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A SEDIMENT BUDGET FOR COON CREEK BASIN IN THE DRIFTLESS AREA, WISCONSIN, 1853-1977

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ABSTRACT. *For any time period, total basin sediment yield can be used to make reliable estimates of upland erosion rates only when no significant change of sediment storage is in progress. In the case of Coon Creek, almost 50 percent of human-induced sediment has historically gone into flood plain storage and less than 7 percent has left the basin. However, some of the stored sediment is now becoming mobile, and the present sediment yield per unit area may actually be increasing downstream with the augmentation coming from storage loss. In general, sediment yield from a basin is limited by the conveyance capacity of the streams and floodplains. When this capacity is exceeded by sediment supply, storage of sediment occurs. If the sediment supply drops below the conveyance capacity, then there may be net loss of storage.*

INTRODUCTION

A sediment budget for a landscape is based on sediment yield, erosion from hillslopes, and changes in volume of sediment stored within the drainage basin. Most studies of this type emphasize quantification of the sediment yield and (or) erosion parts of the equation. This study of sediment budgets emphasizes the importance of changes in sediment storage. The Coon Creek basin in the Driftless Area of southwestern Wisconsin offers an excellent opportunity to compute sediment budgets based on changes in sediment storage, because of the availability of abundant historical data over a period of dramatic change in sedimentation process.

The Coon Creek basin (fig. 1) is a submaturely dissected plateau with local relief of about 135 m, steep valley sides, and narrow valleys. The basin is underlain by consolidated sedimentary rocks — older, coherent to very friable sandstone and shale, and younger, fairly resistant dolomite. The rolling uplands are capped by Pleistocene loess, and the valleys contain a series of sandy terraces that are probably of Pleistocene age (Martin, 1965). Most upland soils have a silt loam texture. Hillside swales and draws have been partly filled with sediment. Although stable at the time of European settlement, many were later gullied. The uplands and valleys have been cultivated, but the steepest slopes have generally remained in woodland, although some were heavily grazed. Like most of the Driftless Area, Coon Creek valley has undergone severe man-induced soil erosion with consequent massive sedimentation in the valleys. The drainage basin was the first (1934) Soil Erosion Control Demonstration Area of the U.S. Department of Agriculture.

A comprehensive long-range study of historical sedimentation in the Coon Creek basin was designed by S. C. Happ for the Soil Conservation Service in 1938. McKelvey (ms) made auger borings on more than a hundred valley cross sections, mapped historical accumulation of sediment on air photos, and analyzed the results. Supplemental boring and mapping was done by Happ and others, and W. F. Witzgall surveyed ground line profiles on the ranges. With the assistance of Happ, I began a restudy of Coon Creek in 1973 and published a preliminary study in 1976 (Trimble, 1976). The estimates of sediment volume stored in the valley reported in that study are generally correct, and efforts since that time have been directed toward establishing the rest of the sediment budget, especially (1) overall sediment yield, (2) changes in rates of sediment movement through time, and (3) relation of rates of erosion and sedimentation to causal factors. The first two goals are reported here, while the third is reported in Trimble and Lund (in press).

SEDIMENT BUDGET CONCEPTS

Stream sediment yields have been long used as the indicator of upland erosional processes. A steady state, or balance between material transported by the stream and that produced on the slopes, has been commonly assumed to exist. However, we now know that significant sediment storage changes occur between upland slopes and a downstream point where sediment yield is measured. Unless changes in storage are accounted for, measurements of sediment yield do not help determine erosion rates (Trimble, 1975a, 1977, and 1981).

Material eroded from upland slopes has three possible fates: it can be deposited as colluvium, deposited in channels and on flood plains as alluvium, or transported directly out of the basin. Only the latter is included in the sediment yield. Material deposited as colluvium may later be dissected and redeposited as colluvium or alluvium, or moved out of the basin. Alluvium may be eroded from the channel or flood plain

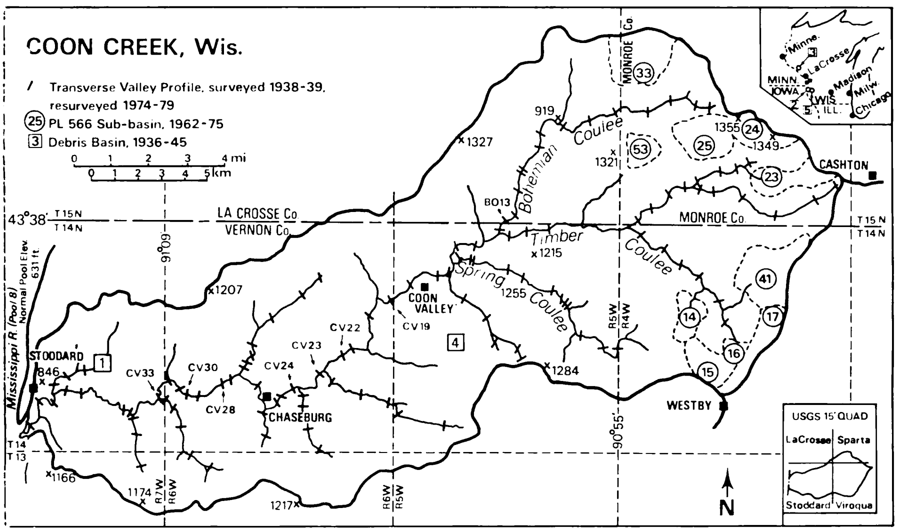

Fig. 1. Map of Coon Creek basin, Wis., and adjacent area showing research locations.

and transported from the basin, or it too can be redeposited farther downstream.

Steady state is a useful concept in analyzing stream basins. In a steady-state system, erosion from slopes equals sediment yield, and there is no net change in sediment storage. However, such an ideal condition rarely exists in nature. Net storage gain by aggradation of slopes and/or channels and/or flood plains has characterized many basins disturbed by intensive agriculture (Trimble, 1975a, 1977, and 1981). In other basins, there are periods when storage loss is greater than storage gain, and a consequent net loss of sediment from storage occurs.

Disruptions of vegetation cover by man, natural fires, and cyclic climatic changes can also change sedimentation regimes. One type of human interference is accelerated erosion on cleared and cultivated slopes, resulting in accelerated sedimentation, of which Coon Creek is a good example. Another type of disturbance is paving of large areas of a basin, causing increased runoff and loss of sediment storage through erosion of stream channels and flood plains.

Human interference is particularly significant in humid areas, where vegetation holds the natural forces of erosion in check. Coon Creek is a good example of a system that was apparently near a steady state at the inception of European agriculture. This paper deals with changes of the sediment budget since that time.

OVERALL SEDIMENT BUDGET

The overall sediment budget for Coon Creek accounts for the storage and transport of the approx 3.6×10^7 Mg of sediment measured in the basin which had been produced between 1853 and 1975 (fig. 2). All measured values except sediment yield were obtained in Coon Creek basin by the techniques described in Trimble (1976). Techniques used to measure sediment yield and to estimate sheet erosion, gullying, and amounts of colluvium are described in this report.

Sediment yield.—Suspended sediment yield from the 360 km^2 Coon Creek basin in 1934-38 was measured to be 180 Mg/km^2 per yr (USDA, 1942). From these data, Hindall (1976) estimated the long-term (over recent decades) sediment yield including bedload to be 160 Mg/km^2 per yr. If applied to the entire period of European settlement (1853-1977), this would have been a total of 7.0×10^6 Mg, but this is not a good estimate of total sediment yield since the time of European settlement because the sediment yield has probably changed through time. An alternative method to estimate total sediment yield is to use reservoir sedimentation data from a surrogate, the Beaver Creek basin, 100 km north of Coon Creek. Besides being the same size as the Coon Creek basin and having similar physical characteristics and land-use history, Beaver Creek has been dammed at the lower end since 1867 forming Lake Marinuka. Moreover, a detailed reservoir sediment survey was done there in 1939 by the USDA Soil Conservation Service. The 1939 maps and profiles were obtained from the National Archives, the sur-

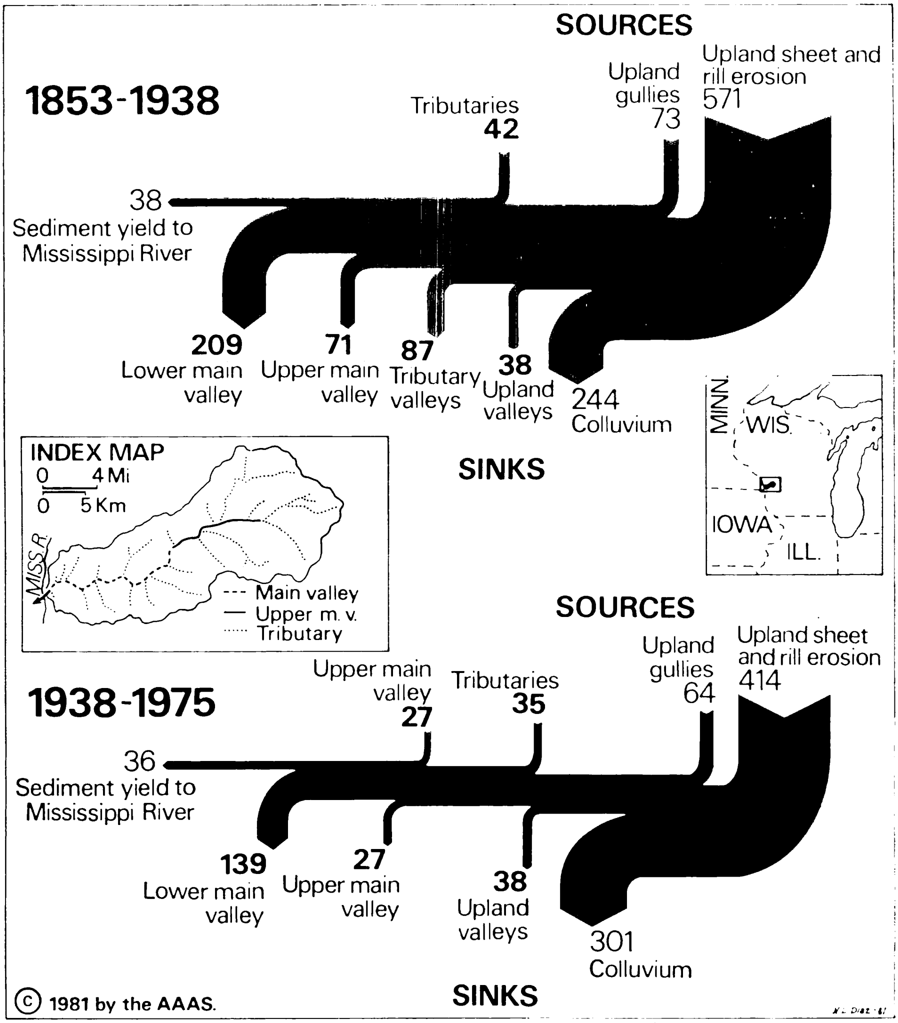

Fig. 2. Sediment budgets for Coon Creek, Wis., 1853-1938 and 1938-75. The basin is about 25 km southeast of La Crosse, Wis., and has an area of 360 km^2. Numbers are annual averages for the periods in 10^3 Mg yr^{-1} and account for 3.6×10^7 Mg of sediment generated between 1853 and 1975. Bold numbers are measured, other numbers are estimated. Note that the upper main valley, which was a sink for sediment in the earlier period, has become a partial source of sediment in the later period.

vey was repeated during the field seasons of 1976 and 1977 and the sedimentation history was computed (fig. 3).

The trap efficiency of the reservoir was obtained by computing the reservoir capacity in 1867, 1939, and 1977 and dividing by the average annual water inflow. The resulting ratios were used in conjunction with the Brune trap efficiency curve (Chow, 1964) to estimate the probable proportion of the average annual sediment inflow that was retained. Values at the beginning and end of each period were averaged to give a mean trap efficiency for the period, and the average sediment accumulation was then appropriately increased to approximate sediment inflow (fig. 3). For example, the average trap efficiency for the period 1867-1939 was 52.5 percent, and the average annual accumulation was about 55 Mg/km^2 per yr; thus the estimated sediment inflow was 55/0.525 or about 105 Mg/km^2 per yr (bulk density of 0.9 g/cm^3 was used for deposits below spillway crest and 1.4 g/cm^3 for higher deposits). The total sediment yield between 1853 and 1938 (all deposits adjusted to a bulk density of 1.4 g/cm^3) was about 2.8×10^6 Mg, whereas the yield between 1938 and 1977 was about 1.4×10^6 Mg. The total sediment yield for Beaver Creek for the two periods by this method was about 60 percent of that obtained by linear extrapolation of Hindall's (1976) estimate of sediment yield for Coon Creek.

Estimate of sheet and rill erosion and colluvial deposition.—The estimates of erosion and deposition of colluvium are by far the most uncertain parts of the budget. Gross sheet and rill erosion were estimated using the Universal Soil Loss Equation (USLE) (USDA, Soil Conservation Service, 1975) for conditions (1) at the time of settlement (1853), (2) during the 1930s, the period of peak erosion (Trimble and Lund, in press), and (3) for the present decade. Although the "universality" of USLE is commonly criticized, its use in the study area is appropriate because soils, climatic, topographic, and erosional factors at the site are within the range of conditions to which USLE applies. Additionally, I believe an upland debris basin surveyed in 1977 (debris dam 4, fig. 1) yields an approximate measure of upland sheet and rill erosion for the late 1930s (Trimble and Lund, in press). Using these four

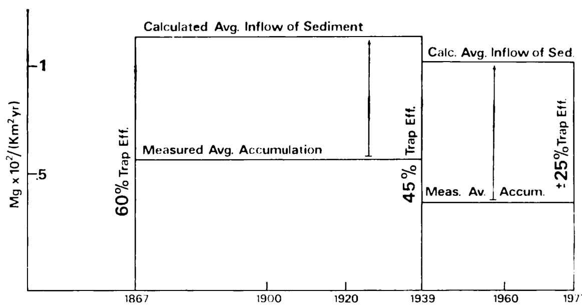

Fig. 3. Sedimentation in Lake Marinuka, Wis. Sediment yield of Beaver Creek, 360 km^2, periods 1867-1939 and 1939-1977. 1939 survey by E. Moser and party. 1976-77 survey by S. Trimble, J. Davis, and party.

data points and general knowledge of the area, I sketched a curve estimating the erosion rate through time (fig. 4). On the same graph, I drew a curve describing the deposition rate of all alluvium stored in the Coon Creek basin. This curve assumes that all stored alluvium was deposited at the same rate as that in the main valley, an amount that comprises about 75 percent of the total with the remainder being in tributaries and upland valley heads.

The total mass of eroded soil thus estimated is obtained for any time period (t=0,n) by computing the area under the erosion curve (fig. 4) for the period. The estimated gross sheet and rill erosion was about 43×10^6 Mg between 1853 and 1938, and 15×10^6 Mg between 1938 and 1975.

Sedimentation rates exceeded sheet and rill erosion rates for the period 1920-40 (fig. 4). I attribute this excess to upland gully erosion and upstream tributary channel erosion and estimate its magnitude as the difference in area under the two curves in figure 4 for the 1920-40 period. Since the total upstream tributary channel erosion is known from ground surveys (Trimble, 1976), the subtraction of this erosion leaves a residual that I consign to upland gully erosion. This residue is probably a minimal estimate of gully erosion for three reasons. First, not all material from sheet and rill erosion was being conveyed directly to stream channels, even at the erosional peak, so that much sediment was probably deposited as colluvium along the lower edges of fields and fence rows. Thus, the contribution of sheet erosion to overall sedimentation was less than the erosion curve alone indicates. Second, gully erosion usually delivers to streams a greater proportion of erosional debris mobilized by that process than does sheet and rill erosion. Third, both gully and tributary channel erosion existed before and after the peak period of about 1920-40 and cannot be estimated for those periods by comparing the two curves. Only for the period when sedimentation exceeded estimated sheet and rill erosion can these estimates of gully and channel erosion be made. Deposition of colluvium was estimated by subtracting the sum of all accretion plus sediment yield, from the total sheet, rill, and gully erosion.

Discussion of budget.—Clearly the most significant pattern to emerge at this stage is that sediment yield is quite small compared to either erosion or sediment storage. In fact, sediment yield is the smallest overall component of the budget. Given that so much emphasis has traditionally been placed on sediment yield as an indicator of erosional processes in stream basins (Trimble, 1975a, 1977), it is sobering to realize that sediment yield was only about 6 percent of all erosion estimated to have occurred between 1853 and 1938 and only 11 percent of the net accretion in stream valleys.

The methods used to estimate erosion are crude, but study of the overall budget suggests that the values obtained are reasonable and are of the proper magnitude. The estimated overall average depth of erosion is 13.2 cm, which compares well with a depth of 17.8 cm computed for the Southern Piedmont by Trimble (1975b) using soil-profile truncations. Haverland (1944), also using soil-profile truncations, estimated that the cropland and pasture of the Coon Creek area had lost about 15 cm of soil by sheet and rill erosion. Because cropland and pasture accounted for only 62 percent of the total area, the equivalent soil loss from the entire basin would be 9.3 cm, but this value excludes gully erosion and all erosion in woodland. All three of these erosional estimates are of a similar magnitude.

Sheet and rill erosion comprise almost 90 percent of all upland erosion whereas gully erosion accounts for about 10 percent. However, the proportion allotted to gully erosion is probably underestimated. It is important to note that most agricultural erosion is of the sheet and rill type (Robinson, 1978).

The estimate for colluvium is the weakest component of the budget, yet it too appears reasonable in light of other work in progress. Measured sediment yield, from 10 sub-basins (Public Law 566 basins) of Coon Creek (fig. 1), was only about 8 percent of estimated upland sheet and rill erosion for the period 1962-76. The remaining eroded material was presumably deposited as colluvium because we could find little evidence of alluvial deposition. Not surprising is the larger proportion of colluvium for the second period (fig. 2). When a landscape is severely eroding as was this basin during the 1920s and 1930s, rills and gullies are well developed and convey a larger proportion of eroded material to streams.

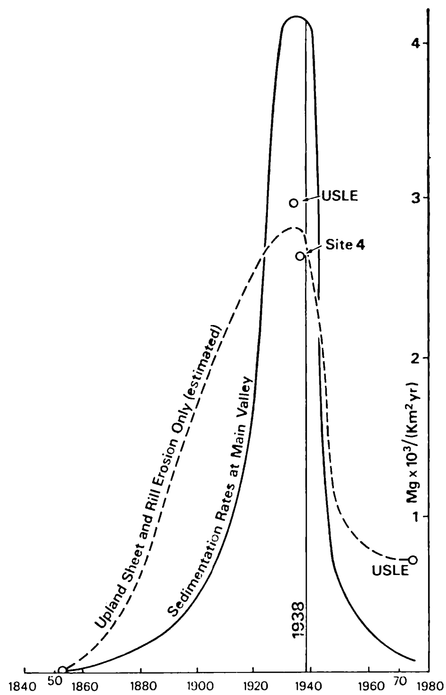

Fig. 4. Estimated rates of erosion and sedimentation, Coon Creek, Wis., 1853-1975.

However, as conservation practices are increased, critically eroding land is removed from production, rills and gullies heal, and less of the eroded material is transported to streams (Trimble and Lund, in press).

VARIATION IN SEDIMENT TRANSPORT AND STORAGE

Variation in sediment transport rates and storage are of great importance in understanding and analyzing processes in the drainage basin. The study thus far has considered primarily average values: total sediment accumulation for a period has been divided by the number of years to give an annual rate (fig. 2). The time of the first sediment survey (1938) in Coon Creek came at an unfortunate time in one sense, because the 1930s were near the peak of erosion and sedimentation (Trimble and Lund, in press). Thus, both average rates (fig. 2) are weighted by the high rates of the 1930s. If rates for additional periods or point rates can be established, it would be possible to reconstruct highly variable rates over time.

A good example of variable sedimentation rates is shown by the valley sedimentation profile CV30, located in the lower main valley of Coon Creek (figs. 1 and 5A). The 1853 (presettlement) flood plain was located in 1938 by borings to the surface horizons of an old alluvial soil, a dark, organic, texturally homogeneous soil (McKelvey, ms). The approximate elevation of the 1904 flood plain, about 0.75 m above that of 1853, shows the slow rate of vertical accretion (0.015 m/yr) during the first 51 yrs of settlement.

The 1904 elevation was approximated by finding the compacted flood plain surface behind a railroad embankment, built in 1904, which acted as a dike, allowing flood-plain aggradation on the streamside but eventually creating a lake between the dike and the adjacent hillside. The elevation thus approximated is probably a maximum value. Because vertical accretion was the dominant process in the main valley, where most sediment was stored, each successively higher flood plain surface was approximately conformal with the one being buried. Thus, a point elevation allowed an approximation of the flood plain of that date.

By 1930, the flood plain had aggraded another 1.5 m (0.06 m/yr), a remarkable increase over the 1853-1904 rate. The 1930 flood plain elevation was established by locating and boring to an old gravel road which crossed the stream at a bridge, the abutments of which have been completely buried. The existence of the road, the year of abandonment (1930), and the fact that the road was at the level of the flood plain were disclosed by elderly local residents. Within 3 yrs of abandonment, the road was completely covered by sediment and not detectable on an aerial photograph made in early 1934. The 1938 profile was a surveyed line (McKelvey, ms). In the 8 yrs following 1930, the flood plain aggraded almost 1.2 m (0.15 m/yr), indicating the very rapid sedimentation during the 1930s. Then, in the 38 yrs between 1938 and 1976, aggradation was only 0.6 m (0.016 m/yr), a greatly reduced rate.

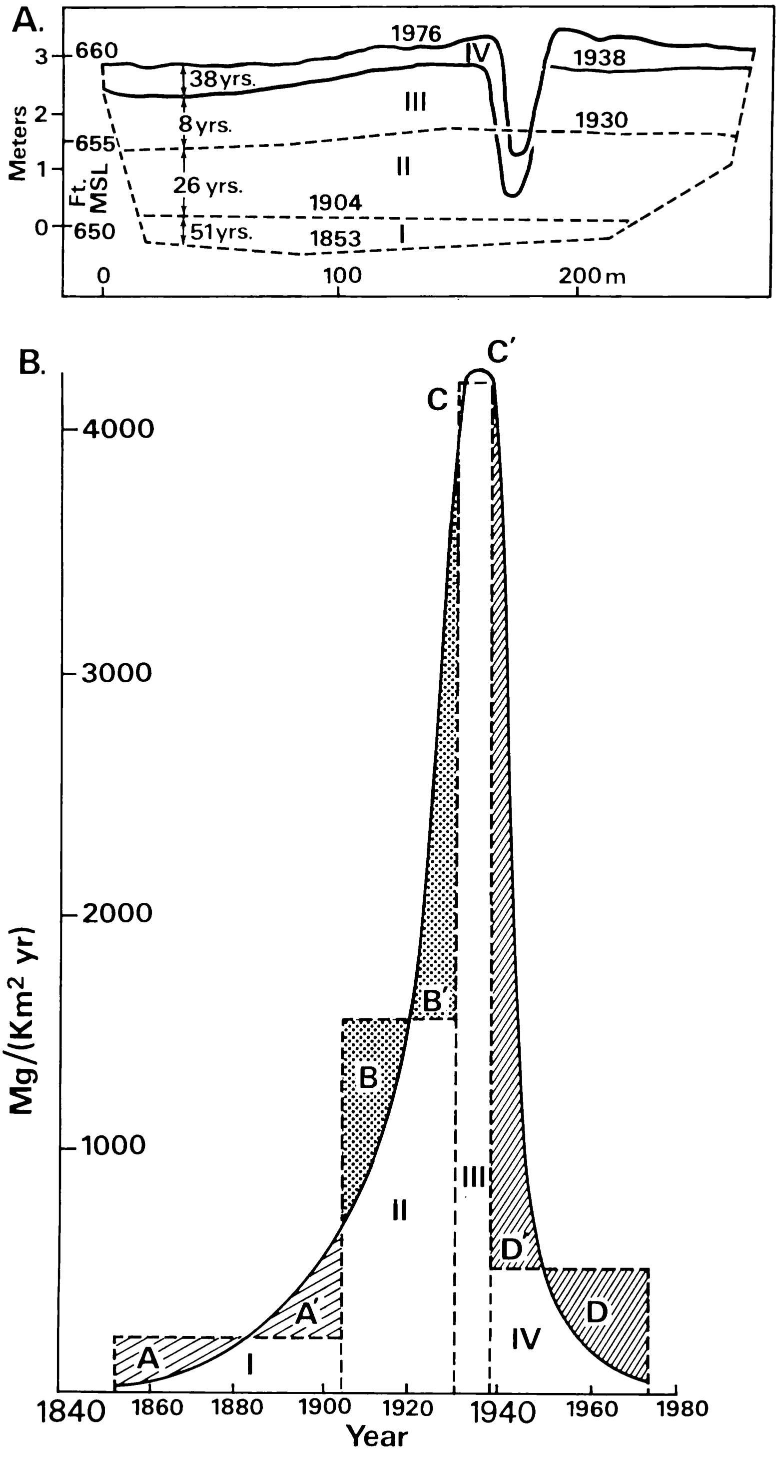

Fig. 5. Mass-rate budgeting. (A) shows flood plain profiles at CV30 (fig. 1) at various dates. Volume of sediment is considered proportional to the cross-sectional area between dates, and this volume is used to compute the sedimentation rates shown in (B).

A mass-rate budgeting method.—The relative deposition rates for the discrete periods above were established from the amount of accretion in cross-sectional profiles (fig. 5, A and B). That is, area I on the profile is proportional to the area of rectangle I on the graph, area II to the area of rectangle II, et cetera. Because channel sizes were not known before 1938, channels were ignored in all cross-section measurements, and all flood plains were considered to extend from valley side to valley side. Although channel size changed through time, the variation in size was small relative to the changes in the total flood plain. These rates give a more complete representation of the deposition history than those obtained from only three surveys (fig. 2). By scaling the graph to the known quantities, the relative rates for the four periods are estimated quantitatively.

The graph can be further improved by end values. We know that erosion and sediment-deposition rates were low at the time of initial European settlement from four lines of evidence: (1) minimal upland erosion from forest and prairie, (2) low stream loads, (3) the presence of well-formed soils on flood plains; and (4) ^{14}C dates in local flood plains. The approximate value used was 10 Mg/(km^2 yr) (Trimble and Lund, in press).

The rate of deposition for recent years can be definitely ascertained only after a few more years when resurveys can be made of the profiles. Deposition on flood plains has been slow in recent years as evidenced by lack of aggradation around fence posts and root crowns of trees, but these observations do not yet give good quantitative data. However, sedimentation surveys for 1962-75 of ten Public Law 566 reservoirs in the Coon Creek basin (fig. 1) give a reasonable estimate of eroded material delivered downstream to tributary channels and flood plains where the dams are located. Of this material, which amounts to an average of 55 Mg/km^2 per yr, an unknown proportion is deposited on downstream flood plains during overbank flows, and the remainder is discharged from the system. Determination of the proportion transported from the basin is complicated by the fact that channel erosion is occurring in tributaries and in the upper main valley. Channel erosion is primarily a reworking of sediment deposits, and any portion later deposited downstream in the channel or on the flood plain cannot be considered a net addition to storage of alluvium. However, assuming that the 55 Mg/km^2 per yr of sediment provided to the ten documented tributaries is representative of the entire basin, this places an upper limit on net addition to sediment storage.

Once the end values are approximated, the stepped rate graph can be smoothed to give continuity. The accumulation rate at each profile site is used to budget all sediment identified in the Coon Creek basin, and the areal base is the entire basin, not the upstream tributary area. This approach facilitates integration of the values to give composite curves. Construction of the curve is effected by shifting areas within time periods of that area (volume) A = A′, B = B′ et cetera (fig. 4). The shape of the curve is thus determined by the number of constraints imposed.

This can be done mathematically but is more easily done by eye and checked with a planimeter. Such a graphical solution is not perfect but is far more precise than the field data on which the curve is based.

The smoothing procedure may be questioned by some, especially those who work in arid regions where significant changes of streams and flood plains are associated with extreme, or even catastrophic, events. Although floods have occurred in the Coon Creek basin, the changes of sedimentation rates have occurred with relatively low-to-medium magnitude, medium-to-high frequency events, and have been generally continuous. Continuous change of hydrologic and sedimentation regimes caused the variation in deposition rates (Trimble and Lund, in press). Three lines of evidence support this contention of low year-to-year variability. The first is historical: the rapid sedimentation rates of the 1920s and 1930s are within the memory of many area farmers. Average vertical accretion rates of that period were about 15 cm/yr, and this was usually from several events each year. Although a single event could bring enough sediment to bury the grass cover of the flood plain, aggradation was usually more insidious, so that fence posts seem to shrink in height over a period of years. Second, detailed precipitation data from the Coon Creek basin for the years, 1934-40, when sedimentation rates were at the highest, show no extreme daily events (USDA, Soil Conservation Service, 1942). However, extreme events (20 cm/24 hrs) did occur in 1951 and 1978 without the high sedimentation rates that occurred in the 1920s and 1930s (Trimble and Lund, in press). Third, superposition of six continuous sedimentation graphs (fig. 6) gives remarkably similar curves. Because the times of observation are different in each of the six cases, the similarity would be highly improbable unless the rates were generally continuous. The curves, however, should be considered as trends and may not be correct for any given year.

Overall sediment budget based on deposition rates in the lower main valley.—Sediment accumulation rates were established at six cross sections in the lower main valley. The peak rates of deposition all occurred in the 1930s and early 1940s and range from 3500 Mg/km^2 per yr to 4700 Mg/km^2 per yr (fig. 6). Because so many uncertainties exist in reconstructing these rates, the variation among sites is probably insignificant, and only a mean or composite value is useful. Considering the difficulties and uncertainties of reconstructing such rates, there is remarkable coincidence of the six curves. Given the different times of observation at each location, the coincidence seems to preclude major polymodal vacillations in the accretion rate. The basic deposition rate (fig. 4) derived on the lower main valley has been used here to budget all alluvium stored in the Coon Creek basin. The composites (fig. 6) indicate that the highest rates of aggradation existed between 1920 and 1945 with the peak occurring in the 1930s. Composite B is the closest approximation of upland sediment supply rates because sediment estimated to have come from tributary channel erosion (Trimble, 1976a) has been excluded from calculations to generate this curve. This peak of about 3700 Mg/km^2 per yr is similar to the weighted value of 4750 Mg/km^2 per yr measured in small reservoirs (debris basins, fig. 1) which controlled small drainage basins upstream from flood plains during about the same period (Trimble and Lund, in press). From this analysis, I conclude that the average net rate of sedimentation on flood plains was over 3500 Mg/km^2 per yr in the 1930s, whereas the rate for recent years appears to be on the order of 35 to 70 Mg/km^2 per yr. This means that the current net sedimentation rate is on the order of 1 or 2 percent of that in the 1930s.

VARIABLE SEDIMENT BUDGETS WITHIN THE COON CREEK BASIN

Evidence from Coon Creek and other Driftless Area streams suggests that no physical basis exists for assuming that one sedimentation curve is applicable to all parts of the drainage basin. Indeed it appears that deposition may occur in one part of the basin while erosion occurs in another. Events in Coon Creek basin and in much of the Driftless Area may have involved the following scenario (Trimble and Lund, in

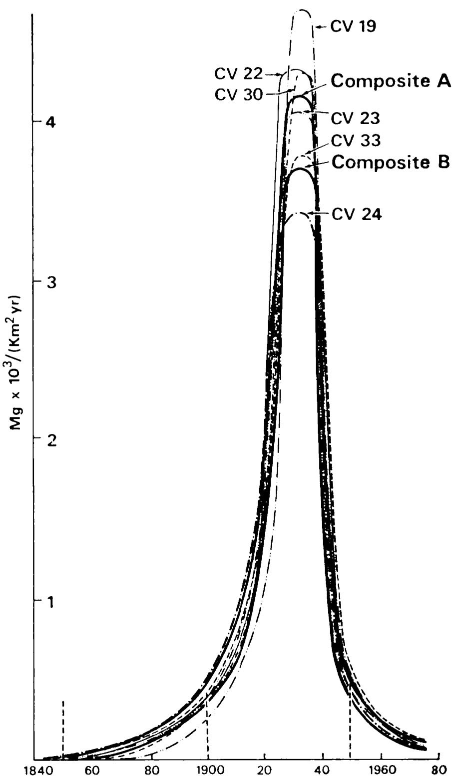

Fig. 6. Sediment accumulation rates at six sites in the main valley, Coon Creek, Wis., 1853-1975. Composite A is from all erosion. Composite B has been reduced 11.2 percent, the proportion due to tributary channel erosion, so that the curve represents sediment from upland sources only.

press). As accelerated erosion began after the Europeans began to cultivate the soil, the erosion was mild and scattered. Most of the material was deposited as colluvium and as alluvium along small tributaries. With time, fields expanded in number and size, and because of the relatively poor agricultural practices, the hydrologic properties of soils degenerated; consequently, rills and gullies became more pronounced. As direct runoff became greater for a given amount of precipitation, increased flow velocities resulted in greatly enlarged channels and a marked reduction in overbank deposition. At the same time, erosional products of tributary channel erosion and upland gullying, rilling, and sheet erosion were transported further downstream where most was deposited. By the 1920s and 1930s, flood plains in the main valley were aggrading at rates of 15 cm/yr.

The recent history of sedimentation is graphically summarized using mass-rate budgeting for three regions (tributaries, upper main valley, and lower main valley) of the Coon Creek basin (fig. 7).

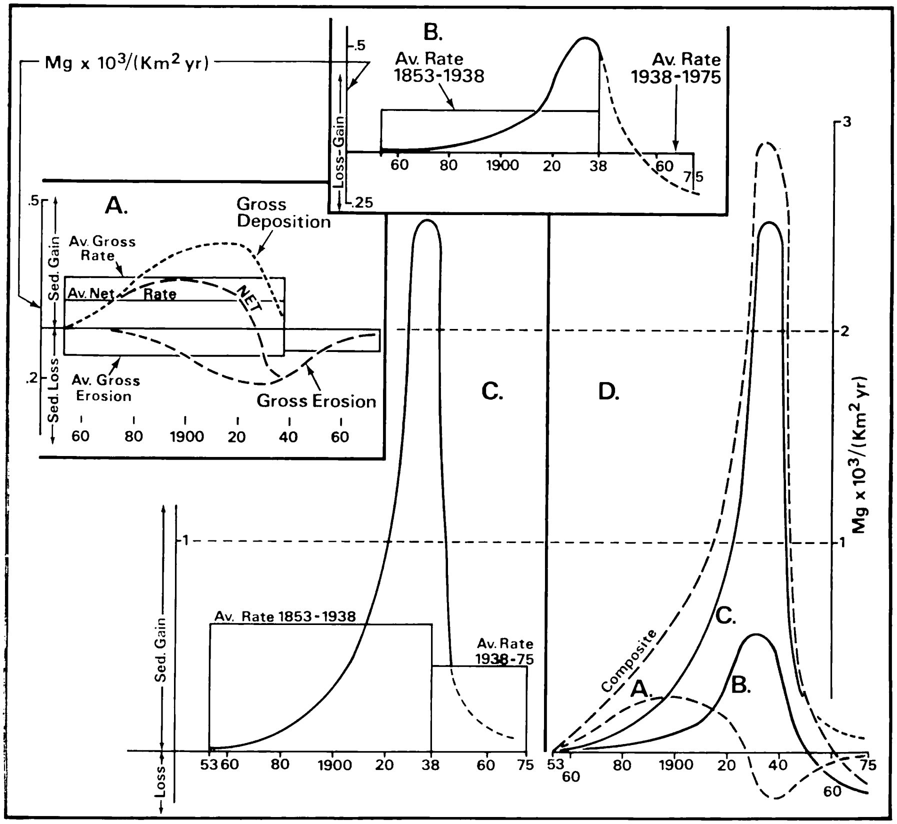

Fig. 7. Differential and composite stream and valley sediment budgets, Coon Creek, Wis., 1853-1975. (A) Tributaries; (B) upper main valley; (C) lower main valley; (D) superimposition and composite. Refer to figure 2 for locations.

Tributaries.—From 1853 to 1938, gross accretion in tributaries occurred at a rate comparable to about 200 Mg/km^2 per yr of drainage area (fig. 2). (All rates are based on the total area of the Coon Creek basin in order to give a common base and thus allow integration of rates, fig. 7.) At the same time, erosion, mostly by channel enlargement, occurred at a rate of about 100 Mg/(km^2 yr) leaving a net accretion of about 100 Mg/km^2 per yr. For the period 1938-75, net erosion was equivalent to 80 Mg/km^2 per yr. Although detailed valley cross sections like CV30 could not be constructed for tributaries, the constraints of the mass-rate technique plus photographic evidence reveal changes in sediment storage in tributaries. Historical photographs indicate that alluviation of tributary flood plains was evident by the early 1900s. Channel trenching apparently was not widespread until after 1905-10 but was common by the 1920s. Based on these constraints, curves of gross deposition and gross erosion are sketched (fig. 7A). By subtracting the erosion curve from the deposition curve, a net curve is drawn that describes peak accretion sometime after 1900, while the channels were still small enough to permit frequent overbank deposition. By the late 1930s, the dominant process was channel erosion with little overbank accretion. Bank and channel erosion has ameliorated in recent years because of (1) decreased frequency of erosive floods and because (2) streams have removed so much of the high bank to either side that bank-to-bank flow is rare. The curve of net change in storage presently is approaching zero (no erosion or accretion), but the approach is asymptotic and net erosion may continue for years.

Upper main valley.—The upper main valley (fig. 7B) has had a history similar to that of the tributaries. Maximum accretion occurred later and to much greater depths than in the tributaries, reaching a maximum rate in the early 1930s. Net erosion has occurred since about 1950. Although bank erosion was active in the 1930s, accretion was dominant so that the slip-off slope opposite a cut bank was aggraded to the level of the cut bank. In recent years, cut banks have continued to retreat, but slip-off slopes have not been aggraded to commensurate levels, so a lower flood plain appears to be forming between the higher banks of the old flood plain. The resulting large channel capacity has increased enough that overbank flow has become infrequent, and the old flood plain, which was rapidly aggrading in the 1920s and the 1930s, now rarely receives overbank deposition. Thus, the upper main valley appears to be undergoing a process similar to that seen earlier in the upstream tributaries, but the peak in sedimentation was more pronounced and occurred more recently in the upper main valley. This sequence of events appears to be moving downstream.

Lower main valley.—The geometry of lower main valley accretion rates (fig. 6) is used to budget only the material actually located in the lower main valley (almost 60 percent of the total sediment stored in the basin since 1853) giving a peak of about 2500 Mg/km^2 per yr during the 1930s (fig. 7C). Because the locus of channel erosion, now in the upper main valley, appears to be moving downstream, the lower main valley may begin to show net sediment losses in the future.

Composite.—Differential rates for each part of Coon Creek drainage basin have the same area base, and since they together account for changes in storage in all the modern alluvial sediment in Coon Creek basin, they can be integrated to give a composite (fig. 7D).

COMPARISON OF SEDIMENT STORAGE AND SEDIMENT YIELD

A net storage gain in alluvial deposits of almost 3000 Mg/km^2 per yr occurred in the 1930s (fig. 7D). However, if Hindall's (1976) adjusted estimate of 160 Mg/km^2 per yr sediment yield for the 1930s is reasonable for that period, sediment leaving the basin was only about 5 percent of that going into storage. The foregoing suggest that given an adequate sediment supply, the maximum long-term sediment-transport capacity of Coon Creek is only about 150 to 200 Mg/km^2 per yr. The concept of a maximum conveyance capacity of stream valleys is strengthened by the fact that the maximum measured long-term sediment yield from any Driftless area stream is less than 200 mg/km^2 per yr (Hindall, 1976). In fact, Hindall's data suggest that little difference exists between present sediment yields and those of the 1930s. Thus, fluctuations of storage volumes have been much larger than changes in sediment yield rate. As an indicator of change in this environment, the oft-used sediment yield is much less sensitive than change in storage.

The concept of a maximum conveyance capacity of stream valleys has a physical basis. Natural stream channels, unlike canals and flumes, are actually low-water conveyance routes, and during the greatest discharges of water and sediment, much of the conveyance may be over the floodplain. In the lower main valley of Coon Creek, the flood plain may be twenty times as wide as the channel so that the "channel" assumes much different proportions during a flood. Flood plain surfaces, usually being vegetated, tend to offer much more hydraulic friction with Manning's n often being several times that of the channel. Depth of flow is also much less over the floodplain than in the channel. Thus, despite the much greater width of the floodplain relative to the channel, the floodplain conveys a much smaller proportion of the water discharge than the relative widths might suggest. Likewise, only a small proportion of the sediment entrained onto the floodplain may be transported because of the decrease in tractive force, and much is deposited as vertical accretion on the floodplain. In following a flood down a stream valley, one sees sediment-laden water leaving the channel at every turn while water from the floodplain, having lost much of its sediment load, returns to the channel. In such an exchange, much of the sediment load from the uplands can be lost to storage in the floodplain. Thus, the floodplain acts as a filter or bottleneck for sediment. This is one reason why, in many streams, sediment yield per unit area tends to decrease downstream.

The effect of the floodplain appears to be greater when streams are transporting heavy sediment loads and less when streams are in equilibrium. Wolman and Leopold (1957) indicate that near-regime streams have floodplains with little vertical accretion. Also, Wolman and Eiler (1958) showed that extreme floods could produce local scour on floodplains of a magnitude similar to accretion.

Floodplain aggradation can be very significant if sediment loads are high enough and vertical accretion of several meters has been recorded on many flood plains (and in channels) since European settlement (Happ, Rittenhouse, and Dobson, 1940). Such deposits are not necessarily coarse material, and, in fact, many are of fine textured sediments. Thus, the idea that a stream will transport all the fine sediment supplied to it (for example, Guy, 1970, p. 19) would apply only as long as the sediment were in the channel. Even then, the presence of deep channel and bank deposits of fine material deposited during the past century (Trimble, 1976) make the assured transportation of all fine material very questionable.

If the present sediment yield from Coon Creek basin is similar to that of comparable basins in the region (50-200 Mg/km^2 per yr), sediment yield per unit area may be greater than the 55 Mg/km^2 per yr supplied to the larger Coon Creek tributaries by upland erosion. Such a condition is suggested by the composite storage budget (fig. 7D) which shows a net loss from storage during recent years. Sediment yield per unit area in Coon Creek may actually be increasing downstream with the augmentation coming from the storage loss. The present widely held concept is that sediment yield per unit area decreases with basin size (Guy, 1970, p. 16; Schumm, 1977, p. 34, 70-72), whereas this analysis suggests that sediment yield per unit area may presently increase with basin size in the Coon Creek basin and, by inference, in many agriculturally disturbed basins of the humid United States. The data also strongly suggest that yield per unit area at a point in the system can change with time as the result of changes in sediment storage. If these inferences are correct, present concepts of the relation of drainage area to sediment yield will have to be rethought and further investigation is necessary.

Although stream and valley deposition may proceed rapidly as already noted, erosion of stream valleys may not be so rapid. While some floodplain deposits, especially sediment in steep, narrow valleys in arid regions, may be highly mobile, many flood plains are relatively immobile, even during extreme discharge events ($\geqslant$ 25 yr return frequency). Fine textured banks and floodplains may be highly resistant to erosion, especially when unsaturated, and rank vegetation may armor them. And as previously discussed, wide floodplains and/or thick vegetation so reduce water velocity that little tractive force is available for erosion of the floodplain surface. Instead, the stream can usually only effectively erode its channel and/or banks. The latter process, lateral or cut-bank erosion, may proceed rather slowly, and cutting across a wide floodplain may actually take centuries. The net result is that a stream flowing through a floodplain may require only a century to deposit, say, 5 m of vertical accretion, but the removal of this material may take millennia. The estimate for a small stream with a floodplain 7 times as wide as the channel is about 1000 yrs (Leopold, Wolman, and Miller, 1964). In short, floodplains may be rapid sediment sinks but slower sediment sources, especially in humid areas where extreme events are less common so that vegetation has a greater opportunity to secure and armor the flood plain. Also important is that loss of sediment from storage in stream and valley deposits appears to occur at low as well as high discharges and to be a long-term phenomenon. This conclusion is in contrast with the concept that such flushing is caused primarily by floods of extremely high magnitude, having a recurrence interval of about 1000 yrs (Schumm, 1977, p. 86).

Analysis of the sedimentation history of the Coon Creek basin suggests that long-term relationships between sediment yield and upland sediment supply are complex (fig. 8). Downstream sediment yield may increase as a function of upland sediment supply up to the maximum stream and valley conveyance capacity (ordinate value A, fig. 8), but beyond that value, sediment yield increases slowly if at all, and the excess sediment goes into storage.

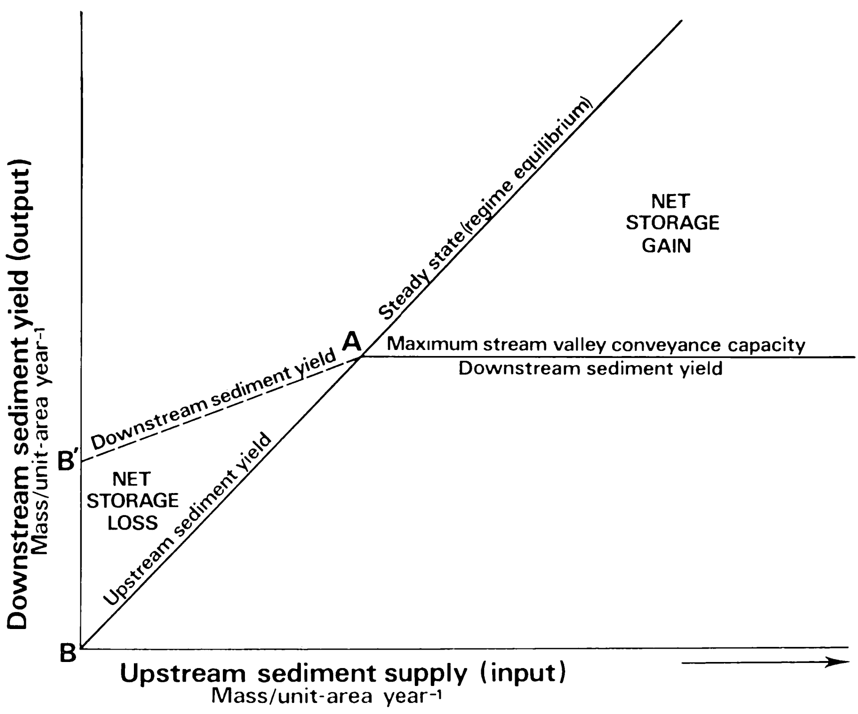

Fig. 8. Schematic relation of downstream sediment yield and upstream sediment supply. Value A is the stream valley conveyance capacity. AB is for a stream with non-erodible bed and banks. AB′ is for a stream with erodible bed and banks. "Upstream" is upstream from significant alluvial storage, whereas "downstream" is at the mouth of the basin.

Sediment yield may be limited by sediment supply or energy available for transport. Line AB′ (fig. 8) is for a stream with erodible bed and banks such as present-day Coon Creek. Even if no sediment were supplied from the uplands, erosion of the bed and banks could still supply substantial sediment yield. Line AB′ is variable depending on the erodibility of the bed and banks. Line AB (fig. 8) describes a stream with nonerodible bed and banks. With little sediment being supplied from the uplands and stream bank and bed, sediment yield is low. This line may describe conditions at the time of European settlement, when stream banks were armored with vegetation that dissipated the erosive energy of the stream. Because there was also little erosion from the uplands at that time, streams were generally clear.

Dynamics of sediment storage have qualitative as well as quantitative implications. For example, many agricultural and industrial chemicals such as pesticides and PCBs adsorb on soil and sediment particles, and stream water and sediment measurements have been an important technique in monitoring the movement of these chemicals into the environment (Willis and others, 1976). Deposition of pollutants with sediment or other release from storage could cause deceptive measures of environmental impact from a given land treatment. For example, a recently-applied pollutant may disappear into storage, giving anomalously low concentrations downstream. Additionally, storage of chemicals attached to sediment particles may pose a long-term pollution problem or, conversely, may provide adequate time for degradation.

RELATION OF VARIABLE SEDIMENT BUDGETS AND STREAM-CHANNEL MORPHOLOGY

Changes in sedimentation regimes described in this paper correlate with variation in stream-channel morphology. A channel in equilibrium or steady state (fig. 9A) exhibits no net gain or loss of sediment. Such a channel may be stable, or lateral erosion may be occurring. If the latter is the case, the slip-off slope opposite the cut bank advances and compensates for the sediment loss so there is no net change of channel size. Such steady-state channels are not now found in the area, but the preagricultural channels in Coon Creek probably approached this condition.

An aggrading channel (fig. 9B) may exhibit vertical accretion only, or more likely, lateral erosion with both net lateral and vertical accretion occurring. In either case, there is a net gain of sediment. This condition is now characteristic of the lower main valley where sediment is still accumulating.

The eroding channel (fig. 9C) shows lateral and/or vertical erosion. In the case of lateral erosion, the slip-off slope does not accrete to the level of the flood plain being destroyed, and, consequently, a new flood plain is created at a lower level. In either case, the channel cross-sectional area to the old, higher, flood plain level becomes larger. The lower flood plain may be diagnostic of a milder hydrologic regime

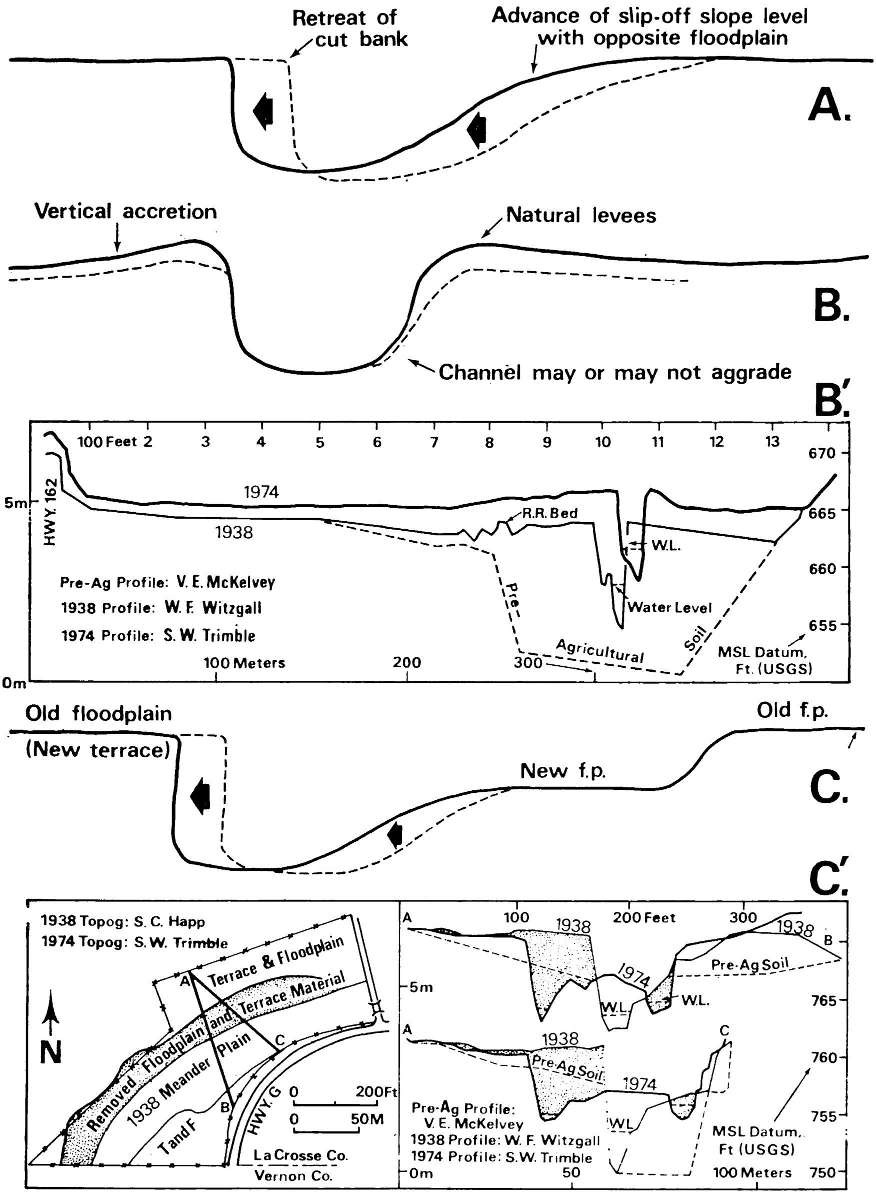

Fig. 9. Stream morphologies of Coon Creek. (A) is an equilibrium channel with no net storage gain or loss. It is characterized by either stability or lateral erosion and accretion, as shown. Such morphology characterized Coon Creek before agriculture. (B) is an aggrading stream. It is normally characterized by vertical accretion, as shown, but lateral erosion and accretion can also coexist. This morphology characterizes the lower main valley (fig. 2). B′ is an example, Coon Creek Profile 28 (CV28, fig. 1). The location is NE1/4NW1/4, sec. 29, T14N, R6W, Vernon Co., Wis. (C) is an eroding stream. Lateral erosion is dominant, but degradation can occur. The new, lower, flood plain is possibly diagnostic of a milder hydrologic regime. This morphology characterizes the tributaries and upper main valley (fig. 2). An example is C′; Bohemian Profiles 13 and 13R (Bo 13, fig. 1). The location is SE1/4, SE1/4, sec. 33, T15N R5W, La Crosse Co., Wis.

wherein any given return frequency event is of a lower magnitude than those that built the higher flood plain.

An eroding channel is presently characteristic of the upper main valley where the largest sediment storage losses are now occurring. Tributaries were formerly of this type, but they have created a lower flood plain so wide that the streams now rarely contact a high bank so that the net loss of material has been greatly decreased in the past 40 yrs (fig. 7A).

CONCLUSIONS

Three approaches to quantifying sediment budgets have been demonstrated for the Coon Creek basin. The first simply gives the mean rate of a process for a long time period. Although data requirements for this method are considerable, they are the least of the three methods. The most significant observations to emerge from such a budget are that storage is the greatest component and sediment yield is the smallest. The primary liability is that the values are means, and variability is not shown. The second approach uses reconstructed deposition rates from the main depositional areas to show the variability of rates over time. Although this is an improvement over the average rate method, it does not show the differential sediment fluxes occurring within a stream system. In the third approach, sediment budgets are constructed for regions within the basin, wherein rates of processes have been relatively homogeneous. Because these budgets are constructed with the same areal and temporal bases, they may be integrated to give a composite budget, which is the most accurate one-graph budget.

This composite budget shows that sediment storage increased after European settlement and increased rapidly after about 1900, reaching a value of almost 3000 Mg/km^2 per yr during the 1930s. During the same period, however, sediment yield was estimated to be only about 160 Mg/km^2 per yr or about 5 percent of the net storage gain. This suggests that the maximum sediment-transport capacity of Coon Creek at that time was on the order of 160 Mg/km^2 per yr. Stream sediment and water discharge characteristics, together with the storage opportunities, apparently create a "bottleneck" that limits the amount of sediment that can be flushed from the basin in a given time period. Material supplied to the stream in excess of its transport capacity goes into storage.

This leads to the question: If sediment supplied to the stream was even greater, would sediment yield have been appreciably higher? My evidence suggests that it would not. Because the stream was already being supplied 20 times as much as it could transport, increasing the factor further would have increased the amount stored and not the sediment yield from the basin.

The volume of sediment stored decreased rapidly after the 1930s, and imperfect data suggest that there is presently a net loss of sediment from storage. That is, some of the present sediment yield from Coon Creek basin is derived from alluvium stored earlier in the 19th and 20th centuries. Thus at any point in the basin, sediment-delivery ratios may change through time.

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