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Development and application of a braided river model with non-uniform sediment transport

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ABSTRACT

This paper presents the development and application of a physics-based morphological model for simulating the evolution processes of braided channels. This model comprises a depth-integrated hydrodynamic sub-model for rapidly varying unsteady flows and a bed load sediment transport sub-model for non-uniform sediments. The sheltering effects of non-uniform particles and the lateral sediment transport due to bed slope and secondary flow are taken into account in the sediment sub-model. Channel bed level change is calculated according to the erosion/deposition rate, and the bank movement is modelled according to the submerged angle of repose, which is valid for braided rivers in natural and experimental conditions. The model has been applied to a braided river produced in a flume experiment, and the numerical model-predicted channel patterns are shown to generally well resemble the experimental river. Most of the morphodynamic processes observed in the experiment can be found in the numerical predictions, including the evolution of the channel from a single straight channel to a multi-thread pattern and local morphologic changes. The mechanisms of the morphodynamic evolution of multi-thread flows are investigated, in which the process of grain sorting occurs under the interaction of fluid and sand, and the effect on channel migration is identified.

1. Introduction

A braided river contains a network of multi-thread flows that split off and rejoin each other to give a braided appearance. Braided rivers often exist near mountainous regions and typically carry rather coarse-grained and heterogeneous sediments down a fairly steep gradient. The high dynamism and complexity of braided networks pose a series of open questions [7]. Natural braided-type channels can be attributed to interconnected factors, including the variety of flow regimes, bed material properties and complex interaction mechanisms between water flow and sediment transport, as well as possible vegetation colonisation and human activities. The morphodynamic process is a highly complex system, even when biological and sociological processes are not taken into account.

In natural gravel-bed rivers, the bed material typically has a wide distribution of grain size, and the size-selective nature of sediment transport has been observed for a wide range of flow conditions ([3,8], p. 106) . At single curved channels, the coarsening of sediment toward the outside bank have been found both in field and laboratory conditions [9,23,57], and mathematical models have been developed to predict this phenomenon [21,22]. Laboratory experiments have been carried out to study the development of simple braided rivers, and sorting has been observed during the dynamic evolution of a central bar, which is a basic characteristic of a braided channel. Ashworth et al. [2], Ashmore [4], and Pyrce and Ashmore [36,37] observed that coarse sediment particles were deposited on the upstream margin of a bar, while fine sediment particles were transported through the bend to the downstream bar margin. It was found from experiments by Bertoldi and Tubino [6] and Lanzoni [28] and that the deposition of coarse particles on bar fronts could slow down bed evolution rate, and this was supported by the theoretical results of Lanzoni and Tubino [29]. Most of these experimental studies were conducted with a low braiding intensity in the initiation stage of a braided pattern [2,4,6,28,36,37]. More recent physical experiments were conducted for higher braiding intensity, with homogeneous bed material being used in most of those studies [1,7,19]. Egozi and Ashmore [16,17] carried out a series of experimental runs with graded sediments, in which braided rivers were created with

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relatively high braiding intensity, and local armouring was found in the evolution process.

With increases in computer power, numerical models have been used to simulate channel evolution processes. Due to the complexity of river evolution, a better understanding of the underlying processes, including fluid flow, sediment transport, bed level changes and the interactions among them, is necessary to predict complex channel evolution processes. In recent years, physics-based numerical models have been increasingly used in modelling fluvial processes [10–12,14,24,35,38], while limited efforts have been made on modelling the processes of braided river evolution with dynamic planform evolution characteristics. Jang and Shimizu [20] used a physics-based numerical model to reproduce the features of braided rivers with erodible bed and banks composed of well-sorted sandy material. Takebayashi and Okabe [43] developed a numerical model and used it to investigate the effects of vegetation and unsteady flow on the dynamic characteristics of braided streams. Schuurman and Kleinhans [39] applied a two dimensional morphological model to produce braided bar patterns from an idealised channel, in which the sediment load was calculated using Engelund–Hansen's total load formula. Nicholas [33,34] developed a morphodynamic model, in which two grain size fractions (sand and silt) were considered, to simulate river and floodplain co-evolution within a general framework for modelling both meandering and braided rivers. In the above studies, sediment sorting in planform was not addressed, although this process has been recognised as a very important process and factor in the evolution of braided rivers [27].

Several researchers have investigated the phenomenon of selective transport of non-uniform sediment, but existing studies have mainly focused on simple planform channels instead of braided patterns. Wu [52] and Wu et al. [54] developed a non-uniform sediment transport model and applied the model to predict bed evolution and sediment sorting. Jia et al. [25] and Zhou et al. [58] applied a loose-layer model for the transport of non-uniform bed materials and used the model to simulate the morphological changes in two reaches of the Yangtze River .Xia et al. [55] modified a 2D numerical model of graded sediment transport to simulate dam-break flows and investigate the effects of bed material size distributions on the flood flow and bed evolution. Tritthart et al. [46] developed a sediment transport model and validated it against experiments by Yen and Lee [57], in which lateral bed elevation change and sorting occurred in single curved channels. Sloff and Mosselman [41] presented a morphological modelling study of a bifurcation of the Rhine with a gravel bed and a meandering planform, and analysed the physical mechanisms of sediment sorting. Xiao et al. [57] used a hydrodynamic–morphological model to simulate the downstream fining process induced by selective sorting.

From field measurements and laboratory observations, it has been found that the phenomenon of selective sediment transport is an important factor in the evolution process of braided channels. However, only a limited number of studies have been conducted in this regard. In the current study, a physics-based morphodynamic model has been developed to simulate the channel evolution processes involving multi-thread flows and selective sediment transport and to investigate the effect of the grain sorting process on the morphodynamic evolution of braided rivers. The model includes a depth-integrated hydrodynamic sub-model for rapidly varying unsteady flows and a non-uniform sediment transport sub-model for morphology. Details of the numerical model are given in Section 2. In Section 3 the application of this model to a physical experiment of a braided river is presented. The results, analysis and discussions are presented in Section 4. Finally, the conclusions obtained from the study are outlined in Section 5.

2. Numerical modelling

The mechanism of braided channel evolution is modelled using physics-based principles. The morphodynamic processes of braided rivers are closely related to water flow, non-uniform sediment transport and their interactions. In this morphological model, a horizontal two-dimensional hydrodynamic model is used for simulating rapidly varying unsteady flows, and a non-uniform sediment transport model is developed for simulating river channel evolution. The mechanism of flow-sediment interaction is included through a sediment transport rate, velocity variation caused by changing bathymetry, and sorting process with local armouring and the wetting and drying process.

2.1. Hydrodynamic model

The depth-integrated shallow water equations, including continuity and the momentum equations, are used as the governing equations of the hydrodynamic model:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = 0 \tag{1a}$$

$$\frac{\partial p}{\partial t} + \frac{\partial (\beta p U)}{\partial x} + \frac{\partial (\beta p V)}{\partial y} = -gH\frac{\partial \zeta}{\partial x} - \frac{gp\sqrt{p^2+q^2}}{H^2C^2} + \varepsilon\left(\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2}\right) \tag{1b}$$

$$\frac{\partial q}{\partial t} + \frac{\partial (\beta q U)}{\partial x} + \frac{\partial (\beta q V)}{\partial y} = -gH\frac{\partial \zeta}{\partial y} - \frac{gq\sqrt{p^2+q^2}}{H^2C^2} + \varepsilon\left(\frac{\partial^2 q}{\partial x^2} + \frac{\partial^2 q}{\partial y^2}\right) \tag{1c}$$

In this set of equations, ζ is the water surface elevation (m), $H = \zeta - z_b$ is the total water depth (m), z_b is the bed elevation (m), U and V are the depth-averaged velocity components (m/s) in the x and y directions, respectively, $(p, q) = (HU, HV)$ are the water mass fluxes per unit width (m^3/s/m) in the x and y directions, respectively, β is the momentum correction factor, g is the gravitational acceleration (m/s^2), $C = 18 \cdot \log_{10}(12H/k_s)$ is the Chezy roughness coefficient ($m^{1/2}$/s), k_s is the hydraulic roughness (m) and ε is the depth-averaged turbulent eddy viscosity (m^2/s).

The present model has been developed to predict the planform of a braided river. The grid size is selected to enable a reasonably good representation of the key braiding elements, such as bars, bifurcations and confluences. In the current study, the hydraulic roughness used in the Chezy equation is predicted using a formula by van Rijn [47], which includes the grain roughness and form roughness and is written as follows:

$$k_s = 3 \cdot d_{90} + 1.1 \cdot \Delta \cdot \left[1 - \exp\left(-\frac{25 \cdot \Delta}{7.3 \cdot H}\right)\right] \tag{1d}$$

where Δ is the bed form height determined by the median grain size.

The flow regime in braided rivers is complex and involves rapidly varying currents, multi-thread flow networks, bifurcations and confluences, complicated bathymetry, varying sediment size distribution, and other features. Both sub- and super-critical flows and trans-critical flows may occur. In the present study, a TVD–MacCormack scheme has been applied to solve the SWEs, which is second-order accurate in both time and space [30,31]. The scheme combines a symmetric TVD scheme with the standard MacCormack scheme. An adaptive time step is used to increase computation efficiency while ensuring that the condition CFL < CFLcr is met, where CFLcr is usually set to 0.7 or smaller. The sediment transport equation is solved using a third-order accurate ULTIMATE QUICKEST scheme [32]. The numerical scheme conserves mass and has the advantage of avoiding spurious oscillations.