RVR Meander - Migration of Meandering Rivers in Homogeneous and Heterogeneous Floodplains using Physically-Based Bank Erosion

Marcelo H. Garcia[1], Davide Motta[2], Jorge D. Abad[3], Eddy J. Langendoen[4]

[1]*Chester and Helen Siess Professor, Ven Te Chow Hydrosystems Laboratory, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA. Email: mhgarcia@illinois.edu*

[2]*Graduate Research Assistant, Ven Te Chow Hydrosystems Laboratory, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA. Email: dmotta2@illinois.edu*

[3]*Assistant Professor, Department of Civil and Environmental Engineering, University of Pittsburgh, Pittsburgh, Pennsylvania, USA. E-mail: jabad@pitt.edu*

[4]*Research Hydraulic Engineer, US Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory, Oxford, Mississippi, USA. E-mail: eddy.langendoen@ars.usda.gov*

1 Summary

The RVR Meander platform for computing long-term meandering-channel migration is presented, together with a method for planform migration based on the modeling of the streambank erosion processes of hydraulic erosion and mass failure. An application to a real-world river, with assumption of homogeneous floodplain soils, shows significant improvements in prediction over the classic migration approach based on the product of a calibrated dimensionless migration coefficient and the excess velocity at the outer bank. The proposed approach is also able to reproduce features such as downstream skewness of meander bends, compound loops, and preferential migration of some portions of a bend, and in general provides more complex planform shapes.

The impact of floodplain heterogeneity on rates and patterns of meander migration is also analyzed. Since heterogeneous distributions of floodplain soils are difficult to describe deterministically, a Monte Carlo approach is adopted to examine the effects of floodplain soils and their distribution on channel-planform development. Focusing on the process of hydraulic erosion of the bank soils, governed by critical shear stress and erodibility coefficient in an excess shear stress relation, we show that migrated centerlines exhibit larger variability for increasing length scales of floodplain-soil heterogeneity, though the relation appears to be less than linear.

2 RVR Meander

2.1 Motivation

Research on freely meandering rivers has been very productive in the last five decades, both in terms of field/laboratory observations and analytical/numerical modeling. Modeling of meandering-river migration requires in general the simulation of the processes of hydrodynamics, sediment transport, bed morphodynamics, and bank erosion. Particularly successful and insightful has been the use of two-dimensional (2D) depth-averaged analytical approaches for long-term river migration, derived for low-sinuosity meanders and steady bed morphology (Ikeda et al., 1981; Blondeaux and Seminara, 1985; Johannesson and Parker, 1989; Sun et al., 1996; Sun et al., 2001; Zolezzi and Seminara; 2001). Such models describe the flow field in a meandering channel (velocity, depth, bed elevation) given inputs such as discharge, slope, width, grain size, and friction coefficient. Less attention has been given to the physical modeling of bank erosion: the migration rate has been commonly related to the near-bank excess velocity multiplied by a dimensionless coefficient (Hasegawa, 1977; Ikeda et al., 1981)

$$R^* = E_0 u_b^* \qquad (1)$$

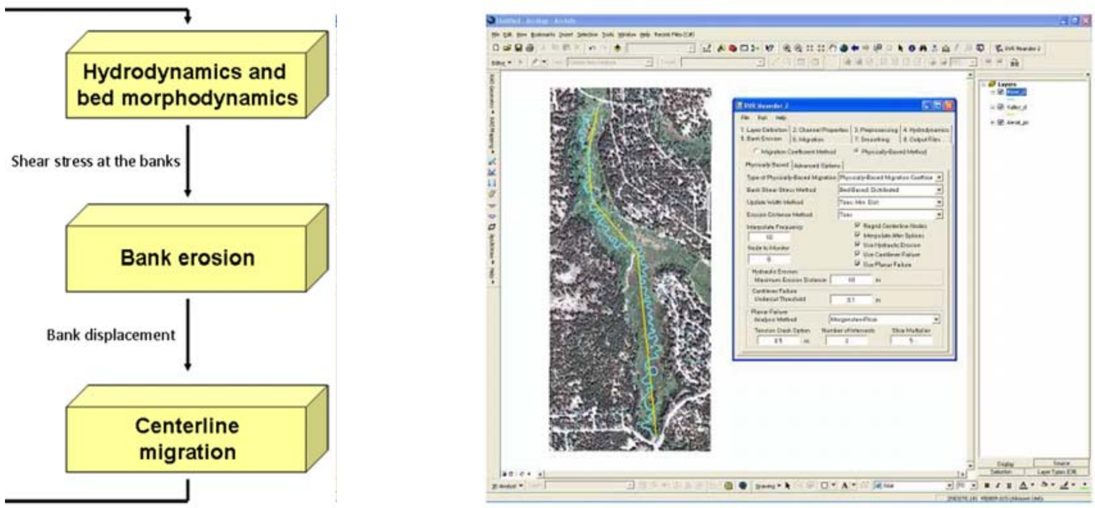
where R^* is the meander migration rate, E_0 the dimensionless migration coefficient, and u^*_b the difference between near-bank depth-averaged velocity and reach-averaged velocity. The subscript "*" indicates value with dimensions. E_0 is usually obtained by means of calibration against historic centerlines and is typically a very small number (10^{-7}-10^{-8}).

The simple classic approach using a calibrated migration coefficient (Eq. 1) cannot adequately capture the planform evolution of natural meandering rivers, because it predicts a smooth and "continuous" migration pattern. There are many additional limitations to that approach. The linearity of the expression which relates centerline migration and excess velocity implies that the only bank retreat mechanism considered is particle-by-particle erosion (also termed hydraulic or fluvial erosion). It does not explicitly account for local, episodic mass failure mechanisms like cantilever, planar, rotational, and seepage-induced failures, which in principle can temporarily change local bank retreat rates thereby altering migration patterns. The formulation does not account for an erosion threshold. Further, it does not consider the effect of the bank geometry either, since it assumes vertical sidewalls. Finally, the classic approach does not consider the impact of the vertical heterogeneity of the bank materials and the associated differences in erodibility and shear-strength of the soils.

Moreover, while the impact of hydrodynamics and bed morphodynamics on planform shape complexity has been extensively studied (as summarized by Seminara et al., 2001 and Frascati and Lanzoni, 2009), complexity resulting from the heterogeneity of the floodplain soils has received less attention. Besides earlier work by Howard (1992;1996) and Sun et al. (1996), on the development of different features in the floodplain caused by river migration and their influence on the future development of the channel, and Perucca et al. (2007), on the role of vegetation for planform dynamics, it is of interest to cite the recent paper by Guneralp and Rhoads (2011), who examined how the scale, magnitude, and stochasticity of floodplain erosional resistance influence the planform evolution of meandering rivers, using power spectra of curvature series of migrated meander sequences, and showed that heterogeneity in erosional resistance has a major influence on meander evolution.

2.2 RVR Meander platform

The RVR Meander platform (Motta et al., 2011a) merges and extends the functionalities of the first version of RVR Meander (Garcia et al., 1994; Abad and Garcia, 2006) and CONCEPTS (Langendoen and Alonso, 2008; Langendoen and Simon, 2008; Langendoen et al., 2009). Its main components are hydrodynamics and bed morphodynamics module, bank erosion module, and migration module (Figure 1a). It runs stand-alone for Windows and Linux operating systems and also has a ArcGIS-ArcMap interface (Figure 1b).



a b

Figure 1 (a) Structure of the RVR Meander platform; (b) interface for ArcGIS-ArcMap.

2.3 Hydrodynamics and bed morphodynamics

Hydrodynamics and bed morphodynamics (first component in Figure 1a) are computed according to the model illustrated by Garcia et al. (1994), which is a slightly modified version of Ikeda et al. (1981)'s and Johannesson and Parker (1985)'s models, based on the analytical and linearized solution of the 2D St. Venant equations for water conservation and momentum balance in streamwise and transverse directions. The solution is obtained for streamwise and transverse velocities and water depth, as function of streamwise and transverse location, local and upstream curvature, sinuosity, half-width to depth ratio, Froude number, and friction coefficient. The bed morphology is described assuming that the transversal bed slope is proportional to the local curvature through a proportionality constant named scour factor. Details of the analytical solution are presented by Motta et al. (2011a). Therefore, the 2D hydrodynamic and morphodynamic fields can be calculated analytically given the arbitrarily-shaped centerline and the river width, assumed as constant.

2.4 Bank erosion

Two alternative methods are used in the RVR Meander for computing bank erosion (second component in Figure 1a): the first is based on the use of the classic calibrated migration coefficient E_0 according to Eq. 1, while the second is a method based on the modeling of the physical processes responsible for bank retreat: hydraulic erosion, cantilever failure, and planar failure. The lateral hydraulic erosion rate E^* (with dimensions of length over time) for each bank-material layer is modeled using an excess shear stress relation, typically used for fine-grained materials (but also applicable to non-cohesive materials)

$$E^* = M^* \left(\frac{\tau^* - \tau_c^*}{\tau_c^*} \right) = k^* \left(\tau^* - \tau_c^* \right) \qquad (2)$$

where M^* is the erosion-rate coefficient (with dimensions of length over time), τ^*_c is the critical shear stress, k^* is the erodibility, and τ^* is the shear stress acting on the bank. M^*, τ^*_c, and k^* are all site-specific, and generally estimated in situ with a submerged jet erosion test (Hanson and Cook, 2004). In the case of cantilever failure (Figure 2a), for given unit weight and shear-strength properties, the extent of the overhang (or undercut) determines its stability. Stability can therefore be assessed using an arbitrary undercut threshold. Planar failure (Figure 2b) is analyzed using a limit equilibrium method in combination with a search algorithm to determine the smallest factor of safety (stability factor), which is the ratio of available shear strength to mobilized shear strength. The available shear strength is a combination of cohesive and frictional forces. The bank is unstable if the factor of safety is smaller than one, and a failure is then simulated. The soil properties needed to evaluate the occurrence of planar failure are groundwater table, unit weight, cohesion, angle of repose, and angle for computing the stability effect of pore water. In this paper we just focus on the hydraulic erosion process.

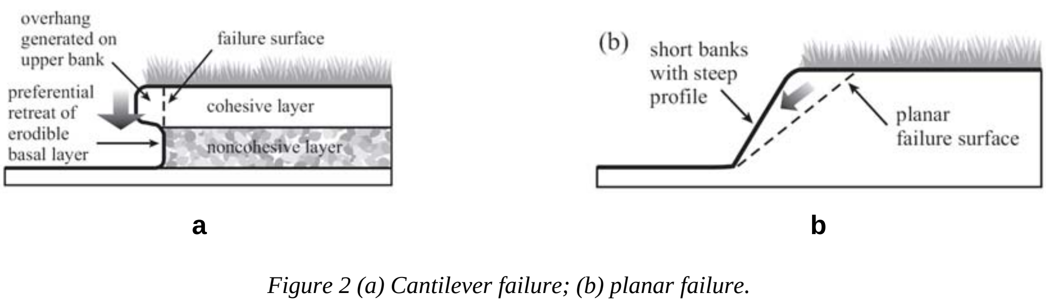


Figure 2 (a) Cantilever failure; (b) planar failure.

2.5 Meander migration

As regards the migration of meandering streams (third component in Figure 1a), the centerline normal displacement is calculated either with Eq. 1 or with a new approach, for which two alternative methods are proposed (Figure 3), that consider natural bank profile and the possible presence of horizontal layers characterized by different properties: (a) the first option (Figure 3a) calculates the centerline displacement from the physically-based erosion of outer and inner bank. This option is suggested for relatively short-term migration scenarios; (b) the second option (Figure 3b) equates the centerline displacement to the physically-based displacement of the outer bank (defined as outer bank the one that experiences more erosion). The inner bank follows the outer bank so that the channel width remains constant, as empirically observed for long-term migration (Ikeda et al., 1981). For both options, all material eroded from banks is assumed to go into suspension and leave the reach of interest.

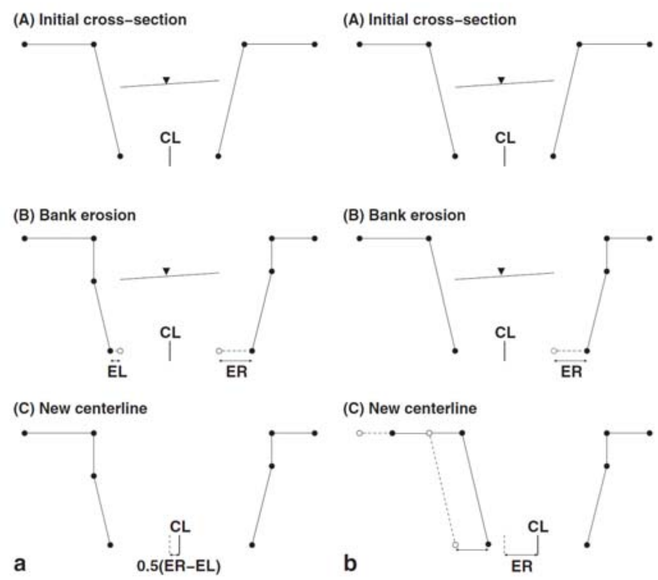


Figure 3 Centerline migration options for the proposed physically-based approach: (a) Option 1 and (b) Option 2. Bank toe displacements (EL and ER at left and right bank respectively) determine centerline (CL) migration. Alternatively, the intersect points between banks and water surface can be used, instead of the bank toes.

Additional components complete the computational platform: curvature filtering for spurious oscillations (Crosato, 2007); Parametric Cubic Splines (PCS) for centerline-nodes regridding and addition of nodes when sinuosity increases; interpolation of bank geometry when new centerline nodes are added; optional Savitzky-Golay filter (Savitzky and Golay, 1964) for centerline smoothing in case very large curvature gradients arise.

2.6 Floodplain representation

In case of heterogeneous floodplain, the resistance to erosion properties of the floodplain soils are defined on a rectangular, equidistant grid characterized by grid spacing Δx^* and Δy^* in the x^* and y^* direction respectively. The parameters M^* (or k^*) and τ^*_c are assigned at each grid node. Values of τ^*_c are generated in purely random fashion adopting a normal distribution (μ,σ), where μ and σ are mean and standard deviation respectively, using the Box-Muller transform (Box and Muller, 1958) in the polar form (Bell, 1968; Knopp, 1969).

Once the value τ^*_c is assigned at a floodplain-grid node, the corresponding value of erosion-rate coefficient k^* is computed using the expression developed by Hanson and Simon (2001) for channels in the loess areas of the mid-continental USA

$$k^*\left[cm^3/(Ns)\right] = 0.2\left(\tau^*_c\left[Pa\right]\right)^{-0.5} \quad (3)$$

that is equivalent, in terms of erosion-rate coefficient, to

$$M^*[m/s] = 0.2 \cdot 10^{-6} \left(\tau_c^*[Pa]\right)^{0.5} \tag{4}$$

Values of τ^*_c and M^* (or k^*) outside the floodplain-grid nodes are computed by interpolation using inverse-distance weighting interpolation (Shepard, 1968).

3 Applications

3.1 Application in homogeneous floodplain

Several applications of the RVR Meander platform and the physically-based migration are presented by Motta et al. (2011a). Here the case of a reach of the Mackinaw River in Illinois, located in Tazewell County about 15 kilometers upstream of the its junction with the Illinois River between the towns of South Pekin and Green Valley, is presented. From an analysis of the discharge record between 1922 and 1956 at the USGS station 05568000 near Green Valley, a modeling discharge of 46.2 m^3/s was selected. The channel width is 38 m. The period from 1951 to 1988 was simulated.

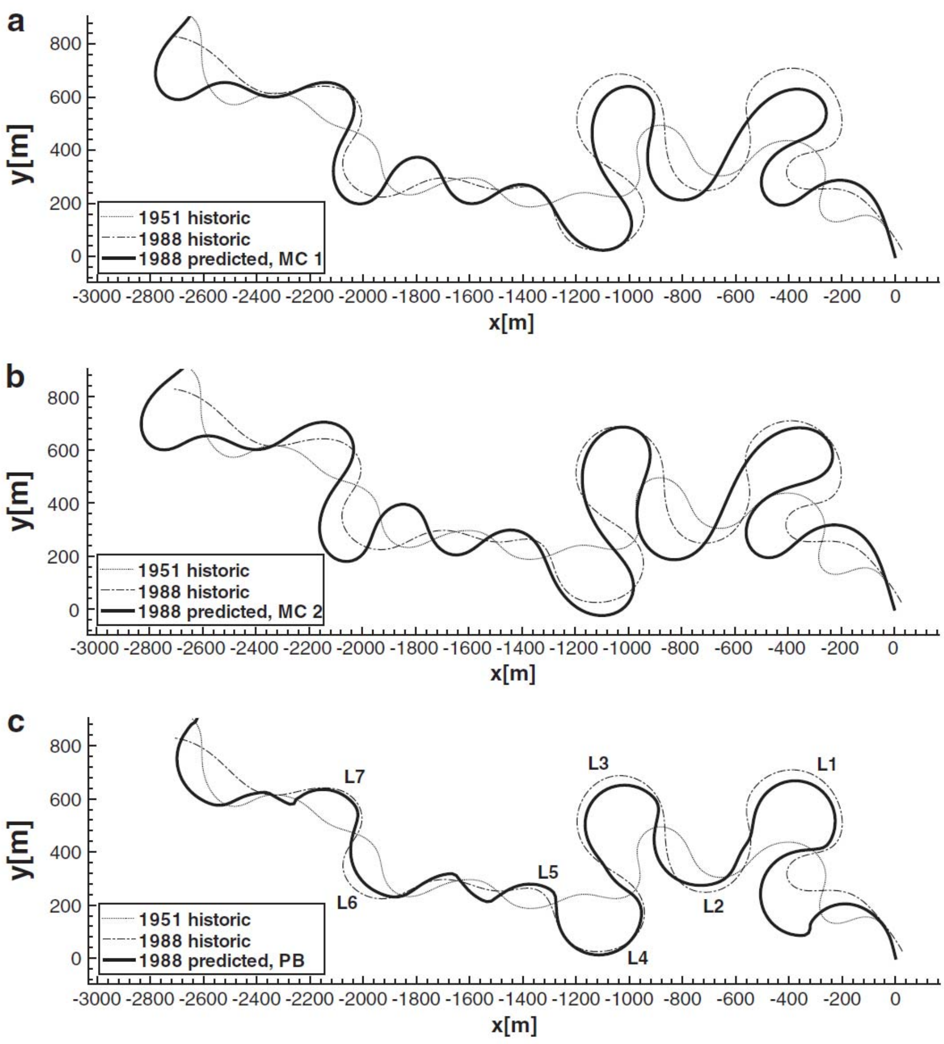


Figure 4 Comparison between historic and simulated 1988 channel centerlines of the Mackinaw River study reach. Flow is from right to left. PB = physically-based method for migration; MC = migration-coefficient method for migration.

From Figure 4 it can be observed that the proposed physically-based approach (PB, with $M^* = 1.2 \cdot 10^{-6}$ m/s and $\tau^*_c = 9$ Pa) shows significant improvements over the classic migration-coefficient approach (MC) in predicting the migration of natural streams: in terms of planform shapes, the PB approach (Figure 4c) can capture the growth of the four upstream lobes (L1, L2, L3, and L4), which, during their migration, preserve their symmetry, differently from the MC method, which is bound to produce lobes which, over a long period and for a dramatically active reach, are strongly upstream-skewed. In particular, the lobes L1 and L3 develop a compound-loop shape which cannot be captured by the MC approach for migration. Playing with the value of the migration coefficient (MC1 with $E_0 = 5 \cdot 10^{-7}$ in Figure 4a or MC2 with $E_0 = 6.5 \cdot 10^{-7}$ in Figure 4b) can match the observed pattern in one bend or the other, but in general the predicted migration is biased in terms of lateral migration (especially in the downstream portion of the reach) and downstream migration. Notice also that the initial complexity of the planform configuration of the Mackinaw River in 1951 contributes to enhancing the differences between the migration patterns predicted by MC and PB methods; in terms of prediction error, measured as the ratio of the area between simulated and observed centerlines to the length of the observed centerline (which is equivalent to an average distance between simulated and observed centerlines), it is significantly reduced using the PB method.

3.2 Application in heterogeneous floodplain

Monte Carlo simulations were performed, using the 1951 Mackinaw centerline as initial centerline, for three values of grid-cell size ($\Delta x^*,\Delta y^*$), considering different "realizations" of normally-distributed critical shear stress values with $\mu(\tau^*_c) = 9.0$ Pa and $\sigma(\tau^*_c) = 1.0$ Pa. The mean value μ is the same as used for the homogenous case illustrated in the previous section and recently confirmed by in situ jet erosion tests. While floodplain-soil properties at grid nodes are random, values at an arbitrary location (x^*,y^*) are obtained through interpolation and are therefore deterministic (see Section 2.6). Hence, the grid-cell size is an indicator of the length scale of floodplain heterogeneity. Figure 5 shows simulated channel centerline migration, over a period of 40 years, for grid-cell size values equaling 1, 2, and 3 times the channel width. 500 floodplain-soil distributions were generated for each of the three cases. This number was visually judged as sufficient to describe the variability of the migrated centerlines.

Figure 5 shows that smaller grid-cell sizes are associated with lower variability in centerline migration. We can define the Variability V as the ratio between the area occupied by all migrated centerlines (whose perimeter was manually digitized) and the length of the migrated centerline obtained for a homogeneous floodplain characterized by mean floodplain-property values ($\tau^*_c = 9$ Pa, $k^* = 6.7 \cdot 10^{-8}$ $m^3/(Ns)$), and normalized by the channel width $2B^*$. From Figure 6 we observe that V increases with grid-cell size. This implies that the characterization of the floodplain soil properties using a finer resolution is, as one could reasonably expect, associated with less variability in the predicted migration of the channel centerline. On the other hand, the increase in V with the length scale of heterogeneity is less than linear and presents a marked logarithmic trend. The less marked increase of centerline variability for larger and larger heterogeneity length scale can be explained as the product of the competition between the existence of larger patches of floodplain characterized by low resistance to erosion and the reduction of shear stresses associated to the increase in channel sinuosity (due to the reduction of friction coefficient and flow velocities). Our stochastic methodology may therefore provide a foundation for determining the suitable spatial density to characterize the physical properties of floodplain soils and vegetation.

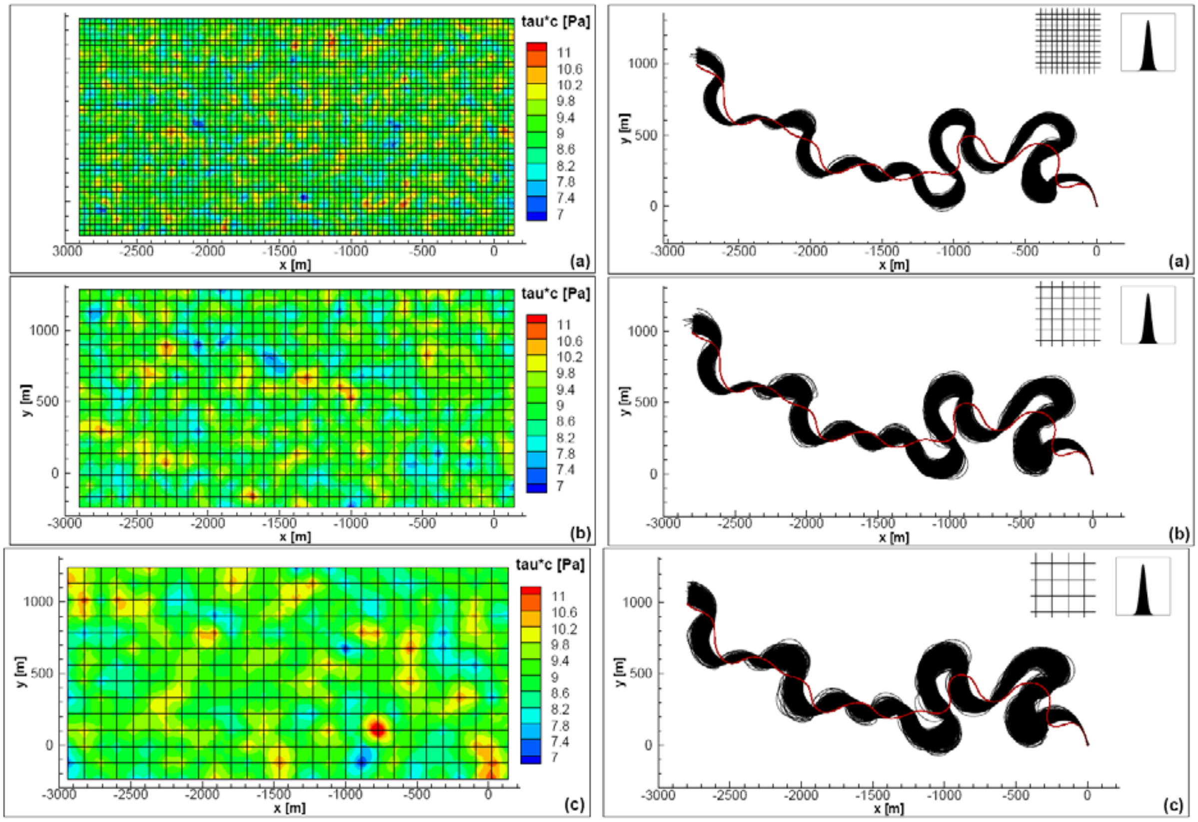


Figure 5 Example realization of floodplain-soil spatial distribution (left) and simulated channel centerline migration (right) for test cases: (a) grid-cell size = 38 m (1 channel width), (b) grid-cell size = 76 m (2 channel widths), and (c) grid-cell size = 114 m (3 channel widths). Flow is from right to left. The initial centerline is colored red and simulated centerlines are colored black.

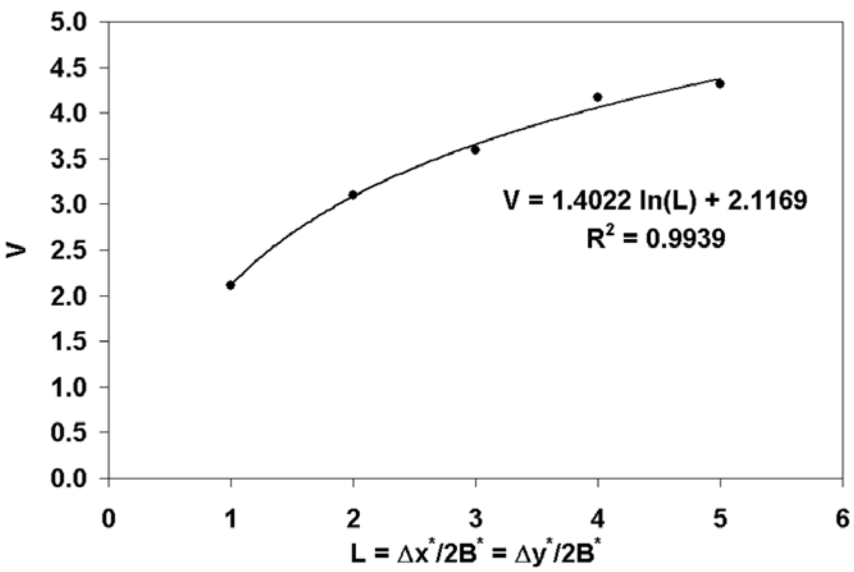


Figure 6 Relation between length scale of heterogeneity, normalized by the channel width, and centerline variability V, for the case of the Mackinaw River.

4 Conclusions

A new physically- and process-based platform which is capable to relate channel migration to the streambank erosion processes of hydraulic erosion and mass failure was developed. This allows for computing channel migration based on measurable soil properties and natural bank geometry. The proposed physically-based method for migration is able to simulate features such as downstream skewness of meander bends, compound loops, and preferential migration of some portions of a bend, which cannot be reproduced by the migration-coefficient approach. Application of the proposed approach to a reach on the Mackinaw River in Illinois showed significant improvements over the classic migration-coefficient approach in predicting both migration rates and shapes of natural streams.

A stochastic analysis of the impact of the horizontal heterogeneity of floodplain soils on rates and patterns of migration of meandering streams was performed. The analysis showed that floodplain-soil complexity can greatly contribute to planform complexity. Moreover, a smaller grid-cell size, i.e. finer scale of soil heterogeneity, results in lower variability of channel-centerline migration. The increase in variability with increasing grid-cell size is less than linear. Additional analysis on the impact of floodplain-soil heterogeneity on meander migration is presented by Motta et al. (2011b).

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