Five common mistakes in fluvial morphodynamic modeling

Mosselman, E; Le, TB

DOI
10.1016/j.advwatres.2015.07.025

Publication date
2016

Document Version
Accepted author manuscript

Published in
Advances in Water Resources

FIVE COMMON MISTAKES IN FLUVIAL MORPHODYNAMIC MODELLING

by

E. (Erik) Mosselman [1,2] and T.B. (Thai Binh) Le [1]

[1] Delft University of Technology, Faculty of Civil Engineering and Geosciences, Stevinweg 1, 2628 CN Delft, the Netherlands

[2] Deltares, Boussinesqweg 1, 2629 HV Delft, the Netherlands

Keywords

River morphodynamics, numerical modelling, alternate bars

Abstract

Recent years have seen a marked increase in the availability of morphodynamic models and a proliferation of new morphodynamic codes. As a consequence, morphodynamic models are increasingly developed, used and evaluated by non-experts, possibly leading to mistakes. This paper draws attention to five types of common mistakes. First, new morphodynamic codes are developed as extensions of existing hydrodynamic codes without including all essential physical processes. Second, model inputs are specified in a way that imposes morphodynamic patterns beforehand rather than letting them evolve freely. Third, detailed processes are parameterized inadequately for application to larger spatial and temporal scales. Fourth, physical and numerical phenomena are confused when interpreting model results. Fifth, the selection of modelling approaches is driven by

the belief that complete data are a prerequisite for modelling and that the application of 2D and 3D models requires more data than the application of 1D models. Examples from fluvial morphodynamics are presented to illustrate these mistakes.

1. INTRODUCTION

Fast technological developments have fuelled impressive advances in two-dimensional depth-averaged (2DH) numerical models of river morphodynamics over the past eighty years. Van Bendegom's (1947) numerical code was solved by hand in the 1930s, when a calculator was still a profession instead of a machine. Today, river engineers visit a river in a far-away country, collect elementary data on the spot, set up a computational grid based on Google Earth in their Wi-Fi-equipped hotel room in the evening, run a morphodynamic simulation, and present plots and animations of the morphodynamic evolution to the client or stakeholders the next morning.

The technological developments have also increased the number, the availability and the user-friendliness of morphodynamic codes. As a consequence, morphodynamic models are increasingly developed, used and evaluated by non-experts. Mosselman (2012) and Sloff & Mosselman (2012) argue, after Van Zuylen et al (1994), that modelling of river morphodynamics requires teams or communities with specialists in (i) domain knowledge based on experience with real rivers; (ii) knowledge about model concepts such as the underlying mathematical equations; (iii) knowledge about model constructs such as grids, time steps, morphological acceleration factors and spin-up times; and (iv) knowledge about model artefacts such as user interfaces and file formats. Mistakes are possible if the modelling team does not cover this full range of expertise. Our objective is to share our experiences on five common mistakes from over 25 years of involvement in executing, supervising and reviewing modelling of river morphodynamics. This has been inspired by Salt's (2008) similar but broader paper on mistakes in simulation modelling that bears relevance for river morphodynamic modelling too.

Our approach in this paper is as follows. We set up a simple numerical model for water flow in a straight channel with a mobile bed. We run simulations with this model to illustrate two of the five mistakes. The other three mistakes are explained without model simulations. We discuss a few considerations behind the list of common mistakes, the use of a morphological acceleration factor, and the implications for model validation. Finally, we provide recommendations for modellers as well as supervisors and reviewers of numerical computations in fluvial morphodynamics.

2. SET-UP OF NUMERICAL COMPUTATIONS

We set up a Delft3D model, based loosely on the numerical model of Crosato et al (2011), for a 10 km long and 90 m wide straight channel (Figure 1). The gradient, i, was equal to 0.1 m/km, the discharge, Q, was 180 m^3/s and the Chézy coefficient for hydraulic roughness, C, was 42.84 m$^{1/2}$/s. These values produced a reach-averaged flow depth, h_0, of 2.793 m and a reach-averaged flow velocity, u_0, of 0.716 m/s. The median sediment grain size, D_{50}, was equal to 0.2 mm. At the entrance of the channel, a 30 m long cross-dam protruded perpendicularly from the left bank into the channel in order to generate the development of a pattern of steady alternate bars downstream (Struiksma et al, 1985). We used the Engelund & Hansen (1967) formula to calculate sediment transport, and the following formula to calculate the influence of transverse bed slopes on the direction of sediment transport:

$$f(\theta) = 0.5\theta^{0.5} \tag{1}$$

where θ denotes the Shields parameter and $f(\theta)$ is a function weighing the influence of transverse bed slopes, following the notation of Struiksma et al (1985) and Talmon et al (1995). We did not attempt to calibrate the model on any particular channel in reality, because the purpose of the computations was simply to demonstrate the effect of certain settings, representing mistakes, on model results.

The computations were carried out with a morphological acceleration factor of 10. The computations were terminated after simulation of 500 days. We computed a reference case, leading to a longitudinal bed level profile along the right bank presented in Figure 2, and two cases illustrating common mistakes. The first illustration regards the effect of omitting the dependence of sediment transport direction on gravity pull along transverse bed slopes. The second effect regards the effect of non-homogeneous distributions of hydraulic roughness.

3. THE FIVE COMMON MISTAKES

3.1 Codes with inadequate representation of physical processes

An important feature of sediment transport in rivers is that its direction can deviate from the depth-average flow direction by two mechanisms. First, the interplay of centrifugal forces and pressure gradients in curved flows gives rise to a helical motion by which flow velocity vectors exhibit an inward deviation near the bed and an outward deviation near the water surface. Accordingly, the direction of bedload differs from the depth-average flow direction. The same holds for the depth-average vector of suspended sediment transport as long as the corresponding concentrations are not distributed homogeneously over the vertical. The second mechanism for deviations between the direction of sediment transport and depth-average flow is that sediment particles move by a combination of flow forces and gravity. Particles moving over a transversely sloping bed thus experience gravity pull in a direction perpendicular to the direction of the flow shear stresses, producing a difference between the directions of flow and sediment transport.

Results of morphodynamic computations appear to depend sensitively on these differences in direction. Well-established morphodynamic codes account for these differences through parameterized representations of these mechanisms. In new codes, however, these effects are not always accounted for, often because they are developed as simple extensions of 2D or 3D hydrodynamic codes with sediment transport formulas and a sediment mass balance. Figure 3 shows the effect of omitting the effect of transverse bed slopes on sediment transport direction from our model. The resulting bed morphology is completely different, with a shorter wave length and less downstream attenuation.

Apparently the bed slope effect has a damping or stabilizing influence on morphodynamic evolution of the river bed. This can be understood by considering the 2D depth-averaged sediment balance for flow in x direction (cf. Mosselman, 2005):

$$\frac{\partial z_b}{\partial t} + \frac{\partial q_{sx}}{\partial x} + \frac{\partial q_{sx} \tan\alpha}{\partial y} = 0 \qquad (2)$$

with

$$\tan\alpha = -\frac{1}{f(\theta)} \frac{\partial z_b}{\partial y} \qquad (3)$$

in which z_b denotes bed level, q_{sx} is the sediment transport rate per unit width in flow direction, α is the angle between the directions of flow and sediment transport, t is time, and x and y are co-ordinates in flow direction and transverse direction, respectively. Substitution of the latter equation into the sediment balance yields

$$\frac{\partial z_b}{\partial t} - \frac{q_{sx}}{f(\theta)} \frac{\partial^2 z_b}{\partial y^2} = \frac{\partial z_b}{\partial y} \frac{\partial}{\partial y}\left(\frac{q_{sx}}{f(\theta)}\right) - \frac{\partial q_{sx}}{\partial x} \tag{4}$$

This is a diffusion equation for bed level, forced by gradients in sediment transport. The diffusive second term is responsible for the damping or stabilization. This explains the reduced attenuation of alternate bars when omitting the effect of transverse bed slopes.

Similar diffusion terms, however, arise from truncation errors in the numerical discretization. For instance, a simple upwind discretization of the transverse bed gradient could be

$$\frac{\partial z_b}{\partial y} = \frac{z_b^n - z_b^{n-1}}{\Delta y} \tag{5}$$

Taylor series expansion results in

$$z_b^{n-1} = z_b^n - \Delta y \frac{\partial z_b}{\partial y} + \frac{(-\Delta y)^2}{2} \frac{\partial^2 z_b}{\partial y^2} + \text{higher order terms} \tag{6}$$

This means that the true representation of the discretized transverse bed level gradient reads

$$\frac{z_b^n - z_b^{n-1}}{\Delta y} = \frac{\partial z_b}{\partial y} - \frac{\Delta y}{2}\frac{\partial^2 z_b}{\partial y^2} + \text{higher order terms} \tag{7}$$

Grid dependent truncation errors can hence have the same effect as inclusion of the physics-based effect of transverse bed slopes. This may hide the effect of omitting this mechanism in the sense that model results could be plausible for the wrong reasons. This renders correct calibration, verification and interpretation challenging.

A closely related, frequently occurring case of inadequate representation of physical processes is the application of sediment transport adaptation lengths to cases where in reality such lengths are negligible. The adaptation of non-equilibrium sediment transport can be described by a relaxation equation

$$q_{sx} + L\frac{\partial q_{sx}}{\partial x} = q_{se} \tag{8}$$

where L is the adaptation length and q_{se} is the equilibrium sediment transport rate per unit width predicted by a sediment transport capacity formula. Substitution into the 1D sediment balance (i.e. eq. 2 without the third term) results in

$$\frac{\partial z_b}{\partial t} + \frac{\partial q_{se}}{\partial x} - L\frac{\partial^2 q_{sx}}{\partial x^2} = 0 \tag{9}$$

The adaptation term appears to have a diffusive effect too. Some modellers use L to make their model stable while claiming that this parameter represents the real physical effect of retarded adaptation of non-equilibrium sediment transport, even if the Rouse number is too large to support this claim. It would be better if they would state L to be a numerical stability parameter right away, to avoid erroneous conclusions about the nature of the sediment transport in the system.

A final example of inadequate representation of physical processes is the confusion between capacity-limited and supply-limited sediment transport. Models based on sediment transport capacity formulas (with or without adaptation lengths for non-equilibrium transport) are sometimes calibrated on measured suspended sediment concentrations that represent a mixture of bed-material load and washload. Only the bed-material load is capacity-limited; washload is supply-limited. In certain codes, sediment transport formulas for capacity-limited transport are erroneously used to calculate the entrainment of sediment from the bed in convection-diffusion approaches that are essentially supply-limited.

3.2 Inputs that impose morphodynamic patterns

A second common mistake occurs when model inputs impose morphodynamic solutions that suppress the real morphodynamic behaviour. A widespread practice, for instance, is so-called "fine-tuning" in which a model is calibrated by adjusting the hydraulic roughness on a point-by-point basis. The resulting spatial roughness distribution generates a morphodynamic response (cf. Sloff & Mosselman, 2012). To illustrate this, we applied a pattern of 416 m long and 45 m wide rectangular roughness patches to the channel in our model (Figure 4). The Chézy roughness values of the patches alternated between 37.49 and 51.41 $m^{1/2}/s$. The equivalent uniform Chézy value with the same average roughness is hence equal to $[0.5(37.49^{-2}+51.41^{-2})]^{-1/2}$ = 42.84 $m^{1/2}/s$, as in the reference case. Figure 5 shows the results of computations with this configuration. The imposed hydraulic roughness pattern produces higher alternate bars than the cross-dam, with a different wave length. Calibration by local adjustment of field parameters can prevent the model river bed from evolving freely and it reduces the predictive power of the model. Spatial variations of field parameter values can be meaningful if they result from physical processes, for instance described by an alluvial roughness predictor. They are not meaningful if they are imposed by fixed values.

Erroneous morphodynamic solutions can be imposed not only by spatial variations in field parameter values but also by boundary conditions if the boundaries are too close to the area of interest. The required distance to boundaries with uncertain conditions depends on the simulation period, because the influence of boundaries reaches further as the period becomes longer. The effect of sediment entry errors propagates into the model at a celerity, c, given by (De Vries, 1965)

$$c = \frac{bq_{sx}}{h} \tag{10}$$

where h denotes flow depth and b is defined by

$$b = \frac{u}{q_{sx}} \frac{\mathrm{d}q_{sx}}{\mathrm{d}u} \tag{11}$$

in which u is the depth-averaged flow velocity. Ideally, the upstream boundary is selected at such a distance, L_b, that sediment entry errors do not reach the area of interest within the simulation period, T_s:

$$L_b > cT_s \tag{12}$$

assuming that these errors are a main source of uncertainty. Similarly, a minimum required distance can be derived from the condition that morphological developments due to interventions in the area of interest should not reach the upstream boundary within the simulation period, as this would compromise the morphological condition imposed at the boundary. The relative effect at the upstream boundary should be smaller than a prescribed tolerance, ε, e.g. $\varepsilon = 0.05$ or $\varepsilon = 0.1$. According to the theory of De Vries (1975) this can be expressed as

$$\operatorname{erfc}\left(L_b \sqrt{\frac{3i}{4bq_{se}T_s}} \right) < \varepsilon \tag{13}$$

where i is the longitudinal river gradient and 'erfc' stands for the complementary error function. Equations 12 and 13 imply that long simulation times might require long distances between the area of interest and the upstream boundary, impractical not only for reasons of computation time but also for reasons of including reaches with unknown water and sediment inflows from tributaries. In practice shorter models are chosen in which, hence, the morphodynamic development is forced by the boundary conditions. Such models have lower predictive power, but can still be meaningful for sensitivity and scenario analyses. They are hence not necessarily mistaken. Ignoring the forcing by boundary conditions when interpreting the results, however, does form a mistake.

Erroneous morphodynamic solutions can also arise from errors in the initial conditions. The effects disappear after some spin-up time if the sediment is uniform and the banks are fixed. In case of non-uniform sediment or erodible banks, however, the effects may last throughout the simulation.

3.3 Inadequate upscaling

Numerical models for fluvial morphodynamics solve equations that result from the integration of small-scale processes over time and space. New concepts or phenomena may emerge from this "parameterization" or "upscaling". For instance, exchange processes due to turbulent fluctuations can be represented on larger time scales by employing eddy viscosities in Reynolds-Averaged Navier-

Stokes (RANS) models. The proper value of the eddy viscosity to be applied in a particular case depends on the dimensions of the flow considered. Selecting a wrong value can be seen as inadequate upscaling of the effects of turbulence.

Another example of this third common mistake occurs in the modelling of mixed-sediment morphodynamics. Here complex processes of grain sorting (cf. Blom et al, 2003) can be scaled up to the Saint-Venant-Hirano model, with an active bed layer in which the changes in bed sediment composition take place. The latter emergent feature has a dominant effect on model results. Under certain conditions it even leads to an elliptic set of equations in time and space, which is physically unrealistic (Ribberink, 1987; Stecca et al, 2014). Outside conditions of ellipticity, the thickness of the active layer governs the competition between two types of morphodynamic adjustment: bed level change and change in bed sediment composition. Mosselman & Sloff (2007) and Sloff & Mosselman (2012) characterize this competition by the ratio of the time scales for adjustment of bed levels, T_{bed}, and adjustment for bed sediment composition, T_{mix}:

$$\frac{T_{mix}}{T_{bed}} \propto \frac{\delta}{h} \tag{14}$$

in which δ represents the active-layer thickness. When modelling laboratory experiments with constant uniform flow, this thickness corresponds typically to the height of bedforms. When modelling real rivers, however, the active-layer thickness represents also the effect of other factors reworking the bed within a morphological time step, such as the variation of cross-sectional bed tilting in river bends under varying discharges and the generation of erosion and deposition waves at locations where water enters or leaves the floodplains during floods. The thickness can thus be much larger than the height of bedforms. Inadequate upscaling by taking the active-layer thickness equal to bedform height can make this layer too thin and hence the time for adjustment of bed sediment composition too short compared to the time for adjustment of bed levels. This leads to erroneous suppression of bed level changes (Sloff & Mosselman, 2012).

3.4 Confusion of physical and numerical phenomena

The fourth common mistake is the confusion of physical and numerical phenomena. The truncation errors of numerical schemes can produce phenomena such as oscillations (“wiggles”), growth (“instability”) and attenuation (“smearing”, “diffusion”). These numerical artifacts can dominate the results or simply alter the physics-based oscillations, growth and attenuation. The examples of transverse-bed slope effects, sediment transport adaptation lengths and numerical truncation errors in Section 3.1 showed that distinguishing numerical effects from physical phenomena can be difficult. Analytical solutions can help in making this distinction. Sometimes numerical diffusion is accepted on purpose when model stability is considered more important than model accuracy. Users of Delft3D, for instance, can choose using an accurate central scheme or a more robust upwind scheme. The choice should be reported when presenting model results.

The effects of truncation errors can be assessed and minimized by reducing the sizes of computational grid cells. Numerical errors also arise, however, from the schematized representation of river geometry. This type of errors is often compensated by modifying model parameters in the calibration. These parameters then lose their strict physical meaning and can no longer be calculated straightforwardly from fundamental considerations. Hydraulic resistance, for instance, becomes a bulk parameter that depends not only on physics-based drag but also on the deviations between the river geometries in the model and in the prototype. The same holds for bank erodibility parameters in morphodynamic models for river planform evolution. A commonly used formula for river bank erosion reads

$$\frac{\partial n}{\partial t} = E\left(\tau - \tau_c\right) \tag{15}$$

where $\partial n / \partial t$ denotes the rate of bank retreat, E is the bank erodibility, τ is the bank shear stress exerted by the flow and τ_c is the critical bank shear stress for erosion. In theory, values of E and τ_c could be derived from material properties of the bank soil. Crosato (2007) demonstrates, however, that values derived in this way are erroneous because the parameters account also for the numerical effects of bankline smoothing and regridding. Proper values for E and τ_c hence require calibration. Assigning values based on soil properties is a mistake in morphodynamic models for river planform evolution.

3.5 Belief that 2D and 3D models require more data than 1D models

The fifth common mistake regards a misconception *about* approaches to modelling rather than an actual mistake *within* approaches to modelling. This regards the belief that 2D and 3D models require more data than 1D models and hence often cannot be used due to a lack of data. This is tenable for neither initial condition data nor boundary condition data. A main initial condition for morphodynamic models is the bed topography, for which all models can use a set of river cross-sections. One-dimensional models incorporate these cross-sections directly. Two- and three-dimensional models use these cross-sections for an initial calibration of bed levels, but this does not present any particular difficulties. On the contrary, it is easier to set up and calibrate a 2D or 3D model than a 1D model because the latter requires an additional step of data schematization. For instance, the flow path between two consecutive river stations can be longer along a sinuous main channel at low discharge than along the more straight floodplains at high discharge. Two- and three-dimensional models reproduce this feature automatically. One-dimensional models require manipulation of stage-dependent hydraulic roughness parameters to translate all distances to the same length in the model.

Boundary conditions for 2D and 3D models must be specified in the form of distributions over the inflow and outflow sections, whereas single values are sufficient for the boundary conditions of 1D models. Reasonable estimates, however, can be made for these distributions, without the need of more field data. The upstream discharge can be distributed in proportion to the conveyance of each part of the inflow section. The supply of sediment to each computational cell at the upstream boundary can be assumed equal to the local transport capacity of the flow to avoid the generation of spurious erosion and sedimentation. Sediment overloading and underloading can be specified as a constant percentage of the supply to each cell. The downstream water level can be assumed horizontal in the outflow section. In 3D models, the vertical distributions of discharges can be specified in accordance with logarithmic flow velocity profiles.

A 1D approach may be sufficient for large-scale sediment budgets and the overall development of longitudinal river profiles. Many morphological problems, however, such as navigability improvement, ask for 2D spatial distributions of channels and bars. The appropriate approach depends on the purposes of the modelling, not on data availability. The false belief that 2D and 3D numerical models require a lot of data often leads to abandoning these options, for the wrong reasons, in favour of 1D numerical models, physical models, or even no model at all.

Assertions that modelling is not possible because of a lack of data are often a fallacy. They could be parried with the assertion that data collection is not possible if there is not any model. Initial modelling helps in identifying data gaps and defining an effective measurement campaign. In reality, of course, data collection and modelling are complementary and go hand-in-hand in successive steps of improvement.

4. DISCUSSION

One of the reviewers suggested our criticism of modellers of fluvial morphodynamics could be seen as a disguised advertisement of our own modelling capabilities. This is not our intention, because we make mistakes too. Rather, by sharing our experiences, we seek to empower the growing community of both executers and users of morphodynamic modelling, academic and applied. We focus on experiences that recur frequently and are specific for fluvial morphodynamics, without detracting from Salt's (2008) more general warnings that are equally relevant for fluvial morphodynamics but not repeated in this paper. The same reviewer also suspected we criticize river engineers who carry out simulations in their Wi-Fi-equipped hotel room in the evening and present animations of the morphodynamic evolution to the client the next morning. On the contrary, we find the technological progress that made this possible a great achievement. Even without full calibration and validation, such simulations can be powerful for a diagnosis of morphological problems and a first assessment of the effectiveness of interventions.

We ran the model with a morphological acceleration factor of 10. This does not affect the results in this case of a constant discharge, uniform sediment and fixed banks. In other cases, however, such factors may introduce errors by distorting the relation between the time scales of different processes (cf. Vanzo et al, 2015). A morphological factor of 2, for instance, implies that a sequence of two identical discharge hydrographs would be merged into a single discharge hydrograph with double duration. Each discharge level would retain the same frequency of occurrence, but the dynamics of the emptying and filling of storage areas would change as the volumes of excess discharges in a single flood would be doubled. The storage dynamics could be corrected by splitting the original two hydrographs into four hydrographs with halved duration each. The morphological factor of 2 would then restore the original two hydrographs. Short sharply peaked flood waves, however, experience stronger attenuation as they travel downstream than longer flood waves with a broader peak, so that this correction of storage dynamics could distort the dynamics of flood wave propagation. Although we do not experience careless use of morphological factors as a common mistake, the possible adverse effects do represent an important caveat.

The common mistakes presented here have a bearing on validation. Mosselman (2012) argues that acceptance criteria for validation should not be limited to metrics for the differences between computed and observed values. Validation methods correcting spatial offsets (Bosboom & Reniers, 2014) may offer improvements but are not sufficient. Validation criteria should also address the reproduction of characteristic features such as wave length and amplitude attenuation. Mosselman (2012) advocates the development of a set of internationally agreed validation cases with corresponding criteria for acceptance. Considering the present paper, these criteria should support the detection of inadequate representation of physical processes, forcing of morphodynamic patterns by manipulated inputs, inadequate upscaling, and confusion of physical and numerical phenomena.

5. CONCLUSIONS AND RECOMMENDATIONS

We have drawn attention to five types of common mistakes in fluvial morphodynamic modelling. First, physical processes can be represented inadequately, especially if new morphodynamic codes are developed as extensions of existing hydrodynamic codes. Second, model inputs can be specified in a way that imposes morphodynamic patterns beforehand rather than letting them evolve freely. Third, detailed processes can be parameterized inadequately for application to larger spatial and temporal scales. Fourth, physical and numerical phenomena can be confused. Fifth, the selection of modelling approaches can be driven by the erroneous belief that complete data are a prerequisite for modelling and that applying 2D and 3D models requires more data than the application of 1D models.

We recommend to all stakeholders of fluvial morphodynamic modelling that they recognize the full range of expertise needed, often requiring team work. We recommend to modellers that they study the background of the processes represented by the mathematical equations, including the pitfalls of common mistakes. Our advice to supervisors and reviewers is that they verify in particular the inputs and modelling settings that correspond to the common mistakes presented in this paper. This involves inquiring about the representation of bed slope effects and helical flow, having maps plotted of hydraulic roughness values and bed sediment grain sizes, evaluating the distances to model boundaries in relation to simulation times, and checking results against estimates from analytical solutions.

ACKNOWLEDGEMENTS

We thank Nunzio Siviglia for his encouragement to write this paper and two anonymous reviewers for their valuable comments.

REFERENCES

Blom, A., J.S. Ribberink & H.. de Vriend (2003), Vertical sorting in bed forms. Flume experiments with a natural and a tri-modal sediment mixture. Water Resources Res., AGU, Vol.39, No.2, p.1025.

Bosboom, J. & A.J.H.M. Reniers (2014), Displacement-based error metrics for morphodynamic models. Advances in Geosciences, 39(1), pp.37-43.

Crosato, A. (2007), Effects of smoothing and regridding in numerical meander migration models, Water Resources Res., AGU, 43, W01401, doi:10.1029/2006WR005087.

Crosato, A., E. Mosselman, F. Beidmariam Desta & W.S.J. Uijttewaal (2011), Experimental and numerical evidence for intrinsic nonmigrating bars in alluvial channels, Water Resources Research, Vol.47, W03511, doi:10.1029/2010WR009714.

De Vries, M. (1965), Considerations about non-steady bed-load transport in open channels. Proc. 11th Congress IAHR, Leningrad (also Delft Hydraulics Laboratory Publication No.36, Delft, the Netherlands).

De Vries, M. (1975), A morphological time-scale for rivers. Proc. 16th Congress IAHR, São Paolo (also Delft Hydraulics Laboratory Publication No.147, Delft, the Netherlands).

Engelund, F. & E. Hansen (1967), A monograph on sediment transport in alluvial streams. Teknisk Forlag, Copenhagen.

Mosselman, E. (2005), Basic equations for sediment transport in CFD for fluvial morphodynamics. Chapter 4 in: Computational Fluid Dynamics; Applications in environmental hydraulics, Eds. P.D. Bates, S.N. Lane & R.I. Ferguson, Wiley, pp.71-89.

Mosselman, E. & C.J. Sloff (2007), The importance of floods for bed topography and bed sediment composition: numerical modelling of Rhine bifurcation at Pannerden. In: Gravel Bed Rivers VI – From process understanding to river restoration, Eds. H. Habersack, H. Piégay & M. Rinaldi, Developments in Earth Surface Processes, 11, Elsevier, Amsterdam, 2008, ISSN 0928-2025, pp.161-180, DOI: 10.1016/S0928-2025(07)11124-X.

Mosselman, E. (2012), Modelling sediment transport and morphodynamics of gravel-bed rivers. Chapter 9 in Gravel-bed rivers: processes, tools, environments. Eds. M. Church, P. Biron & A.G. Roy, 2012, Chichester, John Wiley & Sons: 563pp. ISBN 978-0-470-68890-8, pp.101-115.

Ribberink, J.S. (1987), Mathematical modelling of one-dimensional morphological changes in rivers with non-uniform sediment. Communications on Hydraulic and Geotechnical Engineering, No.87-2, Delft University of Technology, ISSN 0169-6548.

Salt, J.D. (2008), The seven habits of highly defective simulation projects. Journal of Simulation 2, 155-161 (November 2008) | doi:10.1057/jos.2008.7.

Sloff, K. & E. Mosselman (2012), Bifurcation modelling in a meandering gravel-sand bed river. Earth Surface Processes and Landforms, BGRG, Vol.37, pp.1556-1566, DOI:10.1002/esp.3305.

Stecca, G., A. Siviglia, & A. Blom (2014), Mathematical analysis of the Saint-Venant-Hirano model for mixed-sediment morphodynamics, Water Resources Res., AGU, Vol.50, doi:10.1002/2014WR015251.

Struiksma, N., K.W. Olesen, C. Flokstra & H.J. de Vriend (1985), Bed deformation in curved alluvial channels. J. Hydr. Res., IAHR, Vol.23, No.1, pp.57-79.

Talmon, A.M., N. Struiksma & M.C.L.M. van Mierlo (1995), Laboratory measurements of the direction of sediment transport on transverse alluvial-bed slopes. J. Hydr. Res., IAHR, Vol.33, No.4, pp.495-517.

Van Bendegom, L. (1947), Some considerations on river morphology and river improvement. De Ingenieur, Vol.59, No.4 (in Dutch; English transl.: Natl. Res. Council Canada, Tech. Translation 1054, 1963).

Van Zuylen, H.J., D.P. Dee, A.E. Mynett, G.S. Rodenhuis, J.R. Moll, H.J.M. Ogink, H. van der Most, H. Gerritsen & G.K. Verboom (1994), Hydroinformatics at Delft Hydraulics. J. Hydr. Res., IAHR, Vol.32, Extra Issue Hydroinformatics, pp.83-136.

Vanzo, D., A. Siviglia & G. Zolezzi (2015), Long term 2D gravel-bed river morphodynamics simulations using morphological factor: are final configurations always reliable? Advances in Water Resources, [submitted for the same special issue].

LIST OF FIGURES

Figure 1. Basic set-up of numerical model for water flow in a straight-channel with a mobile bed.

Figure 2. Reference bed level profile along the right bank, associated with a pattern of steady alternate bars attenuating in downstream direction.

Figure 3. Bed level profile along the right bank as a result of omitting the effect of transverse bed slopes on sediment transport direction (solid line), compared to the reference profile of Figure 2 (dashed line).

Figure 4. Rectangular roughness patches in model set-up to demonstrate the forcing effect of fixed spatially varying input parameter values.

Figure 5. Bed level profile along the right bank as a result of imposing a pattern of rectangular roughness patches (solid line), compared to the reference profile of Figure 2 (dashed line).

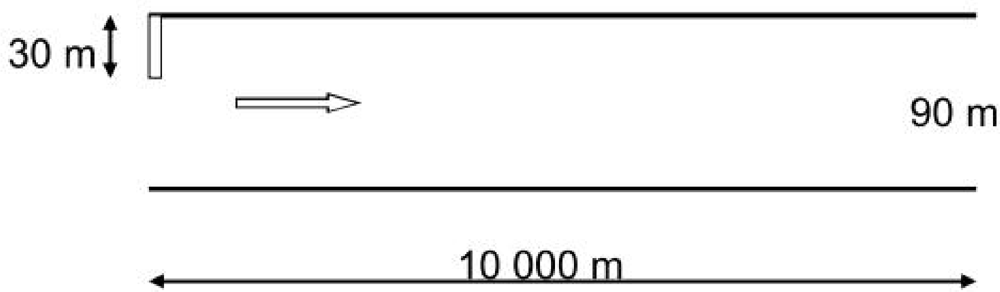

Figure 1. Basic set-up of numerical model for water flow in a straight-channel with a mobile bed.

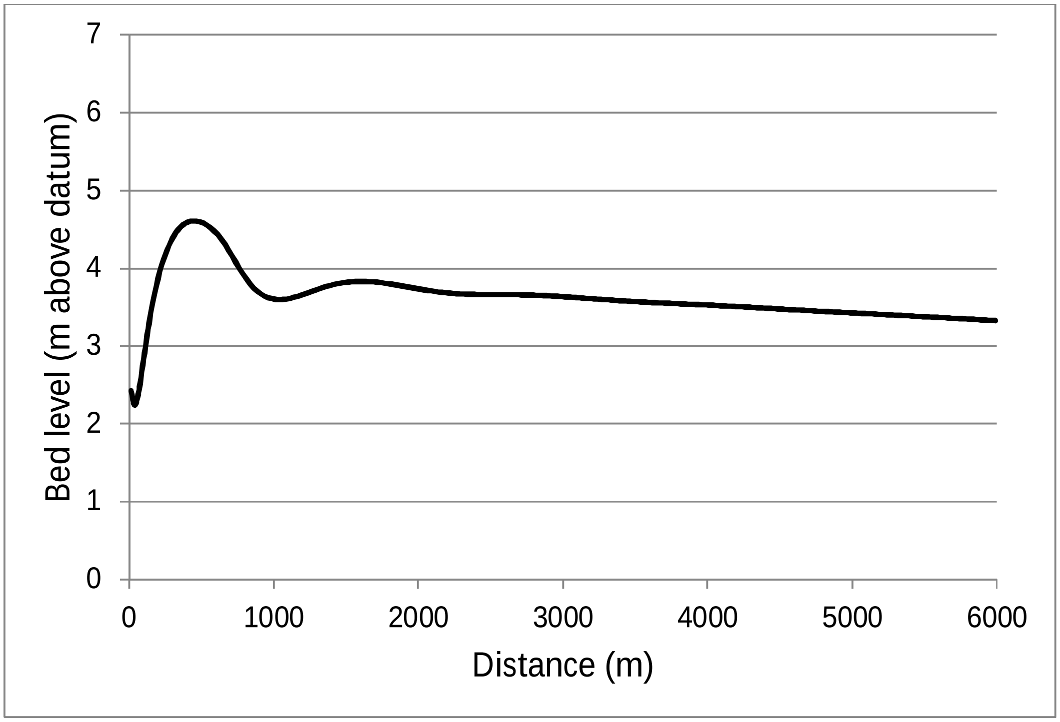

Figure 2. Reference bed level profile along the right bank, associated with a pattern of steady alternate bars attenuating in downstream direction.

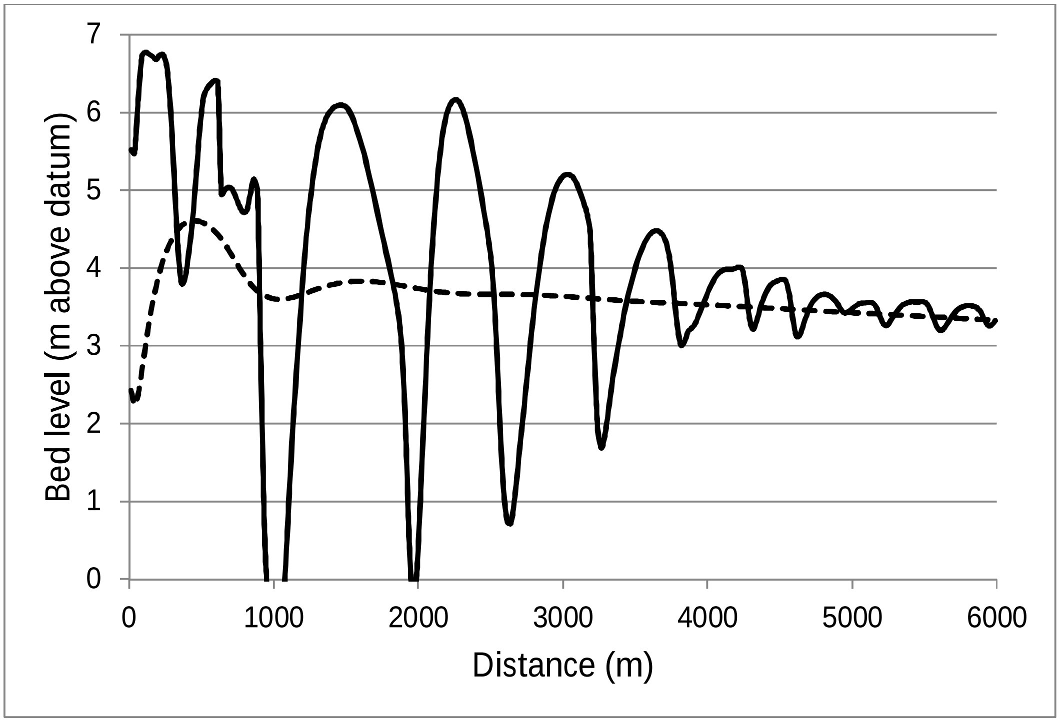

Figure 3. Bed level profile along the right bank as a result of omitting the effect of transverse bed slopes on sediment transport direction (solid line), compared to the reference profile of Figure 2 (dashed line).

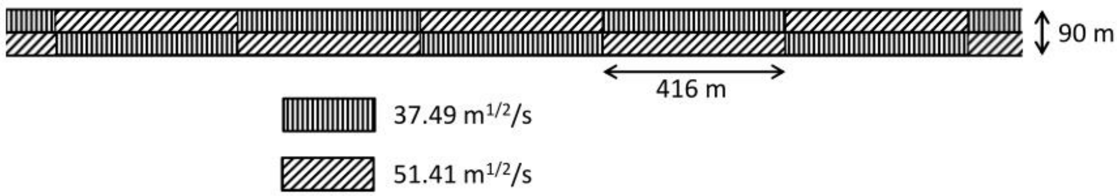

Figure 4. Rectangular roughness patches in model set-up to demonstrate the forcing effect of fixed spatially varying input parameter values.

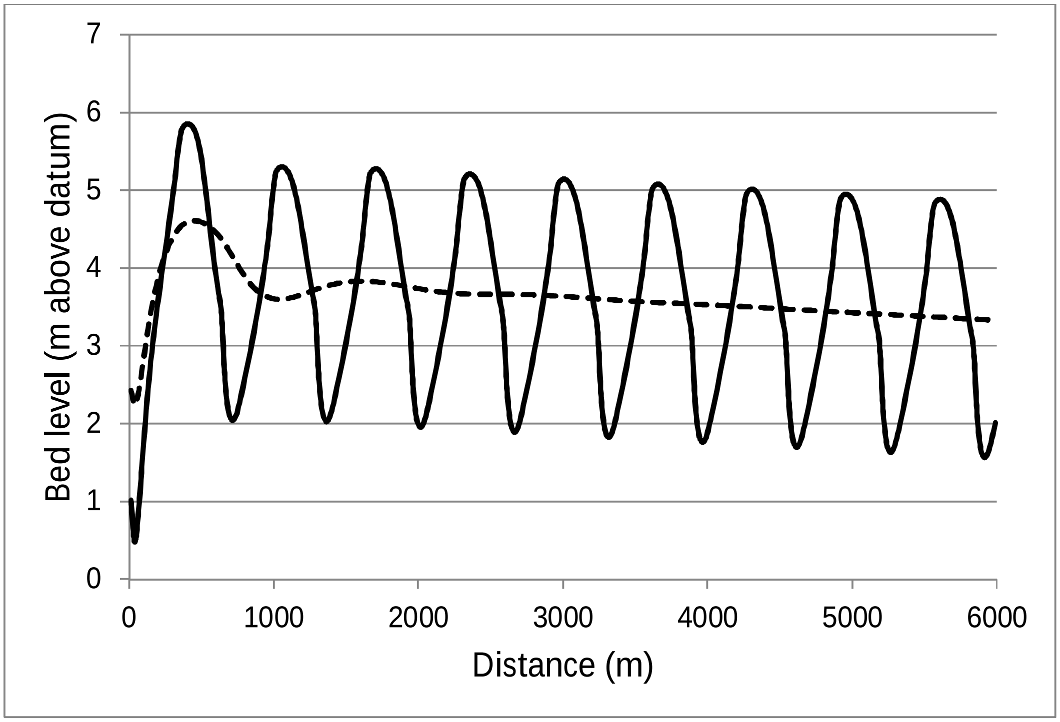

Figure 5. Bed level profile along the right bank as a result of imposing a pattern of rectangular roughness patches (solid line), compared to the reference profile of Figure 2 (dashed line).