases with increasing adhesion as well as with the ratio EPS/sediment. The only exception here is for coarse sediments and an adhesion value of 1.0 N/m², which stays constant. Reasonably good linear relationships were found between the stability and EPS/sediment or adhesion, respectively.

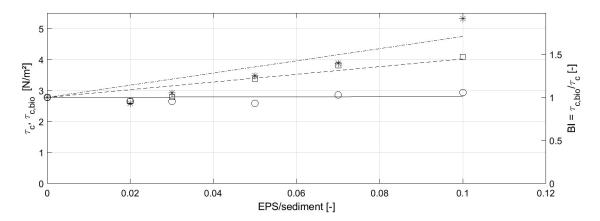


**Figure 14** Observed erosion thresholds for different mixtures with medium sand (D = 0.5 - 0.71 mm). The symbols indicate the adhesion as measured on the EPS. Asterisk: 7.7 N/m², Square: 3.5 N/m² and circle: 1.0 N/m². The right hand axis informs about the biostabilization index (BI).

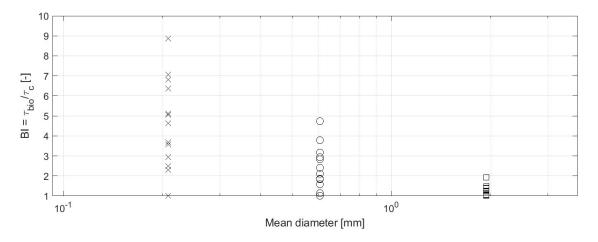
The biostabilization index ranges from 1 (here no EPS was added) to a BI of 8.9. As also illustrated in Figure 16 the width of the BI - range and the maximum stabilization potential (i.e. the highest BI) is mainly dependant on the grain size. The finer the grain size, the larger the range of BI. For the coarse sand, the BI only ranges from 1 to 2, approximately. For medium sand it ranges from 1 to 4.7 and for the fine material it ranges from 1 to 8.9. This means that the stabilizing effects vanish with coarser



grains where it may be speculated that gravitational forces are dominating. Theoretically, for the EPS mixes used in these experiments, the biostabilization effect should be completely negligible at mean grain diameters of around 3 mm.



**Figure 15** Observed erosion thresholds for different mixtures with coarse sand (D = 1.4 - 2.5 mm). The symbols indicate the adhesion as measured on the EPS. Asterisk: 7.7 N/m², Square: 3.5 N/m² and circle: 1.0 N/m². The right hand axis informs about the biostabilization index (BI).



**Figure 16** The biostabilization index plotted versus the mean grain diameter. Crosses: Fine sand, circles: medium sand and squares: coarse sand.

#### 2.4. COMPARISON TO NATURAL BIOSTABILIZATION PROCESSES

The use of commercially available EPS as a surrogate for natural biostabilization has several potential implications for experiments. Before considering these implications, it should be noted that Perkins *et al.* (2004) suggested that commercial EPS is not a good analogue for natural biofilms. Natural biofilms are complex three-dimensional structures which are not well-modelled using Xanthan Gum using the procedure described here. For example, in this study the impact of surface roughness was completely ignored even though it is well known that biofilms shape the surface depending on their surrounding conditions. Furthermore, biofilms can have a layer-wise structure, where older layers are "overgrown"

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by newer ones. All of these factors can have effects on both the stability and the prevailing near-bed hydrodynamics.

Despite these potential reservations, the "designed" biostabilization has some similarities to its natural counterparts. First, the results of this study showed BI values ranging from 1 to 8.9 which is comparable with some reported literature values on non-cohesive substrate (see Table 3).

Study	BI [ -]	Research method
Neumann et al. (1970)	6	In-situ flume
Grant and Gust	4.9, 4.5	Sediment cores
Dade et al. (1990)	3	Laboratory study
Madsen et al. (1993)	4	Laboratory flume
Yallop et al. (1994)	> 10.6	CSM
Vignaga (2012)	2.5	Laboratory study
Thom et al. (2015)	1-10	Laboratory flume
Van de Lageweg et al. (2017)	< 4	CSM

**Table 3** An overview on some of the results of biostabilization on non-cohesive substrates from literature. CSM is the abbreviation for Cohesive Strength Meter.

Second: The mode of erosion is very similar to that which has been described for natural biofilm erosion. In the experimental work we identified three modes of erosion (see Figure 17 a - c): Individual grains rolling (as typical for sediments in absence of biofilms), aggregates of different sizes eroding and mat-like erosion. These modes, and additional modes, have also been identified in an earlier experimental study (Thom *et al.*, 2015).

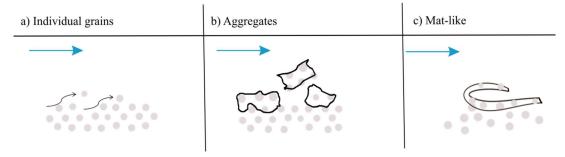


Figure 17 Different modes of erosion as identified during the experiments on surrogates.

In the current study, the mode of erosion depends on all three investigated parameters. Single grains were eroded for all types of sediment with low adhesive EPS and a low ratio EPS/sediment but still with a small biostabilization effect. This is different to the findings of Thom *et al.* (2015) where the single grain erosion was only associated with non-biostabilized sediments. Aggregates (often additionally to single grains) were only eroded for the sediment that was fine and medium in size when one parameter was increased more drastically (i.e. adhesion or ratio EPS/sediment) or when both



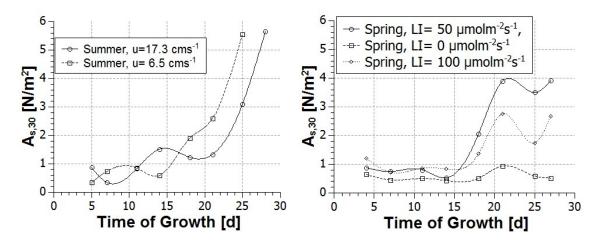
parameters are increased moderately (i.e. adhesion and ratio EPS/sediment). Mat-like erosion occurred for all three sizes of sediment but only when both adhesion and ratio EPS/sediment was increased drastically, with a slight tendency for it to occur at lower adhesion and EPS/sediment values for finer sediments.

The mode of erosion is further linked to the biostabilization capacity (as also indicated in the earlier study of Thom *et al.*, 2015). The most stable mode is the mat-like, followed by aggregates and single grains. In fact, in these experiments the mixtures that lead to mat-like erosion modes all failed at a bed shear stresses far exceeding the bed shear stresses reported for the other erosion-modes. Unfortunately, the mat-like erosion process only occurred at the transition between the test-section and the artificially roughened bed, so that the data could not be properly analysed (and thus is not presented here).

#### 2.5. THE OUTLOOK FOR EXPERIMENTAL SCALING OF BIOSTABILIZATION IN TIME

Using Xanthan Gum as a surrogate has been shown to be useful for modelling biostabilization effects. Qualitatively, the fits presented in Figures 13 - 15 are good which means that biostabilization effects can be designed with a good level of confidence to mimic everything between "no biostabilization effect" to "a ten-fold increase" in biostabilization. The question that then arises is how these data can be used to scale biostabilization in time, for example to simulate different growth states of the biofilm or seasonal effects.

In fact, the data presented here and additional data from literature could form the basis for scaling biostabilization in time by either physical experiments or numerical modelling. For example, biofilm growth could be modelled to determine EPS production and the EPS/sediment ratio (e.g. Mariotti and Fagherazzi, 2012) and adhesion curves could be used to extract adhesion values for different states of biofilm growth (see Figure 18). These two sources of information in addition to the grain size could be used to determine the biostabilization index and model the impact of biofilms on morphology for longer periods of time in numerical studies.



**Figure 18** Adhesion curves for different states of biofilm growth, light intensities, flow velocities and seasons. The original data is from Thom (submitted).

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Alternatively, physical experiments can be used to study the impact of biofilms on different sections of a river transect (for example, modelling shaded river banks, different grain sizes, etc.). Regardless the approach adopted, both data on adhesion and EPS content is required, although this is currently very scarce in the published literature. While it is indeed interesting to model biostabilization using for example the data presented here, it is of urgent necessity for the hydraulic research community to extend the current knowledge on biofilm mechanical properties in order to adequately mimic effects such as the impact of climate change.



#### 3. Scaling Biogeomorphology in Time: Numerical Studies

#### 3.1. NUMERICAL MODELING OF BIOGEOMORPHOLOGY: ADVANTAGES, ISSUES AND PRACTICE

Besides physical modelling of biogeomorphic systems, one can also perform numerical simulations of such systems. The advantages and disadvantages of doing so are very similar to those in purely geomorphological studies. Scalability of numerical models both in space and time is a strong advantage, albeit not without distinct issues related to computation power. Easily switching processes on and off is a strength of numerical models too. Two specific advantages of numerical models are related to the 'bio' term in biogeomorphology: Development and effects of biology can be scaled in time without physical limits, and it is much easier to incorporate multiple species that have distinct life-cycles without the husbandry issues involved in physical modelling, i.e. one can study effects of both full-grown trees and young shrubs in a single simulation.

The issues associated with numerical modelling of biogeomorphology are also similar to those in geomorphological studies; the model is always a simplification, i.e. not all possibly relevant processes can be incorporated fully and correctly. Whereas the field of geomorphology has reached a fair consensus of good modelling practice over many decades (although it has largely ignored biotic influences for a long time), the younger field of biogeomorphology has not yet. One reason for this is the enormous variety of processes possibly involved by simulating biota. Another reason is the limited scientific quantification of biogeomorphic process interactions and thresholds, although this has greatly advanced during the past decade. Hence, there is a substantial risk of missing a crucial process or not describing a relevant process accurately, resulting in incorrect model behaviour. Validation is a key issue with biogeomorphological models too, since there are few datasets that cover both the development of biota and geomorphology over longer time periods.

Another typical issue for numerical biogeomorphological models is shared with physical models: the limited amount of facilities that can deal effectively and efficiently with both morphology and biota; most (commercially available) hydraulic models only account for biota in a very simplistic manner such as bed roughness, whereas many ecological models consider hydraulics and morphology in simplified forms. More interactive models have been developed and used by the high special research community but are not yet very common in engineering practice, e.g. for assessing climate change impacts on natural systems. The community surface dynamics modelling system hosts a model repository at <a href="https://csdms.colorado.edu/wiki/Model download portal">https://csdms.colorado.edu/wiki/Model download portal</a>. This repository contains a large number (>200) of landscape evolution models suited to many different scales and environments (terrestrial, fluvial, coastal, marine), with a number of them including, or allowing the inclusion of ecological processes.

#### 3.2. BASICS OF NUMERICAL ECOLOGICAL MODELING

The field of biogeomorphology focuses predominantly on interactions between organisms and their environment, i.e. ecology, however basic biological processes like growth need to be understood and described to be able to assess changes over time. Numerical modelling of ecology involves two basic



steps: First, the construction of a conceptual model based on knowledge of the natural system, and second, the translation of this concept in mathematical equations (Soetaert and Herman, 2009) that can be solved by numerical methods. The conceptual model involves the identification of main components, also known as state variables (e.g. biomass of riparian trees, number of seagrass shoots per horizontal area), and the flows, or ecological interactions, that describe the exchange of energy or matter between them. In common with morphological modelling, the rate of change of the state variables is governed by the principle of conservation, i.e. the sum of the flows entering and leaving a compartment. The ecological interactions can be described by the product of a maximal rate times the compartment doing the work, times appropriate limiting terms that represent the forcing done by the environment. These principles apply to a wide range of scales of ecological modelling. In biogeomorphological modelling, typically the eco-element to reach scales (meters - tens of kilometres; days to decades) are of interest, not individual organism or river basin development (Baptist, 2001).

In mathematical form, the differential equation used by e.g. Akerboom (2018) and Carr *et al.* (2010) to describe seagrass growth reads:

$$\frac{dN}{dt} = N(t) \left( \max_{Ngrow} F_I(I) F_{phot}(T) N_{lim} R_{lim} - N_{loss} \right)$$
(3)

where dN/dt is the rate of change of number of seagrass shoots N, N(t) the number of shoots a time t in a compartment, and the part between brackets the maximal rate ( $\max_{Ngrow}$ ) times limiting terms minus the shoot mortality ratio  $N_{loss}$  that is independent of environmental conditions. Limiting terms here are photosynthesis inhibited by irradiation  $I(F_l)$  or temperature  $T(F_{phot})$ , a maximum shoot density  $N_{lim}$  and a maximum aboveground to belowground biomass ratio  $R_{lim}$ . Other growth prohibitors or loss terms can be added in a similar fashion, to account for stresses due to, for example, wave motion, grazing or salinity. Likewise, the plant growth model can be expanded with additional equations that account for the development of specific parts (roots, leaves, stem thickness) of the plant. However, if such processes are not well known or expected to be only marginally relevant to the problem of interest then they should not be included; keeping a model simple whilst realistic is a significant challenge but crucial to the successful generation and interpretation of results (cf. Levin, 1987; Phillips, 1995 and many others).

Plant development involves a number of processes; whether or not all of these needs to be incorporated in a model depends on the purpose and timeframe of the study:

- Growth and mortality. On the population level, these processes are always
  intrinsically active but can be limited or stimulated by environmental factors. Even in
  healthy populations, plants or part of plants die of old age or other factors that are
  not modelled explicitly such as diseases.
- Stress. Stress occurs when optimal growing conditions are not fully met, or when a
  negative pressure is exerted. Healthy growing conditions are associated with basic
  plant needs (resources): temperature, light, carbon dioxide and water for
  photosynthesis, oxygen for respiration and nutrients, minerals for structural
  formation and soil for anchoring. Typical stresses are light limitation for aquatic plants
  or undergrowth, drought or inundation for terrestrial plants, high levels of harmful



pollutants (e.g. salt, heavy metals), erosion and deposition, grazing, fire and physical damage by flows or waves.

- Establishment and further spatial distribution. Plants can spread out via different mechanisms: seeding, dispersal of vegetative elements and via the root system (clonal growth or the creation of bulbs). The latter is by definition a local process, often responsible for slow but steady expansion and less sensitive to the occurrence of suitable conditions. The first two can cover substantial distances and can be related to flow patterns and suitable (lack of) dynamics, so called windows of opportunity for establishment.
- **Competition**. Whereas competition is an interaction between organisms rather than organisms and environment, it does affect community structure and therefore the interaction of biota with the physical environment.

For short-time studies, i.e. into the effects of single events, acute stresses are the main drivers and growth, spatial expansion, and competition can be neglected since these processes typically govern the long-term (years-decades) development of ecological systems.

#### 3.3. Size and age classes: plant-based or hydrodynamics-based?

Many ecological models keep track of the development of biota over time using biomass (or derivatives like number of individuals per area, concentration, etc.) or age as the key state variable. These variables are of biological interest and easy to compare against observations. However, for geomorphological modelling they are impractical and of limited use since neither biomass nor age directly affect hydrodynamic processes. Hydrodynamic processes are predominantly governed by the actual size and shape that determine drag forces exerted by organisms. Consequently, biogeomorphological models need to translate biotic parameters into hydrodynamically relevant parameters. To decide how to make this translation, it is useful to know that presence versus absence is usually the most important factor. Hence, the exact size and number of biota is of lesser importance, especially once a typical threshold or blockage factor (Nepf, 2012) is exceeded. This principle typically applies to biogeomorphic models for larger temporal and spatial (reach) scales, as these aim to give insights into behaviour rather than actual processes such as turbulence, for which details of plant morphology does matter (Thomas et al., 2014, Baynes et al., 2018 and references therein). One can use classes to characterize key plant traits in an efficient and understandable manner. Such classes can be based on plant size or age, which are not necessarily related and also species. For example, drag-induced reconfiguration can substantially change the shape or effective size, hence the hydrodynamic effect, of flexible plants of equal age. Likewise, seasonal absence or presence of foliage can affect drag (Västilä and Järvelä, 2017). Using age classes can be relevant from a biogeomorphological perspective, as seedlings have different traits (e.g. more flexible, less resistance to erosion) compared to mature plants. Age is typically a factor for plant die-off too. When studying multiple species with distinct characteristics, the use of different classes is nearly always a necessity, even if different species have very similar effects on hydrodynamics, their response to environmental changes and their dynamics in time are likely to differ (e.g. Schwarz et al., 2018).



#### 3.4. CHARACTERISTIC TIME SCALES

#### 3.4.1. Scaling biology in time in numerical models

The simplest way of scaling, i.e. accelerating, time in numerical models is too increase the computational power: a faster CPU will decrease runtimes of simulations. Given the limits to processor speeds, parallelization is often required to substantially decrease computation times. Parallelization means subdividing the computational domain in subdomains that each run on their own computational core. The necessary communication between these subdomains requires some computational power too, consequently the increase in computation speed does not scale linearly with the number of processors. MPI (Message Passing Interface) is a standard for parallel programming.

Besides this straightforward 'brute force' approach, numerical models offer more advanced techniques for scaling both morphology and biology in time, independently. For morphology, which changes on timescales of minutes to decades versus the timescale of seconds to minutes of the hydrodynamic forcing, two distinct approaches are available: An 'online' approach, where morphological change occurs every hydrodynamic timestep (typically seconds), and an 'offline' approach that applies morphological change only after a given interval. In both cases, numerical models offer the advantage of using a morphological acceleration factor (Morfac; Roelvink, 2009; Figure 19) that increases the rate of bed level change. For example, using a Morfac of 20 allows for studies of 20 years morphological development with only 1 year of computationally expensive hydrodynamics, whereas a Morfac of 26 allows for the use of one spring-neap cycle to simulate an entire year.

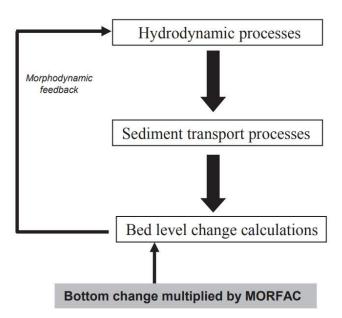


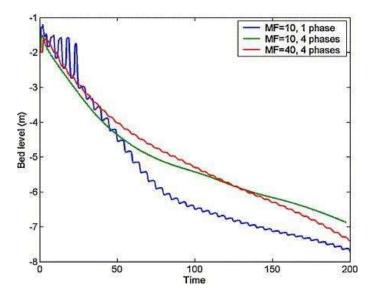
Figure 19 General structure of the Morfac concept in morphodynamic models (from Ranasinghe et al., 2010).

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The disadvantages of using a (large) Morfac are the risk of wiggles and numerical instabilities due to large rates of change (see example in Figure 20), and a temporal mismatch in the feedback relationships between hydrodynamics and morphology. The latter is particularly relevant for systems with considerable variations in forcing input. The Morfac chosen should be sufficiently small, based on the expected dynamics of the modelled system, and the simulation results should be checked for sensitivity to this setting to avoid instabilities to occur. Roelvink (2009) and Ranasinghe *et al.* (2010) amongst others provide guidelines on suitable morphological acceleration techniques.

For biology, which typically changes at even longer timescales (weeks to decades), this 'online' approach seldom makes sense, apart from situations where organisms can rapidly deplete nutrients or are exposed to rapidly changing conditions, such as algae modelling. For plants of interest in biogeomorphogical studies, growth cannot meaningfully be simulated or measured at a timescale of seconds. Consequently, an online approach would accelerate small errors. Typically, a week is a more applicable and robust time interval in situations with strong feedbacks and relatively rapid growth such as seagrass beds or freshwater macrophytes. Whereas a week may be a suitable timescale for updating vegetation health or condition, variations within this period, e.g. hourly water levels related to light available for photosynthesis, are still required for correct modelling of vegetation growth (e.g., Carr et al., 2010, Akerboom 2016, case study in Figure 21). For riparian, tree-like vegetation growth is slower and less governed by strong and frequent plant-water interaction, which allows for the use of longer interaction intervals and biological scaling factors. As for morphology, numerical convergence remains an issue and needs to be addressed by choosing sufficiently small time steps and suitable iteration schemes for the differential equations that describe growth, to prevent overshooting.

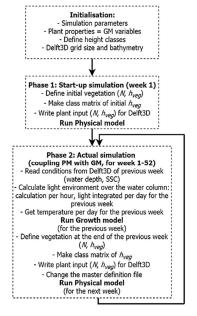


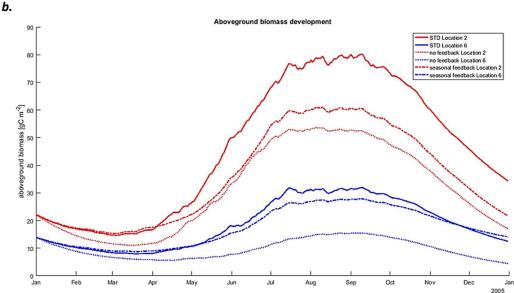
**Figure 20** An example of bed level development over time for different Morfac settings, showing wiggles and differences in final results for coarser approaches (from: Roelvink, 2009).

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**Figure 21** Case study based on the Rødsand coastal lagoon. **a)** The flow diagram for the simulation of eelgrass development with weekly vegetation updating based on an hourly simulated light environment, illustrating the use of vegetation classes with hydrodynamically relevant properties. **b)** Eelgrass biomass development over a year, illustrating the effect of optimal coupling (STD; hourly light and weekly updating) of the physical model (PM in left panel) with the growth model (GM) (continuous lines), seasonal coupling (dash/dot line) and no updating (dotted line). The red lines are for a shallow location (1.6 m depth), the blue lines are deeper (3 m). Without time-dependent feedback, the biomass is substantially lower throughout the year as the initial low plant cover has a limited effect on sediment stabilisation, hence the water remains relatively turbid all year. The seasonal feedback initially leads to a marginally higher biomass in April as the feedback is not affected by eelgrass decline during winter. However, in the growing season growth is slower because the light climate does not benefit from the higher sediment stabilising biomass as it does in the STD simulation. In fall, the opposite occurs for the deeper location: instead of the weekly declining biomass, the high biomass from October acts as a stabiliser in the hydrodynamic model, giving a more favourable light climate and less rapid decline. (from: Akerboom, 2018).



Because biological updating occurs at a very low frequency in comparison with hydrodynamic updating, the computation time of an ecological model is not normally an issue in biogeomorphological simulations. Nevertheless, including biology does introduce additional timescales (see also the next section 'Forcings: calm conditions vs storms and floods') that need to be taken into account correctly, possibly leading to a larger number of hydrodynamic timesteps to be calculated. The longest introduced timescale is that which is related to biological growth. For seasonal plants, which have a very different effects on flow in summer compared to winter, the example of a single spring-neap cycle with a Morfac of 26 to simulate a full year will not work. The shorter introduced timescale is the one related to death or establishment, which can range from seconds to weeks. The time required for such processes, i.e. the time that critical conditions occur, can be expressed in so-called windows of opportunity (e.g. Balke *et al.*, 2011). By keeping track of such windows, e.g. the time the water level exceeds a critical value, one eliminates the need to account for the possibility of critical changes occurring every model time step. As long as no window opens up, the model can keep running using the more efficient growth-related timeframe.

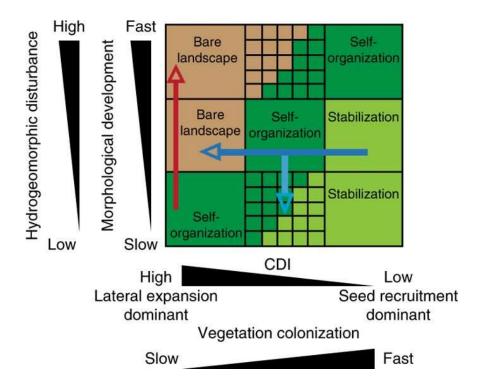
For idealized biogeomorphic models, it is feasible to perform a theoretical stability analysis (Bärenbold *et al.*, 2016). For more complex, process-based models such as Temmerman *et al.* (2007) and Van Oorschot et al. (2015) there is no such mathematical quantification and choosing correct timescales for the problem at hand is a matter of expert judgment. Fagherazzi *et al.* (2012) provide an overview of approaches used in numerical models for salt marsh development. Schwarz et al. (2018) define a colonization dominance index (CDI), which is the ratio between lateral expansion rate and expansion probability. Although this CDI does not provide a quantitative stability criterion like the Courant-Friedrichs-Lewy number does for hydrodynamic calculations, it does provide a conceptual framework (Figure 22) for the emergence of self-organisation, hence the need for a strong coupling of ecology and morphodynamics, in biogeomorphological systems.

#### 3.4.2. Forcings: calm conditions vs. storms and floods

Unlike 'classical' morphological simulations where high energy events (floods, storms) can be driving most change in the system (Lesser *et al.*, 2004, Roelvink and Reniers, 2011), biogeomorphological simulations need to account for long-lasting calm conditions too because the biological development during these periods can be considerable (examples in Bouma *et al.*, 2016; Corenblit *et al.*, 2007). Growth, both in terms of individual plant size and patch size through lateral clonal expansion, is the dominant development process in calm conditions. Note that this growth can also be negative, i.e. decay, due to sub-optimal living conditions or seasonal dynamics (light, temperature) that are independent of geomorphological forcings. High energy events typically lead to destruction or removal of organisms due to excessive forces or lack of oxygen as a consequence of high water levels. This removal can offer opportunities for other organisms to establish. Therefore, transition periods such as the waning stage of a flood wave are often crucial for establishment, despite their short duration. As such, the inclusion of biota introduces an additional time scale to the geomorphic model, leading to a stiffer model, i.e. with less flexibility to scale time.



This removal can offer new opportunities for other organisms to become established. Therefore, the transition periods such as the waning stage of a flood wave are often crucial for establishment, despite their short duration. As such, the inclusion of biota introduces an additional time scale to the geomorphic model, leading to a less flexible model.

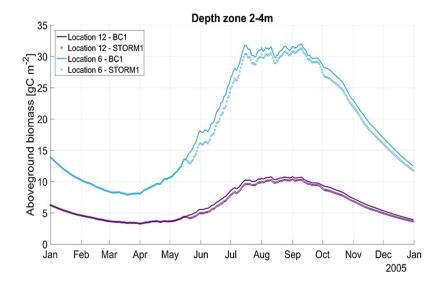


**Figure 22** Conceptual model illustrating the need for a strong (frequent) coupling of models for ecological (horizontal axis) and physical (vertical axis) development in self-organizing systems. The arrows indicate possible changes over time, e.g. the red arrow displays the transition resulting from low colonization rates combined with increasing morphological development. (from: Schwarz et al., 2018)

To illustrate the possible importance of including events and biological responses, Figure 23 shows results of two numerical simulations by Akerboom (2018) for the Rødsand lagoon; one using actual weather conditions, the other with a fictitious severe storm in spring. The effect of this storm on biomass persists throughout the year.

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**Figure 23** Simulation of eelgrass development over a year in the Rødsand lagoon, showing the combined effect of seasonal variations in growth conditions, day-to-day variability in weather forcing and the long-lasting negative effect of a storm half May (dotted lines). (from: Akerboom, 2018).

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#### 4. CONCLUSIONS AND OUTLOOK

The present state of knowledge and exemplifications are presented for scaling biology in time within the context of climate change adaptation. To meet the objective of finding suitable methods to predict river ecosystem trends in vegetation/hydrogeomorphic evolution and improve restoration/stabilisation practices within the context of the immediate impacts of climate change, characteristics time scales are reviewed for laboratory (vegetation and biofilm surrogates) and numerical modelling approaches. In this respect, the methodologies described through the document for scaling biology in time may serve as a framework to guide the design of future studies that aim to represent biogeomorphic interactions and biological cohesion in modelling studies.

In flume studies, Section 1 restricts attention to riparian vegetation and to river-reach settings (for submerged vegetation there is a comprehensive review of recent works in Nepf and Ghisalberti, 2008 and Nepf, 2012). The analogue model of a braiding river included as a case study it illustrates how a short-term experiment (conformed by the impacts of a succession of flood events) can provide useful information on the fundamental mechanisms involving the system vegetation-flow-morphodynamics over long-term time scales; and so that, the importance of including the impacts of flood sequence on river long-term characterization studies. In this respect, the model allowed to elucidate ecogeomorphic feedbacks between riparian plants, morphodynamics and flood events that can apply to address questions related to climate change. Moreover, the laboratory model featured the close relationship between morphodynamics and vegetation and the importance of modelling them coupled. Results from the laboratory also exposed the importance of quantifying spatial heterogeneity in river systems. Vegetation uniformly distributed is rare in nature. However, the inclusion of patchy vegetation may lead the system to irreversible changes (with high scour depths) becoming unachievable the characterization of river's morphological changes in laboratory flumes.

In section 2, time scales linked to the design of biofilm surrogates were presented within the framework of present stabilization approaches. The results reported in this section should help to better understand the interaction between a surrogate EPS, sediment and hydraulics and provide fundamental information to design their experiments that include biostabilization effects. Furthermore, differences and similarities between natural biostabilization processes and surrogates were assessed to help apply the transferability of the laboratory results.

Section 3 discusses the basics of numerical scaling techniques for biogeomorphic problems. Whilst the variety of biota, their (in)sensitivity to steady or infrequent forcings and their effect on morphodynamics does not allow for strict quantitative protocols, this section does provide a framework for choosing appropriate timescales and techniques to represent biogeomorphological dynamics in numerical models. The case study, based on observations in a shallow coastal ecosystem, illustrates that the frequency of interaction between the hydrodynamic model and the plant growth model has an essential effect on vegetation dynamics.

The inclusion of biota in geomorphic models introduces additional characteristic timescales. Experimental models lend themselves well to study relatively short term events such as a quick succession of floods, or long term more steady behaviour, which are both required to understand impacts of climate change. Seasonality and multiple cycles of establishment, removal and recovery



are more difficult to reproduce in flume studies however, especially when multiple species with different life cycles and stabilization effects are involved. Hybrid modelling, i.e. the combination with numerical models, can mitigate some of these issues because more timescales can be resolved. Moreover, once set up, numerical models offer opportunities to study sensitivity to initial conditions, process formulations and climate change scenarios with little effort. The initial setup requires a substantial effort however, and would benefit from a further quantification of tolerance limits.

#### Outlook

This guideline identifies the following knowledge gaps and recommendations for future development:

Develop new hydraulic facilities to investigate ecological processes in a hydraulic context. Such facilities need to be able to sustain living organisms for prolonged periods in controlled conditions, and/or readily deal with plants and soil raised outside the flume. This could also involve field sites with regular and/or event-based recordings of both ecological and hydraulic properties, or portable flumes that can be placed in the field to establish plant responses to stresses. Whereas steady development (growth and decay) of ecosystems is mostly governed by large-scale processes that act over longer times, the dynamics that govern establishment and removal of vegetation act on much smaller temporal and spatial scales. In common numerical models, these spatial scales can only be resolved at high computational costs. Sub-grid techniques, which resolve these scales at more reasonable costs, are becoming available but are not common practice yet.

Both physical and numerical biogeomorphological models mostly lead to a single outcome, in some studies with a limited number of replicates. Hybrid modelling offers opportunities for more stochastic approaches that are relevant for ecosystem management.

The science of agri- and horticulture has developed many techniques to optimize plant growth and favoured plant characteristics, using e.g. spacing, soil, water availability, nutrients, temperature and light as forcings. Likewise, these sciences have developed e.g. satellite or drone-based techniques to quantify these characteristics at field scale. Such techniques could be helpful in raising organisms with desired physical properties for flume experiments and to provide information that can be used for validation and to quantify spatial heterogeneity.



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