Major Bed Slope Effects Affecting All River Morphodynamics Models

F. Schuurman[1,2], M.G. Kleinhans[1]

[1] Dept. of Geography, Fac. of Geosciences, Utrecht University, Utrecht, The Netherlands. f.schuurman@uu.nl
[2] Royal HaskoningDHV, Amersfoort, The Netherlands.

1. Introduction

River and coastal morphodynamics are the result of sediment transport induced by flowing water and gravity on bed slopes, e.g. the transverse slope in a meander bend. The amount and direction of sediment transport induced by flowing water can be estimated by using one of the many empirical sediment transport predictor in combination with flow vectors, but quantification methods for the direct effect of gravity on sediment moving on sloping river beds are scarce and unreliable. Recent studies showed a major influence of the bed slope effect on equilibrium bed topography (e.g. Schuurman & Kleinhans, 2011), dune development (e.g. Paalberg *et al.*, 2009), grain size distribution over tributaries at bifurcations (Sloff & Mosselman, 2012) and grain size distribution in dunes and bends (Frings & Kleinhans, 2008). Despite its unreliability, the bed slope effect has a major effect on morphology and is therefore essential for all numerical process-based river and coastal models as used for engineering practice, reservoir studies and scientific studies.

The goals for the present study are: 1) to elucidate the influence of bed slope effect on bed topography, morphodynamics and sorting trends, and 2) to clarify what study should be undertaken to enable reliable use of physics-based morphodynamic models.

2. Quantification methods

Different methods are available to quantify the deflection of transported grains by gravity (e.g. Hasegawa, 1984; Parker & Andrews, 1985; Talmon *et al.*, 1995). This can be either a rotation of the sediment transport vectors or an addition of transverse sediment transport. Most of the methods are based on sediment mobility and Coulomb friction, although the exact formulations differ, but more troublesome is the presence of multiple calibration parameters. For example, Talmon *et al.* (1995) proposed the following equation:

$$\tan(\varphi_s) = \frac{\sin(\varphi_\tau) - \dfrac{1}{f(\theta)}\dfrac{\partial z_b}{\partial y}}{\cos(\varphi_\tau) - \dfrac{1}{f(\theta)}\dfrac{\partial z_b}{\partial x}} \qquad (1)$$

where

$$f_i(\theta_i) = \alpha\theta_i^{\beta}\left(\frac{D_i}{h}\right)^{\gamma}\left(\frac{D_m}{D_i}\right)^{\delta} \qquad (2)$$

and θ_i is the Shields parameter for grain size fraction i (-), α, β, γ and δ are calibration parameters, h is the water depth (m), D_i is the grain size of fraction i (m), D_m is the median grain size (m), φ_τ is the flow shear stress vector, φ_s is the sediment transport vector deflected on the transverse or longitudinal slope, z_b is the bed level (m). Some agreement exists about the values of β (0.5) and γ (0.3), α needs to be calibrated and δ is based on a hiding and exposure function. Here we show that the exact value of α dramatically affects the bed topography and channel pattern.

3. Bed topography and morphodynamics

As can be seen in Fig. 1, the bed topography and bar shapes produced in the numerical model Delft3D is highly dependent on the bed slope effect. Without the bed slope effect unrealistically narrow bars with extremely steep rims arose. Bars have realistic width-length ratios and height when bed slope effect and spiral flow are included. The effect of spiral flow is however much smaller than that of the bed slope effect.

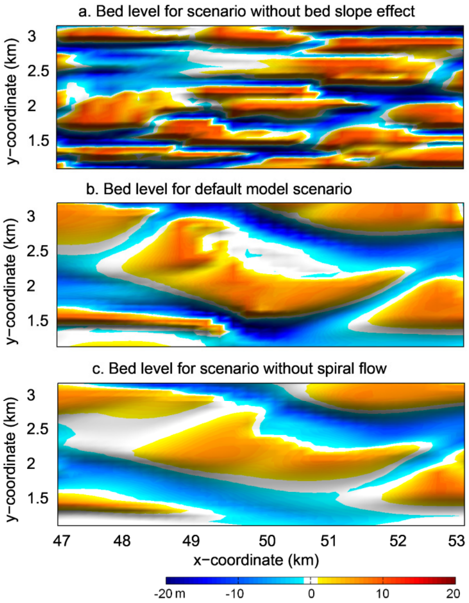

Figure 1: High impact of bed slope effect for bed level predictions in a sand-bed braided river, compared to the low impact of spiral flow. Modelled in Delft3D (Schuurman & Kleinhans, 2011).

Parameterization of the bed slope effect is far from straightforward and introduces significant uncertainty in predicted topography. The exact value of α (Eq. 2) has a major effect on bar amplitude (Fig. 2), scour depth and channel pattern quantified here by an Active Braiding Index, i.e. the average number of parallel channels transporting sediment.

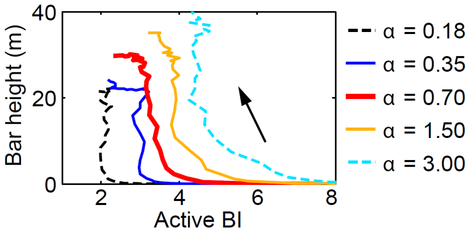

Figure 2: Influence of bed slope effect intensity (α, Eq. 2) on the Active Braiding Index and the final bar height.

4. Grain sorting

Grain sorting processes are strongly affected by bed slope. At the same time, grain sorting strongly affects bar and bend morphodynamics. On flat beds (without dunes), alternate bars armour more strongly on the stoss side than on the lee side, which reduces their migration rate and height (Lanzoni 2000). In bends with flat bed the balance between up-slope spiral flow drag force and down-slope gravity gives the classical bend sorting of coarser sediment in deeper outer-bends and finer sediment towards the shallower inner-bends (Parker & Andrews 1985). In bends with dunes that vertically sort sediment and modify spiral flow, the general bend sorting pattern is also found (Frings and Kleinhans 2008, Fig. 3) but predictions are highly uncertain and depend on yet another free variable: the active mixing layer (Blom et al. 2008). A thin active layer causes rapid sorting response whereas a thick layer causes rapid morphological response (Sloff & Mosselman 2012).

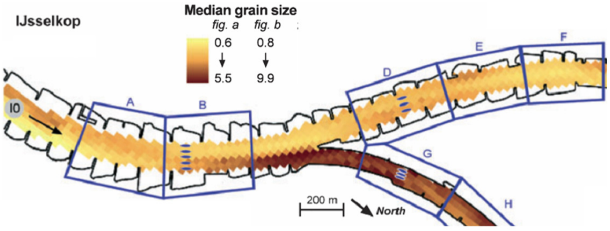

Figure 3: Sediment sorting at a Rhine bifurcation as a result of a transverse bed slope in a bend.

5. Discussion

The bed slope effect has major effect on river morphodynamics, but at the moment an exact parameterization of the bed slope effect for morphodynamic modelling can only be achieved by calibration. Although high quality validations have been obtained in various environments (Lesser et al. 2004), calibrating the bed slope effect by using measured topography is not simple, because it neglects disequilibrium of measured topography *and* sorting, which are the result of a large number of processes, each with specific calibrations.

The uncertainty introduced by the bed slope effect is now one of the limiting factors in modelling river morphodynamics. Increased computational power, enabling the use of relatively fine grids, 3D flow and non-uniform sediment, is no longer the limiting factor. Somewhat annoying is the fact that the bed slope effect is known for decades, but a reliable way of quantification is still lacking.

Consequently, model results depend partly on initial planform (Kleinhans et al., this volume) and calibration. Fundamental research could therefore impose as little as possible on a model and, just like most flume experiments and linear analyses, start from a hypothetical river. But without possibility to calibrate on real rivers and a widely accepted agreement of quantification of the bed slope effect, one is forced to perform a sensitivity analysis to the bed slope effect and to defend a hard-to-defend arbitrary choice for bed slope effect parameterization. Resorting to reduced complexity models is no solution: they may provide good looking results, should still incorporate transverse bed slope effects and often violate basic laws of physics. Future study will increase the potential of morphodynamic models for engineering, fluvial morphodynamics, sedimentology and reservoir geology.

6. Conclusions

The present study showed the importance of the bed slope effect on modelling river morphodynamics. Examples from previous studies showed that the bed slope effect is indispensable, but that quantification requires making arbitrary choices for intensity and quantification method. Also, general agreement on the quantification method is a necessity for future model studies using morphodynamic models as a tool for fundamental research.

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