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Catena 69 (2007) 134–149
CATENA
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Predicting vertical accretion rates at an archaeological site on the Mississippi River floodplain: Effigy Mounds National Monument, Iowa

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Received 24 January 2005; received in revised form 28 April 2006; accepted 4 May 2006

Abstract

The Sny Magill Unit of Effigy Mounds National Monument, Iowa, contains the largest cluster of prehistoric effigy mounds on public land in North America. The mounds are situated atop a low terrace of the Upper Mississippi River, where they are slowly being buried by overbank deposition during floods. The terrace surface includes forest soils with argillic (Bt) or cambic (Bw) horizons developed in up to 1 m of loamy overbank deposits on top of Pleistocene sand and gravel. Radiocarbon evidence suggests that overbank deposits have accumulated since the end of the mound-building period (about 700 years BP), yielding a vertical accretion rate of about 0.6 mm yr^{-1}. On the basis of ^{137}Cs analysis, accretion rates over the past 40–50 years average 1.25–2.07 mm yr^{-1}, with some evidence for a decreasing rate since 1964. If these accretion rates are projected forward, several of the effigy mounds could be buried by flood deposits within 150–300 years. This ^{137}Cs-derived estimate agrees closely with an estimate of burial times based on flood frequency and observed flood deposit thickness during recent floods. However, the floodplain and backwater environments of the Upper Mississippi River are aggrading much more rapidly than the Sny Magill terrace surface, suggesting that burial of the entire terrace could occur within 80–400 years and the entire mound group could be buried within 150–850 years. The projected accretion rates and time to burial are subject to large uncertainties because of environmental change in the watershed, including recent trends toward increasing flood stages and decreasing suspended sediment loads.
Published by Elsevier B.V.

Keywords: Overbank sediments; Sedimentation rates; Cs-137; Upper Mississippi Valley

1. Introduction

Overbank deposition of suspended sediment during floods progressively raises the elevation of floodplain surfaces by vertical accretion. Where rivers are vertically incising into or laterally migrating across their floodplains, overbank sediment is typically eroded faster than it is deposited. In such cases, overbank deposits represent a small proportion of the alluvial valley fill. In aggrading rivers, or those where channel migration is minimal, overbank deposits persist and may comprise a large proportion of the valley fill (Leopold et al., 1964; Ritter et al., 1973; Kesel et al., 1974; Nanson and Hickin, 1986). Given widespread human occupation of floodplains and alteration of land cover in watersheds, it is not surprising that accelerated vertical accretion has become a problem in recent centuries. In some cases, overbank deposits have buried roads, bridges, small dams, buildings, valuable farmland, and other cultural features (Gilbert, 1917; Happ et al., 1940; Trimble, 1974; Trimble and Lund, 1982; Trimble, 1983; Knox, 1987; Barnhardt, 1988; Thoms and Walker, 1993; Phillips, 1997; Trimble, 1998).

Theoretical models of overbank deposition suggest that the accretion rate on a floodplain surface decreases over time as its elevation rises, the inundation period is reduced, and progressively larger floods are required to add more

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0341-8162/$ - see front matter. Published by Elsevier B.V.
doi:10.1016/j.catena.2006.05.002

sediment to the surface (Wolman and Leopold, 1957; Moody and Troutman, 2000). Such models assume stable channel bed elevation and channel size, along with stationary flood frequency and suspended sediment regimes, conditions that are seldom met. In fact, prediction of vertical accretion rates is complicated by a host of geomorphic factors that influence inundation frequency, sediment availability, and local hydraulics. For instance, accretion rates are influenced by changes in surface roughness, development of natural levees, and sudden planform changes such as avulsions (Knight and Demetriou, 1983; Zwolinski, 1992). Even in a fairly stable floodplain environment, the flood frequency regime and sediment load of most rivers vary over time scales of decades to centuries in response to external controls such as climate change and anthropogenic impacts (Knox, 2000, 2001). More subtle changes to the sediment regime, including seasonal effects, hysteresis, and flood sequencing, have also been shown to complicate the stratigraphic record of flood events contained in floodplains (Gomez et al., 1995; Magilligan et al., 1998; Benedetti, 2003).

Field studies have successfully measured vertical accretion rates in many floodplain environments. Most of these studies have involved the use of historical markers such as buried soils, cultural features, radiocarbon, and radioisotopes. Difficulties arise in interpreting these measurements as a result of time averaging and incompleteness of the depositional record. In general, the longer the time period involved, the lower the measured accretion rate will be, as periods of non-deposition or erosion are folded into the measurements of sediment thickness over time (McShea and Raup, 1986; Gardner et al., 1987; Schumm, 1991). Thus, simple extrapolation from observations of individual flood deposits will typically overestimate the actual accretion rates over periods of decades or longer.

This paper presents a case study of recent vertical accretion on a fluvial terrace of the Upper Mississippi River (UMR), within the Sny Magill Unit of Effigy Mounds National Monument, Iowa. The primary objective of this study is to predict future vertical accretion rates to develop an estimate of how long it will take for a group of effigy mounds at the site to be buried by overbank deposition. Our approach is to measure recent accretion rates over several time intervals and to extrapolate forward with consideration of hydrologic and geomorphic factors that will influence future deposition rates at the site. Two independent methods are presented to estimate recent vertical accretion rates: one is based on ^{137}Cesium (^{137}Cs) analysis of sediment samples, the other is based on observed flood deposit thickness and magnitude–frequency analysis. This study highlights some of the difficulties in predicting future floodplain evolution given the uncertainties of environmental change.

2. The Upper Mississippi River

The post-glacial history of the UMR is one of catastrophic incision followed by slow aggradation. During the last glacial maximum, about 18,000 years BP, the river carried meltwater from a large area along the southern margin of the Laurentide ice sheet in central North America. At this time the valley was filled with coarse outwash deposits to the level of the Savanna Terrace, which is preserved at a height of 10–15 m above the active floodplain in tributary valleys (Flock, 1983; Bettis and Hallberg, 1985). Between roughly 14,000 and 9500 years BP, catastrophic outburst floods associated with the drainage of proglacial lakes scoured and entrenched into the outwash surface to an average depth of about 15–20 m below the modern floodplain of the UMR (Clayton, 1982; Knox, 1996). Scoured remnants of the outwash surface exist along the sides of the valley as terraces exhibiting braid-bar surface morphology. The post-glacial UMR, adjusted to modern hydroclimatic conditions, lacks the stream power to transport the sediment load supplied to it by the tributary rivers. Throughout the Holocene, the UMR has slowly aggraded its active floodplain within the trench created by the outburst floods.

Post-glacial aggradation rates for the Upper Mississippi River floodplain are constrained by stratigraphic evidence including radiocarbon dates, buried soils, and archeological sites (Table 1). Church (1985) cites a contact between sandy channel deposits and underlying gravel outwash at a depth of about 15 m, revealed in bore holes for a highway bridge across the floodplain at Prairie du Chien, Wisconsin. Based on this evidence, average aggradation rates since 9500 years BP average about 1–2 mm yr^{-1}. Holocene valley fills in this area include a thin veneer of silty overbank deposits overlying channel deposits of massive fine and medium sand across most of the valley. A period of relative floodplain stability prior to 2500 years BP is suggested by the presence of a prominent buried soil, dated by Knox (2000) at 2490 years BP, and elsewhere associated with archeological evidence from the late Woodland period. Human occupation of the Mississippi River floodplain during the late Woodland period appears to have been widespread, and includes the features of Effigy Mounds National Monument (Bennett, 1952; Dial, 1996). Radiocarbon ages associated with late Woodland archeological sites in Wisconsin and Iowa cluster around 2000–2500 years BP (Lass, 1978; Stoltman, 1979). Rates of aggradation for the mid- and late Holocene, based on these lines of evidence, average 1–2 mm yr^{-1}.

Historical floodplain accretion in the Upper Mississippi Valley has been measured with radiocarbon evidence,

Table 1
Selected Holocene vertical accretion rates for the Upper Mississippi River

Location	Mean rate	Years B.P.	Method	Source
UMR Pool 10	1.3 mm yr^{-1}	9000–0	Erosion surface	Church (1985)
UMR Pool 10	0.9 mm yr^{-1}	2360–0	Radiocarbon, archaeology	Knox (2000)
UMR Pool 10	1.2 mm yr^{-1}	4000–0	Radiocarbon	Knox and Daniels (2002)
UMR Pool 10	1.4 mm yr^{-1}	2500–0	Buried soils	Benedetti (2003)

Table 2
Selected recent vertical accretion rates for the Upper Mississippi River

Mean rate	Years A.D.	Location	Method	Source
2.0 mm yr^{-1}	1937–1983	Pool 7	Bathymetry	Korschgen et al. (1987)
3.0 mm yr^{-1}	1951–1995	Pool 11	Bathymetry	WEST Consultants (2000)
6.7 mm yr^{-1}	1938–1951	Pool 11	Sed. Budget	Nakato (1981)
6.8 mm yr^{-1}	1938–2001	Pool 10	Sedimentology	Theis and Knox (2003)
12.5 mm yr^{-1}	1954–2001	Pool 10	^{137}Cs	Benedetti (2003)
16.4 mm yr^{-1}	1937–1976	Pool 7	Bathymetry	Claflin (1977)
23.0 mm yr^{-1}	1964–1992	Pool 4	^{137}Cs	Faulkner and McIntyre (1996)
25.0 mm yr^{-1}	1964–1975	Pool 10	^{137}Cs	McHenry et al. (1984)
42.0 mm yr^{-1}	1963–1975	Pool 10	^{137}Cs	GREAT I (1980)

radioisotope analysis, and various historical markers such as mining waste and buried cultural artifacts (Table 2). These studies provide evidence of widespread accelerated sedimentation following European settlement and the conversion of native prairie and forest to agricultural land uses. In general, post-settlement accretion rates are an order of magnitude greater than the long-term average rates for the Holocene. The floodplains of tributaries to the Upper Mississippi typically have a well-preserved buried soil that represents the pre-settlement floodplain surface, and up to 4 m of overlying flood deposits laid down during the last two centuries (Happ et al., 1940; Knox, 1987). Accelerated sedimentation on the floodplain of the main stem Mississippi River has not been as dramatic as in the tributaries. Because of spatial and temporal lags inherent in fluvial sediment transport, the initial landscape disturbance of the 19th century did not immediately result in accelerated sedimentation on the Mississippi River floodplain. Several studies have reported accretion rates of 3–42 mm yr^{-1} over recent decades on levees, backswamps, and in navigation pools (Table 2). The variability of these rates is due to geomorphic factors such as elevation above low water, distance from an active channel or tributary mouth, and location in the navigation pools relative to the impounding effect of dams.

3. The Sny Magill site

The Sny Magill Unit of Effigy Mounds National Monument lies along Johnson's Slough, a secondary channel of the UMR just downstream of its confluence with the Wisconsin River near McGregor, Iowa (Fig. 1). It contains

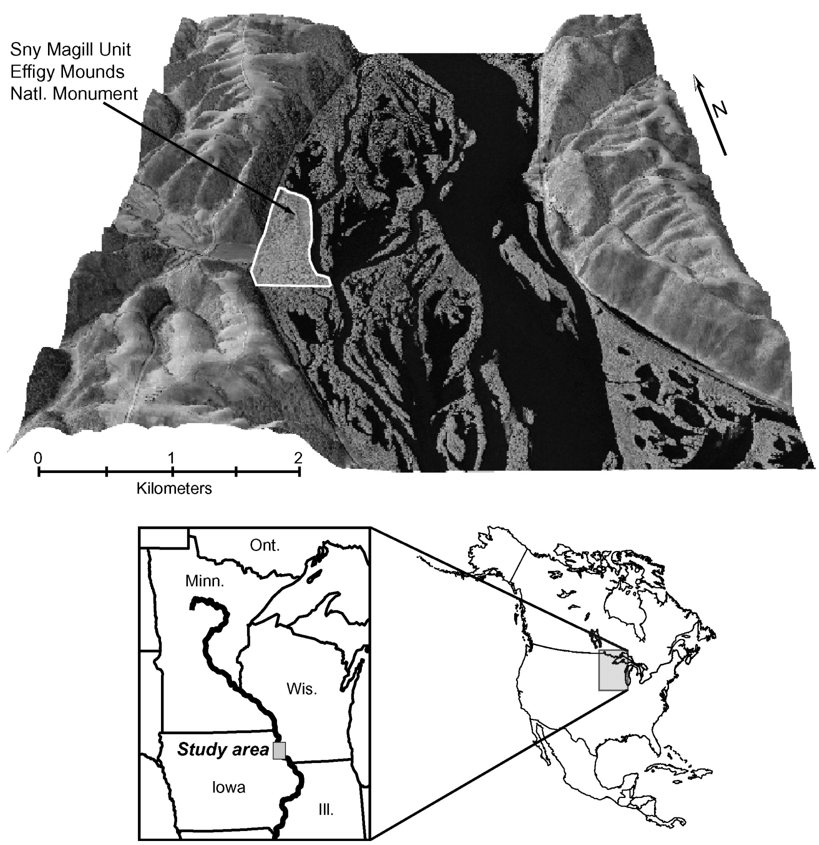

Fig. 1. Site location map. Landsat TM image draped over 30 m DEM (no vertical exaggeration) depicts deeply incised Upper Mississippi River valley, island-braided morphology of the modern floodplain, and location of Sny Magill Unit of Effigy Mounds National Monument relative to the main channel. Location arrow for Sny Magill Unit points to detailed study area. Johnson's Slough flows along east edge of National Monument boundary. Sny Magill Creek flows into southern part of National Monument from valley interrupting western bluff-line.

the largest intact cluster of effigy mounds on public land in North America, including about 100 conical mounds, linear mounds, and effigy mounds in the shape of bears and birds (Fig. 2). The mounds were built as burial sites or for ceremonial purposes between about 2400 and 700 years BP by natives of the late Woodland period (Bennett, 1952). Relief on the mounds varies from 0.2 to 1.8 m. Theodore H. Lewis of the Northwestern Archaeological Survey first mapped the mound group in 1885, and numerous archaeological studies have focused on the site since then (Dial, 1996). The mound group became part of Effigy Mounds National Monument in 1962. Most of the mounds appear to be intact, although a few have been damaged by tree throw, bank erosion, and small-scale cultivation that occurred during the early 20th Century. The low-lying mounds at the southern end of the site have already lost some of their relief due to accretion of flood deposits in the inter-mound areas.

The Sny Magill mounds are situated atop an isolated fluvial terrace that rises between a side channel of the Mississippi River to the east (Johnson's Slough), a poorly drained floodplain swamp to the west, a floodplain lake to the north, and the mouth of Sny Magill Creek to the south. The terrace tread slopes gently away from the bank of Johnson's Slough. Most of the terrace surface lies at elevations of 188.5–189.5 m asl, about 2–3 m above the general elevation of the Mississippi River floodplain and 3–4 m above the normal low water elevation in Navigation Pool 10 (Lynott, 1992). Lock and Dam No. 10, which is 20 km downstream at Guttenberg, Iowa, maintains a 9.5-ft shipping channel at low flow in Pool 10. Dam operations have negligible effects on flood flows at the Sny Magill site.

The Soil Survey of Clayton County, Iowa identifies two major soil series at the Sny Magill site (Kuehl, 1982). The soils on the gravel terrace are mapped as Wapsie Series, well-drained forest soils formed in thin loamy alluvium over gravel (Mollic Hapludalfs). Soils on the adjacent back-swamps of the Mississippi River floodplain are mapped as Caneek Series, poorly-drained soils that lack subsurface horizons and exhibit stratification (Typic Fluvaquents). The soils on the Sny Magill terrace show more evidence of pedogenesis than those of the surrounding floodplain due to their elevation and better drainage.

The terrace stratigraphy includes less than 1 m of loamy overbank deposits atop well-rounded gravel and sand that are interpreted as late Pleistocene glacial outwash. The elongated shape and convex profile of the terrace suggest it formed as a longitudinal bar on the surface that was scoured by late-glacial outburst floods. This interpretation is similar to that of the "Bagley Terrace" described by Knox (1996), which lies about 1–3 m above the present UMR floodplain near the Sny Magill site in the reach downstream of the Wisconsin River mouth. A previous investigation of the surficial geology and soils of the Sny Magill site was conducted by Bettis (1988). He identified buried soils and slope wash deposits surrounding the site that suggest significant disturbance and erosion of the terrace surface during the period of late Woodland occupation and mound building.

4. Data sources and methods

Field sampling was conducted at the Sny Magill site during October 2003 and June 2004. Samples were collected from 82 inter-mound locations along 14 transects that run roughly east-to-west across the site (Fig. 3). At all locations, a surface sample was collected and the depth to Pleistocene gravel was determined by probing with a bucket auger. At 30 of these locations, a soil core was collected of the uppermost 35 cm for ^{137}Cs bulk inventory analysis. Previous work in the area suggested that post-1954 overbank deposits were not likely to be thicker than 10–20 cm on the terrace surface. Reference pits were dug at two locations near the central axis

Fig. 2. Photograph of effigy mounds at the Sny Magill Unit of Effigy Mounds National Monument, Iowa. (Photo credit: J.M. Daniels).

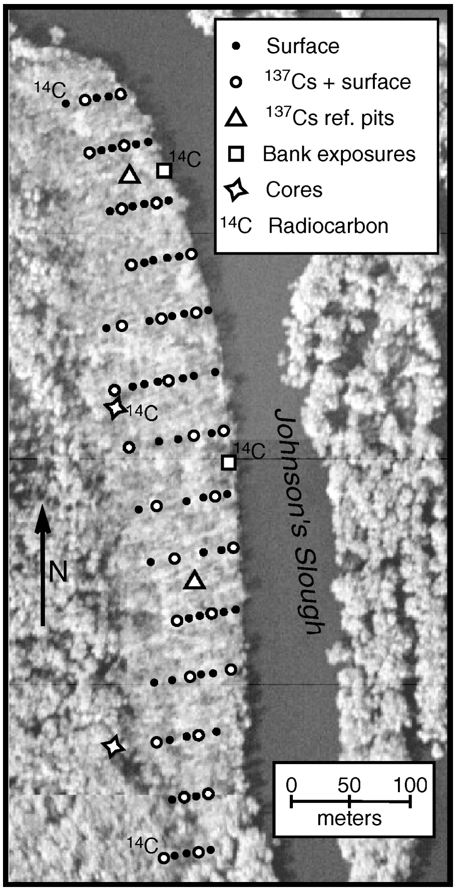

Fig. 3. Sample locations in the study area superimposed on aerial photograph. Reference pits 1 and 2 are shown by northern and southern triangle symbols, respectively.

of the mound group to describe soil properties and to construct detailed ^{137}Cs profiles. Additional soil profiles were described at two bank exposures along Johnson's Slough, and at several other locations where samples were extracted with a bucket auger or core sampler. Sediment samples were described and analyzed at the Soil and Sedimentology Laboratory, University of North Carolina at Wilmington. Percent sand in the samples was determined by wet-sieving, and organic carbon was determined by the Walkley–Black method (Singer and Janitzky, 1986). Several fragments of wood and charcoal were retrieved from the overbank deposits and submitted for AMS radiocarbon analysis at Beta Analytic, Inc.

Reference pit and bulk samples were analyzed for ^{137}Cs activity at the Hydrology and Remote Sensing Laboratory of the U.S. Department of Agriculture, Agricultural Research Service in Beltsville, MD. Samples were dried at 90 °C for 48 h, crushed to pass a 2-mm mesh sieve, and weighed. The ^{137}Cs technique involves counting gamma emissions from the sample to determine the amount of the radioactive isotope present. Worldwide fallout of ^{137}Cs began with the initiation of high-yield thermonuclear bomb testing in 1954, reached a peak in 1964, and has decreased greatly since the 1970s. A discussion of the applications and limitations of the ^{137}Cs technique is given in Ritchie and McHenry (1990). The analytical procedures are described in Ritchie (2000).

A detailed topographic map of the mound group, derived from photogrammetric data, was created by the Midwest Archeological Center in 1986 (Lynott, 1992; Dial, 1996). The map has a contour interval of 0.15 m (0.5 ft) and is tied to the 1929 National Geodetic Vertical Datum (NGVD29). This map was used to determine floodplain surface, terrace surface, and mound top elevations for comparison with flood records and stratigraphic data. All river gage data in this paper were collected from Internet sources of the U.S. Geological Survey (http://water.usgs.gov/) or of the St. Paul District of the U.S. Army Corps of Engineers (http://www.mvp-wc.usace.army.mil/). These records include historical flood discharges and stages, inundation duration tables, water surface elevation profiles, and suspended sediment data. The gaging station for the Mississippi River at McGregor, IA is located 9.8 km upstream of the Sny Magill site and includes 69 years of daily discharge and 26 years of daily suspended sediment values. Water surface profiles were derived from the Upper Mississippi River System Flow Frequency Study (USACE, 2004), which updated flood magnitude and frequency estimates for the entire UMR. All flood frequency estimates in this study, including those from the USACE study, were generated according to the methods outlines in Bulletin 17B of the U.S. Water Resources Council (1981).

5. Results

5.1. Soils and stratigraphy

Detailed soil profiles were described in the field at two reference pits, two bank exposures along Johnson's Slough, and several additional auger holes. Reference pits 1 and 2 are typical of the soil profiles on inter-mound surfaces of the Sny Magill terrace (Fig. 4). In general, soils on the terrace exhibit thick A horizons (mollic epipedons) over weak Bt or Bw horizons (argillic or cambic subsurface horizons) that extend to an abrupt contact with Pleistocene gravel. The A horizon has been over-thickened by slow overbank deposition. The Bt or Bw horizon exhibits a slight clay increase and some development of blocky structure. The soils with Bt horizons generally occur in thicker, siltier overbank deposits, whereas less clayey Bw horizons occur where surface sediments are thinner and sandier. Some of the B-horizon properties extend into the top few cm of the dense gravel beneath, which is typically oxidized to a strong red color. Percent sand increases with depth, from silt loam textures in the top 5 cm to sandy loam near the gravel contact. The loamy surface sediments are less acidic than the sandier sediments at depth, reflecting fairly recent deposition and only moderate leaching of carbonates.

The thickness and texture of overbank deposits on the Sny Magill terrace were described along 14 transects where the surface elevation, sand content (0–5 cm), and depth to gravel

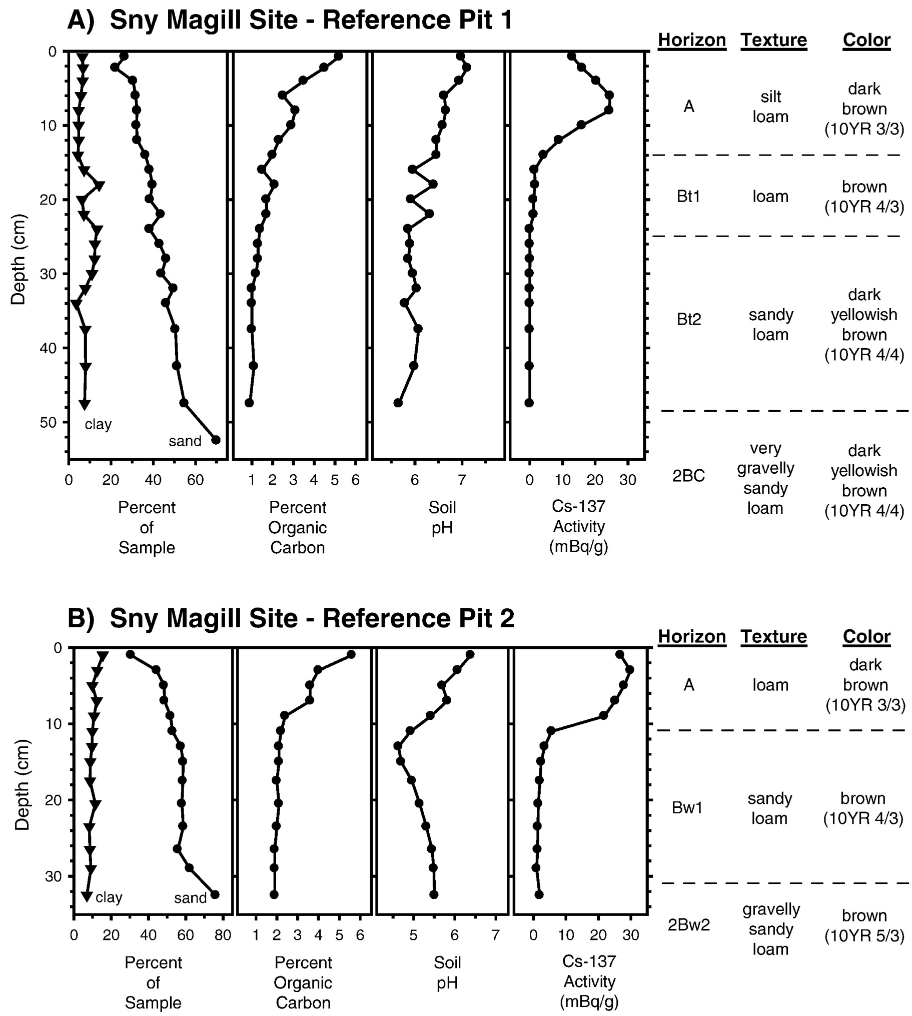

Fig. 4. Physical and chemical data for the soil pits shown in Fig. 3. A. Reference pit 1. B. Reference pit 2.

were recorded (Fig. 5). The highest elevations on the terrace occur along Johnson's Slough at the southern half of the mound group, where the Pleistocene gravel is exposed in the bank at depths of 15–35 cm. The overbank sediments are thinnest and sandiest at the higher elevations, reflecting a topographic high in the underlying gravel bar and the development of a natural levee where coarser sediment is deposited during floods. The gravel surface dips steeply away from Johnson's Slough to the northwest and southwest of the mound group, where it is deeply buried by silty deposits associated with the backswamp and abandoned channel west of the site. Based on 84 sampling points, the mean depth to gravel across the terrace is 43 cm with a standard deviation of 23 cm. Since the gravel bar was deposited (at least 9500 years BP), the long-term average rate of deposition on the terrace surface has been only about 0.05 mm yr^{-1}. As discussed below, this value is misleading since there is a long gap in the Holocene not represented by sediments at the site.

The loamy surficial sediments at the Sny Magill site are interpreted as overbank flood deposits on the basis of their texture, location in the floodplain, and direct observations of sediment deposited at the site during historical floods. However, these sediments do not display the stratification typical of overbank deposits, or the irregular depth trend in organic carbon that is typical of young floodplain soils (fluvents). Strong bioturbation and frost action in the soil zone above the dense gravel is probably responsible for the lack of sedimentary structures. Evidence of these processes includes tree-throw pits, animal burrows, and rounded pebbles that are abundant within the loamy surface deposits. Despite the evidence of mixing processes near the surface, the contact between the overbank deposits and the Pleistocene gravel was abrupt and nearly flat.

To further define Holocene deposition rates at the Sny Magill Site, samples of wood were collected for radiocarbon dating of the fine-grained alluvium atop the late Pleistocene gravel. The samples were collected at various locations across the site from depths of 33 to 71 cm below the surface, and in some cases as little as 10 cm above the gravel contact (Table 3). Two samples (BETA-187408 and 187411) were retrieved from sediment cores in the backswamp area to the west of the terrace; the other four samples were from soil pits and sediment cores atop the terrace. Six samples have

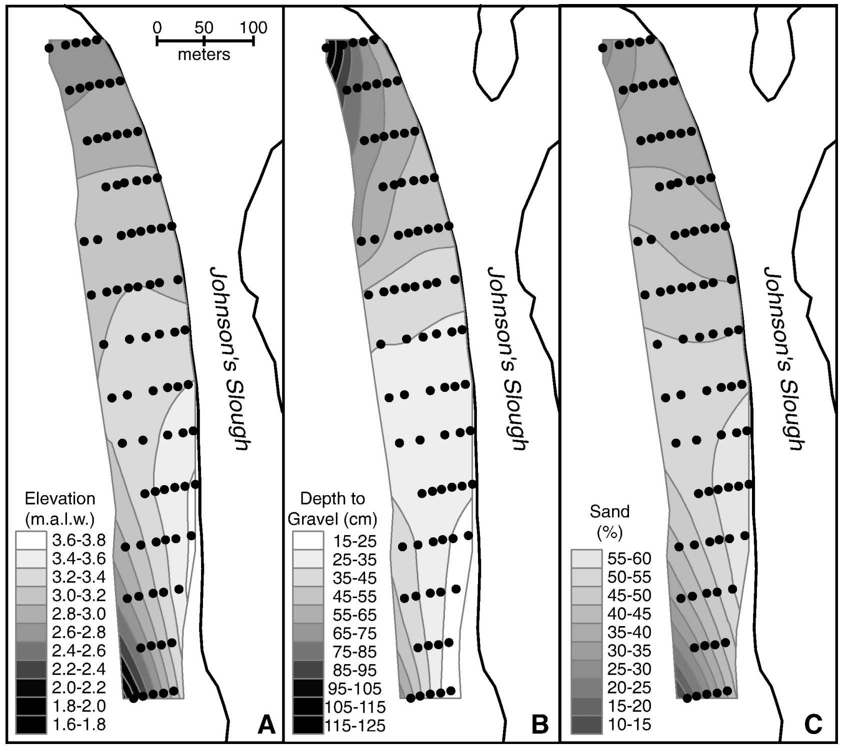

Fig. 5. Map of interpolations based on measured site characteristics. Black dots represent locations of field-based point measurements. Interpolations calculated using a local-polynomial algorithm in Arc-GIS; interpolated fields are therefore smooth and inexact. A. Depth from surface to underlying late-Pleistocene gravel. B. Elevation of terrace surface relative to low water elevation (186.22 m asl, NGVD 1929). C. Surface texture of overbank alluvium.

yielded ages from modern (younger than AD 1950) to no more than several hundred years (maximum antiquity based on the 2 Sigma range is AD 1650). It is worth noting that these ages correspond with a recent episode of large floods in the Upper Mississippi Valley described by Knox and Daniels (2002), which began about 550 years BP and was preceded by a long period of relative floodplain stability.

The radiocarbon evidence suggests that the Sny Magill terrace surface experienced little overbank deposition earlier in the Holocene, or that existing Holocene deposits were removed. Previous work at the site by Bettis (1988) supports the notion that natives excavated the surface soil in the process of building the mounds. He concluded that the overbank deposits had been completely removed from parts of the terrace, resulting in fairly young soils without argillic horizons atop the terrace surface. By contrast, soils with well-developed argillic horizons are preserved along the western edge of the terrace, away from the mound group. It is also possible that the bioturbation processes described above contributed to destroying stratigraphic evidence of the Holocene. Whatever the mechanism, little evidence exists at the site for the period between the deposition of the gravel bar and the time of recent overbank deposition.

If it is assumed that all of the overbank deposits on the Sny Magill terrace have accumulated since the end of the mound-building period around 700 BP, their average thickness of 43 cm yields a mean accretion rate of about 0.61 mm yr^{-1}. This value is an order of magnitude greater than the estimate given above (0.05 mm yr^{-1}) based on the assumption that the overbank deposits represent the entire Holocene. This example illustrates the danger in calculating geomorphic process rates from stratigraphic records where gaps due to periods of non-deposition, erosion, or anthropogenic disturbance are difficult to identify.

Table 3
Radiocarbon ages of samples collected at the Sny Magill site

Beta ID	Material	Sample depth	Radocarbon age (uncalibrated)
187408	Wood	40 cm	Modern (post-1950)
187411	Wood	71 cm	80+/−40 years BP
192855	Wood	60 cm	Modern (post-1950)
192856	Wood	33 cm	180+/−40 years BP
192857	Wood	62 cm	Modern (post-1950)
192858	Charcoal	33 cm	180+/−40 years BP

5.2. Flood frequency and overbank deposition

In an unpublished study of flooding and sedimentation at the Sny Magill site, Pranger (2002) determined that the terrace surface is inundated by floods with a discharge of 4200 m^3 s^{-1} or more at McGregor, having an average recurrence interval (RI) of about 5 years or more. He combined this frequency estimate with observations of sediment deposited at the Sny Magill site during the 2001 flood to project a future accretion rate at the site. He

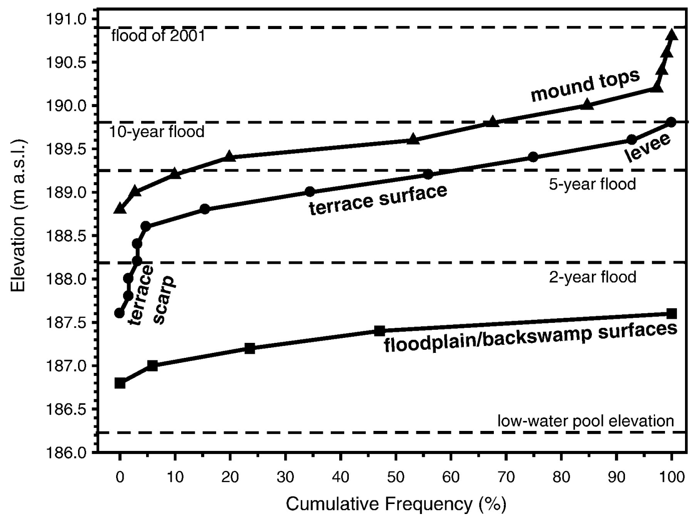

Fig. 6. Cumulative frequency curves for elevation of tops of the Sny Magill effigy mounds, surface of the Sny Magill terrace, and Mississippi River floodplain surfaces near the Sny Magill site.

concluded that most of the mounds could be buried within 100–700 years.

Data from the U.S. Army Corps of Engineers (USACE, 2004) provides more precise estimates of flood profiles and inundation durations at the Sny Magill site. Their estimated 5-year flood profile, with a discharge of 4730 $m^3 s^{-1}$, crosses the Sny Magill reach at an elevation of 189.19 m asl (1929 NGVD). A flood at this elevation inundates about 55% of the terrace surface, and roughly 10% of the mound tops (Fig. 6). The 10-year flood (5560 $m^3 s^{-1}$) inundates the entire terrace surface and about 65% of the mound tops. The flood of 2001, which was the second-highest discharge on record at McGregor (6620 $m^3 s^{-1}$, estimated RI = 70 years), inundated the entire Sny Magill site including all of the mounds. Water depths reached 1.5–2.0 m on the terrace at the peak flood stage, and portions of the terrace were inundated from mid-April to mid-May.

Most of the floods that impact the Sny Magill site are spring events generated by snowmelt, often augmented by rain from storm systems passing over the watershed (Knox, 1988). As a result, high water most commonly occurs within a month of the spring thaw of March and April. Duration tables for Pool 10 (generated from daily stage data for McGregor and Clayton, IA over the period 1972–2001) show that the elevation of the terrace surface is inundated about 6% of the days in April, 1–2% of the days in March, May, June, July, and October, and less than 0.4% of the days in other months. Spring floods are about twice as frequent as summer floods on the UMR, and account for about twice as much of the suspended sediment load over the period of record at McGregor, IA (Benedetti, 2003).

Following the spring flood of 2001, Pranger (2002) observed overbank flood deposits on 8 recently cut tree stumps at the Sny Magill site. The deposits included a 3–10 mm coating of silt and very fine sand. He noted that deposition was inversely related to surface elevation, with the thickest deposits occurring below 189 m and no net deposition occurring on one stump above 190.5 m. The lower stumps experienced greater deposition due to a longer period of inundation, and possibly as a result of being protected from wave action that can re-suspend sediment in the later stages of a flood. A comparison with other observations of individual flood deposits along the UMR shows that the high surface of the Sny Magill terrace experiences less overbank deposition than the lower floodplain surfaces in Pool 10 (Table 4).

Larger floods are expected to leave a thicker overbank deposit, as suggested by Knox and Daniels (2002), but to date there is not enough direct evidence to define the form of this relationship for the UMR. In fact, observations of individual flood deposits show that the relationship between flood magnitude and deposition is complicated at best. Gomez et al. (1995) and Magilligan et al. (1998) demonstrated that the massive 1993 flood in the lower reaches of the UMR (RI > 100 years) was characterized by low sediment concentrations that limited the overbank deposits to 4–5 mm thick near Hannibal, MO. Comparing flood deposition during the 1993, 1997, and 2001 floods on the UMR (RI 14 to 70 years), Benedetti (2003) found deposits 15–80 mm thick on low-lying floodplain surfaces

Table 4
Observed thickness of deposits from recent Upper Mississippi River floods

Flood	Sampling location	Thickness (mm)	Source
1993	Pools 20–22, floodplain	2–5	Magilligan et al. (1998)
1993	Pool 10, natural levees	30–60	Benedetti (2003)
1997	Pool 10, natural levees	15–40	Benedetti (2003)
2001	Pool 10, floodplain island	30–80	Benedetti (2003)
2001	Pool 10, backwater lakes	60–470	Theis and Knox (2003)

for all three events, and concluded that their thickness was more closely related to factors such as duration and sediment concentration than to peak discharge. This study suggested that deposition during the 2001 flood was typical of recent UMR floods of various magnitudes. In the absence of a defined relationship between flood magnitude and sediment thickness, we take Pranger's (2002) observed values of 3–10 mm as a reasonable estimate for the range of accretion on the Sny Magill terrace during floods that inundate most of the terrace surface (RI ≥ 5 years). This reasoning yields average accretion rates of 0.6–2.0 mm yr^{-1} on the terrace under the modern flood frequency and sediment regime of the UMR.

5.3. ^{137}Cs analysis

This study employs two methods of ^{137}Cs analysis to determine recent vertical accretion rates at the Sny Magill site. The first examines detailed ^{137}Cs profiles at the two reference pits, and the second compares the total ^{137}Cs inventory in 30 sediment cores from across the site with the inventory in cores collected the reference pits. The profile method assumes that the vertical variation in ^{137}Cs activity with depth reflects the general trend of atmospheric fallout since the beginning of high-yield thermonuclear bomb testing in 1954. The total inventory method assumes that the total ^{137}Cs activity in a 35 cm core sample is proportional to the net deposition at the sampling site since 1954.

The ^{137}Cs profiles for the two reference pits involved sampling at 1.5–5.0 cm intervals from the terrace surface to the underlying gravel contact. Both profiles show a sharp rise from negligible background ^{137}Cs activity marking the 1954 horizon within 15 cm of the surface, and a clear peak in ^{137}Cs activity marking the 1964 horizon (Fig. 4). Stratigraphic data show that the ^{137}Cs trends are not influenced by any abrupt changes in particle size or organic carbon. The depths of the 1954 and 1964 horizons in each reference pit were used to determine accretion rates (Table 5). The mean accretion rate since 1954 at reference pit 1 is 2.60 mm yr^{-1}, and 1.80 mm yr^{-1} at reference pit 2. Since 1964, the estimated rates are 1.75 and 1.00 mm yr^{-1} for pits 1 and 2, respectively. Although the precision of these estimates is limited by the sampling interval, accretion rates over the interval 1954–1964 are estimated at about 6 mm yr^{-1} at both pits, suggesting a significant decrease in aggradation on the terrace since 1964. The accretion rates also support the notion that most of the fine-grained alluvium on the terrace surface is fairly young, with about 30% of its thickness deposited in the past 50 years. If these accretion rates are projected back through time, the base of the fine-grained alluvium at the two reference pits dates to roughly 200–400 years BP, a value that agrees well with the oldest radiocarbon ages retrieved from these deposits (Table 3).

Table 5
Summary of ^{137}Cs-derived accretion rates at the Sny Magill site

Location	Method of analysis	1954–2003 accretion rate (mm yr^{-1})	1964–2003 accretion rate (mm yr^{-1})
Reference pit 1	Detailed ^{137}Cs activity profile	2.60	1.75
Reference pit 2	Detailed ^{137}Cs activity profile	1.80	1.00
Core samples	Total ^{137}Cs inventory compared to reference pits	Mean = 2.07 Range = 1.46–3.46 P_{10} = 1.68 P_{25} = 1.80 P_{50} = 2.00 P_{75} = 2.23 P_{90} = 2.59	Mean = 1.25 Range = 0.68–2.55 P_{10} = 0.88 P_{25} = 1.00 P_{50} = 1.18 P_{75} = 1.41 P_{90} = 1.74

A 35-cm soil core was collected at each reference pit and analyzed for total ^{137}Cs inventory. The total ^{137}Cs inventory in the core samples agrees with the ^{137}Cs profiles, showing greater ^{137}Cs activity in pit 1 where the accretion rate since 1954 is greater. The core samples for the two reference pits were used to define a relationship between total ^{137}Cs inventory and post-1954 accretion, assuming a linear function of the form described by Walling and He (1999). Using the relationship derived from the reference pits, accretion rates were estimated for the 30 additional locations where 35-cm soil cores were collected and analyzed for total ^{137}Cs inventory. This method produced estimated accretion rates of 1.46–3.46 mm yr^{-1} across the site since 1954, with a mean rate of 2.07 mm yr^{-1} (Table 5).

Since the accretion rate at the reference pits seems to have decreased since 1964, a separate relationship was used to estimate accretion rates for the period 1964–2003 (again assuming a linear relationship with total ^{137}Cs inventory). These rates varied from 0.68 to 2.55 mm yr^{-1}, with a mean of 1.25 mm yr^{-1}. These rates agree well with the flood frequency-based estimates (0.6–2.0 mm yr^{-1}) described in the previous section. They also are notably lower and less variable than most recent accretion rates for lower floodplain surfaces in Pool 10 (Table 2). It is likely that small-scale variations in vertical accretion across the site are related to local variations in the topography of the mound group and surface roughness. In general, thicker overbank deposits are found in the intermound areas than on the mounds themselves, but no clear spatial patterns are evident in the estimated accretion rates across the Sny Magill site as a whole.

6. Discussion

6.1. Burial of the Sny Magill mound group

The tops of the Sny Magill mounds are 0.2–1.8 m above the surface of the terrace. If a simple one-dimensional model of vertical accretion is employed, the rates cited above for accretion of the terrace surface can be used to estimate how long it will take to bury the mound group. Pranger (2002) developed an estimate of 100–700 years to bury most of the mounds but considered this to be a minimum, believing that

Table 6
Estimated years to burial of Sny Magill mounds by accretion of the terrace surface

Proportion of mound group	Elev. (m)	Years to burial at rate of:		
		0.90 mm yr^{-1}	1.25 mm yr^{-1}	1.70 mm yr^{-1}
2%	189.07	300	216	159
25%	189.45	722	520	382
50%	189.55	833	600	441
75%	189.90	1222	880	647
100%	190.65	2056	1480	1088

he had probably overestimated the accretion rate by his flood frequency-based method. However, the ^{137}Cs-derived rates presented here confirm that accretion rates on the order of 1–3 mm yr^{-1} have prevailed over at least the past 50 years, and can reasonably be expected to continue in the near future.

Vertical accretion at the Sny Magill site will progress most rapidly on the lower part of the terrace, eventually leveling the terrace surface and burying the effigy mounds. Rather than attempting to estimate variable accretion rates across the terrace, we applied an estimated accretion rate beginning with the lowest elevation on the terrace (188.8 m), assuming that this rate will apply to higher surfaces as they are overtaken. The time required to bury a given proportion of the mound group was calculated from the mound elevation distribution (Fig. 6). To account for uncertainty in the projected vertical accretion rates, a range of 0.9–1.7 mm yr^{-1} was used. This range represents the 10th to 90th percentile of the ^{137}Cs-derived rates for 1964–2003 (Table 5). These rates are representative of recent conditions at the site, and they agree closely with the independent estimates derived from flood frequency analysis (0.6–2.0 mm yr^{-1}).

If recent vertical accretion rates continue on the terrace surface, burial of the entire Sny Magill mound group will take about 1000–2000 years (Table 6). Roughly half of the mounds will be buried in 400–800 years. The lowest-lying mounds, those at the far southern tip of the mound group, will be buried within 150–300 years. Field observations suggest that the southern-most mounds have already lost some of their relief due to burial, and previous workers have hypothesized that some small mounds are already buried beneath recent flood deposits in that area (Dial, 1996).

The above-cited rates of vertical accretion on the Sny Magill terrace are roughly an order of magnitude less than those that prevail on lower-lying floodplain surfaces of the UMR. The rapid aggradation of backwater areas is partly due to closure of the lock and dam system on the UMR that raised water levels by 1–2 m in the lower half of each navigation pool (Theis and Knox, 2003). In backwater areas of Pool 10, vertical accretion rates of 6–40 mm yr^{-1} have been previously reported (Table 2). Two radiocarbon dates from the backwater area to the west of the Sny Magill site (Table 3; BETA-187408, BETA-187411) suggest average accretion rates of 4–7 mm yr^{-1} over the last century. Even on higher floodplain surfaces in the upper parts of the navigation pools, where the impacts of impoundment are minimal, vertical accretion rates are still in the range of 4–14 mm yr^{-1} (Benedetti, 2003). Since rates of backwater filling and floodplain aggradation are rapid, and the Sny Magill terrace lies only 2–3 m above the surrounding floodplain, it is possible that the mound group could be buried by the general accretion of the floodplain before it is buried by accretion of the terrace alone (Fig. 7).

To account for floodplain aggradation, the mound burial rates were re-calculated using a starting elevation of 187.2 m and a range of vertical accretion rates from 4 to 20 mm yr^{-1}. This range is generally indicative of the rates described above and those documented in Table 2. Rates of about 4–10 mm yr^{-1} are the most relevant because the accreting surfaces surrounding the Sny Magill terrace are most similar to the low levee surfaces, floodplain islands, and shallow floodplain lakes that were studied by Benedetti (2003) and Theis and Knox (2003). In this scenario, the accreting

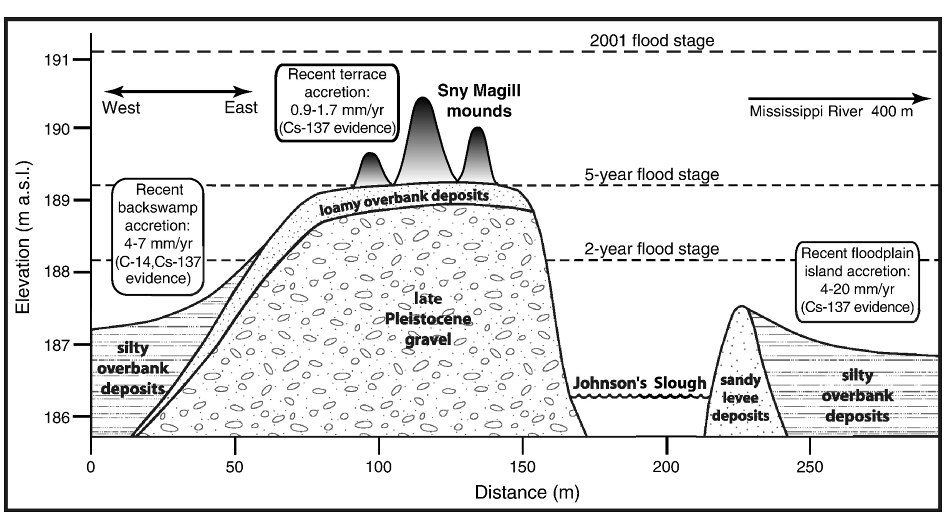

Fig. 7. Generalized cross section of the Sny Magill site, showing topography, stratigraphy, flood stages, and estimated vertical accretion rates.

floodplain merges with the Sny Magill terrace in 80–400 years, and the first low mounds are buried shortly thereafter (Table 7). The mound group is halfway buried in 100–600 years, and the entire mound group is buried by about 200–900 years. Considering the floodplain accretion rate separately from the terrace accretion rate does little to change the time to burial for the low-lying mounds, but it significantly accelerates the burial of the larger mounds. The low mounds will be buried within 500 years under any scenario, while the largest mounds will likely maintain some relief until they are overtaken by aggradation of the general floodplain.

One challenge to projecting future accretion rates at the Sny Magill site is that past rates vary considerably depending on the time interval considered. Geomorphic process rates often appear to accelerate as shorter time scales of measurement are considered, a phenomenon sometimes referred to as time-averaging (Gardner et al., 1987; McShea and Raup, 1986; Schumm, 1991). This occurs because gaps in the geologic record become more abundant and harder to recognize as longer time scales are considered. At the Sny Magill site, undefined gaps exist in the record of overbank deposition due to past changes in the flood frequency regime, bioturbation, erosional events, or prehistoric human disturbance of the site. The vertical accretion rate at the Sny Magill site was measured at 75–250 mm yr^{-1} during the two-week flood of 2001, 3–10 mm yr^{-1} averaged over the year 2001, 1.5–2.5 mm yr^{-1} over the past 40–50 years based on ^{137}Cs evidence, 0.61 mm yr^{-1} over the past 700 years based on radiocarbon evidence, and 0.05 mm yr^{-1} over the past 9500 years based on the inferred age of the gravel terrace. This variability makes it difficult to choose an appropriate accretion rate to project forward through time, even when it is recognized that periods of erosion or non-deposition have occurred. In this case, it was decided that the accretion rates during the late 20th Century (derived from ^{137}Cs analysis) offer the best analogue for conditions in the near future, in terms of flood hydroclimatology, land use and land cover in the watershed, and human impacts on the sediment and flow regime of the UMR.

While the rates cited above are based on somewhat simplistic assumptions, they provide a general time frame for decisions to be made about preservation of the Sny Magill site. Burial of the entire mound group within 200 years seems extreme, since it would also presume burial of several marinas and historical sites in the area. However, the required vertical accretion rates of >20 mm yr^{-1} have been documented for parts of the UMR (Table 2), and continuation or acceleration of those rates into the future is not unimaginable. At a minimum, the estimates presented here suggest that burial of the Sny Magill mounds (and other features at similar elevations) will begin within a few hundred years. This process is rapid enough to cause concern for resource managers and municipalities in the area, but slow enough for awareness to be raised and sound management decisions to be applied to the problem.

Table 7
Estimated years to burial of Sny Magill mounds by accretion of the UMR floodplain

Proportion of mound group	Elev. (m)	Years to burial at rate of: 4 mm yr^{-1}	10 mm yr^{-1}	20 mm yr^{-1}
Terrace surface	188.8	400	160	80
2%	189.07	468	187	94
25%	189.45	563	225	113
50%	189.55	588	235	118
75%	189.90	675	270	135
100%	190.65	863	345	173

6.2. Future controls on vertical accretion rates

The vertical accretion rate on a floodplain surface is controlled by the frequency and duration of inundation, the prevailing sediment concentrations in the floodwater, and geomorphic controls such as the site location relative to meander bends and its height above mean water level in the channel. The predictions given above for the longevity of the Sny Magill mound group are based on the assumption that these controls are static; that the site topography, flood frequency, and sediment load will not change significantly in the near future. Of course, a fully developed predictive model of vertical accretion rates would allow these controlling factors to vary. We did not attempt a comprehensive assessment of these factors, but potential trends that may affect overbank deposition are considered here.

A significant source of uncertainty in predicting future vertical accretion rates at the Sny Magill site involves the influence of rising surface elevations on the frequency and duration of inundation during floods. Most models of floodplain formation assume a decreasing accretion rate over time, as the rising surface elevation results in decreased frequency of floodplain inundation. This concept is valid if a stable channel bed elevation is assumed. The influence of bed elevation changes on stage-discharge relationships is poorly understood, as it depends largely on adjustments in channel capacity and floodplain topography. Theoretically however, in the case of a rapidly aggrading system such as the UMR, the accretion rate on higher floodplain surfaces could accelerate if floodplain surfaces are inundated with increasing frequency.

Although we are not aware of direct evidence of bed aggradation in the UMR in recent history, it is clear from stratigraphic evidence that the floodplain and channel of the UMR have been aggrading throughout the Holocene. Evidence of this process exists in the stratigraphic record of the UMR floodplain where former levee and terrace surfaces have been buried by vertical accretion deposits during the Holocene. For example, buried soils on relict levee surfaces in Pool 10 are evidence of more stable, well-drained conditions in the past when the surfaces were elevated well above the general level of the floodplain

(Church, 1985; Bettis and Hajic, 1995; Knox, 2000; Benedetti, 2003). The presence of an archaeological site of major cultural significance at Sny Magill suggests that, at the time the mounds were built, flooding of the site was less frequent than at present. The absence of overbank deposits older than several hundred years on the Sny Magill terrace also fits this model, suggesting that floods capable of inundating the terrace surface are a relatively recent phenomenon. Even if stationarity is assumed in the flood frequency regime and sediment load of the UMR, accretion on the terrace could continue or accelerate until the surface is overtaken by the general aggradation of the floodplain. Overbank deposition has already buried most of the relict floodplain features that formed during the Holocene, and low-lying Pleistocene terrace remnants such as the Sny Magill site are next to be buried.

Aggradation of the UMR floodplain could be accelerated by changes in climate and land use that may be increasing flood frequencies along the UMR. This topic has received much attention in recent years, including studies of precipitation and snowmelt patterns, the influence of lock and dam operations, and changes in stage/discharge relationships that may be related to sedimentation in the navigation pools (Karl et al., 1995; Knox, 2000; Pinter et al., 2001; USACE, 2004). The annual flood records for the UMR at McGregor and Clinton, Iowa show a trend of increased flood frequency since about 1950 (Fig. 8). The apparent trends include both increasing magnitude of frequent floods (2–5 year RI) and increasing frequency of high magnitude floods (>10 year RI). At Clinton, 10 floods greater than the estimated 10-year RI have occurred since 1950 (in 54 years), while only 6 such floods had occurred prior to 1950 (in 75 years). Some municipalities along the UMR are already dealing with the perceived risk of increased flooding. For example, most of the residences and 18–19th Century historical buildings on St. Feriole Island near Prairie du Chien, Wisconsin were relocated following the record flood of 1965. The island, which lies at roughly the same elevation above low water as the Sny Magill site, was entirely inundated during the flood of 2001.

Knox (2000) has shown that the increased frequency of large floods on the UMR since 1950 is related to a strengthening of meridional circulation patterns that generate slow-moving storm systems over central North America. Other studies have similarly identified increasing rainfall and streamflow, especially in spring, for the north-central United States during the 20th Century (Karl et al., 1995; Baldwin and Lall, 1999). It is not clear whether the climate changes responsible for increased flooding are related to global warming that has occurred in recent decades, but it is worth noting that increased precipitation over central North America is an anticipated result of global warming according to the Intergovernmental Panel on Climate Change (Watson et al., 1998).

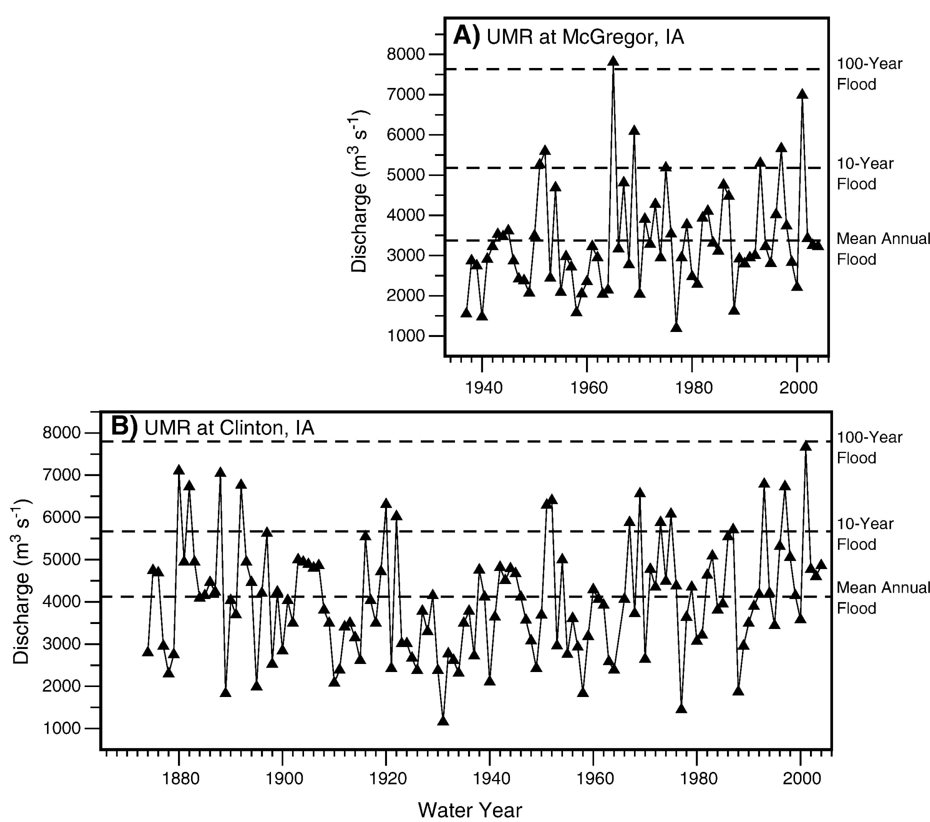

Fig. 8. Historical record of annual peak flood discharges for the Upper Mississippi River at (A) McGregor, Iowa and (B) Clinton, Iowa. Data source: U.S. Geological Survey.

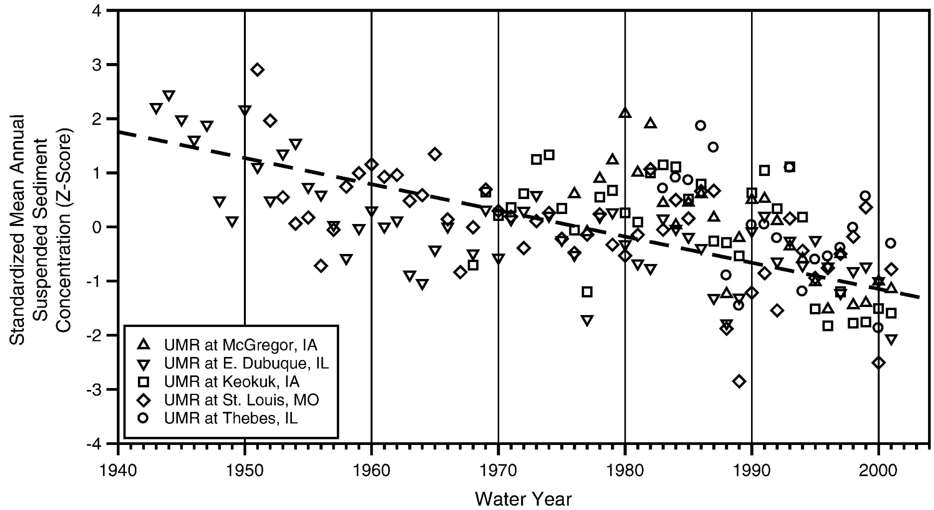

Fig. 9. Standardized mean annual suspended sediment concentration records for stations along the Upper Mississippi River. Sediment concentration data were log-transformed and converted to standard deviation units (*Z*-scores). Dashed line indicates best fit to all data by linear regression. Years with missing sediment data are not shown. Data sources: U.S. Geological Survey, U.S. Army Corps of Engineers.

Reinforcing the influence of climatic trends are channel modifications that have altered the relationships between discharge, velocity, and stage on the UMR (Wasklewicz et al., 2004). Pinter et al. (2001) showed that the stage attained by a given flood discharge has increased systematically over the past 150 years in the Mississippi River between Chester, Illinois and St. Louis, Missouri. They attributed the change mainly to the construction of wing dams and artificial levees that restrict flow in the main channel, reducing velocity and increasing the flow depth. Increased stages would also be expected from accelerated sedimentation in backwater areas, which reduces the cross-sectional area available to convey flood discharges. While the Army Corps of Engineers recognizes that channel modifications influence stage-discharge relationships, they have been reluctant to adjust flood-frequency estimates for stage trends, or to acknowledge that the navigation structures on the UMR might be raising flood stages (Goldman et al., 2002). The USACE Flow Frequency Study, which was commissioned in part to adjust for recent changes in the flood regime, reaches no concrete conclusions about the influence of climate change or channel modifications on flood frequency. Although portions of the study refer to an upward trend in annual flood peaks since 1950, the report concludes that there is no strong evidence of non-randomness in flood discharges across the study area (USACE, 2004). At present, the magnitude of changes in flood frequency due to climate change, land use change, and channel modification are uncertain, and no acceptable method has been developed to incorporate these changes into meaningful flood frequency estimates.

Running contrary to the evidence of increased flood magnitude and frequency, several studies indicate that the suspended sediment load of the UMR and its major tributaries have decreased in recent decades (Keown et al., 1986; Pannell, 1999; Benedetti, 2002). One likely cause of the sediment reduction is soil conservation practices that have been adopted on agricultural land. Beginning in the late 1930s, the U.S. government initiated soil conservation programs that encouraged farmers to limit grazing on steep land, to plant grass strips between fields, and to reduce the spacing of crop rows (Knox, 2001). Erosion was further reduced by contour plowing methods, land-reserve programs, and introduction of herbicides that reduced the need for cultivation. Such measures may have reduced erosion rates by 60% or more in the Mississippi valley since 1930 (Trimble and Lund, 1982; Argabright et al., 1996). Paradoxically, the reduction in upland erosion has not led to reductions in sediment yield from UMR tributary streams, or at least such reductions have not yet been documented. This may be attributable to the complex response of the channel network and remobilization of alluvium stored in the floodplains (Trimble, 1999). In addition to possible reductions from upland sources, sediment transport in the UMR is hindered by the lock and dam structures that aid commercial navigation. Closure of the lock and dam system in 1939 contributed to the reductions in sediment load by trapping sediments in the navigation pools, decreasing flow velocities, diminishing the rate of lateral channel migration processes, and converting some shallow-water areas to terrestrial habitats (McHenry et al., 1984; Collins and Knox, 2003; Theis and Knox, 2003).

Suspended sediment records at several stations in the Upper Mississippi Valley are now long enough to confirm that suspended sediment concentrations have declined over the last 4–5 decades (Fig. 9). Statistically significant decreasing trends exist for both mean annual and peak annual suspended sediment concentration at stations with continuous records for the last 20–50 years. The greatest reductions have been for peak concentrations, which in some reaches have decreased by an order of magnitude (Pannell,

Table 8
Suspended sediment characteristics of the Upper Mississippi River during the period of record at McGregor, Iowa

Period	Mean Q ($m^3 s^{-1}$)	Mean SSC ($mg l^{-1}$)	% of period with SSC > 100 $mg l^{-1}$	Total SSL (Mt)
1976–1984	1110	52.9	10.8	20.24
1985–1993	1210	34.8	3.5	14.77
1994–2002	1290	20.2	0.2	9.19
1976–2003	1200	35.4	4.7	44.20

1999). Reductions in suspended sediment concentrations during spring snowmelt floods, which usually represent the peak annual concentration, are particularly noticeable (Benedetti, 2003). Although the geomorphic effects of reduced sediment load are well documented for the lower Mississippi River (Smith and Winkley, 1996; Biedenharn et al., 2000), little evidence of this sort has been published for the UMR above Dubuque, Iowa. In the tributaries to the UMR, there is ample evidence that diminishing sediment loads have led to reduced floodplain accretion rates in recent decades compared to the earlier period of erosive land use (Trimble and Lund, 1982; Knox, 2001). The apparent reduction in vertical accretion rates since 1964 at the Sny Magill site (Table 5) and elsewhere in Pool 10 (McHenry et al., 1984; Benedetti, 2003) suggest that the UMR floodplain has experienced a similar trend.

In addition to gross reductions in sediment load, the functional relationship between water discharge and sediment discharge has clearly changed over the period of historical sediment records. At McGregor, Iowa, the mean suspended sediment concentration decreased by 62% and the total suspended load decreased by 55% from the period 1976–1984 to 1994–2002 (Table 8). The occurrence of sediment concentrations above 100 mg l^{-1} has also decreased dramatically over the same period, from more than 10% of the days to less than 0.5%. In fact, no suspended sediment concentrations above 200 mg l^{-1} have been recorded at McGregor since the flood of 1993. Given the reduced availability of suspended sediment during floods, the effectiveness of high magnitude floods in terms of their contribution to accretion of the floodplain will be diminished. This analysis suggests that future floodplain development will be driven largely by the occurrence of frequent floods of moderate magnitude, rather than catastrophic events.

7. Conclusion

The case study presented here demonstrates the difficulties inherent in trying to predict future development of a large, complex alluvial floodplain. Two independent methods suggest that the Sny Magill mounds may begin to be buried by vertical accretion within 150–300 years. While the convergence of these two estimates is encouraging, they are both predicated on stationarity in the flood frequency and sediment regimes of the UMR. As long as the conditions that have prevailed over the past 40–100 years continue, these predictions will be fairly legitimate. Given the ongoing environmental changes in the watershed, the assumptions behind these predictions will likely be invalidated before the end of the 21st Century. Of particular concern is the interplay of two opposing trends, increasing flood frequency and decreasing suspended load. Recent studies suggest that large floods have been more frequent since about 1950, as a result of climate change that could be related to global warming trends. The massive floods of 1965, 1993, and 2001, for example, each attained discharges that might be expected once every 100 years on various parts of the UMR (USACE, 2004). Alternatively, several recent studies suggest that sediment concentrations and accretion rates on the UMR floodplain have decreased in recent decades, probably as a result of the impoundment effects of the lock and dam system (Pannell, 1999; Knox, 2001; Benedetti, 2003). Upland erosion rates in the UMV have also decreased in recent decades due to the adoption of soil conservation practices, but this has not led to documented reductions in the sediment loads from most UMR tributaries (Trimble, 1999). More study across spatial and temporal scales will be required to address the apparent discrepancies between upland erosion rates, tributary sediment loads, and main stem sediment loads.

This study illustrates some of the properties of geomorphic systems that make it difficult to predict their future evolution. The geomorphic evolution of large rivers integrates environmental change in the watershed over multiple spatial and temporal scales, making it difficult to predict the response to a given perturbation. At this time, we lack sufficient understanding of the links between global climate change, flood hydroclimatology, land use change, and fluvial sediment transport to integrate the environmental changes in the Upper Mississippi Valley into meaningful predictions of floodplain development beyond the next few decades.

Other cultural features located on low terrace surfaces on the UMR floodplain will be subject to a fate similar to that of the Sny Magill mound group. The reach of the UMR near Sny Magill will be especially subject to this process, since the low terrace remnants here are only 1–3 m above the modern floodplain (Knox, 1996, Fig. 2). Low lying floodplain surfaces along the UMR are subject to frequent flooding and therefore are generally reserved for non-residential uses. However, the low terraces are often occupied by municipal facilities, recreation areas, historical sites, and an undefined number of archaeological sites (Church, 1985). If the vertical accretion rates projected in this study are correct, a significant number of cultural features will be buried or will need to be relocated in the next few centuries.

Acknowledgements

Hal Pranger of the National Park Service, Geologic Resources Division provided the original inspiration for this research. This research was supported by the National Park

Service, Cooperative Ecosystems Study Unit (task agreement H5000 02 0433). The authors thank Rodney Rovang, Bob Palmer, Phyllis Ewing, and the staff of Effigy Mounds National Monument for field support and access to the Sny Magill site. Anne Vawser of the National Park Service, Midwest Archeological Center provided valuable field assistance and access to topographic data.

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