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Accuracy of Numerical Morphological Models based on Simplified Hydrodynamics

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Introduction

Sustainable river management often requires long-term morphological simulations. As the future is unknown, uncertainty needs to be accounted for, which may require probabilistic simulations covering a large parameter domain. Even for one-dimensional models, simulation times can be long. One of the acceleration strategies is simplification of models by neglecting terms in the governing hydrodynamic equations. Examples are the quasi-steady model and the diffusive wave model, both widely used by scientists and practitioners. We established under which conditions these simplified and often more efficient models are accurate.

Method

Based on results of linear analyses of the St. Venant-Exner equations, we assessed migration celerities and damping of long riverbed perturbations (Barneveld et al, 2024). We did this for the full dynamic model, i.e. no terms neglected, as well as for simplified models. For the quasi-steady model the time derivatives in the Saint-Venant equations are neglected. The discharge may still vary over time, but for every time-step steady flow conditions are simulated. The diffusive wave model neglects both inertial terms in the momentum equation. This model has been proven accurate for predicting migration and damping of flood waves in lowland rivers.

The accuracy of the simplified models was obtained from comparison between the characteristics of the riverbed perturbations for simplified models and the full dynamic model.

We executed a spatial-mode and a temporal-mode linear analysis, which differ only in the periodic solution for the linearized set of equations.

We compared the results of the linear analyses and numerical modelling results in terms of propagation and damping of riverbed waves. For the numerical modelling we applied the numerical modelling code ELV (Chavarrías et al., 2019), which allows simulating the full dynamic and both simplified models.

For very small bed waves the linear analyses and numerical modelling should provide identical results. Simulations with larger bed waves are performed to assess whether the linear analyses results can be used for field cases.

Results

The results from the linear analyses and numerical simulations for small (infinitesimal) riverbed perturbations, show to be in good agreement. This provides confidence the approach is valid.

For longer and higher river bed waves the ratio of celerities are shown in Figure 1 as a function of the Froude Number *F* and the dimensionless sediment transport parameter Ψ:

$$\Psi = n \, \frac{s_o}{q_o} \qquad (1)$$

With

n = the power in the sediment transport relation ($s = m \cdot u^n$). For Engelund-Hansen transport predictor *n*=5

s_o = steady uniform sediment transport per unit width ($m^2\ s^{-1}$)

q_o = steady uniform discharge per unit width ($m^2\ s^{-1}$)

In the spatial mode analysis the dimensionless flow variation parameter *E* is the third parameter of importance, which expresses the influence of unsteadiness and non-uniformity of the flow on a scale larger than the local flow depth. For river cases *E* is normally well over 10,000. In the temporal mode analysis the wave length of the river bed waves *L* is the third parameter determining the bed dynamics.

Figure 1 shows that the temporal mode analysis and numerical results for several years are well in line. The spatial mode results deviate from numerical results when *F*>0.2.

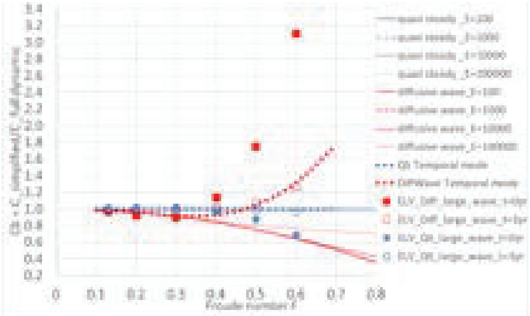

Figure 1. Ratio of celerities obtained from simplified (QS=quasi-steady) and full dynamic models for linear stability analyses and numerical results for long (L = 3,000 m) and large (0.5 m amplitude) bed perturbations under a flood wave regime, Ψ = 5.15 · 10 −5, Δt = 1 s, Δx = 25 m.. The spatial model results are illustrated with the thin lines. The temporal mode analyses results are shown with thick dotted lines and the numerical results are with the markers. Source: Barneveld et al. (2024).

Conclusions

The numerical results appear to match best with the temporal-mode linear analysis.

We show that the quasi-steady model is highly accurate for Froude numbers up to 0.7, probably even for long river reaches with large flood wave damping. Although the diffusive wave model accurately predicts flood wave migration and damping, key morphological metrics deviate more than 5% (10%) from the full dynamic model when Froude numbers exceed 0.2 (0.3). Based on the temporal model analysis Figure 2 provides a design graph for assessing the error of simplified models for various combinations of the parameters Froude number *F*, wave length *L* and one value for the transport parameter *Ψ*.

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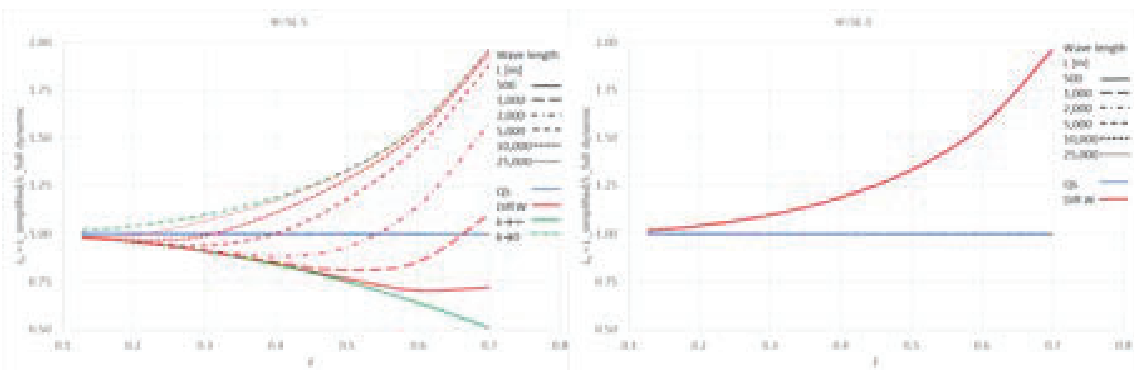

Figure 2. Ratio of migration celerities (left) and ratio of damping length (right) obtained from simplified and full dynamic models for the sediment transport parameter Ψ= 5·10⁻⁵. Green lines in the left panels indicate, for the diffusive wave, limit cases for the wave number $k_r \rightarrow \infty$ (short bed waves, firm line) and $k_r \rightarrow 0$ (long bed waves, dotted line).

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