Impact of River Channelization on Seismic Risk: Shelby County, Tennessee

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Abstract: The lower 35.4 km of the Wolf River, in the city of Memphis, Shelby County, Tennessee, was channelized in 1964 to reduce flooding. Detailed channel surveys conducted in 1959 and 1990 document river and floodplain changes 26 years after channelization. Channelization resulted in a straighter, steeper, deeper, wider, and smoother channel, thus causing an increase in channel velocity, cross-sectional area, and discharge capacity. Subsequent to channelization, Wolf River became shallower near its mouth, entrenched 3 m in its upstream reach, and formed a nick point at the eastern end of the channelized reach that migrated 11.3 km upstream. Tributaries to the channelized segment of the Wolf River have also entrenched. In addition, the floodplain along the channelized reach underwent dissection and denudation and the banks of the Wolf River were an average of 1 m lower in elevation than they were in 1959. Channelization and subsequent river changes have reduced flooding in the channelized portion of the river as intended. However, negative consequences of these river changes include (1) costly bridge and pipeline repair, (2) river and wetlands habitat destruction, (3) probable increased susceptibility for earthquake liquefaction and associated lateral spreading of the Wolf River floodplain, and (4) increased earthquake risk due to building development on the Wolf River floodplain.

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Introduction

The Wolf River is a west-flowing tributary of the Mississippi River that flows through the city of Memphis and Shelby County, Tennessee (Fig. 1). The river heads in northern Mississippi, flows through southwestern Tennessee, and is 138.5 km long. In Shelby County, the Wolf River flows through a wide floodplain consisting of basal point bar sands overlain by clayey silt overbank deposits (Kingsbury and Parks 1993; Broughton et al. 2001).

Wolf River and most other western Tennessee rivers were subject to flooding (Hidinger and Morgan 1912) and have been channelized (Simon 1989; Simon and Hupp 1992). In 1959 the U.S. Army Corps of Engineers conducted a detailed survey with measured river cross sections and sediment coring of the lower 59.6 river km (37 valley km) of the Wolf River from the river's mouth at the Mississippi River to Gray's Creek (Fig. 1) (U.S. Army Engineer District Memphis Corps of Engineers Wolf River and Tributaries Channel Improvement Report 1959). This project was conducted prior to channelizing 35.4 km of the Wolf River in the city of Memphis and Shelby County. In 1964 the channelization was completed, thereby straightening Wolf River by cutting off meander bends and shortening its lower 59.6 km to 35.4 km. The excavated channels were typically trapezoidal in cross section, resulting in a deeper and wider channel with steeper banks than the original river. Removal of vegetation along the channel also reduced channel roughness (Simon 1994). A second detailed survey was conducted in 1990 by the Corps of Engineers from the mouth of Wolf River 57.4 valley km upstream to the Shelby/Fayette County line (Flood Insurance Study, Shelby County, Tennessee, 1990). Wolf River bottom profiles were also surveyed in Collierville, upstream from the channelized river bed, between the Houston Levee Road bridge and the Collierville–Arlington Road bridge in 1977, 1989, 1995, and 1997 (1997 profile not included in this paper) to monitor accelerated erosion and nick point (point of abrupt change or inflection in the longitudinal profile of a stream) retreat occurring in this river reach (U.S. Army Corps of Engineers, Memphis District, Wolf River Memphis, Tennessee, Draft Feasibility Report and Draft Environmental Impact Statement, June, 2000). The 1959 and 1990 surveys allow us to compare the Wolf River prior to channelization with its condition 26 years later from valley km 3.7 to 36.4 and nick point retreat during the 1990s upstream from the channelization.

The Mississippi River valley (Obermeier 1988; Tuttle and Schweig 1995), and the Wolf River floodplain in particular (Van Arsdale et al. 1998; Broughton et al. 2001), experienced liquefaction during the great New Madrid earthquakes of 1811–1812. The three great 1811–1812 earthquakes had estimated moment magnitudes of 8.1, 7.8, and 8.0 (Johnston 1996). Based on paleoseismic studies, these great earthquakes have a recurrence interval of ~450 years (Kelson et al. 1996; Tuttle 1999). Magnitude-frequency relationships indicate that smaller-magnitude events should occur more frequently (Bath 1973). Earthquake-induced liquefaction may cause the ground to lose its bearing strength,

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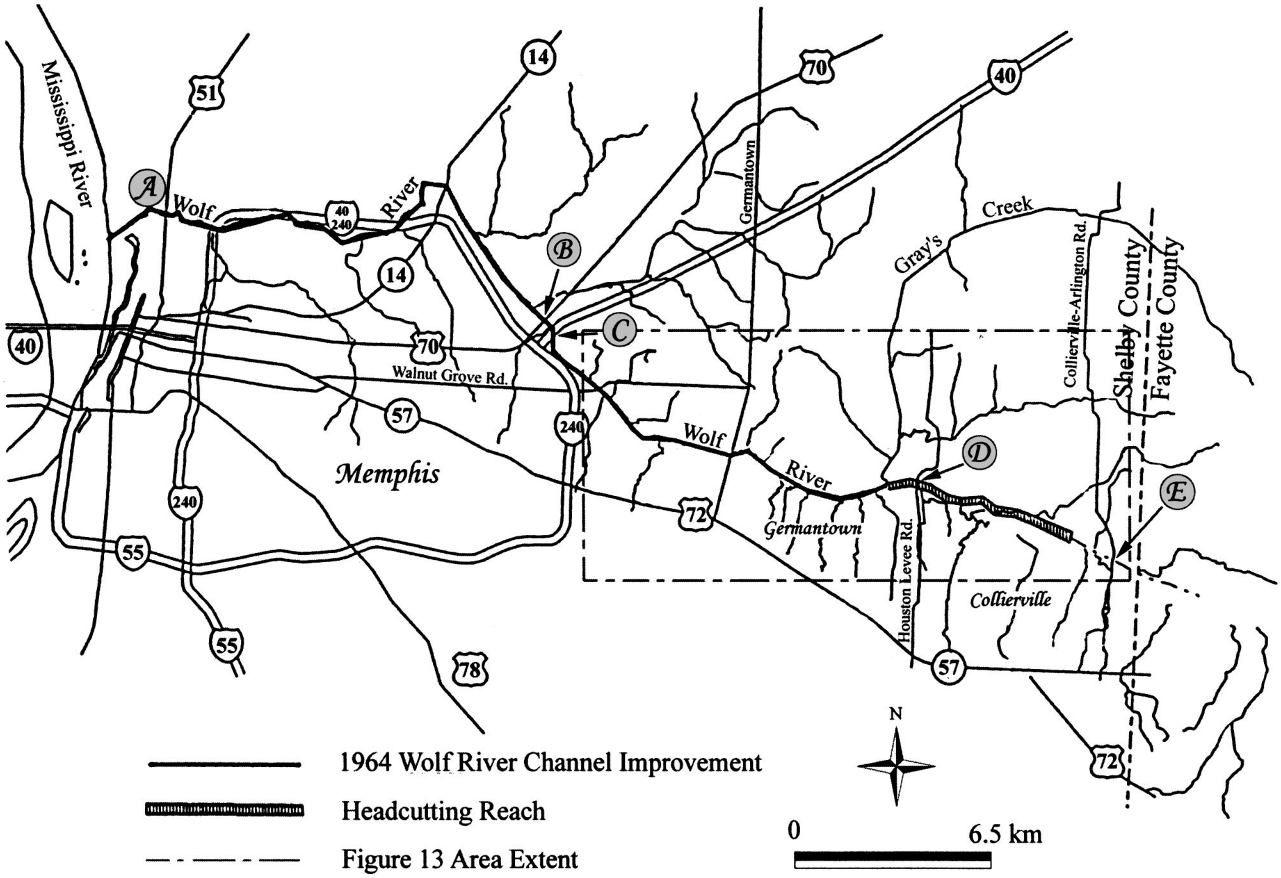

Fig. 1. Map of the 1964 Wolf River channel improvement and reach undergoing headward erosion [four damaged bridge sites are (A) Highway 51, (B) Highway 70, (C) Interstate 40, (D) Houston Levee Road, and (E) the threatened Collierville-Arlington Road]

resulting in heavy objects (buildings, etc.) sinking into the ground, low-density objects (pipes, etc.) floating to the surface, and lateral spreading (Seed and Idriss 1982). Severe earthquake shaking caused liquefaction along the Wolf River floodplain in Memphis, Germantown, and as far east as Collierville (Figs. 1 and 2), as revealed in sand dikes preserved in the banks of Wolf River (Fig. 3) (Broughton et al. 2001). The sand dikes were formed when saturated point bar sand along Wolf River was temporarily liquefied and forcefully ejected to the surface through the overlying overbank silt layer.

The impact of channelization on rivers has been well documented (e.g., Ramser 1930; Daniels 1960; Ruhe 1970; Parker and Andres 1976; Wilson 1979; Bradford and Piest 1980; Winkley 1982; Brookes 1985, 1988; Yodis and Kesel 1993; Knighton 1998), and in particular channelization of western Tennessee rivers (Robbins and Simon 1983; Simon 1989, 1992, 1994; Simon and Hupp 1992). The purpose of our research was to document channel geometry and floodplain changes that occurred between 1959 and 1990 along Wolf River within the urban areas of the city of Memphis and Shelby County. However, our particular interest is to determine if these changes have had any impact on liquefaction susceptibility of the Wolf River floodplain.

Methods

Bank-full widths and bank-full thalweg depths are used in this study (Fig. 4). The widths for the 1959 Wolf River were measured from the 1959 engineering plans and the 1990 widths were provided by the U.S. Army Corps of Engineers (Carl Sekt, written communication, 2000). Using channel bottom elevation and the elevation of the lower of the two opposing banks, maximum bank-full depths were measured directly from the 1959 survey. The 1990 low-bank depths were calculated from the detailed cross-section measurements made in 1990 by the Corps of Engineers. Width and depth measurement locations (stations) are not illustrated in Fig. 1, because there are too many for the scale of the map. In the 1959 data, we measured 114 widths, 140 depths, and calculated 112 cross-sectional areas. The 1990 data set included 87 width, depth, and calculated cross-sectional area measurements. One hundred and ninety-nine stations were used to construct the 1959 river longitudinal profile, and 127 stations were used in the 1990 profile.

Channel cross-sectional areas were calculated by multiplying the bank-full depth by the bank-full width at each station for the 1959 and 1990 data sets. These cross-section values are approximations because they represent rectangular simplifications of the true cross sections (Fig. 4). In fact, each calculated value is higher than the true value, because the rectangular shape is constructed from maximum widths and depths. The velocity and discharge (cross-sectional area times velocity) calculations are based on the cross-section calculations and so are also too high. Nonetheless, we believe each data set reveals down-valley trends, and a comparison of the 1959 and 1990 data sets illustrates how the Wolf River has changed.

Bank-full river velocities for each station were estimated using the Manning Equation:

$$V = 1.49/nR^{2/3}S^{1/2} \tag{1}$$

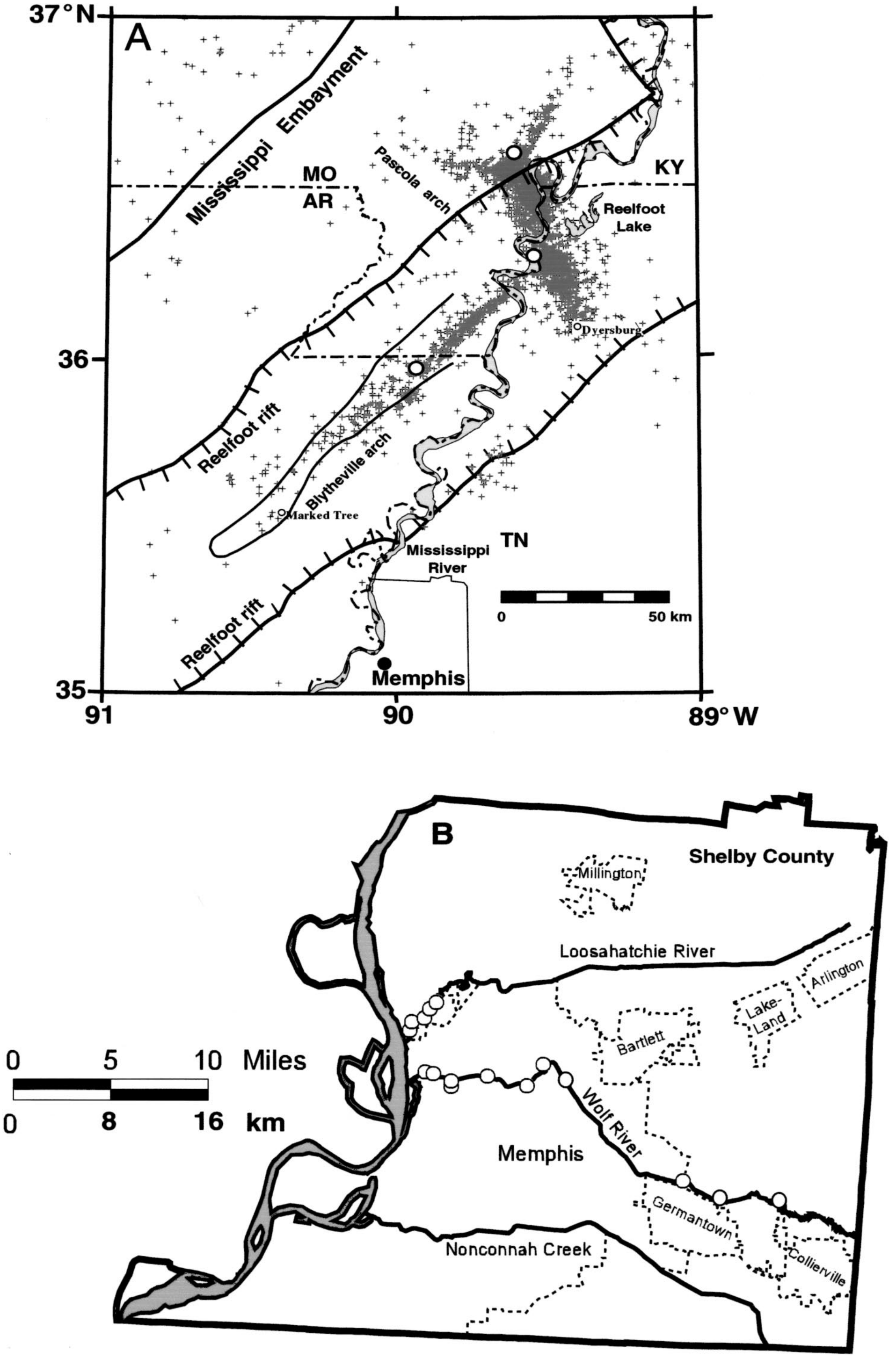

Fig. 2. (A) New Madrid seismic zone [crosses indicate microseismicity and the three circles are the estimated epicenters of the three major earthquakes of 1811–1812 (Johnston and Schweig 1996)]; (B) Shelby County in southwestern Tennessee (o = liquefaction dikes exposed in river cut banks; dashed lines show city boundaries)

where V = average velocity; n = channel bed and bank roughness coefficient; R = hydraulic radius (cross-sectional area divided by the total cross-sectional length of the bed and banks); and S = river bed slope (Ritter 1986). These average velocities were subsequently used to estimate discharge. A n value of 0.035 (winding natural streams and canals in poor condition) was used for the 1959 calculations and a n value of 0.025 (rivers and earth canals in fair condition) was used for the 1990 calculations (see Table 6.1 in Ritter 1986). An average river bed slope of 0.00029 was calculated for the 1959 data by determining the difference in elevation at river km 36 and at the Wolf River mouth, and dividing that value by 36 km. Similarly, an average bed slope of 0.00049 was calculated for the 1990 river.

The water table elevation along the Wolf River is an important factor in the liquefaction susceptibility of the floodplain. Water table elevation contours were constructed by Parks (1990) for the fall of 1988, thus representing typical, low water levels. Using Delaunay triangulation, a triangular irregular network, or TIN,

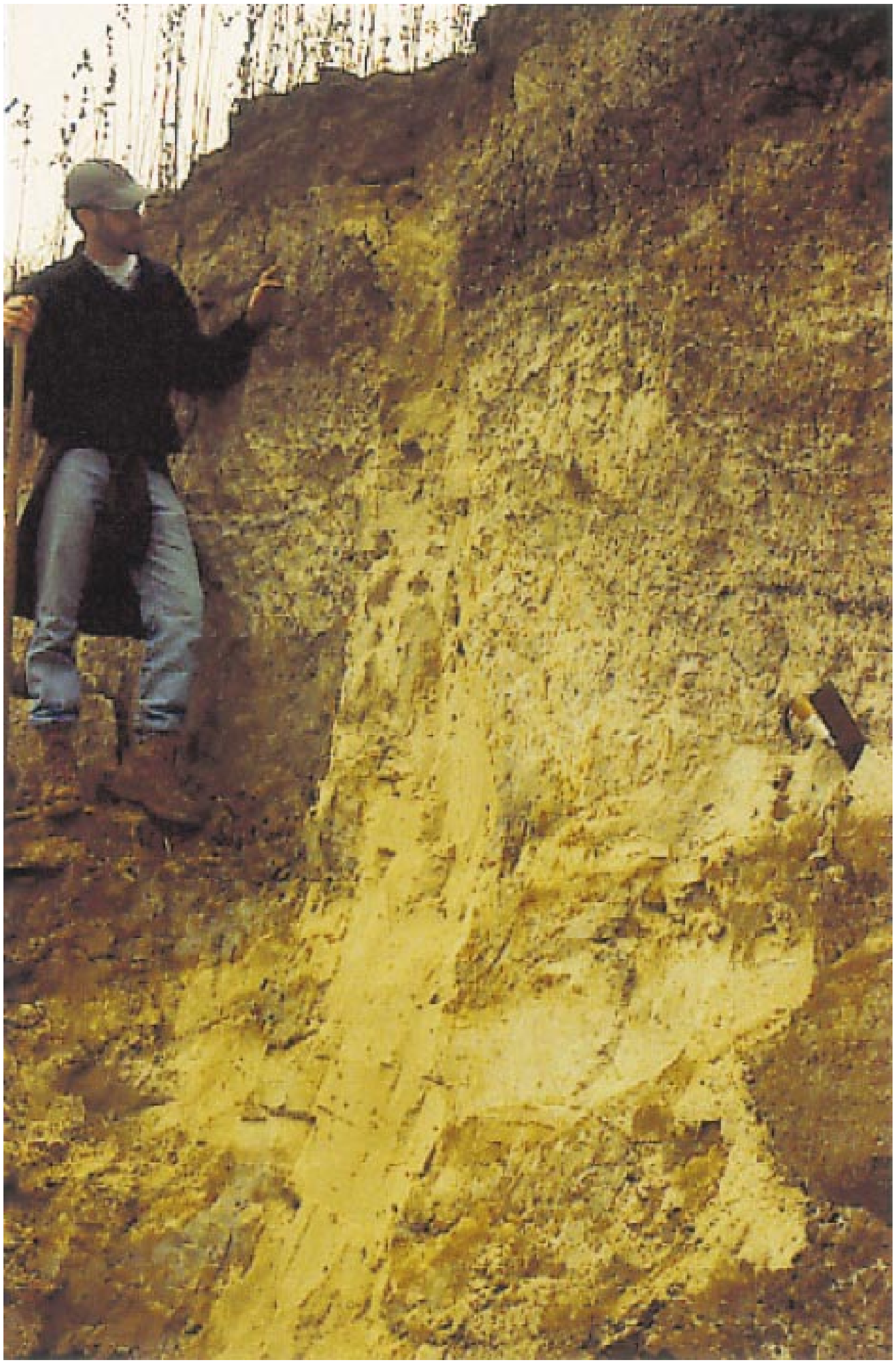

Fig. 3. (Color) Sand dike in northern bank of Wolf River in Memphis, Tennessee; this dike was located (now eroded) at the second dike site upstream from the Mississippi River in Fig. 2(B)

was calculated from these contours. From this TIN, water table elevation was linearly interpolated along the Wolf River floodplain in Shelby County.

Urbanization and, in particular, the construction of bridges across the Wolf River influence local channel geometry. We make no attempt to address the effects of bridge construction across the Wolf River between 1959 and 1990; however, no cross-sections at bridge sites were used in this study.

Results

Channel Cross-Sections

In 1959 the Wolf River was generally less than 6 m deep (Fig. 5). In 1990 the river was generally less than 6 m deep downstream from valley km 16, variable but with a mean value of 6 m deep from valley km 16 to 24, and greater than 6 m deep upstream

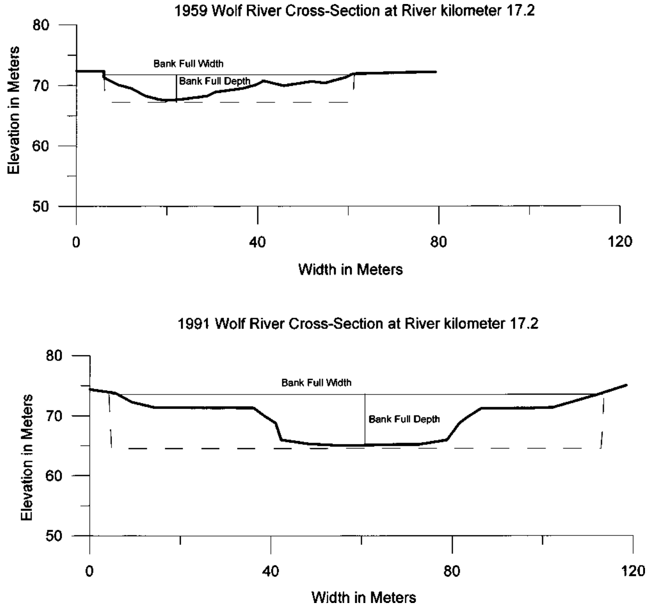

Fig. 4. Bank-full width and depth and calculated cross-sectional area for 1959 and 1990 cross section at river km 17.2

from valley km 24. Downstream from valley km 6.4, the 1990 depths were less than in 1959; however, upstream from valley km 6.4 the 1990 river depths were generally greater than the 1959 river depths.

In comparing the 1990 bank-full channel widths with the 1959 channel widths, it is apparent that Wolf River increased its width upstream of valley km 8 after channelization (Fig. 6).

The 1990 data reveal that the cross-sectional area of Wolf River did not change from 1959 in the lower 8 km of the river (Fig. 7). However, the cross-sectional area of the channel, upstream from valley km 8, increased.

As Fig. 8 illustrates, in 1959 the Wolf River's velocity increased slightly downstream, the 1990 velocity decreased downstream, and the river essentially doubled its velocity between these two years.

Bank-full discharge generally increased downstream in 1959, decreased downstream in 1990, and the river tripled its discharge between these two years (Fig. 9).

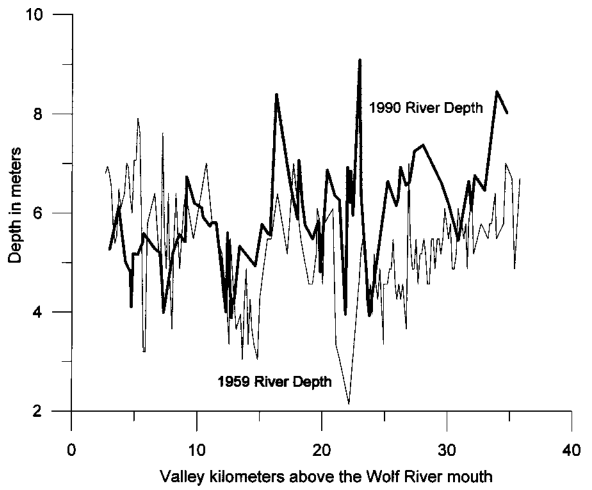

Fig. 5. Wolf River thalweg depths at bank-full stage

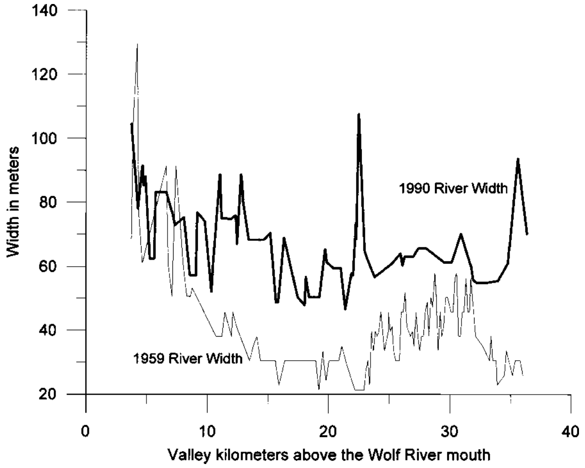

Fig. 6. Wolf River widths at bank-full stage

Wolf River Longitudinal Profiles

Longitudinal profiles reveal the bed and bank elevation changes that the Wolf River has undergone (Fig. 10). The 1977, 1989, and 1995 profiles upstream from valley km 37 in Collierville are from the U.S. Army Corps of Engineers' June 2000 report, entitled "Wolf River, Memphis, Tennessee Draft Feasibility Report & Draft Environmental Impact Statement." These detailed profiles demonstrate the upstream migration of a nick point (nick area) from the end of the 1964 channelization. Channelization created a smooth bottom profile that approximated the elevation of the 1959 profile. The 1990 survey revealed that upstream of valley km 16, the river bed entrenched as much as 3 m below the channel excavation, whereas downstream from valley km 16, the river bed aggraded. It is also apparent that the bank elevation diminished between 1959 and 1990. Therefore, the Wolf River entrenched and apparently denuded its banks.

Bank denudation is supported in Fig. 11. In the 1959 profile [Fig. 11(a)], the sand/silt contact was an average depth of 3 m beneath the floodplain surface. However, in the 1990 profile [Fig. 11(b)], the same contact was an average depth of only 2.1 m beneath the floodplain surface. These observations are simplified and become more apparent using linear regression lines fit to the

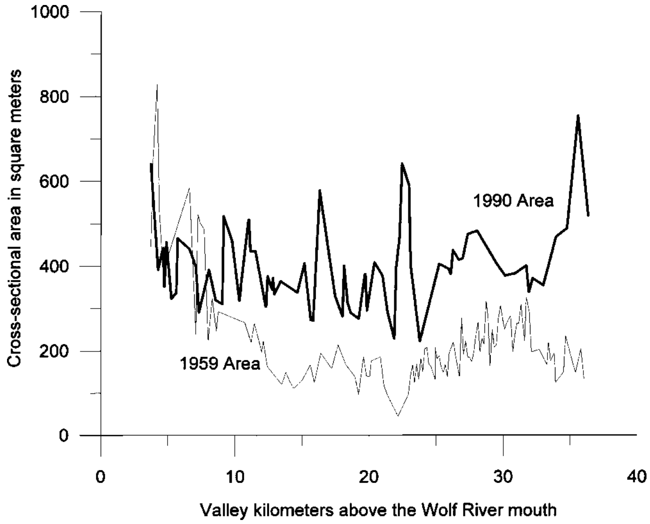

Fig. 7. Calculated Wolf River cross-sectional areas at bank-full stage

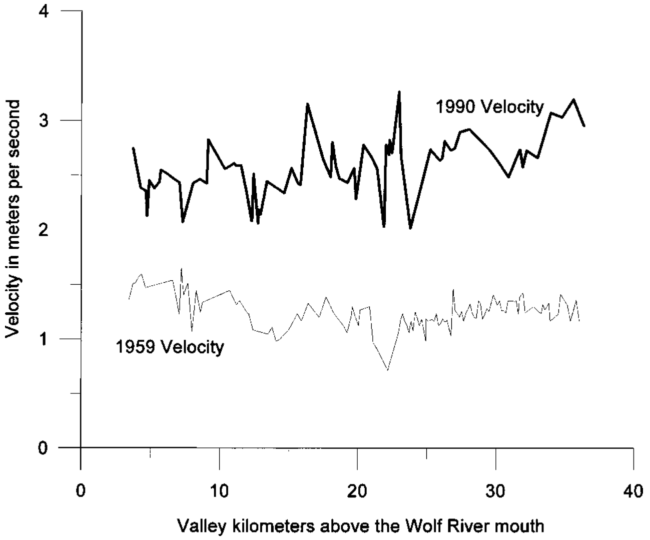

Fig. 8. Calculated Wolf River velocities at bank-full stage

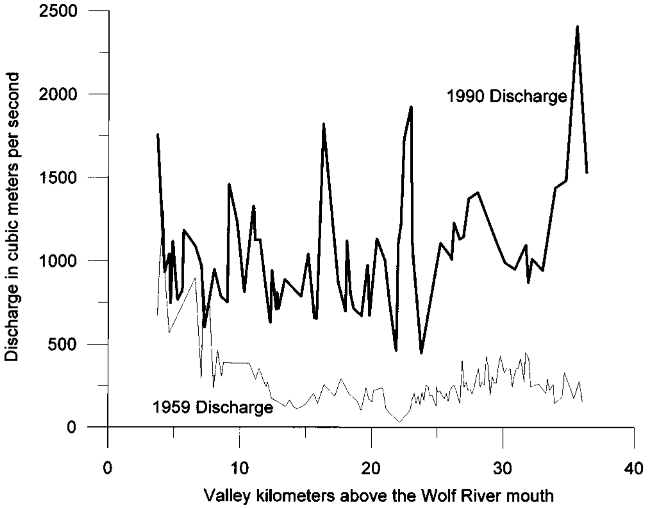

Fig. 9. Calculated Wolf River discharge at bank-full stage

profile data (Fig. 12). Floodplain denudation along the channelized portion of the Wolf River is supported by the very irregular 1990 bank profile [Fig. 11(b)] and does not appear to be restricted to the banks of the river. The digital elevation model of Fig. 13 illustrates a dissected floodplain surface along the channelized reach, but no floodplain dissection upstream from the channelization.

To corroborate floodplain denudation, a difference grid was created using spatial ground surface elevations from the 1965 USGS 7.5 minute quadrangles and 1988 survey data provided by Glenn McDaniel, of the U.S. Army Corps of Engineers. The 1965 elevations are represented as contours and the 1988 as individual points. To create the interpolated surfaces of each time period, a TIN was created from the nodes and vertices of the 1965 contours and from the 1988 points. Using these TINs, elevations were in-

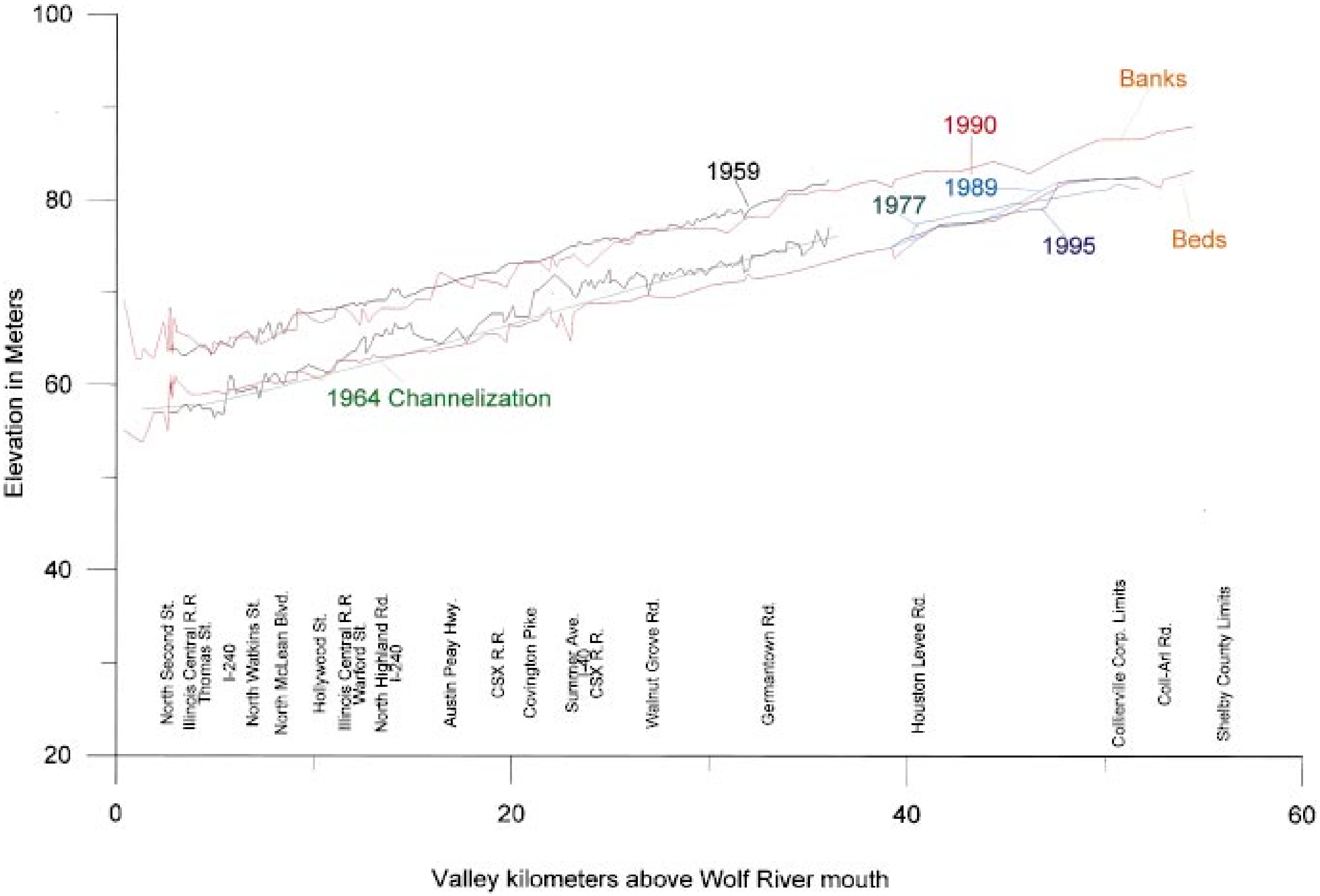

Fig. 10. (Color) Wolf River bed and bank longitudinal profiles and channel bed longitudinal profile

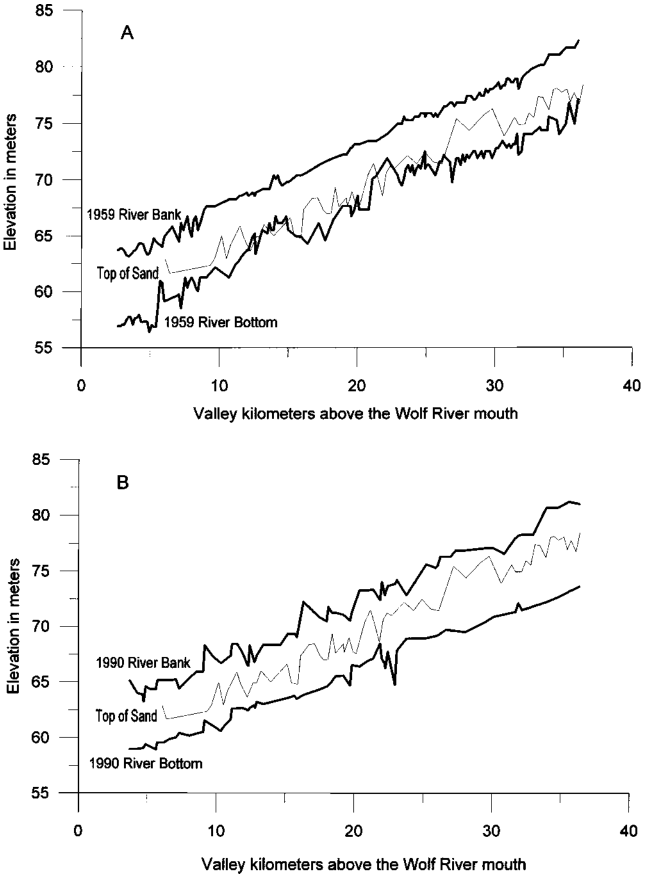

Fig. 11. Wolf River 1959 bed and bank longitudinal profiles and contact between point-bar sand and overlying overbank silt: (A) for 1959; (B) for 1990

terpolated for a uniform grid of 30 meter cells covering the Wolf River floodplain in eastern Shelby County. Both a linear and a breakline bivariate quintic interpolation scheme were used to calculate elevations at the uniform grid cell center. The interpolated grid from 1988 was subtracted from the 1965 grid; thus positive values indicate where denuding has occurred. Preliminary results of denuded areas using the quintic interpolation did not differ much spatially when compared with the linear interpolation; however, an overall greater loss of overbank thickness occurred with the quintic interpolation. Thus, to remain conservative the linear interpolation was used (Fig. 14). Fig. 14 shows that denudation has occurred over most of the floodplain except for those areas where artificial fill was placed for roads and buildings and the spoil pile area along the channelized river. It is also possible, however, that thinning of the overbank occurred in pad areas prior to construction filling. Field inspection revealed that denuded areas are not due to mining activity.

Effect of Reducing Overburden Thickness on Liquefaction Potential

Floodplain overbank thickness appears to have influenced liquefaction susceptibility in Shelby County rivers. Broughton et al. (2001) note that thick overbank sediments appear to have suppressed liquefaction in the Loosahatchie River floodplain during 1811–1812 liquefaction. An increase in liquefaction susceptibility due to the reduction in overbank sediment thickness is suggested by studying empirical liquefaction resistance relationships. These

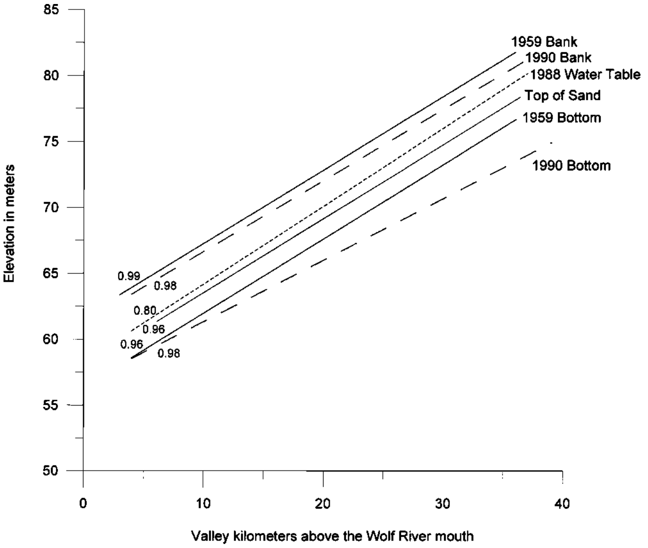

Fig. 12. Linear regression lines with r^2 values for the 1959 (bold solid) and 1990 (dashed) bed and bank longitudinal profiles, the contact between the point-bar sand and overlying overbank silt (fine solid), and the 1988 water table profile (dotted)

empirical relationships compare earthquake-induced cyclic stress ratio (CSR) to a modified penetration resistance $(N_1)_{60}$ at sites of liquefaction and no liquefaction. CSR (Seed and Idriss 1982) is approximated as

$$\mathrm{CSR}=\tau_h/\sigma_o'\approx 0.65\cdot a_{\max}/g\cdot\sigma_o/\sigma_o'\cdot r_d \tag{2}$$

where τ_h = average cyclic shear stress that is approximately 65% of the maximum shear stress; $a_{\max}$ = peak horizontal ground surface acceleration expressed in g (gravity); σ_o = total overburden stress; σ_o' = effective overburden stress; and r_d = depth reduction coefficient to account for flexibility of the soil column. For sites of liquefaction/no liquefaction, CSR is graphed as the dependent variable against $(N_1)_{60}$. $(N_1)_{60}$ is a modified standard penetration test (SPT) blow count value calculated as

$$(N_1)_{60}=C_N\cdot N\cdot \mathrm{ER}/60 \tag{3}$$

where C_N = function of the effective overburden pressure; N = field value of standard penetration resistance; and ER is the energy ratio of the SPT system used to measure N. Using liquefaction data from past earthquakes, empirical relationships indicate that a lower bound for liquefaction resistance can be constructed. Such relationships have been produced for varying earthquake magnitudes by Seed and Idriss (1982). These relationships are direct and nonlinear; however, at lower values of CSR and N_1, the relationship is nearly linear.

To determine if liquefaction could occur, $(N_1)_{60}$ can be calculated from geotechnical boring records using Eq. (3). Seed et al. compiled ER data for various hammer systems and configurations if specific values are not available. For a given value of $(N_1)_{60}$, the cyclic resistance ratio (CRR) can be read from the liquefaction resistance relationship for a specific magnitude earthquake. Using Eq. (2), an earthquake-induced CSR can be estimated. If CSR exceeds CRR, then liquefaction is probable.

For a hypothetical earthquake of constant magnitude and distance to a given site, the first term in Eq. (2) can be considered a constant (C) such that

$$\mathrm{CSR}=\tau_h/\sigma_o'\approx C\cdot\sigma_o/\sigma_o'\cdot r_d \tag{4}$$

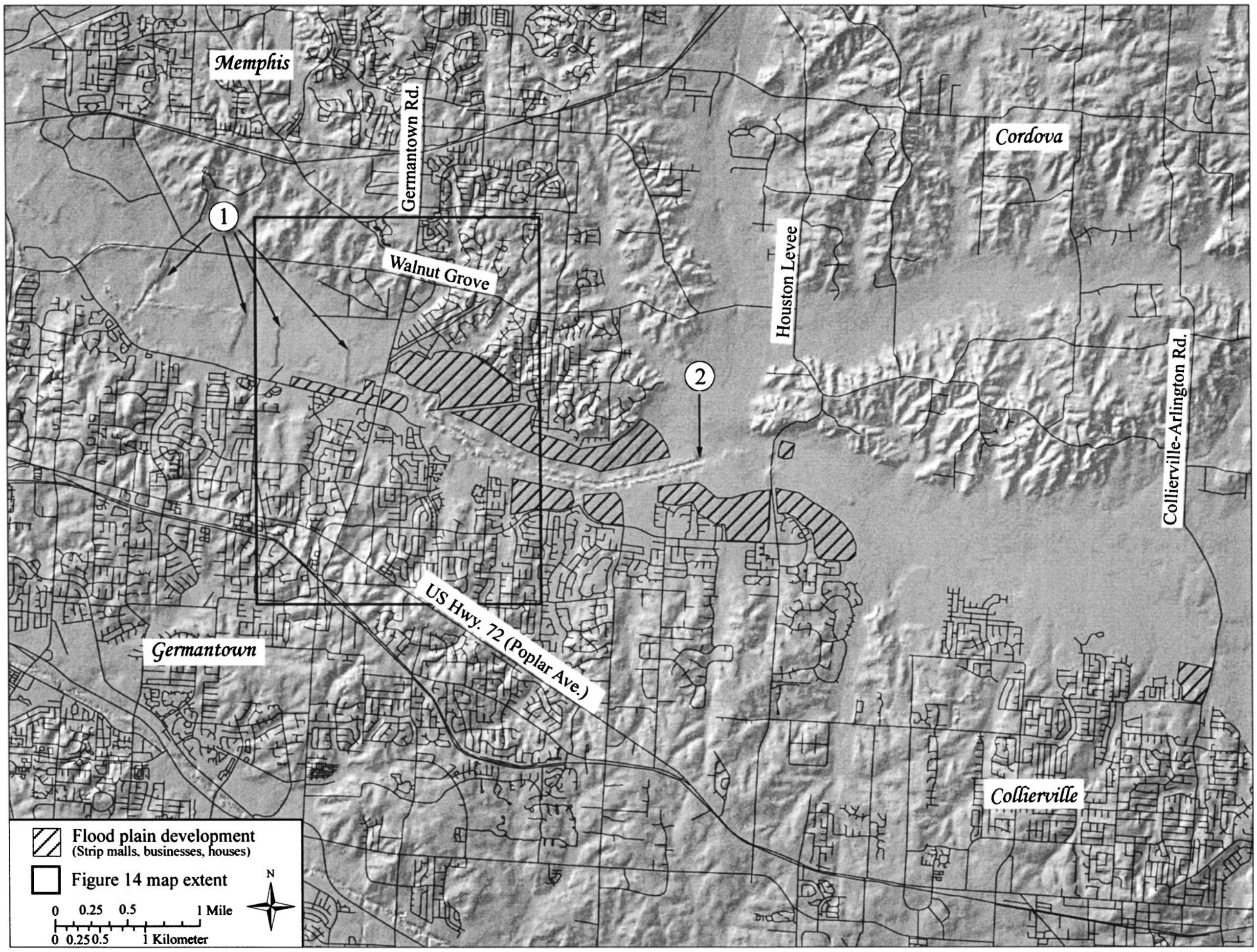

Fig. 13. Digital elevation model of the Wolf River floodplain in eastern Shelby County; features labeled include (1) stream dissection of the floodplain, (2) termination of 1964 channelization, development on Wolf River floodplain, and area illustrated in Fig. 14

Along the length of the Wolf River, the water table is within the alluvial overbank (Fig. 12), and this water table elevation represents low water levels since the measurements were taken in the fall (Parks 1990). Hence, seasonal fluctuations would result in a water table higher in the overbank deposit, especially during the wetter seasons of winter and spring. Thus, removal of overbank deposits by denuding of the bank above the water table reduces both σ_o and σ'_o by the same quantity. However, though the difference between σ_o and σ'_o remain constant as denuding continues, the ratio of (σ_o/σ'_o) increases. Therefore, CSR (for a given earthquake magnitude and distance) tends to increase as the overbank thickness decreases. Also increasing in Eq. (4) is the depth reduction coefficient, r_d;r_d is indirectly proportional to depth. For depths up to 9.1 m (30 ft), r_d ranges between 1.0 and 0.9. Reduction of the overbank reduces the depth to potential source beds of sand, which in turn results in a higher r_d. In addition, a reduction in the effective overburden pressure is proportional to a decrease in the penetration resistance, N. However, N_1 remains nearly the same because C_N increases to compensate for the reduction in penetration resistance. So whereas CSR increases by denuding of the banks, CRR does not change significantly, resulting in a greater potential for liquefaction. To determine conclusively whether bank denudation has increased liquefaction potential along the Wolf River would require quantitative field analyses.

Discussion and Conclusions

Wolf River has undergone significant changes since 1959. A summary of the changes in Wolf River between 1959 and 1990 include river straightening, doubled bed slope, reduced roughness coefficient, increased depth, near doubling of width, doubling of cross-sectional area, doubled velocity, and tripled discharge capacity. The river responded to these changes in hydraulic geometry by aggradation in its lower 16 km and entrenchment upstream from valley km 16 to nearly the eastern edge of Shelby County. Additionally, a nick point has migrated approximately 11.3 km upstream from the eastern termination of the 1964 channelization. The Corps' June 2000 report acknowledges that nick point retreat has also occurred in the tributaries to the channelized reach of Wolf River. Wolf River entrenchment has required pipeline repairs and bridge repairs on Highway 51, Interstate 40, Summer Avenue, Houston Levee Road, and it may undermine the Collierville–Arlington Road bridge in Collierville if the nick point retreat continues (Fig. 1). The U.S. Army Corps of Engineers, in their June 2000 report, have proposed to install weirs in Collierville to halt nick point retreat.

The substantial widening and entrenchment of Wolf River between 1959 and 1990 may have been enhanced by increased runoff due to basin urbanization, sand mining in the floodplain, and

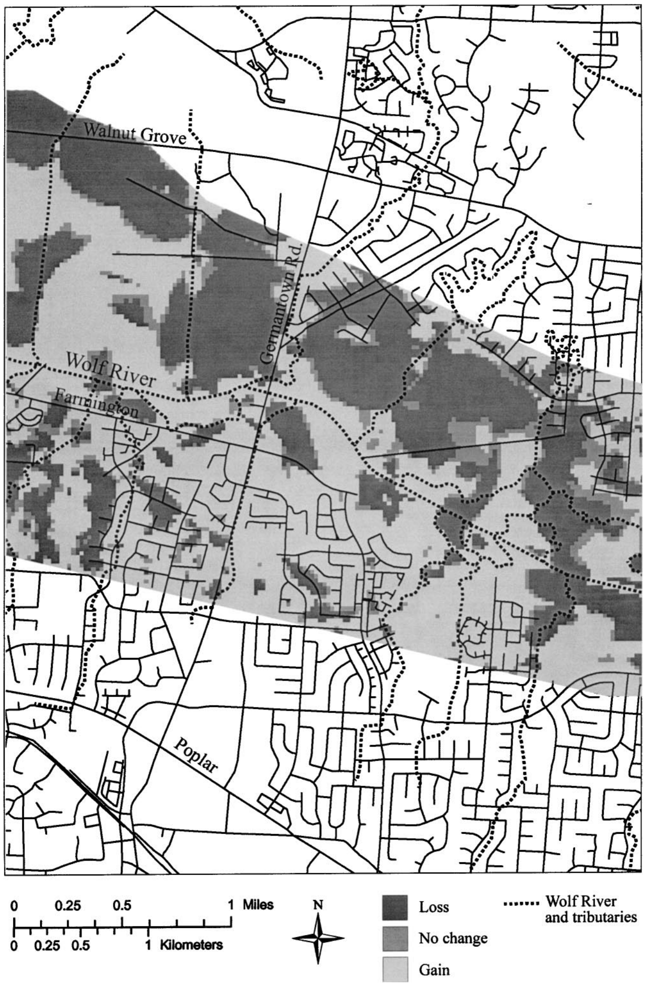

Fig. 14. Areas along Wolf River floodplain in Germantown that have undergone denudation between 1965 and 1988 are shown in dark gray [Most areas that have increased in elevation (light gray) are due to artificial fill (as indicated by roads) and immediately along the Wolf River where spoil from the 1964 channelization was placed; the roads are 2001 data so denuded areas that contain roads have been filled since 1988; area of figure outlined in Fig. 13]

lowering of the Mississippi River flow, but we believe the widening and entrenchment were caused primarily by the 1964 channelization because the dramatic changes to the Wolf River have occurred in the channelized reach and immediately upstream where the nick point has retreated. Furthermore, channelization doubled the velocity of the Wolf River flow that would cause scouring of the channel bed. As the channel entrenched, it exposed a thicker section of noncohesive and easily eroded point-bar sand in the lower banks (Fig. 11). We believe the unstable banks collapsed, causing the channel to widen (Thorne et al. 1981), and that the high velocity river transported the sand and silt downstream where some of the sand apparently was deposited on the channel floor near the mouth of the Wolf River (Simon 1994).

The purpose for the 1964 channelization of the Wolf River was flood control (Simon and Hupp 1992). This it has done. However, it is clear based on today's environment that there have been multihazard and cultural trade-offs in order to develop the Wolf River floodplain for housing and business use. For example, the Corp's June 2000 report documents wetlands habitat destruction along the entrenched reach of Wolf River due to drying of the floodplain. Entrenchment and the tripling of the river's discharge capacity appear to be responsible for the floodplain's drying. Thus, it requires a bigger, less frequent flood to top the river banks and flow across the floodplain. Essentially, the entrenched reach of Wolf River is bounded by a low terrace, which has allowed building development. Although the roads and buildings may not be subject to flooding, their location on unconsolidated floodplain material makes them more vulnerable to liquefaction during earthquakes (Youd and Perkins 1978; Seed and Idriss 1982; Youd 1991). The 1988 water table profile (Parks 1990) indicates that even with channel incision, the basal sand source beds that liquefied in a previous earthquake are still below the water table (Fig. 12). However, assessing the degree of liquefaction vulnerability is difficult. The structures are built on a pad of sediment mined from the Wolf River floodplain. Liquefaction susceptibility of the floodplain sediment may be reduced because of the weight of the pad (Seed and Idriss 1967). However, it must be noted that liquefaction of fill sites on top of floodplains has been documented in the 1923 Kwanto, Japan, 1931, Hawkes Bay, New Zealand, 1960, Chile, 1964, Niigata, Japan, and 1968, Tokachi-Oki, Japan, earthquakes (Youd and Hoose 1977).

Contributing to the liquefaction susceptibility uncertainty is the thinning of the silt overbank layer by erosion of the Wolf River floodplain surface (Fig. 14). Additionally, incision by Wolf River and its tributaries across the floodplain may make the floodplain more susceptible to lateral spreading during liquefaction because of higher, less stable banks. Seismically induced lateral spreading may also be enhanced by the excavation of borrow pits and construction of pads on the floodplain. The original flat floodplain now has more than 6 m of relief from the top of the pads to the bottom of the water-filled borrow pits that may promote lateral spreading.

In the 1960s, our society had different goals and objectives than today. At that time the Environmental Protection Agency did not exist and we did not have programs for protecting wetlands. In the 1960s, we were looking at growth and prosperity and in many areas of the United States flooding was causing distress to homeowners and businesses. This study has brought many of these issues to the forefront. It is true Wolf River channelization has reduced flooding, but channelization has also damaged habitats, bridges, and pipelines and has allowed development on its floodplain. Roads, motels, and homes have been built on a floodplain that has liquefied in the past. Thus, channelization has permitted development on a floodplain that has a very high liquefaction susceptibility (Van Arsdale et al. 1998; Broughton et al. 2001) and that might have become even more susceptible as a consequence of the channelization and development. River channelization and subsequent floodplain development is certainly not unique to Wolf River and Shelby County, Tennessee (Simon 1994; Knighton 1998). Within the United States between 1930 and 1980 over 26,500 km of rivers had been channelized (Brookes 1985). This study has shown how important it is to take a holistic approach to multihazard decision making in the future. In this case, flooding was controlled by channelization as planned, allowing for significant growth and development of homes and businesses along Wolf River and its tributaries without flood losses; however, the multihazard side-effect is that these same homes and businesses were placed in an area subject to liquefaction and lateral spreading, and channelization of Wolf River may have increased this potential. We learn from our experiences. It is clear that liquefaction has occurred in the past along the Wolf River floodplain and will occur in the future. Based on this study, it appears that floodplain alteration can have an impact on the liquefaction and lateral spreading potential in seismically active areas and that more-detailed geotechnical studies should be undertaken to quantify the effects of floodplain alteration.

Acknowledgments

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References

Bath, M. (1973). *Introduction to seismology*, Birkhauser Verlag, Basel, Switzerland, and Stuttgart, Germany.

Bradford, J. M., and Piest, R. F. (1980). ‘‘Erosional development of valley-bottom gullies in the upper Midwestern United States.’’ *Thresholds in geomorphology*, D. R. Coates and J. D. Vitek, eds., George Allen and Unwin, Boston, 75–101.

Brookes, A. (1985). ‘‘River channelization: Traditional engineering methods, physical consequences and alternative practices.’’ *Progress in Physical Geography*, 9, 44–73.

Brookes, A. (1988). *Channelized rivers: Perspectives for environmental management*, Wiley, New York.

Broughton, A. T., Van Arsdale, R. B., and Broughton, J. H. (2001). ‘‘Liquefaction susceptibility mapping in the city of Memphis and Shelby County, Tennessee.’’ *Engineering Geology*, 62, 207–222.

Daniels, R. B. (1960). ‘‘Entrenchment of the Willow Drainage Ditch, Harrison County, Iowa.’’ *Am. J. Sci.*, 258, 161–176.

Hidinger, L. L., and Morgan, A. E. (1912). ‘‘Drainage problems of Wolf, Hatchie, and South Fork of the Forked Deer rivers in west Tennessee.’’ *The Resources of Tennessee, Tennessee Geological Survey*, 2, 231–249.

Johnston, A. C. (1996). ‘‘Seismic moment assessment of stable continental earthquakes, Part 3: 1811–1812 New Madrid, 1886 Charleston and 1755 Lisbon.’’ *Geophys. J. Int.*, 126, 314–344.

Johnston, A. C., and Schwieg, E. S. (1996). ‘‘The enigma of the New Madrid earthquakes of 1811–1812.’’ *Annu. Rev. Earth Planet Sci.*, 24, 339–384.

Kelson, K. I., Simpson, G. D., Van Arsdale, R. B., Haraden, C. C., and Lettis, W. R. (1996). ‘‘Multiple late Holocene earthquakes along the Reelfoot fault, central New Madrid seismic zone.’’ *J. Geophys. Res.*, 101, 6151–6170.

Kingsbury, J. A., and Parks, W. S. (1993). ‘‘Hydrogeology of the principal aquifers and relation of faults to interaquifer leakage in the Memphis area, Tennessee.’’ *USGS Water Resources Investigation Rep. 93-4075*, 18.

Knighton, D. (1998). *Fluvial Forms & Processes, a New Perspective*. Oxford University Press, Oxford, U.K., 383.

Obermeier, S. F. (1988). ‘‘Liquefaction potential in the central Mississippi Valley.’’ *U.S. Geological Survey Bulletin 1832*, Washington, D.C., 21.

Parker, G., and Andres, D. (1976). ‘‘Detrimental effects of river channelization.’’ *Proc., Rivers 76: Conference of the American Society of Civil Engineers*, ASCE, Reston, Va., 1248–1266.

Parks, W. S. (1990). ‘‘Hydrogeology and preliminary assessment of the potential for contamination of the Memphis aquifer in the Memphis area, Tennessee.’’ *U.S. Geological Survey Water—Resources Investigation Rep. 90-4092*, 39.

Ramser, C. E. (1930). ‘‘Erosion and silting of dredged drainage ditches.’’ U.S. Department of Agriculture, *Technical Bulletin 184*, Washington, D.C., 55.

Ritter, D. F. (1986). *Process geomorphology*, Wm. C. Brown, Dubuque, Iowa, 579.

Robbins, C. H., and Simon, A. (1983). ‘‘Man-induced channel adjustment in Tennessee streams.’’ *U.S. Geological Survey Water—Resources Investigations Rep. 82-4098*, 129.

Ruhe, R. V. (1970). ‘‘Stream regimen and man’s manipulation,’’ *Proc., 1st Environmental Geomorphology: Geomorphology Symposium*, D. R. Coates, ed., Publications in Geomorphology, Univ. of New York at Binghamton, Binghamton, New York, 9–23.

Seed, H. B., and Idriss, I. M. (1967). ‘‘Analysis of soil liquefaction: Niigata earthquake.’’ *J. Soil Mech. Found. Div.*, 93(3), 83–108.

Seed, H. B., and Idriss, I. M. (1982). ‘‘Ground motions and soil liquefaction during earthquakes.’’ *Earthquake Engineering Research Institute Monograph*, Berkeley, Calif., 134.

Simon, A. (1989). ‘‘A model of channel response in disturbed alluvial channels.’’ *Earth Surf. Processes Landforms*, 14, 11–26.

Simon, A. (1992). ‘‘Energy, time, and channel evolution in catastrophically disturbed fluvial systems.’’ *Geomorphology*, 5, 345–372.

Simon, A. (1994). ‘‘Gradation processes and channel evolution in modified west Tennessee streams: Process, response, and form.’’ *U.S. Geological Survey Professional Paper 1470*, Washington, D.C., 84.

Simon, A., and Hupp, C. R. (1992). ‘‘Geomorphic and vegetative recovery processes along modified stream channels of west Tennessee.’’ *U.S. Geological Survey Open-File Rep. 91-502*, Washington, D.C., 142.

Thorne, C. R., Murphey, J. B., and Little, W. C. (1981). ‘‘Stream channel stability, Appendix D, Bank stability and bank material properties in the bluff line streams of northwest Mississippi.’’ U.S. Dept. of Agriculture Sedimentation Laboratory, Oxford, Miss., 257.

Tuttle, M. P. (1999). ‘‘Late Holocene earthquakes and their implications for earthquake potential of the New Madrid seismic zone, central United States.’’ PhD dissertation, Univ. of Maryland, College Park, Md., 250.

Tuttle, M. P., and Schweig, E. S. (1995). ‘‘Archeological and pedological evidence for large prehistoric earthquakes in the New Madrid seismic zone, central United States.’’ *Geology*, 23, 253–256.

Van Arsdale, R. B., Broughton, J. H., and Broughton, A. T. (1998). ‘‘Liquefaction in Memphis, Tennessee.’’ *American Geophysical Union (abs.)*, 79(17), S341.

Wilson, K. V. (1979). ‘‘Changes in channel characteristics, 1938–1974, of the Homochitto River and tributaries, Mississippi.’’ *U.S. Geological Survey Open-File Rep. 79-554*, 18.

Winkley, B. R. (1982). ‘‘Response of the lower Mississippi to river training and realignment.’’ *Gravel bed rivers*, R. D. Hey, J. C. Bathurst, and C. R. Thorne, eds., Wiley, Chichester, U.K.

Yodis, E. G., and Kesel, R. H. (1993). ‘‘The effects and implication of base-level changes to Mississippi River tributaries.’’ *Zeitschrift fur Geomorphologie*, 37, 385–402.

Youd, T. L. (1991). ‘‘Mapping of earthquake-induced liquefaction for seismic zonation.’’ *Proc., 4th International Conference on Seismic Zonation*, I, 111–147.

Youd, T. L., and Hoose, S. N. (1977). ‘‘Liquefaction susceptibility and geologic setting.’’ *Proc., 6th World Conference on Earthquake Engineering*, 6, 37–42.

Youd, T. L., and Perkins, D. M. (1978). ‘‘Mapping liquefaction-induced ground failure potential.’’ *J. Geotech. Eng. Div., Am. Soc. Civ. Eng.*, 104(4), 433–446.

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