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EXPANDING THE ANALYTICAL POTENTIAL OF CHANNEL LOCATIONAL PROBABILITY MAPS USING CELLULAR STATISTICS

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ABSTRACT

The planimetric shifts in channel location of large alluvial rivers are a critical component in the creation of diverse structures and functions in riverine habitats. Engineered management schemes must also compensate for this type of channel change to protect resources and maintain navigation channels. The stability of the Lower Mississippi River channel was assessed through an analysis of historical records of channel position produced and archived by the United States Army Corps of Engineers. Channel location was recorded for the years 1765, 1820, 1881, 1915, 1930, 1937, 1960 and 1970. Channel stability was measured by two introduced metrics on a cell-by-cell basis: (1) the standard deviation of Euclidean distance to a channel cell for the entire period of record, and (2) the rate of Euclidean distance change between years in the period of record. At a coarse spatial scale, channel instability increased in the downstream direction. The variability of channel stability also increased in the downstream direction. Analysis of this variability identified alternating areas of high and low stability occurring with greater frequency as distance downstream increased. These findings are validated by past studies of channel stability along the Lower Mississippi River. As a result, the proposed metrics provide a consistent, quantitative, efficient and cost-effective means of identifying areas of channel instability at several spatial scales. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: Lower Mississippi River; locational probability; alluvial river; channel change; stability; instability

INTRODUCTION

The Mississippi River presents an ideal laboratory for analysis of large alluvial river systems. Understanding long-term dynamics of large river systems requires a timescale greater than a single human lifetime. Typically, the limited historical record imposes a significant constraint upon the analysis of fluvial systems. Most hydrologic and geomorphic records of river processes in North America date back 60 to 75 years before present. The Lower Mississippi River (LMR) is a notable exception. The geographic position of the channel of the Lower Mississippi River has been recorded periodically since 1765 (Wasklewicz *et al.*, 2004). The United States Army Corps of Engineers (USACE) has archived these data in both hardcopy and digital format. Channel location was recorded for the years 1765, 1820, 1881, 1915, 1930, 1937, 1960 and 1970. Using these data, Wasklewicz *et al.* (2004) implemented a modified version of Graf's (1981, 1984, 2000) locational probability analysis as a means of identifying channel segments of the LMR that have been historically mobile. The purpose of this article is to provide an alternative method for assessing channel change using these same data. The findings from these analyses are validated using prior studies of channel change along the LMR.

The new methods proposed in this study attempt to answer the following questions: (1) Where has channel change historically occurred in the Lower Mississippi River? (2) How do the new methods of assessing channel change compare to previously proposed methods? (3) How does channel stability prior to and during the artificial cutoffs of the 1930s compare to the post-cutoff period? While these are the same questions asked by many researchers (e.g. Biedenharn *et al.*, 2000; Hudson and Kesel, 2000; Smith and Winkley, 1996; Wasklewicz *et al.*, 2004), this analysis contributes to the discipline of broader river research and management community

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as it (1) provides a simple, efficient means of quantifying channel change using geographic information systems, and (2) allows for the incorporation of a temporal component of channel mobility missing from previous analyses. Raster-based geographic information system analyses of the distance from the main channel identified unstable and stable zones. Rates of change between years for the period of record were calculated for the entire length of the LMR. Post-cutoff deviation and rate of change values are compared to pre-cutoff values. A qualitative assessment of the similarities between locational probability analysis and the proposed methodology is presented. The results will be related to the findings of Biedenharn *et al.* (2000), Hudson and Kesel (2000), Smith and Winkley (1996) and Wasklewicz *et al.* (2004) as a means of method validation.

STUDY AREA

The Lower Mississippi River (LMR), flows through a broad alluvial valley extending from Cairo, Illinois, in the north to the Old River Control Structure (near Red River, Louisiana) in the south. The historic and present channel geometry represents dynamic changes associated with geological, hydrological, glacial and anthropogenic forces acting upon the river. Geological controls include tectonic uplift, faults, and sediment heterogeneity. Tectonic uplift has been identified in two major zones: the Monroe Uplift and the Lake County Uplift (Schumm *et al.*, 1994). Tectonic uplift increases channel gradient. The channel responds by increasing its sinuosity as a means of reducing the channel gradient and maintaining a state of dynamic equilibrium. River stability decreases in areas of tectonic uplift, in turn accelerating meander development. Meander development increases channel sinuosity along that particular reach, effectively reducing stream gradient and increasing reach length and sinuosity. A channel cutoff eventually occurs during the meander cycle. A cutoff occurs in two ways: (1) neck cutoff, where the upstream and downstream arms of a meander intersect; and (2) chute cutoff, where a channel is formed in a point bar. Chute cutoff typically results in fairly large, stable islands in the reaches north of Memphis, Tennessee (Fisk, 1951).

A cutoff results in the presence of an oxbow lake and/or a high water channel. Water and sediment are introduced into the oxbow lakes and high water channels during periodic overbank floods. As floodwaters recede, fine-grained sediments, such as silt and clay, are deposited. The sediments accumulate and eventually generate a clay plug. Clay plugs limit lateral channel mobility in much the same fashion as bedrock. Hudson and Kesel (2000) have shown that channel migration is closely tied to sediment characteristics of the bank and adjacent floodplain. They cite the distribution of clay plugs as the most important variable in channel migration rates.

Anthropogenic activities have also had a significant impact upon the processes and form of the LMR. Early attempts to control flooding were associated with localized levee construction (Smith and Winkley, 1996). A series of levee districts were developed and charged with the task of constructing and maintaining levees. In 1879, the Federal Government initiated the Mississippi River Commission, which was tasked with the organization of existing, and the creation of new, levees along the length of the river (Smith and Winkley, 1996). The disastrous flood of 1927 led Congress to institute the Flood Control Act of 1928, which led to the Mississippi River and Tributaries (MR&T) Project (Smith and Winkley, 1996). USACE was enlisted to implement the four elements of the MR&T Project: construction of levees and floodways, channel improvement, channel stabilization, and tributary basin improvements (USACE, 2003). Each of these elements was incorporated into the MR&T as a means of mitigating disastrous floods and improving navigation on the nation's largest river. During a period from 1933 to 1944, USACE cut off 16 meanders, reducing one section of the LMR from 800 km to 235 km in length (Smith and Winkley, 1996). Geomorphic responses to these cutoffs were rapid and still operate to the present day (Biedenharn *et al.*, 2000). A full review of the engineering programmes associated with the LMR has been conducted by Smith and Winkley (1996).

LOCATIONAL PROBABILITY ANALYSIS

The locational probability of a stream channel is the likelihood that the channel will occupy a given point within the floodplain (Graf, 2000). Early methods of analysing locational probability were developed by Graf (1981, 1984) for alluvial rivers in arid environments, including the Gila River (1981) and Rillito Creek, Arizona

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(1984). Graf (2000) later analysed the Salt River near Phoenix, Arizona, with the purpose of identifying causal mechanisms, and the spatial and temporal components of channel change. This method used high-resolution aerial photography to delineate the channel and six functional surfaces for a 62-year period encompassing the years 1935–1997. Graf found that high probability areas alternated in the downstream direction with low probability areas, with moderate probability areas between the two. This was attributed to natural and engineered controls on channel location, fluctuations in water discharge, sand and gravel mining, dam closure, and urbanization.

Wasklewicz *et al.* (2004) applied Graf's (2000) techniques to six segments of the Lower Mississippi River. This study implemented a slight modification to Graf's (2000) weighting technique designed to calculate the probability of channel location for any given year. This modification allowed for all years to be weighted by the inclusion of the year 2000. Results indicated alternating segments of high and low probability along the path of the LMR. High probability (stable) zones were found near the upper and lower ends of channel cutoffs, areas of confinement by natural landforms, tectonic activity, engineered structures, and large islands. Low probability values were found along meanders, chute and neck cutoff areas, near small islands, and tectonic structures.

The interpretation of locational probability maps to date has relied heavily on the experience of the researcher. This may sometimes lead to misinterpretation of the locational probability results as the researcher may not have detailed knowledge of every river segment, especially in the case of large river systems. For instance, a given reach may have low locational probability values, indicating a relatively unstable channel. However, while the river seldom occupies the same area during the period of study, the reach may be ultimately confined by geological or tectonic controls. As a result, what appears to be unstable at a fine scale may actually be rather stable at a coarser spatial scale. A second shortcoming is that the resultant probability map or surface identifies a single probability value for all years in the period of record. Rivers are both temporally and spatially dynamic. The locational probability approach to channel mobility does not recognize the temporal component of channel mobility. The following method is designed to overcome the aforementioned shortcomings in interpreting locational probability values.

METHODOLOGY

This study utilizes three different methods of geographic information system (GIS) analyses. Each method is presented as a means of furthering the knowledge-base concerned with locational probability and the morphology of the LMR. The first method analyses the standard deviation of the Euclidean distance from the active channel for the eight years in the temporal sequence. The result of this process is referred to as distance deviation for the remainder of this article. The second method calculates the rate of change in Euclidean distance to a channel cell on a cell-by-cell basis. The third method follows Wasklewicz *et al.* (2004) techniques for calculating locational probability.

The LMR was divided into six river segments using major tributary confluences (Figure 1) (Wasklewicz *et al.*, 2004). Four reasons are provided for this delineation: (1) tributary confluences act as long-term markers throughout the temporal sequence of the data; (2) major tributaries influence river form and processes (Saucier, 1996); (3) it provides landmarks for future investigations into the dynamics of the LMR; and (4) it allows for comparisons between the current methods and those of Wasklewicz *et al.* (2004).

Data collection

The geographic position of the channel of the Lower Mississippi River has been recorded periodically since 1765 (Wasklewicz *et al.*, 2004). Wasklewicz *et al.* (2004), have converted the existing data into GIS coverages for further spatial analysis. Some tributary streams included in the original data sources were removed. Those selected for removal were the tributaries that were not found in all years in the period of record. The noise introduced into the output grids as a result of the inclusion of these tributaries provided the rationale for their removal.

GIS analysis

Initial processing. The coverages for each of the eight years of record were converted to separate binary grids with a resolution of 100 m by 100 m. Each grid covered the same extent, and was 7329 rows by 3598 columns (total

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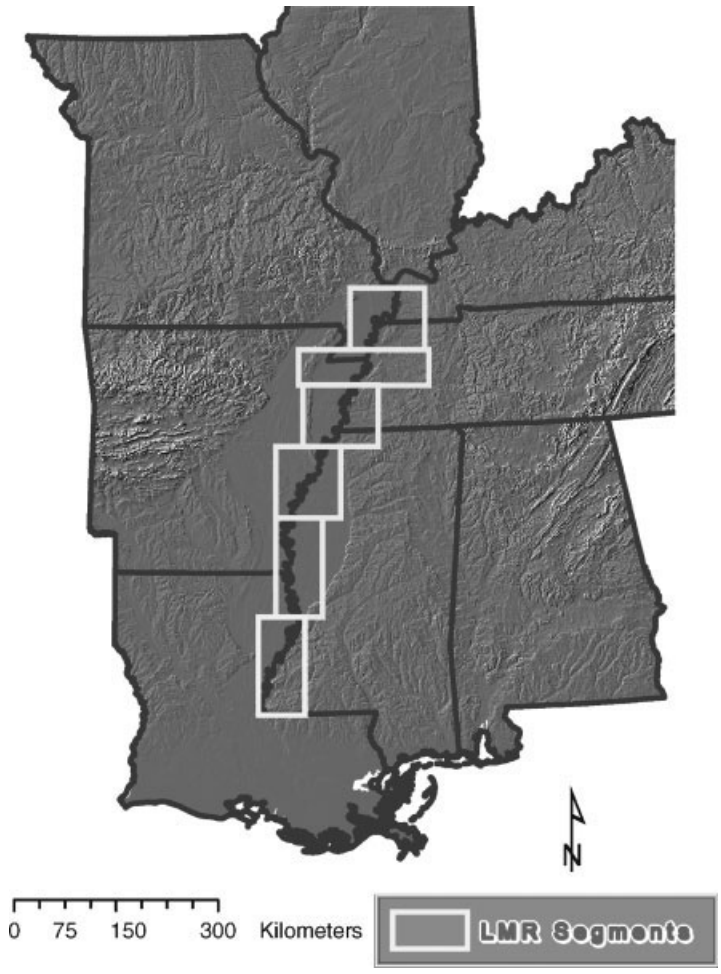

Figure 1. Segment delineation of the lower Mississippi River

area equal to 263 697 km^2). For each grid, the binary value of 1 indicated that a majority of the grid cell was considered to be a part of the channel, as identified on the original coverage. A binary value of 0 identified the cell as not having a majority of its area within the identified channel. Large islands, lakes and ponds were not considered to be a part of the active channel, while backwater environments, such as oxbow lakes and overflow channels, were considered to be a part of the active channel. The output grids for each analysis technique were masked to include only the cells within 3000 m of those cells identified as a channel in any of the eight years within the temporal sequence. This masking was necessary for statistical analysis of the output data. The 3000 m threshold was selected as it was the smallest mask size that would produce a continuous coverage of the channel area. As a result, the surfaces of the largest mid-channel islands were included in the analysis.

Distance deviation. Distance deviation is defined as the standard deviation of the distance of each cell from the active channel, for the eight years in the period of record. The fundamental assumption associated with the metric is that as the distance deviation increases, the overall stability of the channel decreases. For example, if a cell is 1000 m from a channel for the entire period of record, the distance deviation would be equal to zero, indicating stability. As the distance deviation increases, the amount of difference between distance values for each year in the period of record also increases. This increase is indicative of channel instability.

For each of the eight grids, the Euclidean distance function within ArcInfo was performed to identify the distance of each cell from the active channel for each of the eight years in the temporal sequence. The standard deviation of these eight resultant grids was calculated in the GRID module of ArcInfo Workstation. Areas of high

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distance deviation indicate higher channel mobility, while areas of low distance deviation indicate areas of low channel mobility.

One-dimensional analysis of channel mobility. Incorporation of a rate of change of Euclidean distance on a cell-by-cell basis allows for the temporal analysis of channel mobility. The change in Euclidean distance was calculated as the first step in the identification of rates of Euclidean distance change. These surfaces were identified by applying the following equation to a consecutive pairing of grids:

$$\Delta D_{i,j} = |E_{n2} - E_{n1}|$$

where $\Delta D_{i,j}$ represents the change in Euclidean distance for cell (i, j), E_{n2} represents the second map in the consecutive grid sequence (e.g. 1820) and E_{n1} represents the first map in the consecutive grid sequence (e.g. 1765).

The rate of change for each cell was identified applying the following equation to the grids identifying the change in Euclidean distance between consecutive years in the temporal sequence:

$$\Delta R_{i,j} = \Delta D_{i,j} / t_{(n2-n1)}$$

where $\Delta R_{i,j}$ represents the rate of change of Euclidean distance for cell (i, j), $\Delta D_{i,j}$ represents the change in Euclidean distance for cell (i, j), and $t_{(n2-n1)}$ represents the number of years between maps *n1* and *n2*. The inclusion of this variable into a channel location analysis should be significant as it adds a temporal component to the nature of channel change.

RESULTS

Rather than select an arbitrary value as a threshold between 'low' distance deviation and rates of Euclidean distance change ('low' mobility) and 'high' distance deviation and rates of Euclidean distance change ('high' mobility), percentiles were used as a means of describing and comparing the relative mobility of the LMR (Table I). Use of the quartiles allows for the identification of relative magnitudes of channel mobility. Rates of Euclidean distance change (EDC) and their associated percentiles are grouped by their temporal relationship to cutoff (Table II).

An analysis of the distance deviation values shows that the degree of mobility tends to increase in the downstream direction (Table III). Distance deviation values tend to be higher near cutbanks and along meanders with high amplitude and wavelength. These results are particularly reflected in segment 5 (Figure 2). The amount of variation within the segments (characterized by the standard deviation) also tended to increase in the downstream direction. This can be attributed to the fact that multiple artificial cutoffs were constructed in segments 4, 5 and 6 during the 1930s and 1940s. Natural and artificial cutoff processes increase channel gradient in that particular reach. Upstream of the cutoff, sediment is mobilized as the bed is degraded as a response to a lowering of local base level (Smith and Winkley, 1996). Downstream of the cutoff, the channel increases sinuosity as a means of balancing an increased sediment load and flow velocity (Smith and Winkley, 1996). Most of the mobility exhibited by the LMR in areas of artificial cutoff can be related to the river attempting to re-establish a grade that reflects the sediment load and discharge (Mackin, 1948).

Table I. Distance deviation percentiles for the Lower Mississippi River

Percentile	Distance deviation (m)
10	216.5
25	390.7
50	670.5
75	1162.1
90	2002.6

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Table II. Rates of Euclidean distance change ($m\,a^{-1}$) percentiles for all periods of recorded channel location

Percentile	Pre-cutoff	During cutoff	Post-cutoff
10	2.83	0.72	0.00
25	6.01	8.72	4.15
50	10.98	19.53	11.72
75	18.27	43.35	33.30
90	29.85	86.65	94.55

Table III. Distance deviation values: means and standard deviations

Segment	Range of values (m)	Mean (m)	Standard deviation (m)
1	0–2436.9	598.9	405.1
2	0–2812.1	740.9	578.9
3	0–4350.5	889.6	847.3
4	0–3789.2	855.4	645.8
5	0–4569.1	1014.4	769.3
6	0–4535.3	1107.4	943.3
All	0–4569.1	910.2	771.7

The greatest amount of within-segment variation was identified in segment 6. This can be attributed to the channel adjusting to an increased sediment load as the upstream reaches adjusted to artificial channel cutoff projects. An exception to the general downstream increase in mobility and variation is noted in segment 3. In this case, the degree of mobility, as well as the amount of variation within the segment, is greater than the upstream and downstream segments. This can be attributed to a variety of processes, but most prevalent are several meander cutoffs and the formation and migration of islands, which would increase channel location variability (Wasklewicz *et al.*, 2004). Segment 3 also possesses several highly stable sections that are closely related to immobile large islands and clay plugs (Hudson and Kesel, 2000). Alternating areas of low and high distance deviations are a characteristic identified consistently along the length of the lower Mississippi alluvial valley.

Rates of EDC reflected patterns similar to those identified with the distance deviation analysis. Mean rates of EDC increase in the downstream direction for each gap in the period of record (Figure 3). Prior to 1881, the amount of variability within each segment followed a bimodal increase in the downstream direction. Between 1881 and 1937, internal segment variability peaked in segment 3 and segment 6. A return to the consistent downstream increase in internal segment variability occurred after 1937.

The highest overall rates of EDC were identified during the period 1960–1970 near Greenville, Mississippi (Figure 4). This is attributed to cohesive bed material and responses to engineered features both upstream and downstream of this section. The highest average rate of Euclidean distance change for all segments was identified in the years between 1930 and 1937. Artificial cutoff during this period skewed rates of EDC towards the higher rates as new channels were constructed. For all periods and segments, areas of high rates alternate with areas of low rates of Euclidean distance change, as noted in Wasklewicz *et al.* (2004).

The artificial cutoff of meander-bends during the 1930s tremendously influenced the longitudinal profile of the LMR. The river responded to the alteration of gradient and sediment loads by lateral migration. As a result, the greatest rates of change of Euclidean distance occurred during this period (Table IV). Within-segment variation also increased dramatically during this period (Table V). Prior to meander-bend cutoff, the average rate of Euclidean distance change and the within-segment variability of change rates followed a bimodal increase in the downstream direction, peaking in segment 3 and segment 6. Following the cutoff period of the 1930s, both average rate of change and within-segment variability increased in the downstream direction for segments 1–5, and then decreased in segment 6.

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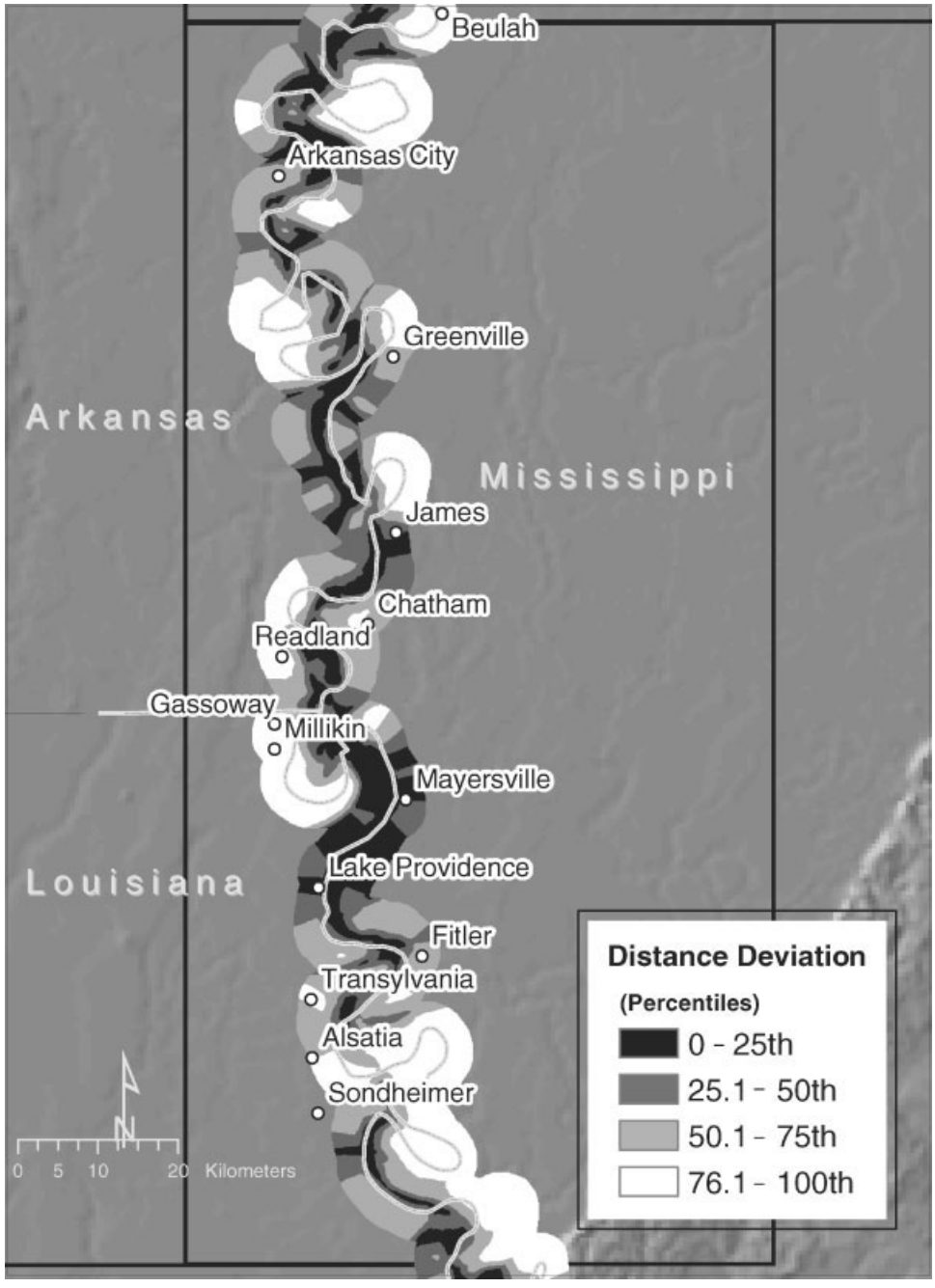

Figure 2. Distance deviation values along segment 5 of the lower Mississippi River

DISCUSSION

The results from the cellular statistical analyses provide new insights into the spatial–temporal characteristics of channel change on the LMR. Fluvial landscapes are often portrayed as multi-scaled nested hierarchies of processes and forms (Poole, 2002). The distance deviation and EDC analyses have shown channel variability on the LMR exists at two nested spatial scales that have been altered over the period examined by the current study. All segments exhibited a high degree of within-segment variability that was related to alternating low and high channel

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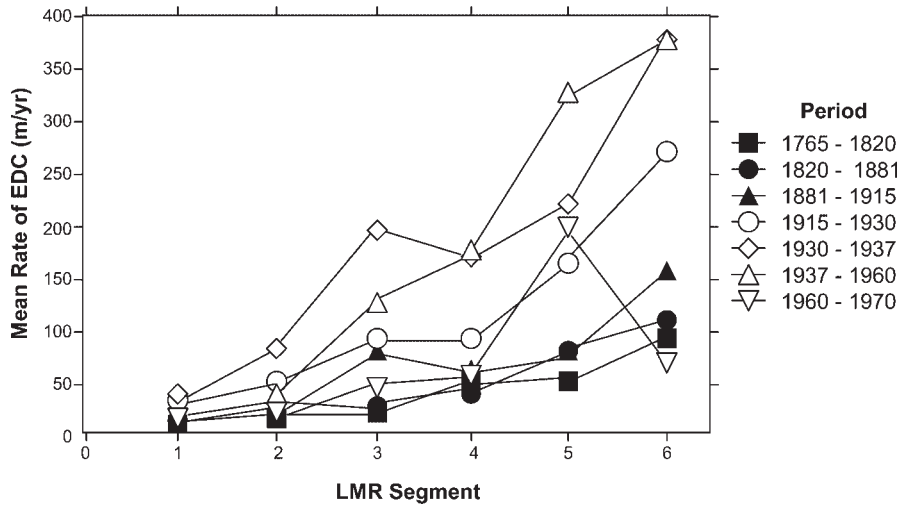

Figure 3. Mean rates of Euclidean distance change for all gaps within the period of record

locational probabilities. The distance deviation maps (Figure 3) showed clear evidence of this finer-scale spatial variability in channel mobility. A discontinuum was also evident at a broader spatial scale. The bimodal distribution in the EDC data prior to the 1930s along the LMR indicated that channel locational variability was spatially discontinuous in a downstream direction. High variability was identified at segment 3 in the middle section of the study area and at segment 6 at the lower end of the study area (see Figure 3, and Tables IV and V). There was also a strong indication for anthropogenic modification of this broad-scale spatial discontinuum. After the introduction of engineered structures in a more systematic fashion during the 1930s there was a change from the bimodal distribution of channel change to an increase in channel variability in a downstream direction. The implications of this broad-scale spatial discontinuum might be better addressed with further study of the more recent channel dynamics (i.e. assessing channel change from 1970 to the present).

There are three major areas where the cellular statistical analyses have corroborated and expanded findings conducted by other studies: the role of lithology, geomorphic features, and tectonic activity. Lithology and bank material composition influence the resistance of the bed and bank materials to entrainment. River banks of more cohesive materials (such as clays) limit the amount of sediment entrainment, thereby reducing channel mobility. Stable meander-bends, such as those at Mayersville, Mississippi, and near Horsehoe Lake, Arkansas, result from tertiary-aged clay deposits constricting the channel. Channel constriction and decreased mobility resulted in the identification of high probability values in these meander-bends. Analysis of the distance deviation values and rates of change in Euclidean distance values also identified these zones of the LMR as being quite stable. At the Mayersville site, distance deviation values fell within the 10th percentile of all values. Rates of change for all periods of the channel location record were also in the lowest quartile ($\leq$25th percentile). The Horseshoe Lake site also demonstrated distance deviation and rates of EDC values in the lowest quartiles for all periods.

Wasklewicz *et al.* (2004) identified island size as having a significant impact upon channel mobility. Large islands tended to create a more stable section of the river, as the flow is constricted to two locations. The presence of small, transient islands tends to lead to decreased stability. Small islands persist for a short period of time and are typically removed by lateral migration of the channel. These dynamics associated with the formation and removal of small islands result in low probability values (Wasklewicz *et al.*, 2004). Wolf Island, just downstream from Columbus, Kentucky, is a large island that has been relatively stable for the entire period of record. Distance deviation values for this location were distributed among all quartiles. Highest distance deviation values were identified on the western edge of the island, and resulted from migration of the overflow channel. Distance deviation values decreased as the distance to the main channel decreased. At the far eastern edge (closest to the thalweg), distance deviation values were in the lowest quartile (<25th percentile). This decrease resulted from the stability of the main channel of the LMR along this section of the river. Rate of EDC values were within the lowest quartile

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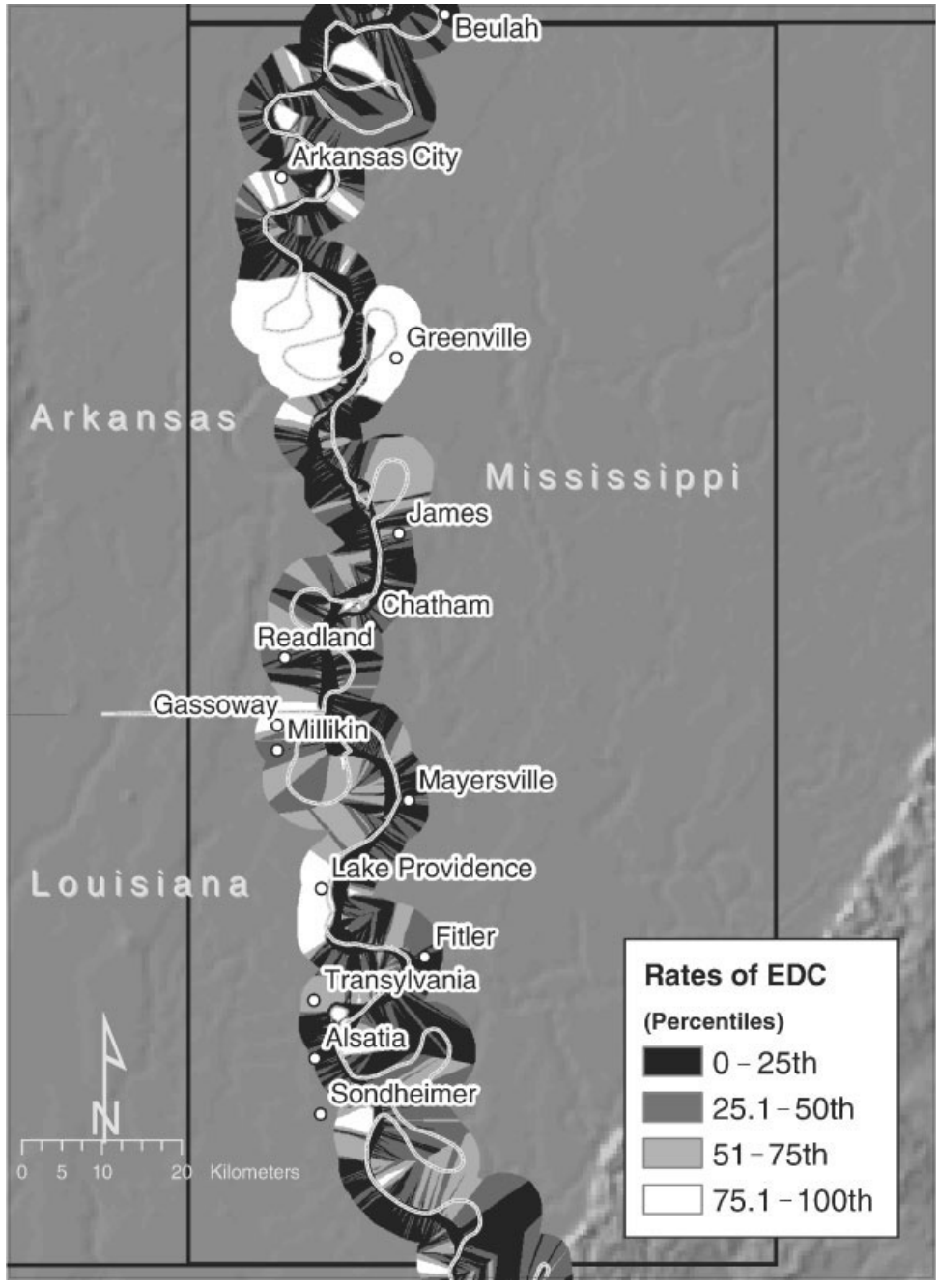

Figure 4. Rates of Euclidean distance change along segment 5 of the lower Mississippi River

(<25th percentile) for the period prior to meander-bend cutoff projects. EDC rates were greatest during the period of meander-bend cutoff projects, and decreased slightly following the cutoff projects.

Tectonic uplift increases local gradient. As a result, the river increases in sinuosity to balance the channel gradient with the sediment load (Biedenharn *et al.*, 2000; Mackin, 1948). Two zones of uplift are found along the LMR, the Monroe Uplift south of Greenville, Mississippi, and the Lake County Uplift near New Madrid, Missouri (Burnett and Schumm, 1983; Schumm and Spitz, 1996). Wasklewicz *et al.* (2004) identified relatively

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Table IV. Mean rates of Euclidean distance change ($m\,a^{-1}$) for the pre-cutoff, during cutoff, and post-cutoff lower Mississippi River segments

Segment	Pre-cutoff	During cutoff	Post-cutoff
1	9.57	32.13	11.97
2	11.33	33.00	12.93
3	13.92	48.36	28.55
4	12.84	32.50	28.72
5	14.09	38.76	52.14
6	19.81	54.08	36.89

Table V. Standard deviations (SD) of Euclidean distance change ($m\,a^{-1}$) for the pre-cutoff, during cutoff, and post-cutoff lower Mississippi River segments

Segment	Pre-cutoff	During cutoff	Post-cutoff
1	6.80	55.35	19.60
2	8.64	37.01	16.72
3	13.95	83.73	38.38
4	10.12	39.14	38.43
5	10.04	73.30	87.61
6	17.47	92.90	52.33

low probability values in these areas. Distance deviation and rates of EDC analysis identified cells within the Lake County Uplift and Monroe Uplift zones as typically being within the highest quartile ($\geq$ 75th percentile).

Anthropogenic activities combine with the natural characteristics of the river to alter channel mobility. The Greenville Bends section of the LMR has been identified as being an area underlain by cohesive, tertiary-aged clay deposits. Historically, this highly sinuous section of river has been relatively stable. The combination of this section's cohesive bed materials and anthropogenic activities upstream, downstream and within the reach have drastically altered the channel location in the post-cutoff period. Artificial cutoffs were constructed both upstream and downstream of this section of the LMR during the 1930s (Biedenharn *et al.*, 2000; Smith and Winkley, 1996). As a result, this historically stable section of river is in the transition zone between channel degradation associated with downstream meander cutoff, and the channel aggradation associated with upstream meander cutoff. Because of the cohesive bed material, the channel responded to the changes in local base-level by lateral migration. However, the increased sediment load resulting from the upstream cutoffs was greater than the transport capacity of the Greenville Bends reach. The river responded by creating a wide, shallow channel with multiple thalwegs. Distance deviation values in this section of the LMR are within the highest two quartiles ($\geq$ 50th percentile). Rates of EDC prior to cutoff fell within the middle of the distribution of values. During cutoff, this section of river had alternating sections of high and low mobility. After the cutoff period, the section of river had the highest rates of EDC of the entire LMR. Rates tended to be nearly an order of magnitude higher than the rates along other sections of the LMR. As the data included in this analysis do not extend beyond 1970, it is unknown how the rates of EDC have responded to the efforts to stabilize this section using revetment, dredging, wing dams and training dykes (Smith and Winkley, 1996).

CONCLUSION

Analysis of channel mobility using cellular statistics is an efficient means of accurately quantifying channel change at coarse and fine spatial scales. This analysis provided new insights into how the LMR has operated over the 235 years of channel location record, and supports the results of previous studies of the dynamics of the LMR

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(Biedenharn *et al.*, 2000; Hudson and Kesel, 2000; Smith and Winkley, 1996; Wasklewicz *et al.*, 2004). At a coarse scale, the amount of variability of channel mobility values increased in the downstream direction. At a fine scale, a repeating pattern of alternating areas of low and high mobility was identified. These findings are consistent with the river discontinuum concept.

The results of this analysis indicate that locational probability studies need to be bolstered with GIS cellular statistics as they provide a quantitative assessment of channel change, rather than relying solely on a researcher's map interpretation skills and field experience (Graf, 2000). While the findings of this study support the results of Wasklewicz *et al.* (2004), they also extend the results by providing a quantitative assessment of channel locational probability. The results can then be used to further elucidate the spatio-temporal variability of the locational probability maps.

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