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Jord J. Warmink, Anouk Bomers,
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Efficient long-term one-dimensional morphodynamic modelling in alluvial rivers using simplified models – theory and validation

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Introduction

Morphodynamic numerical simulations can be time consuming, especially in a stochastic approach when multiple long-term simulations are required to address parameter uncertainty. To improved efficiency the flow and sediment dynamics can be decoupled when Froude numbers are below 0.8 (e.g. de Vries, 1965; Lyn, 1987; Lyn & Altinakar, 2002). A morphological acceleration factor can further speed up simulations. Another approach is to simplify models by neglecting terms in the governing equations. The quasi-steady approach may for example reduce simulation times to less than 25%.

The scope of this research is to assess how and when model simplifications are possible, without jeopardizing the predictive capacity in terms of sediment transport and riverbed development.

This work is part of a PhD research at Wageningen University & Research as part of the Rivers2Morrow programme (2018-2023). The PhD research is supported by the Dutch Ministry of Infrastructure and Water Management, HKV and Deltares.

Methodology

Theoretical analysis

Grijns & Vreugdenhil (1976) performed a theoretical analysis, to assess the impact of simplification of 1-dimensional flow models on the propagation and damping of water waves. We extend their analysis to morphology. Basis are the St. Venant equations for water motion, the sediment mass balance equation and a closure relation for sediment transport.

The flag coefficients α_i ($i = 1 \dots 4$) can be 0 and 1 only. Values of 0 indicate model simplification.

$$\alpha_1 \frac{\partial u}{\partial t} + \alpha_2 u \frac{\partial u}{\partial x} + \alpha_3 g \frac{\partial h}{\partial x} + g \frac{\partial z}{\partial x} = -g \frac{u^2}{C^2 h}$$

$$\alpha_4 \frac{\partial h}{\partial t} + h \frac{\partial u}{\partial x} + u \frac{\partial h}{\partial x} = 0$$

$$\frac{\partial z}{\partial t} + \frac{\partial s}{\partial x} = 0$$

$$s = f(u, \text{parameters})$$

with: t =time, x =longitudinal co-ordinate, u =flow velocity, h =water depth, z =bed level, C =Chézy coefficient, s =sediment transport per unit width, g =acceleration due to gravity.

We consider 2 simplified models:

1. Quasi-steady approach, neglecting time-derivatives: $\alpha_1 = \alpha_4 = 0$
2. Diffusive wave, neglecting inertia: $\alpha_1 = \alpha_2 = 0$

To assess the performance of these models, analytical solutions for the set of non-linear equations are derived through:

1. linearization
2. combination to one linear equation in the water depth h'
3. assuming a harmonic perturbation of flow and bed to get a solution for propagation and damping of water and sediment waves.

The ratio of solutions of the full dynamic model and simplified models determines how well simplified models perform. Three dimensionless parameters are important:

$$\text{Froude number } Fr = \frac{u}{\sqrt{gh}}$$

$$\text{Water wave parameter } E = \sqrt{\frac{g^3 T^2}{C^4 h_0}}$$

$$\text{Transport parameter (uniform material) } \Psi = n \frac{s_0}{q_0}$$

with: T = period of flood wave, n = power in sediment transport relation $s = \mu u^n$, q = discharge per unit width. Index 0 means undisturbed value.

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Validation with numerical model

To check whether the results of the theoretical analysis are valid in practical, non-linear, cases, numerical simulations were performed. ELV is a one-dimensional numerical morphological modelling system (Chavarrías et al, 2019). ELV simulates the full set of equations, the quasi-steady model and the diffusive-wave model. Simulations were done with infinitesimal perturbations as well as with flood waves and larger bed disturbances in a quasi-equilibrium river reach. Flood wave characteristics, bed slope and grain sizes were varied within ranges realistic for lowland rivers. Figure 1 shows a sample result.

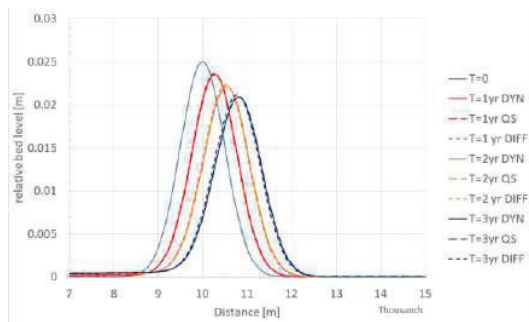


Figure 1. Propagation of small bed perturbation during 3 years with full dynamic (DYN), quasi-steady (QS) and diffusive-wave model (Diff). Vertical axis: bed level relative to mean bed slope. $Fr=0.2$, $E=12,500$ and $\Psi=5.15e-5$.

Results

Figure 2 shows the relative celerity of bed perturbations (c/u) according to theory (lines) and ELV (markers). The agreement is good for Froude numbers up to 0.3. For higher Froude numbers deviations occur.

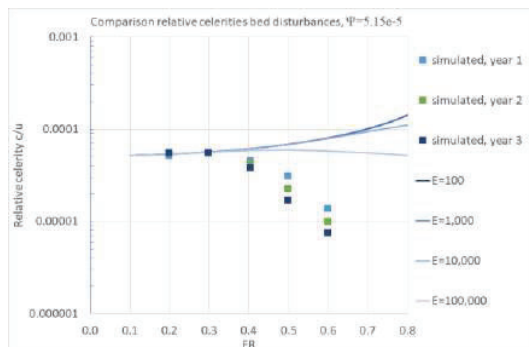


Figure 2. Relative celerity of full dynamic model: theory and simulated (ELV, average over three years).

In Figure 3 the full dynamic model (DYN) and simplified models are compared. The Figure shows the ratios of celerity of bed disturbances from theory (lines) and ELV (markers).

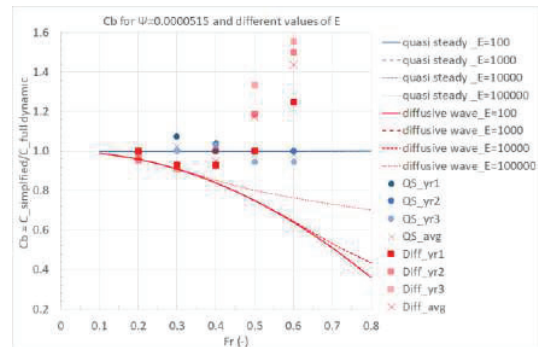


Figure 3. Ratio of celerities (c_b) from theory and ELV.

ELV results in Figure 3 are based on small perturbations for flow and bed. Simulations with large bed disturbances (aggradation 0.5 m over 1 km river length) and flood waves show similar trends.

Discussion

For Froude numbers up to 0.3, celerities of bed disturbances from theory and simulations agree. For larger Froude numbers the theoretical celerities are larger than according to numerical simulations. Nonetheless, for the quasi-steady model the theoretical error prediction for propagation (and damping) of bed disturbances is confirmed by numerical simulations. The quasi-steady model may be applied over a large range of hydrodynamic and morphological conditions. This model does not include flood wave damping. This aspect should be included alternatively.

The diffusive-wave model does describe flood wave damping, but the error prediction deviates from numerical results for $Fr \geq 0.4$. Up to $Fr=0.3$ the error in morphological changes with the diffusive-wave model is restricted to 10%.

Deviations between theory and numerical modelling require further research.

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