The Fate of Eroded Soil: Sediment Sinks and Sediment Budgets of Agrarian Landscapes in Southern Minnesota, 1851–1988

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The fate of soil particles eroded from a hillslope is of interest to many sciences, geography included. The displaced particle changes the soil from which it has been removed, the water that transports it, and the soil upon which it is redeposited. The geomorphologist is of course interested in each of these processes and their adjustments over time to change on the earth's surface. The hydrologist is interested in sediment flux and its effects on infiltration, runoff, water quality, and channel flow. The soil scientist is interested in particle displacement, especially when accelerated by human activity, and its effects on crop productivity. Underlying each of these perspectives is the need for a better understanding of the complexity of fluvial systems. Equally pressing is the need to contain the costs of eroded soil which run annually in the billions of dollars in the United States alone (Steiner 1990).

This paper examines the fate of eroded soil by tracing the distribution of eroded sediment and constructing the sediment budgets of three medium-size drainage basins in southern Minnesota (Figure 1). These sediment budgets offer a snapshot of watershed sediment after 137 years of European settlement and just before the large magnitude floods in the summer of 1993. Like other sorts of budgets, sediment budgets are a means of accounting. In this case, they measure the sediment eroded in, stored in, and delivered from watersheds, all of which is fundamental for and central to geomorphology (Sutherland and Bryan 1991; Phillips 1991). This study, accordingly, analyzes the several geomorphic sites in which sediment is stored within watersheds, compares long-term sediment storage and erosion in watersheds, and compares the sediment budgets of drainage basins in different environments. This research attempts to improve our understanding of sediment sinks and flux, of the dynamic resources of drainage basins, and of what has been called the "sediment delivery problem" (Walling 1983; 1988), that is, the enigma of where soil goes between particle detachment and transport out of a drainage basin (Wolman 1977; Phillips 1991). As numerous authors have attested, we know little of where sediment moves, how long it remains in a particular sink, or how it is stored within watersheds of different scales (Sutherland and Bryan 1991). Moreover, by refining our understanding of the environmental factors that control sediment in watersheds (Jansson 1988), we are better able to manage the many watersheds that are subject to rapid erosion and aggradation around the world.

The Problem of Sediment Sinks

Two separate but related lines of scientific inquiry form the background for this study: the first deals with accelerated soil erosion and valley aggradation and the second with sediment budgets. Much of the erosion and aggradation literature concentrates on two regions in the United States: the Driftless Area of Wisconsin and the Piedmont of the Southeast (Trimble 1985). Research in the Piedmont began as early as 1911 (Bennett 1939) and in the Driftless Area under the aegis of the Soil Conservation Service in the late 1930s (Knox 1987). Several scholars in this period (McKelvey 1939; Adams 1944; Happ 1944) studied valley sedimentation associated with human-induced erosion, and

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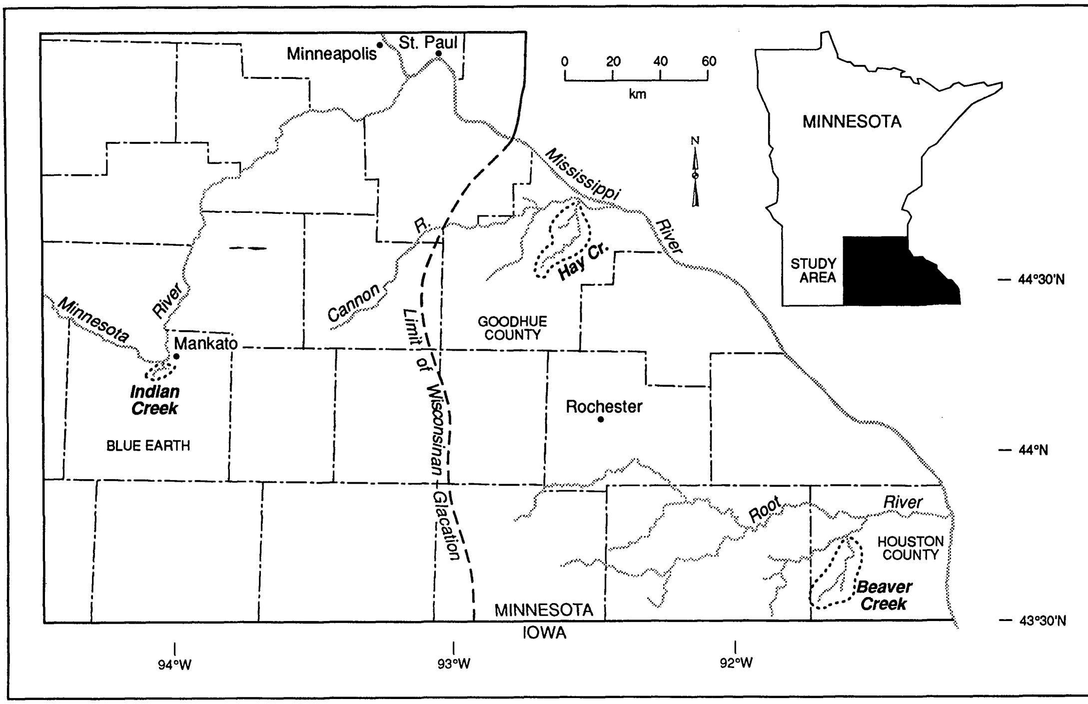

Figure 1. Watershed study areas in southern Minnesota.

these investigations served as baselines for ensuing research in the Driftless Area in the 1970s and 1980s (for example Knox 1972; 1977; 1987; Trimble 1976; 1983; Magilligan 1985). Elsewhere in the Upper Mississippi Valley, however, little research was conducted or published (Beach 1990).

The sediment budget literature is of more recent vintage. Sediment budgets as a way of accounting for watershed sediment production, storage, and delivery date only to the first "field-based fluvial sediment budget" research of Leopold et al. (1966; Sutherland and Bryan 1991). Sediment budget research did not begin in earnest until the late 1970s, when a group of studies on the Pacific Northwest emerged (Dietrich and Dunne 1978; Dietrich et al. 1981; Swanson et al. 1982). By the 1980s, however, research on sediment budgets and sediment storage was underway in the Upper Mississippi Valley (Trimble 1983), the Coastal Plain and Piedmont (Lowrance et al. 1985; Phillips 1986), the Colorado Plateau (Graf 1987), and many other parts of the world (Roberts and Church 1986; Sutherland and Bryan 1991). In their attempts to trace the spatial dimension of sediment storage and flux, scholars developed sediment budgets for many different scales of drainage basins from very small (<0.1 km^2 in Caine and Swanson 1989) to large (>1000 km^2 in Phillips 1991). Although research has concentrated on the smaller drainage basins (<10 km^2), it is equally important to understand sediment storage and flux in larger fluvial systems (Phillips 1991; Walling 1983; Jansson 1988).

Researchers have also pursued several lines of inquiry about human-induced erosion and valley alluviation in the United States. Some have measured sediment storage in a variety of sediment sinks (Costa 1975; Trimble 1983); others have estimated sedimentation rates (Knox 1987; Trimble and Lund 1982); one studied the distribution and processes of floodplain sediment storage (Magilligan 1985); others have studied sediment budgets and sediment delivery (Phillips 1986; 1991); and yet another assessed the reliability of county soil surveys for estimating sediment storage (Beach 1990).

More importantly, this work has tended to unite sediment budget and accelerated erosion research around the "sediment delivery problem" (coined by Walling 1983; and presented earlier by Wolman 1977). This "problem" refers to our uncertainty about the storage and flux of sediments (and their controlling processes) in the interval between soil detachment and sediment yield in watersheds. Research on valley alluviation has improved our understanding of the spatial and temporal dimensions of sediment by clarifying sediment storage, sedimentation rates, and sediment flux in drainage basins. Progress, however, has been slowed by the various typologies of geomorphic storage sites in use, which contribute to our vagary on the transmission of soil erosion, sediment storage, and delivery from smaller to larger drainage basins.

Another problem in the valley sedimentation literature, in particular, is the narrow scope of these investigations. A majority focuses on the Driftless Area of Wisconsin, the Piedmont Province, and the Pacific Northwest. Watersheds in these regions are highly disturbed by human activities, dramatically aggraded, and retain most of their historically eroded sediment in their basins (Meade et al. 1990). These disturbed watersheds are said to have low sediment delivery ratios (SDRs), that is, the ratio of sediment transported out of a basin (yield) to gross erosion. This is in profound contrast to the little disturbed (or undisturbed) drainage basins of glacially influenced regions in which Quaternary sediments have continued to degrade throughout Holocene times and thus have high SDRs (Church and Slaymaker 1989).

Although studies of human-induced erosion in the United States are abundant, few of these have emphasized the downstream and down-valley effects of eroded sediment. While we have been able to characterize erosion rates in different regions of the United States since the erosion surveys of the 1930s and 1940s, and more accurately since 1977 and the quinquennial National Resources Inventories, our knowledge of sediment storage and flux in drainage basins in different environments is meager. This is a serious oversight because off-site costs of soil erosion (e.g., sedimentation, increased flooding, and dredging) may be at least on a par with on-site costs (e.g., decreased fertility). Moreover, sediment from eroded soil is the largest source of water pollution by volume (Steiner 1990).

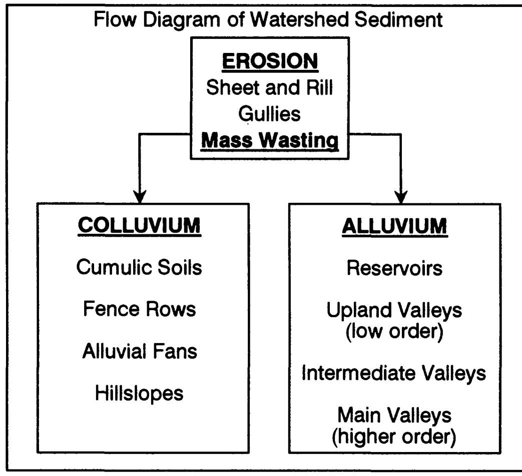

Figure 2. Flow diagram of erosion and sediment sinks. The diagram includes mass wasting for conceptual reasons.

This paper has two aims. First, it systematically quantifies the distribution of historical sediment storage in previously unstudied environments. Second, it constructs sediment budgets of erosion, storage, and delivery for medium-size watersheds and compares these budgets with others in nearby regions. To provide a systematic standard and to overcome the definitional problems of sediment sinks, sediment storage is aggregated by Strahler stream-order floodplains and in five geomorphic sinks: alluvial fans, fenceline berms, reservoirs, cumulic (over-thickened) soils, and hillslope colluvial deposits (Figure 2). To develop overall sediment budgets of storage, sediment production, and delivery, gross storage is then compared with estimates of gross soil erosion. Finally, the sediment budgets of these different environments are compared and environmental factors that have led to differences in sediment storage and delivery are identified.

Study Areas, Gradients, and Comparisons

Field sites are located in three medium-size watersheds in southern Minnesota (Figure 1).

Table 1. Summary of Watershed Characteristics.

	Watershed		
	Beaver	Hay	Indian
Area (km^2)	144	125	17
Order	Fifth	Fifth	Third
Soils	Loess	Loess, Till	Till, Lake Deposits
Steepness	High	Medium	Low
Erodibility	Highest	High	Moderate

Figure 3. Oblique photograph of a modern fourth-order valley reach of Beaver Creek, Minnesota.

These watersheds represent different environments, thus permitting an assessment of environmental effects on watershed sediment budgets with comparable land-use histories and, in two cases, comparable drainage areas (Table 1). Beaver watershed (Figure 3) is a fifth-order basin of 144 square kilometers (km^2); Hay watershed is a fifth-order basin of 127 km^2; and Indian watershed is a third-order basin of 17 km^2. These are small- or medium-sized watersheds, depending on one's definition. As Woolhiser and Brakensiek (1982) note, small watersheds and their hydrologic regimes can be significantly affected by agriculture and silviculture. The watersheds in this study have been significantly affected by land use to be sure, but they are more nearly of medium-size, that is, ones that range between the smaller and more frequently studied watersheds of 1 km^2 or less and large watersheds of 1000 km^2 and more (Phillips 1991).

The three study areas span a number of environmental gradients (Table 1). The first gradient is regional geomorphology, ranging from Beaver Creek's dissected topography similar to Wisconsin's Driftless Area to Hay Creek's moderately dissected Pre-Wisconsin till plain to Indian Creek's moderately dissected Late-Wisconsin ground moraine (Wright 1972; Hobbs 1985). This geomorphic range covaries with steepness. Beaver Creek is the steepest and most deeply dissected watershed, Hay Creek is intermediate, and Indian Creek has the lowest gradient. The geomorphology gradient also parallels soil gradients, ranging from the mostly loess-covered Beaver watershed to the partially loess-, till-, and bedrock-covered Hay watershed to the till- and lacustrine-covered Indian watershed (Beach 1990). These soil and geomorphology gradients produce in turn a clear gradient of soil erodibility: Beaver has the highest erodibility, Hay the secondmost, and Indian the lowest. The climate gradient across the region is modest, with a slight decrease in precipitation and in the frequency of convectional storms from Beaver to Hay to Indian watersheds. The climatic gradient is probably more important indirectly in its influence on vegetation. The original vegetation gradient varies from a prairie and hardwood forest ("Big Woods") transition zone in Beaver watershed to mostly hardwood forest in Hay watershed to mostly prairie in Indian watershed (Grimm 1981). These original vegetation assemblages correspond roughly with regional soil types. Beaver watershed is covered by about 70 percent Mollisols (mostly of the typic hapludoll Great Group) and 20 percent Alfisols (mostly typic hapludalfs); Hay watershed by about 45 percent Alfisols and about 25 percent Mollisols of the same Great Group as Beaver watershed (Poch 1976); and Indian watershed by about 75 percent Mollisols and 20 percent Entisols and Alfisols (Beach 1992). The Mollisol and Alfisol soil orders correspond approximately with the regional prairie and hardwood forest vegetation associations (Paulson 1982).

Settlement and Sediment Analysis: The Role of Buried Paleosols

In the Pre-Wisconsin glaciated and Driftless areas, the baseline for measuring historical aggradation is easily identified by an abundance of buried paleosols. Since the alluvium lying above the buried paleosols is all post-settlement, we can calculate this stored sediment by measuring the volume of sediment above the buried soil surface. These measurements require coring down to or through the paleosol at a sufficient number of sites in cross-valley transects. It is often necessary to drill through the paleosols to determine their authenticity.

It is also necessary to reaffirm the assumption, held by many scholars, that the buried paleosols of the Upper Mississippi Valley represent the soil surface prior to European settlement (McKelvey 1939; Happ 1944; Knox 1977; Trimble and Lund 1982; Magilligan 1985). Ample historical and physical evidence supports this conclusion. That evidence includes many imbeddings of modern artifacts in sediments and radiocarbon dates from historical times. For example, a bison bone (Beach 1989) from near the base of the overbank alluvium in Hay Creek dates from 120 +/– 80 RCYBP (BETA 29990), whereas the buried soils have no modern artifacts and have older radiocarbon dates (Gross 1973). The buried A horizons are very dark (10YR 3/1 or darker), are leached of free carbonates (no reaction to applications of 10 percent solutions of hydrochloric acid), and are granular or subangular blocky in soil structure. In contrast, historical sediments are usually much lighter in color (ranging from 10YR 6/3 to 10YR 3/1), often contain free carbonates, and are usually massive and have prominent laminations. Based on the hydrometer method for texture analysis, the buried A horizons usually have higher clay contents and lower sand contents than overbank alluvium (see also Knox 1987). Based on soil combustion in a *Leco* carbon analyzer and a calibrated loss-on-ignition method (Davies 1974; Dean 1974), buried soils are usually at least 5 percent organic carbon. The buried paleosols often meet the requirements for Mollisols.

Only one previous research effort has studied buried soils and overlying sediments in the

Late Wisconsin glaciated valleys of southcentral Minnesota (Gross 1973). The author maintains that these soils and sediments conform with those in the Pre-Wisconsin glaciated valley sites (Gross 1973), though county soil surveys describe no soil series with post-settlement alluvium in the region (Paulson 1982). The field evidence clearly supports Gross's (1973) contention that the alluvium above buried soils in this region is post-settlement. The buried A horizons in Indian Creek watershed and another watershed in the region (the Rush River, Minnesota) have colors, structures, organic carbon contents, and thicknesses that correspond to pre-settlement soils in the Pre-Wisconsin glaciated and Driftless areas. Moreover, the overlying alluvium is stratified and shows little pedogenesis. Modern artifacts are common throughout the overlying sediments and absent in the buried soils. Also the one radiocarbon date from wood fragments in the top of a buried soil (in the Rush River floodplain) is dated as within the last 250 years (BETA 27129), which does not contradict the notion that the buried soil is the pre-settlement soil surface. Moreover, a study of lake sediments in this region reports that the only dramatic increase of lake sedimentation coincided with the rise of *Ambrosia* (ragweed) pollen that accompanied European settlement (Grimm 1981). Further evidence includes considerable unpublished historical documentation of valley aggradation (Beach 1989).

Field Methods

The first two steps for analyzing the quantity and distribution of historical settlement storage are site selection and data collection. Two major constraints influence site selection: the need for a systematic standard of watershed geomorphology for measuring sediment storage and the lack of previously fixed survey lines (which Trimble and Lund 1982 and Magilligan 1985 used in their studies). The standards selected are Strahler stream orders and five other geomorphic sinks that are easily replicated units when measuring sediment storage. More difficult are the problems created by the absence of previous survey records and mining activities that could provide traceable and datable metal signatures. Their absence precludes study of the chronology of valley sedimentation and, owing to the lack of data on channel widths at different times, reliable estimates of channel erosion.

To calculate sediment storage across valley transects, I drilled 3 to 10 cores using manual augers and recorded several physical characteristics for each transect site: relative elevation, drainage basin area, stream order, floodplain width, and average floodplain gradient (Beach 1990). The database for stored alluvium includes 40 valley transects in Beaver watershed, 52 in Hay watershed, and 7 in Indian watershed (Figure 4). The initial sampling design randomly selects 10 valley transects and systematically selects 10 more intermediate transects in the second- to fifth-order stream floodplains in Hay and Beaver watersheds (Beach 1990). In the third-order Indian watershed, only 5 are randomly selected valley transects in second- and third-order floodplains because field traverses indicated that sediment storage occurs exclusively in the lower valley.

While measuring sediment storage in higher-order floodplains, it became evident that substantial sediment was also stored in first-order floodplains and in colluvium. To more adequately measure sediment storage in first-order valleys and in other geomorphic sites, I added 20 transects in Beaver watershed, 32 in Hay watershed, and 2 in Indian watershed. The number and location of additional transects were determined in field traverses and individual corings. The traverses consisted of systematic traverses through geomorphic sediment sinks, measurements of post-settlement sediment on streambanks and on cumulic footslopes, individual and multiple sediment corings, and surveys of the surface topography. Systematic traverses serve as a test of the representativeness of the initial coring transects and as additional data to fill in the gaps where more data were required for accurate calculations of sediment storage.

Calculating Sediment Storage in Floodplains

Calculating historical sediment storage in floodplains first requires calculations of the cross-sectional area (square meters) of sediment on each transect (Happ et al. 1940). The next step multiplies each transect's cross-sec-

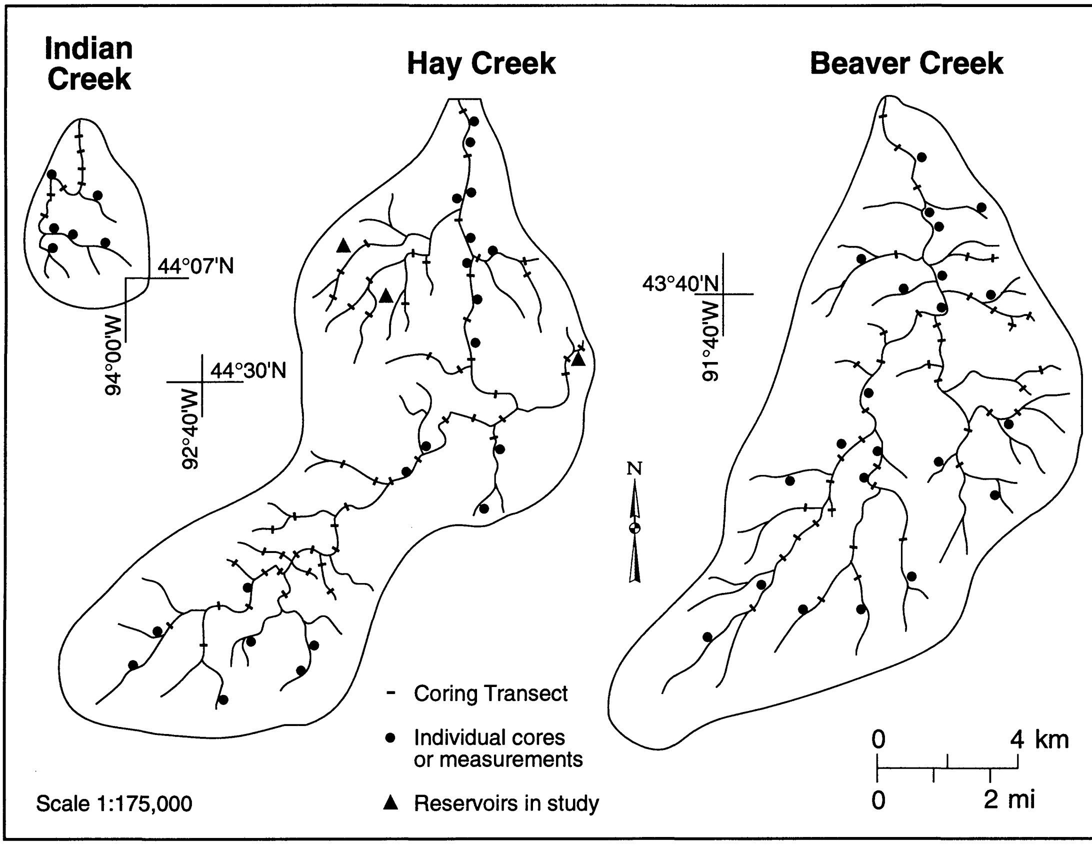

Figure 4. Map of field sites in watershed study areas.

tional area by the length of the valley segment that it represents. These valley lengths are estimated from floodplain morphology, rather than from measures of the mean distance between adjacent transects. Accordingly, an understanding of floodplain morphology is necessary before calculating floodplain sediment storage.

Based on surveys and corings across approximately 100 first- to fifth-order valleys, it is apparent that floodplains in southeastern Minnesota are formed largely by overbank accretion (see also Knox 1977). One major type of floodplain in the region is dominated by overbank accretion with only a narrow band of lateral aggradation near the modern channel. This floodplain has flat cross-valley profiles that result when overbank sedimentation levels out the lows and highs over the soils on the valley floor. This process has created the basic form of the majority of the fourth- and fifth-order valleys in the region. Another major floodplain type combines overbank and lateral aggradation (see Happ et al. 1940; Knox 1987). In this case, most of the floodplain has a level surface from overbank deposition, beneath which the pre-settlement buried surface is preserved. A smaller belt of laterally aggraded floodplain extends to the point bar side of the stream channel. Often in both types, the floodplains are really terraces that no longer receive floods every one or two years. The current floodplain in most valley reaches consists of a relatively narrow, coarse, and unstable band of lateral accretion adjacent to the point bar. A few reaches, however, have two or three terraces between the active floodplain and the overbank-deposited terrace.

Measuring gross historical sediment storage in vertically aggraded floodplains entails measuring or estimating the depth, width, extent, and bulk density of sediment that overlies buried soils. The quantity of historical sediment in cubic meters is measured from corings taken along transects that cross the different geomorphic sinks. Cubic meters (m^3) are converted to megagrams (Mg) by applying a regional average soil bulk density of 1.4, a figure derived from many sources (Trimble and Lund 1982; Lueth 1984).

Several other floodplain forms occur in this region. In a few valleys, floodplains have been trenched after initial aggrading in historical times (Happ et al. 1940). Most of these reaches occur only in third- or larger-order valleys. In other valleys, non- and low-order floodplain sites are depressions where no discernable channels exist at the surface ("unchanneled hillside depressions" in Montgomery and Dietrich 1992). In these depressions, buried channels and buried soils commonly underlie about one meter of stratified sediments. In some valley heads, the historical alluvium covers buried Bt (argillic) or Bw (cambic) horizons presumably because the A horizons have been truncated by early historical erosion. The color, texture, and structure changes from the alluvium to the B horizons is generally very distinct. The B horizons have more reddish hues, higher clay contents, and a subangular, blocky structure.

Stream Order

The next step in calculating sediment storage involves measuring the valley distances of historical deposits by each stream order. Field study, aerial photographs (1:15,840), and topographic maps (USGS 1:24,000) are used to identify Strahler stream orders. Determining subsequent stream order first entails defining the first-order channels. The first-order basin is defined as the area that contributes to an unbranching stream channel (Marcus 1980). Leopold, Wolman, and Miller's (1964) discussion of stream order and map scale warns about estimating stream order on 1:24,000 scale maps for some areas. Field surveys in this region show that the 1:15,840 scale aerial photographs and 1:24,000 scale maps of these basins are relatively accurate for identifying first-order stream valleys, that is, those with the first clear channels.

One problem, however, is that first-order streams commonly have two or more tributary valleys that have channels, but these channels and the adjacent soil surfaces have been buried by historical sediment deposition or by plowing. These sites are classified as non-order floodplains. Since some of these buried channels are associated with buried soils, some of these reaches represent pre-settlement buried channels. More of them, however, represent incision from early accelerated erosion because these channels are associated with buried truncated soils (Bw and Bt horizons). Strahler (1956) argued that accelerated erosion increased stream density because streams extend their lengths through gullies and rills. This would appear to be correct for an early period of accelerated erosion. Aggradation and/or plowing of the small headward valleys occurred sometime after an initial period of channel incision, thus recently reducing the number of lower-order streams and channel density (channel length per area) in these upland drainage basins.

To reiterate, estimates of the total sediment storage by each stream order requires multiplying the cross-sectional areas of stored historical sediment (obtained from field transects) by the lengths of each stream order. Because the distinction between non- and first-order streams is tenuous, they are lumped together as a single sink. Since some of these non-order reaches served as first-order reaches before European settlement, one order should be added to some of the streams to accommodate other classificatory schemes such as in Morisawa (1962).

Alluvial Storage by Stream Order for Hay and Beaver Creek Basins

Hay Creek

The floodplains of Hay Creek watershed store about 11 million megagrams (Mg) of historical sediment (Table 2). This sum is significantly greater than a previous estimate of 8.5 million Mg (Beach 1990) because of the addition of 32 coring transects and many more

Table 2. Total Historical Sediment Storage in Hay Creek Watershed.

Storage Sites	Sediment (million Mg)	Percent of Total
1. Alluvium	11.00	80.6
Non- through Second-Order Floodplains	3.87	28.4
Third- through Fifth-Order Floodplains	7.13	52.2
2. Reservoirs (after 1957)	0.12	<1.0
3. Colluvium	2.53	18.5
Alluvial Fans	0.10	<1.0
Fencerows	0.23	1.7
Valley sides	0.20	1.5
Cumulic soils	2.00	14.7
4. Total	13.65	100.0

individual measurements and first-order transect sites. Adding the first-order sites alone accounts for virtually all (96 percent) of the difference between the previous estimate (Beach 1990) and the current one. The 1990 estimate of 8.5 million Mg, based on 20 sites in second- through fifth-order reaches, is approximately the same as the present estimate of 8.6 million Mg based on 36 sites in second- through fifth-order reaches.

Human-induced aggradation in Hay and Beaver basins in southern Minnesota is reminiscent of valleys in the Driftless Area of Wisconsin. The depths of historical alluvium range from about 50 cm to 4 m in Hay Creek and to 2.5 m in Beaver Creek (Beach 1990) and thus correspond closely to those described by Knox (1972). The findings on alluvium storage by stream order in Hay Creek clearly indicate a two-tiered pattern of sediment storage in the watersheds. About 28.4 percent (3.87 million Mg) of all historical sediment lies in the non- through second-order, upland floodplains, and about 52 percent (8.6 million Mg) lies in the main floodplain of Hay Creek's third-, fourth-, and fifth-order valleys. Intermediate, third-order floodplains contrast sharply with smaller and larger orders. Only eight third-order valley reaches exist, of which three are narrow upland valleys and five exhibit the steepest channels. These steep sections show little evidence of aggradation and appear to be largely at grade. Third-order reaches contribute only about 5 percent to the watershed's total valley length and about 3 percent to its total stored sediment. Hence, third-order valleys in the drainage basins of this region seem to have played the role of sediment conveyance during historical times.

The large amount of storage in the upland low-order valleys (28 percent of total) is caused by the decrease in gradient from hillslopes to valleys and by the large depositional area of upland valleys. More than four-fifths of all valley lengths in the watershed are non- through second-order valleys. The average cross-sectional area of sediment storage is small, about 10 m^2, but there are more than 110 such valleys and over 132 km of valley length. Evidence that recent alluvium overlies buried B horizons in some places suggests that many of the upland valleys were eroded prior to aggradation. Further research may indicate different cycles of sediment pulses or waves in the watershed.

In Hay Creek drainage basin, fourth-order floodplains range from degrading sections that are narrow and steep to the aggrading lower trunks that are wide and low in gradient. The main branch of Hay Creek becomes a fourth-order stream in the uplands and retains that status to within 6.5 km of the point where it debouches onto the Mississippi River floodplain. The fourth-order main stem is the largest sediment-storage site, though the fifth-order valley in its 6.5 km stores nearly as much sediment. By the fifth-order juncture in the main valley, the floodplain is about 300 m wide and contains depths of up to 4 m of historical sediment.

Beaver Creek

Beaver watershed stores about 9.4 million Mg of historical alluvium in its non- through fifth-order valleys (Table 3). This total differs significantly from the 4 million Mg previously reported in second- through fifth-order valleys (Beach 1990). Two sources account for this 5.4 million Mg difference: (1) the addition of non- and first-order valleys contribute 4 million Mg and (2) more intensive coring transects (20) in second- through fifth-order valleys contribute another 1.4 million Mg. The quantity of alluvial storage in Beaver Creek basin is thus comparable to Hay Creek basin. Hay Creek watershed, though about 9 percent smaller, stores about 18 percent more sediment than Beaver basin. Both valleys store large proportions of sediment in alluvial sites in the upland valleys,

Table 3. Total Historical Sediment Storage in Beaver Creek Watershed.

Storage Sites	Sediment (million Mg)	Percent of Total
1. Alluvium	9.36	74.9
Non- through Second-Order Floodplains	4.65	37.2
Third- through Fifth-Order Floodplains	4.71	37.7
2. Reservoirs (after 1954)	0.12	<1.0
3. Colluvium	3.02	24.2
Fencerows	0.22	1.8
Alluvial Fans	0.20	1.6
Valley sides	0.10	<1.0
Cumulic soils	2.50	20.0
4. Total	12.50	100.0

but the basins differ in the distribution of alluvium (Tables 2 and 3). First, Beaver watershed stores almost one million (.8) more Mg in the non- through second-order valleys; these account for 37.2 percent of total storage in Beaver and 28.4 percent in Hay watershed. Second, Hay watershed stores about 3 million Mg more sediment in its lower main valley, the likely result of greater backwater effects from the nearby Mississippi River.

Another factor accounting for differences in the distribution of stored sediment in Hay and Beaver watersheds is the degree of stream dissection. The landscape of Beaver watershed is older and its uplands are more intensively dissected by lower-order valleys. Drainage density, or total stream length divided by contributing area, in Beaver watershed is about 6.5 km km^{-2} as compared with 5.6 km km^{-2} for Hay watershed. This seemingly small difference reflects substantially greater dissection in Beaver watershed, which has about 60 more kilometers of non- through second-order valley length than Hay watershed. Since most of the small-order valleys in both watersheds store an average depth of about one meter of historical alluvium, the extra valley length in Beaver watershed accounts for virtually all of the differential in upland alluvial storage in the two watersheds.

Factors of Alluvial Storage

Statistical regressions are useful for elucidating the factors that influence the distribution of historical alluvium in the watersheds and for comparison with previous research in the Driftless Area. Magilligan's (1985) work in this region indicated that two independent variables together, floodplain width (W_f) in meters and drainage basin area (A_d) in km^2, explain 60 percent of the variance in post-settlement alluvium patterns (measured as the cross-sectional area in m^2 of post-settlement alluvium, C_a). The regression equation is as follows:

$$\log C_a = -0.35 + (0.993) \log W_f + (0.052) \log A_d \quad (1)$$

In Magilligan's work, floodplain width (W_f) is the primary influence on cross-sectional area of historical alluvium (C_a); little correlation exists, however, between drainage basin area (A_d) and the mean depth of historical alluvium (M_d). Regression equations with these and additional variables are equally applicable for Hay and Beaver valleys. The dependent variables are the cross-sectional area (C_a) and mean depth (M_d) of post-settlement alluvium, and the independent variables include floodplain width (W_f), drainage basin area (A_d), relative site elevation (E_s), and mean site gradient (S_m). The independent variables of floodplain width and drainage basin area extend previous research in this region; the relative elevation variable (E_s) conveys a measure of drainage-basin energy and base-level, backwater effects; and the mean site gradient (S_m) measures the kinetic energy of overbank floodwater for the 200 meters surrounding transect sites. In this study, normal, base-10 logarithmic transformations of dependent and independent variables improve the fit of data in all cases and best satisfy the assumptions of linear regression analysis.

Floodplain width (W_f) is the most highly correlated and most significant of the independent variables in the sediment storage (C_a) regressions for Hay ($r^2 = .72$, $p = .01$) and Beaver valleys ($r^2 = .78$, $p = .01$). Drainage basin area, however, is much less significant and more weakly correlated in both Hay ($r^2 = .26$) and Beaver ($r^2 = .25$) valleys with other variables in single and multiple regressions (Figure 5). Running all combinations of multiple regression models with four different data transformations demonstrates that the most parsimonious and explanatory equations in both basins are the following normal log single regression models:

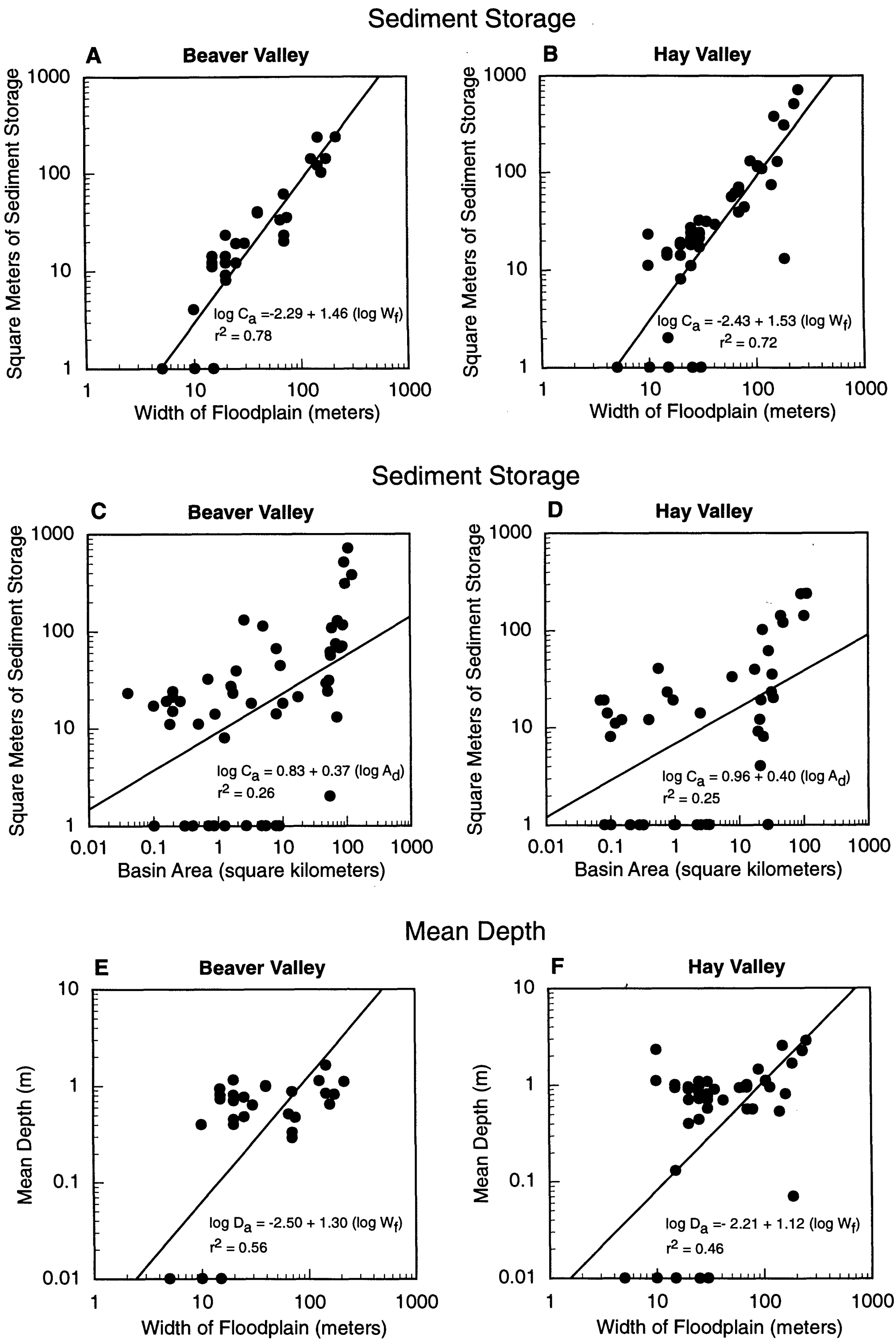

Figure 5. Relationship of cross-sectional area of post-settlement alluvium and floodplain width and drainage basin area (a, b, c, and d) and relationship of mean depth and floodplain width (e and f). The regression lines are calculated and the axes are logarithmic.

$$\log C_a = -2.43 + 1.55 (\log W_f) \quad (r^2 = .72, n = 52, p = .01, \text{Std. Error} = 0.44) \quad \text{Hay Creek} \quad (2)$$

$$\log C_a = -2.29 + 1.46 (\log W_f) \quad (r^2 = 0.78, n = 40, p = .01, \text{Std. Error} = 0.28) \quad \text{Beaver Creek} \quad (3)$$

Alluvial storage is also associated with another dependent variable: the mean depth of sediment storage. For resource managers in particular the mean depth of historical alluvium is more important than cross-sectional area because mean depth is more easily included in resource documents such as soil surveys. Some soil surveys include soil-series descriptions of mean depths to buried A horizons (Beach 1990), and models that can accurately predict mean depth would be helpful to resource managers and to developers of soil-series descriptions. For comparability, I use the same regression procedures for average depth (D_a) as for cross-sectional area (C_a). The log-transformed data again produce the best models, but explained variances for mean depth are lower.

Floodplain width produces the highest explained variance for both watersheds, $r^2 = .46$ for Hay and $r^2 = .56$ for Beaver (Figure 5). None of the other independent variables (A_d, E_s, O_s, and S_m) alone or combined in multiple regressions explain half as much of the variance explained by floodplain width alone. Indeed, floodplain width explains the most variance of sediment storage (both cross-sectional area and mean depth) in all regression equations. Moreover, the findings indicate an even stronger relationship between floodplain width and the cross-sectional area of sediment storage in these Minnesota watersheds than in the Galena River Valley of Wisconsin and Illinois (Magilligan 1985). Drainage basin size probably accounts for these differences. The Galena River basin (526 km^2) is almost four times larger than Hay (127 km^2) and Beaver Creek (144 km^2) basins. More complex factors probably influence the distribution of sediment storage in the much larger Galena basin. In addition, the high correlations in equations 2 and 3 may reflect the many small values from narrow upland valleys where the cross-sectional area of sediment storage (in square meters) is very close to the floodplain widths (in meters). The fact that floodplain width is the only highly correlated variable with sediment storage thus supports Magilligan's (1985) concept of floodplain alluviation in this region. Deeper alluviation, Magilligan concludes, occurs in wider valleys where flood flows decelerate and sediment deposits, whereas thinner alluviation occurs in narrower valleys where flood velocities accelerate, turbulence increases, and sediments tend to stay suspended. Happ et al. (1940) also consider the distribution of modern alluvium in Coastal Plain valleys. Although associating floodplain areas that have deeper modern alluvium with "valley plugs" and reaches upstream from tributary fans, they do not implicitly consider the influence of valley width. Tributary fans, they note, partly obstruct some main valleys and thus induce greater deposition upstream (Happ et al. 1940).

Sediment Storage in Other Geomorphic Sites in Hay and Beaver Basins

Reservoir Sedimentation

Sedimentation occurs in a variety of geomorphic sites other than floodplains (Figure 2). Previous studies of watershed sediment storage have found that reservoirs account for a small fraction of total sediment storage (Trimble and Lund 1982; Gersmehl 1987). To assess the role of these sites, I begin with Hay Creek basin and present the results of coring surveys conducted in three reservoirs that represent a cross-section of the basin's reservoirs. These surveys follow the methods described in the *National Engineering Handbook* (SCS 1971). Each reservoir required 10 to 20 sediment cores along three to five separate transects. The initial plan was to use reservoirs built at different periods to estimate sedimentation rates during those periods, but that plan was altered because few dams were built before the 1950s and these reservoirs have been degraded, filled, or excavated.

To estimate total reservoir sediment storage entails calculating storage in the three reservoirs and using these as an average for reservoir sedimentation in the basin's remaining 28 reservoirs (Beach 1989). These methods produce an estimate of about 0.1 million Mg of sediment stored in Hay basin reservoirs (Table 2). Since these dams and reservoirs date from the 1950s, the total storage estimate applies to reservoir sedimentation after that date. According to these estimates, the annual sedimentation rate has been about 200 Mg km^{-2} yr^{-1}. SCS reservoir sediment surveys in nearby watersheds serve as a cross-check on the methods described above. For the nearby reservoirs, SCS surveys show that four of six reservoirs had sedimentation rates that were double those of the three reservoirs in Hay Creek basin. Since the estimates are quite different, I average the data for the three Hay Creek reservoirs and the SCS surveys to make a second estimate of reservoir sediment storage. This revised estimate yields a sedimentation rate of 340 Mg km^{-2} yr^{-1}, or about .12 million Mg of sediment stored in the watershed's 28 reservoirs over the last 30 years. Except for a dozen small Civilian Conservation Corps (CCC) dams, there were few dams built before the 1950s and none that can be reliably surveyed to calculate sediment storage. Reservoir sediment storage, therefore, is not significant before the 1950s. The overall estimate of reservoir storage is .12 million Mg or less than one percent of total sediment storage.

In Beaver watershed, the estimate for reservoir sedimentation is based on average sediment storage in reservoirs surveyed by the SCS multiplied by the 116 reservoirs in Beaver watershed. The SCS has surveyed seven reservoirs in nearby valleys. Most of these reservoirs were built in the 1950s, as were most of the reservoirs of the Beaver watershed. If we assume that these seven reservoirs are representative, their average sedimentation rates and storage rates can be used to estimate sedimentation in Beaver basin reservoirs. The SCS-surveyed reservoirs, though having deposition rates, trap efficiencies, and sediment delivery ratios (SDR) that are probably similar to Beaver watershed, occupy drainage areas that are much larger than the Beaver watershed reservoirs. A random sample of 14 of the 116 reservoirs in Beaver basin provides an average estimate of drainage area of about .25 km^2 as compared to the SCS average of 2.1 km^2. Given this average of .25 km^2, a total of 116 reservoirs, an average deposition rate of 185 Mg km^{-2}, and an average of 25 years of deposition, I estimate the total amount of reservoir sediment storage at 0.12 million Mg of sediment, which is less than one percent of all sediment stored in the Beaver basin (Table 3).

The problem with these estimates is that we lack information on pre-1950s reservoir sedimentation: studies of pre-1954 reservoir sedimentation for this area are non-existent. The basins do contain at least 100 CCC check dams from the 1930s, and all of those that have been studied are filled to capacity or have been filled and gullied. Because an estimate of CCC dam sediment storage would provide little information about past sedimentation and soil erosion rates, the sediment stored in CCC dams is best measured as a part of stream-order storage sinks. The large number of CCC dams in first- and second-order streams may be, therefore, an additional factor accounting for the large amount of sediment storage in these stream sites.

Colluvial Storage

Several sediment budget models (Costa 1975; Trimble 1983; Phillips 1991) portray colluvium as a significant sink for sediment storage. Definitions for colluvium vary, however, in sediment budgeting; for the purposes of this study, I lump together alluvial fans, fencerows, hillslope colluvium, and cumulic soils as identifiable colluvial sinks. Doubtless, grass waterways, field margins, and other hillslope soils also serve as colluvial sinks, but their contributions are not readily measurable in field studies.

Alluvial Fans. Several scholars have studied alluvial fans in this region, including McKelvey (1939), Happ et al. (1940), Sartz (1970), and Knox et al. (1981). Although these alluvial fans are not the exclusive products of historical erosion, Sartz (1970) notes that alluvial-fan sedimentation is significant and damaging in the Driftless Area during the historical period. To measure historical storage, I ran transects across seven fans in Hay and Beaver watersheds and took twenty individual measurements. The findings suggest that many of the alluvial fans in the basin are historical or have aggraded during historical times. Buried soils and channels underlie and lie within the fans, and modern anthropogenic artifacts are commonly dispersed in fan sediments.

In Hay watershed, the average fan stores about 365 cubic meters (m^3) of historical sediment. Field traverses, 1:24,000 scale topographic maps, and 1:15,840 scale aerial photographs indicate about 150 alluvial fans in the watershed. Fan deposits are coarser than other deposits in the region. In many fans, dolostone boulders make up about one-fourth of the mass, which gives the fans a greater bulk density of about 1.8. Thus, multiplying average fan storage of 365 m^3 by average bulk density of 1.8 by the watershed's 150 fans yields an estimate of about 0.1 million Mg of historical sediment storage on Hay Creek alluvial fans, or less than one percent of all historical sediment storage (Table 2).

Beaver watershed contains two major types of fans. One type occurs on upland hillslopes where gullies or small valleys connect with higher-order floodplains. These 150 or so small fans store only about 160 m^3 of historical sediment. A second type of alluvial fan occurs at steep confluences of larger-order valleys; the basin contains about 60 such fans. Thus, 150 of the smaller fans multiplied by an average of 160 m^3 and a bulk density of 1.8 yields about 40,000 Mg of sediment stored in alluvial fans on upland hillslopes. Similarly, an average of the larger fans (1500 m^3) multiplied by 60 fans in the basin and a bulk density of 1.8 yields about 160,000 Mg. These figures sum to about 0.2 million Mg of historical alluvial fan storage, which is less than 2 percent of total historical sediment storage (Table 3).

Fencerow Berm Sediment Storage. Fencerow berms are rows of sediment that accumulate at slope breaks along fence lines (Gersmehl 1987). Fencerow accumulation probably develops from several contributing factors including sediment entrapment in rows of grass along fencerows, slope breaks from livestock trampling, and damming from erect and toppled fenceposts. These berms of sediment accumulation are nearly ubiquitous along old fence lines in the slightly to moderately sloping areas of these drainage basins. Flat and very steep areas have no fencerows. For Hay watershed, fencerow measurements in a variety of different situations range from no sediment storage to cross-sectional areas of 4 m^2. The overall average is about 2 m^2 of cross-sectional area. I use two methods to estimate the length of depositional fencerows. The first method measures the length of visible fencerows from aerial photographs; the second measures fencerow lengths in the field and extrapolates to the entire drainage basin. Averaging these two methods results in about 90 km of fencerows in Hay watershed. Multiplying that average by the average cross-sectional width of 2 m^2 yields an estimate of about .23 million Mg stored in fencerows. Using these same methods in Beaver watershed produces a nearly identical average of about 0.22 million Mg. Therefore, fencerow sediment storage in both Hay and Beaver watersheds totals somewhat less than 2 percent of historical sediment storage as compared to an estimate of 3 percent for a nearby watershed (Gersmehl 1987).

Hillslope Colluvium and Cumulic Soils. Several studies (Costa 1975; Trimble 1983; Phillips 1991) indicate that hillslope colluvium is a major sediment sink in drainage basins. And Gersmehl (1987) points out that colluvium in "cumulic soils" accounts for about 9 percent of sediment storage in the Rush River of Wisconsin. Field study in the Minnesota watersheds reveals two separate sinks of hillslope colluvium: colluvium above buried soils on the steep main valley sides and the hidden colluvium stored in soils of the *cumulic* subgroup classification. Steep hillside colluvium is a small proportion of total storage. In many places there are only traces of colluvial storage because valley walls are nearly perpendicular, bare rock faces. In field traverses, few indications of incipient historical colluvial deposition are evident. In one site, a buried pre-settlement, colluvial soil has been exposed by lateral stream erosion. The overlying sediment is a typical colluvial deposit with a random mixture of sediment sizes from clays to boulders. The post-settlement colluvium is 1.3 m deep and covers the lower 10 m of the hillslope. How far this layer skirted the hillslope cannot be determined exactly. Even if this deposit covered half of the main valley sides, about 20 km, then colluvium on steep valley sides would add up to no more than 0.5 million Mg. Field traverses indicate that this valley side colluvium covers about 8 to 10 km in Hay watershed (0.2 million Mg) and 4 or 5 km in Beaver watershed (0.1 million Mg) (Tables 2 and 3). Thus, sediment storage on steep valley hillsides is less than 2 percent of storage, about the same as alluvial fan storage.

Of the remaining colluvial storage sinks, cumulic soils store a large but elusive quantity of historical sediment. Cumulic soils develop on footslopes where hillslopes give way to valleys and depressions or in floodplains and depressions. *Cumulic* refers to soil taxonomic subgroups with A horizons thickened or aggraded usually by slopewash deposition. Cumulic soils develop under natural conditions, but aggrade during periods of accelerated erosion. Extensive soil coring in this region (Gersmehl 1987) and coring traverses through Beaver and Hay watersheds reveal a minimal average depth of about 30 cm of lighter and sometimes faintly stratified post-settlement accumulation. The areal extent of cumulic soils is based on field traverses and mapping and point sampling of soil survey maps. Historical sediment storage in cumulic soils sums to about 5.7 km^2 in Beaver watershed and 4.6 km^2 in Hay watershed. Based on the average depths, bulk density of 1.4, and areal extents, about 2.5 and 2.0 million megagrams of historical sediment resides respectively in the cumulic soils of Beaver and Hay watersheds (Tables 2 and 3). However inexact these methods are for estimating historical cumulic soil storage (cf., Daniels et al. 1988), considerable care is taken to estimate a minimum range for this sink. Other colluvial sinks (such as field edges and other slope situations) exist, but field surveys indicate they are probably not significant. The colluvial sinks in this study thus include all that can be detected by field study at the scale of research. These probably account for most colluvial storage.

Total Sediment Storage in Beaver and Hay Creek Basins

The total budgets of historical sediment storage are grouped by their geomorphic sinks in Tables 2 and 3. In Beaver and Hay creeks the non- through second-order floodplains represent upland valleys with ephemeral flow. The third-order floodplains are usually steep, perennial reaches where the uplands grade into the main valleys. Fourth- and fifth-order floodplains occupy the main valleys that grade into the Mississippi River floodplain. And the four remaining sediment sinks are common geomorphic features.

The most salient characteristic of historical sediment storage in both Beaver and Hay watersheds is that about 75 to 80 percent lies in the valleys and floodplains of non- through fifth-order streams. Colluvium, broadly defined, stores most of the remaining sediment, some 18 to 24 percent of all historical sediment. Reservoirs are minor sediment sinks (Tables 2 and 3). An equally important characteristic of historical sediment storage is its two-tiered pattern. Upland valleys (non- through second-order) store 28 and 37 percent of all sediment in Hay and Beaver watersheds respectively, whereas their major floodplains (third- through fifth-order) store 52 and 38 percent, respectively. Third-order valleys, meanwhile, store only 3 percent of historical sediment in Hay watershed and 9 percent in Beaver watershed. In these watersheds, especially Hay Creek, third-order streams are often steep segments, connecting low-gradient upland valleys to low-gradient main floodplains.

In all storage sites, Beaver and Hay watersheds store comparable amounts of sediment: Beaver about 12.5 million Mg and Hay Creek about 13.65 million Mg. The role of geomorphic interpretation in these calculations (in for example floodplain morphology) precludes estimating a range of probable error. By unit area, Beaver Creek stores about 86,806 Mg km^{-2}, which represents an average historical sedimentation rate of 634 Mg km^{-2} yr^{-1}. Hay Creek stores about 24 percent more sediment per unit area, about 107,480 Mg km^{-2} with an average historical sedimentation rate of 785 Mg km^{-2} yr^{-1}. The largest proportion of Hay Creek's greater storage is the 2.4 million more Mg of sediment in its lower main valley. Three factors account for greater sedimentation in this segment of Hay Creek: (1) backwater effects from the Mississippi River at the mouth of Hay Creek; (2) a narrowed valley outlet caused by bridge embankments that back up floodwater; and (3) Beaver Creek's narrower main valley. All of which confirms Magilligan's (1985) finding that narrow valleys in similar size drainage basins promote higher-energy flooding and less deposition.

Indian Creek Basin: Southcentral Minnesota

Indian Creek watershed stores about 1.1 million Mg of historical sediment. The distribution of historical sediment in this basin is relatively simple. Sediment has accumulated as hillslope colluvium in cumulic soils and in the third- order floodplain of the lower 3 km of the valley. Coring transects through the floodplains of Indian Creek indicate about 0.3 million Mg of alluvium. Field traverses and the Blue Earth County Soil Survey (Paulson 1982) document a watershed area of about 2.6 km^2 of cumulic mollisol soil, with an average depth of at least 30 cm of historical sediment, and a bulk density of 1.4. These figures sum to about 0.8 million Mg of historical colluvial storage, which, when added with alluvial storage, yields a total of 1.1 million Mg of sediment storage. This watershed is much smaller (17 km^2) than the other two watersheds and sediment storage per area is about 64,700 Mg km^{-2} (472 Mg km^2 yr^{-1}), that is, 60 to 70 percent of the rates for the more deeply dissected watersheds of Hay and Beaver Creeks.

European settlement of southcentral Minnesota accelerated erosion and sedimentation in the Indian Creek basin much as it did in the Hay and Beaver basins of southeastern Minnesota, but sediment storage and its adverse effects are not as evident in the former. The third-order basin of Indian Creek stores all of its alluvium in its lower floodplain. Traverses through a similar watershed in the region, the Rush River of Minnesota, reveal comparable depths, widths, and distributions of post-settlement alluvium in its lower floodplains. Based on individual corings and measurements, historical alluvium ranges from 50 to 120 cm and is limited to the lowest terraces and floodplains of the valley. In both Indian Creek and the Rush River valleys, alluvial storage is less than in comparable valleys in southeastern Minnesota.

A history of agriculture and conservation in the region indicates that trends in erosive land uses and erosion rates parallel those of southeastern Minnesota (Beach 1989). Erosion rates in Indian watershed, however, are about 18 percent lower than in Hay and Beaver watersheds. These lower erosion rates, owing to less steep terrain and less erodible soil, probably account for part of the lower sediment storage rates. Two other explanations are possible: Indian watershed's soils contain more clay and its drainage density is lower. Most of the soils in Indian watershed are clay loams or silty clay loams, whereas most soils in Hay and Beaver watershed are silt loams. Clay particles remain suspended longer than larger particles during floods, and thus clay is less likely to be deposited in low-order floodplains and upland geomorphic sinks. Additionally, Indian Creek's drainage density of 2.6 km km^{-2} is less than one-half the 5.6 and 6.5 km km^{-2} of the other two drainage basins. Indian watershed, in other words, has fewer floodplains per unit area for alluvial storage.

Historical Erosion and Sediment Budgets

Comparing our estimates of sediment storage in these watersheds with estimates of historical erosion permits us to construct historical sediment budgets for each watershed. In the absence of a completely accepted method for estimating erosion, I use five different and overlapping methods to assess the convergence of erosion estimates. These methods include: the Universal Soil Loss Equation (USLE), a method based on soil survey mapping units, gully measurements, a summation of an SCS study, and a reservoir-sedimentation method. The methods are described in detail elsewhere (Beach 1989; 1992). Although each method uses different data and procedures, their estimates of historical erosion show considerable convergence around the USLE (Table 4). For instance, the USLE estimate for soil loss in Hay watershed between 1955 and 1988 is 3.2 million Mg, which closely corresponds to the erosion estimate based on reservoir sedimentation, corrected for trap efficiency and the sediment delivery ratio (SDR), of 2.7 to 3.5 million Mg. Historical channel erosion could not be estimated because of the lack of historical survey lines to compare channel widths at different time periods.

The USLE is the most commonly used equation for estimating sheet and rill erosion (Renard et al. 1991). Despite several caveats about the equation for watershed applications (Wischmeier 1976; Knox 1989), several studies have applied the equation at this level (Phillips 1991; Wilson 1989; Trimble 1983). Applying the USLE to the Minnesota watersheds, I use field, map, and aerial photography data to estimate the six variables in this empirical equation. Several updates from the revised USLE (RUSLE) are incorporated into this estimate

Table 4. Comparison of Erosion Estimates.

Watershed	USLE (1850–1988)	Soil Survey (1984)	SCS (1850–1938)	Reservoir Sedimentation (1955)	Gully (1850–1988)	USLE + Gully
	Method of Erosion Estimate (in million Mg)					
Beaver	19.1	13.5	11–19	3.6	0.6	19.7
Hay	14.7	9.3	—	2.7+	0.8	15.5
Indian	1.7	—	—	0.4	—	1.7

Source: Beach 1992.

(Beach 1992). The equation is calculated based on a random point sampling inventory of 1.5 samples km^{-2}—a resolution that is finer than suggested by previous research in this region (Gersmehl et al. 1987). The USLE is calculated for these watersheds in a geographic information system at one- or two-decade intervals between 1850 and 1988. It estimates total historical sheet and rill erosion. Field and photogrammetric measurements of gully erosion are added to USLE sheet- and rill-erosion calculations in order to estimate total upland erosion in the three basins.

Based on these decadal estimates of soil erosion, the three southern Minnesota watersheds exhibit an erosional history that resembles Coon Creek, Wisconsin as described by Trimble and Lund (1982). Rates of erosion peak between 1900 and the late 1930s and thereafter subside to less than one-half their peaks by the 1960s (Beach 1992). For Beaver watershed, USLE and gully measurements yield 19.7 million Mg of historical erosion between 1851 and 1988 (Figure 6; Table 4). Given historical sediment storage of at least 12.5 million Mg, the historical sediment delivery ratio (SDR) represents less than 36.5 percent of historical erosion; sediment storage thus represents more than 63.5 percent (Table 5). Sediment yield refers, of course, to the quantity of sediment transported out of the basin, and the SDR is simply the ratio of yield to gross erosion (usually as a percent) over a given time period. Hence, about two-thirds of all soil eroded from Beaver watershed over nearly seven score years remains stored in this 144 km^2, fifth-order basin.

In Hay watershed, historical erosion sums to 15.7 million Mg for the period between 1851 and 1988. Based on the calculated 13.65 million Mg of stored sediment, Hay's historical SDR is just 13 percent (Figure 6; Table 5) and total sediment storage is 87 percent. About nine-tenths of all soil eroded since 1851 in this 127 km^2, fifth-order basin still resides in the basin. Lastly, in Indian watershed historical upland erosion totals 1.7 million Mg, and sediment storage amounts to 1.1 million Mg. This produces an historical SDR of less than 35 percent and a total sediment storage in excess of 65 percent in this 17 km^2, third-order basin (Figure 6; Table 5).

Table 5. Historical Sediment Storage and Sediment Delivery Ratios (SDR), 1851–1988.

Watershed	Gross Erosion (million Mg)	Storage: million Mg	Storage: percent	SDR (percent)
Beaver Creek (144 km^2)	19.70	12.50	63.5	36.5
Hay Creek (127 km^2)	15.50	13.65	87.0	13.0
Indian Creek (17 km^2)	1.70	1.10	65.0	35.0

Several scholars caution about using unmeasured residual terms in sediment budgets (Wolman 1977; Kondolf and Mathews 1991). Kondolf and Mathews (1991), for example, note that sediment budget studies that include unmeasured residual terms are useful provided that these residuals are clearly identified. In this study, sediment yield and SDR are residuals that remain after subtracting storage measurements from soil erosion estimates. One external check on these SDRs and yields is the record of long-term sediment yields for this region (Hindall 1976). The long-term yield rates for the Hay and Beaver Creek region correspond to 80 to 238 Mg km^{-2} and up to 170 Mg km^{-2} for the Indian Creek region. Extrapolating these averages over the historical period, Hay Creek's yield ranges between 1.4 and 4.1 million Mg of sediment; Beaver Creek's between 1.6 and 4.7 million Mg; and Indian Creek's up to 0.4 million Mg. The lower range

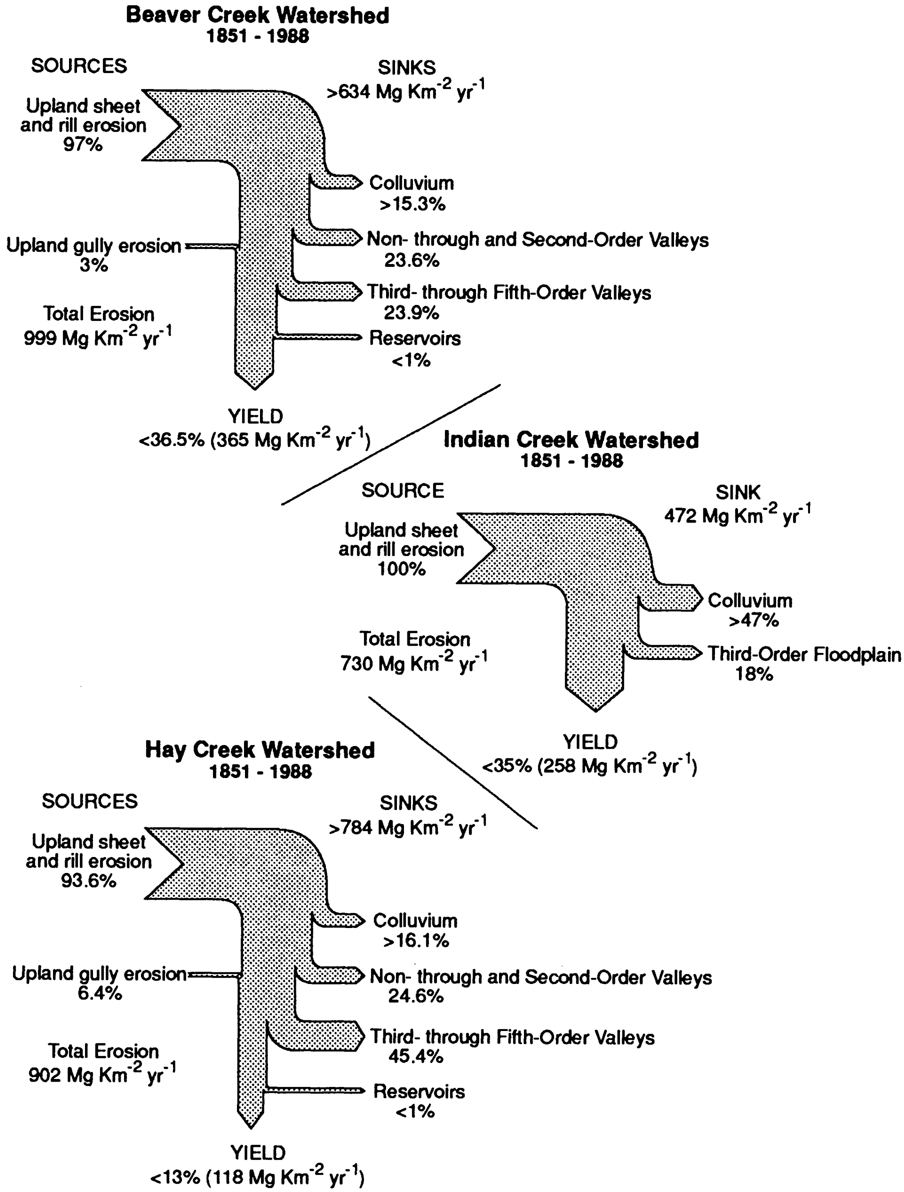

Figure 6. Sediment-budget models showing sediment sources (soil erosion), sediment sinks (storage), and historical sediment yield from the watersheds.

of stream yield (1.4 million Mg) for Hay Creek agrees with the estimated yield (1.5 million Mg), but the high figure for Beaver Creek is about one-third below the estimated yields (7.2 as compared to 4.1 million Mg) and the same applies for Indian Creek (0.6 to 0.4 million Mg). The low yields of Hay Creek reflect, I suspect, backwater effects at the stream's mouth, whereas the high yields of Beaver Creek and Indian Creek probably indicate higher velocity flooding with lower sedimentation through the narrow and steeper lower valley in the former, and the smaller drainage basin and the preponderance of clay size particles that remain suspended for longer times, in the latter. But the fact that yield estimates for Beaver and Indian Creeks are higher than Hindall's (1976) long-term estimates may also be the result of a sampling bias in his estimates, based as they were on the 1960s, a decade that may not adequately reflect the magnitude of historical yields.

In any event, Hay watershed's historical SDR of 13 percent corresponds closely to an estimated SDR of less than 20 percent for Coon Creek (Trimble and Lund 1982) and of 10 percent estimated for the nearby and geomorphically similar Rush River of Wisconsin (Gersmehl 1987). The most likely explanation for the low SDRs of these three streams is that each is strongly influenced by the base level and backwater effects of the Mississippi River, effects that cause anomalously high sediment storage in their lower main valleys. Beaver Creek's SDR of 36.5 percent appears to exceed the region's average. Beaver's higher SDR and lower sediment storage probably result from steeper slopes, narrower floodplains, and less significant backwater effects at its mouth. Indian Creek's historical SDR of 35 percent and sediment storage of 65 percent, though similar to Beaver Creek's, result from different causes. The high SDR of Indian Creek may be explained by a lower sedimentation rate in this system. While floods and runoff events may have been as frequent in this basin, deposition rates were probably much lower due to the greater proportion of clay size sediments. As for the influence of watershed size on SDR, no trend is evident. The study's largest (Beaver Creek) and smallest (Indian Creek) watersheds have similar SDRs, albeit for different reasons. And Hay Creek, though nearly as large as Beaver Creek, has an SDR that more nearly resembles other streams (of different sizes) that flow into the Mississippi River. This similarity of regional SDRs likely reflects the backwater effects of the Mississippi River. Accordingly, further research is needed on how the relationship between SDRs and sediment storage is transmitted to increasingly larger-order drainage basins.

Discussion and Conclusions

The major goals of this research are (1) an understanding of the distribution of sediment storage by geomorphic sites in three watersheds and (2) the development of sediment budgets of erosion, storage, and yield for these watersheds. Beaver and Hay watersheds have similar quantities and patterns of historical sediment storage. The basins are about the same size, have similar environmental characteristics and histories, and store approximately the same amount of historical sediment. Beaver watershed stores about 12.5 million Mg of historical sediment or about 86,806 Mg km^{-2} and Hay Creek stores about 13.65 million Mg or about 107,480 Mg km^{-2}. The average historical sedimentation rates are relatively close, 634 and 785 Mg km^{-2} yr^{-1} for Beaver and Hay basins, respectively. The spatial pattern of sediment storage in these two fluvial systems is also similar. Both have two-tiered patterns of sediment storage: a high percentage of sediment is stored in the uplands in ephemeral, low-order floodplains and cumulic soils as well as in the lower main valley floodplains. In Beaver basin, about 61 percent of all historical sediment resides in the uplands (non- through second-order valleys and colluvium) and about 38 percent in the main floodplains of third- through fifth-order streams. Hay Creek basin is similar: 47 percent resides in the uplands and 52 percent in the lowland higher-order floodplains.

Hay Creek stores 2.42 million more Mg of alluvium than Beaver Creek in its lower main valley. Higher sediment storage rates in the lower main valley reflect the base level control of the low-gradient Mississippi River floodplain. Both backwater effects of Mississippi River flooding and the low-gradient imparted by the Mississippi's floodplain have led to greater floodplain alluviation near Hay Creek's mouth. Beaver Creek's mouth is farther removed from the base level effect of the Mississippi, and thus stores less alluvium in its lower reach. Beaver Creek also has narrower main valleys, which have promoted higher-energy flooding without backwater effects and therefore lower deposition rates (Magilligan 1985).

In comparing these southeastern Minnesota watersheds with Wisconsin's Driftless Area watersheds, both regions have similar quantities and depths of historical alluvium. These range from about 50 cm to about 4 m in Hay Creek and to about 2.5 m in Beaver Creek. The patterns of alluvial storage are also similar to those on a Wisconsin Driftless Area river (Magilligan 1985). The major factor explaining the variation in the depth and area of post-settlement alluvium is the width of floodplains. Other factors (e.g., drainage-basin size) that would be expected to influence sediment storage do not explain significant amounts of variance. This finding supports Magilligan's (1985) model which posits that floodplain alluviation is greater in wide valleys because flood waters in wider valleys have lower velocities that lead, in turn, to higher deposition rates and deeper alluviation.

Indian Creek basin, occupying a low-gradient ground moraine in central Minnesota, stores only about 60 to 70 percent of the sediment per unit area of the more deeply dissected watersheds of Hay and Beaver creeks. Virtually all historical sediment resides in colluvium (mostly in cumulic soils) and in the basin's lower third-order floodplain. Indian basin stores about 1.1 million Mg of historical sediment, which is a historical rate of 64,700 Mg km^{-2} or 472 Mg km^2 yr^{-1}. Whereas Indian basin's largest single sediment sink is colluvium in upland cumulic soils, similar sized third-order sub-basins of Hay and Beaver watersheds have much higher sediment storage and a higher concentration of sediment in the upland floodplains. Transects through a comparable basin in central Minnesota show similar patterns: historical sediment storage is confined to cumulic soils and lower main floodplains.

The sediment budgets for these three basins constitute a snapshot of the various compartments of soil erosion, sediment storage in geomorphic sinks, and yield. Each of the storage sinks is defined on the basis of field study, and erosion estimates are based on careful calculations of numerous field measurements. The yield figures represent residuals that remain after storage estimates are subtracted from the erosion estimates. They are probably upper-bound estimates. Comparing these sediment budgets offers some clues on the present and future equilibrium states of these fluvial systems. Of all upland soil eroded in Hay, Indian, and Beaver basins between 1851 and 1988, no less than 87, 65, and 63.5 percent, respectively, still resides in the watersheds. Since the maximum distance in these watersheds from the drainage divide to their outlets is 25 km, it follows that no more than 13 to 36.5 percent of all eroded sediments has travelled more than 25 km in 137 years. Indeed, 47 to 65 percent of all sediment eroded in the past 137 years has travelled no farther than 3 or 4 km. This assertion is confirmed by the fact that colluvial storage and non- through second-order sediment storage together account for 47 to 65 percent of all eroded sediment and that these sites are never farther than 4 km from their contributing area. These findings support the oft-stated maxim (for example Knox 1977) that accelerated erosion, when gauged over human life spans, transports most soil particles only a short distance from their original point of detachment. Given the large quantities of sediment stored throughout these basins and this region, the potential for remobilization and water pollution is sizable. Moreover, aggraded sediment is inherently more unstable than natural soil because it lacks the coherence of topsoil developed over centuries or millennia. The resource implications are obvious: the large quantities of sediment stored throughout the Upper Mississippi Valley hold greater potential for remobilization by major land use and vegetation changes or by a complex fluvial response (Schumm 1973).

Comparing the sediment budgets of Hay, Indian, and Beaver watersheds with sediment budgets elsewhere, the SDRs are similar to the nearby and much larger Coon Creek (>80 percent) and Rush River (90 percent). The small SDR difference between Hay Creek (87 percent), Rush River (90 percent), and Coon Creek (>80 percent) may be explained by the potential error in estimating soil erosion or colluvial storage. The virtually identical SDRs for these systems suggest certain mathematical regularities between sediment storage and sediment delivery in similar drainage basins with similar land-use histories. All these streams flow into the Mississippi River, and all have deeply buried main valleys (up to 4 m). The influence of the Mississippi, however, differentiates Hay from Beaver and Indian valleys. Beaver and Indian valleys have higher SDRs, less storage, and thinner alluviation in their lower main valleys because they have much weaker backwater effects at their mouths. Beaver watershed's higher SDR can also be explained by its narrow lower valley. Two other major differences in the case of Indian watershed are its lower erosion rates and the surprisingly large role of sediment storage in cumulic soils. The higher SDR of Indian watershed also results perhaps from the watershed's higher proportion of clayey soils that remain suspended longer during floods and, thus, are more readily transported out of the basin. It is tempting to conclude that Indian Creek's higher SDR is a product of the basin's smaller size and lower stream order. Yet, field evidence suggests that significant sediment storage occurs only in cumulic soils and in the main valleys that are graded to the local base level of the Minnesota River Valley.

The stimulus for this investigation was in tracing the fate of eroded soil through geomorphic sinks in drainage basins. Toward this end, the study examined the geomorphic sinks of eroded soil and estimated the sediment budgets of three basins, 137 years after European settlement. The results are a step toward improving our understanding of the relative importance of the several geomorphic sinks and of soil erosion, sediment storage, and sediment yield in the drainage basin. The evidence suggests that historical sediment delivery ratios for these basins range from 13 to 37 percent, a range that is not inapt for generalization to other basins in this region. Further research should attempt to identify the sources of these SDRs, the fractions that come from contemporary upland soil erosion and from stream erosion of historical sediment. The large magnitude floods of the summer of 1993 in the Mississippi Valley also provide an opportunity, not to mention a new variable, in some of these fluvial systems. Since a large proportion of historical sediment remained locked up in the region's drainage basins on the eve of the 1993 floods, these laboratories offer great potential for studying aggradation's impact on flooding and the effects of high-magnitude flooding on geomorphic change. Continued research should focus, perhaps, on the causes and the effects of these major floods: flood amplification, upland erosion, sediment remobilization, and sediment redistribution through increasingly higher-order valleys.

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Beach, Timothy. 1994. The Fate of Eroded Soil: Sediment Sinks and Sediment Budgets of Agrarian Landscapes in Southern Minnesota, 1851–1988. *Annals of the Association of American Geographers* 84(1):5–28. *Abstract.*

Human-induced soil erosion has produced real-world laboratories for studying the fates of eroded soil particles in watersheds all over the world. This article investigates the spatial distribution of historical sediment and the sediment budgets of three of these laboratories in medium-size watersheds of southern Minnesota. Sediment storage is measured in various geomorphic sites or sinks including colluvium, stream-order floodplains, and reservoirs. Two of these watersheds exhibit erosion histories and quantities and patterns of historical alluvium that are comparable with watersheds in Wisconsin's Driftless Area. In these watersheds, the patterns of historical sediment storage are two-tiered, with 47 to 61 percent of all sediment stored in the uplands (in low-order floodplains and colluvium) and 38 to 52 percent stored in the main lower floodplains. In one stream, backwater effects from the Mississippi River cause significantly greater alluviation in the lower floodplain; in another stream, the main floodplain is narrower and alluvial storage is thinner. In both, floodplain width is the major influence on alluvial storage. A third and smaller watershed in central Minnesota reports lower erosion and sedimentation rates and a different pattern of storage; 73 percent of the sediment is stored in colluvium and 27 percent in the lower main floodplain. Based on estimates of soil erosion, historical sediment yields and sediment budgets are estimated for each watershed. Historical sediment yields of about 13 to 36.5 percent are comparable to other estimates for these areas, which means that 63.5 to 87 percent or more of all historically eroded soil still resides within the basins and within 4 to 25 km of original points of detachment. Moreover, in the 137 years of European settlement, 38 to 73 percent of all eroded sediment has travelled no more than 4 km. **Key Words:** Sediment budgets, sedimentation, human-induced soil erosion, sediment yield, sediment delivery ratios.