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Adaptation for Climate Change

Protocols for scaling morphodynamics in time

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ABSTRACT

This deliverable reviews the current knowledge and know-how regarding the scaling of time-dependent morphodynamic processes in physical laboratory studies, to address the Climate Change related evolution of different kinds of aquatic environments ranging from fluvial to coastal systems. Based on this review, protocols are derived to aid with the design and the determination of time-scales of physical models where sediment transport processes and the morphodynamic evolution of aquatic environments are in the focus. The results from this deliverable shows that well designed movable bed models are still and will further be a valuable tool for studying complex morphodynamic processes and features across a wide range of spatial and temporal scales for different river channel morphologies and coastal environments.

KEYWORDS

Similitude; Similarity; Scaled model tests; Morphodynamics; Time scales; Scale effects; Modeling; Climate Change.

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1. BACKGROUND

1.1. GENERAL DESCRIPTION AND OBJECTIVES OF THE DELIVERABLE

The ongoing evolution of Earth's climate will result in major changes of our current environment, some of which we can now start detecting and understand (e.g., Pelletier et al. 2015, Perry et al. 2015, Årthun et al. 2018, Hartter et al. 2018). Historically, these changes have occurred over time scales that are typically short from a geological point of view, but large from a human point of view (Farmer and Cook, 2013). However, since the beginning of industrialization, human activities have accelerated Climate Change and in 2017, human-induced warming reached approximately 1°C above pre-industrial levels. If the global warming continues to increase at the current rate, it is likely to reach 1.5°C between 2030 and 2052 (IPCC 2018). Thus, the present Climate Change effects will impact Earth's environment on a range of time scales spanning from single events (e.g. heavy rainfalls; Cifrodelli et al. 2015) to multi-decennial trends (e.g., Garner et al. 2018, Willner et al. 2018), and its consequences are therefore of interest for many scientific disciplines.

The possibility to model the effects of Climate Change on the aquatic environment at different timescales is therefore a central challenge for experimental investigations. The experimental investigation of hydraulic processes in scaled models is a powerful approach as it allows for the modification of the time scales, either in an attempt to reproduce a miniature facsimile of the real world or to create a small system presenting similar features. Most of the presently conducted experiments are designed for boundary conditions representing a possible future climate state, but the impact of Climate Change will be progressive over time, and experimental methods to study the morphological response of water bodies to longer-term trends are lacking (Baynes et al. 2018). Indeed, our understanding of how to compress or extend the relation between model time and real time is not well understood, particularly regarding morphodynamic processes. Therefore, there is a critical need to develop new approaches to physical modelling, which better represent system evolution over longer time scales that account for relevant scaling criteria of flow and sediment transport.

The main objective of this document is to review and discuss the existing scaling methodologies, investigate recent experimental advances and identify suitable physical scale modelling protocols to improve the representation of system evolution with scaling criteria for flow and sediment transport over time scales relevant to the management of Climate Change adaptation. Thus, this document is set to review and extend the current state of the art to:

- Improve the understanding of the relation between model time and real time regarding morphodynamic processes;
- Review the scaling criteria for simulating long term morphodynamic processes;
- Investigate dynamic scaling and morphodynamic accelerations in distorted models to represent geomorphic work over longer time scales in a robust and repeatable manner;
- Evaluate the significance of non-linear responses of sediment and accelerated model time.

For this purpose, this document is based on a review of previous investigations published in the scientific and grey literature. New approaches for the implementation of the non-linear responses of sediment transport and accelerated model time in physical models are investigated such as the use of surrogate sediments (e.g. composite material, polymers) or model distortion. Some morphodynamic experiments carried out within the Hydralab consortium are also reported and discussed in order to refine the protocols to be used to model Climate Change effects on morphodynamics.

1.2. THE EXPERIMENTAL MODELLING FRAMEWORK

Experimental modelling is closely related to hydraulic engineering, and experimental methods have continuously been adapted to the new needs within many scientific fields, including fluid mechanics (e.g., Muste et al. 2017). In the last century, hydraulic scale models have proven to be an effective and cost-efficient tool to investigate complex dynamic problems at reduced scales following the principle of similitude (e.g., Krey 1911, Rouse and Ince 1957, Spitzer et al. 2012a, b). Since then such models have been used to study and enhance the understanding of many different sediment transport and morphological processes across different spatial and temporal scales (e.g., Kleinhans et al. 2015). The high degree of experimental control in both physical scale models and process models allows for the simulation of varied or rare environmental conditions and hence to obtain measurements for conditions which cannot be measured, for example, at the prototype or prior to the construction of hydraulic structures (Hughes 1993). In addition, large scale morphodynamic models now offer the possibility to deepen the dynamic links between sedimentary time scales and hydraulic and hydrologic time scales, which is one of the keys to understand the morphodynamic evolution in a changing climate (Figure 1). In fact, experimental modelling has been successfully used to develop an improved understanding of how Earth systems operate and react in time, providing 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 therefore plays a key role for the development of a better understanding of Climate Change related impacts by improving our ability to predict these impacts and, thus, to help adapt to Climate Change related challenges (Frostick et al. 2011, 2014).

Figure 1 - Illustration of a hydraulic scaled model investigating the morphological response of a river to various hydrographs *- the model of the Oder at Hohenwutzen at the Federal Waterways Engineering and Research Institute (BAW) in Germany (Henning et al. 2008). The model is built with a horizontal length scale of 1:100 and a vertical length scale of 1:40, thus with a distortion of 2.5. The full length of the model is 80 m, or 8 km in nature. The model bed is made of solid banks with groins and dams and the movable lightweight sediments are a polystyrene plastic granulate.*

1.2.1. The concept of similitude/similarity

Experimental investigations are essential to any research field dealing with hydraulics and fluid mechanics because such experiments allow for a representation of complex processes in similitude to a real situation (Rowinski 2011). The concept of similitude is based on the quantification of the ratios of defined parameters in the model and in the prototype situation (e.g., Ettema and Heller 2017). If these scale ratios are kept constant between the model and the prototype (e.g., length, velocity, and/or force scale ratios), then the similitude is achieved in the model (e.g., geometric similarity, kinematic similarity, and/or dynamic similarity). Because the similitude is defined by a precise mathematical framework, a direct quantification of the processes modeled is possible by upscaling the results obtained according to the scaling laws defined by the similitude (Barenblatt 2003). However, a strict achievement of the similitude is often not possible, as, in the case of dynamic similitude, not all the force ratios can be kept constant at the same time (e.g., Heller 2011, Ettema and Heller 2017). Thus, compromises must be made when scaling down a prototype situation, leading to some relaxation of the scaling criteria. This implies that the degree of similitude of a scaled experiment varies from an application to another, depending on the processes dominating (e.g., Hughes 1993).

The use of physical models allows for the simplification of complex systems (e.g., Bouma et al. 2005), the shortening of the timescales characterizing the morphological evolutions (e.g., Paola 2000), and the isolation and quantification of the impacts of individual forcing mechanisms on system behavior (e.g. Wong and Parker 2006, Lamb and Dietrich 2009). Experimental modelling therefore provides an integral tool for the understanding and modelling of environmental systems due to the opportunity for understanding the dynamics of complex physical processes in the natural environment, as well as the development and calibration of numerical models that can simulate how systems evolve in the future under a range of conditions (e.g., Coulthard and van de Wiel, 2012, Kaergaard et al. 2014, Williams et al. 2016, Banda 2018).

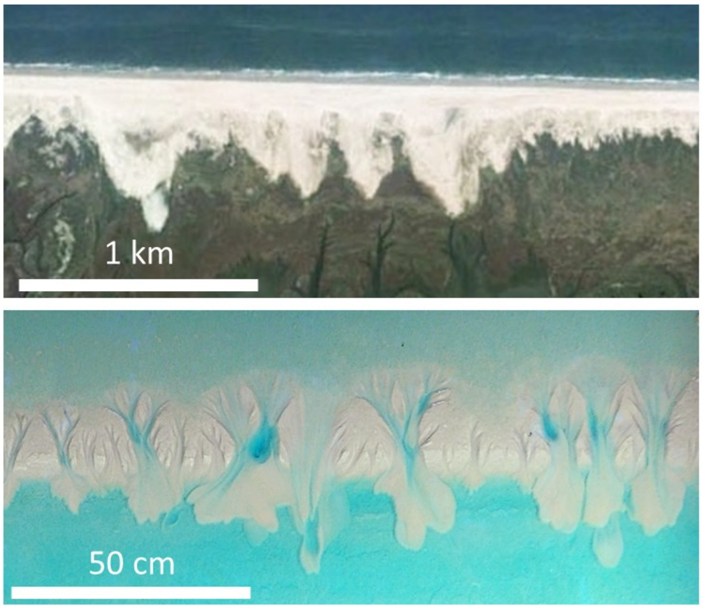

Figure 2 *- Barrier overwash morphology in the field and laboratory as investigated by Lazarus (2016): (top) Washover lobes along an undeveloped barrier island (Core Banks, North Carolina, USA; image from 2005, via Google Earth). (b) Generated overwash morphology with back-barrier features in the laboratory scaled model. Modified after Lazarus (2016).*

The differences between the scaling approaches used in engineering applications or in landscape models are sometimes misunderstood or thought to be incompatible (Henry and Aberle 2018). However, these modelling approaches represent different examples of the notion of similarity. Paola et al. (2009) distinguish between different aspects of similarity:

- *Exact vs. statistical similarity*: Exact similarity implies the conservation of the dimensionless ratios defined by the similitude at different scales and hence that the model is an identical scaled version of the prototype situation. Statistical similarity characterizes systems, which are statistically indistinguishable, but not identical. The latter case is the most commonly found in nature, for example with braided rivers.

- *Internal vs. external similarity*: Internal similarity (also referred as self-similarity) implies that a small part of a system is similar to the whole system (fractal behavior), while external similarity refers to the case where a small version of a large system is similar to the large system (classic scaled model tests).

- *Natural vs. imposed similarity*: As phrased by Paola et al. (2009): “Natural similarity occurs spontaneously, while imposed similarity is imposed by design.”

For example, a hydrodynamically scaled experiment, which would be typically used in hydraulic engineering investigations for the design of hydraulic structures, is characterized by an exact, imposed, external, dynamical similarity (similitude); while the overwash experiments by Lazarus (2016), presented in Figure 2, are characterized by a natural internal (kinematic) statistical similarity.

1.2.2. Similarity in morphodynamic models

Because different degrees of similarity are characterised based on the chosen modelling approach, scaled model tests represent a variable tool to investigate morphodynamic processes. Given a well-defined research question, each model type has its advantages and disadvantages. A classification of the different types of morphodynamic models is suggested in Figure 3 (presented and discussed by Baynes et al. 2018), and can be generalised as follow:

- Process and calibration models (1:1 scale): such models are used to reproduce and isolate a physical process to improve its basic understanding, as well as to calibrate and support other model development (e.g. numerical simulations). The 1:1 scale is the only scale at which the true replication of natural environments is possible (e.g. Stratigaki et al. 2011). This approach has limitations when large spatial or temporal scales or complex behaviour are studied (Hasbergen and Paola 2000, Bonnet 2009), as it does not enable prediction of progressive changes in system forcing at any faster rate than reality. It has thus limited application for the investigation of large-scale morphological changes.

- Scaled models: these are models that are scaled down rigorously according to scaling criterions (no degree of freedom) to reproduce the force ratios of a prototype situation as accurately as possible (with undistorted/distorted models). This is a predictive approach were physical processes can be quantified. As described in Section 2, scaling flow characteristics using Froude-similarity and considering specific scaling criteria for sediment transport allows for scaled versions of a specific geomorphic feature to be analysed. However, scale reduction based on Froude-similarity combined with the scaling of sediment transport processes is limited by sediment properties due to the increasing dominance of cohesive forces as sediment sizes get smaller (see Section 2).

- Analogue models: these are models where force ratios are not strictly quantified (larger degree of freedom), and where the focus is on well-defined features of interests which appear to be scale-independent. This is rather a conceptual approach were processes and time scales can be assessed *a posteriori* (i.e. when analysing the processed datasets). This approach was first advocated by Hooke (1968) and a formal scaling between the experimental conditions and a target natural system is not sought or achieved (Peakall et al. 1996, Paola 2000). In contrast, the experimental setup is treated as a system in its own right, with qualitatively similar behaviour to the natural setting, possibly achieved through different processes, allowing for the reduction of the model-size and duration of experiments. Although there is no exact similarity allowing for a direct upscaling of the results, this approach provides the opportunity to explore a wider range of processes and behaviours (e.g., Hasbergen and Paola 2000, Lague et al., 2003, Tal and Paola, 2007, Malverti et al. 2008, Paola et al. 2009, Wickert et al. 2013, Kleinhans et al. 2015).

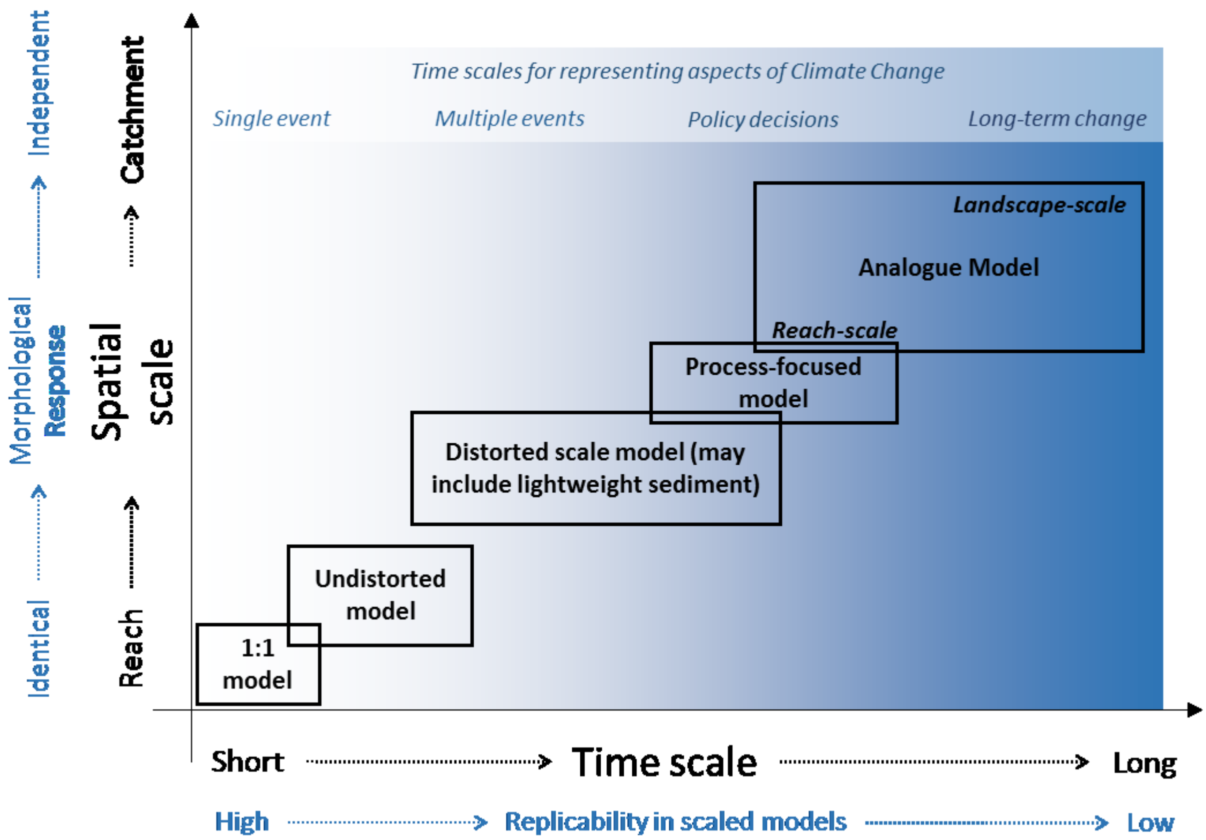

Figure 3 *- The relative application of different approaches for physical modelling, with different approaches being more appropriate for modelling processes over different spatial and temporal scales. Redrawn and modified after Baynes et al. (2018) and Peakall et al. (1996).*

Considering the potential effects of Climate Change on the morphological regimes of hydraulic systems, Baynes et al. (2018) evaluated the suitability of the different modelling approaches to capture processes over time scale of typically 10^1-10^2 years. As suggested in Figure 3, these time scales fall between the classical distorted scaled models and the analogue models. Baynes et al. (2018) thus identified a fourth type of morphodynamic models, so-called “process-focused” models, where the use of lightweight sediments and the innovative representation of biostabilisation in experiments allow for the extension of the time scale in scaled models or for the compression of time scales involved in analogue models. Examples of process-focused models include the experiments of by Friedkin (1945) aiming at the investigation of river meandering and the braided river experiments by Ashmore (1988). Many practical applications of such models indicate their suitability in studying morphodynamic processes within fluvial as well as coastal environments (Hughes 1993, Willson et al. 2007, Kleinhans et al. 2014).

As for experimental investigations, numerical simulations also offer the possibility to focus on various times scales depending on the scope of the investigations, with different approaches such as reduced complexity models, cellular automata, physics-based models, shallow water hydro-sediment-morphodynamic modelling, or other computational fluid dynamics approaches. In addition, some of these models offer the possibility to incorporate external factors such as biological and societal inputs. Although not directly within the scope of this report, the use of numerical approaches in combination with experimental investigations or analyses of available field data (e.g. hybrid modelling or data-driven morphological prediction methods) may offer an alternative to counteract the limitations of the scaled/analogue models to reproduce correctly the various time scales representative of morphodynamic processes (e.g. Harb et al. 2014, Reeve et al. 2016, Mustafa et al. 2017).

In conclusion, the goal of an experiment is to achieve the maximum degree of similarity between the model and prototype situation. Paola et al. (2009) discussed in detail the use of natural similarity and scale independence of processes to model situations where dynamic similarity is impossible (e.g. landscape experiments involving large spatial and temporal scales). Baynes et al. (2018) identified possibilities to fill the gaps between classic scaled models and analogue models. This report takes these considerations further by reviewing the fundamentals of the scaling laws and scale effects in morphodynamic models and hence the current state of the art of morphodynamic physical modelling. More precisely, the time scaling of morphodynamic processes is investigated in detail and addressed based on the latest experience obtained in European laboratories.

1.2.3. Time scales and Climate Change

Climate Change involves long time scales, and 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. Until today, most considerations on the impact of Climate Change on the aquatic environment have been based on stationary boundary conditions reflecting a possible future climate scenario. Focusing solely on the final stage of a future scenario neglects that Climate Change is a progressive process which develops over time. In particular, the morphology of riverine, estuarine and coastal environments will develop progressively over time in response to long term changing boundary conditions. In order to address challenges related to Climate Change it is therefore crucial to develop an understanding of how these environments will adapt to this change over time and finally behave under a different climate regime.

2. Scaling laws and scale effects

The morphology of alluvial river channels, and estuarine, coastal and marine environments is governed by the complex interactions between sediment transport and flow processes (e.g., Church 2002, 2006, DWA 2015, van Maanen et al. 2016) as well as further important factors such as sediment yield, succession, land use, and sea level rise (e.g., Blum and Törnqvist 2000, Lane et al. 2007, Pelletier et al. 2015, Nicholls et al. 2016). The processes governing sediment transport and morphological development depend on a wide range of spatial and temporal scales ranging from a few seconds at the grain scale (e.g., incipient motion, grain motion) through hours and days (e.g., movement of bed forms such as dunes, scouring at bridge piers), years and decades (e.g., evolution of floodplains) to geological time scales (e.g., evolution of catchments) (Kern 1994, Kleinhans et al. 2015).

Focusing on the modelling of morphodynamic processes in scale models, this section addresses the crucial issue of how to compress or extend the relation between model time and real time. This emphasis is important for modelling the evolution of the morphology of water bodies in response to Climate Change effects. These effects define the (varying) boundary conditions for designing and running the model but not the scaling laws themselves, even though the latter govern the overall design. Consequently, existing methods for the representation of morphodynamic processes over longer time scales in scale models are reviewed, scaling laws are addressed, and scale effects are highlighted. The scaling of suspended sediment transport is only partly mentioned, as bed load transport is the most influential parameter in the morphodynamic evolution of water bodies (e.g., Church, 2006). It must be mentioned that suspended load can also contribute to channel morphology (e.g., deposition in still water zones), but its transport is directly related to flow characteristics. Hence, the time scales associated with the transport of suspended sediment are governed by hydraulic time scales, which will be briefly mentioned below.

Not all studies referenced in the following are described in depth as most studies are based on the same scaling laws. Section 2.1 reviews the basic concepts associated with scaling morphodynamic processes, while Section 2.2 deals with the effects of these scaling procedures on the different time scales involved in a physical model. Finally, Section 2.3 details the strategies typically adopted to minimise the scale effects generated by the distortion of the time scales. Last but not least, the focus is set on physical models and numerical modelling studies are not described.

2.1. Scaling principles

As discussed in the previous section and illustrated in Figure 3, prototype models represent a 1:1 replica of the prototype in which flow and sediment dynamics can be recreated with little or no difference from the prototype. Such models are mainly used to study physical processes at the smallest spatial and temporal scales (e.g., incipient motion, bed form generation). Froude scale models are a common engineering tool for the design of hydraulic structures covering larger spatio-temporal scales, while distorted models (models with different geometrical scale ratios in the horizontal and vertical directions), and unscaled analogue models attempt to reproduce selected properties of the prototype (Peakall et al. 1996). In these models the time passes generally faster than in the prototype which makes them attractive to study Climate Change effects. However, as will be outlined below, their design can be challenging since the time scales for flow dynamics are generally quite different from the time scales of fluvial processes (Tsujimoto 1990).

2.1.1. Scaling laws and specific model types

Scaling laws used to design hydraulic models can be derived using dimensional analysis (e.g., Buckingham 1914, Barenblatt 2003). An important prerequisite for the design of a physical model is the dynamic similarity ensuring a constant prototype-to-model ratio of masses and forces acting on the system (e.g., Einstein and Chien 1956, Yalin and Kamphuis 1971, Kobus 1978, Hughes 1993, Frostick et al. 2011, Sánchez-Arcilla et al. 2011) so that the derived dimensionless parameters are equal in model and prototype. A perfect dynamic similarity is not achievable for model scales deviating from the prototype scale, i.e. 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. Scaled models must therefore be designed in a way that the important force ratios are maintained while providing justification for neglecting other force ratios. Neglecting force ratios can result in scale effects if the model is operated at boundary conditions where such force ratios are important; in other words, there will be a divergence between up-scaled model measurements and real-world prototype observations. Scale effects become more significant with increasing scale ratio and their relative importance depends on the investigated phenomenon (Heller 2011). In any model scale effects will have to be accepted. Scale effects relevant for coastal and fluvial scale models are discussed in detail in e.g. Yalin (1971), Hudson et al. (1979), de Vries et al. (1990), de Vries (1993), Hughes (1993), Ettema and Muste (2002), Sutherland and Whitehouse (1998), Heller (2011) and Ettema and Heller (2017).

Fluid flow governs the morphodynamic evolution of water bodies, and the most commonly used scaling criteria for fluid flow is Froude-scaling requiring similarity in the Froude number in model and prototype. This scaling law ensures the constant ratio between inertia and gravitational forces in model and prototype and is of significance for open channel flows so that the water surface will be adequately replicated in the model (Kobus 1978). There exist further hydraulic scaling criteria focusing on the ratio of other forces with inertial forces (e.g., Kobus 1978, Novak et al. 2010, Muste et al. 2017) which are partly mentioned below when highlighting scale effects in different model types.

In the following section, 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 v_r, respectively, are equal to one; the subscript *r* denotes the ratio between model (*m*) and prototype (*p*). Finally, although beyond the scope of this review, it is worth mentioning that scaling considerations for morphological processes in extra-terrestrial environments are also possible (e.g., aeolian dunes on Mars and Venus; Claudin and Andreotti 2006, Dietrich et al. 2017).

Fixed bed models

Fixed bed models are characterized by a stable bathymetry (i.e. no sediment transport). Considering uniform open-channel flow over 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

$$Fr = \text{fct.}\left(Re, \frac{k}{h}, S \right) \tag{2.1}$$

where $Fr = U/(gh)^{0.5}$ denotes the open-channel Froude number (with U = flow velocity, g = gravitational acceleration, h = water depth), $Re = Uh/v$ the Reynolds number (with v = kinematic viscosity), k/h the relative roughness (with k = roughness length scale which is often expressed in terms of the grain diameter d), and S the bed slope.

Within a Froude-scaled model, the flow Reynolds-number $Re = Uh/v$ will differ between the model and prototype (e.g., Heller 2017). Therefore, to avoid scale effects, the flow regime in both the model and prototype needs to be fully turbulent. Moreover, the relative roughness k/h (or submergence h/k) and the slope *S* need to be the same in a non-distorted Froude model. The roughness can be scaled considering similarity in the Darcy-Weisbach friction factor, which in turn depends on *k/h*, or alternatively considering similarity in the Chézy-coefficient or Manning number. However, as the latter two coefficients have dimensions, they also need to be scaled.

Distorted models are characterised by different horizontal and vertical length scales. Thus, the distortion leads to scale effects in the flow field (e.g., Higuchi et al. 1978, Lu et al. 2013, Zhao et al. 2013) so that geometric similarity must 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 rivers, the horizontal dimensions involved are commonly much larger than the vertical dimensions and this will lead to unrealistic scales if the vertical scale (h_r) is selected equal to the horizontal length scale (L_r) (de Vries 1993). Additional care needs to be taken in regard to potential scale effects due to water surface tension if the water depth in the model is low (e.g. 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) since the effect of wetting and drying bank material will change its behaviour, especially when using lightweight material (LWI 2010).

Movable bed models

Movable bed models represent a two-phase flow with a solid and fluid phase (e.g., 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, or particle Reynolds-number $Re_* = u_* d/\nu$, the Shields-number (also partly known as densimetric Froude-number) $Fr_* = \rho u_*^2/[(\rho_s - \rho)gd]$, the relative sediment density ρ_s/ρ, relative submergence h/d (which is in accordance with the definition used for fixed bed models if k is replaced by d, a characteristic grain size diameter such as d_{50}), and relative fall speed v_s/u_*, also referred as Rouse number (e.g., Yalin 1973, Hughes 1993, Peakall et al. 1996). In these definitions, ρ and ρ_s denote the fluid and sediment density, respectively, u_* the shear velocity ($u_*^2 = \tau_0/\rho$ for steady uniform open channel flow, with τ_0 = bed shear stress), and v_s the fall velocity of particles. In order to obtain perfect similitude for sediment transport processes, all these quantities would have to be equal in the model and prototype. Assuming that water is used in both the model and prototype (i.e., $\rho_r = \nu_r = 1$), this results in the following criteria, for which the dimensionless numbers are formulated for unidirectional flow conditions:

$$Re_{*r} = d_r u_{*r} = 1 \tag{2.2}$$

$$Fr_{*r} = \frac{u_{*r}^2}{(\rho_s - \rho)_r d_r} = 1 \tag{2.3}$$

$$\rho_{s,r} = 1 \tag{2.4}$$

$$\frac{h_r}{d_r} = 1 \tag{2.5}$$

$$Rou_{*_r} = \frac{v_{s,r}}{u_{*,r}} = 1 \qquad (2.6)$$

In the case of wave action, wave characteristics become important and need to be considered for scaling of hydrodynamics (e.g. Yalin and Russel 1962, Le Mehaute 1970, Hudson et al. 1979, Hughes 1993, van Rijn et al. 2011). For unidirectional flows the shear velocity can be determined via $u_* = (ghS)^{0.5}$ so that, for such conditions, equation (2.3) can be written as:

$$Fr_{*_r} = \frac{h_r^2}{(\rho_s - \rho)_r L_r d_r} = 1 \qquad (2.7)$$

A general problem encountered in the scaling of shear velocity u_* (or bed shear stress) is that this similarity assumes a flat bed which is not necessarily the case because the bed topography of most coastal and alluvial environments is characterized by bed forms or other morphological features (e.g., Hughes 1993, LWI 2010). If the bed topography or 'form roughness' is not adequately scaled, scale effects will automatically be induced. In this context, Gorrick and Rodriguez (2014) used a non-distorted model of a sand-bed stream to demonstrate the importance of bed forms for the scaling of Fr_* and Re_* (the latter was expressed in terms of $Re_* Fr_*^{-0.5}$) as well as the sediment size distribution. They acknowledged scale effects due to incorrect scaling of relative roughness in such models (i.e. violation of equation (2.5)) but found that for sediment beds with bed forms, or in other words situations where the form drag dominates over grain friction, the relative submergence criterion may be violated as dune dimensions depend mainly on the Shields number (also denoted as densimetric Froude number in this report).

In general, well-designed movable bed models have been shown to be a valuable tool for studying morphodynamic processes and features across a wide range of spatial scales for different river channel morphologies and coastal environments (e.g., Bruun 1966, Hudson et al. 1979, Hughes 1993, Peakall et al. 1996, Paola et al. 2009, LWI 2010, Green 2012, El Kadi Abderrezzak et al. 2014, Kleinhans et al. 2014, Bennet et al. 2015, Yager et al. 2015, Kleinhans et al. 2015). There exist many different studies investigating, for example, the effect of training structures on the flow and morphology of water bodies; local and reach wide morphological development of sand bed rivers and braided gravel bed rivers; step-pool systems to beaches and coastal areas. A detailed overview of each individual study is beyond the scope of this report, but an overview of different approaches is given in section 2.3.1 and in the protocol section (chapter 3) of this report.

The bed-load transport under waves is characterized by an oscillatory sheet flow, which can be characterized by the so-called Sleath number, the ratio of inertial forces to gravitational forces acting on individual grains of sediment (Zala Flores and Sleath 1998). Scaling the wave-induced sediment transport to keep similarity in the regime for the Sleath number, Henriquez et al. (2008) reported that excessively high values of this number (> 0.2) will induce a sediment movement earlier than predicted by the Shields curve. In addition, the mode of transport can become different and sediment will start to move as a block, also known as plug flow (Madsen 1974, Foster 2006).

More specifically, van Rijn et al. (2011) re-analyzed the scaling laws for beach and dune erosion processes. Since all the important dimensionless numbers that characterize sediment transport dynamics cannot be satisfied simultaneously, they proposed that, for accurate scale modelling, it is sufficient that these dimensionless numbers are constrained within a certain range, rather than imposing a fixed value. van Rijn et al. (2011) suggested that for coastal scale models, the most relevant requirement is to attain similarity of the cross-shore equilibrium bed profiles between prototype and model, particularly in the surf zone and the beach and dune zone. In practice this means that the most important criteria for experimental design is the accurate representation of the beach and dune erosion volumes. Following this principle, a general set of scaling laws was derived, valid for both beach and dune erosion volumes under storm conditions with dimensionless parameters describing the equilibrium erosion volumes that are the same in model and prototype.

In all these studies it has been ascertained that, in practice, complete similarity in all dimensionless ratios for the combination of scaling laws for fixed and movable bed models is not possible. As outlined before, scale effects need to be accepted in movable bed models meaning that some of the criteria need to be relaxed to be able to design practical experimental models. Depending on which similarity criterion is violated, Hughes (1993) defined different bed load model types which are briefly introduced here and discussed in detail below, also in light of associated morphological time scales in Section 2.2:

- *Best models* maintain all geometric ratios between model and prototype as well as the similarity in sediment density;
- *Lightweight models* are designed to maintain similarity in both Re_* and Fr_* thereby violating intentionally the criteria given by equations (2.4) to (2.6), i.e. also the sediment density criterion;
- *Densimetric Froude models* are similar to *lightweight models* with the difference that the similitude in Re_* is relaxed;
- S*and models* fulfil only the scaling criteria in regard to the sediment density ratio.

Thus, regarding the classification according to Baynes et al. (2018) (Figure 2), *best models* correspond to undistorted models, *lightweight* and *densimetric Froude models* can be classified either as undistorted or distorted model, and *sand models* can generally be classified as analogue models.

In addition to these bed-load model types, Hughes (1993) defined the *suspension-dominated models,* which are more common in coastal modelling applications than in alluvial river studies. In such models, the dominating physical process is the uplift of the particles due to turbulence induced by waves or currents and their transport in the water column. This process is reflected by the criterion defined by equation (2.6) which corresponds to the ratio of the Rouse-number in the model and prototype. In the nearshore, the triggering of sediment transport by the action of waves implies that both bed-load and suspended load transport occurs simultaneously. For the latter transport process, Henriquez et al. (2008) suggested that keeping the similarity on the ratio of settling time to the wave period constant is more suitable in cases where significant wave breaking occurs. Indeed, as the turbulent energy from wave breaking scales with the ratio of wave height to wave period (e.g. Battjes 1975, Fredsøe and Deigaard 1992), this ensures the similitude of the ratio of turbulence generated by wave breaking to the settling velocity (represented by the Rouse (1939) or Dean (1985) numbers, see e.g. Grasso et al. (2009) for further details). Using such a scaling approach results typically in geometrically undistorted models (Hughes 1993, Vellinga 1986).

In the case of waves, scaling the suspended sediment transport requires the consideration of different physical parameters than bed load models for the definition of scaling criteria and laws according to equations (2.2) - (2.6), such as the characteristic velocity $(gH_b)^{-0.5}$ instead of the shear velocity u_* in equations (2.2), (2.3) and (2.6), and the breaking wave height H_b instead of water depth h in equation (2.5) (Hughes 1993). More details in regard to the scaling laws considering or neglecting the fall-speed dependency for such models can be found in e.g., Hughes (1993) and van Rijn et al. (2011).

From this and the explanation above it becomes obvious that the scaling criteria for suspended load models differ from those of bed load models; it is only possible for one transport mode to be simulated following similarity criteria while the other mode will be affected by scale-effects. Nonetheless, there exist model-tests where it was attempted to simulate both modes (e.g., Grasso et al. 2009). Although not often employed, suspended load models have been used for the investigation of the behaviour of suspended sediments in meandering channels (e.g., Lu et al. 2013) or to study groyne field siltation (e.g., Yossef and de Vriend 2010).

2.1.2. Bed load and suspended load model types

Best Models

Best models are defined by similarity in the geometric ratios between model and prototype, i.e. $h_r = L_r = d_r$ and sediment density, i.e. $\rho_{s,r} = 1$ or $(\rho_s - \rho)_r = 1$. Due to the similarity of the material the porosity ratio ϕ_r can also be assumed to be 1. *Best models* are hence undistorted Froude models fulfilling, by definition, the criteria given by equations (2.3) to (2.5). Besides the fall velocity criteria according to equation (2.6), *best models* violate the grain-Reynolds number criterion (equation 2.2) which for this model type corresponds to $Re_* = L_r^{1.5}$. Therefore, *best models* 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. The limitation of *best models* 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 prototype conditions, then this restriction could easily result in the requirement to use potentially cohesive sediments representing a problem due to the different properties of cohesive sediments compared to granular material. To minimize this issue, special materials such as Ballotini may be used or a different model type may be chosen.

Lightweight models

As indicated by the name, a model sediment is used in *lightweight models* which has a lower density than the prototype sediment. *Lightweight models,* as defined by Hughes (1993), are designed to maintain similarity in both Re_* and Fr_* and this requirement relates the sediment density scale directly to the sediment grain diameter and length scales via $(\rho_s - \rho)_r = d_r^{-3}$ and $(\rho_s - \rho)_r = h_r^3 L_r^{-1.5}$, respectively (note that the latter relationship assumes that bed shear stress can be determined from the depth-slope product; Vollmers and Giese 1972). Moreover, lightweight models can only keep similarity in relative submergence ($h_r/d_r = 1$) if $L_r = h_r^4$. Lightweight models are therefore prone to a range of scale effects due to the incorrect scaling of sediment density and particle size as well as the differences in bed porosity and bed characteristics, hence liquefaction of the bed, and suspended sediment transport will not be correctly represented in the experimental model (Hughes 1993, Petruzelli et al. 2013). Thus, lightweight models need to be distorted using a different ratio of horizontal and vertical scales, and as a consequence, a direct quantification of the model results is difficult. This means that such models require careful calibration. An example for such a model is the Elbe tidal model described by Vollmers and Giese (1972) or the model study carried out by Gorrick and Rodriguez (2012). Note that Yalin (1973) recommended to study dunes in modelling studies using lightweight models in order to keep similarity in both Re_* and Fr_*. However, an aspect that has not yet been treated is how model distortion and the different sediment properties affect bed form shape and kinematics.

Densimetric Froude models

Densimetric Froude models are similar to *lightweight models* with the difference that the similitude in Re_* is relaxed. This relaxation gives more flexibility in specifying model parameters (Hughes 1993) as only similarity in the Shields number Fr_* is required. This requirement in turn gives a general definition for d_r according to $d_r = u_{*r}^2(\rho_s - \rho)_r^{-1}$ (equation 2.3), or $d_r = h_r^2(\rho_s - \rho)_r^{-1}L_r^{-1}$ for unidirectional flows (equation 2.7). *Densimetric Froude models* are typically distorted and operated with lightweight materials. Their design is, however, challenging due to the multitude of scaling laws that need to be considered (e.g. Wei et al. 2001, 2012) and hence they are prone to scale effects as discussed in the above sections. In this context, Gill and Pugh (2009) outlined a method based on the fall velocities of particles to address potential scale effects in Re_* if $Re_{*m} < 100$ while $Re_* > 100$ (see also Pugh and Russell 1991).

Many practical applications of such models indicate their suitability in studying morphodynamic processes within river reaches as well as for coastal environments (e.g. Hughes 1993, Paola et al. 2009, LWI 2010). In fact, *densimetric Froude models* have often been used to study the development of particular river reaches thereby assuming hydraulic rough conditions (e.g. Vermeulen et al. 2014 and the models at the Federal Waterways Engineering and Research Institute, Germany, as summarized in LWI 2010).

Sand models

Sand models fulfil only one of the scaling criteria defined in equations (2.2) - (2.6) which is the sediment density ratio (equation 2.4). According to Dalrymple (1989), sand is the preferable model sediment for coastal transport models. However, such models do not comply with the Fr_* criteria which can result in significant errors. Kamphuis (1985) stated that the non-similarity of Re_* and Fr_* in such models will result in erroneous modelling of sediment transport at low flow velocities and that the period of rest for sediment particles is exaggerated in such models during wave cycles. In general, *sand models* may also correspond to analogue or small-scale models which are discussed in the next section.

Analogue and small-scale models

The evolution of the morphodynamics over larger spatial (and temporal) scales is often investigated in so called small-scale model or micromodels (e.g., Davinroy et al. 2012). Such models aim to reproduce the original existing conditions in the prototype and its future response to climatic or anthropogenic forcing. Moreover, such models also offer the opportunity to investigate different physical phenomena at reduced costs (e.g., Stagonas 2010).

Analogue models are designed to study analogies between the model and prototype and are not designed to keep strict similarity in the above scaling criteria although they can theoretically be classified according to the model-types defined above. In any case, micromodel design should include an assessment of sediment mobility (e.g. Ettema and Muste 2002), which is often achieved using the Shields diagram. However, the aforementioned model types are generally stricter in terms of similarity criteria than analogue or small-scale models for which the validation depends on the judgement of similarity in bed-sediment movement (Ettema and Muste 2002) or on the operator due to the lack of a specific methodology for describing the degree of morphodynamic similarity in model studies (Gaines and Smith 2002). Moreover, Gaines and Smith (2002) stated that the implementation of micromodel or similar small-scale loose-bed modelling requires the development of new measuring techniques in order to accurately determine model parameters.

Analogue or small-scale models have been used to study the effect of sediment supply or sediment composition on the alluvial architecture of river systems (e.g., Moreton 2001, Braudrick et al. 2009, Kleinhans et al. 2014, 2015), to investigate the effects of vegetation on a braided morphology under the simplest conditions (e.g., Tal and Paola 2010), or to study the development of alluvial fans, river deltas and landscapes (e.g., Whipple et al. 1998, Paola et al. 2009, Ganti et al. 2011, Reitz and Jerolmack 2012, Kleinhans et al. 2014, 2015)

Suspended load models

The mechanism of suspended sediment transport is different from the mechanism of bed load transport, therefore the modelling of suspended sediment transport requires the consideration of different physical parameters and scaling criteria such as the ratio of settling velocity to shear velocity, i.e. the Rouse number (equation 2.6). Turbulence is an important parameter in suspended load models and the transport is closely linked to the hydrodynamic time scale so ideally such models should be undistorted, which is significantly different from the types of bed load model described above. If 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). In general, many of the scale effects discussed above can also occur in suspended load models (e.g., the grain size of the model sediment should not fall in the cohesive range etc.) and they are not repeated here.

Focussing on the development of beach and profile erosion during coastal storm events with high energetic waves, USACE (1989) and Kriebel et al. (1987) recommended the use of the criteria stated by Dean (1985) for the design of such models. More recently. Grasso et al. (2009) generalised this scaling approach based on the formulation from Rouse (1939). These models should be designed as undistorted Froude scale models and keep similarity of the fall speed parameter (ratio of wave height and the product of wave period and fall speed). Moreover, these sources explicitly mentioned that scale effects due to viscosity, surface tension, or cohesiveness of particles should be avoided so that the character of wave breaking can be simulated properly.

2.2. TIME SCALES

The previous sections defined different scale-model types and the corresponding basic scaling criteria. In this section, these scaling criteria are used to derive and describe morphological time scales for both flow and transport processes in scale models, because these time scales define the suitability of the different model types to investigate the evolution of morphology in the light of Climate Change.

2.2.1. Time scales for fixed bed models

Based on the similarity in Froude it becomes possible to derive the hydraulic time scale t_r for fixed bed models (e.g., Kobus 1978) according to:

$$t_r = \frac{L_r}{\sqrt{h_r}} \tag{2.8}$$

where, L_r denotes the scale ratio for the horizontal length scales between model and prototype (L_m/L_p) and h_r the corresponding vertical scale ratio. For a non-distorted model where $h_r = L_r$, equation (2.8) yields $t_r = L_r^{0.5}$ showing that time related to bulk flow processes in such models passes faster than in the prototype.

2.2.2. Time scales for movable bed models

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 (e.g., Yalin 1971). This can, in turn, result in undesired scale-effects which become more significant with decreasing experimental model scale.

The determination of sedimentological time scales in movable-bed models is difficult and often subjective. In fact, the sedimentological time-scale cannot be freely chosen as it is the result of the chosen scales of other model parameters (Gehrig 1978) and 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 ($t_{\eta,r}$) and horizontal ($t_{L,r}$) directions, respectively. Corresponding time scales are summarized in general terms in Table 1.

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 u_*, respectively, resulting in the time scales $t_{sg,r}$ defined by equations (2.9) and (2.10), where equation (2.10) results from the additional requirement of similarity in Re_*.

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

Time scale	Eq.	Criteria and comments	Source
$t_{sg,r} = d_r L_r^{0.5} h_r^{-1}$	(2.9)	- individual grain movement	Yalin (1971)
$t_{sg,r} = L_r h_r^{-2}$	(2.10)	- individual grain movement - similarity in Re_*	Yalin (1971)
$t_{\eta,r} = L_r h_r$	(2.11)	- similarity in dimensionless transport rate - similarity in Re_* - equal porosity in model and prototype	Yalin (1971)
$t_{\eta,r} = L_r^{1.5} d_r^{-1} (1-\phi)_r$	(2.12)	- similarity in dimensionless transport rate	Gehrig (1978)
$t_{\eta,r} = L_r^{2.5} h_r^{-2} (1-\phi)_r (\rho_s - \rho)_r$	(2.13)	- similarity in dimensionless transport rate - similarity in Fr_*	Gehrig (1978)
$t_{\eta,r} = L_r h_r^{1.5} d_r^{-7/6} (1-\phi)_r$	(2.14)	- similarity in dimensionless transport rate - similarity in Fr_* - near similarity in Re_*	Tsujimoto (1990)
$t_{L,r} = L_r^{1.5} h_r^{-1}$	(2.15)	individual grain movement	Yalin (1971)

Considering the temporal development of a movable bed surface in an experiment, different scales in the horizontal and vertical directions need to be accounted for. 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 (e.g. Einstein and Chien

1956, Vollmers and Giese 1972,). 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 (e.g., Paola and Voller 2005, Coleman and Nikora 2009). The corresponding time scale can be defined according to (e.g., Tsujimoto 1990, Hughes 1993):

$$t_{\eta,r} = \frac{L_r h_r \left(1-\phi\right)_r}{q_r} \tag{2.16}$$

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 (LWI 2010). Introducing the dimensionless volumetric bed load transport rate $q_* = q/(du_*)$, equation (2.16) can be rewritten according to:

$$t_{\eta,r} = \frac{L_r h_r \left(1-\phi\right)_r}{q_{*r} d_r u_{*r}} \tag{2.17}$$

Assuming similarity in q_* in model and prototype (i.e. $q_{*r} = 1$), equation (2.17) represents the basis for equations (2.11) to (2.14) in Table 1 for which it was assumed that $u_{*r} = (h_r S_r)^{0.5} = h_r L_r^{-0.5}$. Note that for geometrically similar grains with a similar grain-size distribution, $(1 - \phi)_r = 1$ (Gehrig 1978). In addition, for practical purposes, the sediment transport rate is often determined from existing bed load formulae. Using such relationship in equation (2.17) instead of a measured q_* can result in different time scale calculations. In this context, the time scales for *densimetric Froude models* are given by equations (2.13) and (2.14), where the latter was derived by Tsujmoto (1990) by considering the Manning-equation in the derivation of the scaling law, i.e. by assuming additional similarity in bed roughness.

Equation (2.15) in Table1 was derived by Yalin (1971) and describes the time scale related to the evolution of the mobile bed surface in the horizontal direction. This equation is based on the consideration of the movement of a single grain and the relation of the diameter scale with the longitudinal scale. Comparing the different time scales given in Table 1 and eq. (2.17) it becomes apparent that

$$t_{\eta,r} < t_{L,r} < t_r < t_{sg,r} \tag{2.18}$$

i.e. the vertical evolution of the bed surface is the quickest followed by the longitudinal displacement of the bed surface and the hydrodynamic time scale. The slowest time scale is the individual motion of a grain (Peakall et al. 1996).

For *best models* focusing on unidirectional flows the sedimentological time scales are identical ($t_{sg,r} = t_{\eta,r} = t_{L,r} = L_r^{0.5}$) and are equal to the hydraulic time scale t_r. This model type is typically used in studying the evolution of bed surfaces and transport mechanisms in laboratory investigations using downscaled grain-size distributions of the prototype bed material with a hydraulically rough flow regime (e.g., Aberle and Nikora 2006).

The time scales for *lightweight models* can be derived as $t_{sg,r} = (\rho_s - \rho)_r^{-2/3}$, $t_{\eta,r} = h_r^3(1-\phi)_r (\rho_s - \rho)_r^{-2/3}$, $t_{L,r} = h_r^2(\rho_s - \rho)_r^{-1}$ thereby assuming $q_{r*} = 1$ and that the bed shear stress can be determined from the depth slope product. The derived scaling ratios indicate that the similarity conditions for *lightweight* *models* can result in rather impractical scaling ratios. Zwamborn (1966) therefore recommended to replace the Fr_* criterion by $(u_*/v_s)_r = 1$ while keeping near similarity in Re_*.

Densimetric Froude models have often been used to study the development of particular river reaches thereby assuming hydraulic rough conditions (e.g. Vermeulen et al. 2014 and the models at the Federal Waterways Engineering and Research Institute, Germany, as summarized in LWI 2010). For the latter studies the theoretical time scales according to Table 1 ranged between 1:173 to 1:2020 while the comparison with scales determined from field data indicated that the real time scales ranged between 1:1192 to 1:4000. This indicates that in most models the time scales are only roughly met and that there is a need for further investigations in regard to this topic. Note also that most of the model studies mentioned in Section 2.1.1. can be classified as *densimetric Froude models*.

Further time scales than the ones 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. 2015, and references therein).

Time scales for models with suspended load were discussed by e.g. Hughes (1993), Henriquez et al. (2008), Grasso et al. (2009) and van Rijn et al. (2011), but in almost all cases a morphological time-scale of suspended models was derived corresponding to $t_\sigma = h_r^{0.5}$ (where the vertical length scale characterizes wave characteristics, discussed further in the following section), which is the same as the hydraulic time scale in the case of an undistorted scaled model (equation 2.8). Moreover, inserting the hydraulic time scale given by equation (2.8) into equation (2.15) yields:

$$h_r = L_r \tag{2.19}$$

i.e. the dynamics of the suspended load transport can only be modelled exactly using an undistorted model, but this criterion can be relaxed for models focusing on bed load transport.

2.2.3. Time scales in coastal models

Research on scaling laws related to coastal sediment transport modelling and morphological evolution was intensively active in the 1970s and 1980s (e.g., Noda 1972, Kamphuis 1972, Migniot et al. 1975, Vellinga 1982, Hughes 1983), when physical modelling was the only practical method available to address morphodynamic changes over longer time-scales. Despite those significant contributions, Dalrymple (1989) summarized the state-of-the-art in physical modelling of coastal processes by (quoting J.W. Kamphuis) "*Owing to the variety and magnitude of scale effects, [...] modelling coastal areas will continue to appear an art*". The physical modelling techniques that were developed included using artificial materials (mostly lightweight, non-sand) in the laboratory to cope with problems derived from the sediment scaling laws (see also Section 2.1), as well as using distorted models (with different vertical and horizontal length scales, see also Section 2.1). A summary report with several scaling examples from coastal to river sediment dynamics, and using lightweight materials, is also given in Migniot (1994).

Morphodynamic time scales in the nearshore: example from van Rijn et al. (2011)

van Rijn *et al.* (2011) concluded that the morphological time scale $t_{\eta,r}$ depends on the depth scale h_r, the length scale L_r, the sediment size scale d_r and the sediment density scale $(\rho_s\text{-}\rho)_r$ as given by

$$t_{\eta,r} = \left(L_r/h_r\right)^m \left(d_r\right)^n \left(\rho_s - \rho\right)_r^{\ p} \left(h_r\right)^q \tag{2.20}$$

where the exponents *m*, *n*, *p* and *q* can be determined by laboratory model data. Assuming *p*=1, and using results from experiments conducted in Hydralab III at three different scales, they found that:

$$t_{\eta,r} = \left(L_r/h_r\right)^{1.4} \left(\rho_s - \rho\right)_r \left(h_r\right)^{0.4} \tag{2.21}$$

which accurately represents beach erosion volumes. Alternatively, from model experiments where $(\rho_s-\rho)_r=1$, they found the following expression to produce reasonable results for dune erosion volumes:

$$t_{\eta,r} = \left(h_r\right)^{0.56} \tag{2.22}$$

which is similar to that of Vellinga (1982), $t_{\eta,r} = \left(h_r\right)^{0.5} = t_{Tr}$, where $t_{T,r}$ is the wave period scaling. This means that, according to Vellinga's relation, the morphological time scale is equal to the wave period scale, which is the hydrodynamic time scale defined by the Froude similitude in wavy environment (see also Section 2.3.2, equation 2.24).

It is further noted that from the CERC longshore sediment transport (LST) equation, where the LST rate is proportional to the alongshore component of wave power, assuming equal porosity between model and prototype, one can obtain the following expression for the morphological time scale:

$$t_{\eta,r} = \left(L_r/h_r\right)^2 \left(\rho_s - \rho\right)_r \left(h_r\right)^{0.5} \tag{2.23}$$

This equation, derived from LST similarity, is similar to the one from van Rijn et al. (2011) derived from (cross-shore) beach erosion volume similarity, but with slight differences in the value of exponents which suggest that the ratio between horizontal and vertical length scales is more significant for the morphological time scale.

2.3. General approaches for scaling morphodynamics in time

The main idea behind the successful design of a scaled mophodynamic model is to **synchronize all the time scale ratios of the dominating sedimentological and morphological processes to the time scale ratios of the driving hydrodynamic events.** The derivation of the different sedimentological (at the grain-size scale) and morphological (bed-form scale) time scales is detailed in the previous section (Section 2.2).

In practice, and taking the example of river flows, a first estimation of the scaled design should be obtained by ensuring that the dimensionless Shields stress and the particle Reynolds number are the same in the model and the prototype situation for bank-full flow conditions (e.g. Zwamborn 1966, 1981, Zarn 1992). The non-dimensional Shields stress for steady uniform conditions can be written according to (e.g. Garcia 2000, 2017):

$$\tau_* = \frac{\tau_o}{\left(\rho_s - \rho\right) g d} = \frac{\rho h S}{\left(\rho_s - \rho\right) d} \tag{2.24}$$

This equation is thus identical to $Fr_* = \rho u_*^2/[(\rho_s - \rho)gd]$, previously used to obtain equation 2.3. Additionally, the Reynolds number Re_{p*}, which in comparison to the particle Reynolds number Re_*, can be interpreted as a dimensionless surrogate for grain-size (e.g. Garcia 2017), can be derived:

$$Re_p^* = \frac{\sqrt{g\frac{\rho_s - \rho}{\rho}}d^{1,5}}{\nu} \quad (2.25)$$

These dimensionless parameters can be used to identify the different transport regimes in rivers (e.g. Garcia 2000) allowing for the definition of the extended Shields diagram (Figure 4, based on Re_*), or the Shields-Vanoni-Parker (SVP) river regime diagram (Garcia 2017, based on Re_{p*}). The extended Shields diagram shows the values of the Shield stress against the particle Reynolds number Re_* defining the different regimes (Parker 2008).

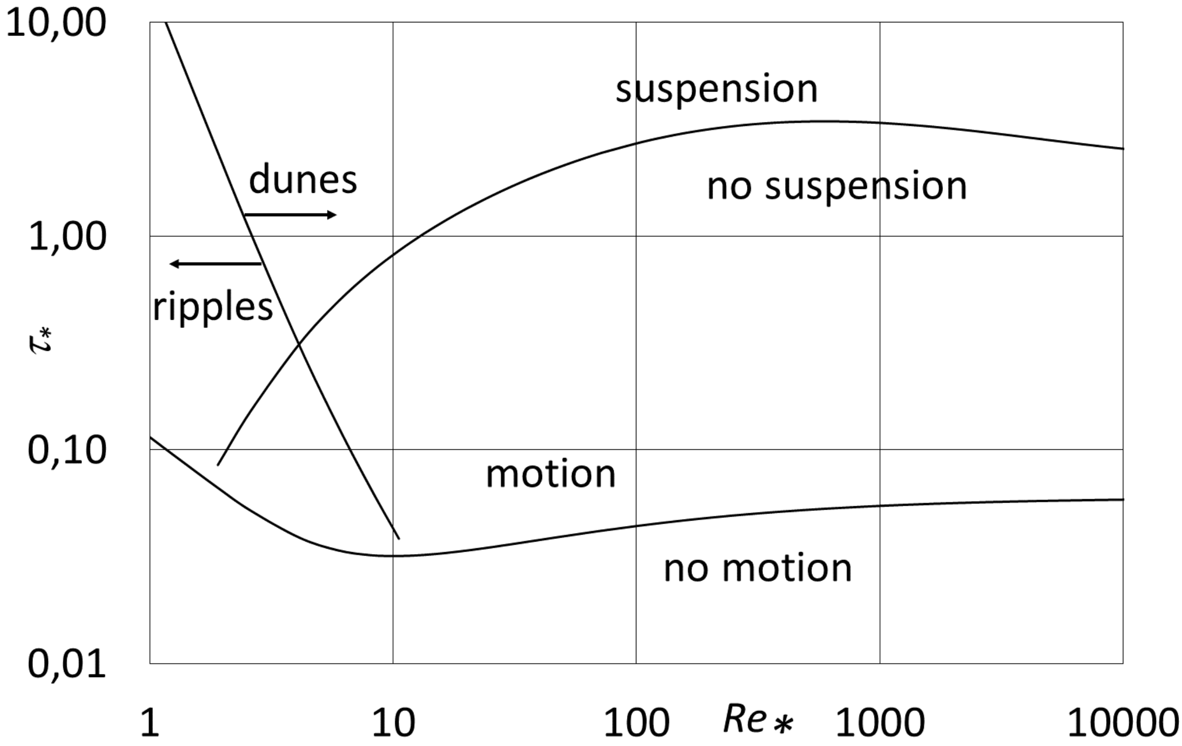

Figure 4 *- The extended Shields diagram, based on the particle Reynolds number* Re_* *(drawn after Garcia 2000).*

However, satisfying simultaneously equations 2.24 and 2.25, while applying the Froude similitude necessary to scale down free surface, may require some degree of relaxation on one of the parameters for large scaling ratios (e.g.in densimetric Froude models). As discussed below, some of the possibilities are, depending on the prototype conditions, relaxing the similitude criteria on the Reynolds number, or using a lightweight model sediment.

In general, the quantification of the potential scale effects is possible by running a scale series analysis (Heller 2011), which consists in comparing results of models of different sizes. Scale effects can be minimised by either avoiding the flow regimes where they start to occur (e.g. the water depth in free surface water flows should be larger than 3-5 cm to avoid significant surface tension scale effects), compromising some of the scaling requirements or by compensating them by e.g. designing distorted models, modifying the model grain size distribution (Zarn 1992), or using of bimodal waves (Baldock et al. 2011). A commonly used guideline to avoid significant Reynolds and Weber number scale effects in various hydraulic models following the Froude similitude is presented by Heller (2011). More specifically, Heller (2017) deepens the concepts of self-similarity and Reynolds number invariance as ways to exclude significant Reynolds number scale effects in Froude scaled models.

Referring to the general sub-division of the different morphodynamic models introduced in section 1.2.2, it is clear that “scale models” are in general relying on the concept of Reynolds number invariance, while “analogue models” are relying on the concept of self-similarity of the morphodynamic processes. These two notions are interrelated as they are the product of a symmetry analysis applied to the Navier-Stokes Equations (Frisch 1995). However, as pointed out by Heller (2017), self-similar criteria are necessary but not sufficient conditions to explicitly observe self-similarity, as it may be over-shadowed by more dominant effects, such as background turbulence. Further, self-similarity and Reynolds-number invariance are idealized asymptotic conditions. For example, to observe self-similarity, the initial conditions may have to be overcome, potentially requiring a long time or distance such that self-similarity may never be reached in a phenomenon.

2.3.1. The use of lightweight sediments

The use of lightweight sediments, i.e. model sediments with a different density than the prototype sediments, is an appealing alternative for designing movable bed models offering additional degrees of freedom by varying both the particle size and density of the sediments. The use of a lightweight material in a physical model does not necessarily mean that the model fulfils the criteria of *lightweight model* as defined in Section 2.1.2, as this type of materials can also be used in other bed load models, such as *densimetric Froude models*, analogue models (see above), or to study physical processes within a dimensionless framework. In fact, as reported in Table 2, there exist a range of movable bed scale model studies in which such sediments have been used (for an overview of the materials see e.g., Franco 1978, Bettes 1990).

Figure 5 *- Polysterene sediments (d_m = 2.1 mm, d_{60}/d_{10} = 2.0, ρ_s = 1055 kg/m³) used in the Oder model shown in Figure 1.*

Lightweight sediments in riverine and estuarine models

Probably the best-known examples of experiments carried out with lightweight sediments are the studies of Shields (1936) related to incipient motion and the experiments of Meyer-Peter and Müller (1948) which resulted in the corresponding well-known bedload transport rate formula. Lightweight materials have also been used to study local erosion processes such as scour development downstream of weir structures (e.g., Ettmer 2004 and references therein), bridge piers and abutments (e.g., Fael et al. 2006, Meyering 2012, Ettmer et al. 2015) and the impact of jets (e.g., Rajaratnam and Mazurek, 2002). The latter studies, in particular, made use of erosion processes being accelerated when lightweight sediments are used instead of natural fluvial sediments, i.e. the equilibrium dimensions of the scour can be reached faster. However, studies related to the impact of event sequencing on the development of scour are rare.

The design of the scale model scour studies with lightweight materials is generally based on similarity in the densimetric Froude number, although in these studies it is defined slightly differently from equation (2.4) since the shear velocity is replaced by a representative and measurable flow velocity due to the complex hydraulic flow patterns (e.g., Ettmer 2004). Similarly, incipient motion is often characterized by considering the ratio of flow velocity to the critical flow velocity resulting in incipient motion, although the latter is often subjectively biased (e.g., Ettmer 2004, Wang et al. 2013).

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 is related to u_*/v_s by a simple power relation and that $q_s \sim u_*^6$ and $\sim v_s^{-5}$. Zwamborn (1966) argued that the Fr_* criterion is essentially the same as the u_{*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_*.

Willson et al. (2007) reported results from a scale model (*analogue 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 ρ_s = 1050 kg/m³ 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 sediment was scaled based on considerations for 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 minutes 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 on aspects of concerns to the public and State and Federal Agencies.

Ettmer and Orlik (2012) tested mixtures of lightweight materials with similar particle diameters but different densities in order to simulate the grain size distribution of a sand-mixture. Their scaling criteria were based on a dimensionless particle diameter (also known as Bonneville parameter), the ratio of flow to settling velocity, and a dimensionless parameter defined by Ettmer (2004) considering the resistance at the grain-scale. Their experiments revealed a range for these dimensionless parameters in which the dunes formed in the lightweight material showed good agreement in relation to both bed geometry and kinematics. However, the effect of sorting and selective transport of particles by material density (see Viparelli et al. 2015) needs to be accounted for in such models.

Henning et al. (2008) investigated the possibility to reproduce simultaneously the development of dunes and scour at groins in *a densimetric Froude model* of a river reach (geometrically distorted model run with lightweight sediments, as illustrated in Figure 1). Using a trial and error approach, the lightweight material was selected to allow the development of dunes of appropriate shape (taking into account the distortion of the model), and a dynamic equilibrium condition in good similarity to prototype situation could be reached. The characteristic morphological time scales factors based on the transport rate (see Table 1) were estimated between 2000 and 4000. However, their experiments suggested that by considering the development of the morphodynamic processes of interest and the dune migration speed, the morphoynamic time scale at which the model operated was between 5000 and 6000. Additional unsteady experiments (unpublished data) further revealed that the morphodynamic time scale might be influenced by the flow magnitude so that the morphodynamic time scale is not necessarily constant when hydrographs are simulated (Henry and Aberle 2018).

To summarize, the use of lightweight material in *lightweight* or *densimetric Froude models* allows for the design of morphodynamic models with smaller spatial scaling ratios, thus covering larger temporal scales. However, the violation of a number of scaling criteria induces a distortion the different time scales characterising a scaled morphodynamic system, in comparison to the real scale prototype situation, which leads to a higher uncertainties. Therefore, the use of *lightweight* or *densimetric Froude models* for time scales relevant for characterising effects of Climate Change still needs to be investigated.

Lightweight sediments in coastal physical models

The use of lightweight sediment to represent sediment transport processes in scaled coastal physical models is highly relevant. Coastal models are typically divided into so-called 2D models, focusing on wave-sediment interactions and cross-shore transport, were both bed-load and suspended load needs to be accounted for, and 3D models, operating with larger scale reduction and focusing on cross-shore profiles and longshore bed-load transport (see e.g. Hughes 1993).

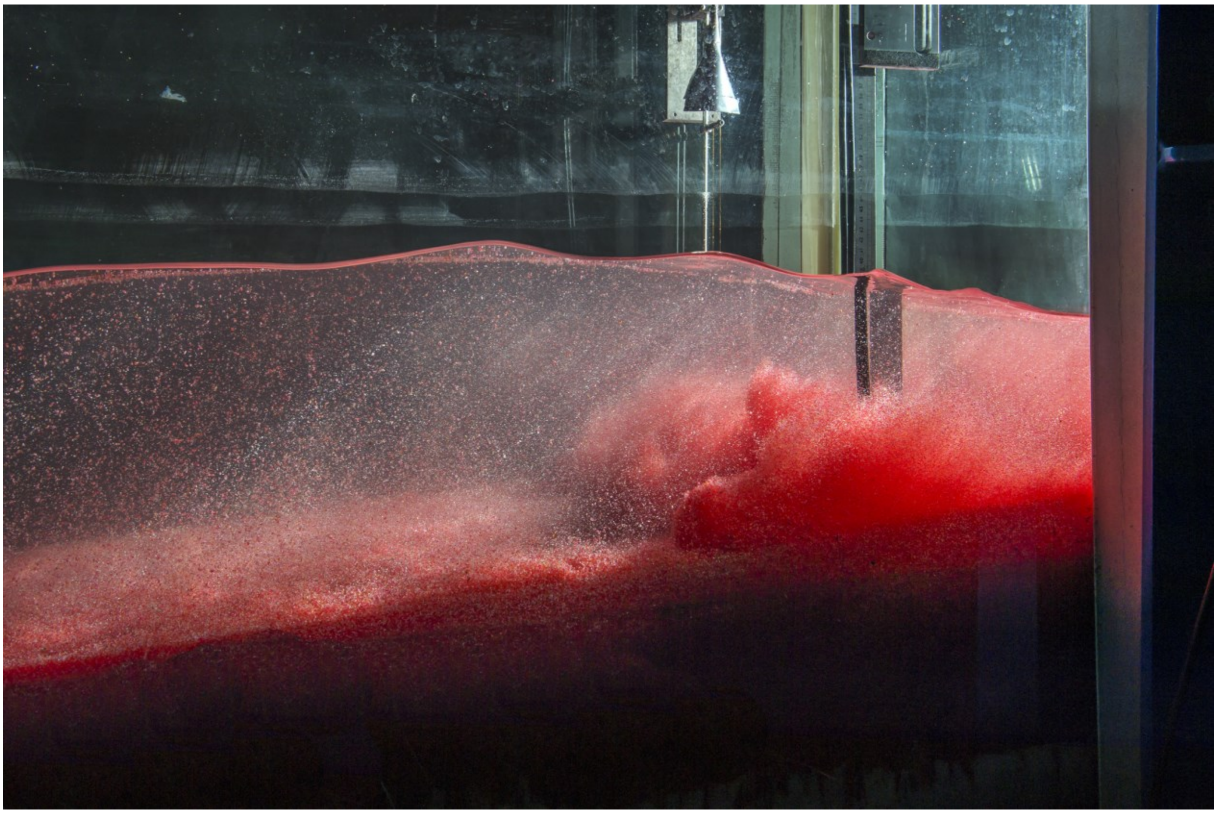

Figure 6 *- Use of PMMA sediments to model bed load and suspended transport during the investigations on beach profile evolution conducted by Rocha (2016), using the similitude framework described by Grasso et al. (2009).*

For 2D models of cross shore transport and beach profile evolution, several investigations were carried to test the scaling principles and quantify the scale effects, such as the work from Paul et al. (1972) Noda (1971, 1972), Kamphuis (1972, 1974), Ranieri (1994, 2002), and references herein. While Hughes and Fowler (1990) concluded that scale effects are negligible when using natural sand in undistorted models up a model-to-prototype ratio of 1:7.5 on the length scales (later validated by van Rijn et al. 2011), Ranieri (1994, 2002) suggested that by using lightweight material such as Bakelite, the scale effects could be acceptable up a model-to-prototype ratio of 1:14 on the length scales. Ranieri (2002) further documented that the breaker location and beach profile were similar in undistorted model using Bakelite up to a model-to-prototype ratio of 1:17.5, but that further scale reduction led to significant scale effects due to the low fall velocity of the lightweight material used, preventing similarity in the reproduction of the suspended load. Such conclusions were also reached in testing different lightweight materials (silica sand, anthracite 2 and duroplast) in the CEMito facilities at the Universidad Polytechnica de Catalunya (LIM-UPC, partially described in Petruzzelli et al. 2013 and Henry and Aberle 2018). These experimental investigations, using lightweight sediments in undistorted scale models of 2D beaches with geometrical scale ratios ranging from 1:15 to 1:50, provided a confirmation of these difficulties.

Grasso et al. (2009) detailed the dimensionless framework allowing the successful design of 1:10 undistorted scaled model quantifying the temporal changes of beach profiles, using lightweight sediments. Based on a dimensional analysis of the physical parameters controlling the hydraulic and transport processes, the similitude in Froude is the primary requirement for physical models involving waves (Dean and Dalrymple, 2001). The Froude number for such environment is expressed as:

$$Fr_w = \frac{H_S \omega_p}{2\sqrt{gh}} \tag{2.26}$$

where H_S is the significant wave height, $\omega_p=2\pi/T_p$ the wave angular frequency associated to the wave period T_p and h the water depth. Grasso et al. (2009) chose an undistorted model in order to reproduce the wave dynamics, shoaling, and breaking, and wave turbulence generation correctly. The Froude similitude between nature and the model thus implies a hydrodynamic time scale given according to equation (2.8) expressed for undistorted models. As for riverine environment, a strict similarity for the wave Reynolds number is not possible. In this case, the Reynolds number is expressed as:

$$Re_w = \frac{A\ \omega_p h}{\nu} \tag{2.27}$$

where A denotes the particle excursion at the bottom. The sediment transport similitude is achieved in both shoaling and surf zones by considering Shields and Rouse scaling criteria. For waves, the Shields number is defined by:

$$\tau_{w*} = \frac{1}{2} f_w \frac{\left(A\ \omega_p\right)^2}{g\left(\rho_S/\rho - 1\right) d_{50}} \tag{2.28}$$

where f_w is a wave friction factor taken according to Swart (1974). Thus, keeping similitude in the Shields number ensures the operation of the model in the same transport regime as in the prototype situation, with a similar bed-form development (see e.g. Nielsen 1992).

The Rouse number for such conditions can be expressed according to:

$$Rou_w = \frac{v_S}{u'} \tag{2.29}$$

where *u'* is the turbulent intensity of the flow field, approximated by $u' = \kappa \sqrt{f_w/2}\ A\ \omega_p$, with *κ* the von Kármán constant (Soulsby 1997). The Rouse number is relevant for characterizing sediment particle motions in a turbulent flow as in the breaking and outer surf zones, where sediment suspension is triggered and fuelled by different turbulence sources (boundary layers, breaking). Considering a characteristic length (the water depth for instance), it can be thought of as the ratio of a turbulent time scale to a settling time scale.

As underlined by Grasso et al. (2009), choosing a length scale and prescribing Froude scaling in an undistorted model imposes all the hydrodynamic scaling. The remaining parameters to be chosen are thus the sediment density and diameter, both of which are to be determined with the Shields and Rouse similitude. In the case of the choice of a lightweight sediment is needed to comply with these criteria, the immersed weight of the sediment cannot be scaled.

The scaling approach formulated by Grasso et al. (2009) differs from the classical approaches adopted by the studies mentioned below and summarised by e.g. Dean and Dalrymple (2001, p.310), where morphological models were mainly based on the similarity on the Froude and Dean numbers. According to Grasso (2009) the additional consideration of the Rouse number (in comparison to the Dean number quantifying morphological beach states (Dean 1973)) makes the formulation of the similitude more general. It is worth mentioning that Grasso et al. (2009) successfully reproduced the cross-shore morphological response of a natural beaches applying this scaling approach.

Regarding the use of lightweight materials in 2D scaled beach models, Petruzzelli et al. (2013) formulated some potential limitations coming from the choice and use of different lightweight material:

- Spherical lightweight materials (low friction angles) tend to show a too severe mobilization
- Fine grain sizes (fine sands and glass microspheres) are not mobilized enough on the emerged part of the beach during small-scale tests, due to the strengthening by capillary forces
- Materials likely to electrify, or which interact with water such as melaminic plastics, are forced to mutual attraction and to flotation of some particles aggregates, thus leading to their not suitability for physical modelling.

***Table 2** - A review of morphodynamic investigations using lightweight sediments (experimental applications) and large time scaling/distortions. Abbreviations used for the publication type: Rp-Review paper; Ep-Experimental paper; Tp-Theoretical paper; R-Report; Ur-Unpublished report. The review-table is not exhaustive.*

Name	Publication type	System scaled/studied	Modelling approach	Additional comments
Branß et al. (2018)	Rp	Formation of natural levees	No scaling. Conceptual model	Lightweight sediment used to accelerate formation of natural levees in compound channels.
Berni et al. (2017)	Ep/Tp	Bed destabilization under waves	Shields number and Rouse number scaling (Grasso et al. 2009; Berni et al. 2013).	Length scaling ratio of 1/10 and a time scaling ratio of approximately 1/3 with two bichromatic wave groups of different periods.
Rocha (2016)	Thesis	Wave nonlinearities and infragravity waves on the nearshore transport	Shields number and Rouse number scaling (Grasso et al. 2009; Berni et al. 2013).	Modulation of the sediment transport and final beach profile by infragravity waves. Same scale ratios as above.
Ettmer et al. (2015)	Ep	Live-Bed Scour at Bridge Piers	No scaling. Test of empirical laws	Lightweight Polystyrene Bed (rel. density 1.06)
Kleinhans et al. (2015)	Rp/Ep	Biomorphodynamics of rivers and deltas	Characterization of scale effects in the ratio bar pattern and bar length to channel width.	Geometric scale effect absents but time scaling problematic as it integrates multiple processes (sediment transport, floodplain formation, bank failure/stratigraphy and riparian vegetation)
Viparelli et al. (2015)	Ep	Sediment sorting and selective transport by weight	No scaling. Use of lightweight sediments for testing sorting/transport processes.	Downstream lightening and upward heavying. Particle mixtures with rel. densities from 1.5 (lightweight) to 4.
Gorrick & Rodriguez (2014)	Rp/Ep	Sand-bed stream	Undistorted Froude scaling and graded lightweight sediments	1/16 model with various types of lightweight sediments (test of pros & cons). Scale effects due to incorrect scaling of relative roughness
Vermeulen et al. (2014)	Ep	River scale model of a training dam	Froude and Shields scaling with lightweight sediments. Nearly undistorted geometry.	Good reproduction of bed forms (dunes/channels) with lightweight sediments but overestimation sediment mobility: amplification scouring, absence deposition.
Berni et al. (2013)	Ep	Surf zone cross-shore boundary layer velocity asymmetry and skewness	Shields and Rouse similitude (Grasso et al. 2009), and boundary layer Reynolds number in the hydraulic rough regime.	Lightweight Polymethyl Methacrylate sediment (Plexiglas, density 1180kg m^{-3}) with a median diameter d_{50}=0.64 mm
Petruzzelli et al. (2013)	Ep	Beach profile morphodynamics	Irregular wave conditions and geometries based on Froude scaling. Use of lightweight materials.	Testing scalability of a benchmark test from 1/15 to 1/50 and 1/100 with different materials covering densities between 1150 kg/m^3 and 2650 kg/m^3 and median diameters from 0.07 mm to 1.5 mm. In addition to settling velocity, mobility rates and beach profile morphodynamics depends on particles intrinsic characteristics
Wei et al. (2012)	Ep	Bed forms and bar system in gently curved river channel	Distorted/undistorted (densimetric) Froude model	Derivation of the scaling laws from 1-dimensional equation of motion, continuity equation, bed deformation equation and the formula of

				bed load transport. Confirmation of the bester suitability of a distorted model to predict bed forms compared to a undistorted model
Ettmer & Orlik (2012)	Ur	Dunes in unidirectional flows characterised by bed material with wide-grain size distributions simulated using lightweight materials	Scaling based on sedimentological diameter D* and ratio of mean velocity to fall velocity as well as ratio of Re_*/Fr_{u*}^2	Investigation of mixtures of lightweight materials; dune shapes observed in corresponding sand experiments could be reproduced
LWI (2010)	Ur	A stretch of the trained Oder river	Distorted lightweight model to simulate morphodynamic development based on different river training structures	Investigation related to morphodynamic time scales related to dune movement under different hydraulic conditions indicating dependence of morphodyanmic time scale from hydraulic conditions
Gill & Pugh (2009)	Tp/Ep	Sediment transport processes	Modified-lightweight (Froude) model, adjusting sediment density and slope of the model to correct for constant dimensionless transport rate.	Scaling laws derived based on keeping the relationship between dimensionless bed shear and dimensionless unit sediment transport. The particle size and density is based on the fall velocity.
Grasso et al. (2009)	Ep	Transients and equilibrium states of intermediate cross-shore beach morphology	Undistorted Froude scaling and nearly scaled Shields number and Rouse numbers (similar regimes).	Length scale about 1/10 and time scale about 1/3 with poly-methyl-methacrylate granules (PMMA) (d_{50} = 0.60 mm and ρ_S = 1190 kg/m3).
Madej et al. (2009)	Ep	Channel responses to varying sediment input	Froude and Shields stress similarity according to bankfull conditions of the study reach	Spatial scale 1/100. Distorted Froude-scale model of the reach and undistorted model of a generic gravel-bed channel that is steeper and coarser than prototype.
Paola et al. (2009)	Rp	Stratigraphic and geomorphic experiments	Internal/external similarity. Scale independence.	Natural scale independence characteristic of morphodynamics. Quantitative understanding of the origins and limits of scale independence better suited than dynamic scaling.
Henriquez et al. (2008)	Tp/Ep	Onshore sandbar migration	Undistorted lightweight model with similitude in Froude's, Shields' and grain size Reynolds' numbers.	Model sediment of a non-saturated polyester (whose trade name is Duroplast) with a density of about 1200 kg/m3 and a mass median diameter of 0.54 mm. Scale effects: steeper beach slopes than expected and liquefaction within the first layers of the bed (wave-induced plug-flow).
Willson et al (2007)	Ep	Mississippi river delta	Froude law and particles scaled so that incipient motion and resuspension were similar in model and prototype.	Horizontal scale 1/500, vertical 1/12000, morphological time scale 1/17857 (1year=30min in model)
Kocyigit et al. (2005)	Ep	Tidal-induced transport in a squared harbour	No proper scaling undertaken, but use of a lightweight sediment with a tide period of 355 seconds	Direct comparison numerical/experimental work, test of sediment transport formulae for lightweight sediment
Moreton et al. (2002)	Rp/Ep	Braided alluvial architecture and subsurface permeability	Generic Froude scale model (relaxation on the scaling of the grain size magnitude)	In addition to comments for Moreton (2001); geologically similar sedimentary sequences of coarse-gravel braided alluvium.

Viguier et al. (2002)	Ep	Tidal model for restoration of the maritime character of Mont-Saint-Michel	Combination of scale model and numerical models. Plastic and sawdust were used in scale model. Similitude laws for sediment transport based on fall velocities and initiation of suspension.	Determination of time scale (1/28) by monitoring bed changes over several tidal cycles. Hydraulic time scale determined via Froude scaling (1/8).
Gaines and Smith (2002)	Rp	Loose-beds	Review and analysis of 16 large scale and 14 small-scale models to assess the primary factors required for morphologic similarity	Morphologic similarity based on Mean squared and cumulative frequency error between prototype and model. Similarity of sediment motion based on incipient particle mobility, the general state of sediment mobility, and the particle's suspension characteristics.
Moreton (2001)	Thesis, Chapt5	Effect of sediment supply grain size on down-basin braided alluvial architecture	Generic Froude scale model (relaxation on the scaling of the grain size magnitude)	Spatial scale:1/50. Sediment composition: 20% sand, 80% gravel. Scaled hydrographs and sediment input
Wallerstein et al. (2001)	Ep	Large woody debris (LWD) flows	Distorted Froude-scaled, Shields scaled, scaled drag for submerged LWD	The time scaling ratio was 1:11.45, thus geomorphic adjustments were modelled in only 45 hours
Peakall et al. (1996)	Rp/Tp	Fluvial Geomorphology	Review of the scaling of time in movable bed models via dimensional analysis of the physical processes and event magnitude-frequency (hydrograph scaling).	Effect of the distortion of the timescale ratio for long-term processes not known - to be investigated. Scale modelling hydrographs can enhance time-scale compression.
Pugh and Russel (1991)	Tp	Mobile sediment beds	Froude scaling with use of the Shields function	Adaptation of the Taylor dimensionless unit sediment discharge curves to determine the appropriate sediment diameters specific gravity.
Peters (1990)	Ep	Sediment transport in large alluvial rivers with very low slopes	Distorted Froude scaled lightweight sed. (Bakelite). Then adjustment velocity for scour ignition (lost Froude condition)	Froude condition lost leading to analogy modelling (comparison patterns)
Powell (1990)	Rp	Short time profile for shingle beaches	Anthracite as model sediment was found to satisfy most of the requirements for reproducing the correct onshore/offshore movement and threshold of motion.	Detailed grading curves of the model sediment given in the report. Detailed considerations regarding scaling criteria provided in an annex.
Low (1989)	Ep	Bed load Transport	No scaling law applied but description of the transport of lightweight sediments (Einstein-Brown, modified Smart formulas).	Lightweight sediment transport rate proportional to the sixth power of the shear velocity and inversely proportional to the fifth power of the grain fall velocity.
Zwamborn (1981)	Ep	Morphodynamics and scour holes around bridge piers	Model designed to keep the similitude on the Froude number and the shear/settling velocity ratio	The horizontal and vertical scales were 1:250 and 1:100 respectively, and the lightweight material used was crushed anthracite. Scour holes were reproduced to an accuracy of about 10 percent in the model

Wulzinger (1981)	R	Estuarine tidal morphodynamics	Distorted Froude scaled lightweight sediment model	Based on tidal models of BAW (see Vollmers and Giese 1972)
Vollmers and Giese (1972)	Ep	Estuarine tidal morphodynamics	Distorted Froude scaling. Choice of lightweight sediment based on Gehring (1967)'s method (based on what??)	Horizontal scale 1/800 and vertical 1/100. Distortion of tide period to match expected bed deformation. Final timescale 1/705 (1day = 2min in model).
Paul et al. (1972)	Tp/Ep	2D beach profile evolution	Similitude for Re*, Froude in undistorted lightweight (bakelite) models, with additional similitude on the grainsize distribution.	Determination of scaling laws and scale effects for mobile bed coastal models. Quantification of the scale effects due to the use of lightweight sediments (coarse sand vs. bakelite, fine sand vs. bakelite).
Le Mehaute, B. (1970)	Tp/Rp	Movable beds in Fluvial/Coastal systems	Review of (Froude) similitude relations for movable bed; "Lacey"-type relationships for geometrical distortion.	Conditions of similitude for beaches are generally less stringent than for rivers (condition on bottom roughness). Discussions on time scale ratios and the use of lightweight materials.
Zwamborn (1966)	Ep	Large river morphodynamics	Modified-lightweight (Froude) model	The Froude criterion was replaced by the scaling the ratio shear-to-settling velocities, keeping a near similarity in Re*.
Einstein and Chien (1956)	Tp/Ep	Rivers with movable bed	Distorted Froude scaling, implying the use of lightweight material.	Detailed scaling procedure derived from the friction, Froude, sediment transport, zero sediment-load and laminar sublayer criteria. Discussion of the issue of loss of similarity and various scaled time scales.
Bagnold (1955)	Ep	Transport processes	No scaling. Exploratory work on transport of very lightweight material	Characterisation of the effects of particle low inertia on transport processes. Sediment relative densities from 1.06 down to 1.0025
USACE (1936)	R	Bed load material	Investigation of the suitability of lightweight materials to simulate bed load transport	Identified suitable materials were further investigated related to their critical tractive force; data charts provided

2.3.2. Other alternatives

The use of a lightweight surrogate sediment is motivated by the fact it allows the modification of a physical constant playing a key role in the sediment transport processes (the sediment density). Similarly, modifying other key physical constants, it is possible to identify other alternatives to the classical design of scaled morphodynamic investigations.

Some investigations have been carried out by changing the properties of the fluid used in the scaled model. For example, Stagonas et al. (2011) used a mixture of 90% distilled water and 10% isopropyl to modify the surface-tension of the fluid in order to quantify the impact of the Weber number and the potential associated scale effects on the aeration process in breaking waves. Kobus (1980) also reported some investigations on the initiation of sediment transport by using coal dust (lightweight sediment) in glycerine (fluid). More recently, Mignot et al. (2018) tested the effect of adding polymer additives in the water to dampen the energy losses in channel flows, thus modifying the hydraulic roughness. Moreover, controlling the water temperature may be another option to aim for better similarity in the Reynolds number, as demonstrated by Young and Davies (1990) who used heated water (30° C) in their experiments. Finally, Faulhaber (2017) also showed the suitability to replace water in aerodynamic investigations of sediment transport in small scale river reaches, although a quantification of the potential scale effects is still needed.

In the analogue modelling of large-scale river systems (see e.g. section 3.1.1) the rapid development of the morphological feature of interest may be partly due to the absence of cohesive elements in the sediment, which prevents the accurate reproduction of bank erosion processes. van Dijk et al. (2013) and Kleinhans et al. (2015) further investigated the effect of adding cohesive materials such as clay and silt, on bank erosion. For the cases with silica flour (van Dijk et al. 2013), the bank migration rate reduced by a tenth compared to the tests by van Dijk et al. (2012). However, strict quantification of the time scales with such experiments is difficult and further investigations are needed to understand what are the optimum sets of parameters to be used (e.g., content of cohesive material, tilting angle and frequency, use of lightweight material, …), as the pervasive distribution of low levels of Extracellular Polymeric Substances (EPS) throughout the sediment controls the bedform dynamics (Malarkey et al. 2015).

Another possibility is the use of particles allowing for the control of cohesive interactions between the sediment grains. More specifically, colloidal forces govern the nanoparticle deposition and aggregation, and for metallic, bimetallic, metal oxide nanoparticles, these forces may be modulated depending on the physical and chemical properties of the liquid phase (Petosa et al. 2010). Because this would allow in principle the design of an experiment with particles in the cohesive-size range, this approach is particularly interesting for situations where the scaled concentration of the suspended material needs to be modelled correctly (e.g. particulates flows and turbidity currents, see Peakall and Summer 2015).

2.3.3. Examples of coupling the hydrodynamic and morphologic time scales

Coupling the hydrodynamic time scales with the morphologic time scales is the most critical part of the design of a scaled morphodynamic experiment and depends on the dominating hydraulic process driving the sediment transport in the prototype. This section provides some examples of successful practices for different applications.

Flood wave propagation: Wang and Kron (1991) investigated the time distortion in large morphodynamic scaled tests. After a classic dimensional analysis of the equations of motion, continuity and bed deformation, they expressed the extent the of the time distortion between the time scale of the flow t_r and bed deformation $t_{\eta,r}$ by the factor $\alpha = t_{\eta,r} / t_r$.

Following their dimensional analysis and the notations introduced in Section 2.2.1, this time distortion can be expressed as $\alpha = L_r h_r (1 - \phi)_r / q_{S,r}$, where $q_{S,r}$ is the scaling ratio of the rate of bed load transport per unit width (see Wang and Kron (1991) for further explanations). Wang and Kron (1991) indicate that $\alpha > 1$ in scaled morphodynamic experiments (typically in the range 5 to 30) implies that the ratio of the speed of bed deformation in the model to the speed in the prototype is much larger than the ratio of the speeds of the wave propagations in model and prototype.

In the case of the propagation of a modelled flood wave, the wave propagates at a speed U_{flood}, which is similar to the prototype with the scaling ratio $U_{flood,r} = L_r/t_r$. Following the Froude similitude, the time needed by the flood wave to propagate from the inflow in the model is multiplied by the ratio $1/t_r$, while the evolution of the hydraulics and bed forms at the outflow is multiplied by $\alpha/t_r = t_{\eta,r}$. Therefore, velocities are not similar and result in dissimilarities in sedimentation and erosion. However, as pointed out by Wang and Kron (1991), the impact of time distortion is serious only in the neighbourhood of the outlet of the modelled reach. The longer the modelled reach and the larger the coefficient of time distortion, α, the larger the influenced area and the more serious the deformation of the bed profile. The effect of such time distortion can be reduced if counter-measures are taken during the test, and Wang and Kron (1991) demonstrated both analytically and experimentally that one such measure can be feeding water into the model during the rising period of the flood wave and withdrawing water from the model during the receding period at several locations along the reach.

River morphology: Flood events can be represented in flume experiments at the event scale by stepped (e.g. Tal and Paola 2010), triangular (e.g. Mrokowska et al. 2018) or trapezoidal (e.g. De Sutter and Verhoeven 2001) hydrographs. In practice, the rising and falling limbs of the hydrographs are reproduced by a stepped flow variation (with the number of steps strongly dependent on the complexity of the flume control equipment, Lee et al. 2004). In the past, flood studies typically focused on single year floods. This approach suggests that rivers accommodate and recover before the next flood. In this approach, floods can be conveniently characterized by flood magnitude, return interval and flood duration. Due to the effects of Climate Change, extreme flood frequency and magnitude are likely to increase, and more recent studies have started to look at the succession or cluster of floods, with focus mainly in the frequency of those events (e.g. Tal and Paola, 2010, Piliouras et al., 2017). Redolfi et al. (2018) investigated further the links between the morphology of scaled gravel rivers and bed load variability, following changes in the flow regime. They quantified that the adaptation of the river morphology to a variable hydrograph produces a clockwise hysteresis in the bed load rating curve, correlating with the ratio of the flood duration relative to the time scale of the bed evolution, and concluded that further research is needed in this direction.

Catchment and rainfall: Some preliminary investigations on the possibility to couple rainfall sequences and long-term catchment evolution were reported by Moulin (2018). The relationship between rainfall, runoff and erosion is known to be highly nonlinear (e.g. Boardman and Favis-Mortlock 1999, Vanmaercke et al, 2011), but there is lack of understanding on the effect of varying magnitude-frequency rainfall event sequences on erosion and sediment dynamics in catchments. The tests reported by Moulin (2018) suggest that the sediment erosion is directly correlated to the intensity of the rain when the sediments are initially fully saturated, in which case the sequencing of the rain events do not appear to have a major influence on the erosion processes. However, there is a decorrelation of the two processes when the sediments are not fully saturated, due to the introduction of capillarity forces between the sediment grains. In this case, the coupling between rain sequences and evolution of saturation appear crucial.

Transport under irregular waves: In scaled morphodynamic tests of nearshore environments, it is common practice to replace random waves by equivalent bichromatic waves in order to speed up the sediment transport process and the beach profile evolution (e.g. Henriquez et al. 2008, van Rijn et al. 2011). For fundamental research, equivalent bichromatic waves produce results that are closer to random waves than equivalent regular waves (Baldock et al. 2011). Bichromatic waves have the advantage to speed up the sediment transport process importantly and at the same time produce repeatable events in the time series which allow ensemble averaging of the events along the times series, which is necessary in order to study suspended sediment transport and bed load transport with the actual measuring equipment.

Coupling coastal transport processes: In order to have an undistorted interaction between the longshore transport and other tidal or steady current, the tide and current intensities are typically distorted (in regard to the original Froude similitude) so that the time scales associated with each transport process matches the sedimentological time scale derived for the longshore transport (Migniot et al. 1975, Migniot 1979). This procedure, at the heart of the design of scaled model tests of coastal environments, is described in more details in Section 3.2.2.

3. PROTOCOLS FOR TIME COMPRESSION IN MORPHODYNAMIC EXPERIMENTS

Among other reference works on the topic, Hughes (1993) emphasizes that the design of a mophodynamic model, and definition of its scale should be dictated by the dominating mode of sediment transport in the prototype situation, and the restrictions imposed by the cohesiveness of the sediments and the capabilities of the facilities (size, equipment and technical support). The factors listed by Hudson et al. (1979) concerning coastal hydraulic models can be generalized to assess the feasibility of setting-up a scaled morphodynamic model:

- Prototype wave environment from measurements and wave hindcasts, and other transient or short-term oscillations in the water body/channel to be scaled;
- Prototype currents generated by tidal flows, hydrograph variation or other long wave phenomena;
- Estimates of transport rates (longshore and cross-shore for coastal environments) in the prototype;
- Size of the prototype area to be studied;
- Type and size distribution of the prototype bottom material;
- Size and capabilities of the model test facilities;
- Available materials for use as model sediment;
- Intended accuracy of the model results;
- Funds available to conduct the study;
- Time available to conduct the study;
- Qualified personnel to conduct the study.

The selection of the scale, determining the size of the model, and the final design of the model should be driven by the best compromise to meet the minimum accuracy expected from the study. For large and/or complex prototype situations, it is common that the determination of the best experimental set-up is sought through the realization of preliminary investigations, either via experimental investigation focusing on a specific process (e.g. Hughes 1993, van Dijk et al. 2012), or the use of numerical investigations (e.g. Bollaert et al. 2017). The following subsections develop the aspects to be considered specifically when dealing with a fluvial, tidal or coastal environment. This information is based on the knowledge developed in hydraulic laboratories around the world, and made available in the published and grey literature. These protocols provide short introductions on how to conduct a morphodynamic experiments.

The experimental investigation of hydraulic and morphodynamic processes can be divided into three main categories depending on period of the dominating hydrodynamic process, which is conditioning the formulation of the dynamic similarity of the model (Hughes 1993). Thus, short wave models are typically designed to reproduce the prototype situations where the period of the dominating oscillations are in the range between 1s and 20s. Long wave models are typically designed for period of the oscillations between minutes and days (Dalrymple 1985), while fluvial models are designed to address unidirectional flow where the period of oscillation tends towards the infinite.

3.1. FLUVIAL ENVIRONMENT

3.1.1. Dynamic river channels: braiding and meandering

Objectives

Predicting the long-term hydro-morphological evolution of fluvial systems requires an understanding of how river morphology responds to long term changes in flood frequency and magnitude. This knowledge is particularly important for restoration and risk management in fluvial environments when evaluating the impact of potential changes in event magnitude and frequency due to the effects of Climate Change and other long-term drivers.

The stability of river channels has been studied for a long time (e.g. Callander 1969, Parker 1976, Fredsøe 1978), and is still the subject of an intense research effort. Indeed, a large variety of parameters influence the channel dynamics, such as the median grain size of the channel (e.g. Ferguson 1987), the presence of bank vegetation (e.g. Millar 2000), sediment cohesion in the floodplain (e.g. van Dijk et al. 2013) or flow unsteadiness (e.g. Redolfi et al. 2018). According to the static and dynamic characteristics, alluvial river patterns can be subdivided into straight, meandering, and braided rivers (Leopold and Wolman 1957), of which the last two are highly dynamic systems.

As summarized by van Dijk et al. (2012), many investigations were carried out focusing on the relation between bank strength and the meandering process (e.g. Friedkin 1945, Schumm and Khan 1972, Smith 1998, Gran and Paola 2001, Peakall et al. 2007, Tal and Paola 2007, Braudrick et al. 2009), while other type of experiments highlighted the formation of a wide braided system by the progressive development of an initial meandering into alternating bars (Parker 1976, Federici and Paola 2003, Visconti et al. 2010).

Earlier studies have shown that the planform geometries of modern rivers are typically scale invariant which suggests that these rivers have reached a state where their morphology is in dynamic equilibrium (Sapozhnikov and Foufoula-Georgiou 1996). This scale invariance is used in most of the experimental investigations of the dynamics of river channels, which by analogy allow for an estimation of the geometries of braided and meandering river deposits.

Facilities and instrumentation

The investigation of the development of scaled meandering and braided systems is typically conducted in wide models, going from temporary table-sized models (e.g. Reitz et al. 2014, test area of 0.75m x 1.5m), to larger flume-sized environments such as the Eurotank in Utrecht (6 x 11m, see e.g. Postma et al. 2008, van Dijk et al 2012), or the river modelling flume at the University of Western Ontario (3 x 18.3 m, e.g. Peirce et al. 2018). Scaled meandering and braided systems require a control of the water levels and discharges up-stream and downstream of the tested sediment layer. This is typically achieved by applying a point or channel inflow in the upstream area (fixed or movable, see e.g. van Dijk et al. 2013), and using a deeper basin with constant water level at the downstream of the model, regulated by a weir (e.g. van Dijk et al. 2012). The discharge can be regulated by low capacity pumps, with a typical rate of a couple of liters per second for the larger experiments (e.g. Egozi and Ashmore 2009, van Dijk et al. 2013).

In order to achieve shear stresses large enough to sustain the sediment motion at the surface of the sediment layer, a slope higher than the ones typically found in natural systems need to be implemented, either by shaping directly the sediment layers in the flume (e.g. van Dijk et al. 2013), or by operating a tillable flume (e.g. Egozi and Ashmore 2009, Reitz et al. 2014). In order to run the model into a dynamic equilibrium, a sediment feed system needs to be implemented upstream of the scaled river system, and sediments need to be collected downstream and recirculated. Note that van Dijk et al. (2012) concluded that bend instability should be consider as an input conditions by moving the sediment inflow, as it controlled and affected the meandering process in their scaled model. Depending on the scope of the investigation, the preparation of a sediment mixture with a set ratio of sediments of different size and densities may be required.

The measurements typically needed in this type of experimentation are topography measurements (for example Terrestrial Laser Scanning or Photogrammetric measurement, see e.g. Aberle et al. 2017), discharge and surface velocimetry measurements (flow rate at the inflow, potentially Large Scale Particle Image/Tracking Velocimetry, see e.g. Aberle et al. 2017), and transport rate measurements (e.g. with a trap and weigh system downstream of the flume, see e.g. Aberle et al. 2017).

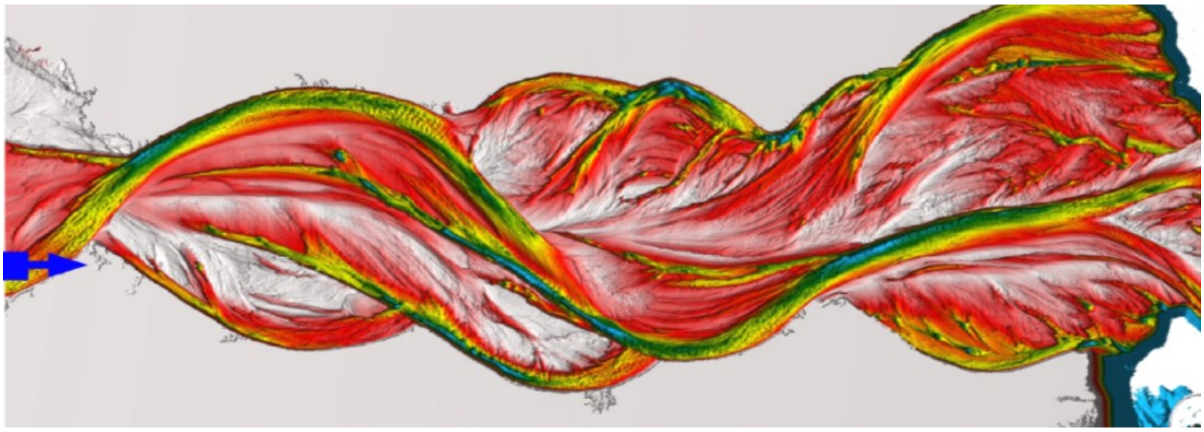

Figure 7 *- Scanner of one of the test done by van Dijk et al. (2012) on channel evolution of a meandering river. Modified from van Dijk et al. (2012).*

Scaling considerations

The scaling principles derived in section 2 also apply to meandering and braided river experiments. The large geometrical scaling ratio applied to represent such systems in laboratory environments implies that most of the criteria imposed by the scaling laws are relaxed, and that the focus of these scaled experiment is to operate the model in a similar transport regime as the natural system considered (e.g. Paola 2009). For example, van Dijk (2012) describes the scaling considerations to operate a scaled model of a meandering river:

- Subcritical flow (Fr < 1)
- Turbulent flow (Re > 2000), but the flow on the floodplainfloodplain may be laminar (e.g. Malverti et al. 2008)
- The flow in the channel should be in the hydraulic rough regime
- Sediment transport should occur (i.e. bed shear stress > critical shear stress)
- For a correct development of the morphological features, the interaction parameter IP as defined by Struiksma et al. (1985) (their equations 26 and 28) needs to be in an underdamped regime (see Struiksma et al. 1985).

Additional scaling requirements include a lower limit for the grain-size to avoid cohesion. The small water depth involved in these experiments imply the need to correct for the low bed shear stresses if natural slopes were to be kept in the scaled model. Thus, steeper modelled slopes may need to be up to 10 times steeper than their natural counterparts (Peakall et al. 1996, 2007).

Postma et al. (2008) discuss that an important remaining problem in comparing experimental with real-world data arises from the fact that sediment transport in the model is very likely to be non-linear, while for the real-world linear transport rates are derived (de Vries 1975, Begin et al. 1981, Paola et al. 1992, Métivier and Gaudemer 1999). Additionally, Postma et al. (2008) point out that the consequences of these different transport rates for the rate of fill of accommodation remain unclear, making it thus difficult to up-scale laboratory results from analogue models to quantify the response of systems in the real world forced by climate, sea-level and tectonic change.

Attempts to use such small physical river models for specific predictive purposed were made in a couple of experimental investigations (see a review by e.g. Maynord 2006), where these micromodels were used to predict the morphodynamic changes induced by hydraulic structures for environmental impact assessments and navigation purposes. However, due to the lack of adherence to similarity principles leading to large relaxations in similitude, it was concluded that such models do not have any predictive capability and should be limited to demonstration, education, and communication (Maynord 2006).

Model calibration and experimental procedure

To refine the experimental procedure, the different discharges of the hydrograph and the associated sediment feed rates must be estimated based on empirical formulations (Meyer-Peter and Müller, 1948) and then adjusted in calibration runs in order to keep an initial desired slope during the all flood sequence (e.g. van Dijk et al. 2012). Another alternative is to increase the slope of the model (tiltable set-up) until its sediment transport capacity becomes almost equal to the sediment input rate (e.g. Kleinhans et al. 2014).

Sediment cohesion can be adjusted to better represent the bank erosion process. In that case, the test of a sediment mixture is required, and such a procedure is described in detail in, for example van Dijk et al. (2012). For this purpose, silica flour is most commonly added to coarser sand to allow finer sediment settling on the floodplain and point bar, which results in slightly more cohesive banks (Peakall et al. 2007). Similarly, silica flour tends to fill the lows in the floodplain and limit the amount of chute cutoffs (Braudrick et al. 2009). For example, the experiments of van Dijk et al. (2012) were realised with a ratio of sand (ρ_S = 2650 kg/m³, d_{50} = 0.51 mm) to silica flour (ρ_S =2600 kg/m³, d_{50} = 0.03 mm) of 4:1.

The calibration of sediment inputs with experimental hydrographs representing a succession of transient hydraulic events still requires some further investigation to be confidently implemented into the design of scaled experiments (see Section 2.3.3).

3.1.2. Bed load transport and bed forms ("in channel processes")

Objectives

Because of their capacity to quantify the sediment transport processes in river channels and around hydraulic structures, scaled experimental investigations are at the heart of the investigations on hydraulic transport since its origins (e.g. Rouse and Ince 1957). Until the recent development of numerical simulations, sediment transport processes in channels could only be investigated with scaled experimental approaches, and thus various experimental methods have been developed to ensure the similitude of those transport processes in effective and cost-efficient scaled models (see e.g. Muste et al. 2017). The knowledge of these methods allow for the use of large-scale models as a predictive tool for engineering and land planning applications (see e.g. Hentschel 2007). The framework defining the similitude presented in the previous sections, some more practical aspects related to scaling bed load transport and bed forms is presented below.

Facilities and instrumentation

The type of facility needed to carry out scaled experimental investigation of in-channel processes depends to a large extent on the physical system to be reproduced. Scaled models can be limited to classic tiltable hydraulic flumes (see e.g. Muste and Uijttewaal 2017) but may require the construction of large structure to be built in research halls/basins (see e.g. Hentschel 2007). In the latter case where large facilities are needed, special systems may be designed for leveling sediments between the different runs, sprinkling the upper sediment layers during the filling phase, or a buried drainage system for avoiding sediment re-mobilization during the emptying process (Hentschel 2007). In order to ensure a good control of the hydrodynamic conditions applied in the model, water level discharge control, and temperature measurements are necessary. A controlled sediment feeding/recirculating system should be implemented upstream (e.g. Hentschel 2007, Simonett and Weitbrecht 2011), and sediment transport rates may be measured by using photogrammetric approaches (e.g. Hentschel 2007), and/or sediment traps and weighing cells (e.g. Simonett and Weitbrecht 2011).

Scaling considerations

The selection of an appropriate scale is a function of the space availability, including as many of the prototype channel features as possible, and the need to maintain a scale ratio large enough to limit the effect of viscous forces. In order to achieve similitude between model and prototype, the dimensionless Shields stress and the particle Reynolds number should be the identical for model and prototype for bank-full flow conditions, in addition to the similarity in Froude and Reynolds numbers (see e.g. Garcia 2017, Gill and Pugh 2009). One common approach is then to use the Extended Shields diagram (see section 3.3) to visualize the effects of the different design possibilities (use of lightweight sediment, distortion of the model slope, e.g. Gill and Pugh 2009, Hentschel 2007) on the modeled dimensionless Shields stress and the particle Reynolds number. A design minimizing the scale effect is a model for which the operating conditions are a similar location in the Extended Shields diagram (and more importantly in the same regime), as the prototype situation to be modelled (see e.g. Garcia 2017).

Some of the approaches used to scale transport processes in hydraulic models may choose to intentionally deviate from a strict similitude. For example, the approach of Zarn (1992) relies on a method to coarsen the model grain size distribution, ensuring a similitude on the shear velocity of the non-cohesive fraction only, and eliminating the cohesive fractions from the distribution. This type of approach ensures that the reduction of the shear velocity from prototype into model scale is consistent with the velocity scale, but requires a distortion of the hydrograph time scale to ensure a correct a similitude on the bed-load rate and thus deposition heights, slopes and water levels (Simonett and Weitbrecht 2011). The best scaling strategy is to be defined by the experimentalist based on the set of requirements that have to be met.

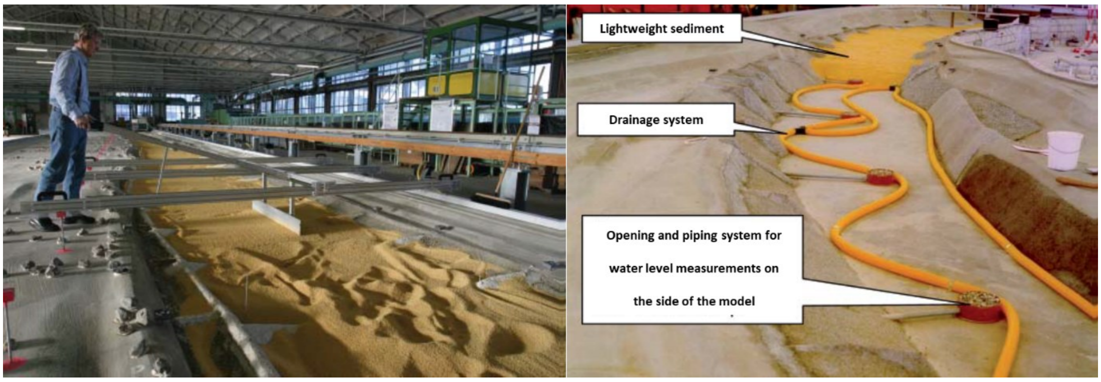

Figure 8 *- Techniques developed o the model of the Oder at Hohenwutzen at the Federal Waterways Engineering and Research Institute (BAW) in Germany to level the sediments between two tests, and implementation of the drainage and water level measurement systems as reported by Hentschel (2007).*

Model calibration and experimental procedure

For all type of hydraulic investigations in scaled models, it is a well-accepted condition that "the model [can] only be declared fit for predictive use when it has successfully reproduced […] past evolutions" (Migniot el al. 1975). Driven by this idea, the experimentalist must aim at reproducing some well documented condition for which hydraulic and morphodynamic measurements are available. A model operates in similarity with the prototype only if the dynamic (e.g. water levels, flow velocities, flow directions) and morphological (e.g. bed form type shape and size) similarities can be quantified (scale effects neglectable). In case of a deviation from the prototype, the sediment model used may require one of the parameters to be changed as sediment grain size and densities are directly influencing the hydraulic roughness, the initiation of motion, and the bed form development. The best sediment model material can be defined using the SVP regime diagram as described previously.

3.2. COASTAL ENVIRONMENT

3.2.1. Short wave models: Shoreline profile evolution and cross shore transport

Objectives

Beaches are a vital element of coastal systems, and a detailed insight into the morphodynamics processes and transient dynamics can be gained from scaled beach profile experiments (e.g. Grasso et al. 2009). Developing such knowledge is necessary to understand the role of Climate Change effects, such as the modification of storm characteristics, on the modification of cross shore transport (e.g. Scott et al. 2016). Even though cross-shore sediment fluxes are usually a few orders of magnitude smaller than longshore transport, the cross-shore beach profile has a strong influence on long-shore velocity profiles and therefore on longshore sediment. The quantification of cross-shore transport has often been done through the characterization of the beach equilibrium profiles (e.g. Dean and Dalrymple 2001), but these processes are in reality transient events (e.g. Dette and Uliczka 1987, Grasso et al. 2009). Short wave models can also be designed to investigate the links between cross-shore and longshore processes (e.g. Silva et al. 2011), and between cross-shore and scour processes (e.g. Hughes and Fowler 1990, Wang et al. 2013)

Facilities and instrumentation

For most of the short wave scaled models of beach profile evolution, the main goal is the quantification of the transport processes in the cross-shore direction, i.e. that the experimental design can be restricted to a 2D scaled beach model in wave flumes (e.g. Kamphuis 1974, Hughes 1993), but some 3D models can be used to investigate the interaction of this cross-shore transport with coastal structures (e.g. Silva et al. 2011). The size of the wave flume available (and thus of the wave height that can be generated) together with the characteristics of the sediment material, are the main factor constrains in the design of the scaled experiment. The instrumentation associated with such facilities should incorporate wave gages, topography measurement system (laser scanners of photogrammetry approaches), acoustic sensors for velocimetry and/or sediment concentration measurements, and potentially fast imagery techniques, pressure sensors (see e.g. Aberle et al. 2017). In cases where short wave models should address 3D effects such as the links between cross-shore and longshore transport, or the interaction with coastal structures, large wave basin with a control of the wave orientation and currents are required (see e.g. Silva 2011, Hughes and Fowler 1990).

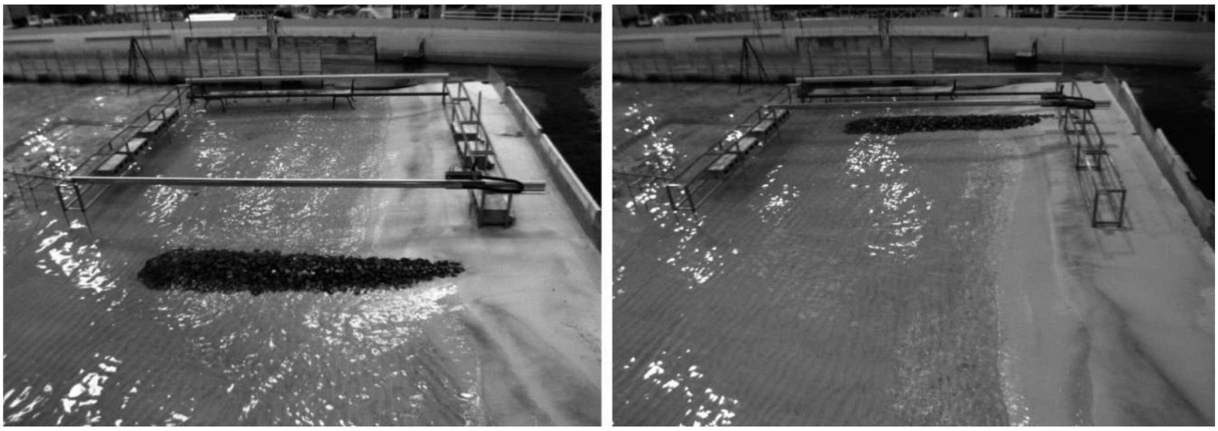

Figure 9 *- View of the 3D short-wave model used by Silva et al. (2011) to investigate the profile evolution and cross shore transport in presence of a groin and long shore transport. Courtesy Francisco Taveira Pinto (Silva et al. 2011).*

Scaling considerations

The different aspects of scaling nearshore morphodynamics in hydraulic models have been discussed in detail in the Section 2 (see also e.g. van Rjin et al. 2011). The successful design of the scaled experiment relies on the good understanding of the dominating transport mode in the prototype situation. Short wave models are mostly aimed at scaling prototype situations were wave shoaling, breaking and ultimately run-up on the beachfront play simultaneously an important role into the transport processes. In this case, both transport modes (i.e. bed load and suspended load), and their balance should be, if not in similitude, in similarity (same transport regime, see also the discussions in section 3.1.2) with the prototype situation (e.g. Grasso et al 2009, Silva et al. 2011). Thus, in addition to the preserving the similarity in Froude and Shields, short wave models should ensure that the fall trajectory of re-suspended model sediments is geometrically similar to the prototype trajectory, and fall with a time proportional to the prototype fall time. This is achieved by preserving the similarity in the settling velocity parameter according to Dean (1985)'s number, but preferably the Rouse (1939)'s number whose formulation is more general, see e.g. Nielsen (1992), Nezu and Nakagawa (1993), which is only feasible in an undistorted model.

Because of the need to preserve the similitude for these three parameters (Dean and Dalrymple, 2001), short wave morphodynamic scaled models often requires fairly large facilities (Hughes, 1993), and are operating best with geometric scales ratios not exceeding 1:10 to 1:15 (e.g. Hughes and Fowler 1990, Ranieri 1994, Grasso et al. 2009).

Model calibration and experimental procedure

Following descriptions presented by Henriquez et al. (2008), the hydraulic conditions to be applied on the scaled model are first estimated by applying the Froude similitude on the prototype conditions, followed by an assessment of the compliance with the Shields and Rouse similitudes. It may happen that the similitude criteria applied to the wave period cannot be obtained due to limitations of the wave maker and the wave flume. In such a case, the wave period in the model may be modulated so that it fits the facility capabilities, as long as the potential scale effects on Shields and Rouse are negligible.

In the case of an experimental design involving the use of lightweight material, the mobilization of the sediment should be tested beforehand, as some undesired effect such as exaggerated mobilization, aggregation, and capillarity effects might be triggered due to the shape and electrostatic properties the artificial material (see e.g. Petruzzelli et al. 2013). The general morphological response of the material should then evaluated by comparing the final beach profiles in models and prototype, as well as by analyzing the evolution of the sediments mobility rates, the shoreline positions and the seaward beach profile slopes (see e.g. Grasso et al. 2009).

3.2.2. Combined long and short wave models: Dynamics of coastal systems

Objectives

As for the large scale river and tidal morphologic investigations, the necessity to implement coastal models covering larger spatial scales is driven by the need to predict complex morphological developments under multiple hydrodynamic forcings, such as a variable wave climate, tides and surges and longshore currents (e.g. Hughes 1993). Until the recent development of numerical simulation capabilities, large 3D coastal models were the only tool available to understand and predict the long-term impacts of engineered hard structures on coastal transport processes. Nowadays, the use of such models is still occasionally required in complement to numerical investigation to characterize the dynamics of complex systems (e.g. Bollaert et al. 2017). Following the classic scaling procedures, coastal physical models operate with large time accelerations, as for example in the work from Anquetin et al. (2006) on a sand spit evolution, where the sedimentological timescale was found to be around 1:7500 (100 years in 5 days). These type of physical modelling approaches is thus, in principle, very suited to address potential long-term effects due to Climate Change on our coastal systems.

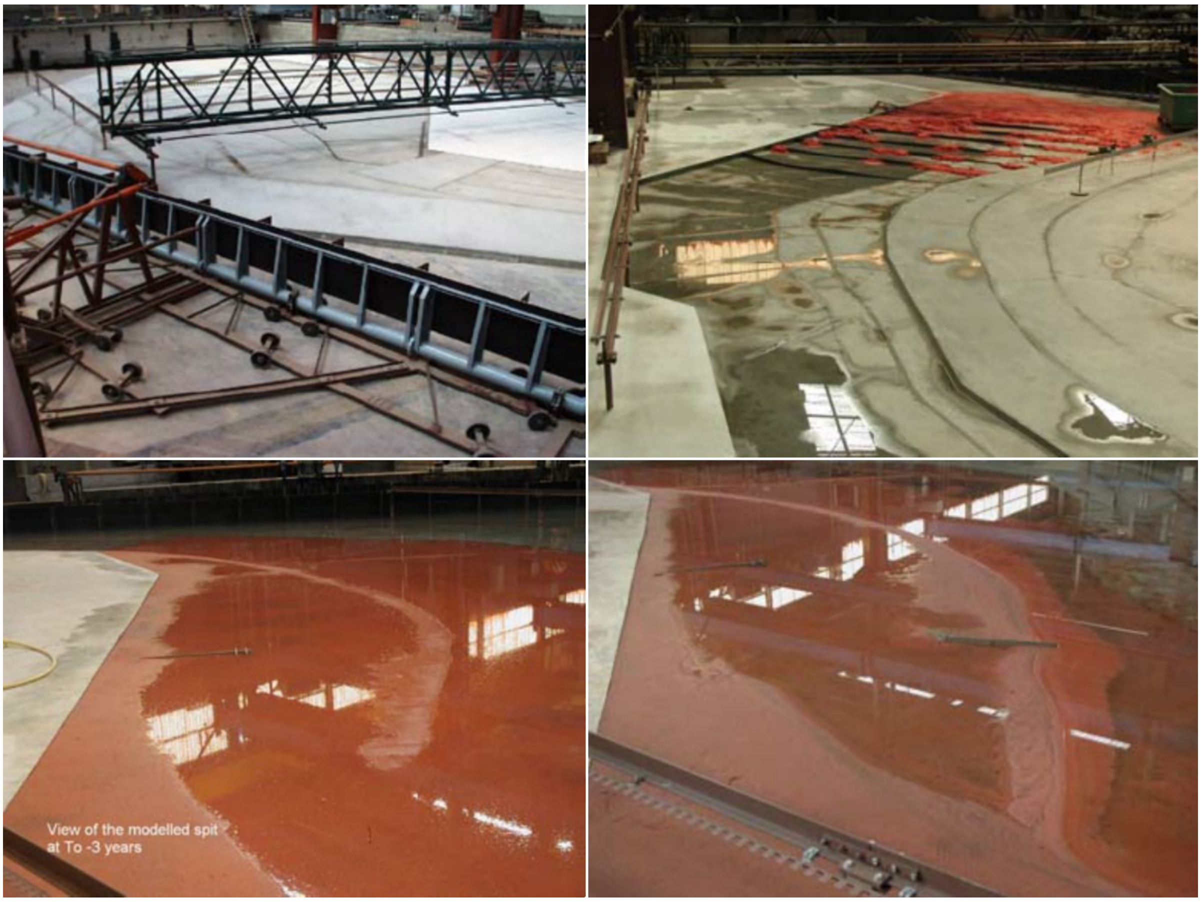

Figure 10 *- Wave maker, scale model construction, and model operation without/with coastal structures on the Kalaat Landalous sandy spit, Tunisia - courtesy Artelia (see Anquetin et al. 2006)*

Facilities and instrumentation

The know-how required to set-up these large scale physical models was developed from the 1940s onwards in several laboratories, as for example the *Laboratoire d'Hydraulique de France*, for which Migniot et al. (1975) and Migniot (1979) summarized the initial 30 years of knowledge development. Although published more than 40 years ago, this expertise is still in use today to successfully conduct morphodynamic investigations of estuarine environment (e.g. Bollaert et al. 2017) or scaled models of coastline evolution (e.g. Anquetin et al. 2006).

The facilities susceptible to host such model should be equipped with a large basin and a workshop equipped for scaled model construction. The facilities should include directional irregular wave maker capabilities, pumps for tide and current generation, and the possibility to use natural and/or preferably lightweight sediments. In some cases, a feeding system for sediment mixture might need to be considered, as for meandering and braided river experiments (section 3.1.1). For an optimum operation of the model, the wave, tide and current generation system, as well as the sediment feeding system should be remotely operated and synchronized, according to the time scales defined during the design of the model. The instrumentation required to monitor the morphodynamic evolution include the classic scanning technology and photogrammetry, and the hydrodynamic processes should be documented with wave gages, flow meter (for bulk current measurements) and potentially acoustic or large-scale image velocimetry measurements (see e.g. Aberle et al. 2017).

Scaling considerations

Coastal models are based on the scaling principle developed in Section 2, and as developed previously, if some scaling criteria have to be relaxed, the similarity between the model and the prototype is kept by operating the model in the same regime as the prototype for the process considered. Thus the initial design of coastal models fulfill the hydraulic similitude according to the Froude-criterion, the similarity in the hydraulic regime considering the Reynolds and the particle Reynolds numbers and the similitude on the Shields number to ensure the correct representation of the dominating transport regime (Migniot 1979). These criteria impose specific sediment characteristics, but to finalize the choice of the model sediment (typically a lightweight material), specific material tests have to be performed to ensure the same sediment trajectories in the modeled and prototype situation under wave action, this step ensuring the similitude on the wave hydraulic roughness (Migniot et al. 1979, Anquetin et al. 2006).

Once the scale ratios for the geometry and the waves, and the sediment material is defined, sedimentological time scale can be derived for the longshore sediment transport (see section 2.1 and 2.2, and Migniot 1975, Anquetin et al. 2006). In order to have an undistorted interaction between the longshore transport and other tidal or steady current, the tide and current intensities should be distorted (in regard to the original Froude similitude) so that the time scales associated with each transport process matches the sedimentological time scale derived for the longshore transport (Migniot et al. 1975, Migniot 1979).

For the case of representing large scaled models of coastal systems, Migniot et al. (1975) underline especially the importance of using irregular waves, the proper location of the breaker zones (preventing exaggerated wave heights being used in the model), and the sequencing the wave condition according to the sedimentological time-scale. The use of any other time scale (hydraulic time scale, or empirically amplified duration to match resulting morphological features) for deriving the scaled storm duration would lead to erroneous results.

Even through all these conditions cannot be fulfilled at the same time, Migniot et al. (1975) argued that in practice they do not contradict each other too much, and that successful compromises can almost always be found. Two recent examples are the studies of Anquetin et al. (2006) and Bollaert et al. (2017).

Model calibration and experimental procedure

In comparison to estuarine environments, Migniot (1979) identifies that for morphological investigations around coastal hard structure, it is necessary to consider a coastline of 4-6 km and to extend the investigation all the way to the -20m iso depth (corresponding to deep-water conditions for most storm waves see e.g. Fredsøe and Deigaard 1992). As discussed above, in order to keep a similarity in the particle trajectory, some distortion between the vertical and horizontal scales are to be expected. On the other hand, the investigations focusing on coastal structure stability (involving scour processes) requires a smaller spatial coverage of the prototype situation, but a higher precision about the details of the structure, and the geometrical scaling ratio are typically between 1/20 and 1/70 without distortion.

Due to the need to need to adjust the scaling ratios applied to the tide, for example, and the need to reproduce the position of the breakers accurately in the model (by adjusting the wave heights in the model), it is well-known that these models requires a dose of subjective judgment from the experimentalist, to conduct the trial and error process that will conduct to the successful scaling of the model (e.g. Le Mehaute 1976, Kamphuis 1985, Hughes, 1993). However, as pointed out by Migniot el al. (1975): “the model [can] only be declared fit for predictive use when it has successfully reproduced […] past evolutions”.

3.3. TIDAL AND ESTUARINE ENVIRONMENT

3.3.1. Long wave models with mobile bed

Objectives

Modelling flow and morphodynamic processes in tidal rivers and estuaries is required for the investigation of large scale flow patterns (e.g., Higuchi et al. 1978, Giese 1987), the long-term morphological development of lagoons and estuaries, its effect on navigation (e.g., Vollmers and Giese 1972, Parthiot 1981), the impact of engineering structures (e.g., Brammer et al. 2014), or the siltation of harbors (e.g. Kocyigit et al. 2005). However, modelling flow and morphodynamic processes in tidal river areas and estuaries is challenging as, compared to fluvial environments, the level of complexity of the interacting physical processes is increased due to variable boundary conditions resulting from the changing water levels during the tidal cycle, tidal currents, potential wave action, and the typically fine sediment composition in such environments. Moreover, estuaries and river mouths are characterized by large spatial scales imposing an additional challenging boundary condition for the construction of physical scale models.

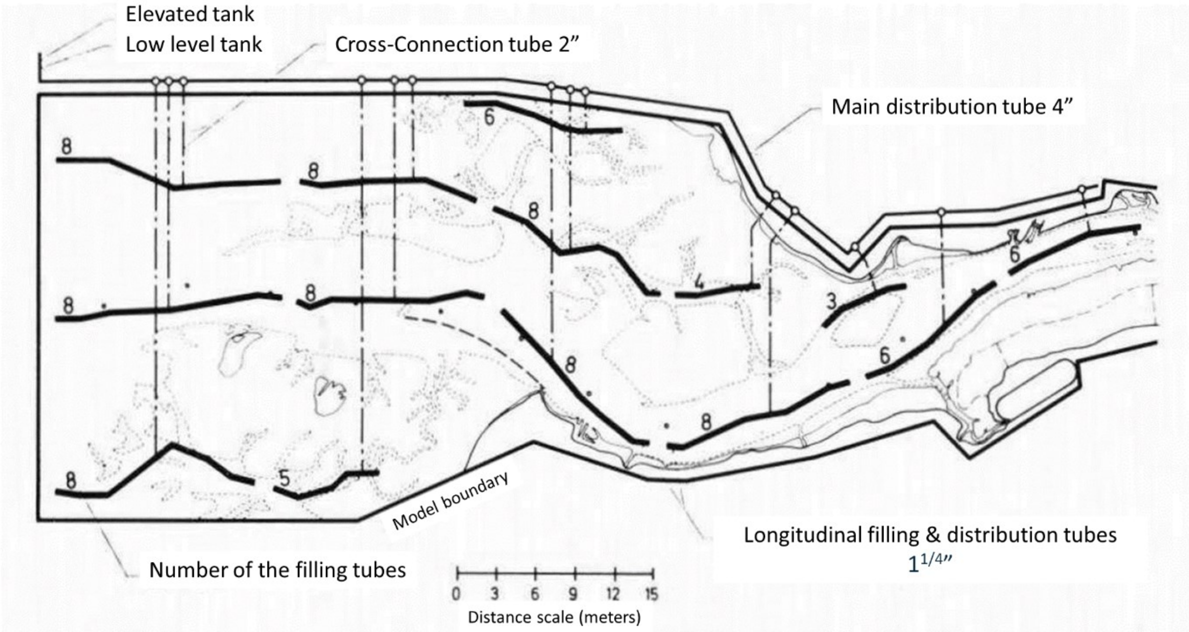

Figure 11: Plan view (top view) of the filling and drainage system of the Elbe estuarine model reported by Vollmers and Giese (1972), redrawn from Vollmers and Giese (1973)

Facilities and instrumentation

Tidal and estuarine models have been realized in many different hydraulic laboratories around the globe (see above). Experiences from five large tidal models aiming at the investigation of expected morphological changes in connection with the maintenance and enlargement of navigation channels in Germany have been reported by Giese et al. (1975). Although this publication is more than 40 years old, it contains valuable information on the construction and operation of tidal models and it serves hence as a basis for the following considerations.

In general, movable bed models should be operated in heatable indoor facilities to avoid larger changes in water temperature which in turn can affect the fluid viscosity and hence the Reynolds number. Moreover, tidal models representing specific rivers should comprise the whole tidal estuary so that the results will not be affected by artificially introduced model geometry. This in turn means that particularly tidal models with movable beds are characterized by large spatial dimensions. For example, the Elbe-River Modell at the German Federal Waterways and Research Institute (BAW), which was approx. 30 m wide and 85 m long (covering about 170 km river length in prototype dimensions), was operated in a 40m x 112m wide and long laboratory (Vollmers and Giese 1972).

The operation of such large models with movable bed requires a sophisticated filling and drainage system so that the so that the movable bed morphology will not be affected during filling and draining. It is also desirable to have an automated traversing system with which each point of the model can be reached for measurements without having to step on the model. Dependent on the question under investigation, state-of-the-art instrumentation may be used for the control and measurement of water levels, flow velocities, sediment transport rates, and morphological parameters (see Muste et al. 2017 for an overview).

Scaling considerations

Tidal models are scaled according to the scaling laws presented in Section 2. However, the design of tidal models with a movable bed is sophisticated as several similitude criteria need to be considered. Specifically, hydraulic similitude is required for the flow in the river and for maritime conditions (taking into account waves, tidal currents, breaking waves) along with similitude of sediment transport, erosion and deposition in the fluvio-marine area (e.g., Parthiot 1981).

As pointed out in Section 2, hydrodynamic time scales differ from morphological time scales, and hence tidal models with movable bed are prone to scale effects. One scale effect becomes obvious from the nature of oscillatory tidal flows. Flow parameters are typically scaled based on Froude-similarity assuming that viscous effects are negligible, i.e. that the flow is fully turbulent. While this may be true for a large portion of the tidal cycle, there will, however, be times and specific locations in the model where the flow is no longer fully turbulent. Thus, designing the model a threshold value for the velocity may be identified based on the critical Reynolds number to determine the critical velocity for turbulent flow, which will be helpful to assess corresponding scale effects (e.g. Harten 1970)

Tidal scale models with a movable bed are typically distorted due to two reasons. The first one is related to the large spatial scales of estuaries so that different horizontal and vertical length scales are needed to adequately model flow characteristics and to be able to measure the water levels accurately. The second reason is associated with the similarity of sediment transport conditions, as the similarity in both Fr_* and Re_* is desirable for models addressing specific estuaries. As highlighted in Section 2, this calls for the use of materials with a different density and the distortion of the model (see also Parthiot 1981). The distortion is chosen based on experience, and Migniot (1979) recommends for such scaled models to kept the distortion close to the cubic root of the horizontal scale, in order to keep the trajectory of the suspended sediment unchanged.

The duration of the tidal cycle is governed by the hydraulic time scale, and the tidal range via the vertical length scale (Dorer 1984). In case riverine hydrographs need to be considered, they should be scaled via the sedimentological timescale (Dorer 1984). However, for many cases, the river discharge may be considered negligible compared to discharge associated with the flood and ebb tides. Density currents and Coriolis acceleration are hardly to realize in distorted models with movable beds (Vollmers and Giese 1972).

Figure 12 *- Physical scale model of the Rhone delta in Lake Geneva-courtesy Artelia (see Bollaert et al. 2017)*

Model calibration and experimental procedure

If possible, tidal models with a movable bed should be calibrated and validated. Such a verification can be achieved in two steps reflecting the dynamical and morphological similarity.

The dynamic (flow) similarity can be investigated on the basis of the comparison of water levels, flow velocities, flow directions, and flood and ebb durations between the model and prototype. Such tests may be carried out with a fixed bed to ease the operation (e.g., Vollmers and Giese 1972), and the tidal waves can be simulated by automatically operating special gates at the model inflow section. However, care needs to be taken regarding the roughness in the model due to model distortion, but also due to differences in form roughness associated with bed forms (see Yalin 1973 for more details). In fact, if the model is too smooth, the water volume flowing into the estuary during a tidal cycle will be overestimated, and if the model is too rough, it will be underestimated. Note that the differences in roughness may be compensated by readjusting the duration of a tidal cycle in the model, as the water volume entering the estuary may be controlled in this way.

The morphological similarity may be investigated by comparing observed natural bed changes with the outcomes of model tests, which can be achieved by modelling historical time series. As the time scale for morphological changes can only be determined empirically, such tests also allow to refine further experimental parameters such as the tide period to achieve morphological similarity (Vollmers and Giese 1972). The tidal cycles may be reproduced by sinusoidal curves representing mean tides but may be more accurately reproduced taking into account a month's tide cycle representing also neap and spring tides. Note also that, dependent on the research question, tidal currents must also be reproduced.

3.3.2. Deltas and bays

Objectives

Following the "Coastal models" (section 3.2.2), characterized by a short and long wave hydrodynamic forcings, and the "Estuarine models" (section 3.3.1), characterized by a long wave forcing combined with unidirectional currents, the models aiming to represent the morphodynamic processes in shallow water bays and deltas have to take into account the combination of the three hydrodynamic forcings. These models are more difficult to design as they rely on the know-how of the experimentalists to find the best combination of distortion to apply on to the different processes to keep the model in similarity with the prototype. Two successful examples from Sogreah/Atelia laboratories (Viguier et al. 2002, Bollaert et al. 2017) are used here as an example of the different aspects to be taken care of. Viguier et al. (2002) report 7 years of experimental and numerical investigations of the morphodynamic response of the inner bay of Mont-Saint-Michel to some restoration project, while Bollaert et al. (2017) provides a recent example of a delta restoration project based on the combined use of numerical and physical scaled model investigations.

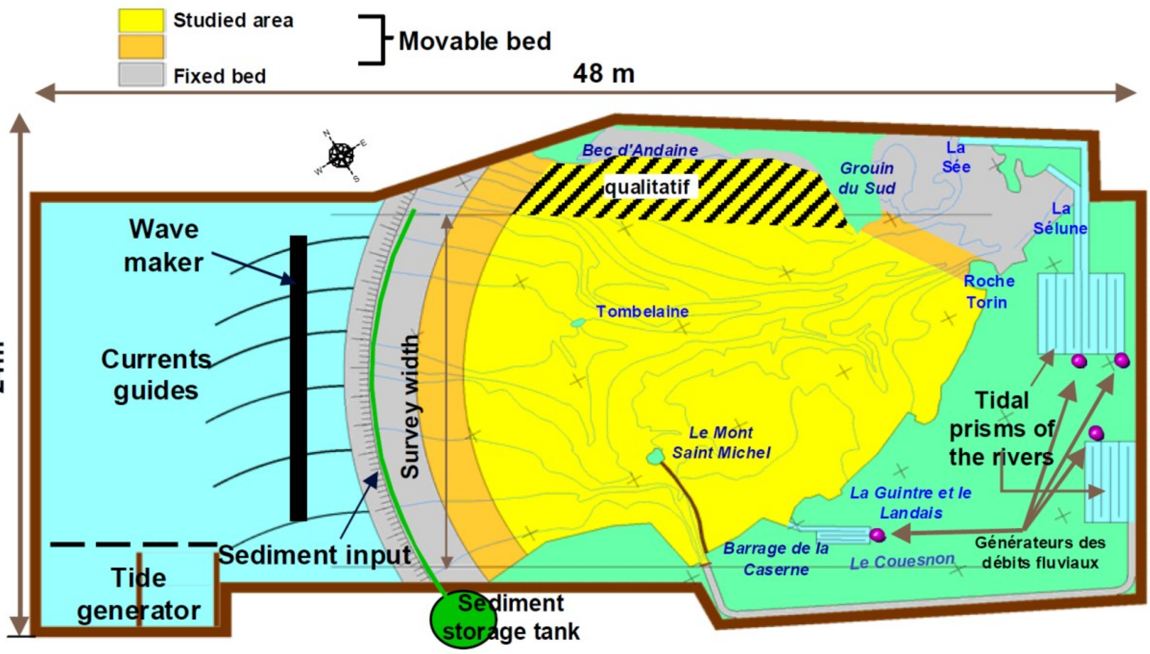

Figure 13 - *Plan view of the set-up of the scaled model of the Mont St Michel's inner bay (Viguier et al. 2002)*

Facilities and instrumentation

Both studies involved a combination of physical scale models and numerical models. Given the validation capability of the various models, this approach ensured that the predictions made by the combined modelling approaches are reliable. In combination to the "numerical facilities", the experimental facilities required to operate such type of model is must have a combination of the equipment mentioned in the previous sections, i.e. a large coastal basin, some additional flumes for side studies on the sediment material and/or of some specific scaled hydraulic structures (Viguier et al. 2002), a tide generator that reproduces the variations in water levels and discharges, wave generators, pumps to reproduce the river discharges and a sediment feeder system to simulate inflow from the offshore and the rivers. The instrumentation must include capacitive probes for measuring water levels, ultrasonic system mounted on a movable beam for performing bottom level surveys on a grid or an equivalent photogrammetric system.

Figure 14: Scaled morphodynamic model of the Mont St Michel inner bay at low tide - Sogreah, Grenoble, France, Nov.28 1997. (Photo by Nicolas LE CORRE/Gamma-Rapho via Getty Images)

Scaling considerations

The design of the scaling framework does not differ from what has been presented before and is essentially the same as for the coastal models (section 3.2.2), following the Froude and Shields similitude. The model is then distorted to ensure that the hydrodynamic time scale of the waves corresponds to the hydrodynamic time scale of the tides/currents and hydrographs of the inflowing rivers (see sections 2.2 and 2.3). Respecting the Shields similitude, these models are typically designed with a bimodal lightweight sediment material. In the case of the scaled test of the Rhône River delta, Bollaert et al. (2017) used PMMA (perspex, 1.18 kg/m^3) transparent thermoplastic granulates, with diameters of 0.2-1.3 mm representing fine bed material on the prototype (sand, small gravel), and

PVC granulates (density of 1.44 kg/m^3) with diameters ranging between 1.0 and 2.2 mm, representing coarse bed material on the prototype (larger gravel, cobbles).

Model calibration and experimental procedure

The particularity of including the use of numerical models into the investigation of scaled morphodynamic processes is that these models can be used to compare the results obtained and adjust the calibration of the model. Thus, the use of numerical simulations also provide an estimation of the potential scale effects triggered (Bollaert et al. 2017). The calibration of the model should also go through the reproduction of a known hydraulic and morphodynamic event before being used for predictive purposes (e.g. Hughes 1993). Thus, all the tide curves, currents and wave climate should be reproduced in similitude in the model, by adjusting the hydraulic roughness of the model if necessary (hydraulic calibration). In the case of the Mont-Saint-Michel scaled test, Viguier et al. (2002) calibrated the model from a sedimentological point of view by examining the behavior of the movable materials and the sensitivity of the bed to the different hydrodynamic forcings, and to adjusting the quantity of sediment inflow at the entrance to the model. A schematic annual cycle of forcings was then finalized, including mean and spring tides, three representative river discharges and three representative wave conditions. A multiple-year river discharge cycle was also introduced, comprising three representative levels. By monitoring bed changes over several cycles, Viguier et al. (2002) concluded on a sedimentological time scale of 1/28, in comparison to a hydraulic time scale of 1/8. The sedimentological times were thus speeded up by a factor of 3.5, corresponding to the schematization chosen for the forcing (elimination of neap tides and calm periods). The validation of the model was then done by quantifying the general changes in the inner bay (location of deposits, sediment balance), quantifying the meandering of the rivers, the progression of the shoreline and the local bed evolution around the Mount at floods and low-flow periods (Viguier et al. 2002).

4. CONCLUSIONS AND OUTLOOK

This deliverable reviewed the current knowledge and know-how regarding the scaling of time-dependent morphodynamic processes in physical laboratory studies to address the Climate Change related evolution of different kinds of aquatic environments ranging from fluvial to coastal systems. Based on the review, protocols were derived to aid with the design and the determination of time-scales of physical models where sediment transport processes and the morphodynamic evolution of aquatic environments are in the focus. The design of such scale models is challenging as several scaling criteria would have to be fulfilled simultaneously to ensure a perfect similitude with the prototype situation. For example, the relevant scaling criteria for similitude in hydraulic processes is governed by the Froude-number, and sediment transport processes depend on a number of other scaling criteria such as the Shields and Rouse numbers, which in turn depend on the turbulent flow field. As a consequence it is, except for a 1:1 replica of the prototype situation, not possible to fulfil the similarity of all scaling criteria at the same time and 'relaxation' (deviations) regarding criteria which are not considered as the most significant ones needs to be accepted in modelling studies.

These issues were highlighted in Sections 1 and 2. Section 1 provided the relevant background for the experimental modelling framework and introduced the concept of similitude in physical scale models, in general, and for morphodynamic scale models, in particular, by introducing different model types which are characterized by a varying degree of similarity. Section 2 focused first on the relevant scaling laws in more detail, and these considerations were then used to define different morphological model types regarding transport modes as well as prototype and experimental boundary conditions. Section 2.2 highlighted the difficulties regarding the determination of morphological time scales in movable-bed models, which is often subjective. In fact, the morphological time-scale cannot be freely chosen as it is defined by the chosen scales of other model parameters and depends on which scaling criteria are intentionally relaxed.

Moreover, it was highlighted that there is the need to distinguish between different time scales for different morphological processes such as individual grain movement and the evolution of the bed surface in the vertical and horizontal directions, respectively. Thus, the whole art of designing a hydraulic scale model is to in introduce enough relaxation on the scaling criteria which cannot be fulfilled easily thereby ensuring a similar regime in the model and prototype, i.e. keeping this relaxation small enough to avoid any significant scale effect. Such aspects were discussed in Section 2.3 highlighting that the main approach to successfully design a scaled morphodynamic experiment should be based on the application of the Froude similitude, i.e. the similarity in the flow regime, and the similarity in the regime of the dominating transport mode, based on the identification of the prototype and modelled situation in the (modified) Shields diagram.

Following these theoretical considerations, practical aspects associated with the design of scaled morphodynamic models were presented in Section 3. In this section, protocols were presented which are grouped into three different categories depending on the dominating hydrodynamic processes (short wave models, long wave models and fluvial models). Although different aspects of such scale models can be considered as well established in experimental hydraulics, some aspects of model design still requires more advanced considerations such as the scaling of complex hydrographs and coupling of hydrographs or varying hydraulic boundary conditions with morphological development (Section 2.3.3), the use of specific lightweight sediment mixture (bimodal sediment distribution, non-cohesive nano-sediments, Section 2.3.2) to scale simultaneously different transport modes, and to some extent, the quantification of scaled processes in models relying on self-similarity.

It was also partly indicated in this report that the combination of physical scale models with numerical simulations can offer additional opportunities to address Climate Change effects. As highlighted by van Os et al. (2004), the focus in hydraulic research has been shifting from an emphasis on experimental scale modelling to an emphasis on numerical modelling, which is also the case for morphodynamic investigations. Similarly, van Os et al. (2004) noted that the amount of field experiments also decreased considerably, due to the extensive costs involved. However, numerical models, like any other modelling activity, need to be validated against some datasets obtained independently. Thus, experimental laboratory research is still needed in hydraulics in general, and morphodynamic processes in particular, to develop investigations in synergy with numerical investigations. In fact, scaled model tests offer the possibility to scale down a combination of processes which are still not completely understood and difficult to model in a satisfactory manner with numerical models. At the same time, it needs to emphasized, that the size and complexity that is achievable in a physical model is limited by the available space and skills in a laboratory as well as the budget to conduct the experimental investigation. Nonetheless, such combined methodologies are needed to tackle certain scientific problems, and often lead to innovation and new knowledge. Some recent example are provided by Viguier et al. (2002) and Bollaert et al. (2017), who demonstrated that numerical and experimental investigations of scaled morphodynamics can compensate for each other's weaknesses, allowing for a reduced uncertainty in the prediction of large morphological changes, over larger time scales.

This type of combined approach is also a common practice in coastal research to study and predict cross shore profile evolution and coastline changes (e.g., Silva et al. 2011). Even if numerical models might usually be preferred to tackle such issues as they also offer the possibility to artificially accelerate the morphological development simulated (e.g. Ranasinghe et al 2011), they do not always live up to expectations and require carful comparison with experimental data (Viguier et al. 2002). Thus, the results from this deliverable showed that well designed movable bed models are still and will further be a valuable tool for studying complex morphodynamic processes and features across a wide range of spatial and temporal scales for different river channel morphologies and coastal environments.

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