Improved numerical modeling of morphodynamics of rivers with steep banks

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A B S T R A C T

The flow and sediment transport processes near steep streambanks, which are commonly found in me- andering, 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 lim- ited 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 re- solves 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 devel- opment 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.

Keywords: Bank erosion,Meander migration,, Numerical model, TELEMAC

1. Introduction

The near-bank region of a river, where the streambed and streambank intersect, is often characterized by large spatial gradi- ents 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 re- sult 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 mor- phodynamics 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 eval- uations 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 the- ory 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 com- puted 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 loca- tions 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.

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 simu- late 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.

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Bank erosion is a combination of fluvial erosion by the flowing water and mass failure of unstable banks [12]. Basal erosion oc- curs 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 erodi- bility (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 conceptualiza- tion often requires calibration of the erodibility coefficient to simu- late erosion rates accurately. Mass failure occurs when gravitational forces (weight of bank material) exceeds the shear strength (char- acterized by cohesion and frictional resistance) of the bank mate- rial, 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 mate- rials. 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 simu- late the near-bank flow and resulting bed and cohesive bank mor- phologic 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. How- ever, such approach is computationally expensive and may only bepractical 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 devel- oped a long-term, nonlinear river morphodynamics model by com- bining 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 ero-sion 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 morpho- dynamics 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 compu- tational 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 op-erator 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, respec- tively, t is time, g is gravitational acceleration, H is the water sur- face 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 di- mensionless friction coefficient. As will be shown below, poros- ity is used in the elements on

the streambanks to r epresent the area blocked by bank material. Hence, porosity varies with flow depth and/or time. These equations are approximated on an irreg-ular or unstructured mesh using the finite element method [32]. TELEMAC-2D has been validated for many analytic, experimental and real-world cases [33,32].

2.2. Bed evolution component

The SISYPHE module of TELEMAC-MASCARET simulates sedi- ment transport and bed morphodynamics [28]. It calculates temporal changes in bed elevation z_b using the Exner equation (4), and incorporates most commonly-used sediment transport equations to calculate the magnitude of the volumetric unit sediment discharge (Q_b). Bed evolution is given by:

$$\frac{\partial z_b}{\partial t} = -\frac{1}{1-\lambda}\nabla \cdot \vec{Q_b} \tag{4}$$

where λ is the porosity of the bed material, and $\vec{Q_b} = (Q_{b_x}, Q_{b_y})$ is the vector of unit sediment discharges in x- and y-direction, respectively.

The bed load discharge $\vec{Q_b}$ is typically aligned with the depth averaged flow direction. However, the direction and magnitude of the bed load transport in meandering or braided streams deviates from that of the depth-averaged flow over a horizontal bed due to the transverse sloping bed and curvature-induced secondary flow, e.g. [15]. SISYPHE uses the formulation of Koch and Flokstra [34] to correct the magnitude of the bed load transport for the bed slope as:

$$\frac{Q_b}{Q_{b0}} = \left(1 - \beta\frac{\partial z_b}{\partial s}\right) \tag{5}$$

where Q_b is the corrected bed load discharge magnitude, Q_{b0} is the uncorrected bed load discharge magnitude, s is the flow direction, and β is an empirical coefficient (set to 1.3 in this study).

The sloping bed also causes the direction of bed load transport to deviate from that of the flow direction, which is approximated as [35]:

$$\tan\alpha = \tan\delta - T\frac{\partial z_b}{\partial n} \tag{6}$$

where α is the direction of the sediment transport relative to the depth-average flow direction, δ is the bed shear stress direction relative to the mean flow, n is the direction normal to the flow, and $T = 2/3\,\theta$ [34].

The effect of the secondary flow on the bottom shear stress di- rection is calculated following Engelund's formulation [35]:

$$\tan\delta = 7\frac{h}{R_c} \tag{7}$$

where R_c the local radius of curvature.

2.3. Bank erosion and accretion component

Meandering rivers migrate by bank erosion along the outer bank of a meander bend and accretion along the inner bank. Bank erosion is governed by two processes: fluvial erosion by the flow- ing water and mass failure by gravity [12]. The fluvial erosion and bank failure algorithms of the CONCEPTS channel evolution com- puter model will be used to calculate retreat of banks with arbi- trary geometry [11]. These algorithms have been successfully used by the 2D RVR Meander model, which is based on the linear mean- der theory of [8], to model meander migration and evaluate chan- nel planform adjustment [10,31,36]. In the present study the focus is on evaluating the conditions of meander bend growth for flood- plain soils with little cohesion. Motta et al. [31] showed that long- term migration of such streams can be accurately simulated using only fluvial erosion with a modified erosion-rate coefficient.

Fluvial erosion is estimated using an excess shear stress relation [13],

$$E = \begin{cases} M_e\left(\frac{\tau}{\tau_{ce}} - 1\right) \text{if} \tau > \tau_{ce} \\ 0 \text{if} \tau \le \tau_{ce} \end{cases} \tag{8}$$

where E is the bank erosion rate due to fluvial erosion, M_e is the erosion-rate coefficient, τ is the shear stress acting on the bank soils, and τ_{ce} is a critical shear stress of the bank soil for erosion to occur.

Bank accretion is similarly computed with the method proposed

by [37]:

$$A = \begin{cases} M_a\left(1 - \frac{\tau}{\tau_{ca}}\right) \text{if} \tau < \tau_{ca} \\ 0 \text{if} \tau \ge \tau_{ca} \end{cases} \tag{9}$$

$$\vartheta(h) = \frac{A_{s,\text{element}} - \frac{V_{\text{bank}}(h)}{h}}{A_{s,\text{element}}} \tag{10}$$

where A_{s} ,element is the surface area of a triangular element and V_{bank} is the volume occupied by bank material at a certain flow depth h. The porosity function allows an accurate representation of arbitrary bank geometry, including undercut banks, and is used explicitly in the set of governing equations. Hence, flow and ap- plied forces on the bank material in the mesh element next to the bank can be more accurately simulated.

The shear stress acting on banks along meander bends is affected by factors such as secondary flow strength, bank slope, width-to-depth ratio, difference in roughness between bed and bank, and bed form progression. Here, we follow the divided chan- nel method of [31], which defines the shear stress acting on each of the bank nodes by scaling the near-bank bed shear stress τ_{nb} us- ing the hydraulic radius of the flow area impinging on each node that itself depends on the bank profile (Fig. 1(c)). For example, in the case of a submerged three-node bank profile (numbered from 1 to 3 from top to toe), the shear stress exerted by the flow on the i-th point is computed as $\tau_i = \tau_{nb} \times \min((A_i P_3 / A_3 P_i), 1)$, where A_i is the flow area impinging on node i and P_i is the wetted perimeter of node i. A simplification of this method adopts the local depth instead of the hydraulic radius for scaling. In spite of the shortcomings associated to these methods and their strict validity for straight channels, they are adopted for their simplicity and hence efficiency to perform medium- to long-term simulations of channel evolution.

After calculating the resulting erosion or accretion distances of the bank nodes, they are moved to their new position resulting into a change of channel geometry and mesh structure. If cumu- lative nodal displacements are small, the mesh can keep the same topology, otherwise if cell distortion exceeds certain quality crite- ria, a new mesh needs to be created. This is discussed in the next section.

2.4. Mesh generation and adaptation component

The initial, computational mesh of triangular cells is generated such that edges of cells adjacent to the bank (both elements in- bank and on the floodplain) align with the bank top (Fig. 1 (a)). This ensures that these cell edges and their vertices remain on the bank top during bank retreat. The initial mesh and its dynamic adaptation are generated using the open source software Triangle [38]. Triangle uses a planar straight line graph (PSLG) representing the bank-top polylines of the studied river reach to align the mesh [39]. When the vertices of the cell edges where bank erosion or accretion is calculated are shifted, the PSLG is updated.

When the bank erodes or accretes, the displacement vector, $\vec{d}$, for each vertex located on the bank top is given by:

$$\vec{d} = \begin{cases} E\Delta t\,\vec{e}_n \text{ in the case of erosion} \\ A\Delta_t\,\vec{e}_n \text{inthecaseofaccretion} \end{cases} \quad (11)$$

where Δt is the time step used in the bank erosion calculations

and $\vec{e}_n$ is the unit vector normal to the bank top (Fig. 2). The affected vertices are moved and the mesh structure is updated (Fig. 3). Eventually, the shifted vertices will reduce the quality of the mesh near the banks, for example the mesh may not be conforming Delaunay anymore. The criteria to generate a new mesh are based on a minimum internal angle, minimum edge length, and a minimum area of the triangular elements (Fig. 3). These parame- ters are checked for those triangles along the bank whose vertices have been shifted. When one of the criteria is violated, Triangle is used to generate a new mesh using the updated PSLG of the bank top (Fig. 4).

2.5. Coupling of the components

As the meander migration time scale is generally greater than the time scales of hydrodynamic and bed morphological adjustment (e.g., [40]), the three simulated processes (flow, bed morphodynamics, and meander migration) are solved separately. The solution sequence is as follows:

1. TELEMAC2D and SISYPHE simulate flow, sediment transport and bed adjustment.
2. The bank erosion module simulates fluvial erosion and mass failure using flow variables computed in the vertices closest to the streambank.
3. In case of bank erosion, the porosity function ϑ (10) is updated for the affected elements.
4. In case of bank-top retreat, the element vertices on the top- bank line and parameters representing mesh quality of the af- fected elements are updated.
5. A new mesh is generated if the quality criteria are violated, and the hydrodynamic variables and bathymetry are then mapped onto the new mesh using a second-order natural neighbor method.

Note, different time steps may be used to resolve flow, sediment transport, bed adjustment, fluvial toe scour and bank mass failure. Therefore, the above steps may be performed out of sequence. The interpolation of water surface elevation, flow velocities, and bathymetry in step five is performed using the natural neighbor method. The updated sediment discharges are then calculated us- ing the interpolated flow variables.

3. Results

We assessed the capability of the model to simulate the mor- phodynamics of meandering streams by studying the conditions that lead to meander bend growth or contraction. Note that the combined TELEMAC-2D and SISYPHE models have already shown to satisfactorily simulate macroscale (dune) and mesoscale (bar) bed form dynamics [41,42].
Based on the analytical model of Ikeda et al. [8], Johannesson and Parker [43] derived the following condition for meander bend growth to occur:

the cases studied by Frias *et al.* (2015) where there was only one main channel and several secondary channels. The mean annual discharge of the Amazon River in the region is 30,700

$$k_{\max} = \frac{\sqrt{2}C_f}{h}\sqrt{A - 1 + F^2} \qquad (12)$$

where $k_{\max} = 2\pi/\lambda_{\min}$ is the maximum wavenumber for meander bend growth, $\lambda_{\min}$ is the minimum meander wavelength for mean- der bend growth, A is the scour factor, and F is the Froude number. Thus, if the wavenumber of a meander bend is smaller than $k_{\max}$, the bend amplitude should increase. The scour factor may be estimated as [44]:

$$A = 3.8\left(1 + \frac{B}{13.9h}\exp\left(\frac{\quad}{B}\right)\right) \qquad (13)$$

where B is the channel width.

Two scenarios were simulated, one scenario with $k < k_{\max}$ (hereafter denoted to as GRW for meander bend growth) and the other scenario with $k > k_{\max}$ (hereafter denoted to as STB for sta- ble meander planform). Table 1 summarizes the values used to calculate $k_{\max}$ (or $\lambda_{\min}$) and A. The initial channel planform for both scenarios consisted of a single meander with a wavelength of 30 m, a channel width of 1.5 m and a channel length of 102 m. The valley slope was set to 0.001 m/m. The flow discharge for the GRW scenario was 0.005 m^3/s (producing a flow depth of 0.0183 m), and the discharge for the STB scenario was 0.04 m^3/s (producing a flow depth of 0.0636 m). The value of the friction coefficients were 0.0054 (GRW scenario) and 0.0035 (STB scenario).

Given the above values, A = 22. 7 and $\lambda_{\min}$ = 3. 24 m for the GRW scenario, and A = 7. 37 and $\lambda_{\min}$ = 32.7 m for the STB sce- nario. The initial meander wavelength for the GRW scenario is therefore about an order of magnitude greater than the minimum value for meander bend growth, whereas it is slightly smaller than the minimum wavelength value for the STB scenario. To suc- cessfully perform the simulations for this scenario, channel width should remain constant (or nearly constant) over the simulation period. The bank erosion and accretion rate coefficients were set to $M_e = M_a = 7.5 \times 10^{-6}$ m/s. Critical shear stresses for bank erosion and accretion were then selected as 0.065 Pa (GRW scenario) and 0.22 Pa (STB scenario) to maintain both a constant channel width and simulate sufficient planform adjustment over a 75 h simula- tion period. The bed and bank materials were homogeneous with a particle size of 0.05 mm. Their transport rate was calculated using the Meyer–Peter and Müller equation. Note, this equation was not developed for such small grain size, however the selection of transport equation is not important for the below analysis.

The computational mesh comprised 9942 nodes and 19721 ele- ments. The mean edge length of a triangular element was about 0.15 m. Simulated bank erosion/accretion will produce meander migration and transform the mesh. The quality criteria of a trian- gular element for remeshing to occur were set as: minimum edge length is 0.09 m, minimum cell area is 0.005 m^2, and minimum internal angle is 15.3 degrees. For example, for the GRW scenario the mesh after 75 h comprised 10472 nodes and 20685 elements, which represents approximately a 5% increase and is similar to the increase in channel length from 102 to 109 m. The lengths of cell edges on the bank lines were initially 0.15 m, which length was also imposed during the remeshing process. The number of vertices on each bank line therefore increased from 680 to 726. The time step for the flow, sediment transport and bed evolution was 0.1 s, whereas the time step for bank migration was 30 min. The water surface elevation at the outlet was held constant at its initial value, while bed elevation was held constant at the inlet. Further, channel width and position were fixed at both the channel inlet and outlet. The initial bed surface was established by running the model without bank erosion for 20 h until a quasi-equilibrium bed morphology had developed. Figs. 5 and 6 show the planform evolution simulated for the GRW and STB scenarios, respectively. The meanders develop fairly quickly downstream of the initial meander bend for the GRW sce- nario, whereas for the STB scenario no new meanders develop and the initial meander bend is locked in place. Note, channel width is not exactly constant during the simulation as some minor widen- ing and narrowing occurs over time. The below sections discuss the modeling results in more detail.

3.1. GRW scenario

The initial equilibrium bed morphology for the GRW scenario shows a series of alternate bars with wavelengths varying from about 7.5 m to 10 m (top plot, zero hours, in Fig. 5). From labratory experiments Ikeda [45] found that bar wavelength $\lambda_b \approx \sqrt{5}\, Bh / C_f$ (possible prediction error is +80 % or −40 %), which would yield a wavelength of about 11 m. This value compares well to that simulated.

The wavelength of the developing meanders (7.5 to 10 m) equals that of the alternate bars. As this wavelength is not significantly greater than the theoretical threshold for meander growth (λ_{min} = 3. 24 m), meander bend amplitude ceases to increase af- ter about 30 h into the simulation. At that time, the bend am- plitude is approximately 2 m. From that point, only downstream translation of the meander bends at a rate of about 0.15 m/h takes place. Pure downstream translation of meander bends can also be observed in nature. For example, Fig. 7 shows the plan- form adjustment of the Wabash River near Grayville, IL between 1938 and 2012 revealing four bends whose adjustment is in the form of downstream migration.
The simulated meander initiation and development agree well with the unified bar-bend theory in which migrating alternating bars induce flow curvature, which pro- duces a meandering planform, and subsequently the free, alternate bars are transformed into forced, point bars resulting in a much smaller bend migration rate than alternate bar migration rate [46].

The formation of alternate bars along the initial meander bend has produced a compound meander loop. Note that the present 2D model maybe unable to simulate the flow complexity in a com- pound meander loop [3]. The multiple bends in the loop have a very small amplitude (≈ 0. 5 m), and their downstream migration rate is about 0.1 m/h. The upstream portion of the compound bend seems to migrate in upstream direction, which is typical for sub- resonant conditions [48].

3.2. STB scenario

The simulated alternate bar wavelength for the STB scenario is between 15 m and 20 m (Fig. 6), which compares well with a wavelength of 26.1 m computed using Ikeda's (1984) relation [45].

Moreover, the simulated bar wavelength is similar to that of the initial meander bend. Only minor planform adjustment is simu- lated with some accompanying channel widening and narrowing. The apex of the bend has migrated approximately 5 m in down- stream direction after 75 h, and the amplitude has reduced by about 1 m.
For the initial planform, the flow exerts an average shear stress on the bank of 0.3 Pa, with peak values of 0.46 Pa. The excess shear stresses on the banks lead to channel widening after 25 h simulation, but no downstream translation of the initial bend or formation of new bends. After 25 h the average shear stress exerted on the bank has reduced to 0.22 Pa, equaling the critical shear stress of the bank material, with largest values in the bend of about 0.35 Pa and smallest values of about 0.12 Pa. This condi- tion persists until 45 h of simulation, when the channel starts to narrow as the shear stresses along the left bank reduce to an av- erage value of 0.17 Pa causing bank accretion. After 75 h of simu- lation, channel narrowing has increased the average shear stresses exerted on the banks to 0.22 Pa again. These interactions between channel width and depth, for example simulated deepening when the channel narrows, helps the channel to preserve its width over the long term.

4. Discussion

Although field and laboratory investigations have helped with improving our understanding of the processes controlling planform adjustment (e.g., [2,5]), such studies are still limited because of constraints on, among others, time, instrumentation, and size of study site. Hence, most of the recent understanding of these processes have relied on linear computer models. However, nonlinear computer models of river morphodynamics should be able to sim- ulate more closely the details of river planform adjustment than linear models as the governing momentum Eqs. (2) and (3) repre- sent the flow physics more fully. To identify the differences in planform adjustment simulated by nonlinear and linear models we applied the linear RVR Meander model [49,10] to the above GRW and STB scenarios using the pa- rameter values listed in Table 1. Figs. 8 and 9 show the planform adjustment for the GRW and STB scenarios simulated by RVR Me- ander, respectively. Similarly to the nonlinear model, RVR Meander simulates adjustment of the initial bend for the GRW scenario and a fairly stable (or slowly evolving) planform for the STB scenario.

4.1. GRW scenario

The simulated adjustment of the initial meander bend during the first 45 h is very similar for both nonlinear and linear model (compare Figs. 5 and 8). The bend develops a more rectangular shape as the bend apex moves in downvalley direction. After 50 h, the alternate bars simulated by the nonlinear model start to exert a greater affect on the shape of this bend, producing a more dis- tinct looking compound meander loop and orienting the upstream portion of the loop more into the upstream direction.

Transverse bed slope in RVR Meander is explicitly related to channel curvature. RVR Meander, therefore, cannot model the formation of alternate bars, and no morphologic adjustment of constraints on, among others, time, instrumentation, and size of study site. Hence, most of the recent understanding of these pro- cesses have relied on linear computer models. However, nonlinear computer models of river morphodynamics should be able to sim- ulate more closely the details of river planform adjustment than linear models as the governing momentum Eqs. (2) and (3) repre- sent the flow physics more fully. To identify the differences in planform adjustment simulated by nonlinear and linear models we applied the linear RVR Meander model [49,10] to the above GRW and STB scenarios using the pa- rameter values listed in Table 1. Figs. 8 and 9 show the planform adjustment for the GRW and STB scenarios simulated by RVR Me- ander, respectively. Similarly to the nonlinear model, RVR Meander simulates adjustment of the initial bend for the GRW scenario and a fairly stable (or slowly evolving) planform for the STB scenario.

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Transverse bed slope in RVR Meander is explicitly related to channel curvature. RVR Meander, therefore, cannot model the formation of alternate bars, and no morphologic adjustment of [45]. The smaller relative bar height appears to have less of an affect on migration rate compared to the GRW scenario. Linear mod- els of meander migration could therefore have greater applicability for meandering streams with smaller aspect ratios.

5. Conclusions

Advances in the understanding of river planform adjustment processes rely greatly on linear computer models. We have reported on the development of an improved depth-averaged, nonlinear river morphodynamics model that can more accurately simulate the flow and therefore boundary shear stresses near steep streambanks by using a porosity method. The improved modeling of near-bank flow results in more accurate simulation of near-bank sediment transport and bed evolution, and consequently bank migration and planform adjustment.

The performance of the model was assessed by simulating me- ander planform adjustment for two scenarios: (1) a meander plan- form that produces active adjustment, and (2) a meander planform that produces no or minor adjustment. Model outcomes were compared to those produced by the linear model RVR Meander. RVR Meander has demonstrated that it can simulate the formation and development of complex meander shapes.

Primary conclusions are: (1) the new nonlinear model is capable of simulating meander initiation caused by the devel- opment of alternate bars; (2) simulated meander development agrees closely with the unified bar-bend theory of Tubino and Seminara [46]; (3) the model is capable of simulating downstream translation of meander bends without changes in bend amplitude; (4) the model is able to simulate a range of superimposed meander wavelengths producing complex meander patterns such as compound loops; and (5) the rate of meander planform ad- justment is greatly reduced if the wavelength of alternate bars is similar to that of meanders, which enables the use of linear models.

The new model has demonstrated that it can realistically simulate the conditions for meander planform initiation and the different modes of planform adjustment using physically-based bank migration algorithms. However, further testing should be conducted against observed long-term evolution of prototype meandering streams, specifically to evaluate the interactions be- tween bed and bank morphodynamics. This fully-tested model can then be used to explore in more detail the river dynamics during meander cutoff and self-organization, which are still poorly understood.

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