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Predicting a migration corridor for a braided river from aggregate statistics of many meandering river simulations

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ABSTRACT

A novel procedure is presented to predict a 100-year migration corridor for a braided river, the 59-mile segment of the Missouri National Recreational River (from Yankton, SD, to Ponca, NE), which is a braided stream and still largely unconstrained despite growing development pressures. The prediction is based on 3612 100-year simulations exploring a constrained parameter space with a single-threaded river meandering model. An analysis of river evolution with respect to input parameters utilized two-dimensional statistics describing the individual and aggregate locations of the whole suite of simulated rivers over time. When compared to actual migration over the previous 100 a, the results suggest that, while individual realizations of the meandering model may not resemble actual river dynamics, the aggregate statistics may nonetheless provide reasonable predictions of braided stream migration suitable for purposes of resource management and planning. *INDEX TERMS: 1815 Erosion, 1816 Estimation and forecasting, 1825 Geomorphology: fluvial, 1847 Modeling, 1856 River channels. KEYWORDS: River meandering, Migration corridor, Geomorphic prediction, Simulation modeling, Missouri River.*

1. Introduction

Numerical simulation models provide a valuable tool for management of migrating streams and their floodplains, but such management applications are typically limited to single-threaded streams, for which river meandering models are reasonably well-suited (e.g., *Abad and Garcia*, 2006; *Johannesson and Parker*, 1985; *Larsen and Greco*, 2002; *Larsen et al.*, 2006). Many natural streams are braided or anastomosing, and as managers of such streams feel pressure for both development and restoration, predictive tools relevant to multi-threaded streams are currently needed. Recent studies [*Coulthard and Van De Wiel*, 2006; *Coulthard et al.*, 2007; *Van De Wiel et al.*, 2007] have advanced cellular modeling of braided stream evolution, but their treatment of lateral channel migration remains rudimentary (cf. *Hickin and Nanson*, 1984). *Howard* [1996] developed a probabilistic model of chute cutoffs, i.e., where scouring of floodplain channels leads to cutoff of meander bends, and this approach is promising, but the model has several unconstrained parameters that currently make it unsuitable for management applications.

Channel migration is of particular importance to the regeneration and fate of riparian cottonwood forests along the Missouri River. Channel migration acts to deliver trees to the river (where they serve as important elements of aquatic habitat) and to provide new, bare sand surfaces where seeds can germinate [*Florsheim et al.*, 2008; *Johnson*, 1992; *Mahoney and Rood*, 1998]. Restoration of some of these natural channel processes has been recognized as a critical goal for the Lower Missouri River [*National Research Council*, 2002]. Restoration of cottonwood communities has also been recognized as a specific requirement for management of bald eagle populations in the Missouri River [*U.S. Fish and Wildlife Service*, 2000; 2003]. An important prerequisite to spatially explicit projections of cottonwood recruitment will be the development and implementation of a predictive model of river channel migration. Moreover, a quantitative migration model can also contribute to design of a migration corridor [*Rapp and Abbe*, 2003; *Weeks et al.*, 2005]. Such understanding can serve to inform management decisions related to bank stabilization projects, sloughing easements, and land acquisitions over planning time horizons.

The objective of this study is to predict the 100-year migration of the 59-mile (97 km) segment of the Missouri National Recreational River (MNRR) by simulating the evolution of its geometry using a previously published meandering model. This segment of the MNRR, on the eastern border between South Dakota and Nebraska, and extending from Gavins Point Dam to Ponca, NE (Figure 1a), has an altered hydrologic regime due to dam operation but a relatively natural channel; presently no more than 33% of the banks have been stabilized [*Elliott and Jacobson*, 2006]. Current river meandering models, including that of *Johannesson and Parker* [1989] (JP model), used herein, represent the river as an idealized single channel with a constant width and a trapezoidal cross-section, and do not account for the multiple channels and braids, or the numerous chutes, islands, and submerged and emergent bars that are natural features of many rivers, including the MNRR. We might therefore expect individual realizations of such models to provide poor predictions of braided channel dynamics.

Rather, we hypothesized that the aggregated statistics of many slightly different single-threaded river simulations might adequately capture braided river dynamics well enough for management and planning purposes. We applied the JP model, which is based on physics that can be applied to real systems, in a large set of slightly different simulations to yield an aggregate probabilistic result. Thus, rather than attempt to predict the evolution of a single simulated river with great accuracy, we used a large set of simulations having moderate accuracy to make statements about the likely evolution of the real river based on the behavior of this population. The “100-year migration corridor” for the river could then be determined from the fraction of simulations that reached various points within the river valley, and from the boundaries that were defined by these regions and the area they enclosed. Finally, historical migration [*Elliott and Jacobson*, 2006] provides a qualitative check on our results.

2. Materials and Methods

We constructed the planform channel of the 97-km river segment from a mosaic of USGS 7.5’ topographic maps. This mosaic provided sufficient detail for digitizing the riverbanks to better than 10 m resolution. With a new geographic information system (GIS), we digitized the coordinates of the MNRR riverbanks and valley walls from the map mosaic, and interpolated these paths to a resolution of 100 m using circular arcs. We did not include chutes or other bifurcations with the main flow, but did include several islands. We combined and resolved conflicting bank data from maps made at different times. The valley boundary was digitized using the 1200-foot contour line, an approximation since the river falls from about 1170’ at Gavins Point Dam to about 1100’ at Ponca. The meandering model requires a river centerline and width at all points as input, and the GIS computed these automatically from the planform. Width of the digitized channel varied between 187–1650 m (mean $\pm \sigma$ of 748±338 m). Distances between points were calculated using oblate ellipsoid geometry.

Another computer program was written to read text files describing the initial shape of the river and simulation parameters, to simulate the river’s evolution, and to display the results. The program also accumulated the neck-type cutoffs that occur as river loops grow and eventually intersect. We used the [*Johannesson and Parker*, 1989] meandering model, which is a solution for the near-bank velocity perturbation, i.e., the amount by which the vertically averaged velocity near the bank differs from the average velocity for the cross-section as a function of several physical inputs, including channel width and depth, discharge, bed grain size, and water surface slope (Table 1), as well as the curvature at each point along the river. Curvature at each point is calculated as the integral of local curvature (inverse of the radius of a circle fit to a point and its two nearest neighbors) along a short upstream interval. As in many studies (e.g., *Camporeale*, 2005; *Hasegawa*, 1989; *Howard*, 1992; 1996; *Ikeda et al.*, 1981; *Lancaster and Bras*, 2002; *Parker and Andrews*, 1986; *Stolum*, 1996; *Sun et al.*, 1996), application of *Johannesson and Parker* [1989] as a model of river meandering employs the assumptions that bank erosion at each point along the channel is proportional to the near-bank velocity perturbation; erosion on one bank is exactly matched by deposition on the other, so that the channel width is constant in time; and channel migration at each point is perpendicular to the downstream direction at that point. To represent the effects of bedrock constraints, channel movement was not allowed past the valley wall. Simulation statistics were compiled with a new database program, which tracked the course of every simulated river over time.

The JP meandering model simulates a single channel with a trapezoidal cross-section, but the MNRR contains many bifurcations, chutes, islands, braids, and submerged and emergent bars [*Elliott and Jacobson*, 2006]. We hypothesized that an informed choice of many slightly different simulations, using restricted ranges of input values, would better serve to approximate, as a population, the likely behavior of the real river over the next 100 years, compared to any single simulation that might be more realistic. Based on tests with individual combinations of the parameters used by the JP model, we chose discrete values of 6 different river parameters as variable inputs to a large set of simulations: (1) maximum attenuated channel width; (2) flow depth; (3) discharge; (4) bed particle diameter; (5) summation distance, which determines the length (in local channel widths) of the curvature integration; and (6) initial erosion rate. Channel widths varied downstream, but the JP model became unstable for channel widths exceeding 800 m. In the different simulations, channel width took various values as governed by a maximum value and a relation that allows variation even at greater widths:

$$w_{sim}(s) = w_{\max} - (w_{\max} - w_{\min})e^{-[w(s) - w_{\min}]/400}, \qquad (1)$$

where s is downstream distance; and w_{sim}, $w_{\max}$, $w_{\min}$, and w are the simulated, maximum attenuated, minimum observed, and actual observed channel widths, respectively. The erosion rate at any given time is a function of the channel centerline geometry and all the simulation parameters, including bank erodibility, which is the constant of proportionality between erosion rate and velocity perturbation (cf. *Wallick et al.*, 2006). Since all simulations had the same initial centerline, initial erosion rate is a function of the parameter values only. At the beginning of each simulation, the initial erosion rate was set by adjusting the bank erodibility, such that the initial erosion rate, averaged over the simulated stream, was equal to either the value 1.2 ha a^{-1} km^{-1} (12 m a^{-1}), measured by *Elliott and Jacobson* [2006], or another prescribed value (Table 1). By examining the final configurations of rivers generated from different combinations of these parameters, we chose discrete values as inputs to the large set of runs (Table 1).

For all parameter combinations (Table 1), 3072 total runs were required. All new programs were written in the Python language and using the WxPython graphics library. Python is a high-level cross-platform object-oriented programming language known for its ease of use and short development time.

3. Results

Every 100-year simulation accumulated 2-dimensional residence time and cumulative erosion arrays, saved every 10 a. The residence time array shows how long the river occupied every 125 m × 125 m square in the valley. Extents of non-zero array values show the range of migration, or coverage area, for each simulation. The common coverage array shows the fraction of all simulated rivers that occupied each point in the valley at least once (Figure 1b) and thus provides a probabilistic interpretation of the potential migration of the actual river: values of array elements are predictions of probabilities that the actual river will reach those points at least once during the next 100 years. The migration corridor can then be defined as the subset of the common coverage array having values greater than or equal to some constant, e.g., a high value, such as 95%, if the objective is to be confident that a site will be visited by the river, or a low value, such as 5%, if the objective is to be confident that a site will not be visited. The migration corridor is therefore different for different acceptable levels of visitation probability, and at different times during the 100-year simulation period.

The cumulative erosion array shows the river's erosion of each 125 m × 125 m square. Eroded area was calculated after every 0.25 a time step, and the cumulative erosion is the total continuously summed erosion at a point (i.e., not the difference between the final and initial land areas adjacent to the river over the 10 a interval). Thus, the simulated river could meander very slightly but nonetheless rework surface area to produce a high value of cumulative erosion within a single square. Cumulative erosion is normalized by the area of each square and expressed as a percentage of area reworked over 100 a. The average turnover percentage in 100 a is then the cumulative erosion averaged over all simulations (Figure 1c). For example, a value of 200% at a point means that, on average, the river erodes that point twice during 100 a. The average cumulative erosion array therefore provides a prediction of the intensity of erosion within the meander corridor, effectively an alternative meander corridor criterion that provides more information than the common coverage array.

Historical mapped banklines and valley bottom topography (Figure 1d) [*Elliott and Jacobson*, 2006] allow qualitative evaluation of model predictions. Comparison with the predictions of visitation probability and average turnover (Figure 1b,c) indicate that the predictions of where the migration corridor is wider vs. narrower coincide with locations of greater and lesser actual river migration during the period, 1894–1999 (e.g., at river mile 790 and 2 mi. downstream, respectively; Figure 1d). The areas of greatest predicted visitation probability and average turnover (e.g., within the 75% and 56% contours respectively; Figure 1b, c) appear to predict greater lateral migration than seen in the historical banklines, whereas the latter indicate greater down-valley migration than predicted. Topographic traces of paleochannels are visible well outside of these areas of greatest predicted visitation probability and average turnover, but the extents of these traces are generally contained within the area visited by at least one simulated river (Figure 1b).

Target areas, corresponding to towns, roads, airstrips, parks, and other geographic landmarks, were defined within the valley with the GIS (Figure 1b,c; Table 2). The coverage arrays for each simulation were saved at intervals of 10 a, and the database determined the first time, to the nearest decade, that any simulated river reached a specific target, if at all. These times were averaged for the subset of simulated rivers that reached designated targets to yield the expected river arrival time, conditional on the river actually reaching those targets (Table 2).

4. Discussion and Conclusions

The objective of this study was to develop a quantitative model of evolution of the 59-mile segment of the MNRR to predict migration domains and ranges that are amenable to potentially different management strategies. As a complex, multi-thread river channel, the Missouri River presents substantial challenges to realistic simulation modeling over extended time frames. Although the JP single-thread model was not constructed to predict migration of a complex channel like that of the Missouri River, we elected to use the model to assess channel positions pseudo-probabilistically. We used combinations of realistic ranges of single-thread model parameters to predict migration channel migration and assessed the probability of channel occupancy over the parameter space and over 100 years of simulation. Each combination of parameters contributed a small part to the overall prediction. Although this approach provides some guidance for determining a migration corridor by illustrating what the river might do during the next 100 years, development of a multiple-thread meandering model clearly would be more appropriate to the specific three-dimensional geometric characteristics, boundary conditions, and bed materials of the MNRR.

Assessment of the model predictions is qualitative and based on past migration patterns. During the time interval, 1894–1999, the closing of dams, including Gavins Point Dam at the head of the study reach in 1957, has cut off sediment supply and diminished flood peaks in the study reach (Table 2), and substantial bank lengths have been artificially stabilized, both effects documented by *Elliott and Jacobson* [2006]. It is therefore likely that future migration will differ substantially from that of the past.

The objective of this modeling study was to provide predictive understanding of the variability of MNRR geometry and dynamics over a planning time frame of 100 years. The probabilistic understanding of how much area the river will tend to migrate over, if unimpeded by bank stabilization projects, may contribute important information to agencies that make decisions about the management of the river and its resources. A quantitative prediction that delineates the probable limits, both nominal and extreme, of river migration during the next century should allow managers to assess proposed intervention activities based on the locations of reaches in which migration rates are higher or lower than the norm. Such information can be used to determine where channel migration can be tolerated, and where it presents unacceptable risks or conflicts with other land and river uses.

5. Acknowledgments

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Figure 1. (a) Location of the 59-mile segment of the Missouri National Recreational River (MNRR) between Gavins Point Dam and Ponca on the Nebraska-South Dakota border. (b,c) 100-year migration predictions for points in the MNRR valley: (b) visitation probability (gray scale and contours labeled with percentages) as percentages of the 3072 simulated rivers visiting those points at least once in 100 a, and (c) average turnover percentage (gray scale and contours labeled with percentages; percentages can be greater than 100% to represent repeated erosion) as cumulative percentages of each pixel eroded in 100 a, averaged over the 3072 simulated rivers. Initial river centerline is drawn, and 13 target areas (Table 2) are outlined and numbered in italics (b, c). (d) Actual migration of the MNRR, 1894–1999, within the valley (thick solid lines) overlain on U.S, Army Corps of Engineers digital elevation model (meters above mean sea level), 1999; adapted from *Elliott and Jacobson* [2006].

Table 1. Parameter values for simulation runs.

Maximum width (m)	Depth (m)	Discharge (m^3/s)	Present flow exceedance (% of days)[1]	Pre-dam flow exceedance, (% of days)[1]	Particle diameter (m)	Lag distance (local channel widths)	Sum distance (local channel widths)	Initial erosion rate (ha/a/km)
500	2.75	800	52	37	0.00050	1	0.75	1.2
600	3.00	1,000	18	29	0.00075		1.00	1.8
700	3.25	1,200	10	23	0.00100		1.25	2.4
800	3.50	1,400	6	18	0.00125			3.6

[1] Calculated from 100 years of daily routing model for Missouri River [*U.S. Army Corps of Engineers*, 1998]

Table 2. Geographic targets within the Missouri River valley adjacent to the MNRR (Figure 1), with mean time to contact by the migrating river channel, assuming no bank stabilization.
[>, greater than]

Geographic Target	Mean Time to Contact (a)
1. Elk Point	62
2. Gayville	91
3. Davidson Field	60
4. Jefferson	100
5. Meckling	> 100
6. Mission Hill	86
7. Ponca State Park	0
8. Richland	> 100
9. Vermillion	69
10. Volin	> 100
11. Westfield	> 100
12. Yankton	17
13. Hwy. 50	72

Figure 1

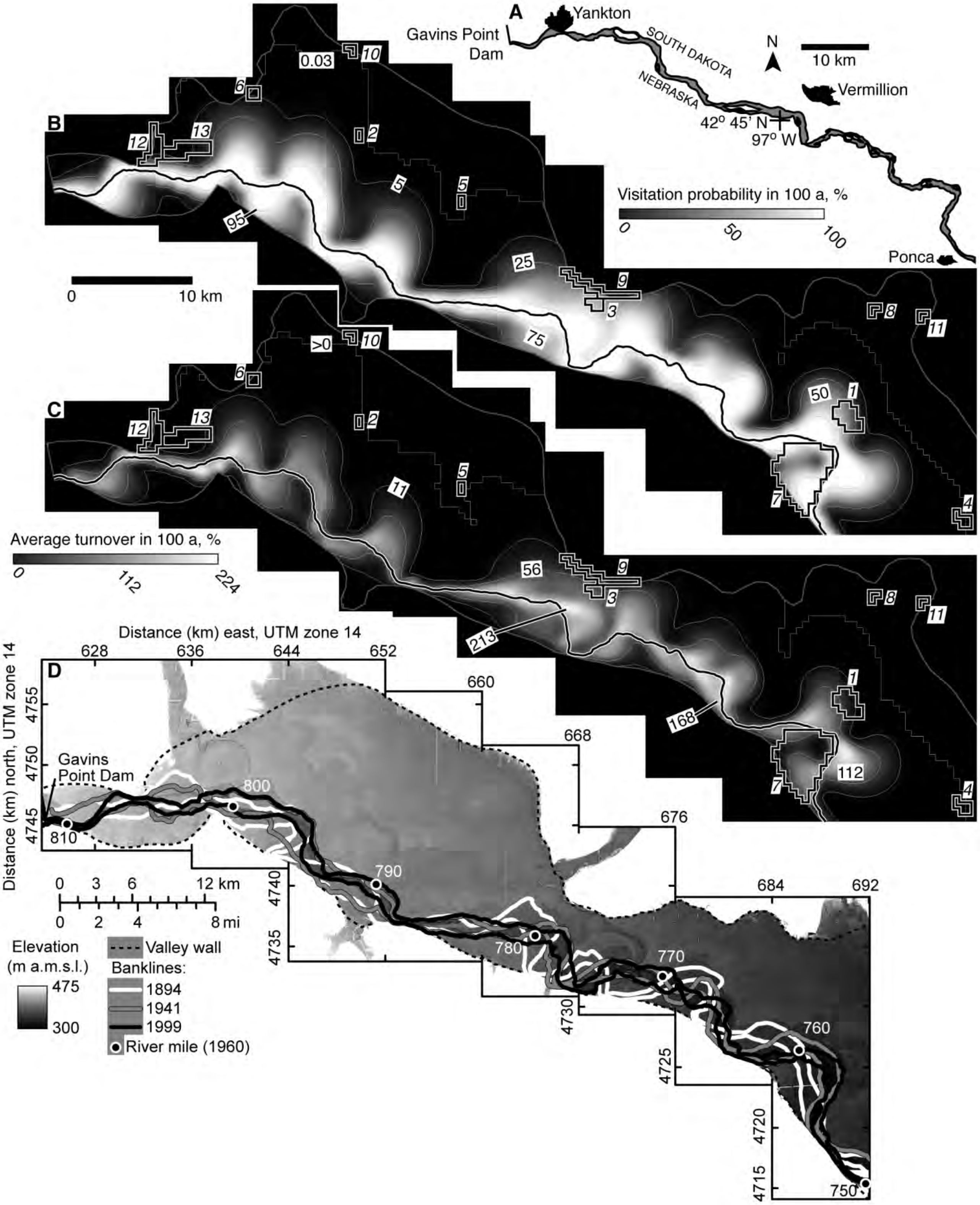
A
Yankton
Gavins Point Dam
SOUTH DAKOTA
NEBRASKA
N
10 km
Vermillion
42° 45' N
97° W
Ponca
B
0.03
10
6
2
12
13
5
5
95
25
9
3
75
50
1
7
8
11
4
Visitation probability in 100 a, %
0
50
100
0
10 km
C
>0
10
6
2
12
13
5
11
56
9
3
213
168
1
7
112
8
11
4
Average turnover in 100 a, %
0
112
224
D
Distance (km) east, UTM zone 14
628
636
644
652
660
668
676
684
692
Distance (km) north, UTM zone 14
4755
4750
4745
4740
4735
4730
4725
4720
4715
Gavins Point Dam
810
800
790
780
770
760
750
0
3
6
12 km
0
2
4
8 mi
Elevation (m a.m.s.l.)
475
300
Valley wall
Banklines:
1894
1941
1999
River mile (1960)

Figure 1 (color for online)