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Urban effects on flood plain natural hazards: Wolf River, Tennessee, USA

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Abstract

The Wolf River and its flood plain in the City of Memphis and Shelby County, TN, have been extensively altered since the flood plain underwent liquefaction during the earthquakes of 1811–1812. Flood plain denudation and aggradation (primarily cut and fill) are documented by subtracting flood plain surface elevations obtained in the 1940s, 1965, 1988, and 2001. The resultant maps, cross-sections, and histograms illustrate the complex history and extreme changes that the flood plain has undergone. As a consequence of these post-1940s changes, liquefaction potential of the flood plain is now very complex; the flood plain's area has locally been diminished by approximately 50%, thereby requiring remapping of the areas that will be inundated by 100- and 500-year floods; and entrenchment of the Wolf River and its flood plain may have increased connectivity between Wolf River water and Shelby County's aquifer.

Keywords: Wolf River; Liquefaction; Flood plain; Flooding

1. Introduction

The City of Memphis and Shelby County, TN, have been subjected to severe earthquake shaking as illustrated by the size and density of liquefaction-induced sand dikes exposed along the banks of the Loosahatchie and Wolf Rivers (Fig. 1) (Van Arsdale et al., 1998). Although the age of these dikes is not well constrained, it is believed that they formed during the great New Madrid earthquakes of 1811–1812 (Broughton et al., 2001). The Wolf and Loosahatchie Rivers flood plains are composed of Holocene, saturated, unconsolidated point bar sand overlain by a clayey silt overbank cap and therefore have been mapped as being of high liquefaction susceptibility in future earthquakes (Broughton et al., 2001). However, the Wolf River flood plain, in particular, has experienced many anthropomorphic changes since 1811–1812. In this paper, we document denudation and aggradation alterations on the Wolf River flood plain that have occurred since the 1940s because these changes may affect liquefaction potential, basin hydrology, and flood potential, thus potentially increasing a number of natural hazards along the Wolf River.

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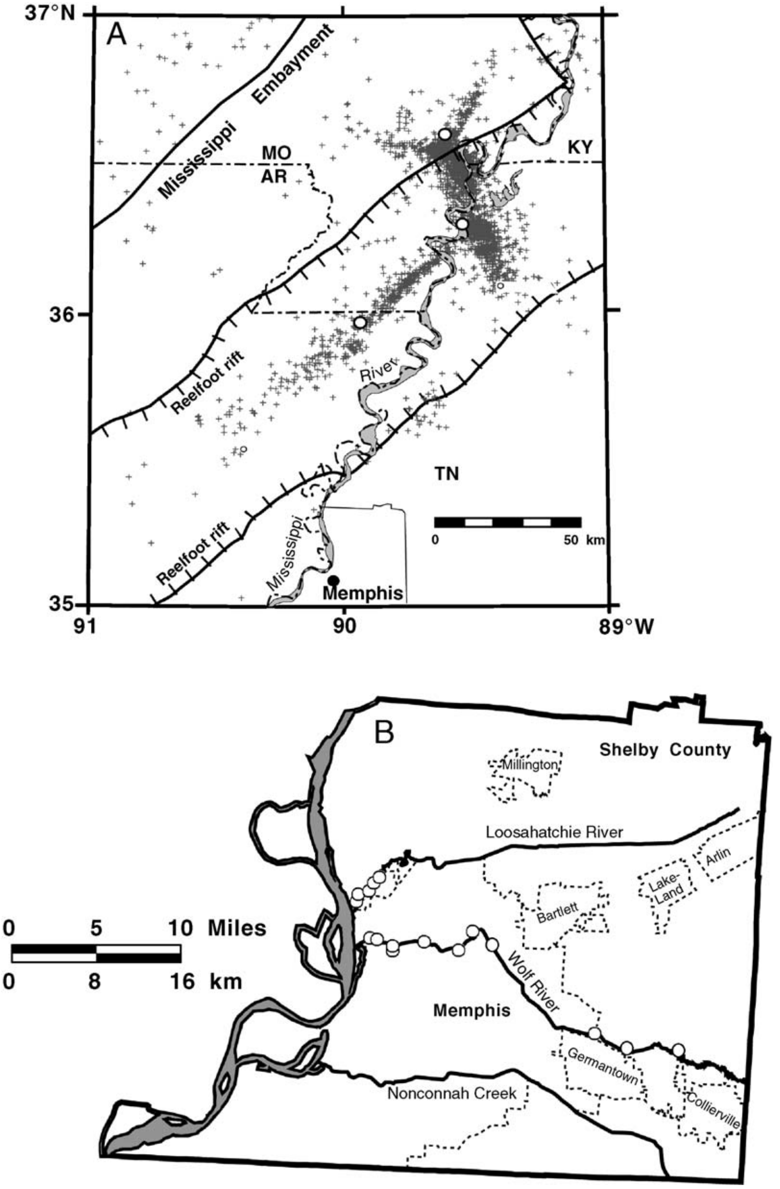

Fig. 1. (A) The New Madrid seismic zone. Crosses indicate microseismic activity and the three circles are the estimated epicenters of the three major earthquakes of 1811–1812 (Johnston and Schweig, 1996). (B) Shelby County in southwestern Tennessee. Circles are locations of liquefaction sand dikes in river cut banks. Dashed lines indicate city boundaries.

One of the most significant changes to the Wolf River has been the straightening of its lower 35.4 km in 1964 (Van Arsdale et al., 2003). A comparison of channel surveys conducted in 1959 and 1990 reveals that channelization made the river straighter and steeper, and lowered its roughness coefficient. As a consequence of these imposed changes, the river became deeper and wider, resulting in increased bank full velocity, cross-sectional area, and discharge capacity. As a consequence of these hydraulic changes, the Wolf River entrenched 3 m in eastern Shelby County and formed a nick point that has migrated 11.3 km east of the termination of the 1964 channelization. River entrenchment has caused expensive bridge and pipeline repair and destruction of river and wetlands habitat (US Army Corps of Engineers, Memphis District, Wolf River, Memphis, TN, Draft Feasibility Report and Draft Environmental Impact Statement, June 2000). Tributary entrenchment has also occurred, thereby dissecting the Wolf River flood plain. Additionally, a comparison of the 1959 riverbank profile with a 1990 profile revealed that the banks had been denuded (Van Arsdale et al., 2003). These observations led Van Arsdale et al. to argue that the liquefaction susceptibility of the Wolf River flood plain may have increased due to the channelization and resultant flood plain changes. Specifically, erosional thinning of the clayey silt cap would reduce overburden pressure and enhance liquefaction. Additionally, entrenchment of the Wolf River and its tributaries has increased bank heights and thus would promote lateral spreading during earthquakes.

Entrenchment of the Wolf River has also formed low terraces adjacent to the river, thereby promoting building and road development on the flood plain. Commonly, a borrow pit is excavated in the flood plain and the sediment from the pit is put on the edge of the flood plain to build a pad that is 0.3 m (1 ft) above the 100-year flood level. Pit and pad construction adds topographic relief to the flood plain that may influence liquefaction susceptibility. The study by Van Arsdale et al. (2003) acknowledges that the Wolf River has undergone substantial changes since 1959, but that study does not fully document coincident flood plain changes.

In this current study, we document denudation and aggradation that have occurred on the Wolf River flood plain since the 1940s by comparing flood plain elevations from the 1940s, 1965, 1988, and 2001 (Yates, 2002). We cannot differentiate between construction cut and fill and river denudation and aggradation, and therefore we combine these processes and refer to them as aggradation and denudation. Furthermore, it must be noted that this is a simplistic denudation and aggradation history because we have only four surveys of the flood plain surface spaced approximately 20 years apart to compare. The very

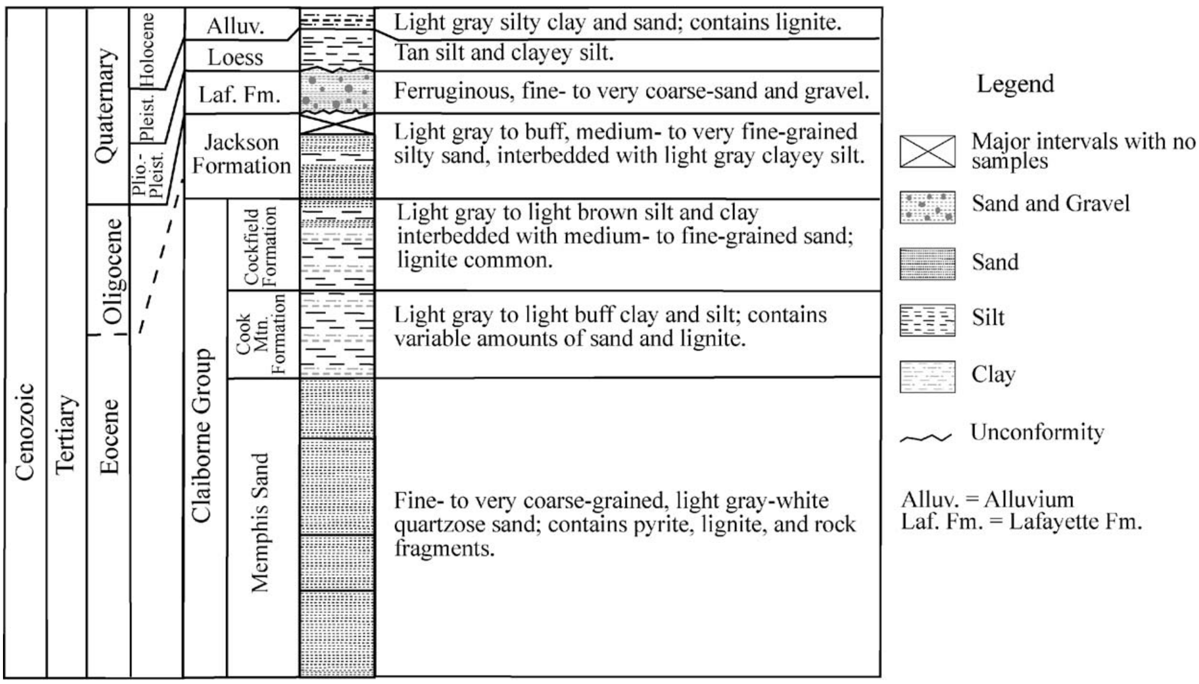

Fig. 2. Tertiary stratigraphy underlying Shelby County, TN (modified from Crone, 1981).

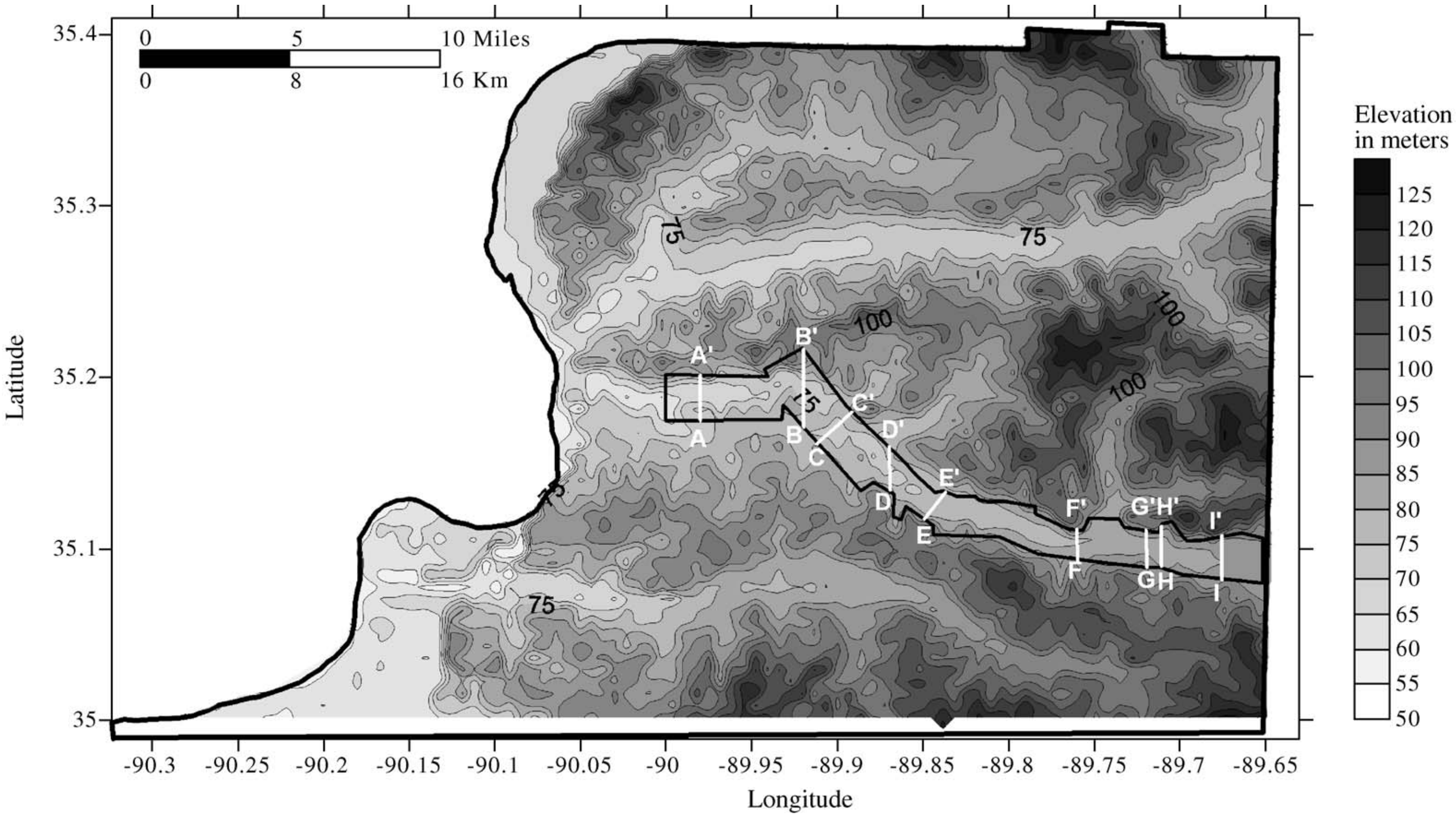

Fig. 3. Surface contour map of Shelby County, TN. Outlined area is the Wolf River flood plain of Fig. 4. Labeled lines are the cross-sections of Figs. 8–10.

simplified, yet complex, denudation and aggradation history of the Wolf River flood plain discussed below illustrates major anthropomorphic changes, river and flood plain responses, and a resultant increase in natural hazards on the Wolf River flood plain.

2. Geology of the Wolf River and vicinity

The lower reach of the Wolf River flows westward through Shelby County and the City of Memphis, TN, to the Mississippi River (Fig. 1). In ascending order, the Cenozoic stratigraphy beneath Shelby County consists of the Eocene Claiborne Group, Oligocene Jackson Formation, Pliocene–Pleistocene Upland Gravel (Lafayette Formation), Pleistocene loess, and Quaternary alluvium (Fig. 2). The Lower Claiborne Group consists of the Memphis Sand, the primary drinking water aquifer for Memphis and Shelby County, serving a population of over 1 million with an average daily withdrawal of nearly 787,000 m^3 (Hutson, 1999). The Upper Claiborne Group consists

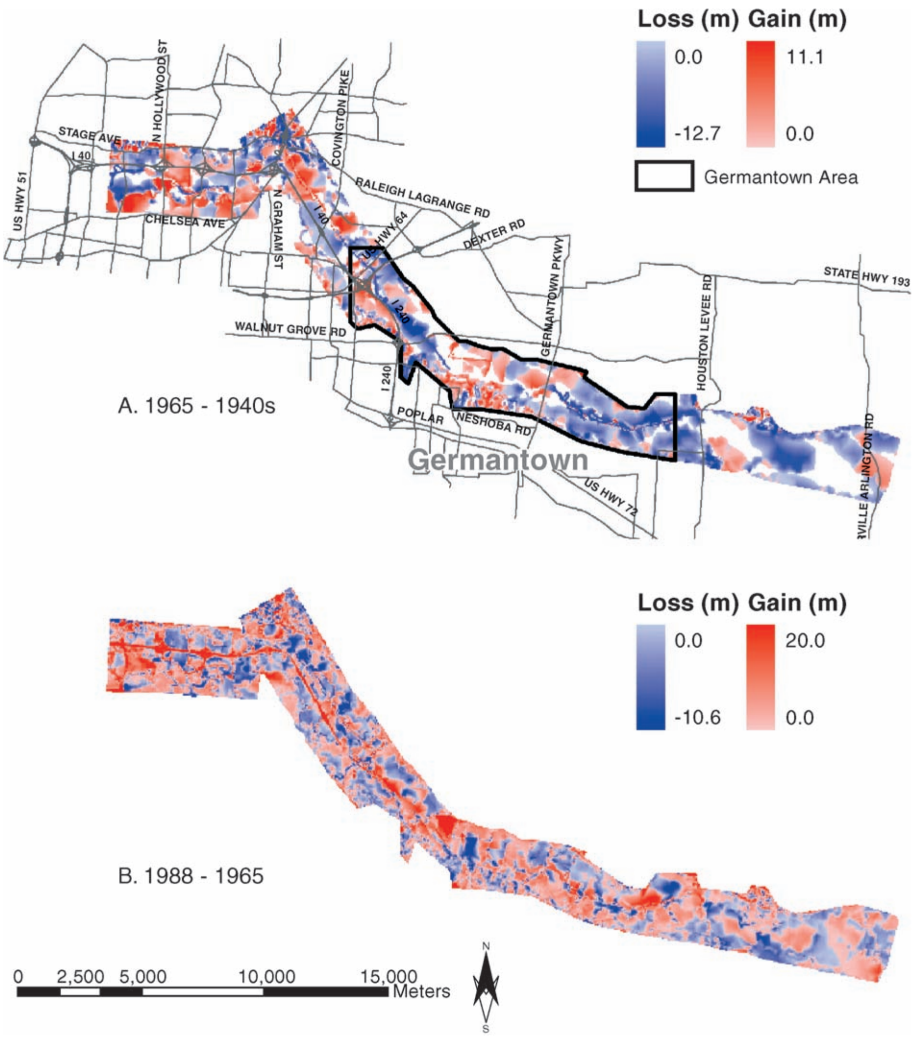

Fig. 4. Maps of the Wolf River flood plain in Shelby County, TN, illustrating areas of denudation (loss) in blue and areas of aggradation (gain) in red. Map (A) is the 1965 minus 1940s elevation and map (B) is the 1988 minus 1965 elevation. Area of map outlined in Fig. 3. Germantown area of Figs. 5 and 6 are outlined in (A).

of the Cook Mountain and the Cockfield formation, which is a confining unit to the Memphis aquifer. However, in this study, we include the Jackson Formation in the Upper Claiborne Group for simplicity of presentation.

3. Methodology

The denudation and aggradation history of the Wolf River flood plain is documented in this study through a comparison of topographic surveys of

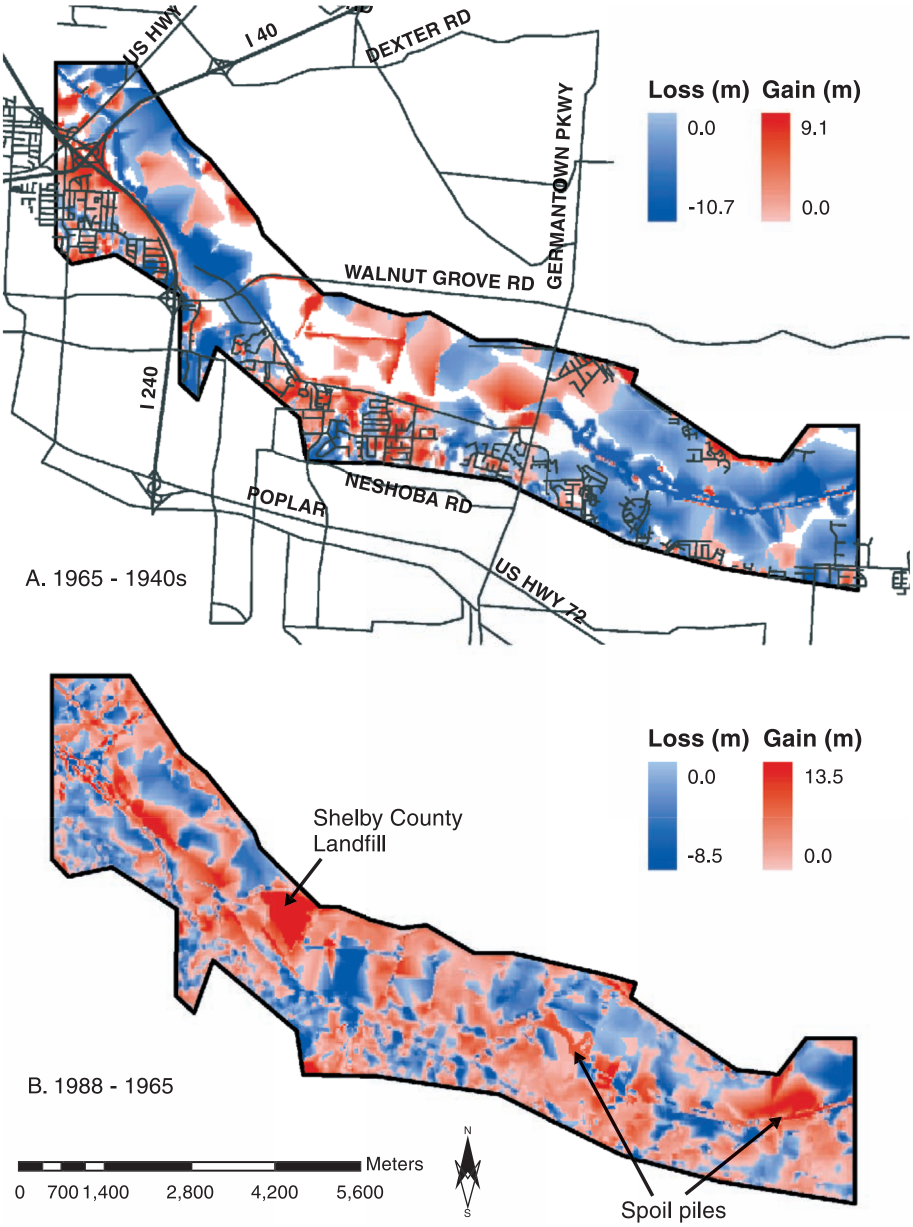

Fig. 5. Maps of the Wolf River flood plain in the Germantown, TN, area illustrating areas of denudation (loss) in blue and areas of aggradation (gain) in red. Map (A) is the 1965 minus 1940s elevation and map (B) is the 1988 minus 1965 elevation. Area located in Fig. 4.

portions of the Wolf River (Fig. 3) in Shelby County, TN, conducted in the 1940s, 1965, 1988, and 2001. US Geological Survey (USGS) maps from 1941 (1:62,500 Bartlett quadrangle), 1948 (1:24,000 Collierville quadrangle), and 1965 (1:24,000 Collierville, Germantown, Ellendale, and Northeast Memphis quadrangles) were digitized using ArcGIS (Yates, 2002). The contour interval for the USGS topographic maps is primarily 10 ft (3 m), except within the flood plain where contour intervals of 5 ft (1.5 m) are specified. The US Army Corps of Engineers provided a detailed topographic survey that was conducted in

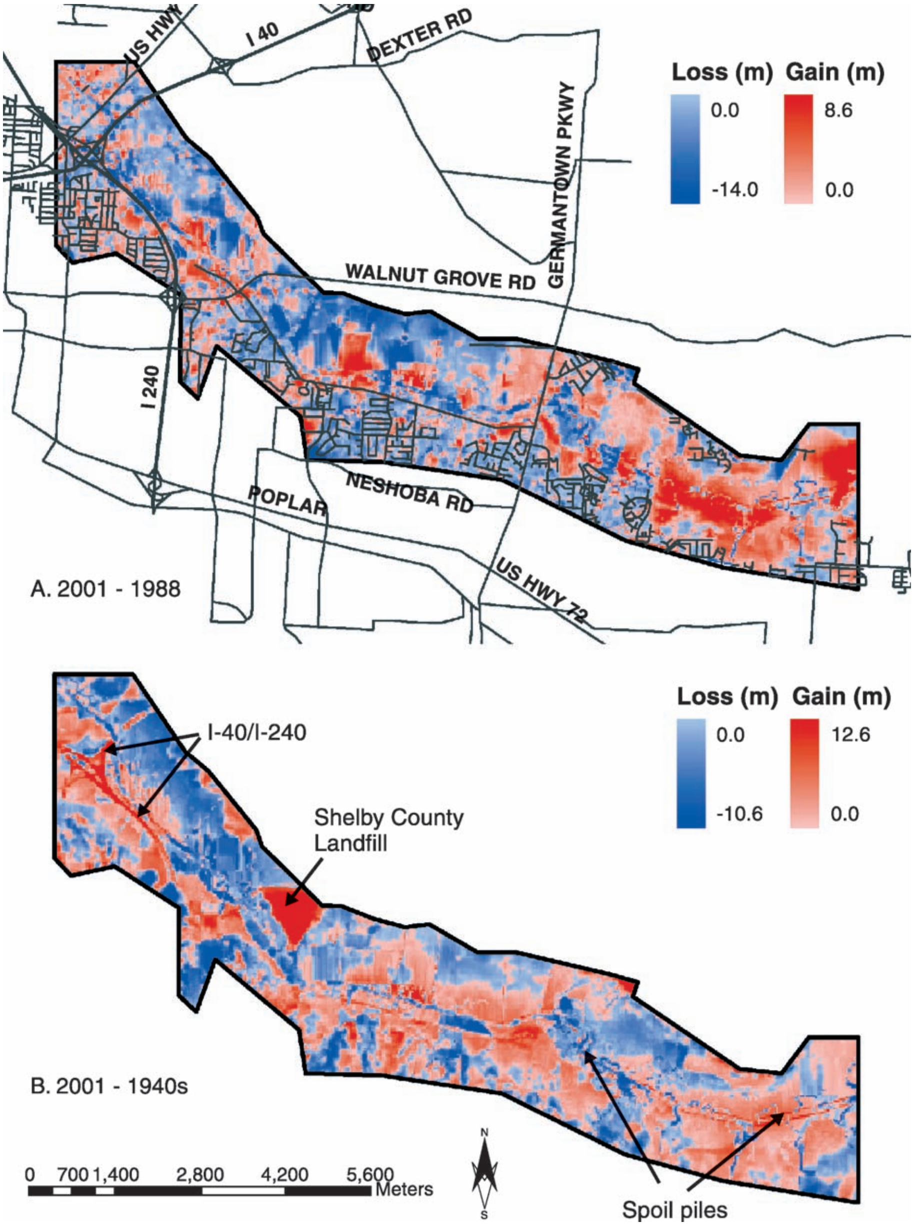

Fig. 6. Maps of the Wolf River flood plain in the Germantown, TN, area illustrating areas of denudation (loss) in blue and areas of aggradation (gain) in red. Map (A) is the 2001 minus 1988 elevation and map (B) is the 2001 minus 1940s elevation. Area located in Fig. 4.

Table 1
Quantification of gains and losses over the entire Wolf River flood plain within this study

	Gain (km^3)	Loss (km^3)	Location remarks
A[a]	102.9	98.5	Within Memphis city limits
B[b]	0.4	1.2	Within Memphis city limits
C	4.4	85.8	East of Germantown Road
D[c]	579.0	220.0	Entire study area
E	2.0[d]		I-40 and I-240
	0.6[e]		Shelby County landfill
F	11.3	9.5	East of Houston Levee Road

[a] Using 2000 City of Memphis boundary.
[b] Calculated using a 100-m buffer from Wolf River.
[c] Gain is represented by 60,541 grid cells.
[d] Gain is a total of 8456 m represented by 2412 grid cells.
[e] Gain is a total of 6003 m represented by 1098 grid cells.

1988 for much of the Wolf River flood plain. The Corps' data are very dense with 35,100 data points. Vertical resolution on this data set is 1 ft (0.3 m). The final data set is from the Tennessee Department of Environment and Conservation (Mark Tuttle, personal communication). This data set is extremely dense, with elevation data retrieved using orthoimagery on a 100-ft spacing (30 m). This resulted in over 125,000 data points having a vertical resolution of 10 ft (3 m) with justifiable interpolation to a 5-ft (1.5 m) contour interval. Wolf River flood plain elevation changes since the 1940s were evaluated using the Environmental Systems Research Institute's (ESRI) ArcGIS. Specifically, the difference between flood plain topographic maps from the four time periods (1940s, 1965, 1988, and 2001) reveals changes in surface elevations (areas of denudation and aggradation) between the selected time periods.

Well logs of the Wolf River area consist of geotechnical borings and water well data obtained from the US Geological Survey, US Corps of Engineers, Shelby County Health Department, Hall Blake and Associates, and publications (Ng et al., 1989; Broughton, 1999a,b). These logs were used to construct structure contour maps of southern Shelby County. The structure contour maps and detailed topographic data sets were combined to make geologic cross-sections of the Wolf River flood plain (Yates, 2002). The cross-sections provide a vertical perspective of the denudation and aggradation history of the flood plain and illustrate the extent of potentially liquefiable sands beneath the flood plain. These cross-sections also illustrate the contact between the Wolf River flood plain alluvium and the geologic units of Shelby County including the Memphis aquifer.

4. Discussion

To illustrate the degree and extent of denudation and aggradation that the Wolf River flood plain has experienced since the 1940s, subtraction maps from the different ages of topographic data were created (Figs. 4–6). These maps illustrate areas of sediment accumulation due primarily to construction, and areas of sediment loss due to flood plain mining and river erosion. Only elevation data from the Germantown portion of the 2001 Wolf River flood plain were currently available, and so we present a general overview of aggradation and degradation of most of the Wolf River in Shelby County between the 1940s and 1988 (Fig. 4) with a more detailed presentation of the Germantown area that includes the 2001 data (Figs. 5 and 6). Volume calculations of aggradation (gain) and denudation (loss) were determined by multiplying the estimated gain or loss represented by a uniform grid cell in ArcGIS by the area of that cell (Tables 1 and 2). All subtraction maps had the same cell dimension of 9687.48 m^2. The aerial distribution of aggradation and degradation is illustrated in Figs. 4–6 with Fig. 7 presenting the frequency of the magnitude of denu-

Table 2
Quantification of gains and losses over the Germantown portion of the Wolf River

	Gain (km^3)	Loss (km^3)	Location remarks
A	2.6	7.4	Western third of Germantown portion
B	0.6	14.7	East of Germantown Road (1965–1940s)
C[a]	0.03	1.1	Entire Germantown portion
D	87.8	27.5	Entire Germantown portion
E	9.3	23.6	West of Germantown Road
F	12.2	1.9	East of Germantown Road (2001–1988)
G	21.8	9.4	South of the Wolf River
H	10.1	9.6	North of Wolf River
I[b]	3.8	2.5	Entire Germantown portion

[a] Calculated using a 500-m buffer from Wolf River.
[b] Using FEMA 1996 100-year floodplain delineation for Wolf River.

dation and aggradation. It should be noted that the governing vertical resolution is approximately ± 1.5 m. High frequencies exist at this low value, as indicated in Fig. 7. We make no attempt to field verify these minor changes to justify their physical meaning in contrast to being data noise. Large changes in aggradation and denudation that can be easily explained are mentioned here, but a more detailed ana-

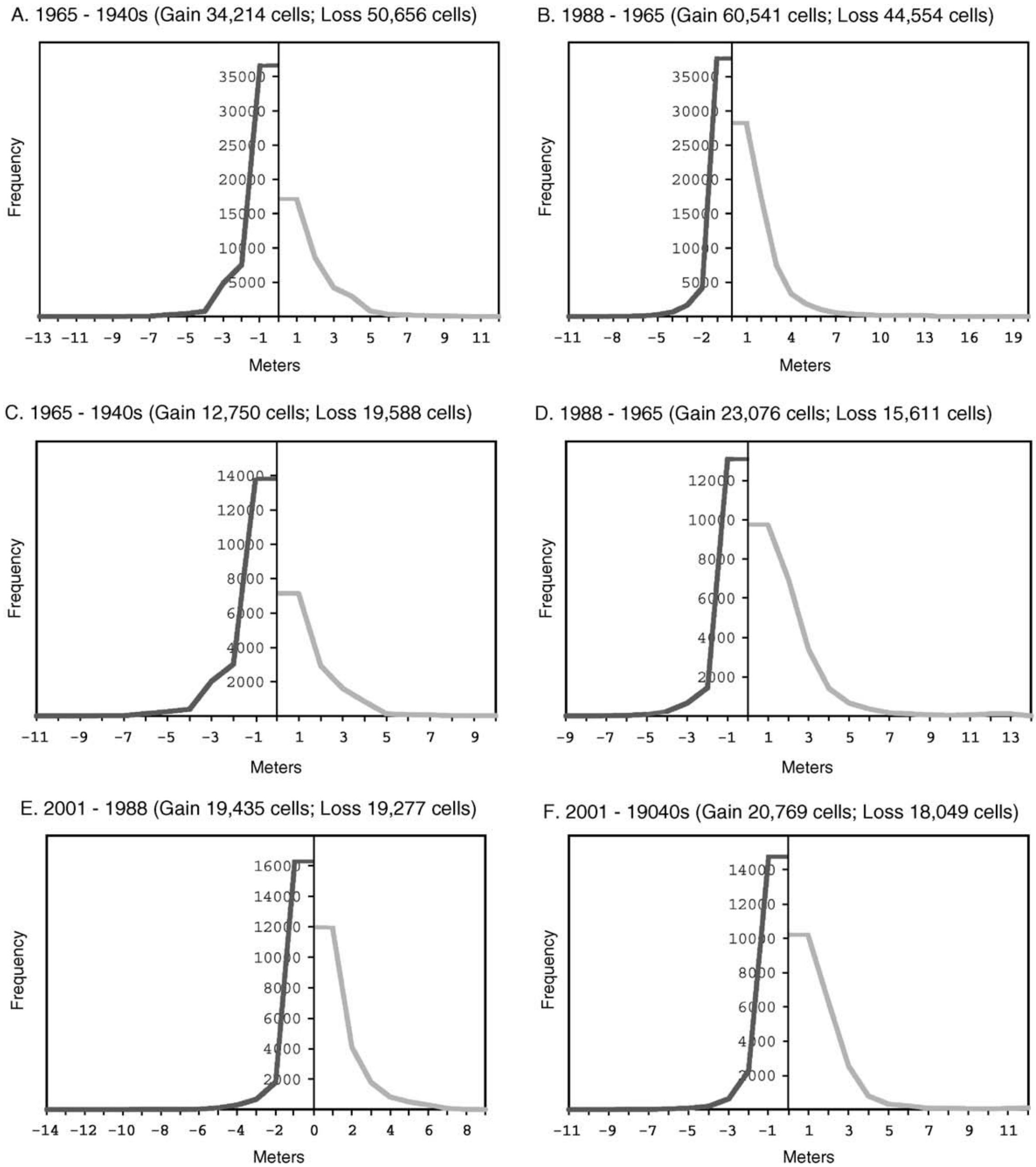

Fig. 7. Histograms indicating the number of grid cells (9687.48 m^2) that have undergone denudation (negative) and aggradation (positive). (A) corresponds with map 4A, (B) with map 4B, (C) with map 5A, (D) with map 5B, (E) with map 6A, and (F) with map 6B. Approximate aggradation and denudation volumes can be obtained by multiplying the frequency for a specific quantity interval by the grid cell area.

lysis on a much finer scale would be needed to fully justify all gains and losses.

4.1. Wolf River flood plain denudation and aggradation in Shelby County between the 1940s and 1988

The 1965 minus 1940s map illustrates denudation and aggradation (cut and fill) that have occurred between these two times (Fig. 4A). The values range from extremes of 12.7 m of sediment denudation to 11.1 m of sediment aggradation, with an average denudation of 1.4 m and an average aggradation of 1.4 m (Fig. 7A). Within the city limits of Memphis, areas of gain and loss are generally interspersed (Table 1, A); however, denudation primarily occurred along the river (Table 1, B). Large areas of flood plain denudation occurred upstream of Germantown Road in the Germantown and Collierville areas (Table 1, C).

The 1988 minus 1965 map illustrates a maximum of 10.6 m of denudation, maximum 20 m of aggradation, average denudation of 1.1 m, and average accumulation of 1.6 m (Figs. 4B and 7B). Between these time periods, the Wolf River flood plain primarily underwent aggradation (Table 1, D). By comparing the ratios of gain versus coverage area, the largest local areas of aggradation were along Interstates 40 (I-40) and 240 (I-240) and the Shelby County landfill (Table 1, E). The area east of Houston Levee Road has undergone both aggradation and denudation in nearly equal proportions (Table 1, F).

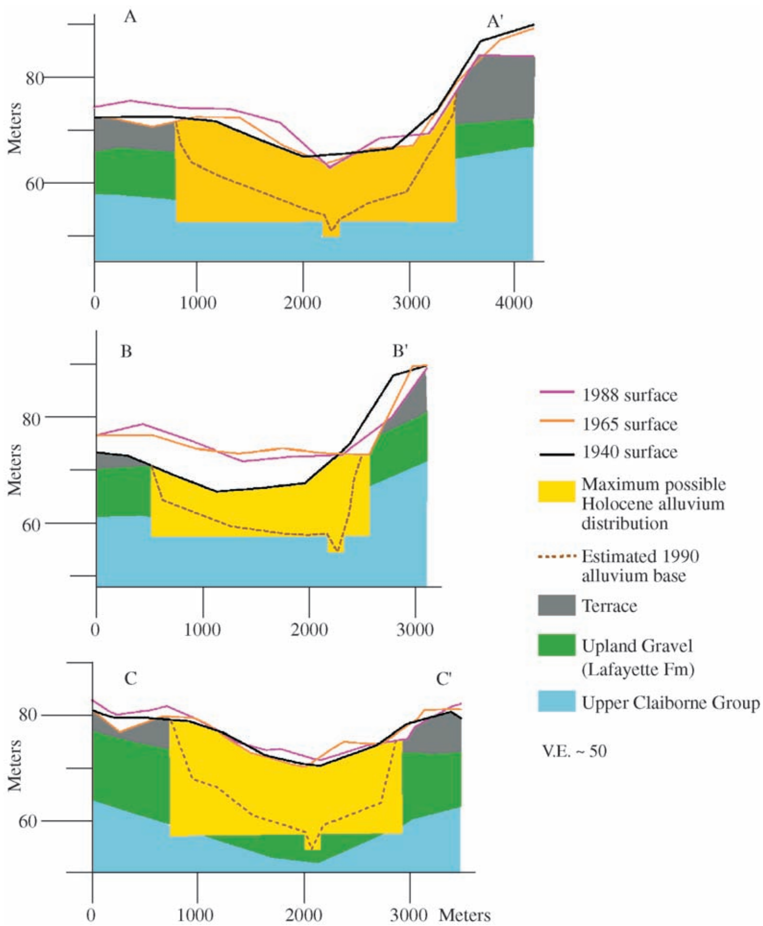

Fig. 8. Geologic cross-sections A–A′, B–B′, and C–C′ of the Wolf River flood plain and their surface elevations in the 1940s, 1965, and 1988. Cross-sections are located in Fig. 3.

4.2. Wolf River flood plain denudation and aggradation in Germantown between the 1940s and 2001

Topographic data sets from the 1940s, 1965, 1988, and 2001 are available for the Germantown area and so a more comprehensive evaluation of denudation and aggradation is possible for this 15-km segment of the Wolf River flood plain (Figs. 5 and 6).

Maximum denudation and aggradation for the 1965–1940s period are 10.7 and 9.1 m, respectively (Figs. 5A and 7C). The western third of the flood plain has experienced primarily denudation with localized aggradation along the interstate systems and Walnut Grove road (Table 2, A). The central portion of the flood plain has undergone aggradation, denudation, and areas of no change. East of Germantown Road, approximately 84% of the entire flood plain, underwent denudation within this time period (Table 2, B). Large amounts of denudation occurred locally along the river (Table 2, C).

Between 1965 and 1988, the maximum denudation has been 8.5 m and the maximum aggradation has

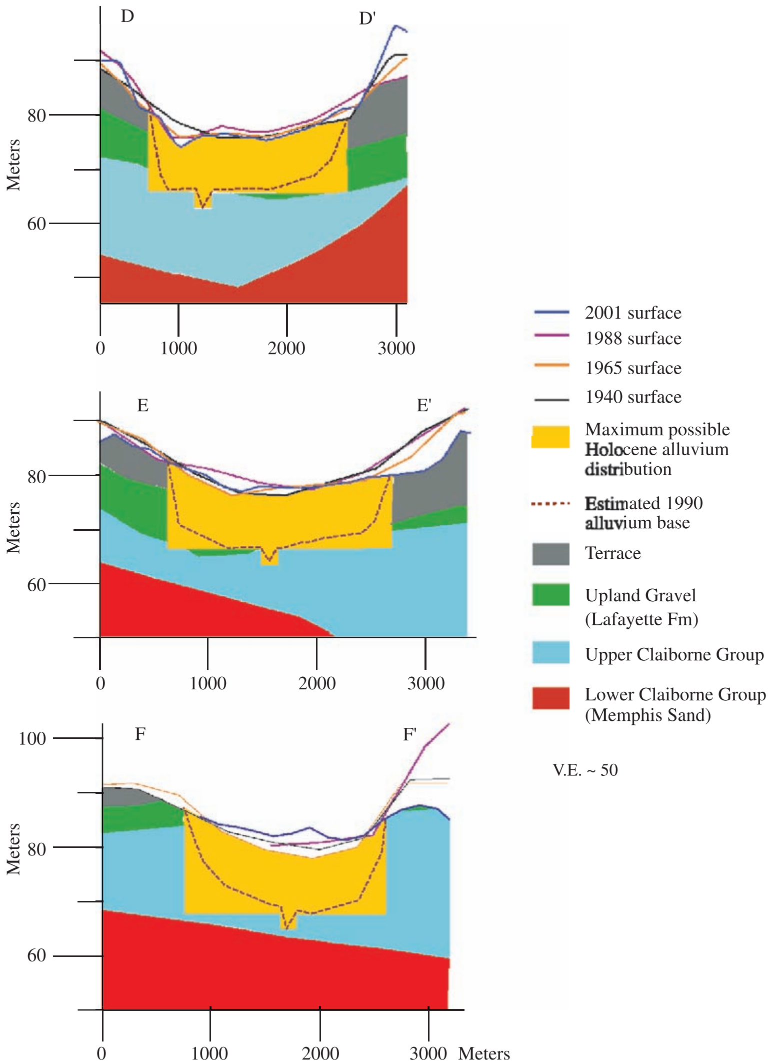

Fig. 9. Geologic cross-sections D–D′, E–E′, and F–F′ of the Wolf River flood plain and their surface elevations in the 1940s, 1965, 1988, and 2001. Cross-sections are located in Fig. 3.

been 13.5 m (primarily along I-40 and the Shelby County landfill) (Fig. 5B). Average denudation between these dates has been 1.1 m and average aggradation has been 1.7 m (Fig. 7D). There was over three times as much aggradation than denudation occurring over the Germantown portion of the Wolf River flood plain during this time period (Table 2, D).

Maximum denudation and aggradation for the 2001–1988 period are 14 m (retreat of valley wall) and 8.6 m, respectively, with average denudation being 1 m and average aggradation being 1.2 m (Figs. 6A and 7E). Denudation occurred primarily west of Germantown Road (Table 2, E), and over six times more aggradation than denudation occurred east of Germantown Road (Table 2, F).

The 2001 minus 1940s map incorporates the flood plain changes revealed in the previous maps (Fig. 6B). Denudation maximum is 10.6 m and aggradation is 12.6 m (Fig. 7F). Aggradation is clearly defined along I-240 and predominates south of the Wolf River (Table 2, G). Denudation and aggradation are nearly equal north of the Wolf River (Table 2, H). It is quite clear that aggradation has occurred over nearly one half of the flood plain (Table 2, I) and that the 2001 flood plain has been reduced to approximately one half its 1940s width.

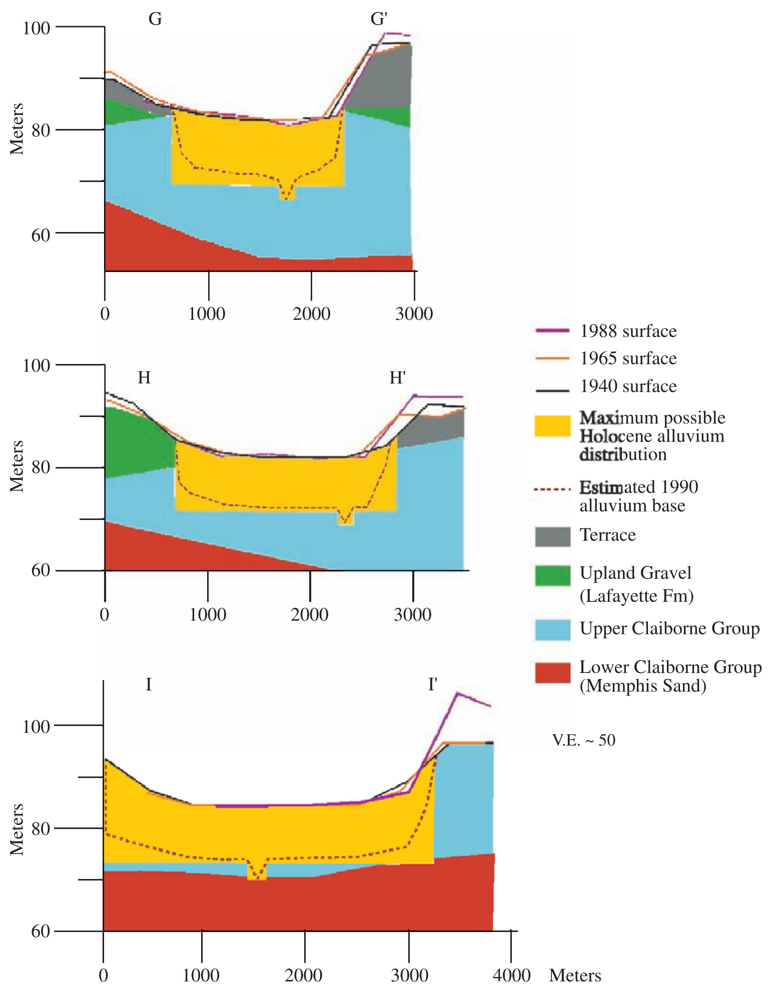

Fig. 10. Geologic cross-sections G–G′, H–H′, and I–I′ of the Wolf River flood plain and their surface elevations in the 1940s, 1965, and 1988. Cross-sections are located in Fig. 3.

4.3. Wolf River cross-sections

Nine geologic cross-sections are presented to provide an additional perspective on the magnitude of flood plain changes that have occurred at these locations since the 1940s (Fig. 3 and Figs. 8–10). The cross-sections depict at most five geologic units. The Holocene alluvium is a product of the Wolf River and has been liquefied in the past (Van Arsdale et al., 1998; Broughton et al., 2001). This unit is inset into river terrace deposits, the Upland Gravel (Lafayette Formation), Upper Claiborne Group, and the Lower Claiborne Group. The Upper Claiborne Group is the confining clay unit over the Memphis aquifer. The Memphis aquifer is indicated in Figs. 9 and 10 as the Lower Claiborne Group (Memphis Sand).

The most dramatic changes to the flood plain have occurred in the downstream cross-sections at A–A′ and B–B′ (Fig. 8). Continued aggradation has occurred since 1940 on the southern valley wall, as indicated in Fig. 8 (sections A–A′ and B–B′). Aggradation along B–B′ is due to the construction of I-240. Since 1940, no accumulative aggradation or denudation has occurred along section C–C′ (Fig. 8). Major changes have occurred to the northern valley wall in cross-sections D–D′, E–E′, and F–F′ with variable change to the flood plain and southern wall (Fig. 9). Only minor flood plain changes have occurred in the upstream sections of G–G′, H–H′, and I–I′ east of the Wolf River nick point near Houston Levee Road (Fig. 10). The cross-sections also illustrate the maximum possible extent of liquefiable sand beneath the Wolf River flood plain. It should be noted that liquefaction of fill sites on top of flood plains 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). The cross-sections indicate that post-

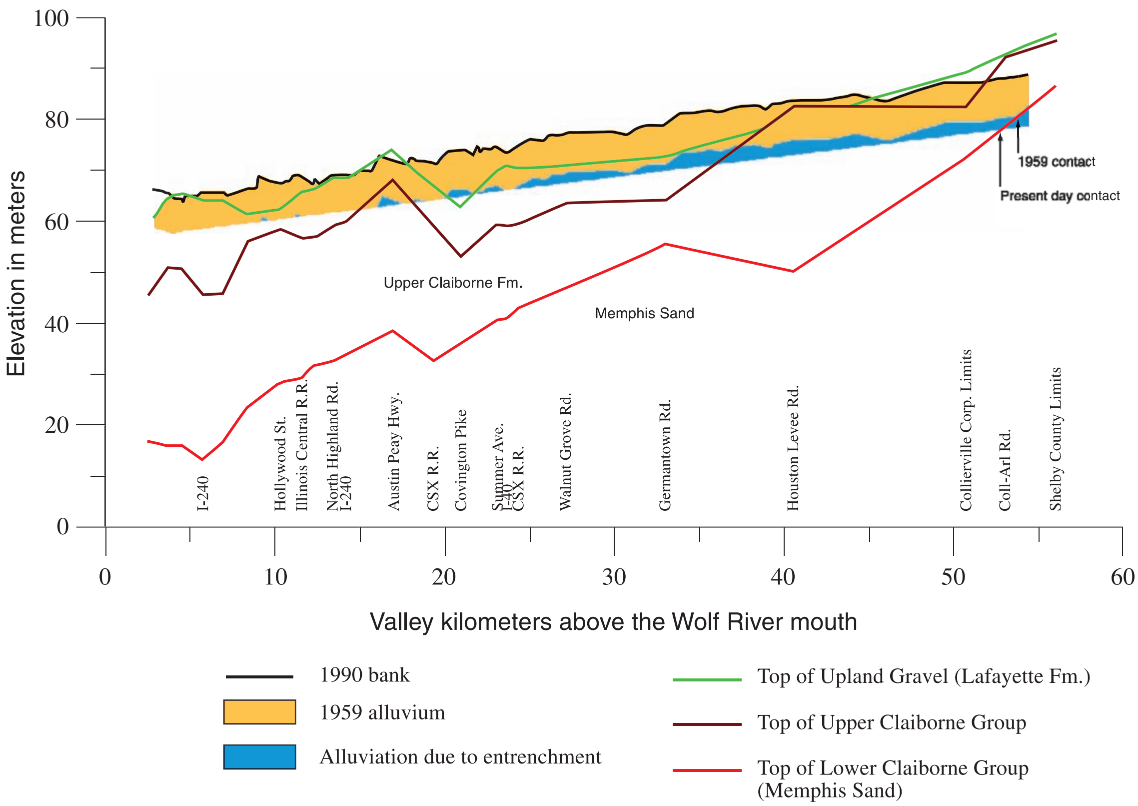

Fig. 11. Longitudinal profile of the Wolf River flood plain. Vertical exaggeration ∼ 300.

1964 entrenchment of the Wolf River has caused deeper inset of the alluvium into the underlying strata (small box at base of alluvium beneath present course of Wolf River in Figs. 8–10). These cross-sections reveal that the Holocene alluvium is almost in contact with the Memphis Sand aquifer at section F–F′ (Fig. 9) and the alluvium is in contact with the Memphis aquifer at section I–I′ (Fig. 10). The entrenchment, due to 1964 channelization (Van Arsdale et al., 2003), has increased the connectivity between the flood plain alluvium and the Memphis aquifer in eastern Shelby County (Yates, 2002) (Fig. 11). As illustrated in Fig. 11, the Wolf River flood plain is inset into the loess, Upland Gravel, and the Upper Claiborne; and in the City of Collierville, it is inset into the Lower Claiborne (Memphis aquifer). Not only does the entrenchment inset the flood plain alluvium deeper into the Memphis aquifer, but entrenchment also shifts the breach point of the overlying aquitard (contact between Upper and Lower Claiborne) 2 km downstream of its 1959 location. The Wolf River drainage basin upstream of Shelby County contributes nonpoint source contamination from farming and livestock. If Wolf River water infiltrates through the base of the flood plain alluvium, there is increased risk of pollutants entering the Memphis aquifer.

5. Conclusions

Undisturbed Wolf River flood plain stratigraphy is rather simple, consisting of a clayey silt overbank cap overlying point bar sands. However, this study demonstrates that the Wolf River flood plain, in the metropolitan Memphis area, has undergone major post-1940s changes. Since the 1940s, areas of flood plain aggradation and denudation have shifted in time and space (Figs. 4–10). The clayey silt cap has locally been thinned, removed, buried, or altered in various combinations of these events. Additionally, a flood plain surface that was essentially flat now has substantial topography from the top of the I-40/I-240 surface to the bottom of borrow pits, resulting in flood plain topographic relief exceeding 30 m. Large areas of the flood plain have been developed and, by 2001, approximately one half of the 1940s flood plain in the Germantown area has been covered with fill, supporting roads and buildings. The filling and construction have primarily occurred on the south side of the Wolf River. During this time period, and probably as a consequence of this construction, the Wolf River preferentially denuded the northern side of its flood plain and valley wall.

The 2001 Wolf River flood plain is clearly not the same flood plain that liquefied in 1811–1812. Thus, a pressing problem is: How will this flood plain, and its building stock, respond to a large future earthquake? Geologic cross-sections illustrate that liquefiable sand underlies the flood plain, but changes in the clayey silt cap thickness, addition of pad material that may itself be susceptible to liquefaction (Youd and Hoose, 1977; Youd and Perkins, 1978), entrenchment of the Wolf River and its tributaries, and excavation of large borrow pits through the cap into the underlying sand will all locally influence earthquake liquefaction. The flood plain is prone to future liquefaction because it has liquefied in the past (Youd, 1984; Sims and Garvin, 1995; Tuttle et al., 2002) and liquefiable sand lies beneath the flood plain (Broughton et al., 2001). However, in view of the dramatic changes that this flood plain has undergone, detailed geotechnical studies are necessary to assess its liquefaction susceptibility (Van Arsdale et al., 2003).

The Wolf River was channelized in 1964 to reduce flooding along the river. Channelization resulted in a bank full discharge capacity that increased threefold from prechannelization in 1959 to its 1990 capacity (Van Arsdale et al., 2003). Increased river discharge capacity and entrenchment made development of the Wolf River flood plain possible—but at what cost? The consequences of channelization include damage to bridges and pipelines, river and wetland habitat destruction, building development on a flood plain that has liquefied in the past, aggradation and denudation on the flood plain that may locally increase liquefaction susceptibility, increased flood plain relief that promotes lateral spreading during an earthquake, a 50% reduction in flood plain area that may increase flood hazards, and probable greater connectivity between the Wolf River alluvium (surface water) and the underlying Memphis aquifer that increases the potential for contamination.

In this study, we document environmental hazards that appear to have increased due to river channelization and development along the Wolf River. Although this primarily concerns Shelby County, TN, this is a common problem in metropolitan areas where high real estate values promote flood plain development. Full assessment of the liquefaction susceptibility, ground water flow, and updated mapping of the 100- and 500-year flood levels along the Wolf River flood plain requires additional quantitative studies that would benefit Shelby County and provide insights into natural hazards in similar metropolitan settings.

Acknowledgements

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