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Long- and short-term episodic storage and removal of sediment in watersheds of southwestern Wisconsin and northwestern Illinois

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ABSTRACT Average annual rates of erosion and sedimentation commonly are used to evaluate long-term movement and storage of sediment in watersheds. Use of average rates often poorly represent actual rates because changing environmental factors may dramatically alter surface runoff, flooding, and channel stability. Dating of historical, Holocene (post-glacial), and Late-Wisconsin (late glacial) hillslope and flood plain sediments in southwestern Wisconsin and northwestern Illinois indicates that rates of sediment erosion, storage, and transportation fluctuate episodically due to changing watershed environmental conditions. In the humid climate Upper Mississippi Valley, periods of sediment storage tend to be relatively slow and progressive whereas removal of sediment from storage tends to be episodic with short periods of dramatically high rates separating longer periods of relatively low rates. Historical erosion and sedimentation rates usually poorly represent long-term natural rates because of anthropogenic disturbance of land cover. The replacement of prairie and forest by agricultural land use in the Upper Mississippi Valley resulted in accelerated flood plain sedimentation that averages 30-50 cm deep on tributary flood plains and as much as 3-4 m deep on flood plains in lower reaches of main valleys near the Mississippi River. The use of lead and zinc trace metals associated with historical mining shows that decadal-scale average historical rates of overbank flood plain sedimentation range from about 0.3 cm year^{-1} to 4.0-5.0 cm year^{-1} and greatly exceed the average presettlement post-glacial flood plain vertical accretion rate of 0.02 cm year^{-1} that was determined for radiocarbon dated alluvial deposits.

INTRODUCTION

The general objective of this paper is to illustrate how long- and short-term changes in rates and types of geomorphic processes influence the linkages, pathways, and time constants that separate erosion of sediment at its source and its ultimate removal from watersheds. To exemplify the character of sediment mobility and storage I use environmental modifications caused by long-term climatic change during the past 20 000 years and short-term variations in land use during the past 175 years. The study area is an unglaciated region in southwestern Wisconsin and northwestern Illinois where nearly flat-lying limestone, dolomite, and sandstone formations of middle Ordovician age are overlain by weathered clayey residuum that is in turn overlain by loess that averages 65-70% silt. Most of the landscape is in moderate to steep slopes and local relief averages between 50 and 120 m km^{-2}. The time range of study is sufficient that environmental conditions have shifted from tundra through boreal forest during the late-Wisconsin, to a mosaic of prairie and deciduous forest during the Holocene, and finally to a mosaic of pasture land, forest, and agricultural fields during the last 175 years of European settlement.

A long-standing principal difficulty in understanding watershed sediment yields has been limited empirical documentation that describes the sensitivity of sediment storage at various time scales and geographic locations within drainage systems (e.g., hillslopes, alluvial fans, flood plains, and channel systems). Existing knowledge of the erosion, transportation, and deposition of sediment in watersheds largely is based upon data collected within the past 50 to 100 years (Meade, 1988). Recent reviews of the literature on watershed sediment delivery ratios indicate considerable diversity between basins of comparable size but influenced by differing environmental conditions (Meade, 1982, 1983; Walling, 1983; Hadley, 1986). The tendency for net storage in modern drainage systems implies a degree of disequilibrium in the erosional and depositional system (Wolman (1977). Trimble and Lund (1982), for example, note that the often implied assumption of a "steady state" between upland erosion and downstream sediment yield rarely, if ever, exists because of sediment storage. Furthermore, the effectiveness to erode, transport, and store sediment in watersheds is subject to considerable spatial variation within drainage hierarchies and the zone of maximum effectiveness may shift with changing processes over time (Graf, 1982; Hereford, 1986).

LONG-TERM CHANGE IN SEDIMENT DELIVERY

Late Pleistocene loess deposits can provide a basis for estimating long-term mobility and storage of sediment in watersheds because it may be possible to determine the original thickness of a depositional unit and well as the time bounds of deposition. A detailed drilling program was undertaken to map the thickness of various late Pleistocene and Holocene stratigraphic units in a 0.4 km^2 southwestern Wisconsin watershed. Theodolite surveys were used to establish vertical and horizontal control for 34 drill sites and underlying stratigraphic units. The survey control permitted the calculation of sediment volumes represented between stratigraphic boundaries. Because of its wide distribution, mapability, and time control, the Peoria loess, a Late-Wisconsin age silt deposited between c. 20 000 and 12 000 years B.P., was selected for detailed assessment of long-term stability.

About 4 m thickness of Peoria loess was deposited on the watershed when during much of the time glacial ice covered areas to the east, north, and west of southwestern Wisconsin. The presence of ice-wedge casts, solifluction deposits, talus block streams, and other frost related features indicate that periglacial climatic conditions prevailed at least during some of this time interval (Péwé, 1983). Mass wasting then became a dominant geomorphic process in these small headwater tributaries as indicated by remaining extensive basal hillslope colluvial deposits that are dominated by silt but include large angular boulders of dolomite.

The relative thickness of the Peoria loess today rapidly thins with increasing slope angle and distance from the drainage divide (Fig. 1). Valley side slopes were active zones of sediment transport during Late-Wisconsin periglacial mass wasting environments. These slopes have only a few tens of centimeters of silt on them today and probably had little more anytime during the

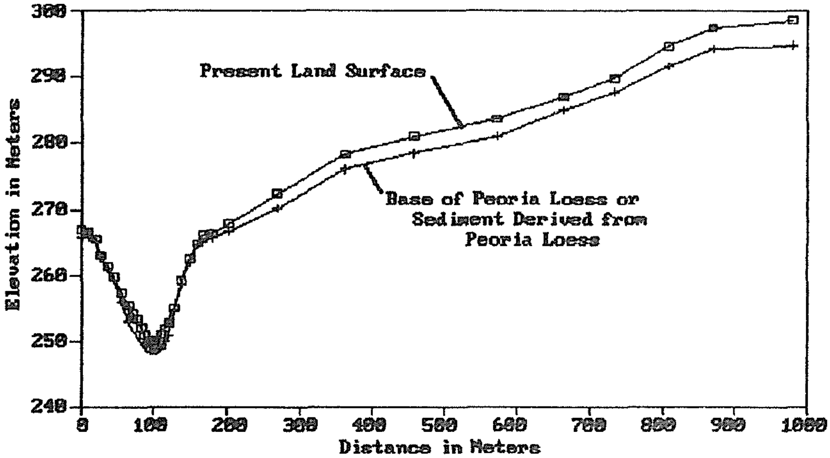

Fig. 1 Loess thickness decreases with increasing distance from the drainage divide and with increasing slope angle. Transect along tributary drainage divides of upper Richman Tributary, Dietzel Site, Grant County, Wisconsin.

Late-Wisconsin even during the period of maximum loess fall. The basal Peoria loess on the shoulders of upland interfluves is often interstratified with pre-Peoria pedisediment and red clay residuum indicating that hillslope stripping was active during the period of loess fall.

Comparison of the volume of sediment associated with the estimated original loess fall of 4 m against the present-day volume of remaining loess indicates the amount of erosion during the past 20 000 years. The comparison shows that 628 000 m^3 of loess were eroded from the upland landscape of this 0.4 km^2 watershed during the past 20 000 years, representing an average annual loss of about 112 t $km^{-2}year^{-1}$. The extensive remnants of colluvial benches along the basal hillslopes permit reconstruction of the volume of colluvial sediment that was stored on the lower hillslopes and valley floor positions (Fig. 2). Prior to Holocene fluvial erosion, these colluvial deposits contained about 447 000 m^3 of sediment. Radiocarbon dates of 20 270 ±650 years B.P. (ISGS 558) for charcoal at the base of the colluvium, and of 12 510 ±120 years B.P. (BETA 8203) for wood from alluvial fill associated with alluvium that is inset against the base of the colluvial sediment is evidence that most of the colluvium accumulated between these bracketing dates. Therefore, the annual rate of accumulation between 20 000 and 12 000 years B.P. was about 200 t $km^{-2}year^{-1}$. If it is assumed that most of the hillslope erosion of the Peoria loess occurred between about 20 000 and 12 000 years ago, then the average annual loss is about 280 t $km^{-2}year^{-1}$. The difference between the erosion and storage rates implies that a minimum of about 70% of the eroded loess was initially stored in the basal hillslope colluvium. However, it is clear that some of the missing upland loess has been eroded during Holocene and modern times. Hence, the quantity of sediment represented in the colluvial terraces probably represents considerably more than 70% of the loess that was eroded between 20 000 and 12 000 years B.P., suggesting that nearly all of the eroded sediment in headwater tributaries was being stored within those tributary systems as colluvium.

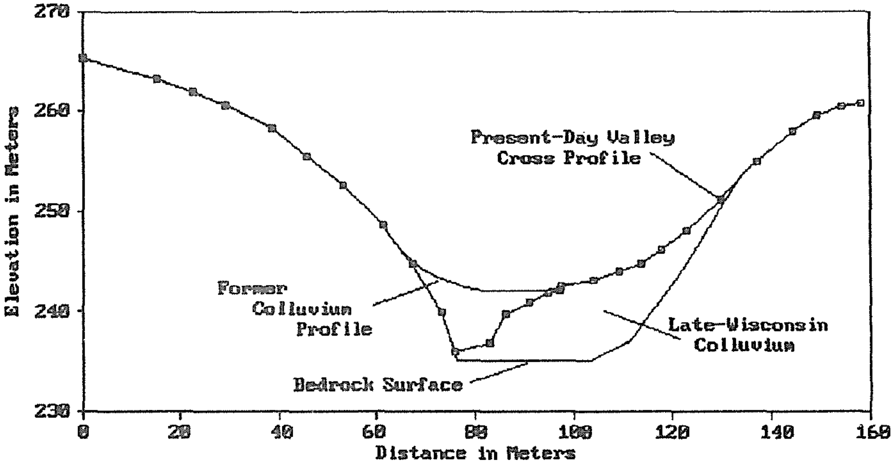

Fig. 2 Magnitudes of hillslope mass wasting between about 20 000 and 12 000 years B.P. were determined from reconstructed cross profiles for valley floor colluvium of that age. Middle Richman Tributary, Grant County, Wisconsin.

When environmental conditions ameliorated and shifted toward climates of the Holocene (post-glacial) overland flow and fluvial processes became dominant. The massive colluvial deposits were quickly incised leading to flushing of vast quantities of stored sediment. Much of the late Pleistocene colluvium that was progressively stored in the drainage system between 20 000 and 12 000 years B.P. was reworked and transported within the next few millennia. Watershed sediment yields would have been extremely high during this period of erosion, but little of the sediment was coming from upland hillslopes.

In conclusion, under long-term time scales climatic changes may be sufficiently great that it completely alters the dominant type of geomorphic process in a watershed. Here, the mass wasting conditions of Late-Wisconsin cold climates resulted in massive sediment storage on basal hillslopes and valley floors of small headwater tributaries. When fluvial processes became dominant under the more warm and moist conditions of the Holocene (post-glacial), much of the sediment that had accumulated gradually over several thousand years was eroded from the system within a relatively brief period.

SHORT-TERM CHANGE IN SEDIMENT DELIVERY

Short-term changes in land use can result in changes in sediment delivery comparable to those produced by long-term natural environmental changes. I will use an example of responses to agricultural land use in southwestern Wisconsin to illustrate the relationship. The pre-nineteenth-century landscape of southwestern Wisconsin was a mosaic of prairie and forest (Trewartha, 1940), but the introduction of agriculture after about 1820 was primarily responsible for massive alteration of the vegetation cover. The replacement of prairie and forest with cropland of corn, oats, wheat, and hay, and grazing of both prairie and forest lands resulted in a dramatic increase in surface runoff, flooding, and soil erosion. Present-day flood peak runoff in tributary watersheds exceeds natural presettlement flood peaks by a factor of 2-3 times, but the differential probably was 4-5 time greater during a period of poor land use practices between the 1870s and the 1940s (Knox, 1977; 1987).

The accelerated hillslope erosion associated with conversion of the natural land cover to agricultural land use was soon followed by accelerated flood plain sedimentation in response to increased magnitudes and frequencies of floods (Knox, 1987; Trimble, 1983). The present-day accumulated depth of overbank flood plain sedimentation averages between 50-100 cm depth on tributaries draining less than 25 km^2 and between 1-2 m depth on main valleys draining 25-300 km^2. On large valleys with low gradients where the controlling baselevel of the Mississippi River is approached, post-1820 overbank sedimentation averages between 3.0-3.5 m depth.

Since the 1950s land use conservation practices have greatly reduced erosion rates on upland hillslopes and, in turn, rates of sedimentation on flood plains. However, flood plain responses to improved land use differ between tributary and lower main valley sites. The development of incipient soils in historical alluvium on tributary flood plains is evidence that little overbank sedimentation has occurred there for some time, whereas overbank sedimentation continues to occur on the downstream lower main valleys, albeit at a greatly reduced rate.

The historical evolution of differing overbank sedimentation rates on southwestern Wisconsin flood plains is documented by trace metal concentrations of lead and zinc adsorbed onto silt and clay particles in the fluvial sediment (Knox, 1987). A once extensive lead and zinc mining industry occurred throughout the region. Atomic absorption spectrophotometry of sediment cores from flood plains downvalley of former mining operations provides a measure of vertical variations in the concentration of lead and zinc concentrations. Because the mining history is well documented and because lead and zinc remain relatively stable in the vertical sediment profile after deposition, fluctuations in vertical concentrations of these metals can be used as an indicator of relative ages of sedimentary horizons within the vertical profile. Figure 3 presents an example of this dating method. The dating of specific sedimentary horizons, in turn, permits establishment of a chronology of changing sedimentation rates (Fig. 4). The step-function variation in sedimentation rates for the three sites represented in Figure 4 reflects the locations of dated horizons.

Figure 4 illustrates how the magnitude of the sedimentation rate as well as the temporal variation of the rate of overbank sedimentation varies with increasing drainage area for three sites in the same southwestern Wisconsin watershed. Several important patterns should be noted concerning differences and similarities among the three sites. First, observe that overbank sedimentation stopped after about 1910 in the headwater tributary of 0.07 km^2. The cessation occurred because a gully formed in the tributary and led to an enlarged channel capacity that could convey all of the incoming surface runoff. Gully development in headwater tributaries was very common in this region around the turn of the century Trowbridge and Shaw (1916, p. 156). The very high overbank sedimentation rates that occurred around 1900-1925 at the Weber Site 1 (drainage area 91 km^2) and at the Hinderman Site 1 (drainage area

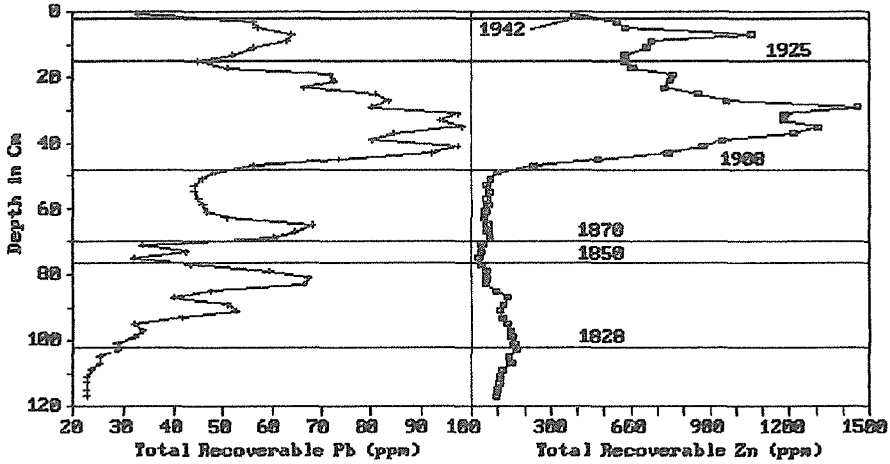

Fig. 3 Concentration of lead and zinc trace metals in overbank flood plain sediment along lower Blockhouse Creek, Weber Site 1, Grant County, Wisconsin. The years for specific horizons correspond with beginning or ending dates of mining activity in the upstream watershed.

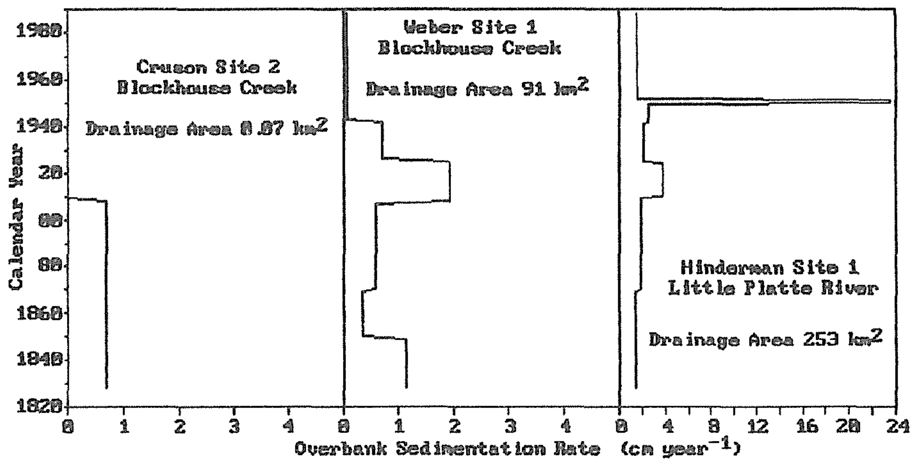

Fig. 4 Use of trace metals for dating sedimentary horizons permits reconstruction of historical variations in flood plain sedimentation rates as well as how those rates have varied temporally in various parts of the drainage system. The large spike for the Hinderman Site resulted from three extremely large floods that occurred in 1951 and 1952.

253 km^2) reflect the prominence of gully activity at that time as well as extremely poor land use practices then.

The reduction in rates of overbank sedimentation after about 1940 at the Weber Site and after about 1950 at the Hinderman Site mainly reflects an improvement in land use practices. The reduction is much greater for the large tributary Weber Site than for the downstream main valley Hinderman Site because enlarged capacities for flood channels developed in the tributary reaches following gullying and intensified lateral channel migration (Knox, 1987).

The enlarged channels now contain most floods that once overflowed stream banks, and because these channels perform a "flume-like" function with relatively little hydraulic roughness compared to that experienced when shallow flood waters are spread across wide flood plains, the floods are quickly routed downstream with considerable velocity and erosive force (Knox, 1987, p. 232-234). The geographic location of the accelerated bank erosion appears to be migrating downstream as a positive feedback effect, but it has not yet reached the more downstream locations, as represented by the Hinderman Site (drainage area 253 km^2). Nevertheless, the containment and fast routing of flood waters in headwater channels appears to explain in large part the continued relatively high overbank sedimentation rates on the main valley flood plains.

In conclusion, initial changes in overbank sedimentation rates caused by changes in the balance between rainfall and runoff were recorded nearly simultaneously throughout the watershed system, but changes in overbank sedimentation rates caused by changes in the capacity and hydraulic resistance of channels have produced a short-term tendency for overbank sedimentation rates between tributaries and main valley sites to be out-of-phase. The short-term average historical rates of overbank sedimentation, that have frequently reached 2-4 cm $year^{-1}$, greatly exceed natural presettlement rates of overbank sedimentation which average about 0.02 cm $year^{-1}$ (Knox, 1985). The large discrepancy between historical rates and natural presettlement rates as well as the extreme range of variation in historical overbank sedimentation rates shows that sedimentation data based on modern short-term monitoring often poorly reflect the long-term mobility and storage of sediment in watersheds.

SUMMARY

The mobility and storage of sediment in watersheds is an episodic process at nearly all time scales. Gradual accumulation of sediment often is followed by relatively abrupt erosion and transportation of that sediment. The sensitivity of a given sector of a drainage system to erode, transport, or store sediment depends strongly on prevailing environmental conditions. Watershed sediment yield responses to external environmental forcing factors often trigger indirect feedback adjustments that may continue long after the initial forcing event has passed. Rates for mobility and storage of sediment measured during the period of instrumental records normally very poorly represent long-term conditions.

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