RVR MEANDER – A TOOLBOX FOR RIVER MEANDER PLANFORM DESIGN AND EVALUATION

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Abstract: Restoring the meandering planform or spatial variability of historically meandering streams that have been channelized or highly disturbed is one of the most difficult aspects in river restoration. River planform and cross-sectional geometry are the result of complex interactions between flow, boundary materials, and channel morphology. Hence, simple methods based on the reference-reach concept or hydraulic geometry relationships have often failed to produce long-term, stable meander reaches without additional bank protection. More sophisticated river meander models use empirical relations to calculate rate of channel migration, limiting their applicability as they do not explicitly account for the physical properties of the floodplain soils. The RVR Meander platform merges the functionalities of: the first version of RVR Meander developed by the University of Illinois, which is based on the classical meander migration model of Ikeda, Parker and Sawai; and the streambank erosion algorithms of the channel evolution computer model CONCEPTS developed by the US Department of Agriculture. It is written in C++ language and is composed of different libraries for preprocessing, hydrodynamics, bank erosion, migration, filtering, plotting, and I/O. It runs as a stand-alone application on Windows and Linux operating systems or as a plugin for ESRI's ArcMap software. RVR Meander has been used to model the migration of various rivers in the US and abroad.

INTRODUCTION

The ongoing modification and resulting reduction in water quality of U.S. rivers have led to a significant increase in river restoration projects over the last two decades (Bernhardt et al., 2005). The increased interest in restoring degraded streams, however, has not necessarily led to improved stream function. Palmer and Allan (2005) found that many restoration projects fail to achieve their objectives due to the lack of policies to support restoration standards, to promote proven methods and to provide basic data needed for planning and implementation. Proven models of in-stream and riparian processes could be used not only to guide the design of restoration projects but also to assess both pre- and post-project indicators of ecological integrity.

One of the most difficult types of river restoration projects concern reconstructing a new channel, often with an alignment and channel form different from those of the degraded pre-

project channel. Recreating a meandering planform to provide longitudinal and lateral variability of flow and bed morphology to improve in-stream aquatic habitat is often desired. Channel meander planform is controlled by a multitude of variables, for example channel width to depth ratio, radius of curvature to channel width ratio, bankfull discharge, roughness, bed-material physical characteristics, bed material transport, resistance to erosion of the floodplain soils, riparian vegetation, etc. Therefore, current practices that use simple, empirically based relationships or reference reaches have led to failure in several instances, for example a washing out of meander bends or a highly unstable planform, because they fail to address the site-specific conditions (e.g., Kondolf, 2006).

Recently, progress has been made to enhance a physically- and process-based model, RVR Meander, for rapid analysis of meandering river morphodynamics with reduced empiricism. For example, lateral migration is based on measurable physical properties of the floodplain soils and riparian vegetation versus the driving forces of the river hydrodynamics. The model can also be used in a Monte Carlo framework to statistically describe the long-term evolution of the meander planform. RVR Meander has been used to evaluate migration rates of restored meandering streams and bends on the Big Sioux River, SD and Trout Creek, CA at engineering time scales. It has also been used to assess the uncertainty and risk associated with the alignment of the meandering low-flow channel of the planned diversion of the Red River of the North around the metropolitan area of Fargo, ND and Moorhead, MN. The RVR Meander model and example applications are presented in the below sections.

RVR MEANDER

The current RVR Meander platform (Motta et al., 2012; http://rvrmeander.org/) extends the capabilities of the original version of RVR Meander (Abad and Garcia, 2006) by merging it with the stream-bank erosion submodel of CONCEPTS (Langendoen and Simon, 2008). The original version employed the classical migration approach (CMA) of Ikeda et al. (1981), who linearly related the local rate of meander migration to the near-bank velocity using a migration coefficient. RVR Meander is composed of modules to simulate hydrodynamics, bed topography, bank erosion, and migration of meandering rivers. It is available as a plugin for ArcGis versions 9.3.x and 10.x.

Hydrodynamics and Bed Topography: The model for hydrodynamics and bed topography implemented in RVR Meander is analytical and obtained from linearization of the two-dimensional depth-averaged Saint Venant equations. It follows the approach first developed by Ikeda et al. (1981) and adopts the secondary flow correction derived by Johannesson and Parker (1989), who introduced an "effective centerline curvature" that lags behind the local channel curvature and determines the transverse bed slope through a coefficient of proportionality named scour factor. Important model assumptions are: spatially- and temporally-constant channel width; bed topography is only a function of channel planform; and spatially-constant friction coefficient.

Bank Erosion and Meander Migration: In the physically-based meander-migration approach (PMA) in RVR Meander developed by Motta et al. (2012), simulated bank retreat is controlled

by the resistance to hydraulic erosion and the occurrence of cantilever and planar failures (Langendoen and Simon, 2008).

Hydraulic erosion requires that the local boundary shear stress exceeds the critical value to detach bank material, and is modeled with an excess shear stress relation. An average erosion distance is computed for each layer comprising the composite bank material. The shear stress acting on each of the bank material layers is obtained by scaling the shear stress at the toe, which is the bed shear stress at the bank computed with the linear hydrodynamic model, using the hydraulic radius of the flow area impinging on the layer.

Cantilever failure is the collapse of an overhanging slab of bank material formed by preferential retreat of more erodible underlying layers or simply by the erosion of the bank below the water level with respect to its upper, unsaturated portion. The occurrence of cantilever failure, for the case of shear collapse mechanism (Thorne and Tovey, 1981) considered here, is simply determined from geometrical considerations, once an undercut threshold is exceeded. The undercut threshold is defined as the ratio of bank material cohesion to unit weight. Mass failures along planar slip surfaces are analyzed using a limit equilibrium method in combination with a search algorithm to find the failure block configuration with the smallest factor of safety (Langendoen and Simon, 2008). Factor of safety is the ratio of available shear strength to mobilized shear strength, and when smaller than one the bank is unstable. The method accounts for the effects of pore-water pressure on bank material shear strength, confining hydrostatic pressure provided by the water in the channel, and can automatically insert tension cracks if the upper portion of the failure block is under tension.

Input Data Requirements: Because RVR Meander is intentionally a simplified 2D model it inputs are limited. The main physical input parameters are: (1) design or bankfull discharge; (2) channel dimensions such as width, depth, and slope; (3) channel centerline to determine channel curvature; (4) valley slope; (5) channel boundary roughness; (6) scour factor; (7) bank profiles; and (8) resistance to erosion properties of the bank soils, i.e. erodibility and shear-strength parameters.

Software: The RVR Meander model can be executed in two modes (Figure 1): (1) as a stand-alone version from the command line in MS Windows or Linux; and (2) through a graphical user interface that is a plugin for ESRI's ArcMap 9.3.x or 10.x software. The compute engine is the same for both modes. The software, its manuals, and tutorial files can be downloaded at the URL http://rvrmeander.org.

The stand-alone version requires four input files: (1) "testdata.txt," pairs of easting and northing coordinates of the initial channel centerline; (2) "valley.txt," pairs of easting and northing coordinates of the valley centerline; (3) "prototype.cfg," general parameters for simulation; and (4) "InitialSectionProperties.dat," initial configuration of channel banks (shape and bank-material properties) for physically-based approach for meander migration. The ArcMap plugin uses the same input files, which are however prepared within ArcMap. The output files for the standalone version are designed to be post-processed using such software as Tecplot and MS Excel. The ArcMap plugin generated files can be directly viewed inside ArcMap with the

exception that the current version does not support "Bank geometry output," and needs plotting software such as MS Excel to view this output.

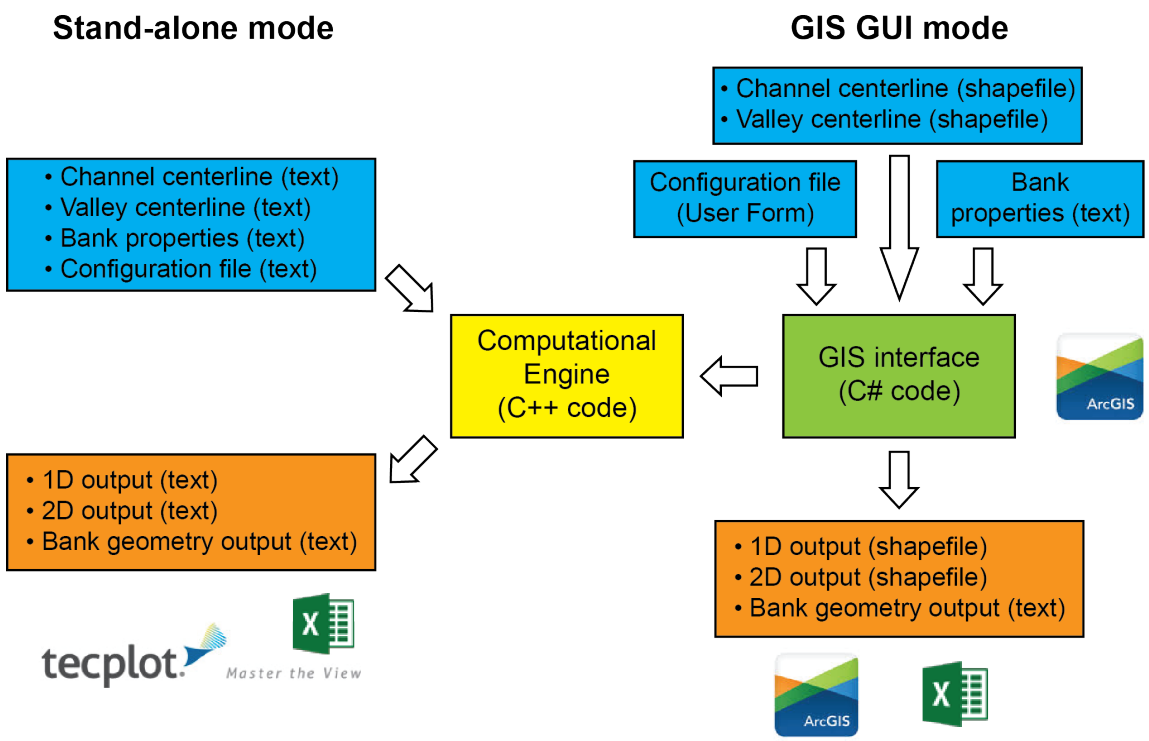


Figure 1 RVR Meander software is available as a stand-alone program for MS Windows and Linux operating systems and as a plugin for ESRI's ArcMap.

APPLICATIONS

Mackinaw River, Illinois: The performance of the proposed approach was tested for a reach on the Mackinaw River in Tazewell County between the towns of South Pekin and Green Valley, Illinois. The average width of the study reach is 38 m, valley slope is 0.47 m/km, and effective discharge is 62 m^3/s. The migration of the centerline between 1951 and 1988 was simulated with RVR Meander using both CMA (migration coefficient calibrated as 3.3×10^{-7}) and PMA. Bank retreat in the physically-based method was assumed to be caused by hydraulic erosion only, and the critical shear stress τ_c =9 Pa (measured critical shear stress is approximately 8 Pa).

Figure 2 compares the centerline migration obtained with the classical migration-based and the physically-based approaches. The channel centerline simulated using PBA agrees well with that observed away from the boundaries of the model reach. The channel centerline simulated using CMA is similar to that obtained by PMA for the upstream part of the study reach. However, CMA significantly overestimates the channel centerline migration, both in terms of meander amplitude and downstream translation, along the downstream part of the study reach.

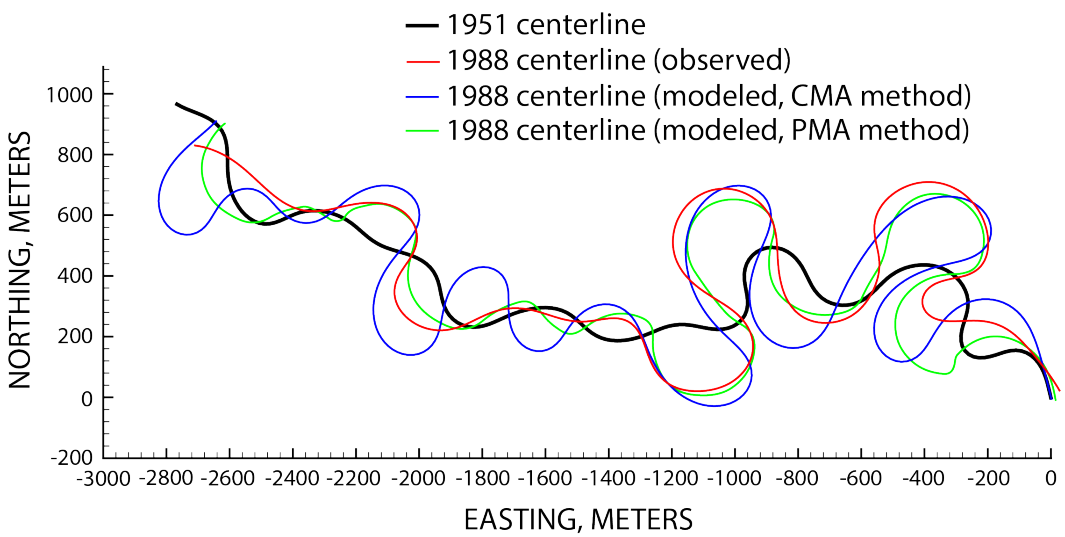


Figure 2 Comparison of observed and modeled centerline migration between 1951 and 1988 of a reach on the Mackinaw River, Illinois, USA. Flow is from right to left.

Big Sioux River, South Dakota: RVR Meander was used to assess potential erosion zones for a 34-km long reach on the Big Sioux River between Dell Rapids and Sioux Falls, South Dakota. The reach is fairly sinuous with an average sinuosity (ratio of channel length over valley length) of 1.6. The average channel top width and depth are 40.5 m and 2.2 m, respectively. The average channel slope is 0.4 m/km, and valley slope is 0.66 m/km. The 1.5-year return period discharge is 57.5 m^3/s, which is assumed to represent the bankfull discharge. The Manning *n* roughness coefficient is 0.052. A scour factor of 7 produced a transverse bed slope similar to that observed. The bed material is sand dominated with the median bed material grain size along the study reach varying between 0.03 and 7.0 mm with a mean value of 1.4 mm. Bank material is cohesive except for the sediments/soils at depth, which consist of sands and gravels. The upper cohesive layer primarily comprises erodible loam and sandy loam soils, but percent clay is found as high as 55%.

Figure 3 shows an example 11 meander bends with large simulated shear stresses near the outer bank. The plotted shear stress distributions were normalized by the reach-averaged shear stress representing uniform flow conditions. RVR Meander simulated high shear stresses at 45 unprotected bends that may potentially lead to enhanced migration rates. Sixteen of these bends have exhibited significant migration between 1991 and 2012, and should be targeted for construction of bank protection works. Eleven of these bends are located along a section of the Big Sioux River where several meander bends were cutoff between 1937 and 1991, which has resulted in increased bank erosion rates due to the channel adjustment caused by the local channel shortening and consequent increased gradient.

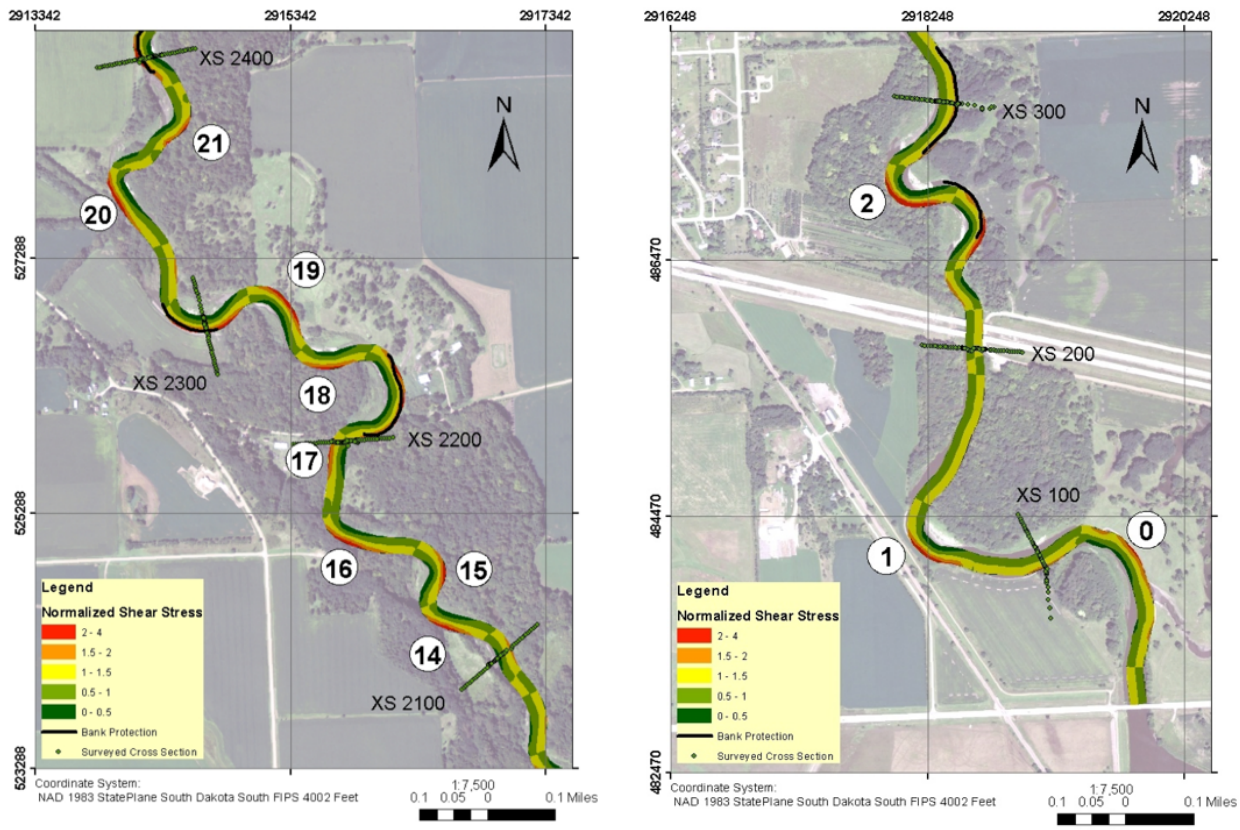


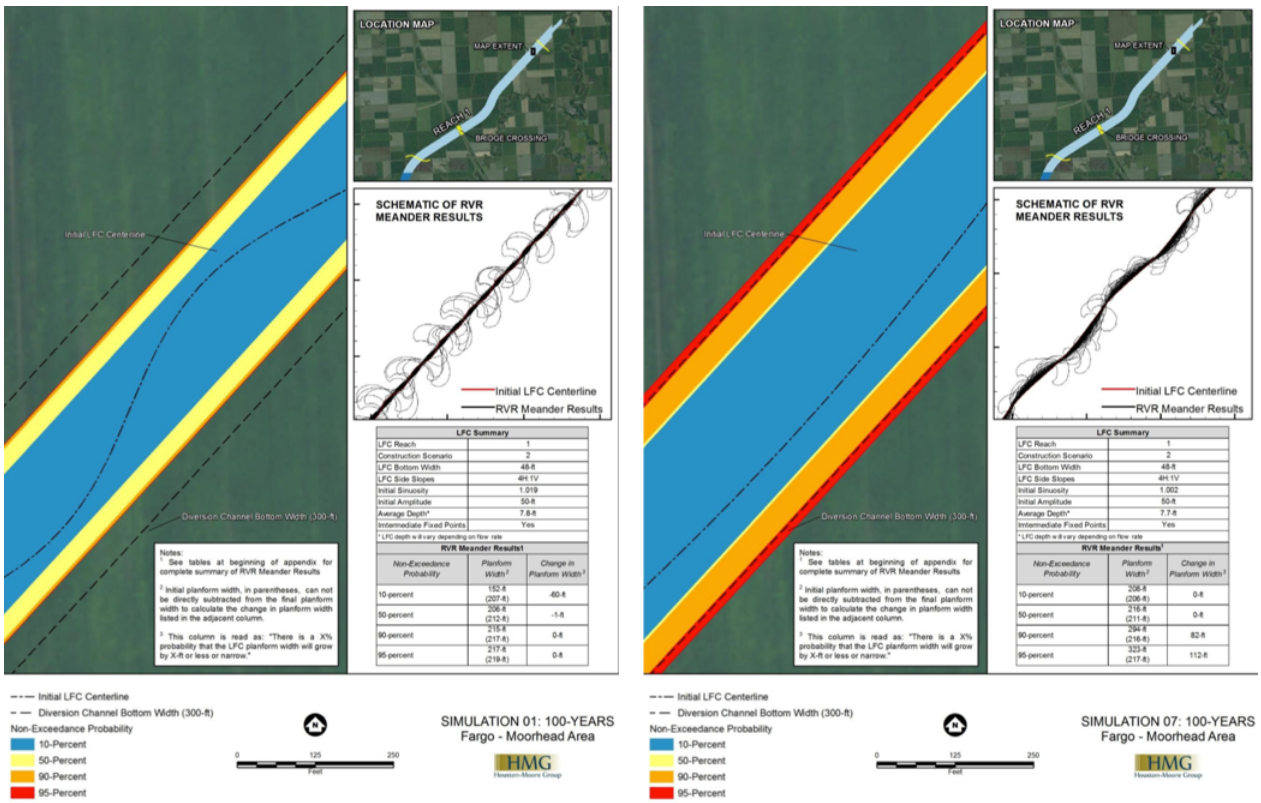
Figure 3 Example locations of large near-bank bed shear stresses simulated by RVR Meander along selected reaches of the Big Sioux River between Dell Rapids and Sioux Falls, South Dakota. Flow is from top to Bottom

Meander Belt Width Analysis, Red River Diversion, North Dakota: The Fargo-Moorhead Metropolitan Area Flood Risk Management Project seeks to prevent flooding of the cities of Fargo, North Dakota, and Moorhead, Minnesota by constructing a 36-mile diversion channel to the west of the metropolitan area. Included in the project plans is a low-flow channel (LFC) with a meandering planform (initial target sinuosity was 1.5) to provide enhanced aquatic habitat to mitigate the loss of approximately 5.5 miles of Lower Rush and Rush River reaches cut off by the diversion. An analysis of flow and sediment conveyance determined the LFC top width at 100 feet. The bottom width of the main diversion channel was set at 300 feet.

RVR Meander was used to determine if a meandering planform of the LFC was feasible given these widths. A Monte Carlo approach was followed, which facilitates risk analysis—in this case, calculating the probability that the meander belt will expand beyond the constraints of the diversion channel, given different conditions (e.g., planform configurations, resistance-to-erosion of boundary materials, channel aspect ratios, construction sequence). For example, only a limited number of soil samples could be collected along the planned course of the diversion (samples from more readily accessible locations were used as substitutions). For each design, a 1000 simulations were conducted over 50- or 100-year periods. The planform was generally sine-generated, and the cross-sectional shape was trapezoidal. We used the 1.5-yr return

discharge as the design discharge. Planform width, sinuosity, and dominant wavelength were the parameters that were assessed (see Figure 4).

The Monte Carlo simulations indicated that the LFC meander belt would generally have a tendency to narrow over time. Of factors considered, the initial wavelength had the largest impact on LFC migration; initial amplitude was also seen to be important. Other parameters such as the channel side slopes and bottom width, however, did not appear to significantly impact meander belt width over the life of the project. Also of note were simulation results for a phased construction scenario — assuming that construction of the diversion channel downstream of the Lower Rush River was completed first. These results suggested that in the first 10 years following phased construction, the change in meander belt width would be very small.



LFC Summary	
LFC Reach	1
Construction Scenario	2
LFC Bottom Width	48-ft
LFC Side Slopes	4H:1V
Initial Sinuosity	1.019
Initial Amplitude	50-ft
Average Depth*	7.8-ft
Intermediate Fixed Points	Yes

* LFC depth will vary depending on flow rate

RVR Meander Results[1]		
Non-Exceedance Probability	Planform Width[2]	Change in Planform Width[3]
10-percent	152-ft (207-ft)	-60-ft
50-percent	206-ft (212-ft)	-1-ft
90-percent	215-ft (217-ft)	0-ft
95-percent	217-ft (219-ft)	0-ft

LFC Summary	
LFC Reach	1
Construction Scenario	2
LFC Bottom Width	48-ft
LFC Side Slopes	4H:1V
Initial Sinuosity	1.002
Initial Amplitude	50-ft
Average Depth*	7.7-ft
Intermediate Fixed Points	Yes

* LFC depth will vary depending on flow rate

RVR Meander Results[1]		
Non-Exceedance Probability	Planform Width[2]	Change in Planform Width[3]
10-percent	208-ft (206-ft)	0-ft
50-percent	216-ft (211-ft)	0-ft
90-percent	294-ft (216-ft)	82-ft
95-percent	323-ft (217-ft)	112-ft

Figure 4 Example results of probabilistic meander belt width analysis of the LFC of the Red River, North Dakota, are presented using non-exceedance contours. (Left) meander planform with an initial sinuosity of 1.02 that tends to straighten. (Right) meander planform with an initial sinuosity of 1.002 that tends to increase its sinuosity and planform width; there is a 10% probability that the LFC will migrate into the diversion sidewall.

REFERENCES

Abad, J.D., and Garcia, M.H. (2006). "RVR Meander: A toolbox for re-meandering of channelized streams," Computer & Geosciences, 32(1), pp 92-101.

Bernhardt, E.S., Palmer, M.A., Allan, J.D., Alexander, G., Barnas, K., Brooks, S., Carr, J., Clayton, S., Dahm, C., Follstad-Shah, J., Galat, D., Gloss, S., Goodwin, P., Hart, D.,

Hassett, B., Jenkinson, R., Katz, S., Kondolf, G.M., Lake, P.S., Lave, R., Meyer, J.L., O'Donnell, T.K., Pa- gano, L., Powell, and B., Sudduth, E. (2005). "Synthesizing U.S. river restoration efforts," Science, 308, pp 636-637.

Ikeda, S., Parker, G., and Sawai, K. (1981). "Bend theory of river meanders. Part 1. Linear development," J. Fluid Mech., 112, pp 363-377.

Johannesson, H., and Parker, G. (1989). "Velocity redistribution in meandering rivers," Journal of Hydraulic Engineering, 115(8), pp 1019-1039.

Kondolf, G.M. (2006) "River restoration and meanders," Ecology and Society, 11(2), pp 42.

Langendoen, E.J., and Simon, A. (2008). "Modeling the evolution of incised streams. II: Streambank erosion," Journal of Hydraulic Engineering, 134(7), pp 905-915.

Motta, D., Abad, J.D., Langendoen, E.J., and Garcia, M.H. (2012). "A simplified 2D model for meander migration with physically-based bank evolution," Geomorphology, 163-164, pp 10-25.

Palmer, M.A., and Allan, J.D. (2005). "Restoring rivers," Issues in Science and Technology, National Academy of Sciences, 22, pp 40–48.

Thorne, C.R., and Tovey, N.K. (1981). Stability of composite river banks. Earth Surface Processes and Landforms, 6(5), pp 469-484.