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Scaling of sediment dynamics in a laboratory model of a sand-bed stream

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Abstract

A movable bed model was designed in a laboratory flume to simulate a mixed load sand-bed stream. The modelling objectives were to reproduce bedload and suspended sediment transport as well as downstream and transverse sediment fluxes in ratios similar to the field site. To meet these objectives the model contained an exact geometric scale and graded lightweight sediments to simulate migrating dunes and suspended load transport. The experiments are somewhat novel in that most mobile bed models have vertical exaggeration, whereas in these experiments exact geometric similitude of channel dimensions was maintained. The goal of this paper is to review the scaling strategy and the level of similarity among dimensionless parameters between model and field. Similarity in dimensionless bed shear stress and the particle Reynolds number enabled the experiments to replicate the dominant sediment dynamics present in the stream during a bankfull flow. There was a conflict in the strategy, in that grain roughness was exaggerated with respect to nature. However, the paper shows that geometric similarity of bedforms and the resulting drag is much closer to what is predicted for nature. In addition, measurements of sediment transport are compared to values computed from well-supported formulations, which is shown to reinforce the validity of the scaling strategy. Lastly, criteria for movable bed equilibrium are defined and it is shown that lightweight sediments contributed to the rapid development of near-equilibrium conditions. Overall, the paper shows a methodology that can be used to model mixed load streams at an exact geometric scale.

Keywords: Movable bed model; Undistorted geometry; Dimensional analysis; Lightweight sediments; Sedimentation timescale; Sand-bed stream

1. Introduction

Scaled movable bed river models provide valuable information on prototype fluvial processes that can be difficult to obtain in the field or with numerical techniques. Similitude between the prototype and model relies on equating dimensionless parameters for the flow and sediment transport thus preserving consistent ratios of the dominant forces (Yalin, 1971). Dimensionless parameters typically include the Froude number, head loss, the particle Reynolds number and a mobility parameter for sediment transport (Julien, 2002). However, maintaining similitude between movable bed laboratory models and the larger rivers they represent is difficult to do exactly (Yalin, 1971). For this reason, various modelling strategies have been developed to ensure processes that are dominant in the prototype are well represented in the model.

One of the first theory based strategies to the design of movable bed models was put forward by Einstein and Chien (1956). They proposed that by matching the values of dimensionless parameters on the Shield's entrainment diagram, in both the model and prototype, similar sediment movement and bed topography could be achieved. The strategy, when applied to most rivers, requires geometric distortion of the model and lightweight sediments to produce an exact match in the dimensionless parameters related to both the flow and sediment. It has the advantage that equality in the most important dimensionless parameters can be achieved but at the expense 2D or 3D processes. In contrast, exact geometric models in which the vertical and horizontal geometric scales are the same are able to reproduce 2D or 3D processes. However for undistorted models it is more difficult to choose a

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sediment size that will match sediment transport parameters as well as roughness and thus yield stage–discharge relationships to scale.

Less strict strategies involve relaxing one or more of the dimensionless parameters related to sediment transport. For instance, instead of matching parameters on the Shields entrainment diagram the settling velocity can be used to select the model sediment according to the Froude scale, which allows greater flexibility in designing the model and can reproduce movable bed changes close to scale (Pugh, 2008; Zwamborn, 1966). For bedload dominated streams it is possible to relax the similitude of near bed turbulent forces, so long as near bed conditions remain fully rough (Julien, 2002). In models of large suspended load streams, flow rates may be adjusted to increase sediment mobility with only minor changes to the Froude number (Julien, 2002). Generally it is not possible to achieve an exact equality in all dimensionless parameters due to practical constraints, and it becomes important to identify the most important parameters in the prototype and investigate the potential scale effects of any inequality.

When looking at reach-scale sediment transport in rivers and the resulting changes in bed morphology it is important to capture detailed flow patterns, including transverse lateral currents, secondary circulation and flow separation regions (Rodríguez et al., 2013, Gorrick and Rodríguez, 2014) as they control local sediment fluxes. This was the case for the present modelling experiment, which was required to reproduce suspended and bedload transport as well as downstream and transverse sediment fluxes in ratios similar to the field site. To meet these objectives the model contained an exact geometric scale and graded lightweight sediments to simulate migrating dunes and suspended load transport. The goal of this paper is to review this scaling strategy and the level of similarity among dimensionless parameters between model and field. A common scaling problem with exact geometric models, such as the present model, is the exaggeration of relative roughness through the use of bed sediments larger than the geometric scale. This paper investigates whether similarity in migrating dunes in the field and model results in greater equality in roughness. The paper also considers the performance of the lightweight sediments, the development of equilibrium conditions and the accuracy of computed sediment transport against measurements. The current paper is based on a methodology used to examine sediment dynamics presented in Gorrick and Rodríguez (2012). The current paper shows a methodology that can be used to model similar mixed load streams.

2. Field stream and laboratory setup

The present movable bed experiments were conducted in a 1:16 laboratory model of the Widden Brook which is situated in south eastern Australia. It has a catchment area of 700 km^2 consisting of a long and narrow incised sandstone valley. The model was based on a 200 m reach characterised by a single-thread sand-bed channel with low sinuosity. The reach-average bed slope is 0.0022 and bed material comprises sand and some gravel. At the time of model experiments, the stream was transport-limited due to extensive volumes of sand in the bed from upstream channel erosion. During bankfull flows (up to 50 m^3/s) most sediment transport occurs in suspension and migrating dunes cover the bed. The reach was chosen due to the small channel dimensions which allowed a reasonably large scale to be maintained in the laboratory model. Table 1 provides a comparison of field and model properties.

The laboratory model was based on a December 2005 DGPS (differential GPS) survey of the field reach (Gorrick, 2011). From surveyed cross sections, plywood templates were constructed and used to guide hot-wire carving of the topography onto polystyrene. The surface of the model was finished with a layer of 0.8 mm glued sand to achieve a rough boundary. The model was put together in a 13 m long by 2 m wide, water recirculating tilting flume. Flow rates were supplied by a centrifugal pump with an electromagnetic flow meter on a butterfly valve (maximum flow rate of 60 L/s; precision ±0.25%). Two fixed point gauges were mounted at either end of the flume for reach water surface slope measurements. A movable carriage mounted on the flume rails was used to position instruments at precise points along the streamwise and transverse axes of the flume.

The investigation took place in two stages. Firstly, during the fixed bed stage the flow velocity and turbulence measurements were collected over a dense grid with a 2D Acoustic Doppler Velocimeter (ADV) under bankfull flow conditions ($Q = 0.0495$ m^3/s). The scaling of flow in these experiments was simply maintained by matching the Froude number and roughness levels. The second stage introduced a sediment feed with no recirculation and the same water flow rate. The sediment feed allowed a fully mobile bed with fixed banks (see Fig. 1). The fixed banks were not a drastic simplification as bankfull flow events in the field rework the stream bed but cause only small amounts of bank erosion. The feed rate was relatively high ($Q_f = 165$ g/s) and was estimated using the Engelund and Hansen (1967) total load equation and assuming transport-limited conditions. The sediment was manually fed into the channel as described in Gorrick and Rodríguez (2012) at regular 7 s intervals. The experiments began by allowing a steady bankfull flow to develop, before starting the sediment feed. A period of 10–15 min was allowed for the mobile bed to develop near-equilibrium conditions. Following this, measurements were

Table 1
Comparison of model and prototype properties, where Q is the water discharge, S is the bed slope, H is the flow depth, D_{50} is the median sediment diameter, D_{90} is the sediment diameter for which 90% of the sample by weight is finer, R is the submerged specific gravity of sediment, A is the cross sectional area of the channel.

	Q (m^3/s)	S (m/m)	H (m)	D_{50} (mm)	D_{90} (mm)	R	A (m^2)
Model	0.0495	0.0033	0.06	1.0	2.1	0.3	0.1
Field	≤ 50	0.0022	0.90	1.1	2.1	1.65	25.6