Sediment Budgets (Proceedings of the Porto Alegre Symposium, December 1988). IAHS Publ. no. 174, 1988.

Morphological controls on sediment delivery pathways

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Abstract Sediment budgets can be used along with morphological measurements of sediment delivery pathways to determine systematic variations in sediment sources that occur with changes in basin area. In the Pequea Creek basin, USA, gully sources decrease in the downstream direction, while bank erosion sources remain constant or increase slightly. The result is a slightly decreasing sediment yield per unit area over the basin as a whole.

Contrôles morphologiques des parcours d'apports de sédiments

Résumé On peut utiliser les bilans de sédiments ainsi que les mesures morphologiques sur les parcours d'apports de sédiments pour déterminer les variations systèmatiques à l'origine, des sédiments avec les changements de dimensions du bassin versant. Dans le bassin versant de Pequa Creek, USA, les sédiments des ravines d'érosion diminuent vers l'aval pendant que les sédiments d'érosion des berges restent constants ou augmentent légèrement. En definitive, la quantité de sédiment qui débouche par unité dans le bassin entier, diminue un peu.

INTRODUCTION

The sediment yield of a drainage basin is hard to predict from its physical characteristics. Erosion from small field plots can be estimated using the Universal Soil Loss Equation (USLE) and similar techniques, but it has long been recognized that the USLE approach cannot be applied to larger areas due to redeposition of sediment on hillslopes and in stream channels (Meade, 1982). This stored sediment forms an important sediment source in some regions (Trimble, 1981). The sediment budget approach of determining the magnitude, frequency, and storage components of each erosion process can improve our understanding of the sources of stream sediment (Dietrich *et al.*, 1982). The approach taken in this paper is to determine the relative amounts of sediment delivered directly to stream channels by different erosion processes. The drainage basin described in this report is one where bank erosion and gully erosion are the dominant sediment sources. Although these processes remain predominant throughout most of the drainage basin, there are variations in their relative contributions in the downstream direction. By examining changes in basin and channel morphology associated with sediment source changes, we hope to be able to explain these variations in sediment contributions.

STUDY SITE AND METHODS

The site chosen for study is the Pequea Creek basin in southeast Pennslyvania, USA. This basin was chosen for both logistical and scientific reasons. The USGS has provided suspended sediment data from the river at six locations and has estimated the sediment yields at these sites (Lietman *et al.*, 1983). Suspended sediment data have been collected for additional locations on small tributaries. The combination of these data sets allows sediment yields to be estimated at 13 sites in the drainage basin. The additional suspended sediment data were collected by McHugh (1983) and Prestegaard & McGeehan (1986).

The basin has been affected by agricultural practices for nearly 200 years. Agricultural erosion has caused sedimentation followed by channel incision in most of the headwater tributaries, a pattern common to agricultural areas in the mid-Atlantic states (Costa, 1975; Vest, 1985). Although land has been removed from agricultural production in much of the northeastern United States, the amount of land in production in the Pequea basin has not undergone such changes. Farming practices have also not changed much; many of the farms in the basin are owned by Amish families who do not use heavy equipment.

The basin is shown in Fig. 1. This figures also shows the sites of suspended sediment data collection and the areas where bank erosion was monitored. Suspended sediment rating curves were determined for each location. Examination of the flow duration curves for small and large streams showed that the distribution of flows is similar for both (Lietman *et al.*, 1983). Therefore, a regional flow duration curve, based primarily on the longer records of the larger rivers, was used to define flow frequencies for all of the sampling sites. Sediment yields were estimated using the suspended sediment-flow duration curve method.

Measurements of bank erosion and gully erosion were made at numerous sites in the drainage basin (Fig. 1). The most intensive data set is that from a study of a small sub-basin located near Strasburg (Prestegaard & McGeehan, 1986). The amount of sediment contributed from various sources, particularly from bank and gully erosion was determined at five sites in a 2.8 km^2 basin. Variations in sediment sources in this basin are caused by variations in runoff sources and in channel morphology. It appears reasonable to assume that runoff sources and channel morphology would influence sediment delivery mechanisms in the larger basins.

To extend our research to larger basins, two morphological features were measured, firstly, channel morphology, which controls bank height and therefore bank erosion and, secondly, the density of gullies entering the stream channel, which is controlled by overland flow sources. Since the study was concerned primarily with sediment delivery to the channel, gully density was determined as the number of gullies per unit length of the stream. Gully

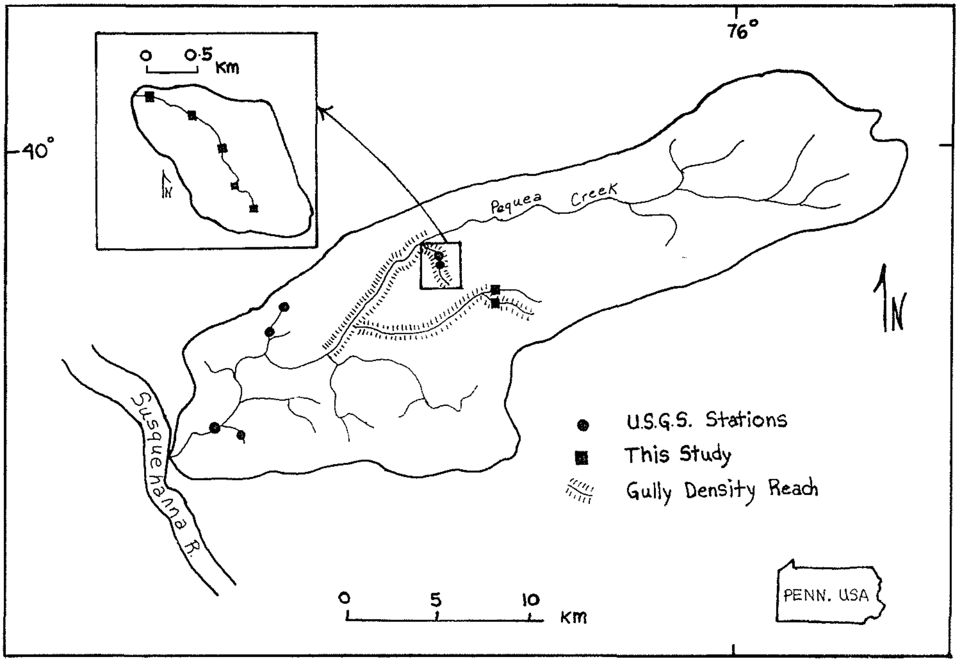

Fig. 1 Pequea Creek basin, showing suspended sediment sampling sites and the gully density reach.

density was determined for a segment of the channel outlined in Fig. 1. The morphological measurements were made in order to estimate sediment derived from various sources and to determine whether there are systematic changes in sediment delivery mechanisms.

SUSPENDED SEDIMENT YIELD

The sediment yield of the Pequea basin, expressed in t km^{-2}, indicates little or no decrease with increasing basin area (exponent = 0 to −0.25). This relationship is often termed the sediment delivery curve, but it tells us nothing about the actual processes of sediment delivery. A major question about sediment delivery curves is whether a decrease in unit sediment yield represents a downstream decrease in the efficiency of sediment delivery mechanisms or an increase in sediment storage in the stream system. This is a question that will be addressed in this research.

Selected sediment rating curves that are representative of those used to determine the sediment yield estimates are shown in Fig. 2. The actual data points have been omitted to simplify the diagram, but correlation coefficients for the sediment data range from 0.75 to 0.91. The diagram illustrates the similarity of slopes of the rating curves for gauging stations representing basins ranging from 0.5 to 414 km^2. If the relationship between sediment load and discharge is expressed as a power function of discharge, then the sediment rating curves have a narrow range of exponents (1.4 to 3.2), but a

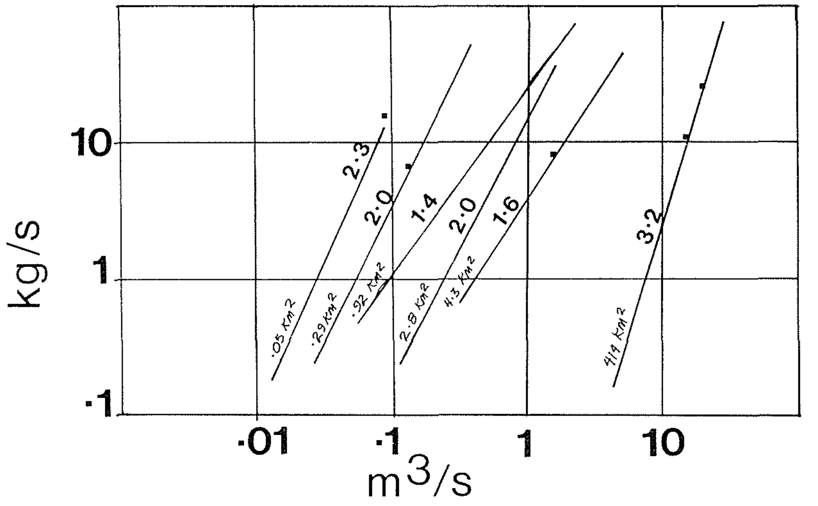

Fig. 2 Suspended sediment rating curves for stations ranging in basin area from gully size (0.05 km²) to the entire Pequea basin (414 km²).

very large range of constants. Even though there is a large downstream increase in discharge, the range of sediment load values is similar for all of the gauged sites. Bankfull levels of discharge and associated sediment loads are indicated on each of the rating curves. These "bankfull levels" actually decrease in recurrence interval downstream from 1.5 to 1.04 years as channel morphology changes from incised channels to frequently flooded channels. At the indicated levels, there is little change in the sediment load in the downstream direction. At flood flows, the incised channels will continue to transmit sediment loads, but a portion of the flow in the downstream channels is carried by overbank flows, leading to sediment deposition on the floodplains.

SEDIMENT BUDGET FOR A SMALL BASIN

A sediment budget was determined for the small basin outlined in Fig. 1 (Prestegaard & McGeehan, 1986). Sediment erosion sources were determined for individual storms by measuring suspended sediment loads during the storm hydrographs at each of the five gauging stations and measuring the suspended sediment loads contributed by the 22 main gullies in the basin. The amount of sediment derived from bank erosion was estimated by determining the sediment in excess of that contributed by gully erosion moving past each of the five stations. Estimates of the annual sediment load derived from each erosion source were made by determining the annual suspended sediment yield for each station by using the flow duration curves and sediment rating curves for each of the five stations. Bank erosion rates were measured on an annual basis for the stream segments between stations.

These bank erosion rates were then used to determine the sediment load derived from bank sources. The remaining portion of the sediment load for each station was assumed to be contributed by gully erosion. The annual sediment budget estimated in this manner provided proportionally the same results as the individual storm data (Fig. 3). The results indicate an increase in sediment load with increasing basin area and an increasing contribution from bank erosion in the downstream direction (Fig. 3). There was also an increasing proportion of sediment derived from bank erosion as fewer gullies entered the stream channel. The gullies in the upper part of the basin initiate from saturated areas developed in gentle swales that dominate the flat carbonate uplands. Hillslope gradients adjacent to the channel increase downstream in the basin, promoting throughflow relative to overland flow during storm events (Prestegaard & McGeehan, 1986).

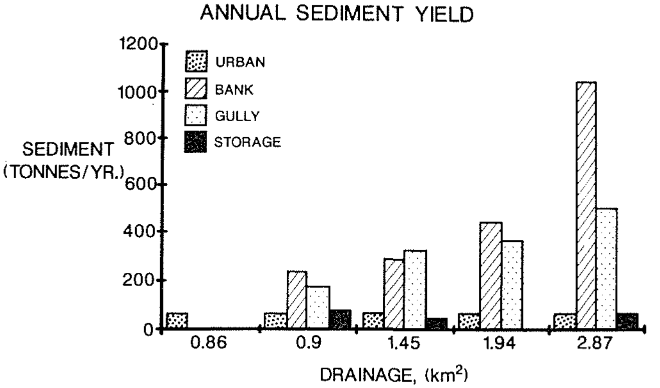

Fig. 3 Sediment sources for a small sub-basin.

The question that must now be addressed is how to extrapolate from the sediment budget for a small basin to the scale of the Pequea Creek Basin, which is two orders of magnitude larger in area. We have done this by examining the morphological controls on the sediment delivery processes.

MORPHOLOGICAL CONTROLS ON SEDIMENT DELIVERY

Bank erosion rates for sites along the main Pequea channel and its tributaries are shown in Fig. 4. This diagram shows two populations of bank erosion rates. The higher rates are the measured values of bank erosion in the basin. Due to the incised nature of headwater tributaries, undercutting of the stream bank provides larger volumes of sediment than for the non-incised parts of the channel. Actual rates of bank erosion therefore do not change over most of the measured sites (Koonz, 1983). Bank erosion rates were also determined for the inset "bankfull" channels that have begun to form within tributary channels. These small, often meandering, inset channels contribute less sediment due to the smaller amounts of exposed channel bank. The

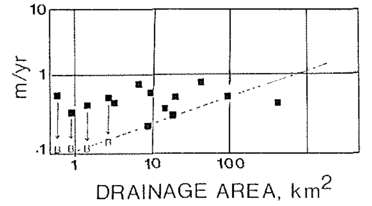

Fig. 4 Streambank erosion rates in the Pequea basin.

magnitudes of bank erosion in the basin are similar to those compiled by Hooke (1980), but they do not show the increase in rates with increasing drainage area expected from hydraulic considerations and normal downstream increases in bank height. The influence of the channel geometry on bank erosion rates is illustrated in Fig. 5, which shows the consistency of bank height in the basin.

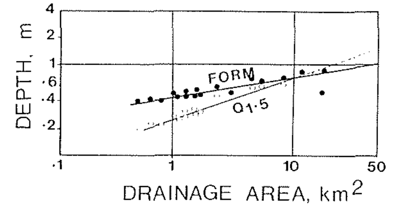

Fig. 5 Bank height and the "bankfull" depth vs. drainage area.

The final control on the sediment yield of the channels is the contribution from gully erosion. In the small sub-basin study, we found that most of the gullies were about the same size, and only a few gullies carried discharges higher than a few hundred ml s^{-1}. Gully erosion rates were largely controlled by stream power. Due to the small size of most of the gullies, the gully gradient determined their erosive power. Most of the gullies, however, were quite short, and the actual slope of the gullies was therefore controlled by the height of the stream bank and the length of the gully. Gullies could be initiated by pipe collapse and by overland flow from source areas, but they can be envisioned as having a brief life. Initially they are quite erosive as they cut through the stream banks. Later, they become mere conveyors of sediment prepared by freeze-thaw and other activity.

Although local gully discharges and sediment loads could be investigated in a small basin, this could not easily be undertaken for the entire drainage basin. Most of the gullies, however, supplied similar amounts of sediment. Large gullies draining large saturated areas on the hillslope become uncommon along the flat floodplains of the main channel. Therefore, the gully as a sediment delivery mechanism becomes largely a function of the gully density along the stream length. The stream bank height in most of the non-incised portions of the channel is not high enough to produce contributing gullies with very steep gradients. Gully densities were measured by counting gully frequency over the channel reach highlighted in Fig. 1. The

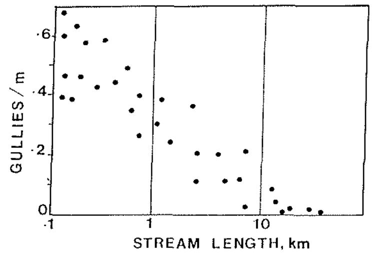

Fig. 6 Gully density vs. stream length.

results are shown in Fig. 6. This diagram shows that downstream changes in stream gully density are quite significant. This corresponds with two main morphological features of the basin. The flat headwater regions of the basins become saturated during storm events and generate many small gullies. The incised tributaries also contribute significant gully sediment along their lengths because of the steep gradients of the gullies that enter the incised channels. Along the main valley of the Pequea river, saturated areas are common, but the flat flood plains generate few gullies.

SUMMARY

The sediment yield per unit area in the Pequea basin remains almost constant in the downstream direction. An examination of the morphological controls of sediment yields suggests that there is a decrease in the delivery efficiency of gullies in the downstream direction, but that bank erosion maintains or slightly increases its effectiveness. The frequent flooding of the channel flood plains in the downstream reaches of the basin increases the amount of sediment that can be stored in the flood plain. These results are summarized in Fig. 7.

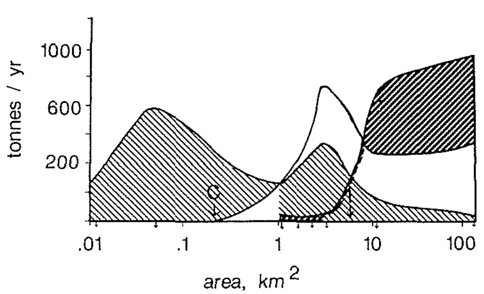

Fig. 7 Sediment yield by source. Right-handed diagonals indicate gully erosion. White area indicates bank erosion. Left-handed diagonals indicate sediment storage. C = channel initiation, I = upper average limit of incised channels. Arrows along the baseline indicate data points.

In the Pequea basin, it is not likely that the sediment stored in the lower basin will simply migrate downstream. The stream gradient steepens downstream prior to entering the Susquehanna River. . Sediment on the streambed and in suspension is transported through to the Susquehanna once it reaches these steep reaches.

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