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Spatial and temporal variations in the grain-size characteristics of historical flood plain deposits, Blue River, Wisconsin, USA

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Abstract

This study examined vertical, lateral, and downstream variations in the grain-size characteristics of historical (post-1830) overbank deposits in a watershed that has experienced high rates of accelerated flood plain sedimentation. More than 800 samples were collected from 53 cores along nine flood plain transects. Overbank deposits exhibit a coarsening-upward sequence attributed to historical changes in the sand content of source materials. The erosion of loess-capped soils increased the exposure, erosion, and transport of sandy parent materials. The average sand content of near-channel cores increases moderately downstream along two of the reaches because sandy source materials are increasingly exposed in larger main valleys in the northern part of the watershed. The two northernmost reaches are coarser overall, but do not display significant downstream trends. The sand content of surface and early historical overbank deposits generally decreases laterally as an exponential function of distance from the channel, suggesting transport by turbulent diffusion. The presence of sand throughout the transects and lateral coarsening at two of the transects, however, suggests that sediment transport by convection is also important.

Keywords: Flood plains; Sediments; Sedimentation; Wisconsin

1. Introduction

Until recently, the investigation of flood plains by geomorphologists has concentrated primarily on the development and evolution of flood plain landforms (Walling et al., 1996), with most interest focused on processes such as lateral channel migration that redistribute sediment and alter morphological features on the flood plain (e.g., Wolman and Leopold, 1957). Although Wolman and Leopold (1957) argued that flood plains are built mainly by lateral accretion, in low-energy rivers or watersheds affected by accelerated soil erosion, the development and evolution of flood plains occurs primarily from the deposition of suspended sediment during overbank flooding (Lewin, 1978; Nanson and Young, 1981; Magilligan, 1992; Lecce, 1997a). In these systems, the storage of overbank sediment on flood plains represents a significant component of fluvial sediment budgets (Trimble, 1983; Walling, 1983; Phillips, 1991; Walling et al., 1998), but until recently has

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received considerably less attention than lateral accretion deposits (Allen, 1978). Because many contaminants and nutrients are preferentially associated with fine-grained sediments (Horowitz, 1991), flood plains are also widely recognized as important sinks for the storage of pollutants adsorbed to suspended sediments (Knox, 1987a; Bradley, 1989; Marron, 1992; Leigh, 1994; Lecce and Pavlowsky, 1997). The grain-size characteristics of overbank deposits, however, may vary in response to the dynamic nature of sediment transport, depositional processes, and remobilization/redistribution (He and Walling, 1997, 1998). Many of the processes operating in overbank environments have been replicated successfully by numerical models that simulate overbank deposition on flood plains (Nicholas and Walling, 1997a,b). Nevertheless, these models may produce inaccurate predictions of deposition rates and grain-size distributions of deposits on natural flood plains characterized by complex flow paths, irregular topography, and variations in hydraulic roughness and inundation times (James, 1985; Pizzuto, 1987; Howard, 1992; Marriott, 1992, 1996; Mackey and Bridge, 1995; Nicholas and Walling, 1997a,b). Furthermore, many such models have not been adequately tested with independent data sets needed for validation and calibration because of the difficulties associated with collecting field measurements of overbank deposition at the event-scale or over longer time periods (Nicholas and Walling, 1997a,b). Understanding variations in the grain-size distribution of flood plain deposits, therefore, is critical to testing models of overbank flow and deposition on flood plains and improving our understanding of flood plain processes and the delivery, distribution, and environmental fate of contaminants in fluvial systems.

Previous research on the grain-size characteristics of overbank deposits has documented lateral, vertical, and downstream variations, but seldom have all three dimensions of grain-size variability been addressed simultaneously (e.g., Walling et al., 1997). The purpose of this paper is to examine spatial and temporal variations in the grain-size characteristics of historical overbank deposits in the Blue River, Wisconsin, a watershed where agriculture has accelerated rates of flood plain sedimentation.

2. Background

The transfer of sediment from the channel to the flood plain during overbank flow can be accomplished by different mechanisms. During a flood, the flow within the main channel is fast and deep, while the flow over the flood plain is relatively shallow and slow. The deeper flow in the channel has a greater capacity to transport sediment, producing higher sediment concentrations in the channel than over the flood plain (Pizzuto, 1987). At the interface between the channel and flood plain, differences in flow velocities and suspended sediment concentrations produce a transfer of momentum (and sediment) that is manifest by turbulent eddies (James, 1985). If there is no component of flow perpendicular to the channel, then turbulent diffusion is the dominant mechanism transferring sediment from the higher concentrations within the channel toward the lower concentrations over the flood plain (Pizzuto, 1987). Because flow velocities decrease with distance across the flood plain, flood plain flow may become overloaded with sediment diffusing away from the channel such that some sediment is deposited. This results in an exponential decrease in grain size and sediment thickness with distance from the channel (Pizzuto, 1987).

In most circumstances, however, some component of flow perpendicular to the channel exists (James, 1985; Marriott, 1992, 1996). This leads to sediment transfer by convection and tends to dampen the exponential decline in grain size and thickness of the deposit (Marriott, 1992, 1996; Middlekoop and Asselman, 1998). Empirical observations of the lateral fining and thinning of overbank deposits (Stewart and LaMarche, 1967; Kesel et al., 1974; Nanson and Young, 1981; Hughes and Lewin, 1982; James, 1985; Pizzuto, 1987; Magilligan, 1992; Asselman and Middlekoop, 1995; Marriott, 1996; Walling et al., 1997; He and Walling, 1998; Middlekoop and Asselman, 1998) may lead to the assumption that turbulent diffusion is the dominant mechanism of sediment transfer across flood plains. Lateral decreases in grain size, however, are frequently observed to be less than model predictions (Pizzuto, 1987; Marriott, 1992; Simm, 1995). Pizzuto's (1987) model, for example, greatly underestimated the transport of sand away from the Brandywine Creek channel (Pennsylvania), a result he attributed to bedload transport and advective suspended sediment transport. The complicated topography and geometry of flood plains may produce irregular patterns of sedimentation that result from the complex combination of diffusion, convection, and variations in the time and depth of inundation (Asselman and Middlekoop, 1995). Recognizing that topographic complexity is a dominant control on inundation and overbank deposition, Nicholas and Walling (1997a,b) attempted to address weaknesses in earlier models by developing a numerical model that sacrificed the representation of process complexity to retain the detailed geometry of natural flood plains. Much work remains to further improve these modeling efforts, a task that is further complicated by particle aggregation and its potential to provide a mechanism for masking the lateral reduction of the size of deposited sediment (Nicholas and Walling, 1996).

Although few studies have investigated downstream trends in the grain-size characteristics of overbank deposits (Walling et al., 1997), the texture of flood plain sediments should be expected to reflect the grain-size composition of the suspended sediment load. For example, Walling and Moorehead (1989) have shown that downstream fining of the suspended sediment load reflects the preferential deposition of the coarser particles upstream. Nanson and Young (1981) attributed the downstream decrease in the grain size of overbank deposits with progressive sorting in association with downstream decreases in valley gradients.

It is well-established in the literature that a fining-upward sequence in overbank deposits would be typical in a stable system where the elevation of the flood plain slowly increased by vertical accretion and where lateral accretion dominates overall (Wolman and Leopold, 1957). However, this ideal situation can be very sensitive to historical changes in sediment sources, flood hydraulics, and channel/flood plain morphology. Larger flood magnitudes are capable of transporting coarser sediment in suspensionto higher surfaces and the development of meander belts conveys sand to downstream areas. Lateral channel migration may shift the locus of sand deposition to areas with finer deposits, producing a time-transgressive coarsening upward sequence.

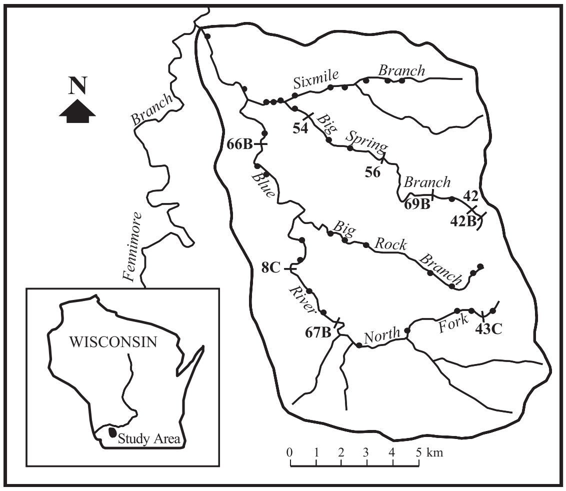

Fig. 1. Map of the Blue River watershed showing the locations of the flood plain transects (numbers). Sites used in the analysis of downstream trends in particle size are identified by dots.

3. Study area and methods

The Blue River watershed (208 km^2) is located in the southern part of the Driftless Area of SW Wisconsin (Fig. 1). The watershed is highly dissected with steep hillslopes and local relief ranging from 30 to 120 m. This area is underlain by Ordovician and Cambrian sedimentary units that dip to the SW, producing a generally E–W orientation in the surface exposure of resistant dolomites and erodible sandstones and shales (Lecce, 1997b). Dolomites and some sandstone underlie uplands and mid-basin reaches, while friable Cambrian sandstones are exposed in the lower main valley and northern tributaries. About 1–2 m of Pleistocene loess caps the uplands.

Settlement and agricultural development of the region in the 1830s led to substantial increases in agricultural runoff and erosion. Presettlement flood plain surfaces with well-developed Mollisols were buried by sediments from increasingly frequent floods (Lecce, 1993, 1997a,b; Lecce and Pavlowsky, 1997). These historical overbank deposits are dominated by fine-grained material derived from the reworking of the loess-mantled uplands and sand from exposed sandstone bedrock. Increases in the magnitude and frequency of flooding led to lateral channel migration and the development of meander belts in headwater and mid-basin reaches (for detailed description of the evolution of the Blue River floodplain, see Lecce, 1997a). The lower main valleys (site 54 and 66B), however, contain meandering channels that are relatively stable and have experienced high rates of sedimentation (Lecce, 1997a,b; Lecce and Pavlowsky, 2001). With the exception of the straight channel section at site 42B, the study reaches contain channels with both straight and meandering sections that wander from valley side to valley side. These reaches contain a variety of topographic features typical of Driftless Area floodplains: abandoned channels, small swales and depressions, minor natural levees, and a few drainage ditches. Land use on the floodplains was mainly pasture, although some of the larger valley bottoms are usually planted in corn. The narrow, isolated valleys tend to be left wooded or in heavy brush. Overall, about 40% of the watershed is currently wooded, while the remaining 60% of the watershed is devoted to pasture and strip-cropping of corn and alfalfa. Historical alluvial deposits are contaminated to varying degrees by trace metals associated with the mining of Pb, Zn, and Cu in the late 19th and early twentieth centuries (Lecce and Pavlowsky, 1997, 2001). Table 1 summarizes characteristics of the floodplain and channel at each site.

We collected about 800 sediment samples at nine cross-valley transects to examine vertical and lateral changes in particle size along the Big Spring Branch and Blue River. Historical overbank deposits were sampled from pits dug at 7 to 12 locations from one side of the channel across each flood plain to the valley wall. Depth-integrated samples were collected every 5 cm down to the surface of the presettlement soil. Where the presettlement soil was too deep to sample by hand, we sampled in 10-cm intervals using a 2-cm diameter Oakfield soil probe or a 5-cm diameter AMS split core sampler. Downstream trends in particle size were examined using composite samples collected by Lecce (1993) from overbank deposits in near-channel cores or bank exposures. The grain-size composition of the deposits at each site was represented using a weighted mean value for the entire thickness of the historical alluvium sampled in the core or bank exposure. Percentages of sand, silt, and clay were determined using standard hydrometer methods.

4. Results and discussion

4.1. Historical variations of grain size

The texture of the presettlement soil typically fines upward and near the surface reflects the long-term grain-size distribution of the presettlement flood plain (Lecce, 1993). Lecce (1993) showed that the lower portions of the overlying historical sediments (mean = 7.1% sand, $n = 11$) are consistently finer than the A horizon of the presettlement soil (mean = 24.3% sand). This may suggest that sandy in-channel sediments were a more important source to the presettlement flood plain than loess, and that the early historical floods were dominated by the accelerated erosion of loess-derived topsoil from newly cultivated fields (Lecce, 1993, p. 145).

Table 1
Site characteristics

Site	Drainage area (km^2)	Valley slope (m/m)	Valley width (m)	Maximum flood plain relief (m)	Lateral channel activity	Flood plain vegetation
Blue River						
43C	5.0	0.015	90	0.28	active	pasture
67B	61.5	0.005	60	0.14	active	wooded and pasture
8C	79.5	0.003	90	0.58	active	pasture
66B	128	0.001	360	1.50	stable	pasture and crops
Big Spring Branch						
42B	2.0	0.012	65	0.39	active	pasture
42	2.4	0.014	70	0.20	active	pasture
69B	4.0	0.007	100	1.06	active	pasture
56	19.2	0.013	80	0.45	active	crops and dense brush
54	30.8	0.004	235	0.74	semiactive	pasture

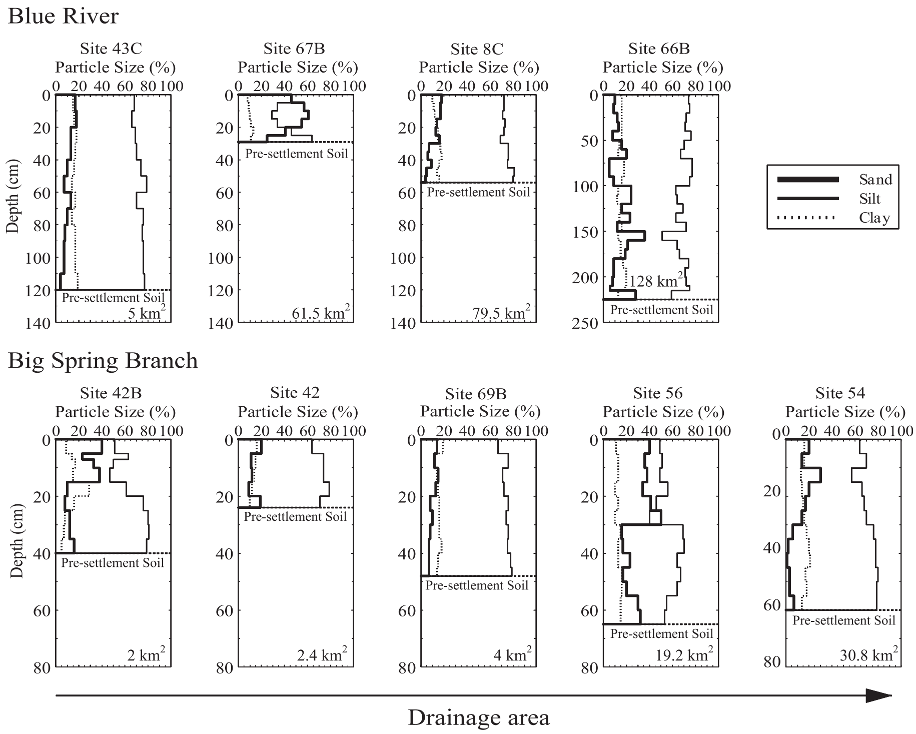

Fig. 2. Percentages of sand, silt, and clay in near-channel cores. Although these data only show vertical trends for near-channel cores, the coarsening-upward was also observed in almost every core across each flood plain transect.

Although most models of flood plain sedimentation suggest a fining-upward sequence for overbank deposits, Fig. 2 shows that throughout the historical period flood plain deposits have become increasingly rich in sand. Excluding site 66B, sediment at the surface of the other eight sites has an average of 12% more sand than in the early historical alluvium. The flood plain at site 66B received little or no historical sedimentation until after 1920 (Lecce and Pavlowsky, 2001); therefore, the alluvium directly overlying the presettlement soil was not deposited during the early part of the historical period. The rate of post-1920 sedimentation has been higher at site 66B than the other sites because the wide valley, low valley and channel gradient, and low stream power favor deposition (Lecce, 1997a,b; Lecce and Pavlowsky, 1997, 2001).

The coarsening-upward sequence in the historical alluvium has been described in earlier Driftless Area studies (e.g., Knox, 1987a; Magilligan, 1992) and could be explained by several possible mechanisms (Lecce, 1993). First, historical changes in land use practices increased surface runoff, producing larger flood discharges that were capable of suspending and transporting coarser sediments. Second, lateral channel migration led to the development of historical meander belts in headwater and mid-basin locations (Lecce, 1997a,b). By reducing flood wave attenuation, the meander belts further increased the magnitude and frequency of flooding and the transport of coarse sediment to downstream areas (Woltemade, 1994; Woltemade and Potter, 1994). The meander belts also have larger cross sections that are capable of containing large magnitude flows (Lecce, 1997a). When floods are large enough to spread overbank, they are likely to transport more sand in suspension than during the early historical period. Third, hillslope erosion in the steeper headwaters has removed much of the relatively thin loess cap. This has exposed sandier parent materials and depleted the source of silt (Lecce, 1993). Fourth, Pb and Zn mining may have increased the availability of sand derived from mine tailings during the peak of mining activities between 1900 and 1920. In addition to fine particles, the tailing contained some dolomitic sand and sand-sized ore particles. The coarsening-upward trend in the Blue River watershed is generally more dramatic than that described by Magilligan (1992) in the larger, more gently sloping Galena River watershed.

Mining activities, meander belt development, and larger flood flows are all likely to have contributed to at least some of the coarsening-upward trend observed in the historical alluvium. Sand supplied by mining activities and larger floods, however, cannot explain the existence of the coarsest sediments on the current flood plain surface. Most of the mining ended in 1920, and no significant mine tailings remain in the basin (Lecce and Pavlowsky, 1997, 2001). Surface Zn concentrations are well below historical maximums (except at site 42) associated with peak mining activities (Lecce and Pavlowsky, 2001). Moreover, several studies have shown that flood magnitudes in similar Driftless Area watersheds have decreased since 1940 (Potter, 1991; Magilligan, 1992; Knox, 1999, 2001). Thus, the erosion of the loess-dominated soils and the exposure of sandier parent materials for erosion are likely to be primarily responsible for the continued coarsening upward trend observed in the most recent historical deposits. This interpretation is supported by the findings of Magilligan (1992), who concluded that because flood magnitude and frequency have not continued to increase up to the present, the coarsening-upward trend in the nearby Galena River basin is explained by historical changes in source material.

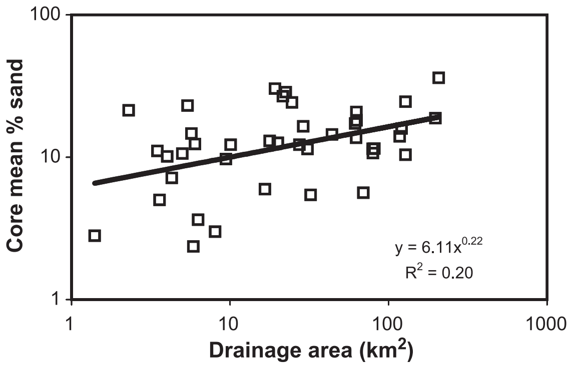

Fig. 3. Downstream changes in grain size for the entire watershed. Data include depth-integrated composite samples of the entire thickness of the historical alluvium from bank exposures (data from Lecce, 1993).

4.2. Downstream variations of grain size

Fig. 3 shows that downstream changes in the mean sand percentage in the historical alluvium for all sites are quite variable, but generally increase downstream. Some of the variability, as pointed out by Walling et al. (1997), may be due to the lack of consistency in channel and flood plain characteristics between sites and the use of near-channel sampling sites (i.e., because grain size is most variable near the channel). When the data were partitioned by reach (Fig. 4), the mean sand percentage increased slightly downstream along the Big Rock Branch and along the north fork of the Blue River. No significant downstream trends are evident in the Sixmile Branch or the Big Spring Branch, although sediments along these reaches tend to be coarser than the southern part of the watershed (particularly in the headwaters).

Nevertheless, the overall trend in the Blue River watershed is characterized by downstream coarsening. Higher sand percentages in the downstream reaches and in the north reflect changes in sediment sources and sediment transport. The north-flowing Blue River has incised into the southwest-dipping strata to expose Cambrian sandstones in the lower portion of its valley. These friable sandstones are also exposed in the northern part of the watershed (e.g., the Sixmile Branch), where greater dissection and steeper slopes have increased the erosion of the loess cap. Many of these soils have been mapped as moderately to severely eroded (Klingelhoets, 1962). Along the Sixmile Branch in particular, sediment sources tend to be dominated by quartz sand from Cambrian sandstones. Some of the sand along the other three reaches is probably derived from tailings materials associated with Pb and Zn mines operated between 1900 and 1920 (Lecce and Pavlowsky, 1997, 2001).

4.3. Lateral variations of grain size

Fig. 5 shows that, overall, the highest sand percentages occur near the channel and decline with increasing distance across the flood plain, a finding that generally is consistent with results from previous studies (Pizzuto, 1987; Marriott, 1992, 1996; Assel-

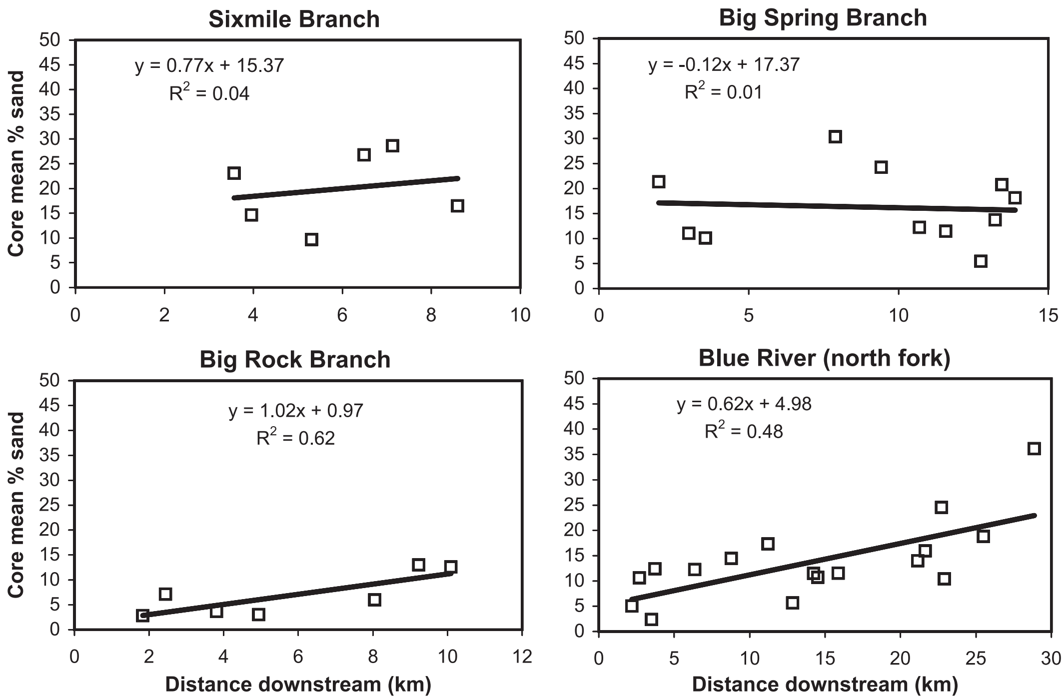

Fig. 4. Downstream changes in grain size for each reach. Data include depth-integrated composite samples of the entire thickness of the historical alluvium from bank exposures (data from Lecce, 1993).

man and Middlekoop, 1995; He and Walling, 1997, 1998). *R*-squared values associated with exponential functions fit to the data are relatively low, but within the range of values found by He and Walling (1997, 1998), suggesting that factors other than distance from the channel are important controls on lateral variations

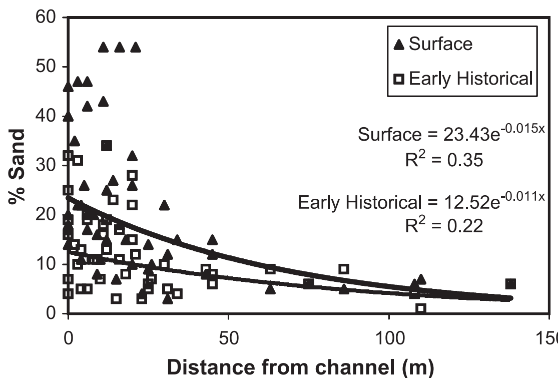

Fig. 5. Lateral changes in grain size for the entire watershed. Surface samples represent the upper 5–10 cm of each core. Early historical samples were collected from the first 2–10 cm of historical alluvium directly overlying the presettlement soil.

of grain size. Similar to Marriott (1992, 1996), Fig. 5 (using data from all sites) shows an abrupt decrease in sand at a distance of about 20 m from the channel.

Inspection of individual transects (Fig. 6), however, shows that sand usually decreases gradually as an exponential function of distance from the channel. Only two sites (42 and 67B) display higher sand percentages away from the channel. Both sites are located downstream from a meander bend where sediment transfer during overbank flows by convective processes is probably greater (James, 1985; Marriott, 1992, 1996). The area around site 42 was also intensively mined between 1900 and 1920 (Lecce and Pavlowsky, 2001). Coarser tailing materials may have been transported down a gently sloping colluvial surface to the edge of the flood plain. Even if the two distal samples at site 42 are eliminated, however, sand still does not decrease with distance from the channel. Overbank sediments at site 67B are considerably coarser than those observed at the other sites. This may be due to high stream power and a narrow valley that increases the transport of sand through the reach. Sand washed in from the steep sandstone bluffs may

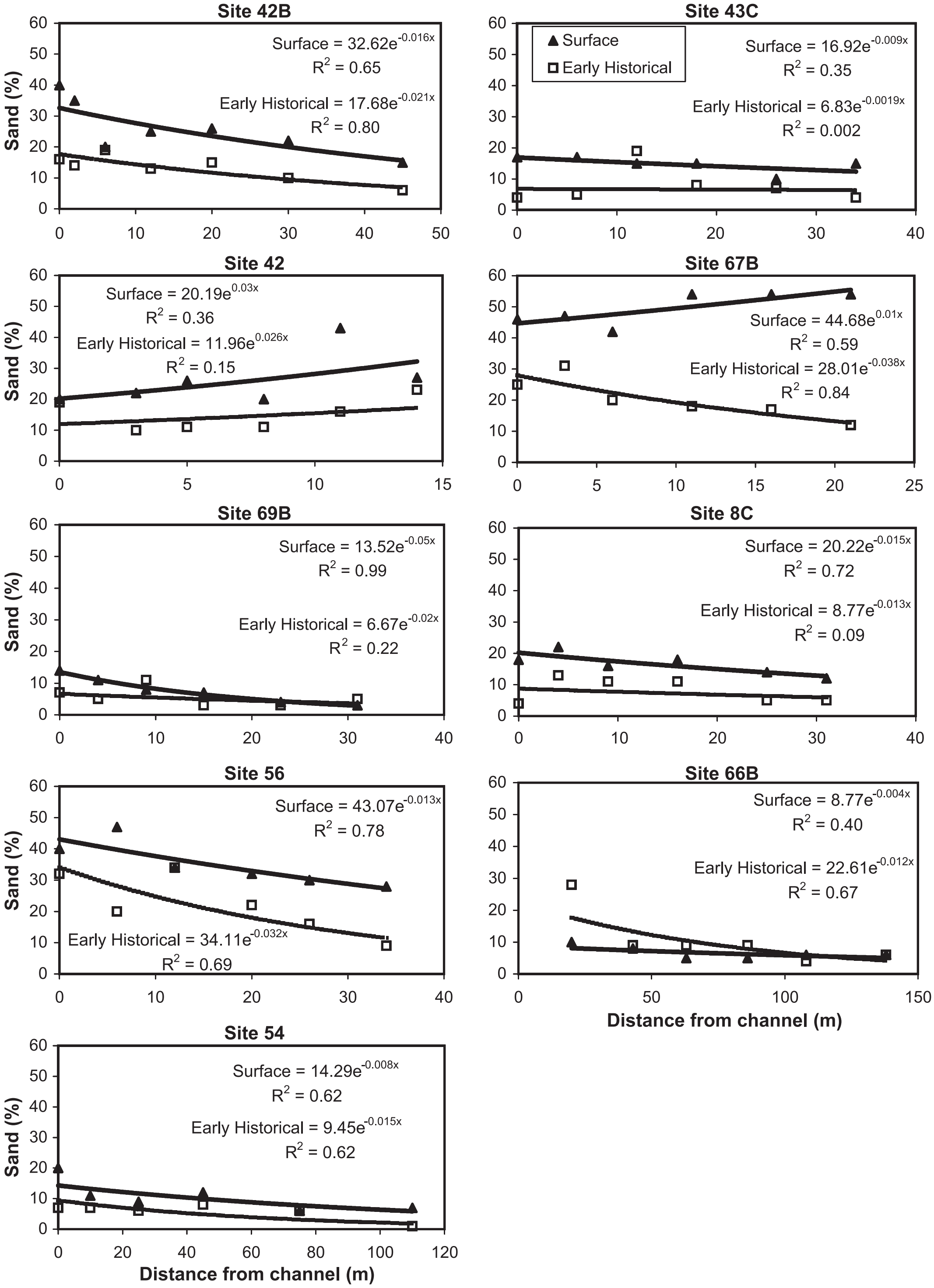

Fig. 6. Lateral changes in grain size at each cross-valley transect. Surface samples represent the upper 5–10 cm of each core. Early historical samples were collected from the first 2–10 cm of historical alluvium directly overlying the presettlement soil.

also explain some of the coarsening of the surface sediments away from the channel.

Several studies (Pizzuto, 1987; Marriott, 1992, 1996) have shown that sand is transported farther across the flood plain than predicted by numerical models of overbank deposition on flood plains, particularly those that rely on turbulent diffusion as the dominant mechanism of sediment transfer. In the Blue River watershed, sand is present throughout the transects, suggesting that convective transport is also an important process influencing overbank deposition. Neither grain size nor rates of deposition (see Lecce and Pavlowsky, 2001) consistently demonstrate the strong exponential decline with distance from the main channel expected where turbulent diffusion is dominant. This should not be unanticipated because the diffusion analogy requires that flow is steady, uniform, and parallel to a straight channel in a straight valley with relatively flat flood plains. Natural channels and flood plains, however, rarely exhibit such simplicity. Consequently, models of overbank deposition will likely have to consider flood-plain topography and transport by convection if they are to produce accurate predictions.

In addition to sediment transport by both diffusion and convection, lateral changes in particle size are influenced by topographic complexity on the flood plain that produces spatial variations in inundation times (Asselman and Middlekoop, 1995; Nicholas and Walling, 1997a,b). This is complicated in the Blue River watershed because both flood magnitudes and flood plain topography have changed historically. Throughout the Driftless Area, valley floor topography has changed as historical sedimentation buried multiple presettlement surfaces, producing more uniform, higher flood plain surfaces (Knox, 1987b; Lecce and Pavlowsky, 2001). The reduction of flood plain topography influences the depth and duration of flood flows. Although we lack three-dimensional representations of flood-plain topography that Nicholas and Walling (1997a,b) used to help explain grain-size and sedimentation patterns along the River Culm (UK), the relief displayed in their topographic maps are comparable to our values for flood-plain relief in Table 1. We presume, therefore, that even small-scale variations in topography may have influenced flow directions and velocities that complicate lateral patterns expected from diffusion-based analogies. The differences between these sites reflect the combined effects of sediment source composition; the flood magnitudes responsible for deposition; channel configuration; meander belt geometry; particle aggregation; and the width, topography, and roughness of the flood plain (Nicholas and Walling, 1997a,b; He and Walling, 1998).

5. Conclusion

The grain-size composition of overbank sediments deposited on flood plains in the Blue River watershed demonstrates significant spatial variability. Vertical and downstream variations of grain size are influenced by the sand content of source materials, which vary both spatially and temporally. The coarsening-upward sequence observed in the historical overbank alluvium is attributed primarily to the erosion of loess-capped soils and the progressive exposure, erosion, and transport of sandier parent materials. The proportion of sand in overbank deposits increases modestly downstream in two of the reaches examined because source materials become sandier lower in the stratigraphic sequence. These materials have greater exposure in the northern part of the watershed and in larger valleys downstream. The degree of dissection is also greater in the north, which has led to the removal of the loess cap and exposure of sandier parent materials. Consequently, the two northernmost reaches display no significant coarsening or fining, but are coarser overall.

Cross-valley transects show that sand is present throughout the transects, but usually decreases gradually as an exponential function of distance from the channel. Despite the modest degree of fining, lateral patterns are generally consistent with sediment transport by diffusion (e.g., Pizzuto, 1987). Convective sediment transport may be important in explaining lateral coarsening at two cross-valley transects with flow components perpendicular to the channel and may explain the presence of sand throughout the other transects. However, many flood plain transects are characterized by a spatially and temporally complex arrangement of factors that also influence the grain-size characteristics of overbank deposits. These factors include irregular flood plain topography, which has been shown to produce spatial and temporal variations in water depths, velocities, and inundation times (e.g., Nicholas and Walling, 1997a); sediment source composition; the flood magnitudes responsible for deposition; channel configuration; meander belt geometry; particle aggregation; and the width, topography, and roughness of the flood plain.

Field information documenting the grain-size characteristics of flood plain deposits is necessary for improving our understanding of the development and evolution of flood plains, explaining the distribution and fate of sediment-associated contaminants, and for improving numerical models of flood plain processes through calibration and validation. The results of this study provide a useful addition to this work, but suggest that there is still a need for more information on the grain-size characteristics of overbank deposits.

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