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Improved numerical modeling of morphodynamics of rivers with steep banks

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ABSTRACT

The flow and sediment transport processes near steep streambanks, which are commonly found in meandering, braided, and anastomosing stream systems, exhibit complex patterns that produce intricate interactions between bed and bank morphologic adjustment. Increasingly, multi-dimensional computer models of riverine morphodynamics are used to aid in the study of these processes. A number of depth-averaged two-dimensional models are available to simulate morphologic adjustment of both bed and banks. Unfortunately, these models use overly simplified conceptual models of riverbank erosion, are limited by inflexible structured mesh systems, or are unable to accurately account for the flow and sediment transport adjacent to streambanks of arbitrary geometry. A new, nonlinear model is introduced that resolves these limitations. The model combines the river morphodynamics computer models TELEMAC-2D and SISYPHE of the open source TELEMAC-MASCARET suite of solvers with the bank erosion modules of the CONCEPTS channel evolution computer model. The performance of the new model is evaluated for meander-planform initiation and development. The most important findings are: (1) the model is able to simulate a much greater variety and complexity in meander wavelengths; (2) simulated meander development agrees closely with the unified bar-bend theory of Tubino and Seminara (1990); and (3) the rate of meander planform adjustment is greatly reduced if the wavelength of alternate bars is similar to that of meanders.

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1. Introduction

The near-bank region of a river, where the streambed and streambank intersect, is often characterized by large spatial gradients in the river's geometry resulting in complex flow patterns and sediment transport rates and directions [1–5]. Further, the grain-size distributions and resistance-to-erosion properties of the bed and bank materials are often quite different. These processes result in lateral (bank) erosion rates that can be orders of magnitude greater than the rate of vertical adjustment of the riverbed [6]. This discrepancy in lateral and vertical erosion rates is prominent in meandering, braided, or anastomosing river systems. Given these observations, multi-dimensional computer models of river morphodynamics have unfortunately either neglected or used overly simplified conceptual models of riverbank erosion, limiting them to studies of riverine environments where banks do not move, small time scales (in case banks do not erode), or rather qualitative evaluations of river morphological adjustment.

A number of depth-averaged, two-dimensional models have been published over the past 30 years to simulate the planform dynamics of meandering and braiding streams. The first meander migration computer models were based on simplified, linear theory of hydrodynamics and bed morphology (for a review see [7]). Bank erosion rate in these models was linearly related to the near-bank excess velocity or flow depth [8,9]. However, such models are unable to simulate the full suite of meander bend shapes as computed bank erosion is not explicitly controlled by the resistance to erosion properties of the bank soils [10]. For example, the meander migration models of [8,9] will produce bank erosion even for locations where applied fluvial shear stresses do not exceed the critical shear stress needed to erode the bank soils. This may be a valid approach for very large time scales (e.g., the time it takes a river to rework its floodplain), but is not valid for time scales simulated by multi-dimensional river morphodynamic computer models.

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Although the implementation of riverbank erosion processes is relatively straightforward for one-dimensional (1D) computer models, such as the CONCEPTS channel evolution computer model [11], their incorporation into multi-dimensional computer models is rather complicated. One-dimensional computer models simulate river morphodynamics using a series of cross sections, and adjust the cross-sectional profile where erosion and deposition occur. These models can handle complex geometry including steep bank sections. Such sections cannot be adequately represented by depth-averaged, two-dimensional (2D) models, which divide the computational domain into a series of elements following either an unstructured or structured organization. The bank profile is therefore prescribed by the elevations at the vertices of an element next or on the bank. As bank profiles can be very steep due to basal erosion, near-bank mesh elements may become too small to perform efficient and numerically stable simulations. Furthermore, bank profiles generally comprise a single, linear segment (or planar surface) in 2D models.

Bank erosion is a combination of fluvial erosion by the flowing water and mass failure of unstable banks [12]. Basal erosion occurs when the shear stress exerted by the flowing water exceeds the erosion-resisting forces of the bank soils. The erosion-resisting forces vary between cohesive and cohesionless bank materials. Those of cohesionless materials are generally a function of particle size and bank slope, whereas those of cohesive bank materials are determined by the electro-chemical bond between the particles. Fluvial erosion is typically calculated using an excess shear stress approach that linearly relates the rate of fluvial erosion to an erodibility (or soil detachment) coefficient and the difference between the shear stress exerted by the flowing water and a critical shear stress required to erode the bank material [13]. This conceptualization often requires calibration of the erodibility coefficient to simulate erosion rates accurately. Mass failure occurs when gravitational forces (weight of bank material) exceeds the shear strength (characterized by cohesion and frictional resistance) of the bank material, which can be evaluated using a stability analysis [12].

More recently, nonlinear models of flow and bed morphology have been integrated with physically-based algorithms of bank erosion mechanics. Darby et al. [14] enhanced the nonlinear meander model of Mosselman [15] with the bank stability model of Darby and Thorne [16] and an excess shear stress approach for fluvial erosion. Duan and Julien [17,18] simulated erosion of cohesionless bank material as a combination of basal erosion and a simple mass failure routine based only on the friction angle of the bank materials. Asahi et al. [19] further advanced the approach of Duan and Julien [17,18] by accounting for the effects of failed cohesive bank materials on meander migration rates. However, these models use simple, linear bank profiles and can therefore not accurately simulate the near-bank flow and resulting bed and cohesive bank morphologic adjustment.

Rinaldi et al. [20] developed a more comprehensive model by loosely coupling a depth-averaged hydrodynamics model (Delft3D [21]) with a comprehensive analysis of erosion of banks with complex geometry, including the effects of pore water dynamics. However, such approach is computationally expensive and may only be practical to simulate a single flow event. Moreover, all the above-mentioned non-linear model approaches use structured, rectilinear meshes that limits accurate characterization of irregular channel planform (that is top-bank lines) and its temporal adjustment.

To overcome these difficulties Lai et al. [22,23] have developed a long-term, nonlinear river morphodynamics model by combining the flow and sediment transport computer model SRH-2D [24], which uses an unstructured hybrid mesh system, with the physically-based bank erosion algorithms from the BSTEM model [25,26]. Lai et al. [22] aligned the mesh edges representing the solid boundary with the toe of the bank. The bank geometries and their erosion are treated in a model component independently from the SRH-2D model geometry and simulation. The bank erosion component uses the near-bank bed shear stress computed by SRH-2D to calculate bank erosion, and the resulting displacement of the bank toe is used to adjust the SRH-2D mesh. Unfortunately, such an approach cannot simulate the direct impact of the bank morphodynamics on the near-bank flow, sediment transport, and bed morphology.

The models described above, which represent the current state-of-the art in modeling both bed and bank adjustment, all have some limitations for studying the long-term river morphodynamics impacted by actively eroding streambanks. In this paper we present an improvement of the Lai et al. [22,23] approach by explicitly simulating the flow near and on the bank, the resulting sediment transport, and bed morphodynamics. Our approach combines the TELEMAC-2D/SISYPHE computer models of river bed morphodynamics of the TELEMAC Modelling System [27,28] and CONCEPTS riverbank erosion algorithms [11]. We highlight the improvements of this nonlinear approach by comparing model outcome to that of a comprehensive linear model of meander migration (RVR Meander [10]) for the case of meander migration in floodplain soils with small cohesion.

2. Model description

The modeling of meandering stream evolution requires computational modules for simulating the hydrodynamics, bed evolution, bank retreat, and optionally a module for meander bend cutoffs [29]. Previous studies have demonstrated that depth-averaged 2D models can satisfactorily capture the evolution of meandering streams, e.g. [18]. However, a 2D model requires a parameterization of flow curvature-induced secondary flow that redistributes the flow momentum, which may be important in meandering streams. Our model to simulate the evolution of streams exhibiting lateral adjustment is based on: (a) the widely-used and well-tested hydrodynamics and bed morphodynamics models TELEMAC-2D [27] and SISYPHE [28] from the open-source TELEMAC-MASCARET suite of solvers [30]; (b) the widely-used bank erosion components of the CONCEPTS model [11] with enhancements to simulate the fate of failed bank material described by Motta et al. [31]; and (c) a flexible, dynamic mesh adjustment module.

2.1. Hydrodynamic component

The equations solved by TELEMAC-2D are the shallow water equations in their non-conservative form [27,32]:

$$\frac{\partial \vartheta h}{\partial t} + \vec{U} \cdot \nabla(\vartheta h) + \vartheta h \nabla \cdot \vec{U} = S_h \tag{1}$$

$$\frac{\partial u}{\partial t} + \vec{U} \cdot \nabla u = -g\frac{\partial H}{\partial x} + S_x + \frac{1}{\vartheta h}\nabla \cdot (\vartheta h \nu_t \nabla u) \tag{2}$$

$$\frac{\partial v}{\partial t} + \vec{U} \cdot \nabla v = -g\frac{\partial H}{\partial y} + S_y + \frac{1}{\vartheta h}\nabla \cdot (\vartheta h \nu_t \nabla v) \tag{3}$$

where h is flow depth, ϑ is local porosity, ∇ is the divergence operator when acting on a vector field or the gradient operator when acting on a variable, $\vec{U} = (u, v)$ is the vector of depth-averaged Cartesian flow velocities u and v in x- and y-direction, respectively, t is time, g is gravitational acceleration, H is the water surface elevation, ν_t is eddy viscosity, and S_h, S_x and S_y are source or sink terms in the conservation of mass and momentum equations. Here, $S_h = 0$, and $S_x = C_f u \|\vec{U}\| / 2h$ and $S_y = C_f v \|\vec{U}\| / 2h$ represent the friction forces in x- and y-direction, respectively, with C_f a dimensionless friction coefficient. As will be shown below, porosity is used in the elements on the streambanks to represent the