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5.3. Modelling Geomorphic Systems: Scaled Physical Models

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ABSTRACT: Physical models are scaled representations of a full-scale physical system which can be applied to inform our understanding of geomorphic process-form interactions. Physical and experimental modelling has been used extensively and has been proven to be of critical importance to the geomorphological user. Physical models can be loosely divided into a number of categories: 1:1 replica models; Froude-scaled models; distorted scale models; and analogue 'similarity of process' models. The choice of physical model type is dependent on the researcher's aims and objectives. Advantages include the ability to: *(i)* isolate variables within a controlled laboratory setting; *(ii)* incorporate actual physical processes rather than simplifications; *(iii)* study infrequent or hypothetical scenarios, and; *(iv)* extract qualitative and quantitative data. Users of physical models must be cautious of the potential shortcomings of using a physical model, such as scale and laboratory effects. Despite these shortcomings, physical models provide a useful technique to observe, visualise and measure process-form interactions. This permits an improved understanding of complex physical relationships which other modelling methodologies may not be able to simulate.

KEYWORDS: Physical modelling, experimental methods, laboratory techniques, scale, similitude.

Introduction

Physical models are scaled representations of a physical system (Hughes, 1993). The use of physical models is well established, offering an alternative or complementary approach to what can be simulated accurately using numerical models or observed and measured through field-based investigations (Peakall *et al.,* 1996; Frostick *et al.,* 2011). Physical models have been applied to understand, assess and inform stakeholder decisions in a number of disciplines, ranging from the biological and environmental sciences to aeronautical and infrastructural engineering. Physical models provide a reputable research technique allowing the reproduction of complex physical phenomena and an understanding of process interactions to be generated in a visual and informative manner (Sutherland and Barfuss, 2011).

Physical modelling has also been used extensively within the field of geomorphology (Peakall *et al.,* 1996) including studies of alluvial fan dynamics (e.g. Clarke *et al.*, 2010; see Figure 1), tsunami waves, jökulhaups or catastrophic dam failure inundation (e.g. Rushmer, 2007; Soares-Frazáo and Zech, 2008; Rossetto *et al.,* 2011), sediment and bedform dynamics (e.g. Guy *et al.,* 1966; Allen, 1982; Southard and Boguchwal, 1990; Warburton and Davies, 1998; Madej *et al.,* 2009) and erosion plot and rill development studies (e.g. Bryan and Poesen, 1989). These studies have emphasised the importance of physical models as a method of visualising, interpreting, observing and measuring physical processes, something which is potentially problematic in a model's full-scale counterpart (Kamphuis, 1991). This permits intrinsic factors to be separated from extrinsic factors (Clarke *et al.*, 2010), allowing the isolation of variables within a controlled laboratory environment. Consequently, physical models provide a number of advantages to the geomorphological user, which will be outlined later.

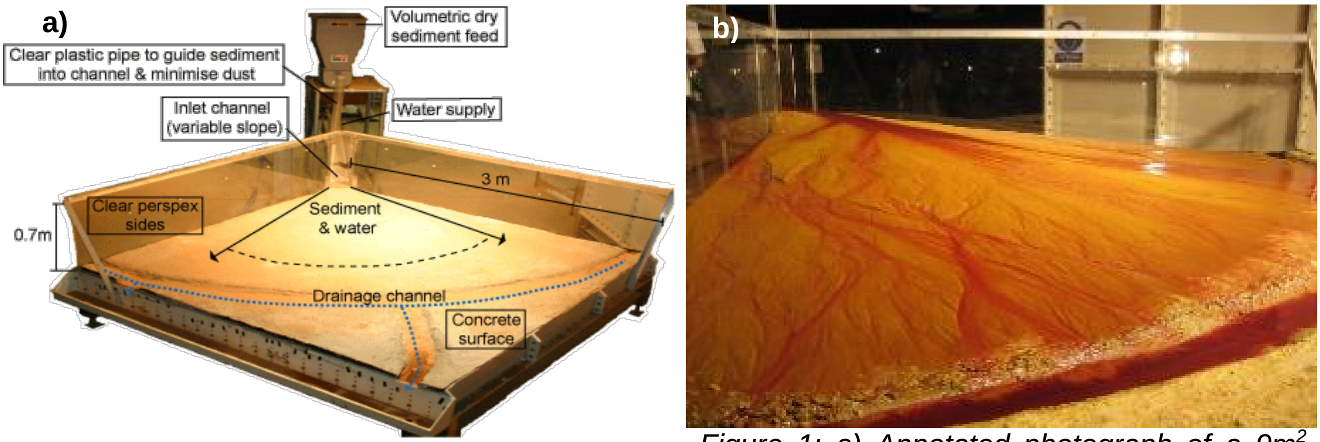

Figure 1: a) Annotated photograph of a 9m^2 experimental alluvial fan at the Sediment Research Facility, University of Exeter, b) experimental alluvial fan with dyed red water to assist in visualisation of surface flow paths. Source: Clarke (2013).

This paper presents: *(i)* a discussion on physical model typology; *(ii)* a brief introduction to the key physical modelling principles; *(iii)* an overview of the applications and importance of physical models for the geomorphological user, as well as *(iv)* a critical assessment of the strengths and weaknesses of using physical models in geomorphology.

Model Typology

The choice of physical model type is dependent on various factors including the project objectives and rationale, as well as cost and space limitations (Frostick *et al.,* 2011). Additionally, the purpose of the physical model will control the type of model that is used, with models generally being constructed for: *(i)* research purposes; *(ii)* communication and education purposes and/or *(iii)* informing decisions or providing foresight (Maynord, 2006; see Table 1).

Two types of boundary condition have been recognised within physical models: fixed-bed, where the model boundaries are non-erodible and no sediment transport can occur; and, moveable-bed, where substrate is free to move within a constrained or non-constrained channel (Hughes, 1993; Peakall *et al.,* 1996; Waldron, 2008).

Table 1: Purposes or aims of physical models

Project aims	**Sub-discipline of geomorphology**	**Examples**
Research tools to study process-form interactions	Fluvial	Influence of in-channel/floodplain vegetation on river morphology (e.g. Gran and Paola, 2010)
	Fluvial	Investigations into alluvial fan dynamics and evolution (e.g. Clarke *et al.,* 2010)
	Hillslope	Investigations into hillslope-channel coupling processes (e.g. Michaelides and Wainwright, 2002)
	Glacial	Investigations into jökulhaups with different hydrograph shapes and their subsequent impacts (e.g. Rushmer, 2007)
	Aeolian / dryland	Wind-tunnel tests on aeolian transport of different sized sand grains under varying wind velocities (e.g. Dong *et al.,* 2003)
Education, demonstration and communication tools	Fluvial	Micro-model flume to communicate channel avulsion processes to the public, students or stakeholders
	Glacial	Glacier dynamics under changing climate experiments using PVC piping valley and viscous flow medium
Screening tools to seek alternative approaches / improve understanding	Fluvial	Use of physical models to inform understanding of the downstream and upstream impacts of channel impoundment or dam removal (e.g. Einhellig *et al.,* 2010)
	Fluvial	Process understanding of ice jams at river confluences (Ettema and Muste, 2001)

Physical models can be loosely divided into a number of categories, including: *(i)* scaled models; *(ii)* Froude number scaled models; *(iii)* distorted scale models; *(iv)* analogue models; and, *(v)* 1:1 replica models. Despite this classification scheme, some overlap may exist, for example, an analogue model may exhibit characteristics associated with all of the other categories.

Scaled models

Scaled physical models that are built and function at reduced scale (or enlarged scale in some cases) are an important type of physical model for examining and measuring processes which are difficult to observe in reality (Michaelides and Wainwright, 2013; see Figures 2 and 3). Scaled models allow geomorphological users to overcome the inherent obstacles associated with investigating physical systems (Hughes, 1993), such as the long spatiotemporal timescales involved and problems associated with working in a naturally variable environment. Scaled physical models conform to scale ratios, shown by Eq. 1:

$$N_x = \frac{X_p}{X_m} = \frac{Value\ of\ X\ in\ Prototype}{Value\ of\ X\ in\ Model} \qquad \text{(Eq. 1)}$$

where N_x is the actual-to-model scale ratio of parameter *x* (which may represent width, depth, length, grain size, time, diameter etc.), and where *p* and *m* represent the actual/original system and model, respectively. Thus, if a river reach has a length of 300 m in reality but this is scaled to 3 m under modelled conditions, the model length is said to be scaled by 1:100.

Scaling occurs in all physical models to varying extents, however, modellers must be cautious when downscaling a model too much from the real world system. Maynord (2006) evaluated a ‘micro-model’ river system (1:14,000 horizontal, 1:1,200 vertical scale; see Figure 3) with a river channel width as small as 4 cm. It was demonstrated that using large scaling factors resulted in models becoming incomparable to the hydrodynamic processes occurring in reality. For example, a river channel width of 560 m in reality cannot be represented as 4 cm width in a physical model due to the significantly different hydrodynamic processes occurring. Additionally, when scaling particle sizes, users must be cautious of cohesive forces becoming a dominant factor in the model while being absent or negligible in reality. This may result in ‘micro-model’ systems

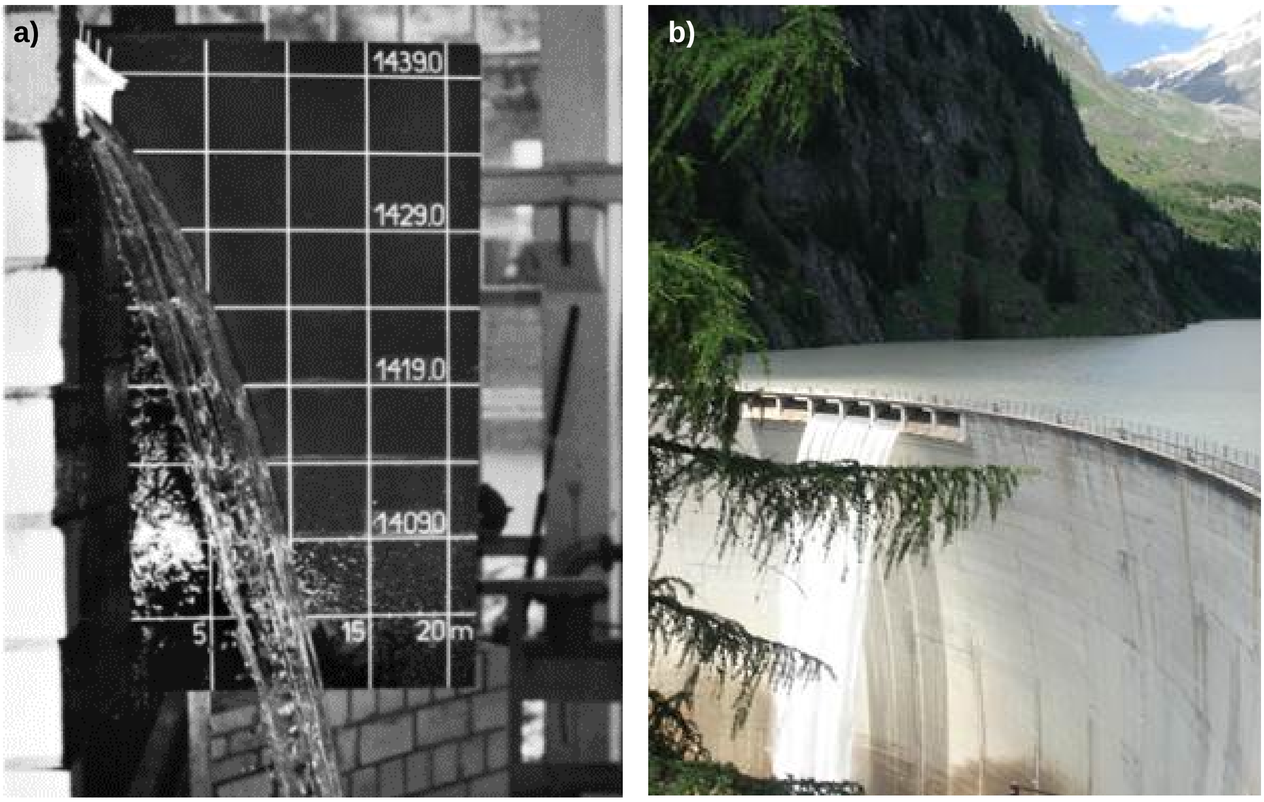

Figure 2: Overflow spillway of Gibidum Dam, Switzerland. a) 1:30 scaled physical hydraulic model, b) real-world, full scale photograph of Gibidum Dam, which the model is based on. Source: Heller (2011).

losing their predictive capabilities and becoming qualitative rather than quantitative. Whether this is disadvantageous or not depends on the researcher's aims; qualitative modelling may still be useful for demonstration, education and communication purposes, as well as a rapid, and visual screening tool to inform research direction (Maynord, 2006).

Figure 3: 'Fluvial geomorphology in a box'. Micro-model river system allowing the study of fluvial dynamics, similar to the one used by Maynord (2006). Source: http://www.EMriver.com.

Froude Number Scaled Models

A true scaled model requires perfect geometric, kinematic and dynamic similitude, something that cannot be achieved when using the same fluid as in the real world system due to equivalent gravitational and fluid motion forces. Therefore, one or more variables must be relaxed in order to achieve model-field similitude (Ashworth *et al.,* 1994; Heller, 2011; Michaelides and Wainwright, 2013). Froude number scaling can be applied, whereby the Reynolds number *(Re), a* dimensionless quantity used to quantify turbulence rate, is relaxed while correctly scaling the Froude number *(Fr)*, a measurement of different flow states, e.g. subcritical, critical and supercritical. If this was not done, experimental models involving water would have a significantly lower Reynolds number than their counterpart full-scale system, resulting in a lack of similarity between model and reality (Paola, 2000). Instead of having to reduce the viscosity of fluid or to build a 1:1 replica model, Froude number scaling allows a smaller-scale physical model involving fluid flow to produce similar characteristics to its real-world counterpart. For free surface flow, gravitational forces are dominant. Therefore, hydraulic similarity can be established by equating the ratio of gravitational forces to that of inertial forces (Waldron, 2008). Examples of the effectiveness of Froude number scaling include the work of Ashmore (1982, 1991, 1993) who classified the mechanisms of river braiding and controls on bar formation and related the internal generation of bedload pulses to channel avulsion (see Figure 4). A Froude number scaled model was applied to produce compariable results within the physical model to that of the field counterpart. In Ashmore's study, the use of a Froude number scaled model allowed an understanding of braided channel morphology, flow characteristics and bedload movement where field measurements and observations were challenging due to the large spatio-temporal scales involved.

Distorted Scale Models

Scaled physical models adhere to dimensional scaling of all axes to the same ratio, whereby all attributes within the model are geometrically similar to the original system. However, it is also common for scaled physical models to be geometrically distorted and skewed. Geometrically distorted scaled models, where the scaling of a model's vertical to horizontal scaling ratio differs, are especially important to the geomorphological user when large spatial scales that cannot correctly be replicated under laboratory conditions or fine sediment sizes are involved (Peakall *et al.,* 1996). Distorted scale models enable small physical models to be built or large physical systems to be modelled. Additionally, distorted scale models may be applied to avoid problem of water or fluids behaving viscid at rigid boundaries. Distorted scale model experiments may involve variables such as width, length, slope and/or grain size/density adhering to differing scaling factors. For example, McCollum (1988) used a distorted flume to understand sediment transport dynamics along a 7km river reach which experienced significant rates of sedimentation. Because of the impracticability of reproducing a 7 km flume under laboratory conditions and because conducting field studies would not allow experimental control over system variables (e.g. slope and/or discharge), a distorted flume with horizontal and vertical scaling ratios of 1:120 and 1:80 respectively was used. Furthermore, crushed coal was used to avoid unrealistic cohesion within the scaled model to ensure the distorted scale model produced a similar response to the field system. The San Francisco Bay Model, a working hydraulic model of the San Francisco Bay and Sacramento-San Joaquin River Delta system is also an example of a geometrically skewed physical model, with horizontal and vertical scaling being 1:1,000 and 1:100, respectively. Furthermore, the model operates at a temporal scale of 1:100, with one diurnal cycle being represented in approximately 15 minutes.

Analogue 'Similarity of Process' Models

Analogue models are models that reproduce certain features of a natural system even though the processes, forms, dynamics, behaviour, materials and/or geometries do not conform to scaling ratios of the actual system (Chorley, 1967; Hooke, 1968). These are useful when true similarity between model and original system is unachievable or unnecessary. Analogue models may appear to be considerably different from the original field system but are based upon Hooke's (1968) 'similarity of process' concept, whereby the laboratory setup is considered a small system in its own right, rather than a scaled down reality. Seen as models and not miniature reproductions, analogue models should be treated as real, albeit simple physical systems (Paola, 2000) relying on the premise that processes occurring within a natural system will be comparable to those within a laboratory environment (Clarke *et al.,* 2010). This allows analogue models to output detailed and transferable process understanding rather than an understanding that is case study specific. Advantages of using analogue models over other physical model types include their potentially rapid

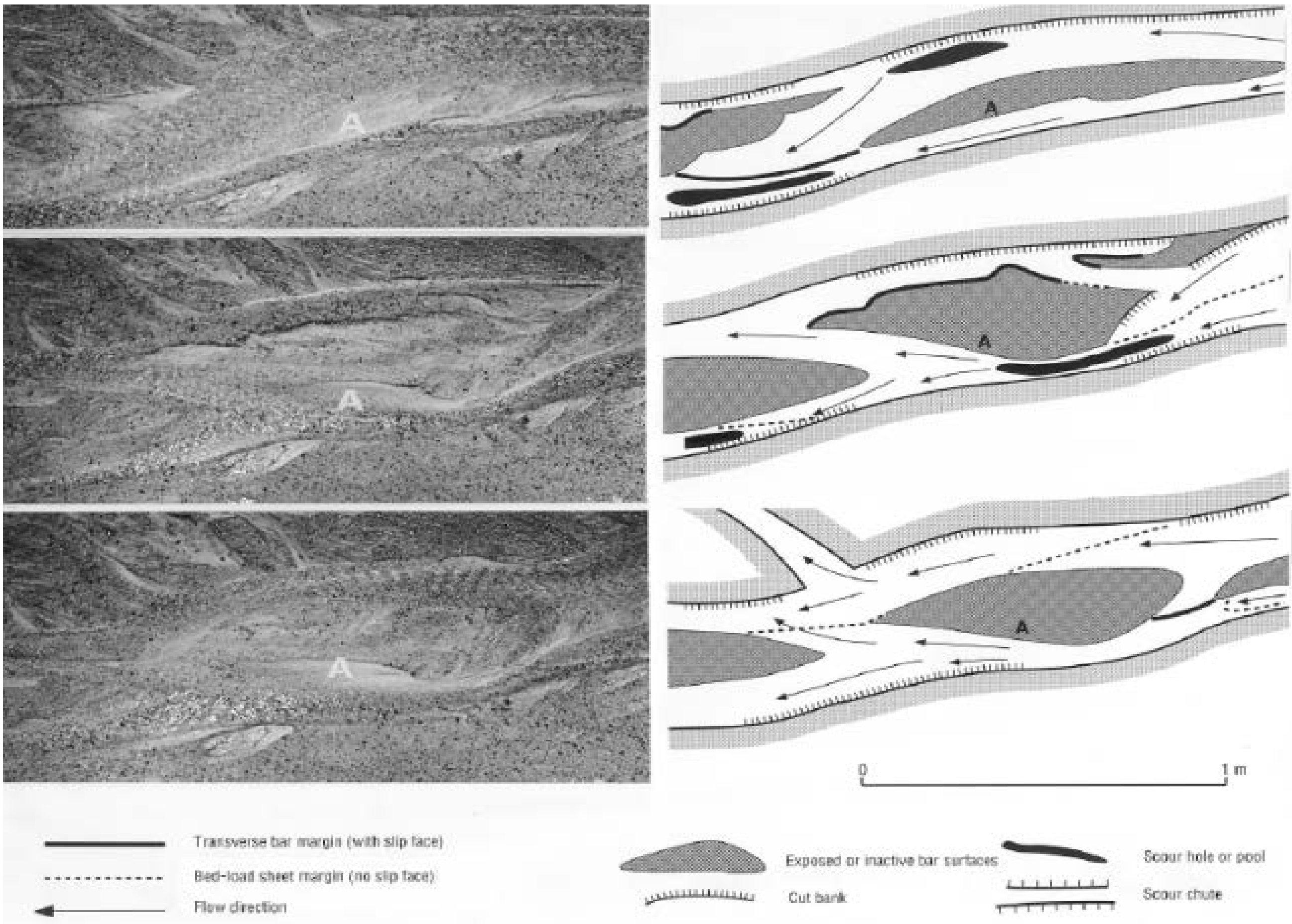

Figure 4: Flume study of a braided river system showing medial bar destruction caused by longitudinal translation and change in total discharge of an upstream confluence, demonstrating the influence that physical modelling has had upon braided river system understanding. Elapsed time of physical model simulation is 1 hour. Source: Ashmore (1991).

setup times, their ability to conduct prompt scenario testing and the reduced quantitative extrapolation required to make conclusions upon. However, analogue models may encounter difficulties with relating measurements and results obtained within the modelling environment to real world situations (Hooke, 1968; Isidoro *et al.,* 2012).

1:1 Replica Models

Some systems are small enough to be replicated in a laboratory and can be simulated at 1:1 scale (i.e. maintaining the exact dimensions of the studied physical system). This allows the studied system to be modelled under laboratory conditions with little or no difference (Peakall *et al.,* 1996). This has a number of advantages, such as a large degree of experimental control over model parameters. However, 1:1 replica models are not suitable for large-scale geomorphological systems due to space limitations within a laboratory setting.

Numerous 1:1 flume studies exist, such as Wilson *et al.* (2013) who used observations from an unscaled flume to understand fluvial bedload abrasion rates. Additionally, 1:1 experiments can be conducted in the field under natural settings but with controlled inputs and conditions. The Outdoor Stream Laboratory, Minnesota, is a field-size reproduction of a fluvial system which is part of the Saint Anthony Falls Laboratory. This allows an understanding of the underlying physical, biological and chemical mechanisms that govern stream and riparian processes and their response to natural and human disturbances under controlled conditions, e.g. steady and unsteady inlet hydrographs, to simulate overbank flood dynamics. Additionally, the Laboratory for Experimental Geomorphology in Leuven, as well as Moss and Walker's (1978) experiments, have conducted 1:1 laboratory experiments focusing on a number of in-situ surface erosion processes and their relationship to surface material properties. These include soil and rain splash erosion plot studies (e.g. De Ploey and Moeyerson, 1975; De Ploey *et al.*, 1976; De Ploey and Mucher, 1981) and tillage experiments and rill development (discussed in Slaymaker, 1991).

Principles of Physical Modelling

Despite the long history of physical modelling studies (Da Vinci used physical models to observe flow characteristics in the 1500s, Reynolds conducted moveable bed models of the River Mersey, UK in 1885 and the US Army Corps of Engineers commissioned multiple large-scale physical modelling experiments from the 1920s onwards, e.g. Coastal Engineering Research Centre and the Waterways Experiment Station; Markle, 1989) there is currently no established framework for conducting experimental and physical modelling studies. At present, laboratories using physical models adopt their own individual approaches based on institutional experience or communication with other similar projects (Frostick *et al.,* 2011). Because physical models may be used for a variety of geomorphological applications, procedures vary significantly between projects. Despite this, there are a number of unifying principles that all physical modelling projects should consider, including: *(i)* similitude requirements; *(ii)* dimensional analysis; and, *(iii)* the materials that are used.

Similitude

Similitude, also known as similarity, involves the model resembling and being correspondent to the system which the model is based upon (Hughes, 1993). Similitude can be divided into three types: geometric *(form)*; kinematic *(motion);* and, dynamic *(force)* similitude (Yalin, 1971). Firstly, geometric similitude involves the physical model being similar to its real world counterpart in regards to its dimensions and measurements, involving similarity in form. Therefore, a reduced or enlarged reproduction of the studied physical system is needed to achieve geometric similitude. Secondly, kinematic similitude involves similarity in motion being achieved between the model and real world system, with the ratio of movement in both systems being directly proportional. As a result, true kinematic similitude produces model particle/flow pathways that are geometrically similar to the actual physical system. Finally, dynamic similitude involves the proportion of relevant forces acting upon fluid flows and boundary surfaces being comparable between the model and full scale systems. This produces length, mass and time measurements that are proportionate, implying a constant ratio of forces between both systems. To achieve dynamic similitude, both geometric and kinematic similitude is required.

The degree to which similitude is satisfied is dependent upon: *(i)* the aims and objectives of the researcher; *(ii)* whether the physical model is generating qualitative or quantitative data and; *(iii)* whether the model can be calibrated and adjusted using existing data or models (Maynord, 2006).

Scale effects which arise due to force ratios being incomparable between a model and its real-world counterpart, and laboratory effects which arise due to the inability of a laboratory to simulate the correct forcing conditions and model boundaries (Chanson, 1999; Heller, 2011) may hinder dynamic similitude. Full dynamic similitude within a scaled physical model is often difficult, if not impossible, to achieve due to force vectors being required to be equal between both systems. Scaled models involving water are unable to achieve dynamic similitude as the model fluid would be needed to have a different viscosity to its real-world counterpart (Ettema, 2000; Frostick *et al.,* 2011). To avoid using a different liquid from the real-world system, users may either use a physical model that functions at full scale (1:1), or use Froude number scaled models to relax the similitude requirements. Because all geomorphic physical models are unique, achieving similarity between model and actual system can be relaxed as long as the similitude requirements are justified and reasonable.

Dimensional analysis

For scaled physical models to be representative of their full-scale system, quantities measured may adhere to scaling laws. Neglect of scaling considerations may render model results meaningless for scientific interpretation or prevent the model from correctly predicting process-form interactions at the actual system scale (Frostick *et al.,* 2011). Scale models are based on similitude theory (above). One method of achieving similitude is by producing a series of dimensionless parameters that are able to form relationships between physical processes (Peakall *et al.,* 1996). Yalin (1971) notes that the dimension of any physical system can be characterised in terms of its fundamental dimensions; *length, time and mass*. Using this concept, dimensional analysis, involving the examination of the relationships between different physical parameters by identifying their fundamental dimensions (*time, mass, length*) to determine the derived quantities (e.g. *area, volume, force, velocity, frequency* which are a function of the fundamental dimensions) can be applied (Yalin, 1971; Hughes, 1993; see Table 2). A detailed overview of dimensional analysis is beyond the scope of this paper and readers should refer to Yalin (1971) and chapter 2 of Hughes (1993) for further discussions.

Table 2: Dimensions of physical entities using a mass system of units. Source: Adapted from Hughes (1993).

Physical property	Dimensions	Type of quantity
Fundamental quantities		
Time	*[T]*	-
Mass	*[M]*	-
Length	*[L]*	Geometric
Temperature	*[ø]*	-
Angle	*[1]*	(Supplementary)
Derived quantities		
Area	$[L^2]$	Geometric
Volume	$[L^3]$	Geometric
Force	$[MLT^{-2}]$	Dynamic
Velocity	$[LT^{-1}]$	Kinematic
Acceleration	$[LT^{-2}]$	Kinematic
Volumetric Flow Rate	$[L^3T^{-1}]$	Kinematic
Strain	*[1]*	Dimensionless

Materials

The use of materials in geomorphological research is often highly project-specific. Because of this, a few case studies and the author's experience have been highlighted allowing users to make informed but not constrained decisions.

Physical models may use the exact materials as their real world counterpart, e.g. soil, gravel, flora and fauna in nature and in the physical model (Frostick *et al.,* 2011). Conversely, physical models may use surrogate / proxy materials that differ from the actual materials present within the physical system. This includes the scaling down of materials within a physical modelling environment and using alternative materials which mimic or substitute the use of the actual materials present in nature. Examples include: *(i)* using sand instead of gravel*; (ii)* substituting live vegetation with a smaller species or using an artificial surrogate*; (iii)* using sponge to represent soil; *(iv)* using lighter bed materials like pumice or charcoal to represent larger clasts; or, *(v)* using of fluids with differing viscosities to that of the real world system.

Using similar sediment in a scaled physical model to that found in an actual system may lead to responses in model behaviour that are not comparable to the real world counterpart. This has been documented in scaled flume studies, where using similar sediments resulted in the formation of ripples that had no equivalent in the field (Peakall *et al.,* 1996). This affected the flow dynamics, leading to supercritical flow, hydraulic jumps and standing waves that influenced bed morphology and rates of erosion (Peakall *et al.*, 1996). To avoid this, lighter bed material such as pumice, charcoal or sand can be used (Hughes, 1993).

Vegetation is commonly used in physical models. When using vegetation in physical models either: *(i*) artificial / surrogate plants; *(ii)* scaled, smaller species; or, *(iii)* natural vegetation can be used (Frostick *et al.,* 2011; see Table 3). When using artificially scaled substitutes, careful consideration must be taken to ensure that these are representative of the actual physical system. Using artificial vegetation has the benefit that it is inert, controllable and easy to use. However, the user must be aware of the limitations associated with using a proxy material to represent a highly variable component of a physical system. Limitations of using artificial vegetation include: *(i)* misrepresentation of a plant surrogate to replicate the behaviour of natural vegetation; and, *(ii)* the vegetation characteristics (e.g. flexibility and density) not being comparable between model and nature. Natural vegetation has the benefit that it is directly comparable to that of a natural system, however, it is also highly variable and potentially difficult to maintain in laboratory conditions (Frostick *et al.,* 2011; Frostick *et al.,* 2014). Scale is also important to consider. Modellers would need to substitute larger vegetation types, e.g. trees, with smaller saplings or shrubs due to the space limitations associated with using an experimental set-up. Therefore, the plant materials used depends upon number factors including the scale of the flume and the purpose of the experiments.

Table 3: Choice of plants in physical modelling. Source: modified from Frostick et al. (2011)

	Choice of plant	**Purpose**	**Example publications**
Artificial / surrogate	Rods or wooden dowels	Stem density effects on drag and flow resistance; Flow resistance on flood plains	Nepf (1999), Stone and Shen (2002), James *et al.* (2004), Gao *et al.* (2011)
	Rods with strips, plastic strips or strips with foliage attached	Flow structures; vegetation-flow interactions	Pashe and Rouvé (1985), Naot *et al.* (1996), Rameshwaran and Shiono (2007), Wilson *et al.* (2008)
	Plastic bushes or grasses	Floodplain roughness on flow structures, bedforms and sediment transport rates	Shiono *et al.* (2009)
Scaled	Smaller vegetation (e.g. *Medicago sativa*)	Flow resistance and controls on stream morphodynamics	Järvelä (2002), Coulthard (2005), Gran and Paola (2001), Clarke *et al.* (2014)
Natural	Natural, full-scale vegetation, such as grass, shrubs or trees	Flow resistance; plant-flow interactions	Stephan and Gutknecht (2002), Wilson and Horritt (2002), James *et al.* (2004), Carollo *et al.* (2005)

Cellulose sponge can be used as a proxy material for soil. Richardson and Siccama (2000) investigated the validity of the simile '*soils are like sponges*', demonstrating through experimental methods that sponges store and release water in much the same ways that soils do, with cellulose sponge having intermediate hydrological characteristics to peat and topsoil (see Figure 5). Although it is identified that sponge has a higher water retention capacity than soil, over 2.5 times than peat soils, Richardson and Siccama (2000) do not address the fact that sponge could be scaled volumetrically by thickness/depth to account for this additional storage, which the author plans to apply within a physical model to simulate soil storage capacity during surface-water flood events. Scaling by storage capacity allows sponge to provide a clean and non-erodible medium to investigate runoff and infiltration processes. Sponge can also be compressed to remove stored water, allowing rapid repetition of experimental runs. This highlights the potential benefits of using sponge as a proxy material in physical models. Although sponge allows numerous benefits to the physical modeller, sponge would not be suitable at 1:1 scale; using soil would produce more realistic outputs and avoids using proxy/surrogate materials.

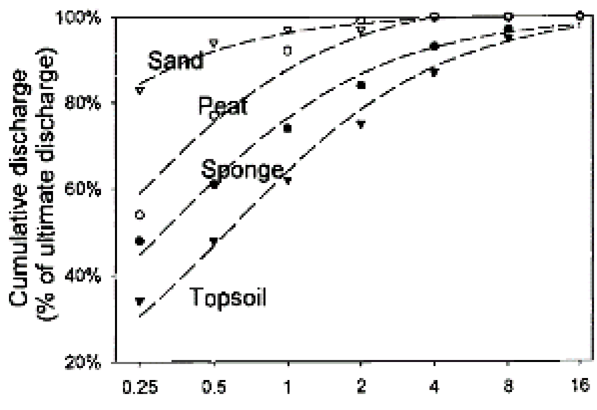

Figure 5: Results from laboratory testing of cumulative discharge of water from four media, demonstrating sponge's ability to act as a proxy material for soil. Other experimental tests including rates of flow, water potential curves and gravimetric water contents in cellulose sponge were also intermediate to that of topsoil and peat. Source: Richardson and Siccama (2000).

Applications of Physical Models

Physical models have an important role in geomorphological research. To demonstrate the scope and potential of physical modelling in geomorphological research, fluvial-, glacial-, aeolian- and bio- geomorphological case studies have been highlighted. Physical models have also been used within coastal- (e.g. Dalrymple, 1985; Markle, 1989; Hughes, 1993; Rossetto *et al.,* 2011) and hillslope-geomorphology / soil erosion studies (e.g. Giménez and Govers, 2001; Parsons and Wainwright, 2006; Michaelides and Wainwright, 2008; Cooper *et al.,* 2012; Turnball *et al.,* 2013). The reader is advised to consult relevant studies and references therein.

Fluvial Geomorphology

Physical models have been used extensively in fluvial geomorphology to understand a plethora of geomorphic processes, including sediment transport, river channel change and the influence of vegetation on channel adjustment. Fluvial geomorphological research using experimental methods is predominantly flume-based. Fluvial physical models were of crucial importance in the work of Hooke (1968), who used laboratory streams to develop the 'similarity of process' model concept, as well as a number of US Army Corps of Engineers projects, e.g. the SEDflume project, a 6m long mobile flume which can analyse fluvial sediment sorting, and the Ice Harbour Lock and Dam Physical Model Study, a 1:55 scale dam commissioned to understand the downstream impacts of river impoundment. Ashworth *et al.* (2007) applied an experimental basin model of an aggrading braided river channel to investigate the relationship between the frequency of channel avulsion, the duration of time that the braidplain is occupied by flow, the spatial pattern of sedimentation and how these respond to a change in sediment supply. Results obtained from the physical model demonstrated a strong positive relationship between sediment supply and channel avulsion rates. Results attained within the physical modelling environment were also able to be extrapolated to real-world examples to gain an understanding of braided river sedimentation. Furthermore, Schumm's (1987) book '*Experimental Fluvial Geomorphology*', compiles research from the fluvial physical modelling literature, comprising studies relating to drainage basin, rivers and fans and fluvial landform development.

Other examples of physical models in fluvial geomorphology include the work of Smith (1998), who applied flume studies to model the development of channel migration and avulsion in high sinuosity meandering channels, and the work of Ashmore (1982, 1991, 1993) which demonstrated how flumes may be applied to study channel morphodynamics. More recently, the work of Braudrick *et al.* (2009) used a scaled flume study to explore mechanisms controlling migration rate, sinuosity, floodplain formation and planform morphodynamics in meandering river channels (see Figure 6). Additionally, Johnson and Whipple (2010) used a scaled experimental flume to model bedrock incision rates by building a weak concrete streambed within a flume to understand rates of erosion relating to sediment flux.

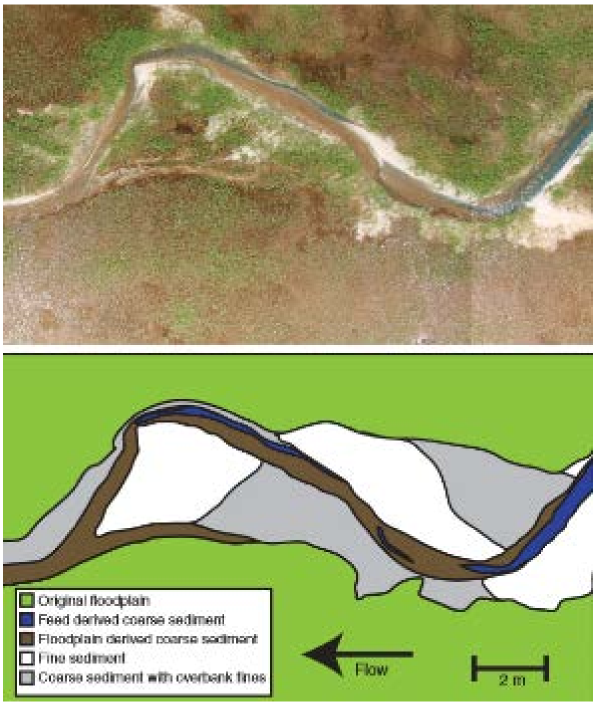

Figure 6: Sediment in second and third bars downstream from the flume inlet. Fine sediment is mapped where the majority of the floodplain thickness was fine sediment. Accumulation of organic matter from the dead alfalfa makes some of the bar appear brown where it is primarily fine sediment. Source: Braudrick et al. (2009).

Glacial Geomorphology

Published research on physical models in glacial geomorphology is sparse. The few studies that exist include Rushmer (2007), who applied experimental flume methods to study the impact of glacial outburst floods with differing hydrographs and Corti *et al.* (2008) who used physical modelling to investigate the influence of bedrock topography and ablation on ice flow direction and velocity using silicone gel (see Figure 7). This study confirmed current conceptual models of ice flow around obstacles, demonstrating that variations in bed topography and internal layers of the ice are strongly influenced by the presence and height of bedrock obstacles.

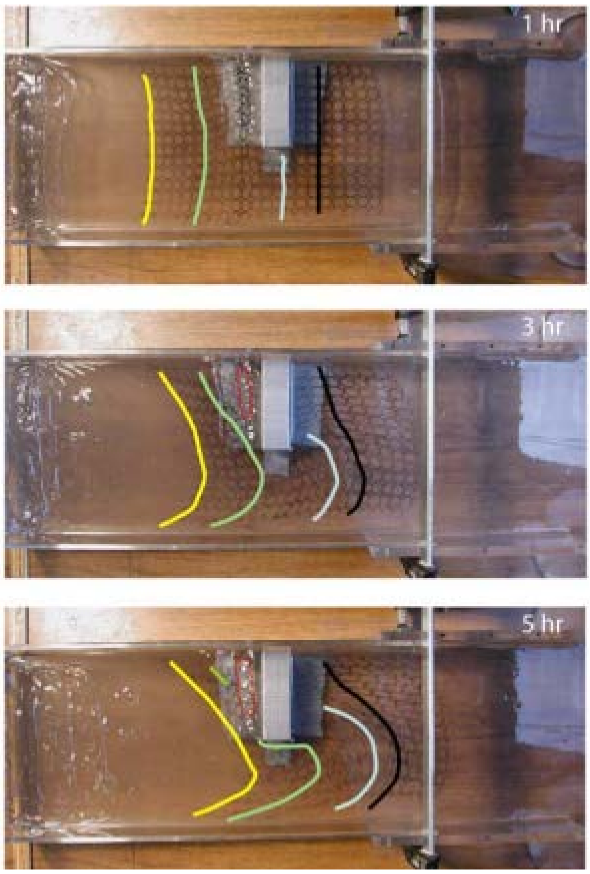

Figure 7: Physical model of a glacier, showing progressive deformation of silicone gel, an ice surrogate material, around an obstacle. Source: Corti et al. (2008).

Glacial geomorphology is generally investigated using numerical, rather than physical models to describe relationships between mass balance, ice dynamics and climate (Rowan, 2014), however, some aspects of glacial behaviour can be simulated using physical models, such as controls on ice melting (e.g. Reznichenko *et al.,* 2010), ice flow (e.g. Glen, 1955) and sub-glacial erosion and sediment transport processes (e.g. Iverson, 1990). Despite this lack of research, Corti *et al.* (2008) express that physical models exhibit numerous opportunities for the glacial geomorphologist, such as the ability to isolate variables and study long spatio-temporal scales.

Aeolian Geomorphology

Theoretical understanding and the development of numerical models of Aeolian processes often contain empirical coefficients that need to be determined using wind tunnel tests, where variables such as grain size and wind speed/direction can be systematically controlled to investigate interactions (Dong *et al.,* 2003). Authors such as Dong *et al.* (2003) and Han *et al.* (2011) have applied experimental wind tunnel tests to understand the relationships between flow velocities and sediment entrainment under differing wind velocity, grain size and moisture scenarios. These studies have confirmed the importance of using physical models to understand aeolian mechanisms.

Biogeomorphology

Biogeomorphology, the study of the interactions between flora and fauna and the development of landforms, is an emerging topic within geomorphology (Frostick *et al.,* 2011). Using flume experiments, Statzner *et al.* (2000) conducted ecological experiments to demonstrate that crayfish activity significantly affects sand and gravel erosion by increasing bed roughness, decreasing bedform height and altering the pool-riffle sequence downstream. More recently, Johnson *et al.* (2010) highlight that the presence of signal crayfish may affect river bed stability by modifying the microtopography and grain-grain fabric of gravel substrates which can significantly affect bed stability during subsequent flood events. Additionally, Gran and Paola (2001) used a series of physical modelling experiments to study the influence of riparian vegetation upon river morphology and braided stream dynamics. Furthermore, Tal and Paola (2010) conducted laboratory experiments to demonstrate that riparian vegetation can cause a braided channel to maintain a dynamic and single-threaded channel. In these studies, physical modelling allowed input variables, such as water discharge, sediment discharge and grain size to remain constant between runs, while vegetation density of alfalfa sprouts was varied between runs, confirming that vegetation acts to increase bank stability and reduce the number of active channels (see Figure 8).

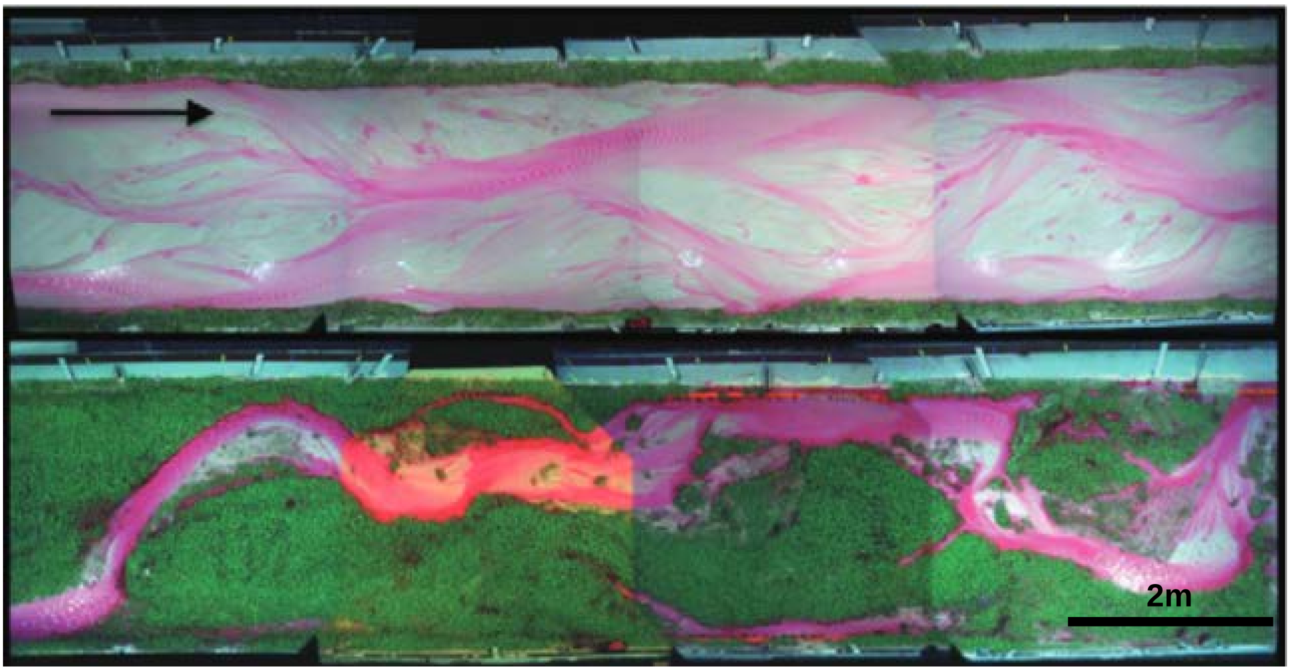

Figure 8: Transition from an un-vegetated braided channel to a dominant single-threaded channel with a vegetated floodplain in an experimental flume experiment. Source: Tal and Paola (2010).

Table 4: Summary of the advantages and disadvantages of using physical modelling and experimental laboratory techniques in geomorphological research framework. Collated using Hughes (1993), HYDRALAB (2004), Frostick et al. (2011), Heller (2011) and Sutherland and Burfuss (2011).

Physical models advantages	**Difficulties associated with using physical models**
Incorporation of the appropriate physical processes without simplification or assumption. Allows the reproduction of complex physical phenomena.	Potential scale effects associated with simulating model variables in incorrect ratios. Consideration must be taken during planning stages.
Experimental control within a closed system allows rapid multi-variant analysis and testing of multiple variables. Ability to exclude extrinsic parameters.	Laboratory / model effects. Factors may be misrepresented / incorrectly reproduced after simulation in a laboratory environment.
Data collected simultaneously and with relative ease over large spatio-temporal scales once model is constructed and calibrated.	Exclusion / neglect of important functions and conditions which may have been overlooked or deemed to be insignificant by the experimenter.
Large degree of experimental control allows easy simulation of infrequent or hypothetical environmental conditions which would be difficult to observe in nature.	Construction and running is potentially expensive, labour intensive and time consuming. May require appropriate and continued support and funding.
Allow instant visual feedback. Provides qualitative insight into physical processes occurring. Calibration may be assisted by visual prompts/direct contact with physical model.	Data extraction can be difficult due to measurement effects. Results obtained may not be upscaled to real-world situations / directly extended beyond the physical model.
Natural non-linear feedbacks and uncertainty in physical systems which may not be fully understood may be represented and modelled.	Construction and application may require previous experience, understanding or specific expertise.
Can be combined with other techniques to create ‘hybrid/composite models’, or used to calibrate or inform numerical model functioning and understanding.	May require specialist facilities and/or a large amount of space. Space constraints/lack of equipment may hinder experimentation.
Well-established technique applied to range of research applications. Numerous measurement techniques available, e.g. particle image velocimetry, Acoustic Doppler Velocimetry, pressure sensors, digital photogrammetry, laser scanning etc.	Substitution of materials may be required to ensure correct scaling. Physical model may not be fully representative of actual physical system.
May have reduced costs associated with data collection when compared to field data collection if using existing facilities/equipment.	Simulation of variables or conditions may not be possible at reduced scale within a physical modelling environment.
Control over system variables and inputs, e.g. sediment, water, vegetation. Bridges what can be simulated in the field and modelled numerically.	Equifinality may result in a misinterpretation of the fundamental processes occurring.

These physical modelling studies demonstrated the role of biota as a significant geomorphic agent. Many aspects of this field remain poorly understood but the use of physical models is of critical importance. Readers are advised to consult Thomas *et al.* (2014) and Frostick *et al.* (2014) which provide detailed overviews of the use of physical models in biogeomorphology, as well as outlines of knowledge gaps and avenues for future research.

Advantages of Physical Models

Physical models provide a number of advantages to the geomorphological user (summarised in Table 4). The main advantages of physical modelling are associated with the controlled, closed environment in which experimentation can take place. Physical models allow rapid analyses of multiple variables with a large degree of experimental control – independent variables can be altered one at a time while dependent variables can remain constant to investigate cause and effect relationships and model responses to changing variables. Additionally, physical models allow the simulation and study of infrequent, hypothetical or large spatiotemporal scale scenarios. This is significant for events which may be impossible to observe or difficult to study in the field because of the long timescales involved, e.g. the influence of autogenic mechanisms on alluvial fan evolution (Clarke *et al.*, 2010). Furthermore, physical models allow complex physical phenomena (potentially not yet described or understood) to be simulated without requiring a mathematical or theoretical simplification of governing processes (Goudie, 2003). This makes physical models an invaluable investigative tool to the geomorphological user.

Physical Model Limitations

Despite offering a number of advantages to the geomorphological user, physical modelling also has a number of shortcomings which the user must be aware of before any experimentation takes place (see Table 4).

Firstly, laboratory effects due to the limitations associated with simulating natural phenomena under a simplified and scaled laboratory set-up may produce occurrences that are not present in natural systems. These may include cohesive and/or adhesive forces between molecules (e.g. clay or water) becoming greater than within a natural system (Schumm, 1960; Goudie, 2003). Additionally, scale effects, whereby fundamental phenomena are unable to be simulated in correct proportions to that of the physical system, may arise (Heller, 2011). These may render results misleading or incorrect. In addition, difficulties in extracting useful and transferable data from physical models may be encountered (Hooke, 1968; Isidoro *et al.,* 2012), whereby data obtained within the physical modelling environment cannot be upscaled to real world scenarios. Problems associated with equifinality, where the same end state is reached through different processes and mechanisms may also be present within physical models. Furthermore, physical models are potentially difficult to validate and determine whether the model is performing adequately because multiple model runs are required to allow adjustment of model variables until the observed effects are comparable to those observed in nature (Hooke, 1968). Validation is essential to ensure that a physical model performs relative to its real-world counterpart but is rarely considered in physical modelling. Despite this, problems with model validation are problematic in other modelling techniques.

Conclusions

Physical models permit clear visualisation, observation, demonstration and measurement of process-form interactions. This allows an understanding of complex relationships that cannot be represented mathematically, as well as allowing the verification of numerical modelling approaches (Frostick *et al.* 2011). Yalin (1971) states that physical models give the user an instant qualitative, visual insight into the processes occurring; something that is difficult in field or numerical modelling situations. Physical modelling provides an excellent tool to geomorphologists, however, users must be conscious of modelling limitations so these can be minimised (Ettema, 2000). Hughes (1993) compares a poorly scaled model to a ruler with incorrect markings – the ruler can be used to make measurements but the measurements are guaranteed to be wrong, with incorrectly designed models always providing inaccurate predictions (Yalin, 1971).

Paola (2000) asserts that it is potentially misleading to treat even the most carefully controlled scaled model as a miniature analogue of its field system due to the limitations associated with scaling and reproducing a model under laboratory conditions. Users must be aware of the limitations of physical modelling approach, as well as procedures to address and reduce model shortcomings, before conducting such experiments.

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